1994


Luis Arnoby Rodriguez hurtado

Louisiana State University and Agricultural & Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_disstheses

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_disstheses/5900

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Historical Dissertations and Theses by an authorized administrator of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
SIMULATION AND TESTING OF A VIBRATING DIGGER BLADE
FOR ROOT CROPS

A Dissertation
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
in
The Interdepartmental Program in Engineering Science

by
Luis Arnoby Rodriguez Hurtado
B.S., Universidad Tecnologica de Pereira, 1972
M.S., Texas A&I University, 1984
December 1994
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to the following individuals and Institutions:

Dr. Malcolm E. Wright, my major professor and chairman of my graduate committee, for his support, help, comments and suggestions to the development of my studies and this project.

The Biological and Agricultural Engineering Department of Louisiana State University, especially to those who cooperated in one way or another in the preparation and testing of the equipment in the field; research associates Steven Smith and Larry Crow, and graduate student Francois Brassart. To Dr. Richard Parish for his help in my enrollment at LSU and Dr. Lalit Verma, Head of the Department.

The members of my Academic Advisory Committee: Dr. Michael Mailander, Dr. Medhy Sabbaghian, Dr. Yalcin Acar, Dr. Hussein Selim, and Dr. Scott Milligan for their valuable suggestions.

The Facultad de Ciencias Agrícolas of the Universidad Nacional de Colombia for supporting and granting me permission to enroll at LSU for my doctoral program.

The Organization of American States for awarding me a scholarship during a period of my studies.

My mother, brothers and sisters for their support and encouragement.
# TABLE OF CONTENTS

Acknowledgments .............................................................. ii

List of Tables ...................................................................... vii

List of Figures ..................................................................... ix

Abstract ........................................................................... xiii

Introduction ....................................................................... 1

Review of Literature .......................................................... 3
  Vibratory Tillage Terminology ......................................... 3
  Draft Reduction in Vibratory Tillage ................................. 5
  Clod Size Distribution ................................................... 9
  Vibratory Digger Blade for Potato Harvesters .................. 13

Kinematic and Dynamic Analysis of the Vibratory Digger .... 20
  Machine and Mechanism Description ................................. 20
  Factors of Variation .......................................................... 25
    Velocity ratio .................................................................. 25
    Phase Angle .................................................................. 26
  The Computer Program ..................................................... 26
  Analysis of Combined Movement ....................................... 29
    Kinematic Analysis .......................................................... 29
      Angular Position .......................................................... 30
      Angular Velocity .......................................................... 34
      Angular Acceleration ...................................................... 34
  Analysis of Points on the Blade ......................................... 36
    Analysis of Point F .......................................................... 36
    Analysis of Point G .......................................................... 39
  Moments of Inertia and Center of Gravity of the Blade Assembly .......................................................... 42
    Center of Gravity of the Blade .......................................... 42
    Moments of Inertia of the Blade ....................................... 45
    Center of Gravity and Moments of Inertia of the Mechanism .......................................................... 47

Dynamic Analysis ............................................................. 47
  Characteristics of Element 2 .............................................. 50
  Characteristics of Element 3 .............................................. 50
  Characteristics of Element 4 .............................................. 51
  Characteristics of Element 5 .............................................. 52
Characteristics of Element 6 .................................. 52
Characteristics of Element 7 .................................. 53
Inertia Forces and Torque ..................................... 54
Static Forces and Torque ..................................... 59
Friction and Total Torque ..................................... 61
Analysis of Longitudinal Oscillation .......................... 67
  Kinematic Analysis ............................................. 68
    Position, Angular Velocity and Acceleration ............ 68
  Analysis of Points F and G .................................. 70
Dynamic Analysis ............................................. 73
Analysis of Lifting Movement ................................. 74
  Kinematic Analysis ............................................. 75
  Dynamic Analysis ............................................. 78
Movement of the Blade and Cutting Angle ..................... 81
  Longitudinal Movement ....................................... 81
    Type of Movement ............................................ 81
    Blade-Soil Contact ......................................... 82
  Lifting Movement ............................................. 86
  Combined Movement .......................................... 88
    Analysis of Phase Angle .................................. 88
    Type of Movement of the Blade ........................... 92
Draft Force .................................................. 96
  Forces on a Non-Vibrating System ......................... 96
  Forces on a Vibrating System .............................. 100
    Draft Ratio (DR) ............................................. 105
    Shear Force ................................................ 105
    Adhesion and Friction Force on the Blade .................. 106
Analysis of the Blade-Soil System ........................... 107
  Dynamic Characteristics of the Block of Soil ............ 107
    Center of Gravity .......................................... 107
    Moments of Inertia ........................................ 108
    Characteristics of the Block of Soil .................... 110
  Dynamic Analysis of the Blade-Soil System ................. 111
    Combined Movement ........................................ 111
      Inertia Forces and Torque .............................. 111
      Static Forces and Torque ................................ 114
      Total and Friction Torque ................................ 119
    Longitudinal Movement ................................... 123
    Lifting Movement ......................................... 124
    Power Requirements of the Blade-Soil System .......... 126
      Power Ratio ............................................... 126
# LIST OF TABLES

1. Center of Gravity and Moments of Inertia of the Digger Blade . 44

2. Centers of Gravity and Moments of Inertia of Elements in the Digger Machine . . . . . . . . . . . . . . . . . . . . . . . . 48

3. Moments of Inertia and Center of Gravity of the Block of Soil . 110

4. Analysis of Variance and Duncan Test for Torque in Horizontal Mode of Vibration . . . . . . . . . . . . . . . . 187

5. Analysis of Variance and Duncan Test for Torque in Vertical Mode of Vibration . . . . . . . . . . . . . . . . 189

6. General Linear Models and Duncan Test for Torque in Combined Mode of Vibration . . . . . . . . . . . . . . . . 192

7. General Linear Models and Duncan Test for Draft Force in Horizontal Vibration . . . . . . . . . . . . . . . . 194

8. Analysis of Variance and Duncan Test for Draft Force in Vertical Mode of Vibration . . . . . . . . . . . . . . . 196

9. General Linear Models and Duncan Test for Draft Force in Combined Mode of Vibration . . . . . . . . . . . . . . . 198

10. General Linear Models and Duncan Test for Power Ratio in Horizontal Mode of Vibration . . . . . . . . . . . . . . . 202

11. Analysis of Variance and Duncan Test for Power Ratio in Vertical Mode of Vibration . . . . . . . . . . . . . . . 204

12. General Linear Models and Duncan Test for Power Ratio in Combined Mode of Vibration . . . . . . . . . . . . . . . 206

13. Analysis of Variance and Duncan Test for Bulk Density in Horizontal Mode of Vibration . . . . . . . . . . . . . . . 209

14. Analysis of Variance and Duncan Test for Bulk Density in Vertical Mode of Vibration . . . . . . . . . . . . . . . 210
15. Analysis of Variance and Duncan Test for Bulk Density in Combined Mode of Vibration . . . . . . . 211

16. Analysis of Variance and Duncan Test for GMD in Horizontal Mode of Vibration . . . . . . . 213

17. Analysis of Variance and Duncan Test for GMD in Vertical Mode of Vibration . . . . . . . 214

18. Analysis of Variance and Duncan Test for GMD in Combined Mode of Vibration . . . . . . . 216

19. Analysis of Variance and Duncan Test for $\sigma_g$ in Horizontal Mode of Vibration . . . . . . . 218

20. Analysis of Variance and Duncan Test for $\sigma_g$ in Vertical Mode of Vibration . . . . . . . 220

21. Analysis of Variance and Duncan Test for $\sigma_g$ in Combined Mode of Vibration . . . . . . . 221

22. Expected and Experimental Mean Values for Each Mode of Vibration . . . . . . . . . 223

B. Tractor and Digger Blade Machine Settings . . . 282

C1. Measurements of Torque in the Laboratory and Results from the Simulation . . . . . . . 287

C2. Raw Data for Torque (Nm) and Draft (N) . . . . . . 289


C4. Raw Data for Bulk Density (kg/m³) . . . . . . 293

C5. Raw Data for Geometric Mean Diameter (mm) . . . . 295

C6. Raw Data for Log Standard Deviation (mm) . . . . 297

C7. Measurements of Torque in the Field and Results from the Simulation . . . . . . . . . 299
<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Description</th>
<th>Page Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Side view of the digger blade machine</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>Digger blade assembly and transmission system</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>Kinematic diagram of the digger blade assembly and supporting elements</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>Position of linkages in combined movement</td>
<td>33</td>
</tr>
<tr>
<td>5</td>
<td>Angular velocity of linkages in combined movement</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>Angular acceleration of linkages in combined movement</td>
<td>35</td>
</tr>
<tr>
<td>7</td>
<td>Displacement and velocity of point F in combined movement</td>
<td>38</td>
</tr>
<tr>
<td>8</td>
<td>Displacement and velocity of point G in combined movement</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>Acceleration of points F and G in combined movement</td>
<td>41</td>
</tr>
<tr>
<td>10</td>
<td>Elements and center of gravity of the blade</td>
<td>43</td>
</tr>
<tr>
<td>11</td>
<td>Position and direction of inertia forces</td>
<td>49</td>
</tr>
<tr>
<td>12</td>
<td>Inertia forces and reactions in combined oscilliation</td>
<td>55</td>
</tr>
<tr>
<td>13</td>
<td>Reactions and resultant inertia force in combined movement</td>
<td>57</td>
</tr>
<tr>
<td>14</td>
<td>Inertia torque components in combined movement</td>
<td>58</td>
</tr>
<tr>
<td>15</td>
<td>Static forces and reactions in combined oscilliation</td>
<td>60</td>
</tr>
<tr>
<td>16</td>
<td>Static torque at the input links 2 and 7 in combined movement</td>
<td>62</td>
</tr>
<tr>
<td>17</td>
<td>Total forces, total and friction torque in combined oscilliation</td>
<td>64</td>
</tr>
<tr>
<td>18</td>
<td>Friction torque at input links 2 and 7 in combined movement</td>
<td>66</td>
</tr>
<tr>
<td>19</td>
<td>Components of total torque in combined oscilliation</td>
<td>67</td>
</tr>
<tr>
<td>20</td>
<td>Angular acceleration for longitudinal movement</td>
<td>68</td>
</tr>
<tr>
<td>21</td>
<td>Angular position and velocity in longitudinal movement</td>
<td>69</td>
</tr>
</tbody>
</table>
22. Acceleration of points F and G in longitudinal oscillation .... 70
23. Displacement and velocity of point F in longitudinal oscillation .... 71
24. Displacement and velocity of point G in longitudinal movement .... 72
25. Inertia, static, friction and total torque in horizontal movement .... 73
26. Shaking, inertia, and reaction forces in longitudinal movement .... 74
27. Position of linkages in lifting movement ................. 75
28. Velocity and acceleration of linkages in lifting movement .... 76
29. Displacement of points F and G in lifting movement .... 77
30. Acceleration of points F and G in lifting movement .... 78
31. Inertia, static, friction, and total torque in lifting movement .... 79
32. Total inertia, shaking, and reaction forces in lifting movement .... 80
33. Total displacement of points F and G in the x and y directions .... 82
34. Contact and cutting angles .......... 84
35. Velocity ratio and contact angles relationship .... 86
36. Displacement of points F and G in lifting movement .... 87
37. Effect of phase angle on torque distribution and total torque .... 89
38. Contact and cutting angles for phase angles 0° and 90° .... 90
39. Contact and cutting angles for phase angles 180° and 270° .... 91
40. Effect of phase angle on displacement of the cutting edge .... 93
41. Effect of phase angle on the displacement of point G .... 94
42. Soil-blade interaction forces for non-vibrating conditions .... 97
43. Soil-blade interaction forces for backward movement of the blade 102
44. Draft force variation for a vibrating blade .... 104
67. Calibration curve for horizontal force on the lower right pin . 161
68. Calibration curve for vertical force on the lower right pin . 162
69. Calibration curve for side force on the lower right pin . 163
70. Calibration curve for horizontal force on the upper pin . 164
71. Calibration curve for vertical force on the upper pin . 165
72. Calibration curve for horizontal force on the second upper pin . 166
73. Calibration curve for the torque cell . . . . . . . 167
74. Forces on the quick-hitch and the implement . . . . . . 169
75. Rotary sieve for clod-size distribution analysis . . . . . 176
76. Clod size distribution plotted on log-probability paper . . 177
77. Output voltage for data taken in a field test . . . . . . . 182
78. Effect of the (forward speed) x (velrat) and (ampl) x (velrat) interactions on the torque in horizontal mode of vibration . 188
79. Effect of the (forward speed) x (velrat) and (ampl) x (velrat) interactions on the torque in vertical mode of vibration . 190
80. Effect of the (amplitude combination) x (forward speed) interaction on the draft force in combined mode of vibration . 199
81. Effect of the (amplitude combination) x (phase angle) interaction on the draft force in combined mode of vibration . . . 200
82. Effects of the (forward speed) x (velrat) and (ampl) x (velrat) interactions on the power ratio in horizontal mode of vibration . 203
83. Effect of the (amplitude combination) x (forward speed) interaction on the power ratio in combined oscillation . . . . 207
84. Effect of the (amplitude) x (velocity ratio) interaction on $\sigma_z$ in horizontal mode of vibration . . . . . . . 219
The performance of a vibrating digger blade machine was simulated in the laboratory and evaluated in the laboratory and in the field. The machine generated three modes of vibration: horizontal, vertical and their combination. A set of fifty-two tests replicated three times were performed in the field by varying amplitude (2 values), forward speed (2 values), and velocity ratio (2 values) for horizontal and vertical oscillation and amplitude combination (4 values), forward speed (2 values) and phase angle (4 values) for combined vibration.

The tests were conducted in a silty-loam soil with the following characteristics: bulk density 1115.2 kg/m³, moisture content from 22.4% to 26 % db during the period of testing, cone index 0.509 MPa, cohesion and soil-soil friction coefficients of 24.77 kPa and 0.422 respectively, adhesion and soil-metal friction coefficients of 2.39 kPa and 0.464 respectively and plastic limit of 28%. The performance of the machine was evaluated by changes in the bulk density, geometric mean diameter of the resulting clods and their log standard deviation, torque, draft, and power ratio.

For horizontal oscillation, forward speed was the factor with the most significant effect. Torque and power ratio increased, and bulk density and log standard deviation decreased as the forward speed increased. The velocity ratio did not produce the expected effects in reducing draft and increasing soil break up.
In vertical vibration, there was moderate agreement between the simulation and the field results. Non-significant effects were obtained for most of the factors of evaluation for the levels of velocity ratio used, but there was an unexpected decrease in draft.

In combined oscillation, the amplitude combination and the phase angle showed the greatest effects on the different factors. Phase angles of 180° and 270°, respectively, and amplitude combinations with smaller amplitudes in the horizontal direction than in the vertical direction yielded the best performance.

Compared to no vibration, the power increase ranged from 75% for vertical oscillation to 120% for horizontal vibration. The increase in power required to vibrate the soil was much higher than the decrease in power due to the decrease in draft.
INTRODUCTION

One of the main objectives of mechanical manipulation of agricultural soils is to change soil density and soil-aggregate size distribution. Tillage tools and movements are studied as a means to meet this objective with minimum energy consumption. Vibration is considered one of the promising techniques to improve energy transfer to the soil in some tillage operations.

The application of forced vibration has received limited consideration in the research and development of tillage tools. It has been studied as a system to reduce the draft necessary for soil preparation. In potato harvesting, vibration has been studied for reducing potato damage and loss, reducing the power required to pull the harvester, and improving the separation efficiency of potatoes from soil.

In white potato harvesting, losses average about 2600 kg/ha. Almost 8.8% of the product is lost by injuries during the first steps of the harvesting operation, digging and initial sorting (Mattila, 1989). Vibratory diggers allow more efficient use of energy in tillage operations and a possible use of smaller tractors, which lower costs and reduce soil compaction. The degree of soil compaction induced during harvesting of previous crops affects soil aeration and the success of potato plantings (Smith, 1968).

The technology of vibrating tillage machines is still developing. More research is necessary to study the soil response to the speed and position of the tool and to the oscillation parameters, frequency and amplitude, and
their relationship to the soil conditions. This work is a contribution to the vibratory tillage technology and was proposed with the following objectives:

1. To simulate the kinematic and dynamic behavior of a digger blade with three modes of vibration in order to select the parameters of variation to test in the field.

2. To evaluate the effects of forward speed, amplitude, velocity ratio, and phase angle between the front and rear of a vibrating digger blade on the clod size distribution and the bulk density of a typical soil.

3. To evaluate the draft and power consumption required to operate the digger blade under different conditions of forward speed, amplitude, velocity ratio, and phase angle.
VIBRATORY TILLAGE TERMINOLOGY

The study of vibratory tillage tools has created a special terminology that should be stated initially. These terms are the components of any oscillating movement and some are specific terms for vibratory tillage:

- $v_{ox} =$ forward or ground speed (m/s)
- $\omega =$ circular frequency of the vibratory forcing function (rad/s)
- $e =$ eccentricity of the vibratory source (m)
- $f =$ natural frequency of the forcing function (Hz)
- $A =$ amplitude of vibration (mm).

Some of the terms used specifically in vibratory tillage have been studied through dimensional analysis by relating the basic factors of the oscillating movement. Dubrovskii, cited by Harrison (1973a), introduced the wavelength of oscillation ($Y$). He found a direct relationship between draft and wavelength. The draft decreased as the wavelength decreased:

$$Y = \frac{v_{ox}}{f}.$$

Gunn and Tramontini (1955) defined a dimensionless factor ($K$) by relating the forward speed and the velocity of the oscillating source:

$$K = \frac{v_{ox}}{(\omega \times e)}$$

Eggenmuller, cited by Harrison (1973a) defined a ratio ($Z$), between the forward velocity and the peak vibration velocity:

$$Z = \frac{v_{ox}}{(f \times A)} = 2\pi K.$$
Kofoed, cited by Harrison (1973a) published his experimental work on vibratory tillage, defining a dimensionless ratio ($\beta$), and suggested values between 0.68 and 3.14 for the most effect of vibration on the soil:

$$\beta = \frac{l_o}{(2e)} = \frac{v_{ox}T}{(2e)} = \frac{v_{ox}}{(2f * e)} = Z / 2$$

$l_o$ = forward travel during one oscillation

$T$ = Period of oscillation.

The most widely used term to relate forward speed and frequency of vibration is the velocity ratio ($\lambda$):

$$\lambda = \frac{\omega * A}{v_{ox}}.$$

Smith, Dais, and Flikke (1972), defined the contact and force ratios. The contact ratio ($\alpha$) is the time per cycle that the tool is in contact with the soil divided by the period of the oscillation:

$$\alpha = \frac{(t_2 - t_1)}{T}$$

$t_1$ = time at which the tool contacts the soil

$t_2$ = time at which the tool leaves the soil.

The force ratio $FR$ is the average of the horizontal force per cycle, acting on the vibrating tool divided by the force that would act on the tool without vibration:

$$FR = \frac{(F_o \alpha + K_v v_{ox})}{(F_o + K_v v_{ox})}$$

$F_o$ = non-velocity dependent component of the tool force

$K_v$ = velocity dependent component of the tool force. $F_o$ and $K_v$ must be experimentally determined.
According to Wolf and Shmuelevich, cited by Narayanarao and Verma (1982b), the power requirements can be expressed by different terms; equivalent traction or draft power, equivalent pto or oscillating power and equivalent tractor or total power. The respective power ratios, draft power ratio, oscillating power ratio, and total power ratio are calculated by dividing the corresponding power by the power required in the non-oscillating mode of the tool.

DRAFT REDUCTION IN VIBRATORY TILLAGE

Verma (1971) defined a tillage tool as an element to apply pressure to the soil by means of inclined planes or wedges or their combinations. The soil is subjected to a compressive stress which results in shearing failure. If the soil has a high resistance to compression, tillage tools need excessive energy to alter soil conditions. New methods should reduce energy requirements, one of the objectives of vibration in tillage. The earliest works stated that draft requirements of a tillage implement can be substantially reduced by oscillation of the soil-working tool. This has been demonstrated in a series of experiments with subsoiling chisels and potato harvesting machines. Research showed the use of vibration as an alternating method for intensifying cultivating processes with substantial reduction in draft and increase in the efficiency of soil break up.

Gunn and Tramontini (1955) studied the effect of oscillation on the draft and power requirements of an experimental tillage implement similar
to a subsoiling chisel. They found that the average net draft could be reduced by oscillating the implement and that higher reduction occurred when the forward speed was lower than the oscillation velocity. These two factors were related by a dimensionless parameter:

$$K' = \frac{v_0}{\omega r}.$$

The tests showed a draft reduction for $K'$ values less than 1. The draft reduction was due to the increased transfer of energy to the soil through the vibrating system, and 0.7 was recommended as the optimum $K'$ value for maximum energy transfer to the soil. Finally, they found that vibration produces more fragmentation in the soil than does a non-oscillating tool.

Shkurenko (1960) studied the effect of oscillations on the cutting resistance of soil. His results indicated a considerable reduction in cutting resistance (up to 60%) at fairly high frequencies, due to vertical or longitudinal oscillation. The effect of vibration increased with the increase of amplitude and frequency of vibration. At the same amplitude and frequency, oscillation in the horizontal direction was approximately 1.6 times more effective than in the vertical direction. Furthermore, the effect of forward speed on cutting resistance was relatively small.

Trapp, Abrahams, and Reece (1967), studied the effect of friction on draft reduction and power increment by analyzing the performance of kinematic and dynamic oscillating earth cutters producing longitudinal oscillation. They concluded that the main reason for draft reduction was the
reduction of effective time for the cutting action. Power increments were attributed to the friction between soil and cutter when it was moving backward and forward but not cutting undisturbed soil. The velocity ratio was the design parameter controlling the performance of kinematic vibrating cutters and only produced draft reduction for values above 1.

Kanafojski, cited by Verma (1971), found the cutting resistance of soil was dependent of the angle of cutting of a straight-edged blade and the vibration of the cutting edge produced a reduction of draft. For constant frequency and amplitude of vibration, greater reduction of draft was achieved by reducing the forward travel speed. Mgilenko, cited by Dubrovskii (1977), stated the efficiency of vibration generally depended on the frequency of oscillation, and its effect is more than that of amplitude.

Eggenmuller, cited by Verma (1971), tested a blade model at various frequencies and amplitudes of oscillation. He obtained a 40% draft reduction at 0.4 m/s forward speed and concluded that the direction of oscillation had considerable effect on reducing frictional forces between the blade and the soil. These forces represented about 60% of the total force on the tool. The blade was oscillated at three different angles 0, 15, and 30° (measured from the horizontal plane). The results indicated that 30° was the best direction of oscillation. Finally, Eggenmuller concluded that tractive resistance decreased at comparatively low frequencies and low forward speeds. In the case of high velocity, higher frequency was required to achieve the same result.
In a theoretical approach, Smith, Dais, and Flikke (1972) studied the effect of the contact ratio, $\alpha$, on the force and power ratios. The formulas derived showed the force ratio was a linear function of the contact ratio, and it was independent of the type of vibrating motion of the tool. A similar conclusion was stated for the power ratio. Furthermore, they concluded that the power required for tillage cannot be reduced by vibration. In an experimental study, Smith, Hillman, and Flikke (1972), tested a vibratory tillage tool consisting of a cam actuated shaker system that oscillated a flat blade fore and aft in the direction of travel, with three different motions; sawtooth, simple harmonic, and modified square. The power ratio was always greater than 1. The overall power was greater when vibration was used. Sawtooth motion approached the predicted performance best.

Brixius and Weber (1975), tested a flat tillage tool and a bulldozer blade model in four artificial soils that ranged from brittle to plastic. The tools were oscillated at frequencies between 0 and 40 Hz at a fixed amplitude of 1.5 mm. High speed movies were used to determine the effect of the contact ratio. They found the type of soil failure depended on the type of soil, the angle of oscillation and the frequency. The force to drive the blades decreased as frequency was increased for all soils and all angles of oscillation (0, 17 and 30°). Draft force decreased rapidly in the velocity ratio range from 1.0 to 1.75. The total torque required to vibrate the blade increased up to a velocity ratio, $\lambda$, of about 1.0 and levelled off at higher frequencies. For velocity ratios greater than 2, more than 50% of the total
torque was used to vibrate the tool. Consequently, a minimum number of moving parts is a major criterion in the design of a vibratory implement.

Butson and McIntire (1986), performed a series of soil bin experiments to evaluate draft and power requirements of a soil cutting blade with sinusoidal vibration in the direction of travel. Frequencies up to 50 Hz, amplitudes up to 8 mm and forward speeds of 0.15 and 0.55 m/s were used. There was no change in draft for velocity ratios less than 1, and a draft reduction greater than 50% was observed for velocity ratios greater than 3. Vibration increased the total power. The power increase was greatest at the higher velocity, at least 200% for velocity ratios over 2.0.

One of the first conclusions is that the application of vibration to a tillage tool was not expected to produce a change in draft until the velocity ratio was greater than 1.0. The last studies were based on the premise that there can be no reduction in draft until the peak vibration velocity is greater than the forward speed. The application of vibration always increases the total power, even at velocity ratios less than 1.0, when there is no or very low reduction in draft.

CLOD-SIZE DISTRIBUTION

The soil pulverization process of tillage can be defined as the loosening of the soil with an increase in pore space and comminution of soil aggregates (Harrison, 1973b). Aggregate size distribution is a determinant of pore-size distribution and a measure of the effectiveness of a tillage tool.
In the field adjacent particles often adhere to each other, but not as tenaciously as do the particles within each aggregate. Separating and classifying soil aggregates necessarily involves a disruption of the original, in situ, structural arrangement. The application of too great a force may break up the aggregates themselves. Hence, determination of aggregate size distribution depends on the mechanical means employed to separate them (Hillel, 1982). Screening through flat sieves is difficult to standardize and entails frequent clogging of the sieve openings.

Chepil and Bisal (1943) presented a detailed plan for a rotary sieve machine. It had a two-section system with six concentric cylinders that sloped 4° from the horizontal and were rotated by an electric motor at a speed of 14 rpm. The system was simplified by Chepil (1956) with a five-cylinder sieve of one section, sloped 4° and rotating at a speed of 7 rpm. This machine was similar to that one described below and used for clod-size analysis in this study. The operation of this machine could be standardized, thus minimizing arbitrary subjective factors. Samples for dry sieving analysis were taken when the soil was reasonably dry, and care had to be taken to avoid change of structure during handling.

Several indexes have been proposed for expressing the distribution of aggregate sizes. One widely used index is the mean weight diameter (MWD) based on weighing the masses of aggregates of the various size classes. This is a graphical method used by Van Bavel (1949) and modified
by Youker and McGuinness (1956) by a numerical method. The MWD is
defined by the following equation:

\[
MWD = \frac{\sum(X_i W_i)}{\sum W_i}
\]

\(X_i\) = mean diameter of any particular size range of soil aggregates
\(W_i\) = weight of the aggregates in that size range as a fraction of the total dry
weight of the sample analyzed.

Mazurak, cited by Kemper and Rosenau (1986), suggested the
geometric mean diameter (GMD) as an index of the clod size distribution:

\[
GMD = \exp\left(\frac{\sum W_i \log X_i}{W}\right)
\]

\(W_i\) = weight of aggregates in a size class of average diameter \(X_i\)
\(W\) = total weight of the sample.

Gardner (1956), suggested that a complementary measure, such as
standard error, was required to define any clod-size distribution. He
reported that aggregates of many soils have a logarithmic-normal
distribution rather than normal. That log normal distribution can be
characterized in terms of two parameters, geometric mean diameter and log
standard deviation.

The break up of the soil is one of the functions of the digger blade of
potato harvesters, and vibratory diggers produce more soil break up than
the non-vibrating ones. Using the mean weight-diameter, Hendrick and
Buchele, cited by Verma (1971), stated that vibration increased the soil
fragmentation as a result of the improvement in the efficiency of energy
application to the soil compared with a rigid tillage tool.
Johnson and Buchele (1969) evaluated the influence of an oscillating blade on the clod size distribution and reported the effect of interaction of the blade angle and the frequency of oscillation. The greatest range of clod-size was obtained at a frequency of 10.5 Hz and a blade angle of 40°. Forward speed, blade angle, and soil condition had a great influence on the mean weight diameter. Similar results were obtained by Misener, McLeod, and McMillan (1984) and Saqib and Wright (1986).

Peak acceleration is an important parameter in potato harvesting to improve the separation of the soil from the potatoes. McGecham (1977) conducted experiments with a vibratory riddle providing simple harmonic motions with components in any of the principal axis; vertical, horizontal or parallel to the riddle. The results showed that riddling was more effective when vibration was perpendicular to the bars, but differences were barely significant. Damage to the potatoes was much less with motion in this direction. Compound motion yielded riddling effectiveness similar to simple vertical oscillation. The experiments showed that the effectiveness of riddling depended on the type of soil. In sandy soils, at least 90% of the soil was removed when peak acceleration was greater than 3g (g is the acceleration of gravity). In clay soil, this condition was obtained with peak acceleration at about 8g. Furthermore, the results showed that the direction of oscillation and amplitude were important factors in the riddling of soil because their influence in the peak acceleration. The peak acceleration chosen was a compromise between adequate removal of a difficult clay soil.
and acceptable potato damage. An important conclusion was that horizontal motion removed loose soil more quickly than did vertical motion and was much less harmful to the potatoes.

VIBRATORY DIGGER BLADES FOR POTATO HARVESTERS

Potato harvesters loosen the soil, lift and clean the potatoes, and load them onto trucks. The initial step of this procedure is the most difficult because the tubers in the soil represent only a very small fraction, 1 - 2% of the total weight (Karpenko, 1968). The machine must loosen and screen more than 200 kg of soil to collect 4-6 kg of tubers. This requires a high operating efficiency of the separating parts and is one of the reasons for the high cost of the operation. Lovering, McIsaac, and Scott, cited by Misener (1984), indicated that machine and labor costs for harvesting, hauling and putting potatoes in the store makes up 17% of the total expenses, while other field machine and labor costs are only 7%.

Vibratory tillage has been studied as an appropriate system to dig and break up the soil and perform the initial soil-potato separation. It is expected to damage the potatoes less, produce higher efficiency in soil break-up and reduce harvesting costs. According to Dubrovskii (1977), the digging process was in three phases:

1. Initial penetration of the working element into the soil, as the draft was applied to overcome frictional and cohesive forces of the soil.
2. Crushing the soil. In this phase the resistance of the implement to motion increases because of the forces caused by the increased internal stress in the soil.

3. Loosening of the soil, caused during shearing and subsequently overcoming inertia forces on the particles thrown upward.

Johnson (1974), built and tested a potato harvester with 3 vibratory digger blades to study damage to the potato, draft reduction and feeding efficiency of material to the harvester. Frequency of vibration was varied between 0 and 750 strokes/min, the amplitude between 19 and 33 mm and the blade angle between 10 and 30°. Draft decreased with increasing vibration frequency. Draft was reduced to 50% when the frequency was 450 strokes/min. There was little further draft reduction for velocities up to 700 strokes/min where the rate of change increased again. Mechanical damage was reduced by 50% compared to the non-vibrating condition. Harvesters with vibratory digger blades, however, cut more potatoes than did harvesters with standard blades, but produced fewer bruise injuries. The larger percentage of cut potatoes was probably due to the blade shape and the action of the vibration. Vibration enhanced soil-potato separation especially for longer strokes. The clod-size distribution was related to the energy input to the soil, but the blade angle did not have a significant effect on the work of the blade. Vibration speed should be at least 450 strokes/min for good soil separation and feeding of material into the harvester. Flow of material and soil separation were better at longer strokes.
Narayanarao and Verma (1982), simulated and tested the performance of an oscillating soil-working tool executing simple harmonic, quick-return and quick-cutting motions and operating at 0.5 m/s. Contact ratio and draft ratio decreased considerably with an increase in the velocity ratio from 1 to 4. For the three types of movement the draft power ratio decreased and the oscillating power ratio increased as well as the total power ratio as the velocity ratio was increased. The greatest changes occurred for velocity ratios between 1.0 and 1.75.

Al-Jubouri and McNulty (1984) used a prototype vibratory digger with orbital oscillation (in the vertical, horizontal plane), operated at 3 km/h (0.83 m/s) at a constant digging depth of 200mm, vibrating amplitudes of 10-25 mm and frequencies of 7.5-18 Hz. The orbital motion helped the blade to lift up the potatoes. Working with power, velocity and amplitude-to-depth ratios (A/h), they concluded that power requirements increased as A/h increased. An increase in the amplitude A, results in greater power required; the draft force increased when the A/h ratio was increased. They found good agreement between predicted and experimental power ratios. Experimental tests revealed a greater than predicted draft reduction, particularly in dry soil. Experimental power ratios, in dry soil and at higher velocity ratios were substantially greater than those predicted by theory.

Saqib and Wright (1986) developed a digger blade to evaluate the effect of amplitude, frequency and forward speed on the geometric mean diameter of the clod size and the change in soil bulk density. The pto driven
machine was operated with two forward speeds (0.9 and 2.3 km/h), two frequencies of vibration (5.2 and 15.6 Hz) and two amplitudes (10 and 30 mm). The digger blade was angled 20° with the direction of travel. Tests were conducted on a silt loam soil with two soil density conditions (1.16 and 1.28 g/cc). Soil aggregates, classified in a rotary sieve, showed smaller average clod size with vibration. Clod-size reduction was greater at higher frequencies of vibration and at lower forward velocities. Greater changes in bulk density were obtained with the vibratory digger than with a stationary blade. These changes increased as higher amplitudes and lower forward velocities were used. Frequency had no significant effect on bulk density.

In a complementary analysis, the results were evaluated as a function of the geometric mean diameter (GMD) and the soil bulk density and showed that peak acceleration values above 3g produce approximately the same clod break up and bulk density reduction. Acceleration values of g or less produced noticeably poor clod break-up. Using the velocity ratio, \( \lambda \), they concluded that values greater than 3 produced approximately the same break up and bulk density reduction in high and low density soils. Furthermore, vibration produced significantly smaller clods than did non-vibratory operation of the blade. The GMD values for low density soil were 7.1 mm and 12.4 mm with vibration and with no vibration, respectively, and 19.3 mm and 70.3 mm for high density soil. These results represented clod size reductions of 57 and 44%, for low and high density soil.
Misener, McLeod, and McMillan (1983) constructed and evaluated a potato harvester with a vibratory digger blade for minimizing machinery cost and tuber damage. It was a two row harvester for digging, sorting and loading the potatoes onto a bulk body. The digger blade operated at an angle of 15° and vibration frequencies from 0 to 5.8 Hz. Results included:

1. Forward speed should be limited to 3km/h (0.83 m/s), greater speeds overload the blade and reduce soil disaggregation.

2. The vibratory blade effectively broke up the soil.

3. Soil separation improved by increasing the vibration amplitude.

4. The machine allowed the reduction of agitation in the main digger chain because 93 to 95% of the soil was removed by the effect of vibration.

5. The machine weighed about 50% less than a commercial harvester. One of the factors contributing to the reduction of size is the vibrating blade and tines which effectively separate a larger portion of the soil from the tubers and consequently allowed the use of a shorter digging bed. The reduction in weight, in turn, reduced soil compaction.

Kang (1985), tested a balanced oscillating digger blade in two different soil conditions. The machine was operated at amplitudes of 3.2, 6.4 and 9.6 mm; at frequencies of 9.7, 18.0 and 25.7 Hz; and at forward speeds of 1.1, 2.2 and 3.2 km/h. Amplitude was the only factor affecting the change in the geometric mean diameter which increased as the amplitude levels increased. The results showed that vibration was very effective in reducing the GMD; it was about 30% of that without vibration in hard soil.
Furthermore, soil clods easily flowed over the blade as the amplitude and frequency levels increased at a given speed. Soil conditions significantly affected the draft of the digger blade. The increase in draft was proportional to the increase in speed and frequency in hard soil. In soft soil, draft decreased as amplitude and frequency increased. This result coincided with that of Gunn and Tramontini in 1955. Greater torque inputs were required to vibrate the digger blade as the amplitude and the frequency increased. Finally, a significant effect on the total power requirements was observed as the amplitude, frequency and travel speed were increased. About 80% of the total power was used to vibrate the blade.

Sharma, Verma, and Bansal (1986) designed and evaluated an oscillatory potato digger with the following operating conditions: peak to peak amplitude, 20 mm; five frequencies of vibration from 0 to 8 Hz; five forward velocities from 0.357 m/s and 0.75 m/s; working depth, 140 mm. Draft was reduced as the frequency was increased at constant forward speed. Draft increased at a lower rate as the forward speed increased maintaining constant amplitude and frequency. Furthermore, skinning damage also increased with the increase in forward speed and frequency of oscillation. Finally, for a given forward speed, the exposure of tubers increased from 50% to 86% when the frequency increased from 0 to 8 Hz.

Kang and Halderson (1991), designed a two-row potato digger with alternating movement and tested it for effects of amplitude and frequency of vibration and travel speed on potato damage, unrecovered potatoes, and
draft requirements. Amplitude had no significant effect on the variables evaluated. Travel speed was the most dominant factor. Draft force decreased as frequency increased and travel speed decreased. Average draft requirements per unit area of furrow slice were 3.3 and 4.2 N/cm² for 1.7 and 3.3 km/h travel speed. This represents 35-80% of the draft for commercial harvesters. Draft could not be measured when the digger was operated without vibration because soil accumulated on the blade.
KINEMATIC AND DYNAMIC ANALYSIS OF THE VIBRATORY DIGGER

MACHINE AND MECHANISM DESCRIPTION

The digger blade machine shown in fig. 1 was composed of the following parts:

1. Frame
2. Eccentric for horizontal or longitudinal vibration
3. Link
4. Link
5. Blade
6. Link
7. Eccentric for vertical vibration or lifting movement
8. PTO drive shaft
9. Main shaft
10. Torque cell
11. Right angle gear box
12. Gear box output shaft
13. Sprocket
14. Counter shaft or shaft for vertical vibration
15. End shaft or shaft for horizontal vibration
16. Skid
17. Tractor lower link.
Figure 1. Side view of the digger blade machine.
The machine was driven by the tractor pto through the main shaft. Shafts 14 and 15 were powered by roller chains, not shown in the figure, from sprocket 13 on the output shaft 12 of the right angle gear box 11 to shaft 14 and then to shaft 15. Oscillating movements of the blade in vertical and longitudinal direction, were generated by the rotation of eccentrics 2 and 7 on shafts 14 and 15. One pair of eccentrics for each mode of vibration was mounted on each shaft. The torque cell 10 sensed the torque required to vibrate the blade. The machine was connected to the tractor through a three-point quick hitch as shown in fig. 2. The sensing system for the draft was mounted on the quick hitch.

Figure 2. Digger blade assembly and transmission system.
Figure 3 is a kinematic diagram of the moving parts of the vibrating system, numbered in square boxes in fig. 1. The system is a seven-element mechanism in which the blade assembly could be oscillated from two different points to produce three modes of vibration:

1. Eccentric 2 rotated to produce a longitudinal or horizontal oscillating movement (mode = 1).

2. Eccentric 7 rotated to oscillate the blade in a lifting or vertical movement (mode = 2).

3. Both eccentrics could rotate simultaneously at given phase angles in combined oscillation (mode = 3).

Elements and dimensions in the mechanism are:

- $r_2$ = eccentric amplitude for longitudinal movement
- $r_7$ = eccentric amplitude for lifting movement
- $O_2$ = Pivot point or center of rotation of eccentric 2
- $O_4$ = Pivot point or center of rotation of link 4
- $O_7$ = pivot point or center of rotation of eccentric 7

- $r_3 = 152$ mm
- $r_5 = 457$ mm
- $s_3 = 294$ mm
- $s_5 = 203$ mm
- $h = 222$ mm
- $CD = 102$ mm
- $r_{ef} = 127$ mm

- $r_4 = 305$ mm
- $r_6 = 305$ mm
- $s_4 = 254$ mm
- $s_6 = 457$ mm
- $BD = 85$ mm
- $r_{bc} = 133$ mm
- $r_{ef} = 474$ mm
Figure 3. Kinematic diagram of the digger blade assembly and supporting elements.
\( \theta_2 \) = angular position of eccentric 2 
\( \theta_4 \) = angular position of link 4 
\( \theta_6 \) = angular position of link 6 
\( \omega_2 \) = angular velocity at input 2 
\( v_{ex} \) = ground speed (m/s)

\( \theta_3 \) = angular position of link 3 
\( \theta_5 \) = angular position of link 5 
\( \theta_7 \) = angular position of eccentric 7 
\( \omega_7 \) = angular velocity at input 7 
\( v_t \) = ground speed (km/h)

Derived terms of interest are:

- \( s_1 = (h^2 + s_4^2)^{1/2} \)
- \( s_2 = s_6 / \cos\phi_2 \)
- \( \phi_1 = \text{atan}(h / s_4) \)
- \( \phi_2 = 0.0 \)
- \( \phi_3 = \pi - \text{atan}(h / s_3) \)
- \( \phi_4 = \text{atan}(BD / CD) \)
- \( \theta_c = \theta_5 - \phi_4 \)
- \( \delta_t = \text{acos}((r_5^2 + r_{ef}^2 - r_{ef}^2) / (2r_5 r_{ef})) \)
- \( \theta_f = \theta_5 + \delta_t \)
- \( \text{c.g.} = \text{center of gravity} \)

Factors of Variation

Four factors of variation were defined for the analysis of the digger blade: amplitude of vibration, forward speed, velocity ratio, and phase angle. The last two factors are defined below.

**Velocity Ratio:** This term was defined as the ratio between the peak velocity of the input link and the ground speed shown in fig. 3. The velocity ratio was calculated as follows:

- \( vr_2 = v_a / v_{ex} \)
- \( vr_2 = \omega_2 r_2 / v_{ex} \) 
- \( vr_7 = v_h / v_{ex} \) 
- \( vr_7 = \omega_7 r_7 / v_{ex} \)
For the combined mode of vibration, \( vr_2 \) was chosen as the primary velocity ratio to describe the movement.

**Phase Angle:** The phase angle was defined as the relative position between the eccentric at the input 2 and the eccentric at the input 7. This angle was measured in the positive direction, from the vertical or horizontal position in such a way that the eccentric for vertical vibration followed the eccentric for horizontal vibration by the phase angle (\( \phi \)) as shown in fig. 3. This relation was:

\[
\theta_7 = \theta_2 + \phi
\]

**THE COMPUTER PROGRAM**

The kinematic and dynamic analyses were made using a computer program written in FORTRAN and included in appendix A. The program calculated the dependent variables for a given set of input conditions and created the files with the results related to the position of the input link. The program, DIGGER.F, consisted of the following parts:

1. Input data; to enter the factors of variation (mode, eccentricities, velocity ratio, forward speed, and phase angle), soil coefficients, blade dimensions, soil-metal coefficients, dimensions of the mechanism, and initial conditions for some variables used in the program.

2. Output files and titles; open and named the seventeen files used to store the results.
3. Kinematic analysis of the mechanism:

3.1. Position analysis; this section calculated the position of each element by solving the system of equations in the matrix ANG(4,5).

3.2. Velocity analysis; this section calculated the velocity of each element by solving the system in the matrix ω(4,5).

3.3. Acceleration analysis; this section calculated the acceleration of each link by solving the system in the matrix ALPHA(4,5).

3.4. Analysis of point F; this section calculated the displacement, velocity and acceleration of point F (front of the blade).

3.5. Analysis of point G; this section calculated the displacement, velocity and acceleration of point G (rear of the blade).

3.6. Analysis of center of gravity; this section calculated the displacement, velocity, and acceleration of the center of gravity of the blade.

4. Dynamic analysis of the mechanism:

4.1. Element characteristics; this section calculated the value, position, and direction of the inertia forces on the links and the block of soil. Mass, c.g., and moment of inertia of each link were entered here. The program calculated these factors for the block of soil.

4.2. Inertia forces and torque; this section calculated inertial torque at the inputs and reactions at joints and supports for the movement of the blade by solving the system in the matrix INERTIAB(18,19).
4.3. Static forces and torque; this section calculated the torque and reactions due to static forces on the blade by solving the system in the matrix STATB(18,19).

4.4. Total forces, friction and total torque; this section calculated total and friction torque in the mechanism, and total reactions at joints and supports by solving the matrix TOTB(18,19).

5. Dynamic analysis of the blade-soil system:

5.1. Draft force; this section estimated the force to pull the blade and other interacting forces in the blade-soil system.

5.2. Inertia forces and torque; this section calculated the torque and reactions due to inertia forces in the blade-soil system by solving the matrix INERSO(18,19).

5.3. Static forces and torque; this section calculated the torque and reactions to static forces on the blade-soil system by solving the matrix STATSO(18,19).

5.4. Total forces, friction, and total torque; this section calculated the total torque, forces and reactions, and friction torque due to movement of the blade-soil system by solving the matrix TOTSO(18,19).

6. Draft without vibration; this section calculated the draft force for the non-vibrating condition.

7. Printing results:

8. Power and draft ratios; this section calculated mean torque and power at the inputs, mean draft, power components, draft and power ratios.
9. Subroutines; the program used 3 subroutines. Two of them
applied the Gauss-Jordan elimination method (Kreyszig, 1988) to solve a
system of equations.

Subroutine KINEM(a,x) solved the systems of equations in the
kinematic analysis of the mechanism.

Subroutine ANGLE(ang,ay,ax) found the direction of a vector given
its rectangular components.

Subroutine TORQ(a,x) solved the systems of equations in the dynamic
analysis of the mechanism.

ANALYSIS OF COMBINED MOVEMENT

The analysis of each mode of vibration was divided in two parts,
kinematic and dynamic. The combined mode of vibration was taken as the
basic mode of vibration, in such a way that the horizontal and vertical
modes were particular cases of the combined movement. Only changes in
the input data were necessary to run the longitudinal and the lifting
movement.

Kinematic Analysis

This analysis included position, velocity, and acceleration for each link
and movement characteristics of different points on the blade such as at F
on the cutting edge, G at the rear of the blade, and at the center of gravity
of the blade.
Angular Position: The angular position of the remaining links \( \theta_3, \theta_4, \theta_5, \) and \( \theta_6 \) shown in fig.3, were calculated by Newton's method. This is an iterative procedure involving first estimating values of the unknown positions, then systematically correcting those values until desired precision is obtained (Hall, 1981). Two vector loops were taken to define the positions of the elements in the mechanism

\[
\text{Loop I: } \quad r_2 + r_3 - r_4 - s_1 = 0 \quad \text{(1)}
\]

The vector loop was broken into scalar components by separating the real and imaginary parts after expressing the loop in a complex form (Suh and Redcliffe, 1978):

\[
\begin{align*}
\mathbf{r} & = r e^{i \theta} = r(\cos \theta + i \sin \theta) \\
r_2 e^{i \theta_2} + r_3 e^{i \theta_3} - r_4 e^{i \theta_4} - s_1 e^{i \theta} & = 0
\end{align*}
\]

where:

\[
\begin{align*}
\theta_c & = \theta_6 - \phi_4 \\
\varepsilon_1 & = r_2 \cos \theta_2 + r_3 \cos \theta_3 - r_4 \cos \theta_4 - r_5 \cos(\theta_5 - \phi_4) - s_1 \cos \phi_1 \\
\varepsilon_2 & = r_2 \sin \theta_2 + r_3 \sin \theta_3 - r_4 \sin \theta_4 - r_5 \sin(\theta_5 - \phi_4) - s_1 \sin \phi_1
\end{align*}
\]

\( \varepsilon_j \) are errors which are to be made to approach zero by adjusting the values of angles \( \theta_j \), adding a correction factor in the iteration process developed by the program:

\[
\theta_j = \theta_j + \text{cor}_j
\]

\[
\text{Loop II: } \quad r_7 + r_6 - r_5 - r_4 - s_2 = 0 \quad \text{(2)}
\]

\[
\begin{align*}
r_7 e^{i \theta_7} + r_6 e^{i \theta_6} - r_5 e^{i \theta_5} - r_4 e^{i \theta_4} - s_2 e^{i \theta} & = 0
\end{align*}
\]
\[ e_3 = r_7 \cos \theta_7 + r_6 \cos \theta_6 - r_5 \cos \theta_5 - r_4 \cos \theta_4 - s_2 \cos \phi_2 \]

\[ e_4 = r_7 \sin \theta_7 + r_6 \sin \theta_6 - r_5 \sin \theta_5 - r_4 \sin \theta_4 - s_2 \sin \phi_2. \]

The estimates of the first values for \( \theta_j \) were taken from a scale drawing of the mechanism in its initial position as:

\[ \theta_3 = 0^\circ \]
\[ \theta_4 = 270^\circ \]
\[ \theta_5 = 180^\circ \]
\[ \theta_6 = 270^\circ \]

The correction factors were calculated solving the simultaneous system [3]. The computer program repeated the process until desired precision was obtained. The computation process would normally converge to an accuracy of 0.01 degree in 3 or 4 iterations, (Hall, 1981). A greater accuracy (0.0001) was necessary because of a small resulting movement in the vertical direction as the blade moves backward and forward. The input matrix to the program was obtained by applying the equation [3]:
ang(1,1) = - r_3 \sin \theta_3 \\
ang(1,2) = r_4 \sin \theta_4 \\
ang(1,3) = r_5 \sin(\theta_5 - \phi_4) \\
ang(1,4) = 0.0 \\
ang(1,5) = - \epsilon_1 \\
ang(2,1) = r_3 \cos \theta_3 \\
ang(2,2) = - r_4 \cos \theta_4 \\
ang(2,3) = - r_5 \cos(\theta_5 - \phi_4) \\
ang(2,4) = 0.0 \\
ang(2,5) = - \epsilon_2 \\
ang(3,1) = 0.0 \\
ang(3,2) = r_4 \sin \theta_4 \\
ang(3,3) = r_5 \sin \theta_5 \\
ang(3,4) = - r_6 \sin \theta_6 \\
ang(3,5) = - \epsilon_3 \\
ang(4,1) = 0.0 \\
ang(4,2) = - r_4 \cos \theta_4 \\
ang(4,3) = - r_5 \cos \theta_5 \\
ang(4,4) = r_6 \cos \theta_6 \\
ang(4,5) = - \epsilon_4 .

Example results from the computer program, showing the position of links 3, 4, 5, and 6 with reference to the rotation of eccentric 2, are plotted in fig. 4 for the following input conditions with their respective units:
mode = 3
vt = 3.0 km/h
ecc2 = 9.52 mm
ecc7 = 9.52 mm
ph = 0.0
vr = 1.5.
Angular Velocity: Angular velocities, shown in fig. 5, were calculated from the first derivative of the vector loops in equations [1] and [2]:

\[- r_3 \omega_3 \sin \theta_3 + r_4 \omega_4 \sin \theta_4 + r_{bc} \omega_5 \sin \theta_c = r_2 \omega_2 \sin \theta_2 \]
\[ r_3 \omega_3 \cos \theta_3 - r_4 \omega_4 \cos \theta_4 - r_{bc} \omega_5 \cos \theta_c = - r_2 \omega_2 \cos \theta_2 \]
\[ r_4 \omega_4 \sin \theta_4 + r_5 \omega_5 \sin \theta_5 - r_6 \omega_6 \sin \theta_6 = r_7 \omega_7 \sin \theta_7 \]
\[ - r_4 \omega_4 \cos \theta_4 - r_5 \omega_5 \cos \theta_5 + r_6 \omega_6 \cos \theta_6 = - r_7 \omega_7 \cos \theta_7. \]

Figure 5. Angular velocity of linkages in combined movement.

Angular Acceleration: Angular accelerations, shown in fig. 6, were obtained from the second derivative of the vector loops in equations [1] and [2]:
\[-r_5 \alpha_3 \sin\theta_3 + r_4 \alpha_4 \sin\theta_4 + r_{bc} \alpha_5 \sin\theta_5 = r_2 \omega_2^2 \cos\theta_2 + r_3 \omega_3^2 \cos\theta_3 - r_4 \omega_4^2 \cos\theta_4 - \]
\[-r_{bc} \omega_5^2 \cos\theta_c \]
\[r_3 \alpha_3 \cos\theta_3 - r_4 \alpha_4 \cos\theta_4 - r_{bc} \alpha_5 \cos\theta_5 = r_2 \omega_2^2 \sin\theta_2 + r_3 \omega_3^2 \sin\theta_3 - r_4 \omega_4^2 \sin\theta_4 - \]
\[-r_{bc} \omega_5^2 \sin\theta_c \]
\[r_4 \alpha_4 \sin\theta_4 + r_6 \alpha_6 \sin\theta_6 - r_5 \alpha_5 \sin\theta_5 = -r_4 \omega_4^2 \cos\theta_4 - r_5 \omega_5^2 \cos\theta_5 + r_6 \omega_6^2 \cos\theta_6 + \]
\[r_7 \omega_7^2 \cos\theta_7 \]
\[r_4 \alpha_4 \cos\theta_4 - r_5 \alpha_5 \cos\theta_5 + r_6 \alpha_6 \cos\theta_6 = -r_4 \omega_4^2 \sin\theta_4 - r_5 \omega_5^2 \sin\theta_5 + r_6 \omega_6^2 \sin\theta_6 + \]
\[r_7 \omega_7^2 \sin\theta_7 . \]

Figure 6. Angular acceleration of linkages in combined movement.
Analysis of Points on the Blade

The most important points on the blade to analyze for movement are F at the cutting edge, G at the rear of the blade, and its center of gravity. The analysis of any point includes displacement, velocity and acceleration.

**Analysis of Point F:** Position of point F with reference to a fix point at the ground at time t was defined by the vector \( \mathbf{r}_f \):

\[
\mathbf{r}_f = r_2 + r_3 - r_{bc} + r_{cf} + v_{ox}t
\]

\[
\mathbf{r}_f = r_2 e^{i\theta_2} + r_3 e^{i\theta_3} - r_{bc} e^{i\theta_c} - r_{cf} e^{i\theta_f} + v_{ox}te^{i\theta_o} = x_f + iy_f
\]

\[
\theta_f = \theta_5 + \delta_f
\]

\[
\delta_f = \frac{\cos((r_5^2 + r_{cf}^2 - r_f^2))}{2r_5r_{cf}}
\]

\[
t = \theta_2 / \omega_2.
\]

The expansion of equation [4] gives the displacement of point F in the x and y directions after separating into real and imaginary parts:

\[
x_f = r_2 \cos\theta_2 + r_3 \cos\theta_3 - r_{bc} \cos\theta_c + r_{cf} \cos\theta_f + v_{ox}t
\]

\[
y_f = r_2 \sin\theta_2 + r_3 \sin\theta_3 - r_{bc} \sin\theta_c + r_{cf} \sin\theta_f
\]

The total velocity of point F is defined by the first derivative of the vector position \( \mathbf{r}_f \). Horizontal and vertical components were:

\[
v_{fx} = -r_2 \omega_2 \sin\theta_2 - r_3 \omega_3 \sin\theta_3 + r_{bc} \omega_b \sin\theta_c - r_{cf} \omega_c \sin\theta_f + v_{ox}
\]

\[
v_{fy} = r_2 \omega_2 \cos\theta_2 + r_3 \omega_3 \cos\theta_3 - r_{bc} \omega_b \cos\theta_c + r_{cf} \omega_c \cos\theta_f
\]

\[
v_f = (v_{fx}^2 + v_{fy}^2)^{1/2}
\]

The acceleration of point F is defined by the second derivative of the vector \( \mathbf{r}_f \). Its components in the horizontal and vertical direction were:
\[ a_x = -r_2 \omega_2^2 \cos \theta_2 - r_3 \alpha_3 \sin \theta_3 - r_3 \omega_3^2 \cos \theta_3 + r_b \alpha_5 \sin \theta_c + r_c \omega_5^2 \cos \theta_c - \\
\quad r_c \omega_5^2 \cos \theta_f - r_c \alpha_5 \sin \theta_f \]
\[ a_y = -r_2 \omega_2^2 \sin \theta_2 + r_3 \alpha_3 \cos \theta_3 - r_3 \omega_3^2 \sin \theta_3 - r_b \alpha_5 \cos \theta_c + r_c \omega_5^2 \sin \theta_c + \\
\quad r_c \alpha_5 \cos \theta_f - r_c \omega_5^2 \sin \theta_f \]
\[ a_t = (a_{x_t}^2 + a_{y_t}^2)^{1/2}. \]

Displacement of point \( F \) in the \( x \) and \( y \) direction and velocity in the \( x \) direction are shown in fig. 7, where:

\[ x_{\Omega} = v_{ox} t \]
\[ x_{f0} \] was the net displacement of point \( F \) in the \( x \) direction
\[ x_{f0} = x_r - x_o \]
\[ x_r = r_2 \cos \theta_2 + r_3 \cos \theta_3 - r_b \cos \theta_c + r_c \cos \theta_f \]
\[ x_o \] was the position of point \( F \) in the \( x \) direction from the center of rotation \( O_2 \) in the initial position of the mechanism
\[ x_{fr} = x_{f0} + x_{\Omega} \]
\[ y_{fr} = y_{f0} = y_r - y_o \]
\[ y_r = r_2 \sin \theta_2 + r_3 \sin \theta_3 - r_b \sin \theta_c + r_c \sin \theta_f \]
\[ y_{f0} \] was the net displacement of point \( F \) in the \( y \) direction
\[ y_o \] was the position of point \( F \) in the \( y \) direction from the center of rotation \( O_2 \) in the initial position of the mechanism
\[ v_{frx} \] was the resultant velocity of point \( F \) in the \( x \) direction
\[ v_{frx} = v_{fx} + v_{ox} \]
\[ v_{fx} = -r_2 \omega_2 \sin \theta_2 - r_3 \omega_3 \sin \theta_3 + r_b \omega_5 \sin \theta_c - r_c \omega_5 \sin \theta_f. \]
Figure 7. Displacement and velocity of point F in combined movement.
Analysis of Point G: Position of point G with reference to a fix point at the ground at a time t was given by vector $r_g$:

\[ r_g = r_7 + r_6 + v_\text{ext}t \]

\[ r_g = r_7 e^{i\theta_7} + r_6 e^{i\theta_6} + v_\text{ext}t e^{i\omega_\text{ext}t} = x_{gr} + i y_{gr} \quad [5] \]

The expansion of equation [5] gives the displacement of point G in the x and y direction after separating into real and imaginary parts:

\[ x_{gr} = r_7 \cos \theta_7 + r_6 \cos \theta_6 + v_\text{ext}t \]

\[ y_{gr} = r_7 \sin \theta_7 + r_6 \sin \theta_6. \]

Velocity and acceleration of point G:

\[ v_{grx} = -r_7 \omega_7 \sin \theta_7 - r_6 \omega_6 \sin \theta_6 + v_\text{ext} \]

\[ v_{gry} = r_7 \omega_7 \cos \theta_7 + r_6 \omega_6 \cos \theta_6 \]

\[ a_{sx} = -r_7 \omega_7^2 \cos \theta_7 - r_6 \alpha_6 \sin \theta_6 - r_6 \omega_6^2 \cos \theta_6 \]

\[ a_{sy} = -r_7 \omega_7^2 \sin \theta_7 + r_6 \alpha_6 \cos \theta_6 - r_6 \omega_6^2 \sin \theta_6 \]

\[ a_g = (a_{sx}^2 + a_{sy}^2)^{1/2}. \]

Displacement and velocity of point G are plotted in fig 8, where:

\[ x_{go} \] was the net displacement of point G in the x direction

\[ x_{g1} = v_\text{ext}t \]

\[ x_{go} = x_g - x_o \]

\[ x_o \] was the position of point G in the x direction from the center of rotation

\[ O_7 \] in the initial position of the mechanism

\[ x_g = r_7 \cos \theta_7 + r_6 \cos \theta_6 \]

\[ x_{gr} \] was the total displacement of point G in the x direction

\[ x_{gr} = x_{go} + x_{g1} \]
Figure 8. Displacement and velocity of point G in combined movement.
was the total displacement of point G in the y direction

\[ y_{gr} = y_{g0} = y_g - y_o \]

\[ y_g = r_7 \sin \theta_7 + r_6 \sin \theta_6 \]

\( y_o \) was the position of point G in the y direction from the center of rotation \( O_7 \) in the initial position of the mechanism

\( v_{grx} \) was the resultant velocity of point G in the x direction

\[ v_{grx} = v_{gx} + v_{ox} \]

\[ v_{gx} = -r_7 \omega_7 \sin \theta_7 - r_6 \omega_6 \sin \theta_6. \]

Acceleration of points F and G are plotted in fig. 9, where: \( a_o, a_{fx}, \) and

Figure 9. Acceleration of points F and G in combined movement.
\( a_y \) are the total acceleration of point F and its components in the x and y direction. The total acceleration of point G and its components are represented as \( a_x, a_y, \) and \( a_z \).

**Moments of Inertia and Center of Gravity of the Blade Assembly**

The vibrating system was subject to static and dynamic forces caused by movements, weights, and soil reactions on the blade. The association between forces and velocities determined the energy requirements to operate the machine. Moments of inertia, masses, and the position of the center of gravity were necessary in these calculations. The values depended on the inertial and static forces on the blade and the inertia and friction in the elements transmitting forces to the blade-soil system.

**Center of Gravity of the Blade:** The blade assembly was composed of seven parts symmetrically distributed about a longitudinal axis parallel with the top surface of the blade (the x' axis) as shown in fig. 10. The x'y'z' axis system was rotated from the global xyz axis system by the rake angle, \( \alpha_b \), of the blade in the xy plane. The position of the c.g. with reference to the x'y'z' axis system at point F was calculated from data in Table 1.

\[
x' = \frac{\Sigma m_i x'_i}{\Sigma m_i} = 0.219 \text{ m}
\]

\[
y' = \frac{\Sigma m_i y'_i}{\Sigma m_i} = 0.027 \text{ m}
\]

\[
z' = \frac{\Sigma m_i z'_i}{\Sigma m_i} = 0.0.
\]
Figure 10. Elements and center of gravity of the blade.
### TABLE 1. CENTER OF GRAVITY AND MOMENTS OF INERTIA OF THE DIGGER BLADE.

<table>
<thead>
<tr>
<th>Element</th>
<th>( m_i ) (kg)</th>
<th>( x'_i ) (m)</th>
<th>( y'_i ) (m)</th>
<th>( z'_i ) (m)</th>
<th>( I_x ) ((\text{kgm}^2))</th>
<th>( I_y ) ((\text{kgm}^2))</th>
<th>( I_z ) ((\text{kgm}^2))</th>
<th>( I_{x'} ) ((\text{kgm}^2))</th>
<th>( I_{y'} ) ((\text{kgm}^2))</th>
<th>( I_{z'} ) ((\text{kgm}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.50</td>
<td>0.230</td>
<td>0.005</td>
<td>0.000</td>
<td>1.620</td>
<td>2.140</td>
<td>0.500</td>
<td>1.634</td>
<td>2.143</td>
<td>0.517</td>
</tr>
<tr>
<td>2</td>
<td>3.40</td>
<td>0.216</td>
<td>0.025</td>
<td>0.362</td>
<td>0.001</td>
<td>0.026</td>
<td>0.026</td>
<td>0.001</td>
<td>0.026</td>
<td>0.026</td>
</tr>
<tr>
<td>3</td>
<td>3.40</td>
<td>0.216</td>
<td>0.025</td>
<td>-0.362</td>
<td>0.001</td>
<td>0.026</td>
<td>0.026</td>
<td>0.001</td>
<td>0.026</td>
<td>0.026</td>
</tr>
<tr>
<td>4</td>
<td>4.70</td>
<td>0.101</td>
<td>0.098</td>
<td>0.362</td>
<td>0.008</td>
<td>0.075</td>
<td>0.013</td>
<td>0.032</td>
<td>0.141</td>
<td>0.102</td>
</tr>
<tr>
<td>5</td>
<td>4.70</td>
<td>0.101</td>
<td>0.098</td>
<td>-0.362</td>
<td>0.008</td>
<td>0.075</td>
<td>0.013</td>
<td>0.032</td>
<td>0.141</td>
<td>0.102</td>
</tr>
<tr>
<td>6</td>
<td>2.90</td>
<td>0.355</td>
<td>0.024</td>
<td>0.362</td>
<td>0.002</td>
<td>0.015</td>
<td>0.008</td>
<td>0.002</td>
<td>0.069</td>
<td>0.062</td>
</tr>
<tr>
<td>7</td>
<td>2.90</td>
<td>0.355</td>
<td>0.024</td>
<td>-0.362</td>
<td>0.002</td>
<td>0.015</td>
<td>0.008</td>
<td>0.002</td>
<td>0.069</td>
<td>0.062</td>
</tr>
</tbody>
</table>
The coordinates were rotated by the rake angle to determine the c.g. with reference to the global system, xyz, solving equations [6] (Anton, 1987):

\[
\begin{pmatrix}
    x_{cg} \\
    y_{cg} \\
    z_{cg}
\end{pmatrix} =
\begin{pmatrix}
    \cos \alpha_b & -\sin \alpha_b & 0 \\
    \sin \alpha_b & \cos \alpha_b & 0 \\
    0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
    x' \\
    y' \\
    z'
\end{pmatrix}
\]

The solutions of this system were:

\[x_{cg} = x' \cos \alpha_b - y' \sin \alpha_b = 0.205 \text{ m}\]

\[y_{cg} = x' \sin \alpha_b - y' \cos \alpha_b = 0.083 \text{ m}\]

\[z_{cg} = z' = 0.0\]

Referenced to point C, the attachment point of the blade and the front link (link 4 in fig. 1), the position of the center of gravity of the blade was:

\[x_{cg} = 0.205 \text{ m}\]

\[y_{cg5} = -r_{cf} + y_{cg} = -0.0127 \text{ m} + 0.083 \text{ m} = -0.044 \text{ m}\]

\[z_{cg5} = z' = 0.0\]

**Moments of Inertia of the Blade:** Moments of inertia of the blade with reference to its center of gravity in the xyz global coordinate system were calculated with the following procedure:

1. Calculation of the moments of inertia \(I_{x'}, I_{y'}, I_{z'}\) of each element with reference to its center of gravity. These results are shown in Table 1. Inertial products \(I_{y'z'}\) and \(I_{x'y'}\) are zero, because \(x'\) is an axis of symmetry.

2. Translation of the moments of inertia, by the parallel axis theorem (Beer and Johnston, 1988), to an axis system \(x''y''z''\) at the c.g.
3. Calculation of the total moments of inertia with reference to the x"y"z" axis at the center of gravity:

\[ I'_{x'} = \Sigma I_{x'i} = 1.704 \text{kgm}^2 \]
\[ I'_{y'} = \Sigma I_{y'i} = 2.615 \text{kgm}^2 \]
\[ I'_{z'} = \Sigma I_{z'i} = 0.894 \text{kgm}^2 . \]

4. Rotation about the z axis to calculate the moment of inertia for the blade bottom with reference to the global axis system, xyz, at the front tip of the blade (point F) by solving equation [7]:

\[ [\Gamma] = [A][\Gamma'][A]^T \]  \hspace{1cm} [7]

[\Gamma] was the inertia matrix referenced to the xyz axis

[A] was the transition matrix

[\Gamma'] was the inertia matrix referenced to the x"y"z" axis.

The solutions of equations [7] were:

\[ I_x = \frac{\Gamma'_{xx} + \Gamma'_{xy} - \Gamma'_{yx} - \Gamma'_{yy} \cos(2\alpha_o) - \Gamma'_{xy} \sin(2\alpha_o) - 1.765 \text{kgm}^2}{2} \]
\[ I_y = \frac{\Gamma'_{xx} + \Gamma'_{xy} - \Gamma'_{yx} - \Gamma'_{yy} \cos(2\alpha_o) + \Gamma'_{xy} \sin(2\alpha_o) = 2.554 \text{kgm}^2}{2} \]
\[ I_z = \Gamma'_{zz} = 0.894 \text{kgm}^2 . \]
Center of Gravity and Moments of Inertia of the Mechanism: The same procedure was followed to determine the moments of inertia and the center of gravity of other elements in the mechanism with reference to a specified point. Step 4 was skipped because none of these elements needs to be rotated. Data are summarized in Table 2.

Dynamic Analysis

The dynamic analysis of the blade was performed to determine the torque requirements to operate the blade without load. Performing the dynamic analysis requires a definition of the characteristics of each element. These characteristics refer to the position of the center of gravity, the acceleration, the inertia forces, and related terms shown in fig. 11 as:

\[ I_{zi} = \text{mass moment of inertia of element } i \text{ about the } z \text{-axis (kgm}^2) \]
\[ m_i = \text{mass of element } i \text{ (kg)} \]
\[ O_i = \text{reference point} \]
\[ x_{cghi}, y_{cghi} = \text{coordinates of center of gravity of the element } i \]
\[ r_{cghi} = \text{location of the center of gravity of the element } i \]
\[ \theta_{cghi} = \text{angular position of the center of gravity} \]
\[ a_{ix} = \text{acceleration of center of gravity in the } x \text{ direction} \]
\[ a_{iy} = \text{acceleration of the center of gravity in the } y \text{ direction} \]
\[ a_i = \text{acceleration of center of gravity of element } i \]
\[ \gamma_i = \text{direction of } a_i \]
\[ \beta_i = \text{direction of inertia force on element } i = \gamma_i + \pi \]
<table>
<thead>
<tr>
<th>Link</th>
<th>( m_i )</th>
<th>Refer.</th>
<th>( x_{cgi} )</th>
<th>( y_{cgi} )</th>
<th>( z_{cgi} )</th>
<th>( I_x )</th>
<th>( I_y )</th>
<th>( I_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.86</td>
<td>O₂</td>
<td>1.33r₂\cos\theta₂</td>
<td>1.33r₂\sen\theta₂</td>
<td>0.0</td>
<td>0.0018</td>
<td>0.0018</td>
<td>0.0017 - 1.26r₂</td>
</tr>
<tr>
<td>3</td>
<td>10.80</td>
<td>A</td>
<td>0.0314\cos\theta₃</td>
<td>0.0314\sin\theta₃</td>
<td>0.0</td>
<td>0.0093</td>
<td>0.0340</td>
<td>0.0350</td>
</tr>
<tr>
<td>4</td>
<td>13.70</td>
<td>O₄</td>
<td>-0.0034</td>
<td>-0.0690</td>
<td>0.0</td>
<td>1.5210</td>
<td>1.4300</td>
<td>0.1200</td>
</tr>
<tr>
<td>5</td>
<td>50.49</td>
<td>F</td>
<td>-0.2050</td>
<td>0.0830</td>
<td>0.0</td>
<td>1.7040</td>
<td>2.6150</td>
<td>0.8970</td>
</tr>
<tr>
<td>6</td>
<td>14.10</td>
<td>O₆</td>
<td>0.069\cos\theta₆</td>
<td>0.069\sin\theta₆</td>
<td>0.0</td>
<td>0.1520</td>
<td>0.0490</td>
<td>0.1290</td>
</tr>
<tr>
<td>7</td>
<td>2.86</td>
<td>O₇</td>
<td>1.33r₇\cos\theta₇</td>
<td>1.33r₇\sin\theta₇</td>
<td>0.0</td>
<td>0.0018</td>
<td>0.0018</td>
<td>0.0017 - 1.26r₇</td>
</tr>
</tbody>
</table>
Figure 11. Position and direction of inertia forces.

\[ f_{oi} = \text{inertia force on element } i \]

\[ l_i = \text{location of inertia force line of action} \]

\[ l_i = r_{cg_i} + \frac{I_{gi}}{f_{oi} \sin(\beta_i - \theta_{cg_i})} \quad \text{(Mabie and Reinholtz, 1987)} \]

\[ W_{gt_i} = \text{weight of element } i \ (N) = m_i g. \]

\[ F_{ijx} \text{ and } F_{ijy} \text{ were the components of the reaction at the joint or support } ij. \]

\[ M_{0_i} = r_x F_y - r_y F_x \quad \text{(Erdman and Sandor, 1984)} \]

\[ M_{0_i} = F_{ijx} r_i \cos \theta_j - F_{ijy} r_i \sin \theta_j. \]

The moment of a resultant force, like the inertia force, was:

\[ M_{0_i} = f_{oi} l_i \sin(\beta_i - \theta_{cg_i}) \quad \text{(Mabie and Reinholtz, 1987)}. \]
Characteristics of Element 2: Center of rotation $O_2$ is the reference point:

$m_2 = 2.86 \text{ kg}$

$I_{z2} = 0.0017 - 1.26r_2 (\text{kgm}^2)$

$x_{cg2} = 1.33r_2 \cos \theta_2$

$y_{cg2} = 1.33r_2 \sin \theta_2$

$r_2 = (x_{cg2}^2 + y_{cg2}^2)^{1/2}$

$\theta_{cg2} = \theta_2$

$a_{2x} = -r_{cg2}\omega_2^2 \cos \theta_{cg2}$

$a_{2y} = -r_{cg2}\omega_2^2 \sin \theta_{cg2}$

$a_2 = (a_{2x}^2 + a_{2y}^2)^{1/2}$

$\gamma_2 = \text{atan}(a_{2y} / a_{2x})$

$\beta_2 = \gamma_2 + \pi$

$f_{02} = m_2a_2$

$l_2 = r_{cg2} + \frac{I_{z2} \alpha_2}{f_{02}\sin(\beta_2 - \theta_{cg2})}$

For vertical movement: $l_2 = r_2 = 0.0$.

Characteristics of Element 3: A is the reference point:

$m_3 = 10.8 \text{ kg}$

$I_{z3} = 0.035 \text{ kgm}^2$

$x_{cg3} = 0.0314 \cos \theta_3$

$y_{cg3} = 0.0314 \sin \theta_3$

$r_{cg3} = (x_{cg3}^2 + y_{cg3}^2)^{1/2}$
\[ \theta_{cg3} = \theta_3 \]
\[ a_{3x} = -r_x \omega_2^2 \cos \theta_2 - r_{cg3} \alpha_3 \sin \theta_{cg3} - r_{cg3} \omega_3^2 \cos \theta_{cg3} \]
\[ a_{3y} = -r_x \omega_2^2 \sin \theta_2 + r_{cg3} \alpha_3 \cos \theta_{cg3} - r_{cg3} \omega_3^2 \sin \theta_{cg3} \]
\[ a_3 = (a_{3x}^2 + a_{3y}^2)^{1/2} \]
\[ \gamma_3 = \text{atan}(a_{3y} / a_{3x}) \]
\[ \beta_3 = \gamma_3 + \pi \]
\[ f_{03} = m_3 a_3 \]
\[ l_3 = r_{cg3} + \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \frac{I_{cg3}}{f_{03} \sin(\beta_3 - \theta_{cg3})} \]

**Characteristics of Element 4:** O_4 is the reference point:

\[ m_4 = 13.7 \text{ kg} \]
\[ I_{z4} = 0.12 \text{ kNm}^2 \]
\[ x_{cg4} = -3.4 \text{ mm} \]
\[ y_{cg4} = -69.0 \text{ mm} \]
\[ r_{cg4} = (x_{cg4}^2 + y_{cg4}^2)^{1/2} \]
\[ \theta_{cg4} = \theta_4 - \pi/2 + \text{atan}(y_{cg4} / x_{cg4}) \]
\[ a_{4x} = -r_{cg4} \alpha_4 \sin \theta_{cg4} - r_{cg4} \omega_4^2 \cos \theta_{cg4} \]
\[ a_{4y} = r_{cg4} \alpha_4 \cos \theta_{cg4} - r_{cg4} \omega_4^2 \sin \theta_{cg4} \]
\[ a_4 = (a_{4x}^2 + a_{4y}^2)^{1/2} \]
\[ \gamma_4 = \text{atan}(a_{4y} / a_{4x}) \]
\[ \beta_4 = \gamma_4 + \pi \]
\[ f_{04} = m_4 a_4 \]
\[ l_4 = r_{cg4} + \frac{L_4\alpha_4}{f_0\sin(\beta_4 - \theta_{cg4})} \]

**Characteristics of Element 5 (blade):** C is the reference point:

\[ m_5 = 50.5 \, \text{kg} \]
\[ I_{z5} = 0.894 \, \text{kgm}^2 \]
\[ x_{cg5} = 205 \, \text{mm} \]
\[ y_{cg5} = -44 \, \text{mm} \]
\[ r_{cg5} = (x_{cg5}^2 + y_{cg5}^2)^{1/2} \]
\[ \theta_{cg5} = \theta_5 - \tan(x_{cg5} / y_{cg5}) \]
\[ a_{5x} = -r_4\alpha_4\sin\theta_4 - r_4\omega_4^2\cos\theta_4 - r_{cg5}\alpha_5\sin\theta_{cg5} - r_{cg5}\omega_5^2\cos\theta_{cg5} \]
\[ a_{5y} = r_4\alpha_4\cos\theta_4 - r_4\omega_4^2\sin\theta_4 + r_{cg5}\alpha_5\cos\theta_{cg5} - r_{cg5}\omega_5^2\sin\theta_{cg5} \]
\[ a_5 = (a_{5x}^2 + a_{5y}^2)^{1/2} \]
\[ \gamma_5 = \tan(a_{5y} / a_{5x}) \]
\[ \beta_5 = \gamma_5 + \pi \]
\[ f_0 = m_5a_5 \]
\[ l_5 = r_{cg5} + \frac{L_5\alpha_5}{f_0\sin(\beta_5 - \theta_{cg5})} \]

**Characteristics of Element 6:** H is the reference point:

\[ m_6 = 14.1 \, \text{kg} \]
\[ I_{z6} = 0.129 \, \text{kgm}^2 \]
\[ x_{cg6} = 0.069\cos\theta_6 \]
\[ y_{cg6} = 0.069\sin\theta_6 \]
\[ r_{cg6} = (x_{cg6}^2 + y_{cg6}^2)^{1/2} \]
\[ \theta_{cg6} = \theta_6 \]
\[ a_{6x} = -r_{cg6} \alpha_6 \sin\theta_{cg6} - r_{cg6} \omega_6^2 \cos\theta_{cg6} \]
\[ a_{6y} = r_{cg6} \alpha_6 \cos\theta_{cg6} - r_{cg6} \omega_6^2 \sin\theta_{cg6} \]
\[ a_6 = (a_{6x}^2 + a_{6y}^2)^{1/2} \]
\[ \gamma_6 = \tan(a_{6y} / a_{6x}) \]
\[ \beta_6 = \gamma_6 + \pi \]
\[ f_0_6 = m_6 a_6 \]
\[ l_6 = r_{cg6} + \frac{I_{cg6}}{f_0_6 \sin(\beta_6 - \theta_{cg6})} \]

**Characteristics of Element 7:** Center of rotation O_7 is the reference point:

\[ m_7 = 2.86 \text{ kg} \]
\[ I_{z7} = 0.0017 - 1.26r_7 \text{ (kgm}^2\text{)} \]
\[ x_{cg7} = 1.33r_7 \cos\theta_7 \]
\[ y_{cg7} = 1.33r_7 \sin\theta_7 \]
\[ r_{cg7} = (x_{cg7}^2 + y_{cg7}^2)^{1/2} \]
\[ \theta_{cg7} = \theta_7 \]
\[ a_{7x} = -r_{cg7} \omega_7^2 \cos\theta_{cg7} \]
\[ a_{7y} = -r_{cg7} \omega_7^2 \sin\theta_{cg7} \]
\[ a_7 = (a_{7x}^2 + a_{7y}^2)^{1/2} \]
\[ \gamma_7 = \tan(a_{7y} / a_{7x}) \]
\[ \beta_7 = \gamma_7 + \pi \]
\[ f_{o_7} = m_7 a_7 \]

\[ l_7 = r_{eg7} + \frac{L_7 a_7}{f_{o_7} \sin(\beta_7 - \theta_{eg7})} \]

For longitudinal movement: \( l_7 = r_7 = 0.0 \).

**Inertia Forces and Torque:** Torque to overcome the inertia of the system was calculated at input links 2 and 7. Equilibrium conditions are stated from the system of forces and reactions shown in fig. 12.

**Element 2:**
\[ \Sigma F_x = 0.0 \quad F_{12x} + F_{32x} + f_{o_2} \cos \beta_2 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad F_{12y} + F_{32y} + f_{o_2} \sin \beta_2 = 0.0 \]
\[ \Sigma M_{O2} = 0.0 \quad - F_{32x} r_2 \sin \theta_2 + F_{32y} r_2 \cos \theta_2 + f_{o_2} l_2 \sin(\beta_2 - \theta_{eg2}) - T_{2b} = 0.0. \]

**Element 3:**
\[ \Sigma F_x = 0.0 \quad - F_{32x} + F_{53x} + f_{o_3} \cos \beta_3 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad - F_{32y} + F_{53y} + f_{o_3} \sin \beta_3 = 0.0 \]
\[ \Sigma M_A = 0.0 \quad - F_{53x} r_3 \sin \theta_3 + F_{53y} r_3 \cos \theta_3 + f_{o_3} l_3 \sin(\beta_3 - \theta_{eg3}) = 0.0. \]

**Element 5:**
\[ \Sigma F_x = 0.0 \quad - F_{53x} + F_{45x} + F_{65x} + f_{o_5} \cos \beta_5 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad - F_{53y} + F_{45y} + F_{65y} + f_{o_5} \sin \beta_5 = 0.0 \]
\[ \Sigma M_C = 0.0 \quad F_{53x} r_{bc} \sin \theta_c - F_{53y} r_{bc} \cos \theta_c - F_{65x} r_5 \sin \theta_5 + F_{65y} r_5 \cos \theta_5 + f_{o_5} l_5 \sin(\beta_5 - \theta_{eg5}) = 0.0. \]

**Element 4:**
\[ \Sigma F_x = 0.0 \quad - F_{45x} + F_{14x} + f_{o_4} \cos \beta_4 = 0.0 \]
Figure 12. Inertia forces and reactions in combined oscillation.
\[ \Sigma F_x = 0.0 \quad - F_{4y} + F_{14y} + f_{04} \sin \theta_4 = 0.0 \]
\[ \Sigma M_{O4} = 0.0 \quad F_{45x}r_4 \sin \theta_4 - F_{45y}r_4 \cos \theta_4 + f_{04}l_4 \sin (\beta_4 - \theta_{eg4}) = 0.0. \]

Element 6:
\[ \Sigma F_x = 0.0 \quad - F_{6x} + F_{76x} + f_{05} \cos \beta_5 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad - F_{6y} + F_{76y} + f_{05} \sin \beta_5 = 0.0 \]
\[ \Sigma M_{H} = 0.0 \quad F_{65x}r_5 \sin \theta_5 - F_{65x}r_5 \cos \theta_5 + f_{05}l_5 \sin (\beta_5 - \theta_{eg5}) = 0.0. \]

Element 7:
\[ \Sigma F_x = 0.0 \quad - F_{76x} + F_{17x} + f_{07} \cos \beta_7 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad - F_{76y} + F_{17y} + f_{07} \sin \beta_7 = 0.0 \]
\[ \Sigma M_{O7} = 0.0 \quad F_{76x}r_7 \sin \theta_7 - F_{76x}r_7 \cos \theta_7 + f_{07}l_7 \sin (\beta_7 - \theta_{eg7}) - T_{7ib} = 0.0. \]

Results in the matrix xinb(18) are inertia torque \( T_{2ib} \) and \( T_{7ib} \) and the components of the reactions at the joints and supports caused by inertia forces on the blade:

\[ F_{12b} = (F_{12x}^2 + F_{12y}^2)^{1/2} = ((xinb(1))^2 + (xinb(2))^2)^{1/2} \]
\[ F_{32b} = (F_{32x}^2 + F_{32y}^2)^{1/2} = ((xinb(3))^2 + (xinb(4))^2)^{1/2} \]
\[ F_{63b} = (F_{63x}^2 + F_{63y}^2)^{1/2} = ((xinb(6))^2 + (xinb(7))^2)^{1/2} \]
\[ F_{45b} = (F_{45x}^2 + F_{45y}^2)^{1/2} = ((xinb(8))^2 + (xinb(9))^2)^{1/2} \]
\[ F_{14b} = (F_{14x}^2 + F_{14y}^2)^{1/2} = ((xinb(10))^2 + (xinb(11))^2)^{1/2} \]
\[ F_{65b} = (F_{65x}^2 + F_{65y}^2)^{1/2} = ((xinb(12))^2 + (xinb(13))^2)^{1/2} \]
\[ F_{76b} = (F_{76x}^2 + F_{76y}^2)^{1/2} = ((xinb(14))^2 + (xinb(15))^2)^{1/2} \]
\[ F_{17b} = (F_{17x}^2 + F_{17y}^2)^{1/2} = ((xinb(16))^2 + (xinb(17))^2)^{1/2}. \]

Additionally, the program calculated the resultant of inertia forces, and the shaking force on the frame of the machine. The resultant \( (Ifob) \) of
the inertia forces and its direction ($\theta_{if}$) were calculated from its components:

$$
\begin{align*}
fo_x &= f_{o2}\cos\beta_2 + f_{o3}\cos\beta_3 + f_{o4}\cos\beta_4 + f_{o5}\cos\beta_5 + f_{o6}\cos\beta_6 + f_{o7}\cos\beta_7 \\
fo_y &= f_{o2}\sin\beta_2 + f_{o3}\sin\beta_3 + f_{o4}\sin\beta_4 + f_{o5}\sin\beta_5 + f_{o6}\sin\beta_6 + f_{o7}\sin\beta_7 \\
I_{ob} &= (fo_x^2 + fo_y^2)^{1/2} \\
\theta_{if} &= \text{atan}(fo_y / fo_x).
\end{align*}
$$

The shaking force, plotted in fig. 13, was defined as the resultant of the reactions on the supports of the mechanism:

$$
\text{shakfb} = ((F_{12x} + F_{14x} + F_{17x})^2 + (F_{12y} + F_{14y} + F_{17y})^2)^{1/2}.
$$

This is the force transmitted by inertia forces to the frame. This

![Figure 13. Reactions and resultant inertia force in combined movement.](image-url)
force must be equal to the resultant inertia force on the system (Ham, 1962) as shown in fig. 13. Total inertia force, shaking force, and reactions at the supports are plotted for the conditions given above.

Inertia torque at the inputs and total torque are plotted in fig. 14, where:

\[ T_{2ib} = \sin b(5) \]

\[ T_{7ib} = \sin b(18) \]

\[ T_{ib} = T_{2ib} + T_{7ib} \]

Figure 14. Inertia torque components in combined movement.
Static Forces and Torque: Static torque at the inputs was caused by the energy required to move the weight of the blade. This torque was calculated from equilibrium conditions of the mechanism in fig. 15, where:

\( P_{ij} \) = reaction force at a joint or support \( ij \) in the \( x \) or \( y \) direction

\( T_{2\text{etb}} \) = static torque at the input 2

\( T_{7\text{etb}} \) = static torque at the input 7.

Element 2:

\[
\sum F_x = 0.0 \quad P_{12x} + P_{32x} = 0.0 \\
\sum F_y = 0.0 \quad P_{12y} + P_{32y} - Wgt_2 = 0.0 \\
\sum M_{02} = 0.0 \quad -P_{32x}r_2\sin\theta_2 + P_{32y}r_2\cos\theta_2 - Wgt_2r_{cg2}\cos\theta_{cg2} - T_{2\text{etb}} = 0.0.
\]

Element 3:

\[
\sum F_x = 0.0 \quad -P_{32x} + P_{53x} = 0.0 \\
\sum F_y = 0.0 \quad -P_{32y} + P_{53y} - Wgt_3 = 0.0 \\
\sum M_A = 0.0 \quad P_{32x}r_3\sin\theta_3 - P_{32y}r_3\cos\theta_3 - Wgt_3r_{cg3}\cos\theta_{cg3} = 0.0.
\]

Element 5:

\[
\sum F_x = 0.0 \quad -P_{53x} + P_{45x} + P_{65x} = 0.0 \\
\sum F_y = 0.0 \quad -P_{53y} + P_{45y} + P_{65y} - Wgt_5 = 0.0 \\
\sum M_C = 0.0 \quad -P_{53x}r_{bc}\sin\theta_{bc} + P_{63y}r_{bc}\cos\theta_{bc} - P_{65x}r_{65}\sin\theta_{5} + P_{65y}r_{65}\cos\theta_{6} - Wgt_5r_{cg5}\cos\theta_{cg5} = 0.0.
\]

Element 4:

\[
\sum F_x = 0.0 \quad -P_{45x} + P_{14x} = 0.0 \\
\sum F_y = 0.0 \quad -P_{45y} + P_{14y} - Wgt_4 = 0.0 \\
\sum M_{04} = 0.0 \quad P_{45x}r_4\sin\theta_4 - P_{45y}r_4\cos\theta_4 - Wgt_4r_{cg4}\cos\theta_{cg4} = 0.0.
\]
Figure 15. Static forces and reactions in combined oscillation.
Element 6:

\[ \sum F_x = 0.0 - P_{65x} + P_{76x} = 0.0 \]
\[ \sum F_y = 0.0 - P_{65y} + P_{76y} - Wgt_6 = 0.0 \]
\[ \sum M_{H} = 0.0 P_{65x}r_6\sin\theta_6 - P_{65y}r_6\cos\theta_6 - Wgt_6r_{cg6}\cos\theta_{cg6} = 0.0. \]

Element 7:

\[ \sum F_x = 0.0 - P_{76x} + P_{17x} = 0.0 \]
\[ \sum F_y = 0.0 - P_{76y} + P_{17y} - Wgt_7 = 0.0 \]
\[ \sum M_{O7} = 0.0 P_{76x}r_7\sin\theta_7 - P_{76y}r_7\cos\theta_7 - Wgt_7r_{cg7}\cos\theta_{cg7} - T_{7stb} = 0.0. \]

Results in the matrix xstb(18) were the components of the reactions to static forces at joints and supports and the static torque at the input eccentric 2 and 7:

\[ T_{2stb} = xstb(5) \]
\[ T_{7stb} = xstb(18). \]

The total torque due to static forces on the blade was:

\[ T_{stb} = T_{2stb} + T_{7stb}. \]

These three values are plotted in fig. 16, for the conditions above.

**Friction and Total Torque:** Total torque was calculated considering inertia and static forces and friction couples at the joints and supports. An iterative method (Hall, 1981) was used for this calculation. This method uses equation [8] to calculate the friction couple at the joints:

\[ t_{ij} = \mu r_{ij}H_{ij}d_{ij} \]  

[8]
Figure 16. Static torque at input links 2 and 7 in combined movement.

t_{ij} = friction couple at the joint of elements i and j

\( \mu = 0.08 \) = friction coefficient. Typically, it is 0.1 or less (Hall, 1981)

\( r_{ij} \) = rolling radius of the joint ij

\( H_{ij} \) = total reaction force at the joint ij

d_{ij} = unity factor defining the direction of the friction couple. The sign of this term depends on the relative velocity between elements i and j

\[
d_{ij} = \frac{\omega_i - \omega_j}{|\omega_i - \omega_j|}
\] [9]
The rolling radii of the joints were:

\[ r_{32} = r_{76} = 31.75 \text{ mm} \]
\[ r_{12} = r_{17} = 23.5 \text{ mm} \]
\[ r_{53} = r_{45} = r_{65} = 18.5 \text{ mm} \]
\[ r_{14} = 19.5 \text{ mm}. \]

Equations to calculate torque and reactions were stated from the equilibrium conditions of the mechanism in fig. 17. \( T_{2b} \) and \( T_{7b} \) were the total torque at the input links 2 and 7.

**Element 2:**

\[ \Sigma F_x = 0.0 \quad H_{12x} + H_{32x} + f_{o2}\cos\beta_2 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad H_{12y} + H_{32y} - Wgt_2 + f_{o2}\sin\beta_2 = 0.0 \]
\[ \Sigma M_{O2} = 0.0 \quad - H_{32x}r_2\sin\theta_2 + H_{32y}r_2\cos\theta_2 - Wgt_2r_{cg2}\cos\theta_{cg2} + \]
\[ f_{o2}\sin(\beta_2 - \theta_{cg2}) - T_{2b} + t_{12b} + t_{32b} = 0.0. \]

**Element 3:**

\[ \Sigma F_x = 0.0 \quad - H_{32x} + H_{53x} + f_{o3}\cos\beta_3 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad - H_{32y} + H_{53y} - Wgt_3 + f_{o3}\sin\beta_3 = 0.0 \]
\[ \Sigma M_A = 0.0 \quad - H_{53x}r_3\sin\theta_3 + H_{53y}r_3\cos\theta_3 - Wgt_3r_{cg3}\cos\theta_{cg3} + \]
\[ f_{o3}\sin(\beta_3 - \theta_{cg3}) - t_{32b} + t_{53b} = 0.0. \]

**Element 5:**

\[ \Sigma F_x = 0.0 \quad - H_{53x} + H_{45x} + H_{65x} + f_{o5}\cos\beta_5 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad - H_{53y} + H_{45y} + H_{65y} - Wgt_5 + f_{o5}\sin\beta_5 = 0.0 \]
\[ \Sigma M_C = 0.0 \quad H_{53x}r_{bc}\sin\theta_c - H_{53y}r_{bc}\cos\theta_c - H_{65x}r_5\sin\theta_5 + H_{65y}r_5\cos\theta_5 - \]
\[ Wgt_5r_{cg5}\cos\theta_{cg5} + f_{o5}\sin(\beta_5 - \theta_{cg5}) - t_{53b} + t_{45b} + t_{65b} = 0.0. \]
Figure 17. Total forces, total and friction torque in combined oscillation.
Element 4:

\[ \sum F_x = 0.0 \quad - H_{45x} + H_{14x} + f_0 \cos \theta_4 = 0.0 \]
\[ \sum F_y = 0.0 \quad - H_{45y} + H_{14y} - W_{gt4} + f_0 \sin \theta_4 = 0.0 \]
\[ \sum M_{04} = 0.0 \quad H_{45x} r_4 \sin \theta_4 - H_{45y} r_4 \cos \theta_4 - W_{gt4} r_{cg4} \cos \theta_{cg4} + \]
\[ f_0 l_4 \sin (\beta_4 - \theta_{cg4}) \quad - t_{45b} + t_{14b} = 0.0. \]

Element 6:

\[ \sum F_x = 0.0 \quad - H_{65x} + H_{76x} + f_0 \cos \theta_6 = 0.0 \]
\[ \sum F_y = 0.0 \quad - H_{65y} + H_{76y} - W_{gt6} + f_0 \sin \theta_6 = 0.0 \]
\[ \sum M_{16} = 0.0 \quad H_{65x} r_6 \sin \theta_6 - H_{65y} r_6 \cos \theta_6 - W_{gt6} r_{cg6} \cos \theta_{cg6} + \]
\[ f_0 l_6 \sin (\beta_6 - \theta_{cg6}) \quad - t_{65b} + t_{76b} = 0.0. \]

Element 7:

\[ \sum F_x = 0.0 \quad - H_{75x} + H_{17x} + f_0 \cos \theta_7 = 0.0 \]
\[ \sum F_y = 0.0 \quad - H_{75y} + H_{17y} - W_{gt7} + f_0 \sin \theta_7 = 0.0 \]
\[ \sum M_{07} = 0.0 \quad H_{75x} r_7 \sin \theta_7 - H_{75y} r_7 \cos \theta_7 - W_{gt7} r_{cg7} \cos \theta_{cg7} + \]
\[ f_0 l_7 \sin (\beta_7 - \theta_{cg7}) \quad - t_{75b} + t_{17b} - T_7 = 0.0. \]

Initially, the friction couples \( t_{ijb} \) were set to zero and the system was solved for the reactions at joints and supports. The total torque and the reactions \( H_{ij} \) were calculated from results in matrix \( xttb(18) \) as:

\[ H_{ij} = (H_{ix}^2 + H_{iy}^2)^{1/2} \quad [10] \]

These total reactions were used to calculate new friction couples using equation [8]. The procedure was repeated until the difference of the friction couples between two consecutive iterations reached the expected accuracy. This level was set to 0.1 Nm. Total and friction torque were:
Friction torque at input 2: \( T_{2fb} = T_{2b} - T_{2ib} - T_{2tb} \)

Friction torque at input 7: \( T_{7fb} = T_{7b} - T_{7ib} - T_{7tb} \)

Total friction torque: \( T_fb = T_{2fb} + T_{7fb} \)

Total Torque: \( T_b = T_{2b} + T_{7b} \)

The three values of friction torque are plotted in fig. 18.

![Graph showing friction torque at input links 2 and 7 in combined movement.](image)

Figure 18. Friction torque at input links 2 and 7 in combined movement.

The four total values of torque \( T_{2b}, T_{7b}, T_{fb}, \) and \( T_b \) are plotted in fig. 19.

Mean torque values at the conditions given above were:

\( T_{2mb} = 43.31 \text{Nm} \)
Figure 19. Components of total torque in combined oscillation.

\[ T_{mb} = 4.40 \text{ Nm} \]
\[ T_{mb} = 47.71 \text{ Nm}. \]

ANALYSIS OF LONGITUDINAL OSCILLATION

The longitudinal movement was originated by the rotation of the eccentric 2. The analysis was performed by the same procedure used for combined movement. An example of input data for this oscillation was:

Mode: 1
ecc_2 = 9.52 mm
ecc_7 = 0.0
v_i = 3.0 km/h
v_r = 1.5
p_h = 0.0.

Kinematic Analysis

Position, Angular Velocity and Acceleration: Results of the kinematic analysis of longitudinal movement are shown in figs 20 and 21. Comparing

Figure 20. Angular acceleration in longitudinal movement.
Figure 21. Angular position and velocity in longitudinal movement.
these plots with those obtained in combined movement, an important difference was observed for the movement of the blade (element 5). For longitudinal movement, the results showed a constant angular position with the corresponding zero angular velocity and acceleration. In this case the blade does not rotate, it makes a back and forward translation movement parallel to its initial position.

Analysis of Points F and G: Movement characteristics of points F and G in the x and y directions are plotted in fig. 22, fig. 23 and fig. 24. These points

![Graph showing acceleration of points F and G in longitudinal oscillation.](image)

**Figure 22.** Acceleration of points F and G in longitudinal oscillation.
Figure 23. Displacement and velocity of point F in longitudinal oscillation.
Figure 24. Displacement and velocity of point G in longitudinal movement.
have similar displacements, velocities, and accelerations in both directions in this mode of vibration. The displacement of the points in the y direction approach zero as a result of the non-rotating movement of the blade.

Dynamic Analysis

Results of the dynamic analysis of longitudinal movement of the blade are plotted in fig. 25 and fig. 26. Inertia, static, friction, and total torque at eccentric 2 are shown in fig 25. The torque value $T_{7b}$ obtained at eccentric 7 is the net value of the friction couples $t_{7b}$ and $t_{17b}$.

![Figure 25. Inertia, static, friction, and total torque in horizontal movement.](image-url)
torque for this mode of vibration was:

\[ T_b = T_{2b} + T_{7b} \]

The mean torque for the set of input conditions was: \( T_{mb} = 37.14 \text{ Nm} \).

Inertia, shaking and reaction forces are shown in fig. 26.

ANALYSIS OF LIFTING MOVEMENT

The lifting or vertical oscillation is originated by the rotation of eccentric 7. Input data for this mode of vibration can be as follows:

mode = 2
$\text{ecc}_2 = 0.0$

$\text{ecc}_7 = 9.52 \text{ mm}$

$v_t = 3.0 \text{ km/h}$

$vr = 1.5$

$ph = 0.0.$

**Kinematic Analysis.**

Results of the kinematic analysis of the lifting or vertical movement are plotted in fig. 27, fig. 28, fig. 29, and fig. 30. These include position,
Figure 28. Velocity and acceleration of linkages in lifting movement.
Figure 29. Displacement of Points F and G in lifting movement.
Dynamic Analysis

Results of the dynamic analysis of lifting movement are plotted in fig 31 and 32. Inertia, static, friction, and total torque at the input 7 are plotted in Fig 31. The torque value $T_{2b}$ obtained at eccentric 2 was the net value of the friction couples $t_{12b}$ and $t_{22b}$.

The total torque was: $T_b = T_{2b} + T_{7b}$

The mean torque for the set of input conditions was: 13.3 Nm.
Plots in fig. 19, fig. 25, and fig. 31 show a big difference in the torque values for longitudinal and lifting movement. The mean torque for combined oscillation was approximately the summation of the mean torque in the other two modes of vibration. Total inertia, shaking, and reaction forces are plotted in fig. 32. The values for these forces in lifting movement were much lower than were those for combined or longitudinal movement.
Figure 32. Total inertia, shaking, and reaction forces in lifting movement.
MOVEMENT OF THE BLADE AND CUTTING ANGLE

The movements of the blade with reference to the displacement of the tractor and the cutting action of the blade were analyzed to predict their effect on soil disaggregation, draft reduction and power consumption. The first step was to determine the type of movement of the blade with relation to the displacement of the tractor. This was accomplished by analyzing the movement of points F and G in x and y directions in figs. 7, 8, 23, 24 and 29. The second step, the effect of the blade on the soil, was analyzed by the cutting action of the blade and the contact between the blade and the block of soil. Data was taken from the kinematic analysis and the results were used to select some of the conditions to test in the field.

LONGITUDINAL MOVEMENT

Type of Movement

The movement of points F and G was the resultant of their displacements in the x and y directions. As shown in fig 33, for longitudinal movement, the total displacement of points F and G practically coincided in both directions; there was a negligible rotation about the z-axis. In the vertical direction points F and G oscillated with very small amplitude, only 0.15 mm peak to peak, due to the equal length of links 4 and 6 in fig 3. This was also deduced from the kinematic analysis in figs 20 and 21; the angular position, $\theta_9$, of the blade was a constant with corresponding zero
values for angular velocity and acceleration. The movement of the blade was basically a back and forward translation parallel to its initial position.

Blade-Soil Contact

The cutting action of the blade was analyzed by the displacement of point F in the x direction. It was divided into four sections according to the direction of the resultant movement of the blade, the displacement of the tractor and soil conditions caused by the blade. These sections defined five

Figure 33. Total displacement of points F and G in the x and y directions.
angles expressed as a function of the period of rotation of the input link $\theta_2$ or $\theta_7$. These angles, shown in fig. 34, were defined as follows:

F was the angle through which the cutting edge of the blade moved in the forward direction. During this part of the cycle, the blade pushed and cut the soil. This was the contact angle including movement in tilled and untilled soil and used by Smith, Dais, and Flikke (1972) to define the contact ratio relating it to the period of oscillation.

FF was the angle for forward movement in fresh or untilled soil. This was the cutting angle corresponding to portions OA and CD of the curve.

BL was the angle corresponding to movement in the backward direction in loose or tilled soil. This was the return angle, the blade did not work the soil (AB on the curve, fig. 34).

FL was the angle of movement in the forward direction in loose soil (BC on the curve). Cutting forces must have lower values in this section, because of the tilled condition of the soil.

L was the angle for movement in loose soil (AC on the curve). From the above definitions:

\[ F = FF + FL \]
\[ L = FL + BL. \]

Angles and displacements in fig. 34 corresponded to the following conditions:

Mode = 1 (longitudinal)

Speed of the tractor: $v_t = 3 \text{ km/h}$
Figure 34. Contact and cutting angles.

$\text{ecc}_2 = 9.52 \text{ mm}$

Velocity ratio: $vr = 1.5$.

Contact and cutting angles were:

$BL = 95^\circ$

$FL = 57^\circ$

$L = 152^\circ$

$FF = 142^\circ + 28^\circ = 170^\circ$

$F = FL + FF = 227^\circ$
Points A and B were defined using velocity plots of point F in the x direction. At these two points, the direction of the movement changes and the corresponding total velocities were zero.

Tests were run on the computer for each mode of vibration to determine the respective angles for different operating conditions: two forward speeds, three amplitudes and six velocity ratios. The results showed that the forward speed and the input amplitude did not have appreciable effect on the angles, but these were heavily affected by the angular velocity represented in this case by the velocity ratio as shown in fig. 35. For velocity ratios below 1, the blade was always moving forward, blade and fresh soil were in continuous contact and vibration had a minor effect on draft reduction, as reported in most of the previous work. The fastest change in the angles was at velocity ratios between 1.0 and 2.0 and tend to level off at velocity ratios above 2.0. Smith, Hillman, and Flikke (1972), Narayanarao and Verma (1982) found that draft sharply decreased for velocity ratios greater than 1 and remain approximately constant and equal to 1 for velocity ratios below 1.

Causes for draft reduction and soil break up were related to the cutting angle and the angle for movement in loose soil. Fig. 35 shows that the cutting angle decreased and the angles for movement in loose soil increased with the velocity ratio. In other words, the angle for the cutting action decreased, as the angle to vibrate the soil increased. If these two angles were equal more action on the soil was expected, because this
condition should assure equilibrium between the volume of soil cut in the forward stroke and the volume shaken in the movement of the loose soil.

Figure 35. Velocity ratio and contact angles relationship.

LIFTING MOVEMENT

Analysis for the interaction between the blade and the soil was based on the same factors used for longitudinal movement. Fig 36 shows the displacements of points F and G in the x and y directions. The four displacements differed, especially those in the y direction. Because, the blade rotated about the z-axes. Point G oscillated in the y direction with a
simple amplitude equal to the eccentricity $r_7$, while point F oscillated only in the x-direction.

Displacements of points F and G in fig 36, correspond to a velocity ratio 2.0. There was no backward and forward movement of this point with reference to the displacement of the tractor. This meant that velocity ratios greater than 2.0 were necessary for a significant reduction in draft. For velocity ratios lower than 2.0, the blade continuously cut the soil, draft was supplied by the pulling action of the tractor and the energy supplied to the vibratory system was used only to vibrate the soil.

Figure 36. Displacement of points F and G in lifting movement.
COMBINED MOVEMENT

Analysis of Phase Angle

The phase angle was defined as the relative position of the eccentricities 2 and 7 in combined movement. This was a positive angle measured from the origin of the coordinate system. In this condition, the eccentricity at input 2 advanced the eccentricity in input 7.

From the dynamic analysis of the blade, it was noted that the mean torque in combined movement was approximately the summation of the mean torque in the two independent movements. But in a general sense, this condition depends on the phase angle, ph. Before the analysis of the cutting and contact angles, it was necessary to define the effect of the phase angle on the mean torque. The program was run at different amplitude, forward speed, and velocity ratio conditions varying the phase angle between 0° and 360°. The results are plotted in fig. 37 for mean torque at inputs 2 and 7 and total mean torque for ecc2 = ecc7 = 9.52 mm, v_t = 3 km/h and vr = 1.5. These plots were used to select the phase angles for field testing in the combined mode of vibration. Four points were selected in the figure according to total torque value and torque distribution at the inputs:

\[ \text{ph}_1 = 0.0^\circ \text{ (point of maximum mean torque difference at the inputs)} \]
\[ \text{ph}_2 = 90.0^\circ \text{ (point of minimum total mean torque)} \]
\[ \text{ph}_3 = 180.0^\circ \text{ (point of minimum mean torque difference at the inputs)} \]
\[ \text{ph}_4 = 270.0^\circ \text{ (point of maximum total mean torque)}. \]
Contact angles for the selected points are plotted in fig. 38 and fig. 39 to observe the effect of the phase angle. These plots show that phase angle is an important factor in the cutting and contact angles. Combining the two movements allows back and forward movement of the blade for velocity ratios lower than 1.0. This fact may favor the expected draft reduction at lower angular velocities than in independent movements. On the other hand, as shown in fig 38 for $\phi_h = 90^\circ$, there is back and forward movement of the blade only for velocity ratios greater than 1.5. There will be significant
Figure 38. Contact and cutting angles for phase angles $0^\circ$ and $90^\circ$. 
Figure 39. Contact and cutting angles for phase angles 180° and 270°.
draft reduction only above this level. Furthermore, the lower torque level at this point meant less energy was transferred to the soil. Phase angles of 0° and 180° showed a great similarity in total torque requirements and contact angles. A special difference was observed between these two angles; the distribution of torque at the inputs. The larger torque at input 2 for phase angle zero, caused larger reactions at the supports of the mechanism and more vibration was transmitted to the frame, as it was observed in the laboratory tests. The same results were obtained plotting the reactions on the supports as was done in the dynamic analysis. Operation of the machine was smoother at the 180° phase angle due to the more balanced distribution of torque at the inputs.

Type of Movement of the Blade

The effect of the phase angle on the type of movement of the blade, was analyzed by examining the displacement of points F and G shown in figs. 40 and 41 in both the x and y directions for the following conditions:

vr = 1.0
\(ecc_2 = ecc_7 = 9.52 \text{ mm}\)
\(v_t = 3.0 \text{ km/h}\)
phase angle = 0°, 90°, 180°, 270°.

The cutting edge oscillated in the y direction with a very small amplitude, only 0.25 mm peak to peak, for the maximum torque case at phase angle 270°. This was a basic backward and forward movement of
Figure 40. Effect of the phase angle on the displacement of the cutting edge.
Figure 41. Effect of phase angle on the displacement of point G.
point F parallel to the direction of displacement of the tractor. The main characteristic in the movement of point G was its oscillation in the y direction with a simple amplitude equal to the eccentricity ecc, as shown in fig. 41.
DRAFT FORCE

One of the objectives of this work was to evaluate the draft required to pull the digger blade through the soil and the draft reduction due to the introduction of vibration. Different theories have been tested to determine draft requirements for agricultural implements, one of them was initially developed for inclined blades by Soehne (Gill and Vanderberg, 1968, Srivastava, Goering, and Rohrbach, 1993) and complemented later by Rowe and Barnes (1961). Their procedure calculated the draft force considering the passive resistance of soil as it was cut and pushed by the blade. The geometry and dimensions of the block of soil cut by the blade, shown in fig. 42, are determined by the plane of failure and the dimensions of the blade.

FORCES ON A NON-VIBRATING SYSTEM

Forces on the blade mainly depend on soil conditions, speed, blade dimensions and position, and working depth. These were first analyzed for a non-vibrating system. The blade and the block of soil were subject to forces described as follows:

\[ W_s = \text{weight of block of soil on the blade} \]
\[ A_s = \text{cross section of plane of failure} \]
\[ N_s = \text{normal reaction on the plane of failure} \]
\[ C_s = \text{soil cohesion coefficient} \]
\[ \phi_s = \text{soil friction angle} \]
Figure 42. Soil-blade interaction forces for non-vibrating conditions.
\( \beta_r = \text{angle of plane of failure} = \pi/4 - \phi_s/2 \)

\( \mu_s = \tan \phi_s = \text{soil friction coefficient} \)

\( I_a = \text{soil inertia force due to the movement of the tractor} \)

\( \alpha_b = \text{rake angle of the blade} \)

\( \mu_b = \text{friction coefficient on the blade-soil surface} \)

\( N_b = \text{normal reaction between soil and blade} \)

\( A_b = \text{contact surface between soil and blade} \)

\( C_a = \text{soil-metal adhesion coefficient} \)

\( F_v = \text{resultant of vertical forces on the blade} \)

\( DF = \text{draft force} \)

\( \rho = \text{soil bulk density} \)

\( b = \text{blade width} \)

\( l = \text{blade length} \)

\( d_w = \text{working depth} \)

\( l_{s1} = d_w \cos(\alpha_b + \beta_r) / \sin \beta_r \)

\( l_{s2} = 1 \)

\( l_{s3} = d_w \sin(\alpha_b + \beta_r) \tan \alpha_b / \sin \beta_r \)

\( d_1 = d_w \sin(\alpha_b + \beta_r) / \sin \beta_r \)

\( v_{ox} = \text{ground speed} \)

\( v_x = \text{speed of the cutting edge of the blade in the direction of displacement} \)

\( v_x = v_{tx} = v_{ox} + v_{fx} \).

Volumes, masses, and weight of soil on the blade in fig. 42 were:

\( V_1 = l_{s1}d_1b / 2 \)

\( m_1 = \rho V_1 \)
\[ V_2 = l_2 d_2 b \quad \text{m}_2 = \rho V_2 \]
\[ V_3 = l_3 d_2 b / 2 \quad \text{m}_3 = \rho V_3 \]
\[ V_{\text{tot}} = V_1 + V_2 + V_3 = bd_1(2l_2 + l_3 + l_3) / 2 \quad \text{m}_4 = \rho V_{\text{tot}} \]
\[ W_s = m_s g = \rho g V_{\text{tot}}. \]

Equations for the different forces as a function of soil coefficients, blade dimensions and position and operating speeds were deduced from the equilibrium conditions of the blade-soil system.

Forces on the block of soil:
\[ \Sigma F_x = 0 \quad - I_n \cos \beta_f + (\mu_b N_b + C_a A_b) \cos \alpha_b + N_b \sin \alpha_b \quad - (C_a A_s + \mu_b N_s) \cos \beta_f - N_s \sin \beta_f = 0 \]
\[ \Sigma F_y = 0 \quad - I_n \sin \beta_f - (\mu_b N_b + C_a A_b) \sin \alpha_b + N_b \cos \alpha_b \quad - (C_a A_s + \mu_b N_s) \sin \beta_f + N_s \cos \beta_f - W_s = 0 \]

Forces on the blade:
\[ \Sigma F_x = 0 \quad D F - (\mu_b N_b + C_a A_b) \cos \alpha_b - N_b \sin \alpha_b = 0 \]
\[ \Sigma F_y = 0 \quad F_y + (\mu_b N_b + C_a A_b) \sin \alpha_b - N_b \cos \alpha_b = 0 \]

Solving the system of equations
\[ D F = \frac{W_s + I_n + C_a A_s}{k_c} + \frac{C_a A_b}{k_c \sin \beta_f + \mu_b \cos \beta_f} + \frac{C_a A_b}{k_c \sin \alpha_b + \mu_b \cos \alpha_b} \quad [11] \]
\[ k_c \] is the geometric factor (Srivastava, Goering, and Rohrbach, 1993)
\[ k_c = \frac{\cos \beta_f - \mu_b \sin \beta_f}{\sin \beta_f + \mu_b \cos \beta_f} + \frac{\cos \alpha_b - \mu_b \sin \alpha_b}{\sin \alpha_b + \mu_b \cos \alpha_b} \]
\[ A_s = \frac{bd_2}{\sin \beta_f} \]
\[ A_b = 1 \times b \]
These equations show that for a non-vibrating system, the draft is a function of the blade dimensions and position, soil conditions and tractor speed.

FORCES ON A VIBRATING SYSTEM

A procedure similar to that above was used to determine the draft for any combination of velocity ratio, amplitude, and forward speed in a vibrating system. But with vibration, the displacement of the cutting edge (point F) described in the kinematic analysis and the contact angles became important factors. The blade moved back and forth at a variable speed in tilled or untiled soil. These conditions produced variations in the draft and the torque developed by the tractor to pull the machine and vibrate the blade. The causes of these variations are itemized below.

1. For \( vr \geq 1.0 \), the equations for the non-vibrating condition were applied for the forward movement of the blade, with a forward speed:

\[
v_x = v_{fr} = v_{ex} + v_{fr}.
\]
2. Separate cohesion coefficients and soil-soil friction angles were used for the tilled and untilled soil contacted by the blade. Typical values for untilled soil are 22.0 kPa and 38°, for the tilled condition these are 6.9 kPa and 20° (McKyes, 1985).

3. There were no cutting and inertia forces during the backward movement of the blade.

4. The volume and weight of soil on the blade changed as follows:

\[ V_{\text{tot2}} = ldhis \]
\[ W_{s2} = \rho gV_{\text{tot2}}. \]

In the backward movement of the blade, the block of soil did not follow the blade, rather it fell by gravity perhaps contacting the blade or freely. Forces acting on the blade for the backward movement were dependent on the relative movement between the blade and the soil after the start of the backward stroke. This condition was evaluated by considering the acceleration of the blade in the vertical direction (\(a_{y_b}\)) during the backward movement and comparing it with the acceleration of gravity. For \(a_{y_b} > -9.81 \text{ m/s}^2\), the block of soil contacts the blade producing a friction force in the opposite direction to that considered for the non-vibrating condition. For the retreat movement of the blade, the draft was determined from the system of forces shown in fig. 43.

Forces on the block of soil:

\[ \Sigma F_x = 0 \quad N_b \sin \alpha_b - (\mu_s N_b + C_s A_b) \cos \alpha_b = 0 \]
\[ \Sigma F_y = 0 \quad -W_{s2} + N_b \cos \alpha_b + (\mu_s N_b + C_s A_b) \sin \alpha_b = 0 \]
Figure 43. Soil-blade interaction forces for backward movement of the blade.
Forces on the blade:

\[ \sum F_x = 0 \quad DF - N_b \sin \alpha_b + (\mu_b N_b + C_n A_b) \cos \alpha_b = 0 \]

\[ \sum F_y = 0 \quad F \cdot N_b \cos \alpha_b - (\mu_b N_b + C_n A_b) \sin \alpha_b = 0 \]

Solving the system of equations:

\[ N_b = \frac{W_a - C_n A_b \sin \alpha_b}{\cos \alpha_b + \mu_b \sin \alpha_b} \]

\[ DF = \frac{W_a (\sin \alpha_b - \mu_b \cos \alpha_b) - C_n A_b}{\cos \alpha_b + \mu_b \sin \alpha_b} \quad [14] \]

\[ F \cdot N_b (\cos \alpha_b + \mu_b \sin \alpha_b) + C_n A_b \sin \alpha_b \quad [15] \]

For \( a_{xy} < -9.81 \text{ m/s}^2 \), there were no friction or normal force on the blade with a corresponding zero value for the draft. Results from the computer program showed that as the blade moved backward with a negative acceleration in the x direction, the acceleration in the y direction was still positive assuring a continuous contact with the corresponding friction and normal force on the blade.

These conditions and equations were used to calculate the draft. Results from the computer program were plotted in fig. 44 for the following input conditions:

\( \text{mode} = 1 \) (longitudinal)

\( v_t = 3.0 \text{ km/h} \)

\( vr = 1.5 \)

\( \text{ecc}_2 = 9.52 \text{ mm} \)
Figure 4. Draft force variation for a vibrating blade.

\[ \text{ecc}_c = 0.0 \]

\[ \text{ph} = 0.0 \]

\[ C_s = 22.0 \text{ kPa} \text{ (cohesion coefficient for untilled soil)} \]

\[ C_a = 6.9 \text{ kPa} \text{ (cohesion coefficient for tilled soil)} \]

\[ \phi_s = 38.0^\circ \text{ (soil-soil friction angle for untilled soil)} \]

\[ \phi_a = 20.0^\circ \text{ (soil-soil friction angle for tilled soil)} \]

\[ \rho = 1300 \text{ kg/m}^3 \]

\[ \alpha_0 = 15.0^\circ \]
$C_a = 0.0$

$\mu_b = 0.5$

$l = 0.47 \text{ m}$

$b = 0.55 \text{ m}$

$d_w = 0.24 \text{ m}$.

The main effects of vibration occur at two different intervals: (1) during the backward stroke, when forces on the blade produced a negative draft force that pushes the tractor, and (2) during the forward movement of the blade in tilled soil where there were lower soil cohesion and friction coefficients. The mean value of the draft force for the above conditions was: $DF = 3066.5 \text{ N}$. For the non-vibrating operation of the blade, $DF = 4751.03 \text{ N}$, a constant.

**Draft Ratio (DR)**

This is one the terms used to evaluate draft reduction. This is the ratio of the mean draft for the vibrating condition to the draft for the non-vibrating condition. For the settings established above the draft ratio was: $\text{DR} = 3066.5 \text{ N} / 4751.03 \text{ N} = 0.645$.

**Shear Force**

Interacting forces between the blade and soil depended among other factors, on the soil mechanical conditions determined by the soil cohesion, adhesion, and friction coefficients. The shear force, $F_s$, in the plane of
failure was given by the Coulomb equation:

\[ F_s = C_s A_s + \mu_s N_s. \]

The values of the soil coefficients depended on the tilled or untilled condition of the soil. For the latter, the coefficients were experimentally determined in a direct shear box from samples of untilled soil taken from the plots. For the tilled condition values, were used as mentioned above.

Adhesion and Friction Force on the Blade

Soil-metal interacting forces consisted of both adhesive and frictional components related by:

\[ F_b = C_b A_b + \mu_b N_b. \]

Tangential sliding forces are generally found to vary with the soil texture and moisture content, slider material type and finish, normal stress, sliding distance and sliding velocity (Hendrick and Bailey, 1982). Although, friction and adhesion coefficients can be experimentally determined in a direct shear box (Das, 1990), it is impractical to separate the effects of these two components. The usual practice in laboratory testing is to represent their combined effect by an apparent coefficient of friction (Kepner, Bainer, and Barger, 1978).
ANALYSIS OF THE BLADE-SOIL SYSTEM

The kinematic analysis for the blade-soil system was similar to that for the movement of the blade alone. The first step was to determine the dynamic characteristics and related terms of the block of soil.

DYNAMIC CHARACTERISTICS OF THE BLOCK OF SOIL

Center of Gravity

Dimensions, masses, and shape of the block of soil were defined above. The center of gravity of the mass of soil in fig. 45, was calculated

Figure 45. Mechanical description of the block of soil.
with reference to an axis system \( x'y'z' \) at the center of the cutting edge as:

\[
x' = \frac{\sum m_i x'_i}{\sum m_i}, \quad y' = \frac{\sum m_i y'_i}{\sum m_i}, \quad z' = \frac{\sum m_i z'_i}{\sum m_i}.
\]

Values for \( x'_1, y'_1, \) and \( z'_1 \) were given as follows:

\[
x'_1 = \frac{l_{s1}}{3}, \quad x'_2 = \frac{l_{s2}}{2}, \quad x'_3 = \frac{1 + l_{s3}}{3},
\]
\[
y'_1 = \frac{2d_1}{3}, \quad y'_2 = \frac{d_1}{2}, \quad y'_3 = \frac{2d_1}{3},
\]
\[
z'_1 = 0.0, \quad z'_2 = 0.0, \quad z'_3 = 0.0.
\]

Coordinates were rotated about \( z' \) axis by solving the system [6]:

\[
x_{cg} = x' \cos \alpha_b - y' \sin \alpha_b
\]
\[
y_{cg} = x' \sin \alpha_b + y' \cos \alpha_b
\]
\[
z_{cg} = z' = 0.0.
\]

Referred to point C: \( x_{cg} = x_{cg} \)

\[
y_{cg} = -r_{cf} + y_{cg}
\]
\[
z_{cg} = z' = 0.0.
\]

**Moments of Inertia**

Moments of inertia of the block of soil were calculated following the same procedure used to calculate those of the blade. But, only inertia moments about \( z'-axis \) were considered. \( I_{z'} \) were the mass moments of inertia of the three volumes with reference to their centers of gravity. These moments were calculated by integration procedures as:

\[
I_{z1'} = \frac{\rho bl_{s1}^3 d_1}{48}
\]
\[
I_{z2'} = \frac{\rho bl_{s2}^3 d_1}{12}
\]
\[
I_{z3'} = \frac{\rho bl_{s3}^3 d_1}{48}.
\]
\( I_{x'} \) were the moments of inertia referred to a parallel axis system 
\( x'y'z' \) at the center of gravity of the total volume. These were obtained by 
translation using the parallel axis theorem:

\[
\begin{align*}
I_{x'1} &= I_{x1} + m_1(x_1'^2 + y_1'^2) \\
I_{x'2} &= I_{x2} + m_2(x_2'^2 + y_2'^2) \\
I_{x'3} &= I_{x3} + m_3(x_3'^2 + y_3'^2) \\
\end{align*}
\]

where, \( x_i = x' - x'_i \)

\( y_i = y' - y'_i \).

\( I'_{x'} \) was the total moment of inertia with reference to the \( x'y'z' \) axis 
at the center of gravity:

\[
I'_{x } = \Sigma I'_{x'i}. 
\]

There was no rotation of this moment. The \( z'' \)-axis coincided with the 
global \( z \)-axis.

\( I_z = I_{x'} = I_{zs} \)

Volumes, masses, coordinates of the center of gravity and moments 
of inertia were calculated by the program. Values for the conditions given 
above are summarized in Table 3. The total values were:

\[
\begin{align*}
m_s &= 186.11 \, \text{kg} \\
I_{zs} &= 9.717 \, \text{kgm}^2 \\
x_{cgs} &= 0.090 \, \text{m} \\
y_{cgs} &= 0.105 \, \text{m} \\
z_{cgs} &= 0.0. 
\end{align*}
\]
TABLE 3. MOMENTS OF INERTIA AND CENTER OF GRAVITY OF THE BLOCK OF SOIL.

<table>
<thead>
<tr>
<th>Volume No</th>
<th>$m_i$ (kg)</th>
<th>$x'_i$ (m)</th>
<th>$y'_i$ (m)</th>
<th>$z'_i$ (m)</th>
<th>$I_z$ (kgm$^2$)</th>
<th>$I_{x'}$ (kgm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53.10</td>
<td>-0.138</td>
<td>0.239</td>
<td>0.0</td>
<td>0.377</td>
<td>4.743</td>
</tr>
<tr>
<td>2</td>
<td>120.70</td>
<td>0.235</td>
<td>0.180</td>
<td>0.0</td>
<td>2.222</td>
<td>3.300</td>
</tr>
<tr>
<td>3</td>
<td>12.40</td>
<td>0.502</td>
<td>0.239</td>
<td>0.0</td>
<td>0.005</td>
<td>1.674</td>
</tr>
</tbody>
</table>

The same procedure was followed to calculate the c.g. and the moments of inertia of the block of soil during the retreat of the blade. Only small changes must be introduced to the dimensions of the block:

\[ l_{s1} = l_{a1} = d_1 \tan \alpha_b \]

\[ l_{s2} = l - l_{s1} \]

\[ x'_1 = 2l_{s1} / 3 \]

\[ y'_1 = d_1 / 3. \]

Characteristics of the Block of Soil

$C$, in fig. 3, was the reference point, $m_a$, $I_{za}$, $x_{cgs}$, $y_{cgs}$, and $z_{cgs}$ were calculated as above. Other characteristics were:

\[ r_{cgs} = (x_{cgs}^2 + y_{cgs}^2)^{1/2} \]

\[ \theta_{cgs} = \theta_5 - \tan(y_{cgs} / x_{cgs}) \]

\[ a_{sx} = - r_4 \alpha_4 \sin \theta_4 - r_4 \omega_4^2 \cos \theta_4 - r_{cgs} \alpha_5 \sin \theta_{cgs} - r_{cgs} \omega_5^2 \cos \theta_{cgs} \]

\[ a_{sy} = r_4 \alpha_4 \cos \theta_4 - r_4 \omega_4^2 \sin \theta_4 + r_{cgs} \alpha_5 \cos \theta_{cgs} - r_{cgs} \omega_5^2 \sin \theta_{cgs} \]

\[ a_s = (a_{sx}^2 + a_{sy}^2)^{1/2} \]

\[ \gamma_s = \tan(a_{sy} / a_{sx}) \]
\[ \beta_s = \gamma_s + \pi \]
\[ f_{0_s} = m_s a_s \]
\[ l_s = r_{cgs} + \frac{I_s \omega_s}{f_{0_s} \sin(\beta_s - \theta_{cgs})} \]

DYNAMIC ANALYSIS OF THE BLADE-SOIL SYSTEM

The dynamic analysis of the blade-soil system was based on the combination of the different factors involved in the performance of the machine in the field, including kinematics of the mechanism, soil mechanical conditions, and dynamic characteristics of the system. This analysis was performed for each movement by determining the torque requirements to overcome inertia, static, and friction forces in a procedure similar to that used in the dynamic analysis of the mechanism alone.

Combined Movement

Inertia Forces and Torque: For the retreat stroke of the blade \((v_{tx} < 0)\), the inertia force on the block of soil was \(f_{0_s} = 0.0\). The torque required to overcome inertia in order to vibrate the blade-soil system was determined from the equilibrium conditions as shown in fig. 46.

Element 2:

\[ \Sigma F_x = 0.0 \quad F_{12x} + F_{32x} + f_{0x} \cos \beta_2 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad F_{12y} + F_{32y} + f_{0y} \sin \beta_2 = 0.0 \]
\[ \Sigma M_{O2} = 0.0 \quad - F_{32x} r_2 \sin \theta_2 + F_{32y} r_2 \cos \theta_2 + f_{0y} l_2 \sin(\beta_2 - \theta_{cgs}) - T_{2iso} = 0.0. \]
Figure 46. Inertia forces on the blade-soil system in combined movement.
Element 3

\[ \Sigma F_x = 0.0 \quad -F_{32x} + F_{53x} + f_3 \cos \beta_3 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad -F_{32y} + F_{53y} + f_3 \sin \beta_3 = 0.0 \]
\[ \Sigma M_A = 0.0 \quad -F_{53x} r_3 \sin \theta_3 + F_{53y} r_3 \cos \theta_3 + f_3 l_3 \sin (\beta_3 - \theta_{cg3}) = 0.0 \]

Element 5:

\[ \Sigma F_x = 0.0 \quad -F_{53x} + F_{45x} + F_{65x} + f_5 \cos \beta_5 + f_4 \cos \beta_4 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad -F_{53y} + F_{45y} + F_{65y} + f_5 \sin \beta_5 + f_4 \sin \beta_4 = 0.0 \]
\[ \Sigma M_C = 0.0 \quad F_{53x} r_c \sin \theta_c - F_{53y} r_c \cos \theta_c - F_{65x} r_5 \sin \theta_5 + F_{65y} r_5 \cos \theta_5 + f_5 l_5 \sin (\beta_5 - \theta_{cg5}) + f_4 l_4 \sin (\beta_4 - \theta_{cg4}) = 0.0 \]

Element 4:

\[ \Sigma F_x = 0.0 \quad -F_{45x} + F_{14x} + f_4 \cos \beta_4 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad -F_{45y} + F_{14y} + f_4 \sin \beta_4 = 0.0 \]
\[ \Sigma M_{O4} = 0.0 \quad F_{45x} r_4 \sin \theta_4 - F_{45y} r_4 \cos \theta_4 + f_4 l_4 \sin (\beta_4 - \theta_{cg4}) = 0.0 \]

Element 6:

\[ \Sigma F_x = 0.0 \quad -F_{65x} + F_{76x} + f_6 \cos \beta_6 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad -F_{65y} + F_{76y} + f_6 \sin \beta_6 = 0.0 \]
\[ \Sigma M_{O6} = 0.0 \quad F_{65x} r_6 \sin \theta_6 - F_{65y} r_6 \cos \theta_6 + f_6 l_6 \sin (\beta_6 - \theta_{cg6}) = 0.0 \]

Element 7:

\[ \Sigma F_x = 0.0 \quad -F_{76x} + F_{17x} + f_7 \cos \beta_7 = 0.0 \]
\[ \Sigma F_y = 0.0 \quad -F_{76y} + F_{17y} + f_7 \sin \beta_7 = 0.0 \]
\[ \Sigma M_{O7} = 0.0 \quad F_{76x} r_7 \sin \theta_7 - F_{76y} r_7 \cos \theta_7 + f_7 l_7 \sin (\beta_7 - \theta_{cg7}) - T_{7iso} = 0.0 \]

The total inertia torque was:

\[ T_{iso} = T_{2iso} + T_{7iso} \]
These values are plotted in fig. 47. The peaks in the curves, specially at the input eccentric 7, were the joint effect of the phase angle and the forces caused by the soil on the blade. Only the phase angle of 90° yielded smooth curves. Reactions to inertia forces, inertia forces and the shaking force were also obtained from the program.

Figure 47. Inertia torque in combined movement of the blade-soil system.

**Static Forces and Torque:** Static forces on the mechanism were due to the cutting action of the blade, friction and gravity. Torque and draft requirements to overcome these forces were determined from the
equilibrium conditions shown in fig. 48. \( F_b \) and \( N_b \) depended on the relative movement between the blade and the tractor. The total velocity of the cutting edge, the direction of the movement of the blade, and the soil conditions were considered as follows:

For \( v_{frx} < 0.0 \) and \( a_{sy} \leq -9.81 \m/s^2 \):

\[
N_b = 0.0
\]
\[
F_b = 0.0.
\]

For \( v_{frx} < 0.0 \) and \( a_{sy} > -9.81 \m/s^2 \):

\[
N_b = \frac{W_b^2 - A_b C_b \sin \alpha_b}{(\cos \alpha_b + \mu_b \sin \alpha_b)}
\]
\[
F_b = -(C_a A_b + \mu_b N_b).
\]

For any other condition:

\[
N_b = \frac{W_b}{K_c} + \frac{I_n + A_b C_b + A_b C_k K_3}{K_c (\sin \alpha_b + \mu_b \cos \alpha_b)(\sin \beta_f + \mu \cos \beta_f)}
\]
\[
K_3 = \cos \alpha_b (\mu \sin \beta_f - \cos \beta_f) + \sin \alpha_b (\mu \cos \beta_f + \sin \beta_f)
\]
\[
F_b = -(C_a A_b + \mu_b N_b).
\]

\( C_a \) and \( \mu_a \) depended upon whether the movement of the blade was in tilled or untilled soil.

Element 2:

\[
\sum F_x = 0.0 \quad P_{12x} + P_{32x} = 0.0
\]
\[
\sum F_y = 0.0 \quad P_{12y} + P_{32y} - W_{gt_2} = 0.0
\]
\[
\sum M_{O2} = 0.0 \quad -P_{32x} r_2 \sin \theta_2 + P_{32y} r_2 \cos \theta_2 - W_{gt_2} r_2 e_2 \cos \theta_2 - T_{2s\text{cco}} = 0.0.
\]
Figure 48. Static forces on the blade-soil system in combined movement.
Element 3:
\[ \Sigma F_x = 0.0 - P_{32x} + P_{53x} = 0.0 \]
\[ \Sigma F_y = 0.0 - P_{32y} + P_{53y} - Wgt_3 = 0.0 \]
\[ \Sigma M_A = 0.0 \quad P_{32x} \sin \theta_3 - P_{32y} \cos \theta_3 - Wgt_3 r_{cg3} \cos \theta_{cg3} = 0.0. \]

Element 5:
\[ \Sigma F_x = 0.0 - P_{53x} + P_{45x} + P_{65x} - N_b \sin \alpha_b - F \cos \alpha_b = 0.0 \]
\[ \Sigma F_y = 0.0 - P_{53y} + P_{45y} + P_{65y} - Wgt_5 - N_b \cos \alpha_b + F \sin \alpha_b = 0.0 \]
\[ \Sigma M_C = 0.0 - P_{53x} r_{bc} \sin \theta_5 + P_{53y} r_{bc} \cos \theta_5 - P_{65x} r_5 \sin \theta_5 + P_{65y} r_5 \cos \theta_5 - N_b r_{cg5} \cos \theta_{cg5} = 0.0. \]

Element 4:
\[ \Sigma F_x = 0.0 - P_{45x} + P_{14x} = 0.0 \]
\[ \Sigma F_y = 0.0 - P_{45y} + P_{14y} - Wgt_4 = 0.0 \]
\[ \Sigma M_{04} = 0.0 \quad P_{45x} r_4 \sin \theta_4 - P_{45y} r_4 \cos \theta_4 - Wgt_4 r_{cg4} \cos \theta_{cg4} = 0.0. \]

Element 6:
\[ \Sigma F_x = 0.0 - P_{65x} + P_{76x} = 0.0 \]
\[ \Sigma F_y = 0.0 - P_{65y} + P_{76y} - Wgt_6 = 0.0 \]
\[ \Sigma M_{06} = 0.0 \quad P_{65x} r_6 \sin \theta_6 - P_{65y} r_6 \cos \theta_6 - Wgt_6 r_{cg6} \cos \theta_{cg6} = 0.0. \]

Element 7:
\[ \Sigma F_x = 0.0 - P_{76x} + P_{17x} = 0.0 \]
\[ \Sigma F_y = 0.0 - P_{76y} + P_{17y} - Wgt_7 = 0.0 \]
\[ \Sigma M_{07} = 0.0 \quad P_{76x} r_7 \sin \theta_7 - P_{76y} r_7 \cos \theta_7 - Wgt_7 r_{cg7} \cos \theta_{cg7} - T_{7stso} = 0.0. \]

Solutions to the system are shown in fig. 49. Total static torque was:
\[ T_{stso} = T_{2stso} + T_{7stso}. \]
The value of the draft $DF$ and the vertical force on the blade $F_v$ were obtained from the results by considering the horizontal and vertical reactions on the joints of the blade. These values must coincide with those obtained in the previous chapter using the Sohene approach in equations [11] to [15]:

$$DF = -P_{53x} + P_{45x} + P_{65x}$$

$$F_v = -P_{53y} + P_{45y} + P_{65y}$$
Total and Friction Torque: Total and friction torque for the blade-soil system were calculated by the same procedure used in the dynamic analysis of the blade. The values for $N_b$, $F_b$, and $f_o$ in the element 5 depended on the same conditions established for static and inertia forces according to the total velocity of point $F$ in the $x$ direction and the acceleration of the blade in the $y$ direction in its backward stroke. Equations were established from equilibrium conditions in fig. 50.

Element 2:

\[
\begin{align*}
\sum F_x &= 0.0 \quad H_{12x} + H_{32x} + f_o \cos \beta_s = 0.0 \\
\sum F_y &= 0.0 \quad H_{12y} + H_{32y} - Wgt_2 + f_o \sin \beta_s = 0.0 \\
\sum M_{O2} &= 0.0 \quad - H_{32x}r_2 \sin \theta_2 + H_{32y}r_2 \cos \theta_2 - Wgt_2 r_{cg2} \cos \theta_{cg2} + f_o l_2 \sin (\beta_2 - \theta_{cg2}) - T_{zso} + t_{12so} + t_{32so} = 0.0.
\end{align*}
\]

Element 3:

\[
\begin{align*}
\sum F_x &= 0.0 \quad - H_{32x} + H_{53x} + f_o \cos \beta_3 = 0.0 \\
\sum F_y &= 0.0 \quad - H_{32y} + H_{53y} - Wgt_3 + f_o \sin \beta_3 = 0.0 \\
\sum M_A &= 0.0 \quad - H_{53x}r_3 \sin \theta_3 + H_{53y}r_3 \cos \theta_3 - Wgt_3 r_{cg3} \cos \theta_{cg3} + f_o l_3 \sin (\beta_3 - \theta_{cg3}) - t_{32so} + t_{53so} = 0.0.
\end{align*}
\]

Element 5:

\[
\begin{align*}
\sum F_x &= 0.0 \quad - H_{53x} + H_{45x} + H_{65x} + f_o \cos \beta_5 + f_o \cos \beta_s - N_b \sin \alpha_b - F_b \cos \alpha_b = 0.0 \\
\sum F_y &= 0.0 \quad - H_{53y} + H_{45y} + H_{65y} - Wgt_5 + f_o \sin \beta_5 + f_o \sin \beta_s - N_b \cos \alpha_b + F_b \sin \alpha_b = 0.0 \\
\sum M_c &= 0.0 \quad H_{53x}r_b \sin \theta_c - H_{53x}r_b \cos \theta_c - H_{65x}r_5 \sin \theta_5 + H_{65x}r_5 \cos \theta_5.
\end{align*}
\]
Figure 50. Total forces on the blade-soil system in combined movement.
\[ N_b r_{cg} \cos(\theta_{cg} + \alpha_b) + F_b r_5 \sin(\theta_5 + \alpha_b) + \theta_{cg} \sin(\beta_5 - \theta_{cg}) - Wgt_5 r_{cg} \cos \theta_{cg} + \theta_{cg} \sin(\beta_5 - \theta_{cg}) - t_{5350} + t_{4550} + t_{6550} = 0.0. \]

Element 4:
\[ \Sigma F_x = 0.0 - H_{45x} + H_{14x} + f_0 \cos \beta_4 = 0.0 \]
\[ \Sigma F_y = 0.0 - H_{45y} + H_{14y} - Wgt_4 + f_0 \sin \beta_4 = 0.0 \]
\[ \Sigma M_{O4} = 0.0 H_{45x} r_4 \sin \theta_4 - H_{45y} r_4 \cos \theta_4 - Wgt_4 r_{cg} \cos \theta_{cg} + \theta_{cg} \sin(\beta_4 - \theta_{cg}) - t_{4550} + t_{1450} = 0.0. \]

Element 6:
\[ \Sigma F_x = 0.0 - H_{65x} + H_{76x} + f_0 \cos \beta_6 = 0.0 \]
\[ \Sigma F_y = 0.0 - H_{65y} + H_{76y} - Wgt_6 + f_0 \sin \beta_6 = 0.0 \]
\[ \Sigma M_{O6} = 0.0 H_{65x} r_6 \sin \theta_6 - H_{65y} r_6 \cos \theta_6 - Wgt_6 r_{cg} \cos \theta_{cg} + \theta_{cg} \sin(\beta_6 - \theta_{cg}) - t_{6550} + t_{7650} = 0.0. \]

Element 7:
\[ \Sigma F_x = 0.0 - H_{76x} + H_{17x} + f_0 \cos \beta_7 = 0.0 \]
\[ \Sigma F_y = 0.0 - H_{76y} + H_{17y} - Wgt_7 + f_0 \sin \beta_7 = 0.0 \]
\[ \Sigma M_{O7} = 0.0 H_{76x} r_7 \sin \theta_7 - H_{76y} r_7 \cos \theta_7 - Wgt_7 r_{cg} \cos \theta_{cg} + \theta_{cg} \sin(\beta_7 - \theta_{cg}) - t_{7650} + t_{1750} - T_{750} = 0.0. \]

The total and the friction torque, plotted in fig. 51, were calculated as follows:

Total Torque: \( T_{so} = T_{2so} + T_{7so} \)

Friction torque at input 2: \( T_{2fo} = T_{2so} - T_{2iso} - T_{26iso} \)

Friction torque at input 7: \( T_{7fo} = T_{7so} - T_{7iso} - T_{7tsso} \)

Total friction torque: \( T_{fso} = T_{2fs0} + T_{7fo}. \)
The four values of total torque $T_{so}$, $T_{iso}$, $T_{sso}$, and $T_{iso}$ were plotted in fig. 52. The mean torque values to operate the machine in combined oscillation were:

$T_{2mso} = 132.02$ Nm

$T_{7mso} = -7.12$ Nm

$T_{mso} = 124.90$ Nm
Figure 52. Inertia, static, friction and total torque in the blade-soil system in combined movement.

**Longitudinal Movement**

Results from the dynamic analysis of the blade-soil system are plotted in fig. 53. Mean torque values for the conditions analyzed were:

\[ T_{2_{mean}} = 113.29 \text{ Nm} \]
\[ T_{7_{mean}} = 21.04 \text{ Nm} \]
\[ T_{mean} = 134.34 \text{ Nm}. \]
The torque at eccentric 7, $T_{7_{760}}$, is the net value of the friction couples at joint 76 and support 17:

$$T_{7_{760}} = t_{7_{760}} - t_{17_{760}}.$$ 

Figure 53. Torque components for the blade-soil system in longitudinal vibration.

Lifting Movement

Results from the dynamic analysis of the blade-soil system in lifting movement are plotted in fig. 54. The total torque and its components are plotted as a function of the rotation of the input eccentric 7.
Mean torque values for the conditions established earlier were:

\[ T_{2\text{mso}} = 21.17 \text{ Nm} \]
\[ T_{7\text{mso}} = 12.62 \text{ Nm} \]
\[ T_{m\text{so}} = 33.79 \text{Nm}. \]

The value of mean torque at eccentric 2 is the net value of the friction couples at the joint 32 and the support 12:

\[ T_{2\text{so}} = - t_{12\text{so}} - t_{32\text{so}} \]
Power requirements of the Blade-Soil System

Power requirements to operate the machine were an important factor in the evaluation of the digger blade. Vibration has been reported to increase the power requirements in agricultural machines. This increment was evaluated by comparing the power required to operate the machine with and without vibration.

Power Ratio: The power ratio was defined as the ratio between the power used to operate and pull the machine with vibration to the power used to pull the machine without vibration. To calculate this value, it was necessary to define the different power conditions of the machine.

The power for the non-vibrating condition was:

\[ N_{uv} = UDF \times \frac{v_{ax}}{1000.0} \]

\( N_{uv} \) = power for non-vibration condition (kW)
UDF = draft for the non-vibration condition (N).

The total power \( (N_t) \) for the vibrating condition was divided into two parts: the power for vibration \( (N_v) \) and the power to supply the draft requirements of the machine \( (N_{df}) \):

\[ N_t = N_v + N_{df} \]

\[ N_v = \frac{T_m \omega_b}{1000.0} \]

\( T_m \) = mean torque at the input link (N.m)
\( \omega_b \) = frequency of vibration of the blade (rad/s)

\[ N_{df} = DF \times \frac{v_{ax}}{1000.0} \].
None of these calculations includes the draft required to overcome the sliding resistance of the skids which support the machine. The power ratio as defined above was:

\[ PR = \frac{N_t}{N_{uv}} \]

The combination of mean draft and power ratio were used to decide on the selection of the factors of variation to use in the field.
MATERIALS AND METHODS

SELECTION OF FIELD TEST CONDITIONS

The massive number of tests for the complete evaluation of the machine and the weather conditions required to operate it in the field were concerns of main importance. It was necessary to reduce the number of tests. Results from the computer program were used in selecting the test conditions based on the following variables:

Draft ratio
Power ratio
Oscillation power
Contact angles.

As in the literature review, draft reduction had its maximum change for velocity ratios between 1 and 2. From this, it was decided that field tests would be at velocity ratios within this range.

The selection of the amplitudes to be tested was made based on the power for vibration and draft and power ratios. For short amplitudes, the oscillation power and the power ratio were very high at velocity ratios above 1.0. For a longitudinal oscillation, with 4.76 mm amplitude, a velocity ratio of 1.0 and a forward speed of 3.0 km/h, the oscillation power was calculated to be about 18 kW, the power ratio was 5.43 and there was not draft reduction. This would be an ineffective use of vibration. Further, from the literature review, small amplitudes require low ground speeds to have a
significant effect on soil disaggregation. The selection of the amplitudes of vibration was based on the eccentricities available with the machine and the power related terms. For constant velocity ratio and forward speed, increasing the amplitude reduced the power required for oscillation and the power ratio. In the combined mode of vibration, the velocity ratio was included in the selection because, with different eccentricities operating at the same frequency in the horizontal and vertical direction, the velocity ratio was different. The decision was for large amplitudes; 9.52 mm and 12.7 mm. Three km/h was selected as the basic forward speed based on the fact that commercial potato harvesters operate at or above this speed.

Contact angles had a great influence in the selection of the variables in combined movement. As was shown in the contact angles analysis at phase angles of 0, 180, and 270°, there was a draft reduction for velocity ratios below 1.0. Results from the computer program showed draft reductions as great as 40% with a velocity ratio 1.0 in combined movement. On the other hand, power consumption for velocity ratios above 1.0 was very large. For these reasons, only velocity ratio of 1.0 was selected for field tests to avoid tests with high power consumption and the massive number of tests. Selection of the phase angle was made based on the contact and cutting angles as was explained above.

As reported by Shkurenko (1960), longitudinal oscillations are 1.5 to 1.6 times more effective in reducing draft than those in lifting movement. Results from the computer program showed that in longitudinal movement
there was draft reduction for velocity ratios above 1.0. But for velocity ratios above 1.5, the oscillation power and the power ratio were high. These results were used to select 1.0 and 1.5 as velocity ratios to test in longitudinal and lifting movement, although velocity ratios of 2.0 or above were necessary to obtain a significant draft reduction with this mode of vibration. The final selection for machine conditions was:

Longitudinal and lifting movement:
Eccentricities or amplitudes of vibration: 9.52 and 12.7 mm
Forward speeds: 2 and 3 km/h
Velocity ratios: 1.0 and 1.5.

Combined movement:
Eccentricities or amplitudes of vibration: 9.52 and 12.7 mm
Forward speeds: 2 and 3 km/h
Velocity ratios: 1.0
Phase Angles: 0, 90, 180 and 270°.

Settings for the Machine and Tractor

Tractor settings to use in the field were calculated from data in the manual and its actual conditions. The tractor was a John Deere 2640. The factors to set were: engine speed, gear shift position, and type of PTO. Gears and chain lengths were the factors to set in the digger machine. Basic data for the calculations was:
Standard PTO speed: \( n_{PTO} = 1000 \text{ rpm or } 540 \text{ rpm} \)
Engine speed for standard PTO speed: \( n_e = 2400 \text{ rpm} \)

Engine-PTO ratio: \( i_{PTO} = 2.40 \) or 4.44.

Transmission ratios in the tractor in the low and high range were:

1st gear: \( i_t = 302.6 \) \( 254.3 \)

2nd gear: \( i_t = 215.2 \) \( 180.4 \)

3rd gear: \( i_t = 145.8 \) \( 122.3 \).

These ratios were calculated from data in the tractor's manual as the average for tabulated speeds at 1500, 2100 and 2500 rpm engine speed:

\[
i_t = n_r r_t / (2.65v)
\]

\( v = \) tabulated forward speed (km/h)

\( r_t = \) the tire rolling radius. This value was calculated from the rolling circumference for 16.9-28 tires as 0.674 m (Goodyear, 1991).

Engine speed for the tests was calculated by:

\[
n_e = 2.65v_o i_t / (1-s)r_t a
\]

\( s = \) slippage. This value was assumed to be 5%.

\( r_t a = \) the actual loading radius of the tire 0.670 m.

In the low speed range, a ground speed of 2 km/h was obtained in 2nd gear and 1890 engine rpm or in 3rd gear at 1260 engine rpm. A ground speed of 3 km/h was obtained in 3rd gear at 1890 engine rpm. In the high speed range, a ground speed of 2 km/h was obtained in 2nd gear at 1500 engine rpm. A ground speed of 3 km/h was obtained in 3rd gear at 1530 engine rpm. Engine speeds above 2000 rpm and below 1200 rpm were not used to avoid low power levels at low speed and the need for large reduction
gears in the machine due to high PTO speed. Most of the tests were performed in the low speed range.

The gears for the chain transmission between shafts II and III, shown in fig. 55, were selected considering two PTO speeds for each engine speed. The gear ratio of the bevel gear box was 1.0. The gear ratio between shafts III and IV (i_{34}) was 1.0 in combined movement to maintain the phase angle. It was a purpose to keep the same ratio for horizontal and lifting movement. Tests for longitudinal movement with a different gear ratio required entering the value of i_{34} to the program. The speeds for the shafts were:

\[ i_{23} = \frac{n_{III}}{n_{II}} = \frac{n_{PTO}}{n_{PTO}} = \frac{n_{IV}}{n_{PTO}} \]

\[ i_{23} \] = gear ratio between shafts II and III

\[ n_{II} \] = speed of shaft II (rpm) = \( n_{PTO} \)

\[ n_{III} \] = speed of shaft III = input (\( n_r \)) in lifting and combined oscillation.

\[ n_{IV} \] = speed of shaft IV = input (\( n_r \)) in horizontal and combined oscillation.

Oscillation frequencies of the blade were calculated from three of the four variables to be tested in the machine as:

\[ w_b = \frac{v_{ox}.vr_i}{r_i} \text{ (rad/s)} = \frac{v_{ox}.vr_i}{(2\pi r_i)} \text{ (Hz)} \]

\( r_i \) is the eccentricity or simple amplitude \( r_2 \) or \( r_7 \) (m).

Settings for the tractor-digger system are summarized in Table B in appendix B, where: (*) corresponded to tests with the 540 rpm PTO shaft, the remaining tests were conducted with the 1000 rpm PTO shaft:

\[ i_t \] = calculated total speed ratio = \( i_{23}i_{34} = i_{23} \)

\[ i_u \] = total speed ratio used in the machine.
A total of 48 different tests with vibration were performed to evaluate draft, power consumption and soil disaggregation. Two tests were performed to evaluate the same variables for the non-vibration condition and two tests to determine the skidding resistance of the machine.

MEASUREMENT OF FORCES AND TORQUE

Draft and power requirements of implements, or the ability of tractors to do work are evaluated by measuring the magnitude and direction of the forces interacting in the soil-implement-tractor system or by measuring the torque required to operate a machine. Different types of
dynamometers are used to measure forces and torques; most are based on electrical resistance-strain gages mounted in specially constructed load cells (Kirisci et al., 1993). For three-point-hitch implements there are two basic types of dynamometers: frame type and link type. In the link type dynamometers, transducers are mounted in the links of the tractor hitch or in especially constructed links. In the frame system, transducers are mounted in a frame inserted between the tractor and the implement.

Forces on the Sensing System

A frame type dynamometer, similar to that used by Chung (1981) and Hamman (1985), was used to evaluate the draft requirements of the digger blade. It consisted of a quick three-point hitch with load cells in the mounting pins to the tractor. The hitch was designed to account for the horizontal forces in the direction of travel, the vertical forces, the lateral forces, and the moment about each of the axes (six degrees of freedom). Due to the symmetry of the digger blade, lateral forces were considered negligible. The following force analysis determined the characteristics of the sensing pins, based only on the horizontal and vertical forces transmitted from the soil to the tractor as shown in fig. 56, where:

C.R. = center of resistance of the implement

α = direction of the resultant of forces on the blade in the vertical plane

\[ F_v = \text{Vertical component of soil forces} = DF \times \tan \alpha \]

\[ h_1 = \text{vertical distance between the C.R. and the lower pins} \]
\( b_1 \) = horizontal distance from the C.R. to the lower pins in the implement
\( h_2 \) = vertical distance from the lower pins to the upper pin, or mast height
\( b_2 \) = horizontal distance from the sensing pins to the pins of the implement
\( b_3 \) = horizontal distance between the sensing pins and the center of gravity of the quick hitch. This point was assumed at the center of the frame
\( \beta \) = angle of the resultant force on the upper link of the tractor
\( P_y \) = vertical forces on the lower pins of the implement. Forces on each direction were assumed to be equal in both lower pins
\( P_x \) = horizontal forces on each lower pin of the implement
\( F_{ux} \) = resultant force on the upper pin of the implement
\( F_{ux} \) = horizontal component on the upper sensing pin
\( F_{uy} \) = vertical component on the upper sensing pin
\( F_{lx} \) = horizontal component on each lower sensing pin
\( F_{by} \) = vertical component in each lower sensing pin
\( W_h \) = weight of the quick-hitch
\( R_s \) = skidding resistance in the soil-machine contact surface
\( c_1 \) = distance from the lower pins to the sliding surface.

Forces acting on the sensing pins were calculated from the equilibrium conditions of the implement-hitch-tractor system.

Equilibrium conditions in the implement:

\[
\begin{align*}
\sum F_x &= 0 \quad \text{DF} + F_{ux} - 2P_x + R_s = 0 \\
\sum F_y &= 0 \quad 2P_y - F_y = 0 \\
\sum M_A &= 0 \quad \text{DF} \times h_1 - F_{by} - F_{ux}h_2 + R_s c_1 = 0.
\end{align*}
\]
Figure 56. Forces on the quick hitch-implement system.
This system was solved for forces on the pins of the digger blade machine with the following results:

\[
P_y = \frac{F_x}{2} = \frac{DF \cdot \tan \alpha}{2} \quad [16]
\]

\[
F_{ux} = \frac{DF \cdot h_1 - F_x b_1}{h_2} = \frac{DF(h_1 - b_1 \tan \alpha) + R_x c_1}{h_2} \quad [17]
\]

\[
P_x = \frac{DF + F_{ux} + R_x}{2} = \frac{DF(h_1 + h_2 - b_1 \tan \alpha) + R_x(c_1 + h_2)}{2h_2} \quad [18]
\]

For the equilibrium conditions in the quick hitch:

\[
\Sigma F_x = 0 \quad 2P_x - 2F_{lx} + F_{ux} - F_{tx} = 0
\]

\[
\Sigma F_y = 0 \quad F_{uy} - 2P_y + 2F_{ly} - W_h = 0
\]

\[
\Sigma M_B = 0 \quad -2P_y b_2 - F_{ux} h_2 - W_h b_3 + F_{tx} h_2 = 0.
\]

Solving for the forces on the upper sensing pins:

\[
F_{ux} = \frac{2P_y b_2 - W_h b_3 + F_{tx} h_2}{h_2} \quad [19]
\]

\[
F_{uy} = F_{ux} \tan \beta \quad [20]
\]

For the lower sensing pin:

\[
F_{lx} = \frac{F_{ux} + 2P_x - F_{lx}}{2} \quad [21]
\]

\[
F_{ly} = \frac{2P_y + W_h - F_{ly}}{2} \quad [22]
\]

The lower links of the tractor were assumed at an horizontal position and the working depth was controlled by setting the position of the skids.

For the digger blade some dimensions used in the above equations were
determined after combining dimensions in the tractor, the implement, and the sensing system as shown in fig. 57, where:

\[ d_w = \text{working depth} = 240\text{mm} \]

\[ c_1 = \text{height of the lower links} = 430\text{mm} \]

\[ h_t = \text{clearance of the tractor} = 340\text{mm} \]

\[ c_2 = \text{height of the upper point in the tractor} = 838\text{mm}. \]

The line of action of the draft was assumed to coincide with that of the soil passive resistance:

\[ c_3 = \frac{2d_w}{3} = 160\text{mm}. \]

The horizontal distance from the lower pins on the implement to the center of resistance was assumed as the standard distance for determining the lifting capacity of the tractor (ASAE Standards, 1986):

\[ b_1 = 610\text{mm}. \]

Vertical distance from the lower pins to the crest of the bed:

\[ c_4 = s_1 - d_w = 430\text{mm} - 240\text{mm} = 190\text{mm}. \]

Vertical distance from the lower pins to the line of action of the draft:

\[ h_1 = c_3 + c_4 = 160\text{mm} + 190\text{mm} = 350\text{mm}. \]

Length of the upper link:

\[ l_u = 700\text{mm}. \]

Height of the tower (standard for CAT II three-point hitch system):

\[ h_2 = 483\text{mm}. \]

Height of the upper sensing pin:

\[ c_5 = c_1 + h_2 = 430\text{mm} + 483\text{mm} = 913\text{mm}. \]
Figure 57. Tractor-bed-hitch-implement relationship.
Angle of inclination of the upper link:

\[ \beta = \sin\left(\frac{c_6}{l_u}\right) = \sin\left(\frac{c_5 - c_2}{l_u}\right) = \sin\left(\frac{75}{700}\right) = 6.1^{\circ} \]

From the quick hitch system:

\[ b_2 = 203 \text{ mm} \]
\[ b_3 = 103 \text{ mm} \]
\[ W_h = 890 \text{ N} \]

The total draft force (DT) was the summation of the forces necessary to pull the blade through the soil at its working position and the skidding resistance of the machine. The former was estimated in the simulation as being equal to the draft for the non-vibrating condition:

\[ DF = 4800 \text{ N} \]
\[ R_s = \mu_s W_m = \text{sliding resistance} \]
\[ \mu_s = \text{friction coefficient between the soil and the skids} = 0.5 \]
\[ W_m = \text{Weight of the machine} = 4900 \text{ N} \]
\[ R_s = 0.5 \times 4900 \text{ N} = 2450 \text{ N} \]
\[ DT = DF + R_s = 7250 \text{ N} \]

Forces were obtained by replacing values in equations [19] to [22].

Vertical component of the soil reaction:

\[ F_v = DF \times \tan\alpha = 4.8 \text{ kN} \times \tan15^{\circ} = 1.29 \text{ kN} \]

Forces on the implement pins:

Horizontal force on the upper pin: \[ F_{tx} = 4.03 \text{ kN} \]
Horizontal force on the lower pins: \[ P_x = 5.64 \text{ kN} \]
Vertical force on the lower pins: \[ P_y = 0.64 \text{ kN} \]
Forces on the sensing pins:

Horizontal force on the upper pin: \( F_{ux} = 4.38 \text{ kN} \)
Vertical force on the upper pin: \( F_{uy} = 0.47 \text{ kN} \)
Horizontal force on the lower pins: \( F_{lx} = 5.82 \text{ kN} \)
Vertical force on the lower pin: \( F_{ly} = 0.85 \text{ kN} \).

Pin Dimensions

Pin lengths were fixed; therefore pin diameters were calculated based on the stresses caused by the forces on the pins. The position of the forces and strain gages are shown in fig. 58, where:

\( l_1 = \) distance from the point of application of the force to the point of maximum bending stress in the pin = 63mm
\( l_2 = \) distance from the point of application of the force to the point of application of the strain gages = 53 mm

The lower pins were made of steel AISI 1018 cold drawn with a yield point strength \( S_y = 372000 \text{ kPa} \) (Shigley, 1981).

Lower Pin Diameter: The lower pins were subject to bending due to horizontal and vertical forces and tension due to side forces. These forces were not considered in this analysis. The total bending moment and the bending stress on the lower pins were:

\( M_i = (F_{lx}^2 + F_{ly}^2) l_1 = F_l l_1 \)
Figure 58. Position of gages and direction of forces on the lower pins.
\[ \sigma_z = \frac{M_c}{I} K_r = \frac{32M_i}{\pi d^3} K_r = \frac{32F_i}{\pi d^3} K_r = \frac{S_y}{N} \]

\( F_i = \text{Resultant bending force} \)

\[ F_i = (F_{ix}^2 + F_{iy}^2)^{1/2} = (5.82^2 + 0.85^2)^{1/2} = 5.88 \text{ kN} \]

\( c = d/2 \)

\( I = \text{Area moment of inertia} = \pi d^4/64 \)

\( K_r = \text{stress concentration factor} = 1.2 \)

\( N = \text{safety factor} = 2.0. \)

The pin diameter was:

\[ d = \left( \frac{32F_i K_r N}{\pi S_y} \right)^{1/3} = \left( \frac{32 \times 5.9 \text{kN} \times 0.063 \text{m} \times 1.2 \times 2.0}{\pi \times 372000 \text{kPa}} \right)^{1/3} = 0.029 \text{ m} \]

Pins were machined with a diameter of 28.6 mm.

**Upper Pin Diameter:** This pin was made of a higher strength material to protect the sensing system during the lifting action. Due to the weight of the implement, forces on the upper pin can be larger during lifting or in transporting than while the machine is working. Forces on the sensing pins in the lifting position are shown in Fig. 59. The center of gravity of the digger blade-quick hitch system was experimentally determined in the laboratory by measuring the force to lift the system by the upper pin and applying the equilibrium conditions. This was located at 680 mm from the sensing pins in the horizontal direction and the weight of the system was 5730 N. Forces on the pins during lifting depended on the position of the system. For \( \beta=15^\circ \), these forces were:
Material of the upper pin is medium-carbon alloy steel, Q&T with a yield point strength $S_y = 1034$ MPa (Shigley, 1981).

$$d = \left( \frac{32F_y}{\pi S_y N K f} \right)^{1/3} = \left( \frac{32 \times 8.35 \text{kN} \times 0.063 \text{m} \times 2.0 \times 1.2}{\pi \times 1034000 \text{kPa}} \right)^{1/3}$$

$$d = 0.023 \text{m} = 23.0 \text{ mm}$$

The final diameter for the upper pin was 25.4 mm.
Transducers Arrangement

A set of strain gages was used to sense each force on the pins. Twelve strain gages were mounted on each lower pin as shown in fig. 60. Gages 1, 2, 3, and 4 sensed the horizontal force. Gages 5, 6, 7, and 8 were used to sense the vertical force and gages 9, 10, 11, and 12 sensed the side forces. The upper pin had two sets of gages to sense vertical and horizontal forces. Each set of gages was connected in a Wheatstone bridge as shown for gages 1, 2, 3, and 4. The relationship between input and output voltage in the bridge is given by equation [23] (Dally, Riley, and McConnell, 1984):

\[ V_o = \frac{R_1 R_2}{R_1 + R_2} \left( \frac{\Delta R_1}{R_1} + \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} + \frac{\Delta R_4}{R_4} \right) V_i \]  \[23\]

\( V_i \) = input voltage

\( V_o \) = output voltage

\( R_1 = R_2 = R_3 = R_4 \) = strain gage resistance

\( \Delta R_i \) = resistance change due to the strain in the gages.

By definition, the relative change in the resistance is equal to the product of the gage factor (\( S_g \)) and the strain on the resistance (\( \varepsilon \)):

\[ \frac{\Delta R}{R} = S_g \varepsilon. \]

Replacing these terms in equation [23]:

\[ V_o = \frac{1}{4} S_g (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)V_i \]  \[24\]

The output voltage from the bridge is a function of the gage factor, the strain on the gages, the input voltage, and the number of active gages.
Figure 60. Strain gages distribution and Wheatstone bridge connections.

**Calibration Constant and Sensitivity of the Transducers**

The sensitivity ($s$) of an instrument is the ratio of the linear movement of the pointer on the instrument to the change in the measured variable causing this motion (Holman, 1984). The sensitivity, expressed in mV/kN, is the coefficient of the calibration equation. The calibration constant ($C_c$) or constant of proportionality is the inverse of the sensitivity. The load is linearly proportional to the output voltage. This coefficient is expressed in kN/mV.

For sensing horizontal forces on the lower pins, the calibration constant and the sensitivity were calculated as follows:

Gages 1 and 3 are in tension and gages 2 and 4 are in compression,

$$\varepsilon_1 = -\varepsilon_2 = \varepsilon_3 = -\varepsilon_4.$$
Replacing these strains in equation [24]:

\[ V_o = S_g \varepsilon V_i. \]

From Hooke's law, \( \varepsilon = \frac{\sigma}{E} = \frac{Mc}{IE} = \frac{32F_{l2}}{\pi d^3E} \)

\[ V_o = \frac{32S_x F_{l2}}{\pi d^3E} V_i \]

\[ F_{lx} = \frac{\pi d^3E}{32S_x l_2 V_i} V_o = C_c V_o \]

\[ C_c = \frac{\pi d^3E}{32S_x l_2 V_i} = \frac{F_{lx}}{V_o} = \text{Calibration constant} \quad [25] \]

I = area moment of inertia

c = d/2

E = modulus of elasticity = 207E+6 kPa for steel (Shigley, 1981)

\( V_i = 5.0 \text{ Volts} \)

\( S_x = 2.04 \)

\( l_2 = 53 \text{ mm.} \)

For the lower pins:

\[ C_c = \frac{879.4}{kN} \frac{kN}{V} = 0.8794 \frac{kN}{mV} = \frac{879.4}{N} \frac{N}{mV} \]

\[ s = \frac{V_o}{F_{lx}} = \frac{1}{C_c} = 0.0011 \frac{mV}{N} = 1.1 \frac{mV}{kN} \]

For the transducer sensing horizontal forces on the upper pin:

\[ C_c = 616.0 \text{ N/mV} = 0.616 \text{ kN/mV} \]

\[ s = 0.0016 \text{ mV/kN} = 1.6 \text{ mV/kN}. \]
The theoretical calibration constants and sensitivities for the transducers sensing vertical forces in both lower pins must have the same values. The calibration constant for the gages sensing the side forces on the lower pins can be calculated with the same procedure for gages 9 and 10 sensing the axial strain and gages 11 and 12 sensing transversal strain:

\[ V_o = \frac{1}{4} S_g (\varepsilon_9 - \varepsilon_{10} + \varepsilon_{11} - \varepsilon_{12}) V_i \]  

\[ \varepsilon_a = \sigma / E = F_z / (AE) \]
\[ \varepsilon_t = - \nu \varepsilon_a \]
\[ \varepsilon_9 = \varepsilon_{11} = \varepsilon_a \]
\[ \varepsilon_{10} = \varepsilon_{12} = \varepsilon_t = - \nu \varepsilon_a. \]

Replacing the strains in equation [26]:

\[ V_o = \frac{(1 + \nu)}{2} \varepsilon_a S_g V_i = \frac{(1 + \nu)}{2AE} S_g F_z V_i \]
\[ F_z = \frac{2AE}{S_g (1 + \nu) V_i} V_o = C_c V_o \]

\[ A \] = cross section of the pin = \( \pi d^2 / 4 = 6.4E-04 \) m²

\[ \nu = \text{Poisson ratio} = 0.3 \text{ (for steel)} \]

\[ F_z \] = side force
\[ \varepsilon_a \] = axial strain
\[ \varepsilon_t \] = transversal strain.

Replacing the values for E, \( \nu \), V_i, A and \( S_g \):

\[ C_c = 20.46 \text{ kN/mV} = 20460 \text{ N/mV} \]

\[ s = 1 / C_c = 4.89E-05 \text{ mV/N}. \]
Strains on the Gages

Bending stresses on the lower sensing pins, shown in fig. 61, were given by:

\[ \sigma_z = \frac{(M_x I_y - M_y I_x)x - (M_x I_y + M_y I_x)y}{I_x I_y - I_{xy}} \] (Ugural and Fenster, 1987) [27]

\( I_x, I_y = \) area moments of inertia about the \( x \) and \( y \) axes

\( I_{xy} = \) Inertia product = 0.0 (by symmetry)

\( I_x = I_y = I = \frac{\pi d^4}{64} \)

\( x \) and \( y \) are the coordinates of a point in the cross section of the sensing pin.

For maximum stress \( x = y = \frac{d}{2} \)

Figure 61. Forces and moments on a lower pin
\[ M_x = F_y l_2 \] (bending moment in the x-direction)

\[ M_y = F_x l_2 \] (bending moment in the y-direction).

At point \((0, -d/2)\):

\[ \sigma_y = \frac{-M_y}{I \pi d^3} = \frac{32M_y}{\pi d^3} = \frac{32F_y l_2}{\pi d^3} = \sigma_{yz}. \]

The stress on the gages sensing vertical forces was:

\[ \sigma_{yz} = \frac{32 \times 0.85 \text{kN} \times 0.053 \text{m}}{\pi (0.0286 \text{m})^3} = 19615.3 \text{ kPa}. \]

The strain at these gages was:

\[ \varepsilon = \frac{\sigma}{E} = \frac{19615.3 \text{kPa}}{(207 \times 10^6 \text{kPa})} = 0.000095 = 95 \mu \varepsilon. \]

At point \((d/2, 0)\):

\[ \sigma_x = \frac{M_x}{I \pi d^3} = \frac{32M_x}{\pi d^3} = \frac{32F_x l_2}{\pi d^3} = \sigma_{xz}. \]

The stress on the gages sensing horizontal forces was:

\[ \sigma_{xz} = \frac{32 \times 5.82 \text{kN} \times 0.053 \text{m}}{\pi (0.0286 \text{m})^3} = 135410.8 \text{ kPa}. \]

The strain at these gages was:

\[ \varepsilon = \frac{\sigma}{E} = \frac{135410.8 \text{kPa}}{(207 \times 10^6 \text{kPa})} = 0.000654 = 654 \mu \varepsilon. \]

Equation [27] applied to the upper pin also. The strain on the gages sensing the horizontal force on this pin was:

\[ \sigma_{zx} = \frac{M_x}{I \pi d^3} = \frac{32F_x l_2}{\pi d^3} = \frac{32 \times 4.38 \text{kN} \times 0.053 \text{m}}{\pi (0.0254 \text{m})^3} = 144294.0 \text{ kPa}. \]

\[ \varepsilon = \frac{\sigma}{E} = \frac{144294.0 \text{kPa}}{(207 \times 10^6 \text{kPa})} = 697 \mu \varepsilon. \]
Interaction

The effect of interaction between the loads and cells is eliminated by the position of the different transducers. This is the analysis for the effect of horizontal forces on the transducers measuring vertical and side forces. These transducers are shown in fig. 61. Gages 5, 6, 7, and 8 sensing the vertical force were connected in a Wheatstone bridge for which:

\[ V_o = \frac{1}{4} S_g (\varepsilon_5 - \varepsilon_6 + \varepsilon_7 - \varepsilon_8) V_i. \]

For horizontal forces \( R_5 \) and \( R_6 \) were in compression; and \( R_7 \) and \( R_8 \) were in tension:

\[ -\varepsilon_5 = -\varepsilon_6 = \varepsilon_7 = \varepsilon_8 = \varepsilon \]

\[ V_o = \frac{1}{4} S_g (-\varepsilon + \varepsilon + \varepsilon - \varepsilon) V_i = 0. \]

The effect of the horizontal force on the gages sensing side forces was calculated by a similar procedure. Gage 9 measured positive axial strain (tension), gage 10 measured transversal negative strain (compression), gage 11 measured negative axial strain (compression) and gage 12 measured positive transversal strain (tension):

\[ V_o = \frac{1}{4} S_g (\varepsilon_9 - \varepsilon_{10} + \varepsilon_{11} - \varepsilon_{12}) V_i. \]

\[ \varepsilon_9 = -\varepsilon_{11} = \varepsilon_9 = \varepsilon \]

\[ \varepsilon_{10} = -\varepsilon_{12} = \varepsilon_1 = -\nu \varepsilon = -\nu \varepsilon. \]

\[ V_o = \frac{1}{4} S_g (\varepsilon + \nu \varepsilon - \varepsilon - \nu \varepsilon) V_i = 0. \]
The effect of the side force on the sets of gages sensing vertical or horizontal forces is analyzed using the transducer formed by \( R_1, R_2, R_3, \) and \( R_4 \). These resistances are subject to tensile strain due to the side force:

\[
V_0 = \frac{1}{4} S_g \left( \varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 \right) V_i
\]

\[
\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon
\]

\[
V_0 = \frac{1}{4} S_g \left( \varepsilon - \varepsilon + \varepsilon - \varepsilon \right) V_i = 0.
\]

**Torque Measurement**

An SR-4 BLH torque cell with a 565 Nm maximum capacity was used to measure the torque required to vibrate the blade. Torque cells are transducers to convert torque to an electric signal and consist of a shaft with a circular cross section usually with four strain gages mounted on two perpendicular 45-degree helixes forming two rosettes with two 350 \( \Omega \) gages each, as shown in fig. 62. The helixes define the principal stress and strain directions for the shaft subjected to pure torsion (Dally, Riley, and McConnell, 1984):

\[
\sigma_1 = -\sigma_2 = \tau_{xz} = \frac{T \cdot r}{J} = \frac{16T}{\pi d^3}
\]

\( T \) = torque transmitted by the shaft.

\( r \) = radius of the shaft

\( J \) = polar moment of inertia

\( \sigma_1, \sigma_2 \) = principal stresses
\[ \tau_{xx} = \text{shear stress.} \]

From Hooke's law, principal strains for a plane state of stress are:

\[ \varepsilon_1 = \frac{1}{E} (\sigma_1 - \nu \sigma_2) = \frac{16T}{\pi d^3} \left(\frac{1 + \nu}{E}\right) \quad [29] \]

\[ \varepsilon_2 = \frac{1}{E} (\sigma_2 - \nu \sigma_1) = -\frac{16T}{\pi d^3} \left(\frac{1 + \nu}{E}\right). \quad [30] \]

Strain gages in the torque cell are connected in a Wheatstone bridge arrangement for which equation [23] applies:

\[ \varepsilon_1 = -\varepsilon_2 = \varepsilon_3 = -\varepsilon_4 = \varepsilon \]

Replacing equations [28], [29], and [30] into equation [24]:

\[ V_o = S_k \varepsilon V_i = \frac{16T}{\pi d^3} \left(\frac{1 + \nu}{E}\right) S_k V_i \]

\[ T = \frac{\pi d^3 E}{16 (1 + \nu) S_k V_i} V_o = C_c V_o. \quad [31] \]
Replacing the values in equation [31]:

\[ d = 27.0 \text{ mm} \]
\[ v = 0.3. \]

The calibration constant for the torque cell was: \( C_c = 60.3 \text{ Nm/mV} \).

The theoretical calibration equation was: \( T = 60.3 V_0 \).

The sensitivity of the torque cell was:

\[ s = \frac{V_0}{T} = \frac{1}{C_c} = 0.0166 \frac{\text{mV}}{\text{N.m}} = 16.6 \frac{\text{mV}}{\text{kNm}} \]

**Calibration Procedure.**

The strain gages on the pins and the torque cell were calibrated in the laboratory by applying forces or torques at constant increments. A TL-14 Dianachart Datalogger, was used for data acquisition during calibration.

**Calibration of the Strain Gages:** The sensing system was calibrated twice. In the first instance, pins were individually calibrated using the stand shown in fig 63, which is a modification of that used by Hamman (1985). Bending and normal stresses were applied to the pins in the positions A (bending) or B (tension). Loads were applied up to 7136 N by adding weights by increments of 446 N. The output voltage was recorded for each load. The sequence for the calibration of each pin was as follows:

1. Pin calibration for side forces by applying a normal stress to the pin in the B position.
2. Pin calibration for horizontal force by applying a bending stress to the pin in the A position.

3. Rotation of the pin 90° and calibration for vertical force by applying a bending stress to the pin in the A position.

The second calibration was made with the pins directly mounted on the quick hitch-digger blade system and applying vertical and horizontal forces up to 4500 N using two different systems. Horizontal forces were applied using the same stand used in the first calibration. It is clearly noted that with these systems the horizontal load on the upper pin was applied in the opposite direction to that in the field. Vertical loads on the pins were applied using the lever-scale-turnbuckle system shown in fig. 63. The turnbuckle was tightened between the beam and the pin until a required reading on the scale was reached. The reading was obtained by the relationship between the load required on the pin and the arms of the beam. This was a closer approach to the work in the field, and the complete sensing system was connected to the datalogger. Equations from the first calibration were kept for the side forces on the lower pins.

Calibration equations for each set of transducers were calculated by a regression analysis of the data. For this purpose, the pins and forces were identified as l (lower left), r (lower right) and u (upper) and the forces, designed as follows:

\[ F_{lz} = \text{side force on the lower left pin} \]
\[ F_{rz} = \text{side force on the lower right pin} \]
Figure 63. Systems used for calibration of the sensing pins.
\( F_{lx} \) = horizontal force on the lower left pin
\( F_{rx} \) = horizontal force on the lower right pin
\( F_{ly} \) = vertical force on the lower left pin
\( F_{ry} \) = vertical force on the lower right pin
\( F_{uy} \) = vertical force on the upper pin
\( F_{ux} \) = horizontal force on the upper pin.

Forces on the pins were calculated from the calibration equations as follows:

\[ V_{ab} = C_1 + C_2 F_{ab} \]  \[ 32 \]

\[ F_{ab} = \frac{-C_1}{C_2} + \left( \frac{1}{C_2} \right) V_{abc} = C_3 + C_c V_{ab} \]  \[ 33 \]

where the constants and subindexes were assigned as follows:

a = selected pin (1 = lower left pin, r = lower right pin, u = upper pin)

b = type of gages sensing the force (x for readings from the gages to sense forces in horizontal direction, y for readings from gages to sense vertical forces and z for readings from gages to sense side forces)

\( C_1 \) and \( C_2 \) are the constants from the calibration curves

\( C_3 = - \frac{C_1}{C_2} \)

\( C_c = \frac{1}{C_2} = \text{calibration constant.} \)

The results from the calibration process were plotted in figs. 64 to 71 which show force-output voltage relationship for each bridge on each pin. A regression analysis was performed for each curve. The determination coefficients and the calibration equations were added to the plots.
Figure 64. Calibration curve for horizontal force on the lower left pin.

\[ V_{lx} = -0.177 + 248.0E-06 F_{lx} \quad F_{lx} = 713.7 + 4032.3 V_{lx} \]  \[ r^2 = 0.9996 \]
Figure 65. Calibration curve for vertical force on the lower left pin.

\[ V_{ly} = 1.96 - 240.0 \times 10^{-6} F_{ly} \quad F_{ly} = 8166.7 - 4166.7 V_{ly} \]

\[ r^2 = 0.9893 \]
Figure 66. Calibration curve for side force on the lower left pin.

\[ V_{lz} = 2.303 - 10.0E-06 F_{lz} \quad F_{lz} = 230300.0 - 100000.0 V_{lz} \]  \[ r^2 = 0.9946 \]
Figure 67. Calibration curve for horizontal force on the lower right pin.

\[ V_{rx} = 1.056 + 258.0E^{-06}F_{rx} \quad F_{rx} = -4093.0 + 3876.0V_{rx} \]  
\[ r^2 = 0.9988 \]
Figure 68. Calibration curve for vertical forces on the lower right pin.

\[ V_{ry} = 2.473 + 265.0E-06 F_{ry} \]
\[ F_{ry} = -9332.1 + 3773.6 V_{ry} \]  \[ r^2 = 0.9495 \]
Figure 69. Calibration curve for side force on the lower right pin.

\[
\begin{align*}
V_{rz} &= 2.348 - 7.8E-06F_{rz} \\
F_{rz} &= 301025.6 - 128205.1V_{rz}
\end{align*}
\]  

\[r^2 = 0.9896\]
Figure 70. Calibration curve for horizontal force on the upper pin.

\[ V_{ux} = 1.864 + 230.0 \times 10^{-6} F_{ux} \quad F_{ux} = -8104.3 + 4347.8 V_{ux} \]  
\[ r^2 = 0.9994 \]
Figure 71. Calibration curve for vertical force on the upper pin.

\[ V_{uy} = -1.484 - 250.0 \times 10^{-6} F_{uy} \]
\[ F_{uy} = -5936.0 - 4000.0 V_{uy} \]  \[ 41 \]

\[ r^2 = 0.9962 \]
A failure before the starting of the tests made necessary to replace the upper sensing pin. The new pin had one set of strain gages only to sense the horizontal force. The calibration curve is shown in fig 72.

![Calibration curve for horizontal force on the second upper pin.](image)

\[ V_{ux} = 0.13 + 254.0E-06 F_{ux} \quad F_{ux} = -511.8 + 3937.0 V_{ux} \quad [42] \]

\[ r^2 = 0.9999 \]
Calibration of the Torque Cell: The torque cell was calibrated in the stand used by Smith (1992). The cell was subjected to pure torsion by applying torques from 0 to 556 Nm by 22.6 Nm increments. The calibration curve is shown in fig. 73.

\[ V_0 = 0.165 + 0.002949T \quad T = -55.95 + 339.1V_0 \]  [43]

\[ r^2 = 0.9999 \]
Calculation of Forces on the Blade

Forces acting on the blade were calculated as a function of the forces on the sensing pins or as a function of the readings from the strain gages. These relations can be calculated from the equilibrium conditions in the quick hitch and the implement shown in fig. 74, where:

DF = draft or horizontal force on the implement

Fv = vertical force on the blade

L = side or lateral force on the implement

Plz = side force on the left pin of the implement

Plx = horizontal force on the lower left pin of the implement

Plv = vertical force on the lower left pin of the implement

Prx = horizontal force on the lower right pin of the implement

Prv = vertical force on the lower right pin of the implement

Prz = side force on the right pin of the implement.

Forces in the quick hitch:

\[ \Sigma F_y = 0 \quad F_{uy} + F_{ly} + F_{ry} - W_h - P_{ry} - P_{ly} = 0 \]

\[ \Sigma F_x = 0 \quad F_{rx} + F_{lx} - F_{ux} - P_{rx} - P_{lx} + F_{tx} = 0 \]

\[ \Sigma F_z = 0 \quad F_{lz} = P_{lz} \quad \text{or} \quad F_{rz} = P_{rz} \]

Forces in the implement:

\[ \Sigma F_y = 0 \quad P_{ly} + P_{ry} - F_v = 0 \]

\[ \Sigma F_x = 0 \quad P_{rx} + P_{lx} - F_{tx} - DF - R_s = 0 \]

\[ \Sigma F_z = 0 \quad P_{lz} = L \quad \text{or} \quad P_{rz} = L \]
Figure 74. Forces on the quick-hitch and the implement.
These two systems were solved for the forces acting on the blade as a function of the forces recorded by the sensing pins.

Vertical force: 
\[ F_v = F_{uy} + F_{ly} + F_{ry} - W_h \]  
[44]

Draft: 
\[ DF = F_{rx} + F_{lx} - F_{ux} - R_s = 0 \]  
[45]

Side force: 
\[ L = F_{iz} \quad \text{or} \quad L = F_{rz} \]  
[46]

The sliding resistance was measured in the field at the ground speeds selected for the tests.

TESTING PROCEDURE

Two type of tests were performed with the machine. The first set of tests was made in the laboratory to measure the torque requirements for the operation of the machine without load. The second part was the testing of the machine in the field.

Laboratory Testing

Tests in the laboratory were conducted by running the machine with the same settings used in the field. Two types of measurements of torque were taken for each condition. The first was the measurement of the torque required by the elements and factors not evaluated in the simulation, including the bevel gear box, the two chain transmissions, friction in the eccentrics for the vertical movement and supports and the effect of the gear ratio between shafts II and III. The machine was operated at the settings to use in the field. The blade, the eccentrics, and the links were
disconnected from the system. The second set of measurements were made to evaluate the torque to operate the blade. Results were compared after processing the laboratory tests as follows:

\[ T_{bl} = (T_{tb} - T_{fs}) i_{23} \]  

\( T_{bl} \) = net torque used to operate the blade (laboratory) (Nm)  
\( T_{tb} \) = total torque to operate the blade (Nm)  
\( T_{fs} \) = friction and inertia torque in the shafts (Nm)  
\( i_{23} \) = gear ratio between shafts II and III.  
\( T_{bs} \) = net torque to operate the blade (simulation) (Nm)

Results from the laboratory tests and the simulation are shown in Table C1 in the appendix C, including total torque to operate the blade, friction and inertia torque in shafts, gear ratio and net torque. The mean values for the different modes of vibration are analyzed in the next chapter.

Field Testing

Number of Tests: A set of 52 tests were conducted to evaluate the three modes of vibration. Forty eight tests corresponded to the oscillating movements, two tests for the non-vibrating condition, one at 2.0 km/h and one at 3.0 km/h, and two tests to measure the skidding resistance of the machine at these speeds. Each test was replicated three times.

Plots and Tests Assignment: The tests were conducted at the Burden Research Farm of the Louisiana Agricultural Experiment Station. Plots for
the tests were prepared in August, 1993 by disking and forming the beds and leaving them to compact by weathering. Four applications of chemicals were performed to eliminate plants and roots effects. Tests were run in two sets in early June and July, 1994. Beds were single ridge about 200 mm high, and 15 m long and off-bared before the tests to avoid the effect of row edges. A total of 198 plots were initially available in an area of 195 x 54 m. Rows were marked from A to R and the plots in each row were numbered from 1 to 11. Extra plots were used as replacement plots. Tests were numbered from 1 to 52 following an order such that some settings used in one test could be used for the following ones to reduce the time required to make changes in the machine between tests. Working days were considerably reduced during the test period by frequent rains. For this reason, the tests were not randomized, but the plots were assigned to the tests in a complete randomized design and, in each case, three replications were run at the same time.

**Soil Physical Conditions:** Soil physical conditions prior to the tests were evaluated by bulk density and moisture content. One sample was taken from each plot for this purpose. Sampling was made with a cylindrical core, 76 mm inside diameter and 76 mm height. Samples were oven dried at 105°C for 24 hours in a forced draft convection oven. Soil conditions were the determining factor for starting the field testing. The tests were initiated when the soil moisture of samples taken at the surface, midway, and, at the
bottom of the beds averaged 28% db. This was the average of the plastic limit of five samples tested in the laboratory. Tilling processes are more efficient below this limit. Moisture content above 30% db is considered an adverse condition for harvesting and below 22% db is a dry condition (McLeod, Misener and McMillan, 1986). Moisture affected the movement of the soil over the blade due to adhesion forces. In preliminary tests, it was observed that a compacted layer of soil formed and stuck on the blade at high moisture levels. This was another reason to delay the tests until the moisture in the soil was low enough to prevent sticking. It was also the reason for removing the soil on the blade after each test. The soil was classified as a silty loam by the hydrometer method, from soil samples taken from 5 different plots in the field. The average content of the primary particles were: 11.91% clay, 59.94% silt and 28.15% sand.

**Soil Mechanical Conditions**

The soil mechanical conditions were characterized by measuring penetration resistance, shear resistance and the plastic limit. A soil cone penetrometer was used to provide a standard, uniform method of characterizing the penetration resistance of the soil (ASAE, 1986). The instrument, a CN-973 Corps of Engineers, WES type cone penetrometer as described by Perumpral (1987) was pushed into the soil in 30 different plots. Readings were taken at the surface, 80, and 100 mm depths. The overall average penetration resistance was 0.509 MPa.
The shear resistance of the soil was determined by means of direct shear tests performed in a translational shear box in the Soil Mechanics Laboratory in the Civil Engineering Department. Average soil cohesion and friction coefficients were determined for 30 samples taken from randomized beds. The Coulomb equation for these tests was:

$$\tau_{\text{max}} = 24.77 + 0.422\sigma$$

$$\tau_{\text{max}} = \text{maximum shearing stress (kPa)}$$

$$\sigma = \text{normal stress (kPa)}$$

$$C_i = \text{soil cohesion coefficient} = 24.77 \text{ kPa}$$

$$\mu_s = \text{soil-soil friction coefficient} = 0.422$$

$$\phi_s = \text{soil internal friction angle} = \text{atan}(0.422) = 22.9^\circ.$$  

A second set of tests were performed to determine the mechanical coefficients for the blade-soil interaction surface. These are adhesion and friction coefficients characterizing the resistance of the soil to sliding on the blade. These coefficients were determined in the direct shear box after replacing the lower half of the box by an iron plate of the same characteristics of that used in the blade. The procedure for this test was similar to that used to determine the shear resistance of the soil. The final equation for this set of tests was:

$$\tau_{\text{max}} = 2.39 + 0.464\sigma$$

$$C_a = \text{adhesion coefficient} = 2.39 \text{ kpa}$$

$$\mu_b = \text{soil-metal friction coefficient} = 0.464.$$
The coefficients were used as input data for the simulation to compare the results with the field torque, power and draft.

The plastic limit was determined following the traditional method of rolling an small mass of soil to a thread of 3.25 mm diameter. Approximated to the nearest whole number, the plastic limit was: 28.0%.

Evaluation Parameters

Draft, power consumption, soil bulk density and clod-size distribution were the parameters used to evaluate the efficiency of vibration. Power was measured in its two components, power to pull the machine and power to vibrate the soil as described before. The effect of vibration on the soil was evaluated by taking samples to determine soil bulk density and the clod-size distribution. At the same time, the original soil conditions were characterized by bulk density, moisture content, cone index, and shear resistance.

Effect of Vibration on Soil Conditions: The effect of vibration on soil conditions was evaluated by the variation of the bulk density and the clod-size distribution. Two samples were taken after each treatment to determine bulk density. Both samples were taken at the same depth because it was assumed that vibration produced a mixture of soil clods, and bulk density was uniform with depth; i.e. the period of vibration was not sufficiently long to produce any sorting of clod-sizes.
To evaluate the clod-size distribution, two soil samples of about 20 kg were taken at random locations from each plot after the application of vibration. The sampler was a galvanized iron sheet box 584 mm long, 203 mm wide and 216 mm deep. It was pushed into the soil until undisturbed soil was reached. Soil surrounding the sampler was removed and an open sheet metal box was inserted under the box to lift the sample and carefully transfer it to a cardboard box. Samples were air dried to a moisture content of approximately 12% wb. Soil samples were then separated into seven fractions of different clod-size in a rotary sieve similar to that described by Chepil (1962) and shown in fig. 75. This machine had concentric cylinders of 254 mm, 457 mm, 559 mm, 635 mm, and 711 mm respectively. The diameters of the sieve openings from the inner to the outer cylinder were

Figure 75. Rotary sieve for clod-size distribution analysis
Soil samples were fed to the rotary sieve by a hopper, a flat belt conveyor, and a chute. A flat square-holed screen in the hopper separated soil clods larger than 76.2 mm. The rotary sieve was operated at 6 rpm and adjusted to a slope of 6°. The seven clod-size separates were weighed and used to calculate the geometric mean diameter (GMD) and the log standard deviation ($\sigma_g$). The percent finer or undersize particles and the opening

![Diagram](image)

**Figure 76.** Clod-size distribution plotted on log-probability paper
diameter were plotted in log-probability paper as shown in fig. 76 for the clod-size distribution of a sample corresponding to the test f04O6 (test 04 in plot O6). The plot is an straight line, showing that the clod-size is really a log-normal distribution. The geometric mean diameter was the diameter corresponding to 50% undersize and the log standard deviation was given by (Gardner, 1956, Svarovsky, 1977, Orr, 1966, Allen,1981):

\[ \sigma_g = \frac{\text{size at 84\%}}{\text{size at 50\%}} = \frac{\text{size at 50\%}}{\text{size at 16\%}} \]

The parameters of the clod-size distribution in fig. 76 were:

GMD = 9.2 mm and \( \sigma_g = 39.3 / 9.2 = 4.27 \) mm.

Data for bulk density, GMD and \( \sigma_g \) is included in Tables C4, C5, and C6 in appendix C.

**Torque and Draft Measurement:** The data acquisition system was composed of the sensing system (pins and torque cell), the datalogger and the computer, powered by the electric system of the tractor. The datalogger, a 14 channel DianaChart PCA-14, was connected through a stabilizer circuit to have a constant 12 V DC input. Two dataloggers of the same type were used at different times during the tests. The computer, a 386-20MHz LapTop was connected through an inverter supplying 115 V AC. Data was recorded from 8 active channels in the following order:

1. Horizontal force in the lower left pin (LH)
2. Vertical force in the lower left pin (LV)
3. Side force in the lower left pin (LS)
4. Horizontal force in the lower right pin (RH)
5. Vertical force in the lower right pin (RV)
6. Side force in the lower right pin (RS)
7. Horizontal force in the upper pin (UH)
8. Torque

Only one reading was made in the upper pin at the time of the tests due to a failure in the original pin. The second pin was built and calibrated to only sense horizontal forces. To measure the draft force, only the horizontal components in the three sensing pins were necessary. For each test data was recorded for 10 seconds using the High Speed Option (HS) available in the software for the datalogger. The amount of data collected ranged between 150 and 170 sets per test. The system was checked several times every day by recording the zero values (no load on the machine). Data recorded with the HS option was converted to an ASCII file to be used in Quattro or Lotus. The final results for draft and torque were obtained using the following procedure for each file or test:

1. Average of the readings on each channel
2. Calculation of forces and torques using the calibration equations with a given zero ($Z_i$) value according to the datalogger used in the test:

   \[ \text{LH} = F_{lx} = Z_1 + 4032.3V_{lx} \]
   \[ \text{LV} = F_{ly} = Z_2 - 4166.7V_{ly} \]
   \[ \text{LS} = F_{lz} = Z_3 - 121951.2V_{lz} \]
\[ RH = F_{rx} = Z_4 + 3876.0V_{rx} \]
\[ RV = F_{ry} = Z_5 + 3773.6V_{ry} \]
\[ RS = F_{rz} = Z_6 - 156250.0V_{rz} \]
\[ UH = F_{ux} = Z_7 + 4347.8V_{ux} \]
\[ TC = T = Z_8 + 339.1V_o. \]

The values \( V_{ab} \) are the averages obtained in step 1.

For tests 29 to 36 the zero values were respectively: -4971.8 N, 10804.25 N, -13856.7 N, -22351.0 N, 1452343.8 N, -7350.4 N, -21.7 Nm. For the remaining tests the zero values were respectively: -5028.2 N, 10616.7 N, -326829.3 N, 271.3 N, -28309.4 N, 1487968.8 N, -3803.1 N, -12.85 Nm.

3. Calculation of draft force for each test. Data acquisition for draft force represented the most difficulty. The levels of vibration during the operation and the stresses caused during the movement within the plots and transportation of the machine affected the sensing system. A failure in the lower right link of the tractor that caused the misalignment of the machine with the tractor did serious damage in the lower right pin. There was a second failure in the upper pin, possibly because the pin got loose during one of the tests or because of bouncing during movement in the field.

It was necessary to adopt the following procedure for the calculation of draft after a careful observation of the data as follows:

Draft was calculated based only on the horizontal forces. As was expected, vertical and side forces were small enough to neglect their effect
on the readings for horizontal forces. The draft force was first calculated based on the reading of the lower left pin and the upper pin.

\[ DF = 2*\text{LH} + \text{UH} - R_s \]

The average of the skidding resistance, \( R_s \), was 4750 N. Data for draft showed a large range of variation. Values larger or smaller than the mean draft ± 3\( \sigma \) (for each mode of vibration) were recalculated with one of the following equations, using the reading of the lower right pin if it was available:

\[ DF = \text{LH} + \text{RH} + \text{UH} - R_s \]
\[ DF = 2*\text{RH} + \text{UH} - R_s \]

If the reading of the upper pin was not available, it was replaced by the average of several readings in the same mode of vibration. The last option was to take a partial section of the file, discarding data not applicable because of its large or small value. If none of these options was reliable, data for draft was discarded. The data acquisition for torque presented minimum problems. Data for torque, draft, and power ratio is presented in Tables C2 and C3 in appendix C.

An example of the data taken in the field is shown in fig. 77. The output voltage is plotted as a function of time. These records corresponded to the horizontal loads on the pins (LH, RH, and UH), a side load (LS), and the reading on the torque cell (TC). The levels of the output voltage in the figure do not correspond to the levels of the forces because the calibration equations are different. The reading for the side force showed a nearly
Figure 77. Output voltage for data taken in a field test.
constant value. This meant there was no variation of this force and the reading should approximate the zero value of the calibration equation.

**Testing Procedure**

Tests were performed in the field using the following procedure:

1. Setting of the machine following Table B in appendix B.
2. Sampling for initial bulk density and moisture content.
3. Position of the machine at the beginning of the plot with the blade in working position, for the first replication.
4. Setting of the computer. File names were assigned as fxxyy, f stands for field, xx is the number of the test (Table B) and yy corresponds to the number of the plot. Filenames for laboratory tests were lxx.
5. Setting of the speed of the tractor.
6. Powering of the PTO shaft to activate the vibrating system with the blade at its working position.
7. Setting of the engine speed.
8. Run the test and take data for 10 seconds.
9. Slow down the engine, stop the tractor, disengage the PTO, lift the machine, and remove the soil on the blade.
10. Repeat steps 3 to 9 for the second and third replication.
11. Sampling for conditions after treatment (two samples for bulk density and two samples for clod-size distribution).
12. Go to 1 for the next test.
RESULTS AND DISCUSSION

The discussion on the results of the field testing and the simulation was based on the statistical analysis of the factors of evaluation, made separately for each mode of vibration. For longitudinal and lifting movements, the factors of variation were: amplitude (2), forward speed (2) and velocity ratio (2). For combined movement, the factors were: forward speed (2), phase angle (4) and amplitude combination (4). The factors of variation were designated as follows:

\[ a_1 = \text{ecc}_1 = 9.52 \text{ mm} \] (amplitude)
\[ a_2 = \text{ecc}_2 = 12.7 \text{ mm} \] (amplitude)
\[ v_1 = 2.0 \text{ km/h} \] (forward speed)
\[ v_2 = 3.0 \text{ km/h} \] (forward speed)
\[ v_{r1} = 1.0 \] (velocity ratio = velrat)
\[ v_{r2} = 1.5 \] (velocity ratio = velrat)
\[ \phi_{h1} = 0^\circ \] (phase angle)
\[ \phi_{h2} = 90^\circ \] (phase angle)
\[ \phi_{h3} = 180^\circ \] (phase angle)
\[ \phi_{h4} = 270^\circ \] (phase angle)
\[ c_{o1} = \text{amplitude combination (ecc}_2 = 9.52 \text{ mm, ecc}_7 = 12.7 \text{ mm)} \]
\[ c_{o2} = \text{amplitude combination (ecc}_2 = 12.7 \text{ mm, ecc}_7 = 12.7 \text{ mm)} \]
\[ c_{o3} = \text{amplitude combination (ecc}_2 = 9.52 \text{ mm, ecc}_7 = 9.52 \text{ mm)} \]
\[ c_{o4} = \text{amplitude combination (ecc}_2 = 12.7 \text{ mm, ecc}_7 = 9.52 \text{ mm)} \]
Data for the dependent variables: bulk density, geometric mean diameter, log standard deviation, torque, draft, and power ratio were analyzed at 5% significance level by using the analysis of variance ANOVA or the general linear models GLM depending on the balancing conditions of the data and the Duncan multiple range test (Cody and Smith, 1985). For horizontal and vertical vibration the statistical model was:

\[ Y = \mu + \tau_a + \tau_s + \tau_{vr} + \tau_{a\cdot s} + \tau_{a\cdot vr} + \tau_{a\cdot s\cdot vr} + \varepsilon \]

For the combined mode of vibration, the statistical model was:

\[ Y = \mu + \tau_a + \tau_s + \tau_{ph} + \tau_{a\cdot ph} + \tau_{a\cdot s\cdot ph} + \tau_{a\cdot s\cdot ph} + \varepsilon \]

\( Y = \) dependent variable
\( \mu = \) general mean
\( \tau_a = \) effect of amplitude
\( \tau_s = \) effect of the forward speed
\( \tau_{vr} = \) effect of the velocity ratio
\( \tau_{ph} = \) effect of the phase angle
\( \tau_{a\cdot s} = \) effect of the interaction amplitude*forward speed
\( \tau_{a\cdot vr} = \) effect of the interaction amplitude*velocity ratio
\( \tau_{s\cdot vr} = \) effect of the interaction forward speed*velocity ratio
\( \tau_{a\cdot ph} = \) effect of the interaction amplitude*phase angle
\( \tau_{a\cdot ph} = \) effect of the interaction forward speed*phase angle
\( \tau_{a\cdot s\cdot ph} = \) effect of the interaction amplitude*forward speed*phase angle
\( \varepsilon = \) experimental error.
ANALYSIS FOR TORQUE

The torque requirements for the three modes of vibration showed values in the same order as the simulation. The total values included torque for the movement of the mechanism and the block of soil:

Mean torque for horizontal vibration: 60.90Nm
Mean torque for combine vibration: 55.10 Nm
Mean torque for vertical vibration: 44.36 Nm

Horizontal Mode of Vibration

From the results in the simulation it was expected that there would be an increase in the torque with an increase in the velocity ratio and the forward speed or a decrease in the amplitude. The ANOVA and the Duncan tests in Table 4, showed significance to the effect of forward speed on torque. The mean value increased 26.7% by increasing the speed from 2 to 3 km/h. There was no significant effect due to the variation of the amplitude, but the torque was significantly affected by the velocity ratio and the forward speed. As expected the torque increased by 20.7% with an increase in the velocity ratio from 1.0 to 1.5. Torque variations due to changes in forward speed or velocity ratio are directly related to the changes in the frequency of vibration originated by both factors. Any increase in the frequency caused increase in the torque and the power for vibration. This power increase may be partially due to friction at pivots and joints and soil acceleration (Al-Jubouri and McNulty, 1984). Fig. 78
shows the effects due to the (speed) x (velocity ratio) and (ampl) x (velocity ratio) interactions. From the first interaction it was concluded that increasing the forward speed and/or the velocity ratio increased the torque requirements. For the (amplitude) x (velocity ratio) interaction, the

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7</td>
<td>4198.34</td>
<td>599.76</td>
<td>5.80</td>
<td>0.0018</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>3.39</td>
<td>3.39</td>
<td>0.03</td>
<td>0.8585</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>1236.11</td>
<td>1236.11</td>
<td>11.96</td>
<td>0.0032</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>772.71</td>
<td>772.71</td>
<td>7.48</td>
<td>0.0147</td>
</tr>
<tr>
<td>Speed*Ampl</td>
<td>1</td>
<td>81.77</td>
<td>81.77</td>
<td>0.79</td>
<td>0.3869</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>502.88</td>
<td>5502.88</td>
<td>4.87</td>
<td>0.0423</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>1570.11</td>
<td>1570.11</td>
<td>15.19</td>
<td>0.0013</td>
</tr>
<tr>
<td>Speed<em>Ampl</em>VelRat</td>
<td>1</td>
<td>31.37</td>
<td>31.37</td>
<td>0.30</td>
<td>0.5892</td>
</tr>
<tr>
<td>Error</td>
<td>16</td>
<td>1653.30</td>
<td>103.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>5851.64</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels

\[ a_1 = 61.3 \text{ Nm}, \quad a_2 = 60.5 \text{ Nm} \]

Forward speed levels

\[ v_2 = 68.1 \text{ Nm}, \quad v_1 = 53.7 \text{ Nm} \]

Velocity ratio levels

\[ v_{r2} = 66.6 \text{ Nm}, \quad v_{r1} = 55.2 \text{ Nm} \]

Note: Means underlined by the same line are not significantly different
torque requirements increased as a result of the increase in the velocity ratio but it was expected that the highest torque values at any velocity ratio for the tests would occur at the smallest amplitude. Furthermore, the largest amplitude showed an unexpected torque reduction as the velocity ratio increased from 1.0 to 1.5. The reason for this result can be related to the effect of vibrations of a largest amplitude on the sensing system. It was observed during the tests that vibrations transmitted to the tractor were more severe using the largest amplitude.

Figure 78. Effect of the (forward speed) x (velrat) and (ampl) x (velrat) interactions on the torque in horizontal mode of vibration.
Vertical Mode of Vibration

From the simulation, it was expected that there would be increase in the torque with an increase in the velocity ratio and the forward speed or a decrease in the amplitude. The ANOVA and the Duncan test in Table 5, showed a highly significant effect of the forward speed and the velocity

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7</td>
<td>1795.22</td>
<td>256.46</td>
<td>9.33</td>
<td>0.0001</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>29.53</td>
<td>29.53</td>
<td>1.07</td>
<td>0.3154</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>350.83</td>
<td>350.83</td>
<td>12.77</td>
<td>0.0025</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>493.77</td>
<td>493.77</td>
<td>17.97</td>
<td>0.0006</td>
</tr>
<tr>
<td>Speed*Amplitude</td>
<td>1</td>
<td>8.12</td>
<td>8.12</td>
<td>0.17</td>
<td>0.5942</td>
</tr>
<tr>
<td>Speed*Vel. Ratio</td>
<td>1</td>
<td>262.68</td>
<td>262.68</td>
<td>9.56</td>
<td>0.0070</td>
</tr>
<tr>
<td>Ampl*Vel. Ratio</td>
<td>1</td>
<td>316.68</td>
<td>316.68</td>
<td>11.52</td>
<td>0.0037</td>
</tr>
<tr>
<td>Speed<em>Ampl</em>VelRat</td>
<td>1</td>
<td>333.61</td>
<td>333.61</td>
<td>12.14</td>
<td>0.0031</td>
</tr>
<tr>
<td>Error</td>
<td>16</td>
<td>439.67</td>
<td>27.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>2234.89</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels

\[ a_2, a_1 \]

45.5 Nm 43.3 Nm

Forward speed levels

\[ v_2, v_1 \]

48.2 Nm 40.6 Nm

Velocity ratio levels

\[ vr_2, vr_1 \]

48.9 Nm 39.8 Nm

Note: Means underlined by the same line are not significantly different.
ratio on the torque. The results showed an 18.7% torque increase as the forward speed increased from 2.0 to 3.0 km/h. A 22.9% torque increase was the effect of the increase in the velocity ratio from 1.0 to 1.5. From the tests in the laboratory, it was concluded that these effects were due to the increase in the frequency to meet the increase in velocity ratio or forward speed or the decrease in amplitude. It represented an increase in the friction torque at joints and supports. Figure 79 shows the significant interactions between forward speed, amplitude, and velocity ratio. The

Figure 79. Effect of the (forward speed) x (velrat) and (ampl) x (velrat) interactions on the torque in vertical mode of vibration.
torque increased by increasing the speed and/or the velocity ratio. As expected, for a given amplitude, the torque must increase by increasing the velocity ratio, but the higher torque due to the larger amplitude at velocity ratio 1.0 was an unexpected value. Torque requirements must be higher for smaller amplitudes at any velocity ratio due to the higher frequencies.

Combined Mode of Vibration

From the simulation, it was expected that there would be larger values of torque for amplitude combination 2, with the smallest amplitude for horizontal vibration, the highest forward speed and phase angles at 180° and 270°. The GLM and the Duncan test in Table 6 showed significant effects of the forward speed, the amplitude combination and the phase angle on the torque. The mean torque value increased a significant 21.3% as the forward speed was increased from 2.0 to 3.0 km/h. This increase is partially represented as friction torque in eccentrics, joints and supports of the machine and soil acceleration. For a given velocity ratio, an increase in the forward speed requires a proportional increase in the frequency that leads to the increase in the torque due to friction. Results on the effect of the amplitude combination and the phase angle are concerns of main importance in combined oscillation. The first one had a highly significant effect on the torque. Combinations 1 and 3 showed lower torque requirements. The maximum mean torque difference within the amplitude combinations reached 40.7%. An opposite result was expected. These
TABLE 6. GENERAL LINEAR MODELS AND DUNCAN TEST FOR TORQUE IN COMBINED MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>31</td>
<td>14430.89</td>
<td>465.51</td>
<td>3.18</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ampl. combination</td>
<td>3</td>
<td>6559.75</td>
<td>2186.58</td>
<td>14.93</td>
<td>0.0001</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>2753.73</td>
<td>2753.73</td>
<td>18.88</td>
<td>0.0001</td>
</tr>
<tr>
<td>Phase</td>
<td>3</td>
<td>1507.11</td>
<td>502.37</td>
<td>3.43</td>
<td>0.0223</td>
</tr>
<tr>
<td>Ampl. comb.*Speed</td>
<td>3</td>
<td>212.55</td>
<td>70.85</td>
<td>0.48</td>
<td>0.6949</td>
</tr>
<tr>
<td>Ampl. comb.*Phase</td>
<td>9</td>
<td>1933.36</td>
<td>214.82</td>
<td>1.47</td>
<td>0.1802</td>
</tr>
<tr>
<td>Speed*phase</td>
<td>3</td>
<td>109.68</td>
<td>36.56</td>
<td>0.25</td>
<td>0.8614</td>
</tr>
<tr>
<td>Ampl<em>Speed</em>Phase</td>
<td>9</td>
<td>1355.25</td>
<td>150.58</td>
<td>1.03</td>
<td>0.4282</td>
</tr>
<tr>
<td>Error</td>
<td>63</td>
<td>9229.53</td>
<td>146.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>94</td>
<td>23660.42</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ampl. combination levels  
\( c_0^4 \)  \( c_0^2 \)  \( c_0^1 \)  \( c_0^3 \)  
65.7 Nm  60.4 Nm  47.3 Nm  46.7 Nm

Forward speed levels  
\( v_2 \)  \( v_1 \)  
60.3 Nm  49.8 Nm

Phase angle levels  
\( ph_1 \)  \( ph_2 \)  \( ph_4 \)  \( ph_3 \)  
60.5 Nm  57.3 Nm  53.9 Nm  49.0 Nm

Note: Means underlined by the same line are not significantly different.

Combinations with smaller amplitude in the shaft for horizontal vibration must demand the highest torque levels as a result of the higher frequencies. The phase angle is an important factor in the level and distribution of torque at the inputs. Minimum and maximum torques were
obtained for 180° and 0° respectively with a 23.4% significant difference in the mean values. The minimum value was expected for 90°. At this setting the action of vibration on the soil is limited by the contact and cutting angles with no retreat movement of the blade. As was observed in the laboratory tests, the phase angle of 180° showed the smoothest operating conditions in the field, less frame vibration, as a result of the better distribution of torque at the inputs.

ANALYSIS FOR DRAFT FORCE

The mean values for each mode of vibration showed the expected draft reduction for horizontal and combined oscillation, but draft reduction for vertical oscillation was not expected in the magnitude shown in the field. Shkurenko (1962) reported opposite results stating that horizontal vibration was 1.6 times more effective in reducing draft than vertical oscillation. The mean values obtained in these tests were:

Mean draft for no vibration: 5081.4 N
Mean draft for combined vibration: 4638.1 N
Mean draft for horizontal vibration: 4110.2 N
Mean draft for vertical vibration: 3614.6 N.

**Horizontal Mode of Vibration**

From the simulation, it was expected there would be a significant effect of the velocity ratio on the draft. The GLM and the Duncan Test in
Table 7, showed that none of the factors of variation had a significant effect on the draft force to pull the machine. Although, the GLM showed a significant effect of the velocity ratio on the draft, the pairwise comparison of the Duncan test showed a non-significant effect of this factor. The results partially agreed with those from the computer program. The amplitude

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
</table>
| Model                | 6  | 16331037.1  | 2721839.5    | 1.84  | 0.1552
| Amplitude            | 1  | 1166714.7   | 1166714.7    | 0.79  | 0.3882
| Speed                | 1  | 1985166.8   | 1985166.8    | 1.34  | 0.2642
| Velocity Ratio       | 1  | 7338127.4   | 7338127.4    | 4.95  | 0.0408
| Ampl*Speed           | 1  | 6254817.1   | 6254817.1    | 4.22  | 0.0567
| Ampl*VelRat          | 1  | 8797.6      | 8797.6       | 0.01  | 0.9396
| Speed*VelRat         | 1  | 147125.6    | 147125.6     | 0.10  | 0.7568
| Error                | 16 | 23724448.4  | 1482778.0    |       |      |
| Total                | 20 | 40055485.5  |              |       |      |

Amplitude levels
\[ a_1, a_2 \]

4502.9 N 3586.4 N

Forward speed levels
\[ v_2, v_1 \]

4283.5 N 3980.1 N

Velocity ratio levels
\[ vr_2, vr_1 \]

4647.6 N 3707.1 N

Note: Means underlined by the same line are not significantly different
and forward speed should not affect the draft significantly. The main difference was due to the velocity ratio. For this case, the velocity ratio of 1.0 was more effective in reducing draft than the velocity ratio of 1.5. The difference was 20.3%. Most of the information on this topic reports higher draft reduction as the velocity ratio increased. Narayanarao and Verma (1982a), Shkurenko (1960), Sharma, Verma and Bansal (1986), Narayanarao and Verma (1982b), Kang and Halderson (1991) and Al-Jubouri and McNulty, (1984) reported a draft reduction as the velocity ratio increased. The decrease in friction forces are the main argument to explain this fact caused by the decrease in the contact angle and the increase in the angle for movement of the blade in loose soil. These angles depended exclusively on the velocity ratio as discussed above. The amplitude of vibration showed no significant effect on the draft. This was an expected result coinciding with that reported by Kang (1991) but disagrees with those of Narayanarao and Verma (1982a) reporting a draft decrease at a given frequency and tractor speed by an increase in the amplitude.

Vertical Mode of Vibration

The ANOVA and Duncan test results presented in Table 8 showed a non-significant effect of the factors of variation on the draft. This was expected due to the levels of velocity ratio used in the tests. But, draft reduction was expected only for velocity ratios above 2.0 and the mean draft was expected to be closer to the value for the non-vibration condition. One
TABLE 8. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR DRAFT FORCE IN VERTICAL MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7</td>
<td>5605534.7</td>
<td>800790.7</td>
<td>0.67</td>
<td>0.6975</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>3332310.9</td>
<td>3332310.9</td>
<td>2.77</td>
<td>0.1154</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>433386.3</td>
<td>433386.3</td>
<td>0.36</td>
<td>0.5566</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>896.7</td>
<td>896.7</td>
<td>0.00</td>
<td>0.9785</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>59710.4</td>
<td>59710.4</td>
<td>0.05</td>
<td>0.8265</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>94112.9</td>
<td>94112.9</td>
<td>0.08</td>
<td>0.7832</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>1594183.8</td>
<td>1594183.8</td>
<td>1.33</td>
<td>0.2664</td>
</tr>
<tr>
<td>Ampl<em>Speed</em>VelRat</td>
<td>1</td>
<td>90934.0</td>
<td>90934.0</td>
<td>0.08</td>
<td>0.7868</td>
</tr>
<tr>
<td>Error</td>
<td>16</td>
<td>19234531.9</td>
<td>1202158.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>24840066.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels

\[ a_2 \quad \text{3987.2 N} \quad a_1 \quad \text{3221.5 N} \]

Forward speed levels

\[ v_2 \quad \text{3747.0 N} \quad v_1 \quad \text{3459.7 N} \]

Velocity ratio levels

\[ vr_2 \quad \text{3608.5 N} \quad vr_1 \quad \text{3600.2 N} \]

Note: Means underlined by the same line are not significantly different.

of the reasons for this result was a possible effect of the mode of vibration on the skidding resistance of the machine. In the field test it was assumed that amplitude, velocity ratio and mode of vibration did not affect the value of this force, only the effect of the forward speed was considered. The skidding resistance was measured at 2.0 and 3.0 km/h with the blade in
static position. The average of the six tests was considered the skidding resistance for every test. This result indicates the necessity to study this mode of vibration in future work with this machine because the reduction in the skidding resistance would greatly reduce total draft.

**Combined Mode of Vibration**

From the simulation it was expected that the phase angle would affect the draft. Results from the GLM and Duncan tests in Table 9 showed significant effects on the draft force due to the three factors of variation; amplitude combination, forward speed, and to the phase angle and the interactions of the amplitude combination with the forward speed and the phase angle. The amplitude combination showed a significant effect with a lower mean draft for the combinations using the largest eccentricity in both positions. This was an unexpected result because the program predicted a slight effect due to the amplitude combination with the largest draft decrease for combination c01 using the smallest amplitude for horizontal vibration and the largest one in the vertical direction. This setting uses higher frequency. The ground speed had significant effect on the draft. The lowest draft was obtained at the lowest speed with a 26.6% difference between the two means. Results from the computer program predicted a slight increase in draft by an increase in the forward speed. Although, the increase in forward speed requires an increase in the frequency of vibration for the same velocity ratio, this effect does not off-set
TABLE 9. GENERAL LINEAR MODEL AND DUNCAN TEST FOR DRAFT FORCE IN COMBINED MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>22</td>
<td>151154233</td>
<td>6870647</td>
<td>4.61</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ampl. combination</td>
<td>3</td>
<td>17567140</td>
<td>5855713</td>
<td>3.93</td>
<td>0.0119</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>55009216</td>
<td>55009216</td>
<td>36.92</td>
<td>0.0001</td>
</tr>
<tr>
<td>Phase</td>
<td>3</td>
<td>15389263</td>
<td>5129754</td>
<td>3.44</td>
<td>0.0213</td>
</tr>
<tr>
<td>Ampl. comb.*Speed</td>
<td>3</td>
<td>41506208</td>
<td>13835403</td>
<td>9.29</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ampl. comb.*Phase</td>
<td>9</td>
<td>32238611</td>
<td>3582067</td>
<td>2.40</td>
<td>0.0196</td>
</tr>
<tr>
<td>Speed*Phase</td>
<td>3</td>
<td>2991297</td>
<td>997099</td>
<td>0.67</td>
<td>0.5738</td>
</tr>
<tr>
<td>Error</td>
<td>69</td>
<td>102795017</td>
<td>1489783</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>91</td>
<td>253949251</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ampl. combination levels

<table>
<thead>
<tr>
<th>Ampl. combination levels</th>
<th>co_3</th>
<th>co_4</th>
<th>co_1</th>
<th>co_2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5511.4 N</td>
<td>4684.8 N</td>
<td>4434.0 N</td>
<td>4004.7 N</td>
</tr>
</tbody>
</table>

Forward speed levels

<table>
<thead>
<tr>
<th>Forward speed levels</th>
<th>v_2</th>
<th>v_1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5342.7 N</td>
<td>3922.2 N</td>
</tr>
</tbody>
</table>

Phase angle levels

<table>
<thead>
<tr>
<th>Phase angle levels</th>
<th>ph_2</th>
<th>ph_1</th>
<th>ph_3</th>
<th>ph_4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5142.4 N</td>
<td>4818.4 N</td>
<td>4448.4 N</td>
<td>4149.7 N</td>
</tr>
</tbody>
</table>

Note: Means underlined by the same line are not significantly different.

that of the speed. The variation of the phase angle showed expected effects on the draft. The maximum and minimum draft corresponded to 90° and 270° respectively with a 19.3% difference. There was no significant difference between the phase angles 270° and 180°. Complementing results,
these angles yielded lower draft and torque and lower levels of vibration were transmitted to the frame and the tractor at phase angle $180^\circ$.

The (amplitude) x (forward speed) interaction is shown in fig. 80. An increment of draft due to the speed was expected for each amplitude combination but not in the levels obtained in the field. A closer agreement was obtained for the effect of the (amplitude combination) x (phase angle) interaction. Phase angles $180^\circ$ and $270^\circ$ showed more efficiency reducing draft as used with combinations 1, 2 or 4 as shown in fig. 81. It was

![Graph](image)

**Figure 80.** Effect of the (amplitude combination) x (forward speed) interaction on the draft force in combined mode of vibration.
Figure 81. Effect of the (amplitude combination) x (phase angle) interaction on the draft force in combined mode of vibration.

expected that 270° and amplitude combination 1 or 3 (smallest amplitude for horizontal vibration) would yield the lower draft requirements.

ANALYSIS FOR POWER RATIO

The power ratio is an indicator of the power consumption for each mode of vibration compared to the non-vibrating condition:

Power ratio for horizontal vibration: 2.203
Power ratio for combined vibration: 1.800

Power ratio for vertical vibration: 1.735

Power ratio for no vibration: 1.0.

These values were in the expected level and order with highest and lowest power requirements for the horizontal and vertical mode respectively.

**Horizontal Mode of Vibration**

From the simulation, it was expected that the power ratio would increase by increasing the velocity ratio and the forward speed or decreasing the amplitude. Results from the GLM and the Duncan tests in Table 10, showed the power ratio was significantly affected by all the factors of variation and the interactions of amplitude and forward speed with the velocity ratio. That the power used to vibrate the blade is the main factor in these results. It can be easily explained by using the definition of velocity ratio. This factor relates forward speed, amplitude, and frequency of vibration which partially determine the total power to operate the machine as a summation of power for draft and vibration. For a given amplitude, higher velocity ratios demand higher frequencies and power for vibration. On the other hand, for given velocity ratio and forward speed, increasing the amplitude decreases the frequency with the consequent reduction in power for vibration and power ratio, as expected. Finally, for a given velocity ratio, increasing the forward speed demanded an increase in the frequency
### TABLE 10. GENERAL LINEAR MODELS AND DUNCAN TEST FOR POWER RATIO IN HORIZONTAL MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7</td>
<td>11.3117</td>
<td>1.6160</td>
<td>26.01</td>
<td>0.0001</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>1.4132</td>
<td>1.4132</td>
<td>22.75</td>
<td>0.0002</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>1.8213</td>
<td>1.8213</td>
<td>29.32</td>
<td>0.0001</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>5.8206</td>
<td>5.8206</td>
<td>93.70</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>0.0022</td>
<td>0.0022</td>
<td>0.04</td>
<td>0.8532</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>0.9032</td>
<td>0.9032</td>
<td>14.54</td>
<td>0.0017</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>0.8718</td>
<td>0.8718</td>
<td>14.03</td>
<td>0.0019</td>
</tr>
<tr>
<td>Ampl<em>Speed</em>VelRat</td>
<td>1</td>
<td>0.0571</td>
<td>0.0571</td>
<td>0.92</td>
<td>0.3528</td>
</tr>
<tr>
<td>Error</td>
<td>15</td>
<td>0.9318</td>
<td>0.0621</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>22</td>
<td>12.2435</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels  
\[ a_1, a_2 \]  
\[ 2.475, 1.906 \]

Forward speed levels  
\[ v_2, v_1 \]  
\[ 2.489, 1.941 \]

Velocity ratio levels  
\[ vr_2, vr_1 \]  
\[ 2.733, 1.717 \]

Note: Means underlined by the same line are not significantly different.

with the consequent increase in the power for vibration. The same concepts apply to the expected effects of the double interactions shown in fig. 82. The power ratio increased by increasing the velocity ratio and/or the forward speed. The reduction in power for draft does not compensate for the increase in power for vibration. For a given amplitude, the power ratio and
the power for vibration increased as the velocity ratio was increased as reported by Narayanarao and Verma (1982b). Furthermore, it is concluded from the figure that any increase in the forward speed produced an increase in the power ratio. On the other hand, for any velocity ratio, the power ratio decreased by increasing the amplitude due to a reduction in the power for vibration and the constant value in the power for draft because as expected the amplitude did not affect the draft.

Figure 82. Effects of the (forward speed) x (velrat) and (ampl) x (velrat) interactions on the power ratio in horizontal mode of vibration.
**Vertical Mode of Vibration**

Results from the Analysis of Variance in Table 11 showed a significant effect of the velocity ratio on the power ratio. As expected, the power for vibration must increase as the velocity ratio increased as a result of the increase in the frequency. This result was reported by Al-Jubouri and

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7</td>
<td>3.2633</td>
<td>0.4662</td>
<td>5.41</td>
<td>0.0025</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>0.0931</td>
<td>0.0931</td>
<td>1.08</td>
<td>0.3138</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>0.2495</td>
<td>0.2495</td>
<td>2.90</td>
<td>0.1081</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>2.4187</td>
<td>2.4187</td>
<td>28.09</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>0.0254</td>
<td>0.0254</td>
<td>0.30</td>
<td>0.5944</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>0.2906</td>
<td>0.2906</td>
<td>3.38</td>
<td>0.0848</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.00</td>
<td>0.9558</td>
</tr>
<tr>
<td>Ampl<em>Speed</em>VelRat</td>
<td>1</td>
<td>0.1857</td>
<td>0.1857</td>
<td>2.16</td>
<td>0.1614</td>
</tr>
<tr>
<td>Error</td>
<td>16</td>
<td>1.3778</td>
<td>0.0861</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>4.6411</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels

\[ a_1, \quad a_2 \]

\[ 1.797, \quad 1.673 \]

Forward speed levels

\[ v_2, \quad v_1 \]

\[ 1.837, \quad 1.633 \]

Velocity ratio levels

\[ v_{r2}, \quad v_{r1} \]

\[ 2.053, \quad 1.418 \]

Note: Means underlined by the same line are not significantly different
McNulty (1984). The power ratio increased 44.8% as the velocity ratio increased from 1.0 to 1.5. The mean values matched an expected low increase with an increase in the forward speed or a decrease in the amplitude.

**Combined Mode of Vibration**

The results from the GLM and the Duncan test are shown in Table 12. The amplitude combination, the forward speed, the phase angle and the interaction within amplitude and forward speed showed a significant effect on the power ratio. The power consumption did not follow a defined trend related to the amplitude combination. Larger power ratios were expected with combinations 1 and 3, but only this one met that expectation. The lowest value yielded by combination 1 was unexpected because settings with the smaller amplitude in the shaft for horizontal vibration must require higher power for vibration. The reduction in power for draft did not compensate for the increment due to power for vibration.

The phase angle significantly affected the power ratio. Phase angles $180^\circ$ and $270^\circ$ showed the lowest mean values. This result partially met those from the simulation. Lower power ratios were predicted for $0^\circ$ and $270^\circ$ but the result was directly related to the power for vibration caused by the torque as discussed above. As expected, the forward speed affected the power ratio as a result of the increment in power for vibration. Fig. 83 shows the (amplitude combination) x (forward speed) interaction. The
TABLE 12. GENERAL LINEAR MODELS AND DUNCAN TEST FOR POWER RATIO IN COMBINED MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>31</td>
<td>14.3891</td>
<td>0.6541</td>
<td>6.40</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ampl. combination</td>
<td>3</td>
<td>3.2920</td>
<td>1.0973</td>
<td>10.74</td>
<td>0.0001</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>2.1309</td>
<td>2.1309</td>
<td>20.86</td>
<td>0.0001</td>
</tr>
<tr>
<td>Phase</td>
<td>3</td>
<td>0.9291</td>
<td>0.3097</td>
<td>3.03</td>
<td>0.0350</td>
</tr>
<tr>
<td>Ampl. comb.*Speed</td>
<td>3</td>
<td>6.7208</td>
<td>2.2403</td>
<td>21.93</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ampl. comb.*Phase</td>
<td>9</td>
<td>1.3159</td>
<td>0.1462</td>
<td>1.43</td>
<td>0.1920</td>
</tr>
<tr>
<td>Speed*Phase</td>
<td>3</td>
<td>0.0972</td>
<td>0.0324</td>
<td>0.32</td>
<td>0.8129</td>
</tr>
<tr>
<td>Error</td>
<td>69</td>
<td>7.0482</td>
<td>0.1021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>91</td>
<td>21.4373</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ampl. combination levels
\[\begin{array}{cccc}
co_3 & co_4 & co_2 & co_1 \\
2.021 & 1.941 & 1.757 & 1.507 \\
\end{array}\]

Forward speed levels
\[\begin{array}{cc}
v_2 & v_1 \\
1.941 & 1.659 \\
\end{array}\]

Phase angle levels
\[\begin{array}{cccc}
ph_1 & ph_2 & ph_4 & ph_3 \\
1.946 & 1.876 & 1.715 & 1.673 \\
\end{array}\]

Note: Means underlined by the same line are not significantly different.

general trend followed the expected results. For any amplitude combination, the power ratio increased by increasing the forward speed. Only the amplitude combination 1 showed an opposite and unexpected result.
ANALYSIS FOR BULK DENSITY

The mean values of bulk density after the treatments with vibration were compared to the values for the non-vibrating condition and the original condition of the soil. Mean values were:

Bulk density before treatment: 1115.2 kg/m³
Bulk density for no vibration: 970.25 kg/m³
Bulk density for vertical vibration: 924.28 kg/m³

Figure 83. Effect of the (amplitude combination) x (forward speed) interaction on the power ratio in combined oscillation.
Bulk density for combined vibration: 910.54 kg/m³

Bulk density for horizontal vibration: 898.06 kg/m³.

These values agreed with the expected action of the blade on the soil. The larger reduction in bulk density (19.5%) was for the horizontal mode of vibration; as explained above, the contact angles between the blade and the soil assures more action of the blade on the soil. For the treatments including vibration, the vertical mode was expected to have the lowest effect on the soil, because the shaking action of the blade was limited for velocity ratios below 2.0. Intermediate effects were expected for combined vibration. The reduction of bulk density for the non-vibration treatment was 13.0%.

**Horizontal Mode of Vibration**

Results from the ANOVA and the Duncan test are shown in Table 13. Only the forward speed showed a significant effect on the bulk density. As expected, the increase in forward speed should increase the effect of the treatment on soil break up as a result of the higher frequency and torque used to vibrate the soil. There was no significant effect of the velocity ratio. This factor was expected to cause the largest effect due to the increase in the frequency and the possibility of more energy transferred to the soil. Saqib and Wright (1985) reported non-significance in the variation of bulk density due to amplitude, frequency and forward speed in compacted soil while larger amplitudes and lower forward speeds (larger velocity ratios) produced greater changes in low density soils.
TABLE 13. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR BULK DENSITY IN HORIZONTAL MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>6</td>
<td>46580.29</td>
<td>7763.38</td>
<td>2.42</td>
<td>0.0429</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>3798.52</td>
<td>3798.52</td>
<td>1.18</td>
<td>0.2829</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>25254.19</td>
<td>25254.19</td>
<td>7.87</td>
<td>0.0077</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>9492.19</td>
<td>9492.19</td>
<td>2.96</td>
<td>0.0930</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>1291.69</td>
<td>1291.69</td>
<td>0.40</td>
<td>0.5293</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>2655.19</td>
<td>2655.19</td>
<td>0.83</td>
<td>0.3683</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>4088.52</td>
<td>4088.52</td>
<td>1.27</td>
<td>0.2656</td>
</tr>
<tr>
<td>Error</td>
<td>41</td>
<td>131564.52</td>
<td>3208.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>178144.81</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels: \( a_2 \) \( 907.0 \text{ kg/m}^3 \) \( a_1 \) \( 889.2 \text{ kg/m}^3 \)

Forward speed levels: \( v_1 \) \( 921.0 \text{ kg/m}^3 \) \( v_2 \) \( 875.1 \text{ kg/m}^3 \)

Velocity ratio levels: \( v_{r2} \) \( 912.1 \text{ kg/m}^3 \) \( v_{r1} \) \( 884.0 \text{ kg/m}^3 \)

Note: Means underlined by the same line are not significantly different.

Vertical Mode of Vibration

None of the factors of variation showed a significant effect on the bulk density as shown in Table 14. For the vertical mode of vibration, energy transferred to the soil was mainly used to vibrate the blade and the soil. This was energy used to overcome forces in the mechanism and reactions to gravity, friction and inertia forces caused by the block of soil. One of the
TABLE 14. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR BULK DENSITY IN VERTICAL MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&lt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>6</td>
<td>36691.29</td>
<td>6115.22</td>
<td>1.59</td>
<td>0.1744</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>13635.02</td>
<td>13635.02</td>
<td>3.55</td>
<td>0.0668</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>638.02</td>
<td>638.02</td>
<td>0.17</td>
<td>0.6859</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>14595.19</td>
<td>14595.19</td>
<td>3.80</td>
<td>0.0582</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>1668.52</td>
<td>1668.52</td>
<td>0.43</td>
<td>0.5137</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>5786.02</td>
<td>5786.02</td>
<td>1.50</td>
<td>0.2269</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>368.52</td>
<td>368.52</td>
<td>0.10</td>
<td>0.7584</td>
</tr>
<tr>
<td>Error</td>
<td>41</td>
<td>157627.69</td>
<td>3844.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>194318.98</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels a<sub>1</sub>, a<sub>2</sub>

941.8 kg/m<sup>3</sup> 908.1 kg/m<sup>3</sup>

Forward speed levels v<sub>1</sub>, v<sub>2</sub>

928.6 kg/m<sup>3</sup> 921.3 kg/m<sup>3</sup>

Velocity ratio levels vr<sub>1</sub>, vr<sub>2</sub>

942.4 kg/m<sup>3</sup> 907.5 kg/m<sup>3</sup>

Note: Means underlined by the same line are not significantly different

Effects of these reactions observed in the field for this mode of vibration was that oscillation of the blade helped the soil to move over the blade. When the tractor was stopped at the end of the tests, the soil continued its backward movement due to the vibrating action of the blade.
Combined Mode of Vibration

The analysis of Variance showed that none of the factors of variation had significant effects on the bulk density, but the Duncan test showed significant effects of the phase angle, as shown in Table 15. This result partially coincided with the report of Saqib and Wright (1985) noted above.

### TABLE 15. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR BULK DENSITY IN COMBINED MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>22</td>
<td>197608.61</td>
<td>8982.21</td>
<td>1.54</td>
<td>0.0678</td>
</tr>
<tr>
<td>Ampl. combination</td>
<td>3</td>
<td>16104.77</td>
<td>5368.26</td>
<td>0.92</td>
<td>0.4333</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>55.26</td>
<td>55.26</td>
<td>0.01</td>
<td>0.9227</td>
</tr>
<tr>
<td>Phase</td>
<td>3</td>
<td>35750.68</td>
<td>11916.89</td>
<td>2.04</td>
<td>0.1104</td>
</tr>
<tr>
<td>Ampl. comb.*Speed</td>
<td>3</td>
<td>20460.10</td>
<td>6820.03</td>
<td>1.17</td>
<td>0.3241</td>
</tr>
<tr>
<td>Ampl. comb.*Phase</td>
<td>9</td>
<td>94122.05</td>
<td>10458.01</td>
<td>1.79</td>
<td>0.0735</td>
</tr>
<tr>
<td>Speed*Phase</td>
<td>3</td>
<td>31115.77</td>
<td>10371.92</td>
<td>1.77</td>
<td>0.1540</td>
</tr>
<tr>
<td>Error</td>
<td>169</td>
<td>197608.13</td>
<td>5845.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>191</td>
<td>1185485.75</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ampl. combination levels: \( c_0 \), \( c_2 \), \( c_3 \), \( c_4 \)

919.1 kg/m³, 914.1 kg/m³, 913.9 kg/m³, 895.1 kg/m³

Forward speed levels: \( v_2 \), \( v_1 \)

911.1 kg/m³, 910.0 kg/m³

Phase angle levels: \( p_3 \), \( p_4 \), \( p_2 \), \( p_1 \)

928.3 kg/m³, 918.8 kg/m³, 901.2 kg/m³, 893.9 kg/m³

Note: Means underlined by the same line are not significant different
ANALYSIS FOR GEOMETRIC MEAN DIAMETER

The clod-size distribution for each mode of vibration was characterized by the GMD and $\sigma_g$. These parameters were:

Vertical vibration: $\text{GMD} = 16.56 \text{ mm} \quad \sigma_g = 4.958 \text{ mm}$

Combine vibration: $\text{GMD} = 12.28 \text{ mm} \quad \sigma_g = 4.633 \text{ mm}$

Non-vibration: $\text{GMD} = 12.08 \text{ mm} \quad \sigma_g = 5.059 \text{ mm}$

Horizontal vibration: $\text{GMD} = 11.35 \text{ mm} \quad \sigma_g = 4.693 \text{ mm}$

It was expected that the largest GMD would occur for the no vibration condition. A cause for this unexpected result may be the moisture content of the soil. The soil was in the driest condition when the no vibration tests were performed. For the second set of tests, average moisture during the first day was 26.03% db and for the last day it was 22.4% db. Better performance of the machine was observed as the soil became drier. Tests for vertical vibration were made during the first and second day of testing. Moisture affects the movement of the soil over the blade due to adhesion forces as explained above.

Horizontal Mode of vibration

Although this mode of vibration showed the largest clod-size reduction, there was no significant effect of the factors of variation on the GMD as shown in Table 16. According to the Duncan test, the effect of the amplitude did not match the expected results. The GMD must decrease as a result of the higher frequency caused by a decrease in amplitude or an
TABLE 16. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR GMD IN HORIZONTAL MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>6</td>
<td>90.57</td>
<td>15.10</td>
<td>1.46</td>
<td>0.2170</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>4.03</td>
<td>4.03</td>
<td>0.39</td>
<td>0.5365</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>22.28</td>
<td>22.28</td>
<td>2.15</td>
<td>0.1502</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>36.56</td>
<td>36.56</td>
<td>3.53</td>
<td>0.0674</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>0.46</td>
<td>0.46</td>
<td>0.04</td>
<td>0.8341</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>19.64</td>
<td>19.64</td>
<td>1.90</td>
<td>0.1761</td>
</tr>
<tr>
<td>Speed* VelRat</td>
<td>1</td>
<td>7.60</td>
<td>7.60</td>
<td>0.73</td>
<td>0.3967</td>
</tr>
<tr>
<td>Error</td>
<td>41</td>
<td>424.73</td>
<td>10.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>515.30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels $a_1, a_2$

11.64 mm 11.06 mm

Forward speed levels $v_1, v_2$

12.03 mm 10.67 mm

Velocity ratio levels $v_{r1}, v_{r2}$

12.23 mm 10.48 mm

Note: Means underlined by the same line are not significantly different.

increase in forward speed or velocity ratio. Working with the mean weight diameter, Narayanarao and Verma (1982a) found an inverse relationship between the clod-size and the velocity ratio. The mean weight diameter decreased as the velocity ratio increased.
Vertical Mode of Vibration

Results in Table 17 showed that none of the factors of variation significantly affected the GMD. This mode of vibration presented the lesser effect on the soil with less clod-size reduction. Observing the mean values, the variation of the GMD due to the velocity ratio didn't match the expected results. The GMD was expected to decrease as the amplitude

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>6</td>
<td>468.42</td>
<td>78.07</td>
<td>0.77</td>
<td>0.5995</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>404.26</td>
<td>404.26</td>
<td>3.98</td>
<td>0.0528</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>20.41</td>
<td>20.41</td>
<td>0.20</td>
<td>0.6565</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>28.06</td>
<td>28.06</td>
<td>0.28</td>
<td>0.6022</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>1.80</td>
<td>1.80</td>
<td>0.02</td>
<td>0.8947</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>3.15</td>
<td>3.15</td>
<td>0.03</td>
<td>0.8611</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>10.74</td>
<td>10.74</td>
<td>0.11</td>
<td>0.7469</td>
</tr>
<tr>
<td>Error</td>
<td>41</td>
<td>4168.86</td>
<td>101.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>4637.28</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels

\[ a_2 \quad a_1 \]

19.47 mm 13.67 mm

Forward speed levels

\[ v_1 \quad v_2 \]

17.22 mm 15.92 mm

Velocity ratio levels

\[ vr_2 \quad vr_1 \]

17.33 mm 15.80 mm

Note: Means underlined by the same line are not significantly different
decreased and the forward speed or the velocity ratio increased as a result of the higher frequency for any of these variations. Kang (1985) reported a significant effect of amplitude on the GMD and better flow of the clods over the blade as the amplitude and the frequency increased.

**Combined Mode of Vibration**

The GMD was significantly affected by the amplitude combination as shown in Table 18. Settings with the larger amplitude in the shaft for the vertical oscillation gave the smaller GMD or the larger clod-size reduction. This result is explained by the velocity ratio and the frequency of vibration. The best result was obtained with the smallest amplitude for the horizontal movement. It used larger frequencies and produced a velocity ratio larger than 1.0 in the vertical direction because both eccentrics oscillated at the same frequency to maintain the setting of the phase angle. The ANOVA showed a non-significant difference due to the variation of the phase angle, but the pairwise comparison of the Duncan test showed a real significant difference between 0° and 270°. It partially met the expected results, for the largest and the smallest values of GMD at 270° and 90°. A non-significant difference was observed between the means with lower GMD at 180° and 270°.
### TABLE 18. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR GMD IN COMBINED MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>22</td>
<td>775.98</td>
<td>35.27</td>
<td>1.53</td>
<td>0.0713</td>
</tr>
<tr>
<td>Ampl. combination</td>
<td>3</td>
<td>283.41</td>
<td>94.47</td>
<td>4.08</td>
<td>0.0079</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>0.21</td>
<td>0.21</td>
<td>0.01</td>
<td>0.9236</td>
</tr>
<tr>
<td>Phase</td>
<td>3</td>
<td>154.84</td>
<td>51.61</td>
<td>2.23</td>
<td>0.0864</td>
</tr>
<tr>
<td>Ampl. comb.*Speed</td>
<td>3</td>
<td>93.60</td>
<td>31.20</td>
<td>1.35</td>
<td>0.2602</td>
</tr>
<tr>
<td>Ampl. comb.*Phase</td>
<td>9</td>
<td>116.64</td>
<td>12.96</td>
<td>0.56</td>
<td>0.8280</td>
</tr>
<tr>
<td>Speed*Phase</td>
<td>3</td>
<td>127.27</td>
<td>42.42</td>
<td>1.83</td>
<td>0.1428</td>
</tr>
<tr>
<td>Error</td>
<td>169</td>
<td>3908.53</td>
<td>23.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>191</td>
<td>4684.51</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ampl. combination levels  
- $co_4$  
- $co_3$  
- $co_2$  
- $co_1$  

13.94 mm  12.95 mm  11.18 mm  11.05 mm

Forward speed levels  
- $v_1$  
- $v_2$  

12.31 mm  12.25 mm

Phase angle levels  
- $ph_1$  
- $ph_2$  
- $ph_3$  
- $ph_4$  

13.73 mm  12.21 mm  11.85 mm  11.32 mm

Note: Means underlined by the same line are not significantly different.

### ANALYSIS FOR LOG STANDARD DEVIATION

The norm was a clod-size distribution approximated to a straight line as plotted on log-probability paper, as shown in fig. 76. In some cases, the distributions presented deviations at the end corresponding to the larger clods. This type of deviation was expected for any real distribution.
(Gardner, 1956). For this case, these deviations can be related to the shape of the openings on the separator used. The screen to retain the larger clods was square-holed. Tanner and Bourget (1952) mentioned the importance of using openings of the same shape in all the sieves. A second reason can be the relation between the dimension of the square holes in the screen to the openings in the sieves. Values of $\sigma_g$ showed a certain similarity:

No vibration condition: $\sigma_g = 5.059$ mm

Vertical vibration: $\sigma_g = 4.958$ mm

Horizontal vibration: $\sigma_g = 4.693$ mm

Combined vibration: $\sigma_g = 4.633$ mm

**Horizontal Mode of Vibration**

Results from the ANOVA in Table 19 showed a significant effect of the forward speed and the interaction (amplitude) x (velocity ratio) on $\sigma_g$. These results partially coincided with those of Kang (1985) reporting significant effects of the amplitude and the interaction (amplitude) x (frequency) x (forward speed). The $\sigma_g$ of the GMD decreased as the forward speed increased. This meant that increasing the speed, increased the uniformity of the clod-size, reducing the dispersion of the data about the GMD. This result keeps some relation with the effect of the speed on the GMD. As expected for other factors like bulk density and GMD, the largest speed yielded a smaller clod-size distribution. The interaction between
amplitude and velocity ratio shown in Fig. 84, did not completely meet the expected results. The log standard deviation should decrease as the velocity ratio increased for any amplitude. The largest amplitude used in the tests showed an opposite variation.

TABLE 19. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR $\sigma_s$ IN HORIZONTAL MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>6</td>
<td>5.9256</td>
<td>0.8465</td>
<td>2.45</td>
<td>0.0347</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>0.0212</td>
<td>0.0212</td>
<td>0.06</td>
<td>0.8055</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>4.0310</td>
<td>4.0310</td>
<td>11.65</td>
<td>0.0015</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.00</td>
<td>0.9864</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>0.0928</td>
<td>0.0928</td>
<td>0.27</td>
<td>0.6075</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>1.5088</td>
<td>1.5088</td>
<td>4.36</td>
<td>0.0432</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>0.0063</td>
<td>0.0063</td>
<td>0.02</td>
<td>0.3862</td>
</tr>
<tr>
<td>Error</td>
<td>41</td>
<td>13.8388</td>
<td>0.3460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>19.7645</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels

$\text{a}_1 \quad 4.715 \text{ mm}$

$\text{a}_2 \quad 4.673 \text{ mm}$

Forward speed levels

$v_1 \quad 4.983 \text{ mm}$

$v_2 \quad 4.404 \text{ mm}$

Velocity ratio

$v_{r_2} \quad 4.695 \text{ mm}$

$v_{r_1} \quad 4.692 \text{ mm}$

Note: Means underlined by the same line are not significantly different
Vertical Mode of Vibration

In this mode of vibration, the amplitude had a significant effect on $\sigma_g$ as shown in the Analysis of Variance in Table 20. The same result was reported by Kang (1985) working with a digger blade with similar movement in the rear part of the blade but different oscillation at the front of the blade. Data in the analysis of GMD showed that smaller amplitudes yield smaller clods; now the amplitude shows a significant effect in the range of
TABLE 20. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR $\sigma_g$ IN VERTICAL MODE OF VIBRATION.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>6</td>
<td>12.6076</td>
<td>2.1013</td>
<td>1.70</td>
<td>0.1460</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1</td>
<td>6.2208</td>
<td>6.2208</td>
<td>5.03</td>
<td>0.0304</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>2.3674</td>
<td>2.3674</td>
<td>1.91</td>
<td>0.1741</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1</td>
<td>0.1200</td>
<td>0.1200</td>
<td>0.10</td>
<td>0.7571</td>
</tr>
<tr>
<td>Ampl*Speed</td>
<td>1</td>
<td>2.1000</td>
<td>2.1000</td>
<td>1.70</td>
<td>0.2000</td>
</tr>
<tr>
<td>Ampl*VelRat</td>
<td>1</td>
<td>0.7550</td>
<td>0.7550</td>
<td>0.61</td>
<td>0.4393</td>
</tr>
<tr>
<td>Speed*VelRat</td>
<td>1</td>
<td>1.0443</td>
<td>1.0443</td>
<td>0.84</td>
<td>0.3637</td>
</tr>
<tr>
<td>Error</td>
<td>41</td>
<td>50.7444</td>
<td>1.2377</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>63.3520</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude levels $\ a_2 \ a_1$

5.318mm 4.598mm

Forward speed levels $\ v_1 \ v_2$

5.180mm 4.736mm

Velocity ratio levels $\ vr_2 \ vr_1$

5.079mm 4.908mm

Note: Means underlined by the same line are not significantly different.

size for those clods. This result coincides with that of Kang (1985) who reported a corresponding relationship for the variation of the GMD and $\sigma_g$.

Combined Mode of Vibration

The Analysis of Variance in Table 21 showed a significant effect of the amplitude combination and the phase angle. The Duncan test showed that
\( \sigma_g \) for the two settings using the largest amplitude for the vertical oscillation are significantly different from the two settings using the smallest amplitude for vibration in this direction. The reason for this behavior is related to the frequency of vibration as explained for the GMD. This is corroborated by the fact that one of those settings running with the smallest

---

**TABLE 21. ANALYSIS OF VARIANCE AND DUNCAN TEST FOR \( \sigma_g \) IN COMBINED MODE OF VIBRATION.**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MSE</th>
<th>F</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>22</td>
<td>42.6596</td>
<td>1.9391</td>
<td>3.79</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ampl. combination</td>
<td>3</td>
<td>24.2946</td>
<td>8.0982</td>
<td>15.84</td>
<td>0.0001</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>0.0176</td>
<td>0.0176</td>
<td>0.03</td>
<td>0.8529</td>
</tr>
<tr>
<td>Phase</td>
<td>3</td>
<td>6.1647</td>
<td>2.0549</td>
<td>4.02</td>
<td>0.0085</td>
</tr>
<tr>
<td>Ampl. comb.*Speed</td>
<td>3</td>
<td>1.4906</td>
<td>0.4969</td>
<td>0.97</td>
<td>0.4073</td>
</tr>
<tr>
<td>Ampl. comb.*Phase</td>
<td>9</td>
<td>7.5612</td>
<td>0.8401</td>
<td>1.64</td>
<td>0.1065</td>
</tr>
<tr>
<td>Speed*Phase</td>
<td>3</td>
<td>3.1309</td>
<td>1.0436</td>
<td>2.04</td>
<td>0.1099</td>
</tr>
<tr>
<td>Error</td>
<td>169</td>
<td>86.3813</td>
<td>0.5111</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>191</td>
<td>129.0409</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ampl. combination levels: \( co_4 \), \( co_3 \), \( co_2 \), \( co_1 \)  
5.062mm, 4.893mm, 4.383mm, 4.195mm

Forward speed levels: \( v_1 \), \( v_2 \)  
4.643mm, 4.624mm

Phase angle levels: \( ph_1 \), \( ph_3 \), \( ph_2 \), \( ph_4 \)  
4.917mm, 4.639mm, 4.543mm, 4.434mm

Note: Means underlined by the same line are not significantly different
amplitude and the highest frequency yield the lowest $\sigma_g$ value. The phase angle showed some effect on the uniformity of the clod-size. Phase angles $270^\circ$, $90^\circ$ and $180^\circ$ had no significant difference and conformed the set of angles with better results on the $\sigma_g$. Furthermore, two of these angles $270^\circ$ and $180^\circ$ showed smaller GMD. This meant that these two angles were the best options for clod-size distribution with low values of GMD and $\sigma_g$. Finally, as a general conclusion, the amplitude was the factor of variation with the most effects on $\sigma_g$.

RESULTS FROM SIMULATION AND FIELD TESTS

Results obtained in the simulation, the laboratory and the field testing of the machine were compared using the same approach used for the statistical analysis. The mean values of the factors of variation for each mode of vibration are compared in Table 22. The standard error of the mean for each mode of vibration was included for the field tests. This was calculated using data from the statistical analysis as:

$$S_\gamma = \pm (MSE/n)^{1/2} \cdot t_{a, dof}$$

$S_\gamma$ = Standard error of the mean

MSE = Mean square error

$n$ = number of tests for each mode of vibration

$t$ = critical value of $t$

$\alpha$ = significance level = 0.05

dof = degrees of freedom of error.
For comparison purposes, data for torque in the field test were processed using equation 47 to correct for friction and inertia forces, and gear ratios not included in the simulation. This data is presented in table C7 in appendix C.

From data table 22, it was concluded that for the laboratory tests (movement of the blade only) the simulated values were lower than the values obtained in the laboratory. Results in the simulation depended greatly on the value of the friction coefficient at bearings, joints and

| TABLE 22. EXPECTED AND EXPERIMENTAL MEAN VALUES FOR EACH MODE OF VIBRATION |
|-----------------------------------------------|---------------|--------------|--------------|
| Factor of Variation | Type of Test | Mode of Vibration |              |              |
| Torque (Nm)         | Simulat.      | 17.30     | 9.20     | 14.33 |
| (blade only)        | Laborat.      | 28.80     | 19.01    | 19.45 |
| Torque (Nm)         | Simulat.      | 57.00     | 27.40    | 42.12 |
| (blade-soil)        | Field         | 36.70     | 23.85    | 37.25 |
| Sf (Nm)             |               | (±4.4)    | (±2.3)   | (±2.1) |
| Draft (N)           | Simulat.      | 3803.3    | 4712.4   | 3823.3 | 4697.2 |
|                     | Field         | 4110.2    | 3614.6   | 4638.1 | 5081.4 |
| Sy (N)              |               | (±563.3)  | (±474.5) | (±212.4) |
| Power ratio         | Simulat.      | 2.32      | 1.68     | 1.65 |
|                     | Field         | 2.20      | 1.74     | 1.80 |
| Sy                  |               | (±0.11)   | (±0.13)  | (±0.06) |
eccentrics of the machine. For the field test, differences are probably influenced by the effect of vibration on the accuracy of the sensing system as shown in the data for torque in the horizontal mode of vibration with a high level of vibration transmitted to the frame of the machine and the tractor at the highest velocity ratio and forward speed. Draft differences were possibly caused by factors like friction forces not included in the simulation. These forces acted on vertical faces as the soil moved over the blade. The skidding supports as the machine sank in the ground could have had an effect depending on the moisture of the soil. Reaction forces, as the soil moved along the blade, were presented at the external part of the low eccentrics and at the front of the vertical elements in the blade as big clods moved to the side. These effects were partially reduced by the off-baring of the plots before the tests.
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

This study was conducted for simulating and testing a vibrating digger blade to be used in root crop harvesting. The blade was pulled and powered by a tractor, and operated with three different modes of vibration: horizontal, vertical, and combinations of horizontal and vertical vibrations. The performance of the machine was simulated using a computer program in FORTRAN for the following types of analysis:

1. Kinematic and dynamic analysis of the blade.
2. Analysis of forces on the blade-soil system.
3. Dynamic analysis of the mechanism-blade-soil system.

Results from the program were used to select the factors of variation based on the following considerations: power requirements, frequency and torque levels, and contact and cutting angles. The factors of variation selected for the field testing in horizontal and vertical vibration were: simple amplitude, 9.52 mm and 12.7 mm; forward speed, 2.0 and 3.0 km/h; velocity ratio, 1.0 and 1.5. For the combined oscillation, the factors of variation were: four amplitude combinations, velocity ratio of 1.0; and phase angles of 0, 90, 180, and 270°.

The machine was tested in the laboratory and in the field. The laboratory tests were conducted in the Power and Machinery Laboratory at the Biological and Agricultural Engineering Department. The blade was run
at the same operating conditions to be tested in the field. In addition, the power requirements to overcome friction in the bearings and other machine elements not considered in the simulation were evaluated. The results from these tests showed a closer agreement with those from the simulation at higher speeds and velocity ratios. At lower speeds and velocity ratio settings the correspondence was poor. The friction coefficient of bearings and joints may have the greatest influence on the results.

The field testing was conducted at the Burden Research Farm of the Louisiana Agricultural Experiment Station in a silty-loam soil with the following average conditions: bulk density, 1115.2 kg/m³; moisture content varied between 26 and 22.4% db during the test; average cone index, 0.509 MPa; cohesion and soil-soil friction coefficients were 24.77 kPa and 0.422 respectively; adhesion and soil-metal friction coefficients were 2.39 kPa and 0.464 respectively; plastic limit was 28%. These properties were determined at the USDA Soil Laboratory in the Biological and Agricultural Engineering Department and the Soil Mechanics Laboratory in the Civil Engineering Department. The field test beds were prepared in August, 1993 and maintained with periodic weed control to eliminate root and plant which may affect soil break up. The beds were off-bared to allow more space for the skids supporting the machine, reduce friction and reactions at the sides of the blade, and reduce contact of the supports of the lower eccentrics and links with soil moving back over the blade. The blade, with an effective width of 550 mm and 15° rake angle, was operated at 200 mm depth.
Results from the field testing were evaluated by soil bulk density, clod geometric mean diameter and its log standard deviation, torque, draft, and power ratio. Two samples per plot were taken after each treatment to determine the bulk density. The geometric mean diameter and the log standard deviation were determined from two samples of approximately 20 kg each. These samples were air dried for 3 to 5 weeks to a moisture content of approximately 13% wb and graded into seven clod sizes in a rotary sieve. The undersize percentage of the clod size distribution for each sample was plotted on log-probability paper to determine the geometric mean diameter and its log standard deviation. Torque was measured by a torque cell and the draft force to pull the machine was sensed by load cells mounted on the quick hitch, which attached the machine to the tractor.

The results from the field testing for the torque showed lower values than those expected from the simulation. The main difference corresponded to the horizontal mode of vibration. The levels of vibration transmitted to the frame and the tractor, especially in the tests with the largest amplitude, may have had an effect on the sensing system. For lower levels of vibration on the frame, as in the vertical and combined modes of vibration, the results were in closer agreement. The forward speed showed the most significant effects on the torque in the horizontal and vertical oscillations, while the three factors of variation in combined oscillation, amplitude combination, forward speed, and phase angle, significantly affected the torque to operate the machine.
The results for the draft force showed that there was a draft reduction for the three modes of vibration, but there were two notable differences when compared to the simulation. The velocity ratio did not yield the expected draft reduction in any of the oscillating movements. The main difference was the larger draft reduction shown by the vertical mode of vibration. No draft reduction was expected for the levels of velocity ratio used for this mode of vibration.

The power ratio was significantly affected by the variation in amplitude, forward speed, velocity ratio and phase angle in the horizontal and combined movements. This was explained by the larger torque levels registered by these two movements causing larger increase in the power for vibration. The decrease due to the draft reduction did not compensate for those increases.

Although, the average value of the bulk density for each mode of vibration decreased, compared to the original condition of the soil, the effects of vibration were lower than expected. Only the forward speed showed significant effects on the bulk density in horizontal oscillation. The phase angle also showed a significant effect in combined oscillation. This was explained by the difference in the degree of retreat movement of the blade for the phase angles used in the tests.

The geometric mean diameter showed another unexpected result. Only the horizontal mode of vibration was more efficient in reducing the clod size than the non-vibrating condition. This result can be a product of
the non-randomized procedure for the tests and the variation of soil conditions, especially the moisture content. Tests for horizontal and non-vibrating conditions were performed at the end of the testing procedure, with the soil perhaps at the optimum conditions for tilling. The non-vibrating condition showed the largest dispersion of the clod size distribution, with the largest value of the log standard deviation.

CONCLUSIONS

The analysis of results and the observation of the work of the machine in the laboratory and the field allowed the following conclusions:

1. The use of vibration produced a decrease in the soil bulk density. This decrease varied from 13.0% to 19.5% in the vertical and horizontal modes of vibration respectively.

2. The geometric mean diameter was reduced only by horizontal vibration with reference to the non-vibration condition.

3. The vertical mode of vibration showed the lowest level of torque and the lowest increase in power consumption, a 75% increase, with reference to the tests with no vibration.

4. The increase in velocity ratio did not yield the expected results of reducing the draft in the horizontal mode of vibration.

5. The velocity ratio was the factor of variation with the most effect on the power increase.
6. The phase angle of 180° represented the best selection for this factor, with low levels of torque, draft, geometric mean diameter and vibrations transmitted to the frame. The second best option was 270°.

7. Amplitude combination 1 with the smallest amplitude for horizontal vibration and largest one for the vertical direction represented the best option with low levels of draft, torque, power ratio, bulk density and GMD.

8. Draft for vertical oscillation was much lower than expected.

9. The combined mode of vibration at the velocity ratio of 1.0, yielded results at comparable levels to those in the horizontal direction. This was advantageous because of the lower frequencies used in combined oscillation.

10. Only the horizontal mode of vibration was more effective in reducing the size of the clods than the non-vibrating condition.

11. Data taken in the laboratory were better approximated by the simulation at the highest velocity ratios. In the field the best correspondence was at lower velocity ratios and lower speeds.

12. Moisture content in the soil is an important factor in the flow of soil over the blade. Lower variation in this property during the tests would be preferable.

13. Tests with the largest amplitude transmitted higher levels of vibration to the machine and the tractor.
14. The sensing system must be protected to reduce the effects of bouncing during transportation of the machine.

RECOMMENDATIONS

1. It is recommended especial attention be paid to the vertical mode of vibration in this machine. The lower torque and draft levels give notable advantages to this oscillation with reference to the horizontal mode. This result is opposite to former reports. Furthermore, this mode of vibration represents a substantial simplification in the transmission system of the machine. The system can be reduced to a four bar mechanism eliminating elements 2 and 3 in fig. 1 and the corresponding supports with the consequent reduction in friction torque, power and weight of the machine.

2. Modifications on the blade are recommended. The rear of the blade must be changed to riddled bars to eliminate the smallest clods as these are still moving over the blade and allow a direct contact of the blade with the larger clods. In the actual conditions, small clods dampen the effect of vibration on larger clods. It was observed that larger clods remained at the surface. Other two advantages of this modifications are weight reduction and the consequent reduction of friction forces on the blade.

3. It is recommended the machine be tested with smaller amplitudes like, 9.52 mm and 6.35 mm or 7.94 mm and 4.76 mm.
4. A balancing system is recommended to reduce vibrations transmitted to the frame and increase the accuracy of the sensing system. Another advantageous of vertical oscillation in this machine was related to the possible balancing system. It is easier to design a balancing system for this mode of vibration. Balancing the horizontal movement requires more modifications in the machine.

5. A mound was observed to form in front of the skidding supports. A rounded surface is recommended to reduce the skidding resistance, which averaged 4750 N.

6. A modification using a screen with round holes of 101.6 mm is recommended for the rotary sieve. This diameter follows the progression of the openings in the other sieves.
BIBLIOGRAPHY


ASAE. 1986. Soil cone penetrometer. ASAE Standard S313.2. ASAE, St. Joseph, MI.


Goodyear. 1991. Farm tire handbook. Goodyear Farm Tire Marketing Department, Akron, OH.


CSAE, Ottawa, Ontario, Canada.


Kirisci, V., B. S. Blackmore, R. J. Godwin, and J. Blake. 1993. Design and calibration of three different three-point linkage dynamometers. ASAE paper No. 931009. ASAE, St. Joseph, MI.


PROGRAM FOR THE KINEMATIC AND DYNAMIC ANALYSIS
OF THE DIGGER BLADE MACHINE
integer n1,m1,n2,m2,mode,ref
parameter (n1=4,m1=5,n2=18,m2=19)
real r2,r3,r4,r5,r6,rbc,s1,s2,s3,s4,s5,rcf,h,rbc,rbd,rdc
real vox,voy,vfx,vfrx,vfy,vfry,afx,afy,af,afx,agx,agy,ag,vgx,vgrx,
& vgy,vgr,yv,t,yfo,ygo,yg1
real yf,yf,xo,yo,xfo,xfr,yfr,yg,xgo,xg,r,ygr,xxo,yyo
real e1,e2,e3,e4,ang(n1,m1),xan(n1),w(n1,m1),xw(n1),alpha(n1,m1),
& xal(n1),cor3,cor4,cor5,cor6
real w2,w3,w4,w5,w6,w7,ww2,ww7,alpha3,alpha4,alpha5,alpha6,
& alpha2
real k1,pithetai,thet3,theta4,theta5,theta6,th2,th3,
& th4,th5,th6,thc,phi1,phi4,phi2
real vr,theta7,th7,alp7,r7,phase,ph
real statb(n2,m2),xstb(m2),t2stb,wgt2,wgt3,wgt4,wgt5,wgt6,wgt7
real xcg4,ycg4,xcg5,ycg5,Iz2,Iz3,
& Iz4,Iz5,Iz6,ma2,ma3,ma4,ma5,ma6,rcg2,rcg3,rcg4,rcg5,rcg6,
& delta4,delta5,thcg2,thcg3,thcg4,thcg5,thcg6,a2x,a2y,a3x,a3y,
& a4x,a4y,a5x,a5y,a6x,a6y,a2,a3,a4,a5,a6,gamma2,gamma3,
& gamma4,gamma5,gamma6,beta2,beta3,beta4,beta5,beta6,
& fo2,fo3,fo4,fo5,fo6,fo7,l3,l4,l5,l6,inerb(n2,m2),xinb(m2),t2ib,t7ib,
& Iz7,ma7,thcg7,a7y,a7,gamma7,beta7,f07,l7
real foxb,foyb,thfob,thetfob,anfo2,anfo3,anfo4,anfo5,
& anfo6,shakb
real r12,r14,r76,r32,r53,r45,r65,r17,totb(n2,m2),xxtb(n2),mu,
& t2mb,t12b,t32b,t14b,t76b,t53b,t45b,t65b,t17b,t2fb,t2b,t7mb,
& t7fb,t7b,th
real d12,d14,d76,d32,d53,d45,d65,d17
real f12b,f32b,f53b,f45b,f65b,f14b,f67b,f17b,thi12b,thi32b,thi53b,
& thi45b,thi14b,thi67b,thi17b,theti12b,theti32b,theti53b,theti65b,
& theti65b,theti53b,theti67b,theti17b,theti45b,t2ib,t7ib,thimb,
real h12b,h32b,h53b,h45b,h65b,h14b,h76b,h17b,t12b,t23b,t54b,
& t53b,t56b,t76b,dt12b,dt32b,dt53b,dt45b,dt65b,dt76b,dt14b,
& h17b,t17b,t71b,r17,dt17b,t41b
real xcg5,ycg5,xas,mas,Izs,rcgs,asx,asy,as,gammas,betas,anfos,fos,
& l,dw,b,ws
real alphab,mub,x2,y2,incrx,incrv,area,b,ca,d3,xmax,DF,Nb,Fv,cs,phis,
& mus,beta,area,ka,In,ddfsum,v1,v1,bdsoil,dfm,l,b,UDF,DR,Nuv,
& Nd,Nv,Na,Pr,k3
real inerso(n2,m2),xiso(m2),t2iso,t7iso,tsiso,f12so,f32so,f53so,f45so,
& f14so,f65so,f67so,f17so,shakso,foyso,foxso,f0so,thfoso,thefoso
real statso(n2,m2),xstso(m2),t2stso,t7stso,tstso
real h12so,h32so,h53so,h45so,h65so,h14so,h76so,h17so,t21so,t23so,
1. INPUT DATA

1.1 FACTORS OF VARIATION AND COEFFICIENTS

Ground speed $v_t$ (km/h), velocity ratio $v_r$, eccentricities $e_{cc2}$, $e_{cc7}$ (mm), phase angle and mode of vibration: 1 for longitudinal, 2 for lifting and 3 for combine movement.

Mode = 2
$e_{cc2}$ = 0.0
$e_{cc7}$ = 9.52
$v_t$ = 3.0
$v_r$ = 1.5
Phase = 0.0

1.2 SOIL CONDITIONS

$c1$ = 24.77
$c2$ = 6.9
$\phi_{is1}$ = 22.9° * $k1$
$\phi_{is2}$ = 20.0° * $k1$
$bd_{soil}$ = 1120.0

1.3 BLADE DIMENSIONS (m) AND WORKING POSITION

$l$ = 0.47
$b$ = 0.55
$dw$ = 0.20
$rakang$ = 15.0
SOIL-METAL COEFFICIENTS
mub = 0.464
cad = 2.39

FRICITION COEFFICIENT FOR BEARINGS
mu = 0.08

1.2. DIMENSIONS AND INITIAL CONDITIONS

DIMENSIONS

\[ r_2 = \frac{e_{cc_2}}{1000.0} \]
\[ r_7 = \frac{e_{cc_7}}{1000.0} \]
\[ v_{oy} = 0.0 \]
\[ v_{ox} = \frac{v_t}{3.6} \]
\[ a_{reab} = l*b \]
\[ \alpha_{hab} = \rho_{akang} * k_1 \]
\[ r_3 = 0.152 \]
\[ r_4 = 0.305 \]
\[ r_5 = 0.457 \]
\[ r_6 = 0.305 \]
\[ h = 0.220 \]
\[ s_4 = 0.254 \]
\[ s_5 = 0.203 \]
\[ s_1 = \sqrt{h^2 + s_4^2} \]
\[ s_2 = s_4 + s_5 \]
\[ s_3 = \sqrt{h^2 + s_5^2} \]
\[ r_{bc} = 0.133 \]
\[ r_{cf} = 0.127 \]
\[ r_{gf} = 0.474 \]
\[ r_{bd} = 0.085 \]
\[ r_{dc} = 0.102 \]

INITIAL CONDITIONS

\[ x_1 = 0.0 \]
\[ v_1 = v_{ox} \]
\[ t_{sumb} = 0.0 \]
\[ t_{2sumb} = 0.0 \]
\[ t_{7sumb} = 0.0 \]
\[ d_{fsum} = 0.0 \]
\[ t_{sumso} = 0.0 \]
\[ t_{2sumso} = 0.0 \]
\[ t_{7sumso} = 0.0 \]
\[ x_{sum} = 0.0 \]
\[ d_{fvsum} = 0.0 \]
\[ h_{tsum} = 0.0 \]
1.3. INPUT FREQUENCIES AND MODES OF VIBRATION

\[ i34 = 1.0 \]

if(mode .eq. 1) then
  \[ w2 = -vr*vox/r2 \]
  \[ w7 = i34*w2 \]
  \[ wi = w2 \]
  ~vibration='longitudinal'~
  \[ ref=2 \]
else if(mode .eq. 2) then
  \[ w7 = -vr*vox/r7 \]
  \[ wi = w7 \]
  \[ w2 = i34*wi \]
  ~vibration='lifting'~
  \[ ref=7 \]
else
  \[ w2 = -vr*vox/r2 \]
  \[ w7 = w2 \]
  \[ wi = w2 \]
  ~vibration='combine'~
  \[ ref=2 \]
endif

2. OUTPUT FILES AND TITLES

open(unit=60, file='pos', status='unknown')
open(unit=61, file='vel', status='unknown')
open(unit=62, file='acc', status='unknown')
open(unit=63, file='anafx', status='unknown')
open(unit=64, file='anafy', status='unknown')
open(unit=65, file='anagx', status='unknown')
open(unit=66, file='anagy', status='unknown')
open(unit=67, file='torb', status='unknown')
open(unit=68, file='ttorb', status='unknown')
open(unit=69, file='inforb', status='unknown')
open(unit=70, file='shakb', status='unknown')
open(unit=71, file='draft', status='unknown')
open(unit=72, file='torso', status='unknown')
open(unit=73, file='ttorso', status='unknown')
open(unit=74, file='shakso', status='unknown')
open(unit=75, file='ratios', status='unknown')
open(unit=76, file='accfg', status='unknown')

OUTPUT FILES TITLE

***************
write(60,20) vibration
20 format(4x,'ANGULAR POSITION - MOVEMENT: ',A12)
write(60,22) ecc2,ecc7,vr,vt,phase
22 format(x,'r2=',f5.2,'mm r7=',f5.2,'mm velrat=',f3.1,
& ' vox=',f3.1,'km/h ph ang=',f5.1)
write(60,25) ref
25 format(x,'THETA',I1,' THETA3 THETA4 THETA5
& THETA6')
write(61,30) vibration
30 format(4x,'ANGULAR VELOCITY - MOVEMENT: ',A12)
write(61,22) ecc2,ecc7,vr,vt,phase
write(61,35) ref
35 format(x,'THETA',I1,' W3 W4 W5 W6')
write(62,40) vibration
40 format(4x,'ANGULAR ACCELERATION - MOVEMENT: ',A12)
write(62,22) ecc2,ecc7,vr,vt,phase
write(62,45) ref
45 format(x,'THETA',I1,' ALPHA3 ALPHA4 ALPHA5
& ALPHA6')
write(63,50) vibration
50 format(3x,'DISPLACEMENT AND VELOCITY OF POINT F IN X
& AND Y DIR - MOVEMENT: ',A12)
write(63,22) ecc2,ecc7,vr,vt,phase
write(63,55) ref
55 format(x,'THETA',I1,' XF1 XF0 XFr YFr
& Vox VFx VFrx VFry')
write(64,60) vibration
60 format(3x,'DISPLACEMENT AND VELOCITY OF POINT F IN Y
& DIR - MOVEMENT: ',A12)
write(64,22) ecc2,ecc7,vr,vt,phase
write(64,65) ref
65 format(x,'THETA',I1,' YF1 YFo YFr Voy
& VFy VFry')
write(65,70) vibration
70 format(3x,'DISPLACEMENT AND VELOCITY OF POINT G IN X
& AND Y DIR - MOVEMENT: ',A12)
write(65,22) ecc2,ecc7,vr,vt,phase
write(65,75) ref
75 format(x,'THETA',I1,' XG1 XGo XGr YGr
& Vox VGx VGrx VGry')
write(66,80) vibration
80 format(3x,'DISPLACEMENT AND VELOCITY OF POINT G IN Y
& DIR - MOVEMENT: ',A12)
write(66,22) ecc2,ecc7,vr,vt,phase
write(66,85) ref
85 format(x,'THETA',I1,' YG1 YGo YGr Voy 
& VGY VGr')
write(67,90) vibration
90 format(4x,'TORQUE COMPONENTS (N.m) - BLADE ONLY - 
& MOVEMENT: ','A12)
write(67,22) ecc2, ecc7, vr, vt, phase
write(67,95) ref
95 format(x,'THETA',I1,' T2ib T7ib T2stb T7stb T2fb 
& T7fb')
write(68,100) vibration
100 format(4x,'TOTAL TORQUE COMPONENTS -BLADE ONLY- 
& MOVEMENT: ','A12)
write(68,22) ecc2, ecc7, vr, vt, phase
write(68,105) ref
105 format(x,'THETA',I1,' Tib Tstb Tfb Tb T2b 
& T7b')
write(69,110) vibration
110 format(4x,'INERTIA FORCES ON THE MECHANISM - 
& MOVEMENT: ','A12)
write(69,22) ecc2, ecc7, vr, vt, phase
write(69,115) ref
115 format(x,'THETA',I1,' Fo2 Fo3 Fo4 Fo5 
& Fo6 Fo7')
write(70,120) vibration
120 format(4x,'SHAKEN, TOTAL INERTIA AND REACTION FORCES 
& - MOVEMENT: ','A12)
write(70,22) ecc2, ecc7, vr, vt, phase
write(70,125) ref
125 format(x,'THETA',I1,' SHAkb IFob F12b F14b 
& F17b')
write(71,130) vibration
130 format(4x,'DRAFT FORCE - MOVEMENT: ','A12)
write(71,22) ecc2, ecc7, vr, vt, phase
write(71,135) ref
135 format(x,'THETA',I1,' DF UDF")
write(72,140) vibration
140 format(4x,'TORQUE COMPONENTS - BLADE-SOIL SYSTEM - 
& MOVEMENT: ','A12)
write(72,22) ecc2, ecc7, vr, vt, phase
write(72,145) ref
145 format(x,'THETA',I1,' T2iso T7iso T2stso T7stso 
& T2fso T7fso')
write(73,150) vibration
150 format(4x,'TOTAL TORQUE COMPONENTS - BLADE-SOIL 
& SYSTEM - MOVEMENTP: ','A12)
write(73,22) ecc2,ecc7,vr,vt,phase
write(73,155) ref
155 format(x,'\text{THETA}',l,'  Tiso Tstso Tfso Tso & T2so T7so')
write(74,160) vibration
160 format(x,'\text{SHAKEN, TOTAL INERTIA AND REACTION FORCES - & BLADE-SOIL SYSTEM - MOVEMENT: }',A12)
write(74,22) ecc2,ecc7,vr,vt,phase
write(74,165) ref
165 format(x,'\text{SHAKso IFoso Fos F12so & F14so F17so}')
write(76,170) vibration
170 format(x,'\text{ACCELERATION OF POINTS F AND G - MOVEMENT: & }',A12)
write(76,22) ecc2,ecc7,vr,vt,phase
write(76,175) ref
175 format(x,'\text{THETA}',l,'  Afx Afy Af Agx & Agy Agx')

3. KINEMATIC ANALYSIS OF THE MECHANISM
3.1 ANGULAR POSITION ANALYSIS

Initial Position of the Mechanism
th3=0.0*k1
th4=275.0*k1
th5=180.0*k1
th6=280.0*k1

phi1=atan(h/s4)
phi4=atan(rbd/rdc)
phi2=0.0
ph=phase*k1

do 1000 thetai=0.0,-360.0,-10.0
if (mode .eq. 1 .or. mode .eq. 3) then
  th2=thetai*k1
  th7=th2 + ph
  thi=th2
else
  th7=thetai*k1
  th2=0.0
  theta7=thetai
  thi=th7
endif
200  e1=r2*cos(th2)+r3*cos(th3)-r4*cos(th4)-rbc*cos(th5-phi4)-
    & s1*cos(phi1)
  e2=r2*sin(th2)+r3*sin(th3)-r4*sin(th4)-rbc*sin(th5-phi4)-
    & s1*sin(phi1)
  e3=-r4*cos(th4)-r5*cos(th5)+r6*cos(th6)+r7*cos(th7)-s2*cos(phi2)
  e4=-r4*sin(th4)-r5*sin(th5)+r6*sin(th6)+r7*sin(th7)-s2*sin(phi2)
  if(abs(e1) .gt. 0.001 .or. abs(e2) .gt. 0.001) go to 210
  if(abs(e3) .gt. 0.001 .or. abs(e4) .gt. 0.001) go to 210
  go to 220
210  ang(l,1)=-r3*sin(th3)
  ang(l,2)=r4*sin(th4)
  ang(l,3)=rbc*sin(th5-phi4)
  ang(l,4)=0.0
  ang(l,5)=-e1
  ang(2,1)=r3*cos(th3)
  ang(2,2)=r4*cos(th4)
  ang(2,3)=-rbc*cos(th5-phi4)
  ang(2,4)=0.0
  ang(2,5)=-e2
  ang(3,1)=0.0
  ang(3,2)=r4*sin(th4)
  ang(3,3)=r5*sin(th5)
  ang(3,4)=-r6*cos(th6)
  ang(3,5)=-e3
  ang(4,1)=0.0
  ang(4,2)=-r4*cos(th4)
  ang(4,3)=-r5*cos(th5)
  ang(4,4)=r6*cos(th6)
  ang(4,5)=-e4

  call kinem(ang,xan)
  cor3=xan(1)
  cor4=xan(2)
  cor5=xan(3)
  cor6=xan(4)
  th3=th3+cor3
  th4=th4+cor4
  th5=th5+cor5
  th6=th6+cor6
  go to 200

220  theta6=th6/k1
  theta5=th5/k1
  theta4=th4/k1
  theta3=th3/k1
\[ \theta_7 = \frac{\theta_7}{k_1} \]
\[ \text{thc} = \theta_5 - \phi_4 \]

### 3.2 VELOCITY ANALYSIS

\[ w(1,1) = -r_3 \sin(\theta_3) \]
\[ w(1,2) = r_4 \sin(\theta_4) \]
\[ w(1,3) = r_{bc} \sin(\text{thc}) \]
\[ w(1,4) = 0.0 \]
\[ w(1,5) = -r_2 w_2 \sin(\theta_2) \]
\[ w(2,1) = r_3 \cos(\theta_3) \]
\[ w(2,2) = -r_4 \cos(\theta_4) \]
\[ w(2,3) = -r_{bc} \cos(\text{thc}) \]
\[ w(2,4) = 0.0 \]
\[ w(2,5) = -r_2 w_2 \cos(\theta_2) \]
\[ w(3,1) = 0.0 \]
\[ w(3,2) = r_4 \sin(\theta_4) \]
\[ w(3,3) = r_5 \sin(\theta_5) \]
\[ w(3,4) = -r_6 \sin(\theta_6) \]
\[ w(3,5) = r_7 w_7 \sin(\theta_7) \]
\[ w(4,1) = 0.0 \]
\[ w(4,2) = -r_4 \cos(\theta_4) \]
\[ w(4,3) = -r_5 \cos(\theta_5) \]
\[ w(4,4) = r_6 \cos(\theta_6) \]
\[ w(4,5) = -r_7 w_7 \cos(\theta_7) \]

\[ \text{call kinem}(w,w_3, w_4, w_5, w_6) \]

### 3.3 ACCELERATION ANALYSIS

\[ \alpha(1,1) = -r_3 \sin(\theta_3) \]
\[ \alpha(1,2) = r_4 \sin(\theta_4) \]
\[ \alpha(1,3) = r_{bc} \sin(\text{thc}) \]
\[ \alpha(1,4) = 0.0 \]
\[ \alpha(1,5) = r_2 w_2^{**2} \cos(\theta_2) + r_3 w_3^{**2} \cos(\theta_3) - r_4 w_4^{**2} \cos(\theta_4) - r_{bc} w_5^{**2} \cos(\text{thc}) \]
\[ \alpha(2,1) = r_3 \cos(\theta_3) \]
\[ \alpha(2,2) = -r_4 \cos(\theta_4) \]
\[ \alpha(2,3) = -r_{bc} \cos(\text{thc}) \]
\[ \alpha(2,4) = 0.0 \]
\[ \alpha(2,5) = r_2 w_2^{**2} \sin(\theta_2) + r_3 w_3^{**2} \sin(\theta_3) - r_4 w_4^{**2} \]
\[ & \cos(\theta_4) - r_{bc} w_5^{**2} \sin(\text{thc}) \]
& \sin(\theta_4) - r_{bc}w_5^2\sin(\theta_c)

alpha(3,1) = 0.0
alpha(3,2) = r_4\sin(\theta_4)
alpha(3,3) = r_5\sin(\theta_5)
alpha(3,4) = -r_6\sin(\theta_6)
alpha(3,5) = -r_4w_4^2\cos(\theta_4) - r_5w_5^2\cos(\theta_5) + r_6w_6^2\cos(\theta_6) - r_7w_7^2\cos(\theta_7)

alpha(4,1) = 0.0
alpha(4,2) = -r_4\cos(\theta_4)
alpha(4,3) = -r_5\cos(\theta_5)
alpha(4,4) = r_6\cos(\theta_6)
alpha(4,5) = -r_4w_4^2\sin(\theta_4) - r_5w_5^2\sin(\theta_5) + r_6w_6^2\sin(\theta_6) - r_7w_7^2\sin(\theta_7)

\text{call kinem(alpha,xal)}
alpha3 = xal(1)
alpha4 = xal(2)
alpha5 = xal(3)
alpha6 = xal(4)

3.4. ANALYSIS OF POINT F

deltaf = \arccos((r_5^2 + r_{cf}^2 - r_{gf}^2)/(2.0 * r_5 * r_{cf}))

thf = th_5 + deltax

xf = r_2\cos(\theta_2) + r_3\cos(\theta_3) - r_{bc}\cos(\theta_c) + r_{cf}\cos(\theta_f)
yf = r_2\sin(\theta_2) + r_3\sin(\theta_3) - r_{bc}\sin(\theta_c) + r_{cf}\sin(\theta_f)

if (\theta_{ti} \geq 0.0) go to 300
xo = xf
yo = yf
300 xo = xf - xo

xf1 = vox * \theta_{ti}/wi
xfr = xo + xf1
yf = yo - yf
yf1 = voy * \theta_{ti}/wi
yfr = yf + yf1

Vfx = -r_2w_2\sin(\theta_2) - r_3w_3\sin(\theta_3) + r_{bc}w_5\sin(\theta_c) - r_{cf}w_5\sin(\theta_f)

vfrx = vox + Vfx

if (\text{mode} > 1) go to 305
if (vfrx \leq 0.0 \text{ and} \ vr \geq 1.0) then
vfrx = 0.0
go to 305
else
305 vfy = r_2w_2\cos(\theta_2) + r_3w_3\cos(\theta_3) - r_{bc}w_5\cos(\theta_c) + r_{cf}w_5\cos(\theta_f)

vfry = voy + vfy  
\[ \text{vf} = \sqrt{(vf_{rx}^2 + vf_{ry}^2)} \]

\[ \text{afx} = -r2 \cdot w2^2 \cdot \cos(th2) - r3 \cdot \alpha3 \cdot \sin(th3) - r3 \cdot w3^2 \cdot \cos(th3) + rbc \cdot \alpha5 \cdot \sin(thc) + rbc \cdot w5^2 \cdot \cos(thc) - rcf \cdot \alpha5 \cdot \sin(thf) - rcf \cdot w5^2 \cdot \cos(thf) \]

\[ \text{afy} = -r2 \cdot w2^2 \cdot \sin(th2) + r3 \cdot \alpha3 \cdot \cos(th3) - r3 \cdot w3^2 \cdot \sin(th3) - rbc \cdot \alpha5 \cdot \cos(thc) + rbc \cdot w5^2 \cdot \sin(thc) + rcf \cdot \alpha5 \cdot \cos(thf) - rcf \cdot w5^2 \cdot \sin(thf) \]

\[ \text{af} = \sqrt{(afx^2 + afy^2)} \]

3.5. ANALYSIS OF POINT G

\[ \text{xg} = r7 \cdot \cos(th7) + r6 \cdot \cos(th6) \]
\[ \text{yg} = r7 \cdot \sin(th7) + r6 \cdot \sin(th6) \]

if (thetai .lt. 0.0) go to 320

\[ \text{xxo} = xg \]
\[ \text{yyo} = yg \]

320 \[ \text{xgo} = xg - xxo \]
\[ \text{xgl} = v0x \cdot \text{thi} / wi \]
\[ \text{xgr} = xgo + xgl \]
\[ \text{ygo} = yg - yyo \]
\[ \text{yl} = v0y \cdot \text{thi} / wi \]
\[ \text{yr} = ygo + ygl \]

\[ \text{vgx} = -r7 \cdot w7 \cdot \sin(th7) - r6 \cdot w6 \cdot \sin(th6) \]
\[ \text{vgrx} = v0x + vgx \]
\[ \text{vgyx} = r7 \cdot w7 \cdot \cos(th7) + r6 \cdot w6 \cdot \cos(th6) \]
\[ \text{vy} = v0y + vgy \]
\[ \text{vg} = \sqrt{(vgy^2 + vgrx^2)} \]

\[ \text{agx} = -r7 \cdot w7^2 \cdot \cos(th7) - r6 \cdot \alpha6 \cdot \sin(th6) - r6 \cdot w6^2 \cdot \cos(th6) \]
\[ \text{agy} = -r7 \cdot w7^2 \cdot \sin(th7) + r6 \cdot \alpha6 \cdot \cos(th6) - r6 \cdot w6^2 \cdot \sin(th6) \]
\[ \text{ag} = \sqrt{(agx^2 + agy^2)} \]

3.6. ANALYSIS OF THE C.G. OF THE BLADE

\[ \text{ycg5} = -0.044 \]
\[ \text{xcg5} = 0.205 \]
\[ \text{rcg5} = \sqrt{(xcg5^2 + ycg5^2)} \]
\[ \text{delta5} = \text{atan}(ycg5 / xcg5) \]
\[ \text{thcg5} = \text{th5} - \text{delta5} \]
\[ \text{xcg} = r2 \cdot \cos(th2) + r3 \cdot \cos(th3) - rbc \cdot \cos(thc) + rcg5 \cdot \cos(thcg5) \]
\[ \text{ycg} = r2 \cdot \sin(th2) + r3 \cdot \sin(th3) - rbc \cdot \sin(thc) + rcg5 \cdot \sin(thcg5) \]

if (thetai .lt. 0.0) go to 322
\[
\begin{align*}
xxxo &= xcg \\
yyyo &= ycg \\
322 \quad xcko &= xcg - xxo \\
xcgo &= xcgo + xcg \\
ycko &= ycg - yyyo \\
ycgo &= voy + xcg \\
ycgo &= xcgo + ycgo \\
vcko &= -r2 \times w2 \times \sin(\text{th2}) - r3 \times w3 \times \sin(\text{th3}) + rbc \times w5 \times \sin(\text{thc}) - \\
&\quad rbcg5 \times w5 \times \sin(\text{thcg5}) \\
vckox &= xgo + vcko \\
vcko &= r2 \times w2 \times \cos(\text{th2}) + r3 \times w3 \times \cos(\text{th3}) - rbc \times w5 \times \cos(\text{thc}) + \\
&\quad rbcg5 \times w5 \times \cos(\text{thcg5}) \\
vckoy &= voy + vcko \\
vcko &= \sqrt{vckox^2 + vckoy^2} \\
vcgo &= -r2 \times w2 \times \sin^2(\text{th2}) - r3 \times \alpha3 \times \sin(\text{th3}) - r3 \times w3 \times \sin^2(\text{th3}) + \\
&\quad rbc \times \alpha5 \times \sin(\text{thc}) + rbc \times w5 \times \sin^2(\text{thc}) - \\
&\quad rbcg5 \times \alpha5 \times \sin(\text{thcg5}) - rbcg5 \times w5 \times \sin^2(\text{thcg5}) \\
vckox &= xgo + vcko \\
vcko &= \sqrt{vckox^2 + vckoy^2} \\
acgo &= \sqrt{acgx^2 + acgy^2} \\
\text{4. DYNAMIC ANALYSIS OF THE MECHANISM} \\
\text{4.1 ELEMENTS CHARACTERISTICS} \\
\text{ELEMENT 2 (reference point=center of rotation 02)} \\
Iz2 &= 0.0017 \\
ma2 &= 2.86 \\
wgt2 &= ma2 \times g \\
rcg2 &= 1.33 \times r2 \\
\text{thc2} &= \text{th2} \\
a2x &= rcg2 \times w2 \times \cos(\text{thc}) \\
a2y &= rcg2 \times w2 \times \sin(\text{thc}) \\
a2 &= \sqrt{(a2x^2 + a2y^2)} \\
call angle(gamma2, a2y, a2x) \\
beta2 &= gamma2 + \pi \\
\text{anf02} &= beta2 / k1 \\
f02 &= ma2 \times a2 \\
\text{if (mode .eq. 2) then} \\
l2 &= rcg2
\end{align*}
\]
else
  l2=rcg2+Iz2*alpha2/(fo2*sin(beta2-thcg2))
endif

ELEMENT 3 (reference point=A)
Iz3=0.035
ma3=10.8
wgt3=ma3*g
rcg3=0.0314
thcg3=th3
a3x=-r2*w2**2*cos(th2)-rcg3*alpha3*sin(thcg3)-rcg3*w3**2*
&  cos(thcg3)
a3y=-r2*w2**2*sin(th2)+rcg3*alpha3*cos(thcg3)-rcg3*w3**2*
&  sin(thcg3)
a3=sqrt(a3x**2+a3y**2)
call angle(gamma3,a3y,a3x)
  beta3=gamma3+pi
anfo3=beta3/kl
fo3=ma3*a3
l3=rcg3+Iz3*alpha3/(fo3*sin(beta3-thcg3))

ELEMENT 4 (reference point = O4)
xcg4=-0.0034
ycg4=-0.069
Iz4=0.12
ma4=13.7
wgt4=ma4*g
rcg4=sqrt(xcg4**2+ycg4**2)
delta4=atan(ycg4/xcg4)
  thcg4=th4-delta4+pi/2.0
a4x=-rcg4*w4**2*cos(thcg4) - rcg4*alpha4*sin(thcg4)
a4y=-rcg4*w4**2*sin(thcg4) + rcg4*alpha4*cos(thcg4)
a4=sqrt(a4x**2+a4y**2)
call angle(gamma4,a4y,a4x)
  beta4=gamma4+pi
anfo4=beta4/k1
fo4=ma4*a4
l4=rcg4+Iz4*alpha4/(fo4*sin(beta4-thcg4))

ELEMENT 5 (reference point = point C)
ycg5=-0.044
xcg5=0.205
Iz5=0.883
ma5=50.5
wgt5=ma5*g
rcg5 = sqrt(xcg5**2 + ycg5**2)
delta5 = atan(ycg5 / xcg5)

thcg5 = th5 - delta5

\[ \alpha5x = -r4*\alpha4*\sin(\theta4) - r4*w4**2*\cos(\theta4) - rcg5*\alpha5*\sin(\theta5) - \]
\[ - rcg5*w5**2*\cos(\theta5) \]

\[ \alpha5y = r4*\alpha4*\cos(\theta4) - r4*w4**2*\sin(\theta4) + rcg5*\alpha5*\cos(\theta5) - \]
\[ - rcg5*w5**2*\sin(\theta5) \]

a5 = sqrt(a5x**2 + a5y**2)
call angle(gamma5, a5y, a5x)

\[ \beta5 = \gamma5 + \pi \]

\[ \alpha5 = \beta5/k1 \]

\[ f05 = ma5*a5 \]

\[ l5 = rcg5 + Iz5*\alpha5/(f05*\sin(\beta5-\theta5)) \]

\[ I7 = 0.129 \]

\[ ma6 = 14.1 \]

\[ wgt6 = ma6*g \]

\[ rcg6 = 0.069 \]

\[ \theta6 = th6 \]

\[ \alpha6x = -r7*w7**2*\cos(\theta7) - rcg6*\alpha6*\sin(\theta6) - rcg6*w6**2* \]
\[ - \cos(\theta6) \]

\[ \alpha6y = -r7*w7**2*\sin(\theta7) + rcg6*\alpha6*\cos(\theta6) - rcg6*w6**2* \]
\[ - \sin(\theta6) \]

a6 = sqrt(a6x**2 + a6y**2)
call angle(gamma6, a6y, a6x)

\[ \beta6 = \gamma6 + \pi \]

\[ \alpha6 = \beta6/k1 \]

\[ f06 = ma6*a6 \]

\[ l6 = rcg6 + Iz6*\alpha6/(f06*\sin(\beta6-\theta6)) \]

\[ I7 = 0.0017 \]

\[ ma7 = 2.86 \]

\[ wgt7 = ma7*g \]

\[ rcg7 = 1.33*r7 \]

\[ \theta7 = th7 \]

\[ \alpha7x = -rcg7*w7**2*\cos(\theta7) \]

\[ \alpha7y = -rcg7*w7**2*\sin(\theta7) \]

a7 = sqrt(a7x**2 + a7y**2)
call angle(gamma7, a7y, a7x)

\[ \beta7 = \gamma7 + \pi \]

\[ \alpha7 = \beta7/k1 \]

\[ f07 = ma7*a7 \]

if (mode .eq. 1) then
l7=rcg7
else
l7=rcg7+Iz7*alpha7/(fo7*sin(beta7-thcg7))
endif

c BLOCK OF SOIL (C is the reference point)
c INERTIA MOMENT AND CENTER OF GRAVITY
betaf=pi/4.0-phisl/2.0
d1=dw*sin(alphab+betaf)/sin(betaf)
if (vfrx .ge. 0.0) then
ls1=dw*cos(alphab+betaf)/sin(betaf)
ls2=1
ls3=dw*sin(alphab+betaf)*tan(alphab)/sin(betaf)
x1s=-ls1/3.0
y1s=2.0*d1/3.0
go to 330
else
ls1=dw*sin(alphab+betaf)*tan(alphab)/sin(betaf)
ls2=1-ls1
ls3=d1*tan(alphab)
x1s=2.0*ls1/3.0
y1s=d1/3.0
endif
330 vls=ls1*d1*b/2.0
v2s=ls2*d1*b
v3s=ls3*d1*b/2.0
vol=vls+v2s+v3s
m1s=bdsol*v1s
m2s=bdsol*v2s
m3s=bdsol*v3s
mas=m1s+m2s+m3s
if (vfrx .lt. 0.0) go to 335
mas1=mas
335 z1s=0.0
x2s=ls2/2.0
y2s=d1/2.0
z2s=0.0
x3s=l+ls3/3.0
y3s=2.0*d1/3.0
z3s=0.0
xprs=(m1s*x1s+m2s*x2s+m3s*x3s)/mas
yprs=(m1s*y1s+m2s*y2s+m3s*y3s)/mas
zprs=(m1s*z1s+m2s*z2s+m3s*z3s)/mas
dx1=xprs-x1s
dx2=xprs-x2s
dx3=xprs-x3s
dy1=yprs-y1s
dy2=xprs-y2s
dy3=xprs-y3s
Iz1pr=bdsoil*b*l1**3*d1/48.0
Iz2pr=bdsoil*b*l2**3*d1/12.0
Iz3pr=bdsoil*b*l3**3*d1/48.0
c TRANSLATION
Iz1=Iz1pr+m1s*(dx1**2+dy1**2)
Iz2=Iz2pr+m2s*(dx2**2+dy2**2)
Iz3=Iz3pr+m3s*(dx3**2+dy3**2)
Izs=Iz1+Iz2+Iz3
c ROTATION OF COORDINATES OF C.G.
xcg=xprs*cos(alphab)-yprs*sin(alphab)
ycg=xprs*sin(alphab)+yprs*cos(alphab)
zcg=zprs
c CENTER OF GRAVITY FROM POINT C
xcgs=xcg
ycgs=-rcf+ycg
zcgs=0.0
c CHARACTERISTICS
rcgs=sqrt(xcgs**2+ycgs**2)
deltas=atan(ycgs/xcgs)
thcgs=th5-deltas
asx=-r4*alpha4*sin(th4)-r4*w4**2*cos(th4)-rcgs*alpha5*sin(thcgs)
& -rcgs*w5**2*cos(thcgs)
asy=r4*alpha4*cos(th4)-r4*w4**2*sin(th4)+rcgs*alpha5*cos(thcgs)-
& rcgs*w5**2*sin(thcgs)
as=sqrt(asx**2+asy**2)
call angle(gammas,asy,asx)
betas=gammas+pi
anfos=betas/k1
fos=mas*as
ls=rcgs+Izs*alpha5/(fos*sin(betas-thcgs))
ws=mas*g
c ***************************************************
c 4.2 INERTIA FORCES AND TORQUE (BLADE)
c ***************************************************
c INERTIA FORCES MATRIX INERB(18,19)
do 340 i=1,n2,1
    do 340 j=1,m2,1
        inerb(i,j)=0.0
        340 continue
c inerb(1,1)=1.0
inerb(1,3)=1.0
inerb(1,19)=-fo2*cos(beta2)
inerb(2,2)=1.0
inerb(2,4)=1.0
inerb(2,19)=-fo2*sin(beta2)
inerb(3,3)=-r2*sin(th2)
inerb(3,4)=r2*cos(th2)
inerb(3,5)=-1.0
inerb(3,19)=-fo2*l2*sin(beta2-thcg2)
inerb(4,3)=-1.0
inerb(4,6)=1.0
inerb(4,19)=-fo3*cos(beta3)
inerb(5,4)=-1.0
inerb(5,7)=1.0
inerb(5,19)=-fo3*sin(beta3)
inerb(6,6)=-r3*sin(th3)
inerb(6,7)=r3*cos(th3)
inerb(6,19)=-fo3*l3*sin(beta3-thcg3)
inerb(7,6)=-1.0
inerb(7,8)=1.0
inerb(7,12)=1.0
inerb(7,19)=-fo5*cos(beta5)
inerb(8,7)=-1.0
inerb(8,9)=1.0
inerb(8,13)=1.0
inerb(8,19)=-fo5*sin(beta5)
inerb(9,6)=rbc*sin(thc)
inerb(9,7)=-rbc*cos(thc)
inerb(9,12)=-r5*sin(th5)
inerb(9,13)=r5*cos(th5)
inerb(9,19)=-fo5*l5*sin(beta5-thcg5)
inerb(10,8)=-1.0
inerb(10,10)=1.0
inerb(10,19)=-fo4*cos(beta4)
inerb(11,9)=-1.0
inerb(11,11)=1.0
inerb(11,19)=-fo4*sin(beta4)
inerb(12,8)=r4*sin(th4)
inerb(12,9)=-r4*cos(th4)
inerb(12,19)=-fo4*l4*sin(beta4-thcg4)
inerb(13,12)=-1.0
inerb(13,14)=1.0
inerb(13,19)=-fo6*cos(beta6)
inerb(14,13)=-1.0
inerb(14,15)=1.0
inerb(14,19)=-f06*sin(beta6)
inerb(15,12)=r6*sin(th6)
inerb(15,13)=-r6*cos(th6)
inerb(15,19)=f06*r6*sin(beta6-thcg6)
inerb(16,14)=-1.0
inerb(16,16)=1.0
inerb(16,19)=-f07*cos(beta7)
inerb(17,15)=-1.0
inerb(17,17)=1.0
inerb(17,19)=-f07*sin(beta7)
inerb(18,14)=r7*sin(th7)
inerb(18,15)=-r7*cos(th7)
inerb(18,18)=-1.0
inerb(18,19)=-f07*r7*sin(beta7-thcg7)

c
call torq(inerb,xinb)
t2ib=xinb(5)
t7ib=xinb(18)
tib=t2ib+t7ib

c REACTIONS TO INERTIA FORCES
f12b=sqrt(xinb(1)**2+xinb(2)**2)
call angle(thi12b,xinb(2),xinb(1))
theta12b=thi12b/k1
f32b=sqrt(xinb(3)**2+xinb(4)**2)
call angle(thi32b,xinb(4),xinb(3))
theta32b=thi32b/k1
f53b=sqrt(xinb(6)**2+xinb(7)**2)
call angle(thi53b,xinb(7),xinb(6))
theta53b=thi53b/k1
f45b=sqrt(xinb(8)**2+xinb(9)**2)
call angle(thi45b,xinb(9),xinb(8))
theta45b=thi45b/k1
f14b=sqrt(xinb(10)**2+xinb(11)**2)
call angle(thi65b,xinb(11),xinb(10))
theta65b=thi65b/k1
f65b=sqrt(xinb(12)**2+xinb(13)**2)
call angle(thi14b,xinb(13),xinb(12))
theta14b=thi14b/k1
f67b=sqrt(xinb(14)**2+xinb(15)**2)
x67b=-xinb(14)
y67b=-xinb(15)
call angle(thi67b,y67b,x67b)
theta67b=thi67b/k1
f17b=sqrt(xinb(16)**2+xinb(17)**2)
call angle(thi17b,xinb(17),xinb(16))
theti17b=thi17b/k1

SHAKING FORCE, TOTAL REACTION TO INERTIA FORCES
shakb=sqrt((xinb(1)+xinb(10)+xinb(16))**2+(xinb(2)+xinb(11)+
& xinb(17))**2)
foyb=fo2*sin(beta2)+fo3*sin(beta3)+fo4*sin(beta4)+fo5*sin(beta5)+
& fo6*sin(beta6)+fo7*sin(beta7)
foxb=fo2*cos(beta2)+fo3*cos(beta3)+fo4*cos(beta4)+fo5*cos(beta5)+
& fo6*cos(beta6)+fo7*cos(beta7)
Ifob=sqrt(foxb**2+foyb**2)
call angle(thfob,foyb,foxb)
thetafob=thfob/k1

4.3 STATIC FORCES AND TORQUE (BLADE)

STATIC FORCES MATRIX STATB(18,19)
do 350 i=1,n2,1
do 350 j=1,m2,1
   statb(i,j)=0.0

350 continue

statb(1,1)=1.0
statb(1,3)=1.0
statb(2,2)=1.0
statb(2,4)=1.0
statb(2,19)=wgt2
statb(3,3)=-r2*sin(th2)
statb(3,4)=r2*cos(th2)
statb(3,5)=-1.0
statb(3,19)=wgt2*rcg2*cos(thcg2)
statb(4,3)=-1.0
statb(4,6)=1.0
statb(5,4)=-1.0
statb(5,7)=1.0
statb(5,19)=wgt3
statb(6,6)=-r3*sin(th3)
statb(6,7)=r3*cos(th3)
statb(6,19)=wgt3*rcg3*cos(thcg3)
statb(7,6)=-1.0
statb(7,8)=1.0
statb(7,12)=1.0
statb(8,7)=-1.0
statb(8,9)=1.0
statb(8,13)=1.0
statb(8,19)=wgt5  
statb(9,6)=rbc*sin(thc)  
statb(9,7)=-rbc*cos(thc)  
statb(9,12)=-r5*sin(th5)  
statb(9,13)=r5*cos(th5)  
statb(9,19)=wgt5*rcg5*cos(thcg5)  
statb(10,8)=-1.0  
statb(10,10)=1.0  
statb(11,9)=-1.0  
statb(11,11)=1.0  
statb(11,19)=wgt4  
statb(12,8)=r4*sin(th4)  
statb(12,9)=-r4*cos(th4)  
statb(12,19)=wgt4*rcg4*cos(thcg4)  
statb(13,12)=-1.0  
statb(13,14)=1.0  
statb(14,13)=-1.0  
statb(14,15)=1.0  
statb(14,19)=wgt6  
statb(15,12)=r6*sin(th6)  
statb(15,13)=-r6*cos(th6)  
statb(15,19)=wgt6*rcg6*cos(thcg6)  
statb(16,14)=-1.0  
statb(16,16)=1.0  
statb(17,15)=-1.0  
statb(17,17)=1.0  
statb(17,19)=wgt7  
statb(18,14)=r7*sin(th7)  
statb(18,15)=-r7*cos(th7)  
statb(18,18)=-1.0  
statb(18,19)=wgt7*rcg7*cos(thcg7)

c

STATIC TORQUE

call torq(statb,xstb)
t2stb=xstb(5)
t7stb=xstb(18)
tstb=t2stb+t7stb

************

4.4 TOTAL FORCES, FRICTION AND TOTAL TORQUE (BLADE)

ROLLING RADIUS
r12=0.0235
r32=0.03175
r14=0.0195
r17=0.0235
r53=0.0185
r45=0.0185
r65=0.0185
r76=0.03175
c
t12b=0.0
t32b=0.0
t53b=0.0
t45b=0.0
t65b=0.0
t14b=0.0
t76b=0.0
t17b=0.0
c
t21b=t12b
t23b=t32b
t35b=t53b
t54b=t45b
t56b=t65b
t41b=t14b
t67b=t76b
t71b=t17b
c
TOTAL FORCES MATRIX TOTB(18,19)
do 380 i= l,n2,l
do 380 j= l,m 2,l
  totb(ij)=0.0
380 continue
  totb(1,1)=1.0
  totb(1,3)=1.0
  totb(1,19)=-fo2*cos(beta2)
  totb(2,2)=1.0
  totb(2,4)=1.0
  totb(2,19)=wgt2-fo2*sin(beta2)
  totb(3,3)=-r2*sin(th2)
  totb(3,4)=r2*cos(th2)
  totb(3,5)= 1.0
  totb(3,19)=wgt2*rcg2*cos(thcg2)-fo2*12*sin(beta2-thcg2)-t12b-t32b
  totb(4,3)= -1.0
  totb(4,6)=1.0
  totb(4,19)=-fo3*cos(beta3)
  totb(5,4)= -1.0
  totb(5,7)=1.0
  totb(5,19)=wgt3-fo3*sin(beta3)
  totb(6,6)= -r3*sin(th3)
\[
totb(6,7) = r_3 \cos(\theta_3) \\
totb(6,19) = w_5g_3 + r_3c_3 \cos(\theta c_3) - f_3l_3 \sin(\beta_3 - \theta c_3) + t_{32}b - t_{53}b \\
totb(7,6) = -1.0 \\
totb(7,8) = 1.0 \\
totb(7,12) = 1.0 \\
totb(7,19) = -f_5 \cos(\beta_5) \\
totb(8,7) = -1.0 \\
totb(8,9) = 1.0 \\
totb(8,13) = 1.0 \\
totb(8,19) = w_5f_5 \cos(\beta_5) \\
totb(9,6) = r_{bc} \sin(\theta_c) \\
totb(9,7) = -r_{bc} \cos(\theta_c) \\
totb(9,12) = -r_5 \sin(\theta_5) \\
totb(9,13) = r_5 \cos(\theta_5) \\
totb(9,19) = w_5g_5 \cos(\theta c_5) - f_5l_5 \sin(\beta_5 - \theta c_5) + t_{53}b - t_{45}b - t_{65}b \\
totb(10,8) = -1.0 \\
totb(10,10) = 1.0 \\
totb(10,19) = -f_4 \cos(\beta_4) \\
totb(11,9) = -1.0 \\
totb(11,11) = 1.0 \\
totb(11,19) = w_4f_4 \cos(\beta_4) \\
totb(12,8) = r_4 \sin(\theta_4) \\
totb(12,9) = -r_4 \cos(\theta_4) \\
totb(12,19) = w_4g_4 \cos(\theta c_4) - f_4l_4 \sin(\beta_4 - \theta c_4) + t_{45}b - t_{14}b \\
totb(13,12) = -1.0 \\
totb(13,14) = 1.0 \\
totb(13,19) = -f_6 \cos(\beta_6) \\
totb(14,13) = -1.0 \\
totb(14,15) = 1.0 \\
totb(14,19) = w_6f_6 \cos(\beta_6) \\
totb(15,12) = r_6 \sin(\theta_6) \\
totb(15,13) = -r_6 \cos(\theta_6) \\
totb(15,19) = w_6g_6 \cos(\theta c_6) - f_6l_6 \sin(\beta_6 - \theta c_6) + t_{65}b - t_{76}b \\
totb(16,14) = -1.0 \\
totb(16,16) = 1.0 \\
totb(16,19) = -f_7 \cos(\beta_7) \\
totb(17,15) = -1.0 \\
totb(17,17) = 1.0 \\
totb(17,19) = w_7 \cos(\beta_7) \\
totb(18,14) = r_7 \sin(\theta_7) \\
totb(18,15) = -r_7 \cos(\theta_7) \\
totb(18,18) = -1.0 \\
totb(18,19) = w_7g_7 \cos(\theta c_7) - f_7l_7 \sin(\beta_7 - \theta c_7) + t_{76}b - t_{17}b
call torq(totb,xttb)

c
TOTAL REACTIONS AT JOINTS AND SUPPORTS

\[ h_{12b} = \sqrt{(x_{ttb}(1))^2 + (x_{ttb}(2))^2} \]
\[ h_{32b} = \sqrt{(x_{ttb}(3))^2 + (x_{ttb}(4))^2} \]
\[ h_{53b} = \sqrt{(x_{ttb}(6))^2 + (x_{ttb}(7))^2} \]
\[ h_{45b} = \sqrt{(x_{ttb}(8))^2 + (x_{ttb}(9))^2} \]
\[ h_{14b} = \sqrt{(x_{ttb}(10))^2 + (x_{ttb}(11))^2} \]
\[ h_{65b} = \sqrt{(x_{ttb}(12))^2 + (x_{ttb}(13))^2} \]
\[ h_{76b} = \sqrt{(x_{ttb}(14))^2 + (x_{ttb}(15))^2} \]
\[ h_{17b} = \sqrt{(x_{ttb}(16))^2 + (x_{ttb}(17))^2} \]

call angle(th32b,xttb(4),xttb(3))
\[ \theta_{32b} = \frac{\text{th32b}}{\text{kl}} \]
call angle(th76b,xttb(15),xttb(16))
\[ \theta_{76b} = \frac{\text{th76b}}{\text{kl}} \]

c
\[ w_1 = 0.0 \]
c
if (mode .eq. 2) then (Note: use this if when \( w_2 = 0 \))
\[ d_{12} = 0.0 \]
c
else
\[ d_{12} = (w_1 - w_2) / \text{abs}(w_1 - w_2) \]
endif
\[ d_{32} = (w_3 - w_2) / \text{abs}(w_2 - w_3) \]
\[ d_{63} = (w_5 - w_3) / \text{abs}(w_3 - w_5) \]
\[ d_{45} = (w_4 - w_5) / \text{abs}(w_4 - w_5) \]
\[ d_{65} = (w_6 - w_5) / \text{abs}(w_6 - w_5) \]
\[ d_{76} = (w_7 - w_6) / \text{abs}(w_7 - w_6) \]
\[ d_{14} = (w_1 - w_4) / \text{abs}(w_1 - w_4) \]
\[ d_{17} = (w_1 - w_7) / \text{abs}(w_1 - w_7) \]

c
\[ t_{12b} = \mu * r_{12} * h_{12b} * d_{12} \]
\[ t_{14b} = \mu * r_{14} * h_{14b} * d_{14} \]
\[ t_{32b} = \mu * r_{32} * h_{32b} * d_{32} \]
\[ t_{53b} = \mu * r_{53} * h_{53b} * d_{53} \]
\[ t_{45b} = \mu * r_{45} * h_{45b} * d_{45} \]
\[ t_{65b} = \mu * r_{65} * h_{65b} * d_{65} \]
\[ t_{76b} = \mu * r_{76} * h_{76b} * d_{76} \]
\[ t_{17b} = \mu * r_{17} * h_{17b} * d_{17} \]

c
\[ dt_{12b} = t_{12b} - t_{21b} \]
\[ dt_{32b} = t_{32b} - t_{23b} \]
\[ dt_{53b} = t_{53b} - t_{35b} \]
\[ dt_{45b} = t_{45b} - t_{54b} \]
\[ dt_{65b} = t_{65b} - t_{56b} \]
\[ dt_{76b} = t_{76b} - t_{67b} \]
dt14b = t14b - t41b  
dt17b = t17b - t71b

c  
if(abs(dt12b) .gt. 0.1) go to 360  
if(abs(dt32b) .gt. 0.1) go to 360  
if(abs(dt53b) .gt. 0.1) go to 360  
if(abs(dt45b) .gt. 0.1) go to 360  
if(abs(dt65b) .gt. 0.1) go to 360  
if(abs(dt14b) .gt. 0.1) go to 360  
if(abs(dt76b) .gt. 0.1) go to 360  
if(abs(dt17b) .gt. 0.1) go to 360

c  
TOTAL AND FRICTION TORQUE
390  
t2b = xttb(5)  
t7b = xttb(18)  
t2sumb = t2sumb + t2b  
t7sumb = t7sumb + t7b  
t2fb = t2b - t2ib - t2stb  
t7fb = t7b - t7ib - t7stb  
tfb = t2fb + t7fb  
tb = tib + tstb + tfb  
tsumb = tsumb + tb

5. ANALYSIS FOR THE BLADE-SOIL SYSTEM

5.1 DRAFT FORCE

395  
x2 = xfr  
v2 = vfrx  
incre = v2 - v1  
incre = x2 - x1  
if(incre .ge. 0.0 .and. incre .lt. 0.0) then  
xmax = x2  
else  
endif  
difv = abs(vfx - vox)

if(vfrx .lt. 0.0 .and. a5y .ge. -9.81) then  
Nb = (ws - areab * cad * 1000.0 * sin(alphab)) / (cos(alphab) + mub *  
& sin(alphab))  
DF = Nb * (sin(alphab) - mub * cos(alphab)) - areab * cad * 1000.0 *  
& cos(alphab)  
go to 420  
else if (vfrx .lt. 0.0 .and. a5y .lt. -9.81) then  
Nb = 0.0
DF=0.0
  go to 420
else if(vfrx.gt.0.0.and.xfr.lt.xmax) then
  cs=c2
  phis=phis2
  go to 410
else
  cs=c1
  phis=phis1
  go to 410
endif

c
410  mus=tan(phis)
  betaf=pi/4.0-phis/2.0
  areaf=b*dw/sin(betaf)
  kc=(cos(betaf)-mus*sin(betaf))/(sin(betaf)+mus*cos(betaf))+
    (cos(alphab)-mub*sin(alphab))/(sin(alphab)+mub*cos(alphab))
  In=bdsol*b*dw*vfrx**2*sin(alphab)/sin(alphab+betaf)
  DF=ws/kc+(areaf*cs*1000.0+In)/(kc*(sin(betaf)+mus*cos(betaf)))+
    & cad*areab*1000.0/(kc*(sin(alphab)+mub*cos(alphab)))
  Nb=(DF-cad*areab*1000.0*cos(alphab))/(sin(alphab)+mub*+
    & cos(alphab))
  Fv=Nb*(cos(alphab)-mub*sin(alphab)-cad*areab*1000.0*+
    & sin(alphab)+wgt5

c
420  dfsum=dfsum+DF
  x1=x2
  v1=v2

c
5.2 INERTIA FORCES AND TORQUE (BLADE-SOIL SYSTEM)

INERTIA FORCES MATRIX INERSO(18,19)
do 500 i=1,n2,1
  do 500 j=1,m2,1
    inerso(i,j)=0.0
  continue

INERTIA FORCES MATRIX
inerso(1,1)=1.0
inerso(1,3)=1.0
inerso(1,19)=-fo2*cos(beta2)
inerso(2,2)=1.0
inerso(2,4)=1.0
inerso(2,19)=-fo2*sin(beta2)
inerso(3,3)=-r2*sin(th2)
inerso(3,4) = r2*cos(th2)
ingerso(3,5) = -1.0
inerso(3,19) = -fo2*12*sin(beta2-thcg2)
ingerso(4,3) = -1.0
inerso(4,6) = 1.0
inerso(4,19) = -fo3*cos(beta3)
ingerso(5,4) = -1.0
inerso(5,7) = 1.0
inerso(5,19) = -fo3*sin(beta3)
ingerso(6,6) = -r3*sin(th3)
ingerso(6,7) = r3*cos(th3)
ingerso(6,19) = -fo3*13*sin(beta3-thcg3)
ingerso(7,6) = -1.0
inerso(7,8) = 1.0
inerso(7,12) = 1.0
inerso(7,19) = -fo5*cos(beta5)-fos*cos(betas)
ingerso(8,7) = -1.0
inerso(8,9) = 1.0
inerso(8,13) = 1.0
inerso(8,19) = -fo5*sin(beta5)-fos*sin(betas)
ingerso(9,6) = rbc*sin(thc)
ingerso(9,7) = -rbc*cos(thc)
ingerso(9,12) = -r5*sin(th5)
ingerso(9,13) = r5*cos(th5)
if(vfrx .ge. 0.0) go to 510
fos = 0.0

510
inerso(9,19) = -fo5*15*sin(beta5-thcg5)-fos*ls*sin(betas-thcgs)
ingerso(10,8) = -1.0
inerso(10,10) = 1.0
inerso(10,19) = -fo4*cos(beta4)
ingerso(11,9) = -1.0
inerso(11,11) = 1.0
inerso(11,19) = -fo4*sin(beta4)
ingerso(12,8) = r4*sin(th4)
ingerso(12,9) = -r4*cos(th4)
ingerso(12,19) = -fo4*14*sin(beta4-thcg4)
ingerso(13,12) = -1.0
inerso(13,14) = 1.0
inerso(13,19) = -fo6*cos(beta6)
ingerso(14,13) = -1.0
inerso(14,15) = 1.0
inerso(14,19) = -fo6*sin(beta6)
ingerso(15,12) = r6*sin(th6)
ingerso(15,13) = r6*cos(th6)
ingerso(15,19) = -fo6*16*sin(beta6-thcg6)
\text{inerso}(16,14) = -1.0 \\
\text{inerso}(16,16) = 1.0 \\
\text{inerso}(16,19) = -f_7 \cos(\beta_7) \\
\text{inerso}(17,15) = -1.0 \\
\text{inerso}(17,17) = 1.0 \\
\text{inerso}(17,19) = -f_7 \sin(\beta_7) \\
\text{inerso}(18,14) = r_7 \sin(\theta_7) \\
\text{inerso}(18,15) = -r_7 \cos(\theta_7) \\
\text{inerso}(18,18) = -1.0 \\
\text{inerso}(18,19) = -f_7 \sin(\beta_7 - \theta_{cg7})
\begin{verbatim}
c call torq(inerso, xiso)

t2iso = xiso(5) \\
t7iso = xiso(18) \\
tiso = t2iso + t7iso
\end{verbatim}

\textbf{REACTIONS TO INERTIA FORCES}
\begin{verbatim}
f12so = sqrt(xiso(1)**2 + xiso(2)**2) \\
f32so = sqrt(xiso(3)**2 + xiso(4)**2) \\
f53so = sqrt(xiso(6)**2 + xiso(7)**2) \\
f45so = sqrt(xiso(8)**2 + xiso(9)**2) \\
f14so = sqrt(xiso(10)**2 + xiso(11)**2) \\
f65so = sqrt(xiso(12)**2 + xiso(13)**2) \\
f67so = sqrt(xiso(14)**2 + xiso(15)**2) \\
f17so = sqrt(xiso(16)**2 + xiso(17)**2)
\end{verbatim}
\begin{verbatim}
c \textbf{SHAKING FORCE, TOTAL REACTION TO INERTIA FORCES}
shakso = sqrt((xiso(1) + xiso(10) + xiso(16))**2 + (xiso(2) + xiso(11) + \\
& xiso(17))**2) \\
foyo = f02*sin(beta2) + f03*sin(beta3) + f04*sin(beta4) + f05*sin(beta5) + \\
& f06*sin(beta6) + f07*sin(beta7) + fos*sin(betas) \\
foxs = f02*cos(beta2) + f03*cos(beta3) + f04*cos(beta4) + f05*cos(beta5) + \\
& f06*cos(beta6) + f07*cos(beta7) + fos*cos(betas) \\
ifsos = sqrt(foxs**2 + foyo**2) \\
call angle(thfos, foyo, foxs) \\
thefos = thfos/k1
\end{verbatim}

\textbf{5.3 STATIC FORCES AND TORQUE (BLADE-SOIL SYSTEM)}

\textbf{STATIC FORCES MATRIX STATSO(18,19)}
\begin{verbatim}
do 520 i = 1, n2, 1 
  do 520 j = 1, m2, 1 
    statso(i, j) = 0.0 
  continue
\end{verbatim}
\text{c}
\begin{align*}
\text{statso}(1,1) &= 1.0 \\
\text{statso}(1,3) &= 1.0 \\
\text{statso}(2,2) &= 1.0 \\
\text{statso}(2,4) &= 1.0 \\
\text{statso}(2,19) &= \text{wgt2} \\
\text{statso}(3,3) &= -r_2\sin(th_2) \\
\text{statso}(3,4) &= r_2\cos(th_2) \\
\text{statso}(3,5) &= -1.0 \\
\text{statso}(3,19) &= \text{wgt2}\text{rcg2}\cos(th_2) \\
\text{statso}(4,3) &= -1.0 \\
\text{statso}(4,6) &= 1.0 \\
\text{statso}(5,4) &= -1.0 \\
\text{statso}(5,7) &= 1.0 \\
\text{statso}(5,19) &= \text{wgt3} \\
\text{statso}(6,6) &= -r_3\sin(th_3) \\
\text{statso}(6,7) &= r_3\cos(th_3) \\
\text{statso}(6,19) &= \text{wgt3}\text{rcg3}\cos(th_3) \\
\text{statso}(7,6) &= -1.0 \\
\text{statso}(7,8) &= 1.0 \\
\text{statso}(7,12) &= 1.0 \\
\text{statso}(8,7) &= -1.0 \\
\text{statso}(8,9) &= 1.0 \\
\text{statso}(8,13) &= 1.0 \\
\text{statso}(9,6) &= \text{rbc}\sin(th_3) \\
\text{statso}(9,7) &= -\text{rbc}\cos(th_3) \\
\text{statso}(9,10) &= -r_5\sin(th_5) \\
\text{statso}(9,11) &= r_5\cos(th_5) \\
\text{statso}(10,8) &= -1.0 \\
\text{statso}(10,10) &= 1.0 \\
\text{statso}(11,9) &= -1.0 \\
\text{statso}(11,11) &= 1.0 \\
\text{statso}(11,19) &= \text{wgt4} \\
\text{statso}(12,8) &= r_4\sin(th_4) \\
\text{statso}(12,9) &= -r_4\cos(th_4) \\
\text{statso}(12,19) &= \text{wgt4}\text{rcg4}\cos(th_4) \\
\text{statso}(13,12) &= -1.0 \\
\text{statso}(13,14) &= 1.0 \\
\text{statso}(14,13) &= -1.0 \\
\text{statso}(14,15) &= 1.0 \\
\text{statso}(14,19) &= \text{wgt6} \\
\text{statso}(15,12) &= r_6\sin(th_6) \\
\text{statso}(15,13) &= -r_6\cos(th_6) \\
\text{statso}(15,19) &= \text{wgt6}\text{rcg6}\cos(th_6) \\
\text{statso}(16,14) &= -1.0 \\
\end{align*}
statso(16,16)=1.0
statso(17,15)=-1.0
statso(17,17)=1.0
statso(17,19)=wgt7
statso(18,14)=rcg7*sin(thcg7)
statso(18,15)=-rcg7*cos(thcg7)
statso(18,18)=-1.0
statso(18,19)=wgt7*rcg7*cos(thcg7)

if(vfrx .lt. 0.0 .and. a5y .ge. -9.81) then
   Nb=(ws-areab*cad*1000.0*sin(alphab))/(cos(alphab)-mub*sin(alphab))
   & Fb=-areab*cad*1000.0-mub*Nb
goto 540
else if(vfrx .lt. 0.0 .and. a5y .lt. -9.81) then
   Nb=0.0
   Fb=0.0
goto 540
else if(vfrx .gt. 0.0 .and. xfr .lt. xmax) then
   cs=c2
   phis=phis2
else
   cs=c1
   phis=phis1
endif
   mus=tan(phis)
   betaf=pi/4.0-phis/2.0
   areaf=b*dw/sin(betaf)
In=bdsoil*b*dw*vfrx**2*sin(alphab)/sin(alphab+betaf)
k3=mus*sin(alphab+betaf)-cos(alphab+betaf)
Nb=ws/(kc*(sin(alphab)+mub*cos(alphab)))+areaf*(cs*1000.0+
   & areab*cad*1000.0*k3)/(kc*(sin(alphab)+mub*cos(alphab)))*
   & (sin(betaf)+mus*cos(betaf)))
   Fb=areab*cad*1000.0+mub*Nb
   
c
540 statso(7,19)=Nb*sin(alphab)+Fb*cos(alphab)
statso(8,19)=Nb*cos(alphab)-Fb*sin(alphab)+wgt5
statso(9,19)=Nb*rcgs*cos(thcgs+alphab)-Fb*r5*sin(th5+alphab)+
   & wgt5*rcg5*cos(thc5)
   
c
   call torq(statso,xstso)
t2stso=xstso(5)
t7stso=xstso(18)
tstso=t2stso+t7stso
DFV = -xstso(6) + xstso(8) + xstso(12)
DFVsum = DFVsum + DFV

5.4 TOTAL FORCES, FRICTION AND TOTAL TORQUE
(BLADE-SOIL SYSTEM)

**TOTAL FORCES MATRIX TOTSO(18,19)**

```fortran
600  t21so = t12so
     t23so = t32so
     t35so = t53so
     t54so = t45so
     t56so = t65so
     t41so = t14so
     t67so = t76so
     t71so = t17so

620  continue
     totso(1,1) = 1.0
     totso(1,3) = 1.0
     totso(1,19) = -fo2*cos(beta2)
     totso(2,2) = 1.0
     totso(2,4) = 1.0
     totso(2,19) = wgt2 - fo2*sin(beta2)
     totso(3,3) = -r2*sin(th2)
     totso(3,4) = r2*cos(th2)
     totso(3,5) = -1.0
     totso(3,19) = wgt2*rcg2*cos(thcg2) - fo2*12*sin(beta2 + thcg2) - t12so -
                   & t32so
     totso(4,3) = -1.0
     totso(4,6) = 1.0
     totso(4,19) = -fo3*cos(beta3)
     totso(5,4) = -1.0
     totso(5,7) = 1.0
```

\[
\begin{align*}
totso(5,19) &= wgt3 - f03 \cdot \sin(\beta3) \\
totso(6,6) &= -r3 \cdot \sin(\theta3) \\
totso(6,7) &= r3 \cdot \cos(\theta3) \\
totso(6,19) &= wgt3 \cdot rcg3 \cdot \cos(\theta cg3) - f03 \cdot 13 \cdot \sin(\beta3 - \theta cg3) + t32so - t53so \\
totso(7,6) &= -1.0 \\
totso(7,8) &= 1.0 \\
totso(7,12) &= 1.0 \\
totso(8,7) &= -1.0 \\
totso(8,9) &= 1.0 \\
totso(8,13) &= 1.0 \\
totso(9,6) &= rbc \cdot \sin(\theta c) \\
totso(9,7) &= -rbc \cdot \cos(\theta c) \\
totso(9,12) &= -r5 \cdot \sin(\theta 5) \\
totso(9,13) &= r5 \cdot \cos(\theta 5) \\
totso(10,8) &= -1.0 \\
totso(10,10) &= 1.0 \\
totso(10,19) &= -fo4 \cdot \cos(\beta 4) \\
totso(11,9) &= -1.0 \\
totso(11,11) &= 1.0 \\
totso(11,19) &= wgt4 - fo4 \cdot \sin(\beta 4) \\
totso(12,8) &= r4 \cdot \sin(\theta 4) \\
totso(12,9) &= -r4 \cdot \cos(\theta 4) \\
totso(12,19) &= wgt4 \cdot rcg4 \cdot \cos(\theta cg4) - fo4 \cdot l4 \cdot \sin(\beta 4 - \theta cg4) + t45so - t14so \\
totso(13,12) &= -1.0 \\
totso(13,14) &= 1.0 \\
totso(13,19) &= -fo6 \cdot \cos(\beta 6) \\
totso(14,13) &= -1.0 \\
totso(14,15) &= 1.0 \\
totso(14,19) &= wgt6 - fo6 \cdot \sin(\beta 6) \\
totso(15,12) &= r6 \cdot \sin(\theta 6) \\
totso(15,13) &= -r6 \cdot \cos(\theta 6) \\
totso(15,19) &= wgt6 \cdot rcg6 \cdot \cos(\theta cg6) - fo6 \cdot l6 \cdot \sin(\beta 6 - \theta cg6) + t65so - t76so \\
totso(16,14) &= -1.0 \\
totso(16,16) &= 1.0 \\
totso(16,19) &= -fo7 \cdot \cos(\beta 7) - fob7 \cdot \cos(\beta ab7) \\
totso(17,15) &= -1.0 \\
totso(17,17) &= 1.0 \\
totso(17,19) &= wgt7 - fo7 \cdot \sin(\beta 7) + wb7 - fob7 \cdot \sin(\beta ab7) \\
totso(18,14) &= r7 \cdot \sin(\theta 7) \\
totso(18,15) &= -r7 \cdot \cos(\theta 7) \\
totso(18,18) &= -1.0 \\
totso(18,19) &= wgt7 \cdot rcg7 \cdot \cos(\theta cg7) - fo7 \cdot l7 \cdot \sin(\beta 7 - \theta cg7) + t76so - 
\end{align*}
\]
if(vfrx .lt. 0.0 .and. a5y .ge. -9.81) then
   Nb=(ws-areab*cad*1000.0*sin(alphab))/(cos(alphab)+mub*
   & sin(alphab))
   Fb=-areab*cad*1000.0-mub*Nb
   go to 640
else if(vfrx .lt. 0.0 .and. a5y .lt. -9.81) then
   Nb=0.0
   Fb=0.0
   go to 640
else if(vfrx .gt. 0.0 .and. xfr .lt. xmax) then
   cs=c2
   phis=phis2
else
   cs=c1
   phis=phis1
endif
   mus=tan(phis)
   betaf=pi/4.0-phis/2.0
   areaf=b*dw/sin(betaf)
   aa=(mub*cos(alphab)+sin(alphab))*(mus*sin(betaf)-cos(betaf))+
   & (mub*sin(alphab)-cos(alphab))*(mus*cos(betaf)+sin(betaf))
   bb=ws*(mus*cos(betaf)+sin(betaf))
   In=bdsoil*b*dw*vfrx**2*sin(alphab)/sin(alphab+betaf)
   Nb=(-In-cs*areafi:1000.0-cad*areab*1000.0*(mus*sin(alphab+betaf)-
   & cos(alphab+betaf))-bb)/aa
   Fb=areab*cad*1000.0+mub*Nb
640 totso(7,19)=Nb*sin(alphab)-fos*cos(betas)-fo5*cos(beta5)+
   & Fb*cos(alphab)
   totso(8,19)=Nb*cos(alphab)-fos*sin(betas)-fo5*sin(beta5)-
   & Fb*sin(alphab)+wgt5
   totso(9,19)=Nb*rcgs*cos(thcgs+alphab)-Fb*r5*sin(th5+alphab)-
   & fos*ls*sin(betas-thcgs)+wgt5*rcg5*cos(thcg5)-
   & fo5*15*sin(beta5-thcg5)+t53so-t45so-t65so+
   & wgt5*rcg5*cos(thcg5)
call torq(totso,xtso)
cTOTAL REACTIONS AT JOINTS AND SUPPORTS
h12so=sqrt(xtso(1)**2 + xtso(2)**2)
h32so=sqrt(xtso(3)**2 + xtso(4)**2)
h53so=sqrt(xtso(6)**2 + xtso(7)**2)
h45so = sqrt(xtso(8)**2 + xtso(9)**2)
h14so = sqrt(xtso(10)**2 + xtso(11)**2)
h65so = sqrt(xtso(12)**2 + xtso(13)**2)
h76so = sqrt(xtso(14)**2 + xtso(15)**2)
h17so = sqrt(xtso(16)**2 + xtso(17)**2)

call angle(th32so, xtso(4), xtso(3))
  thet32so = th32so/k1
call angle(th76so, xtso(15), xtso(16))
  thet76so = th76so/k1

t12so = mu*r12*h12so*d12
t14so = mu*r14*h14so*d14
t32so = mu*r32*h32so*d32
t53so = mu*r53*h53so*d53
t45so = mu*r45*h45so*d45
t65so = mu*r65*h65so*d65
t76so = mu*r76*h76so*d76
t17so = mu*r17*h17so*d17

dt12so = t12so - t21so
dt32so = t32so - t23so
dt53so = t53so - t35so
dt45so = t45so - t54so
dt65so = t65so - t56so
dt76so = t76so - t67so
dt14so = t14so - t41so
dt17so = t17so - t71so

c  if(abs(dt12so) .gt. 0.1) go to 600
  if(abs(dt32so) .gt. 0.1) go to 600
  if(abs(dt53so) .gt. 0.1) go to 600
  if(abs(dt45so) .gt. 0.1) go to 600
  if(abs(dt65so) .gt. 0.1) go to 600
  if(abs(dt14so) .gt. 0.1) go to 600
  if(abs(dt76so) .gt. 0.1) go to 600
  if(abs(dt17so) .gt. 0.1) go to 600

c  TOTAL AND FRICTION TORQUE

 650  t2so = xtso(5)
    t7so = xtso(18)
    t2sumso = t2sumso + t2so
    t7sumso = t7sumso + t7so
    t2fso = t2so - t2iso - t2stso
    t7fso = t7so - t7iso - t7stso
tfso = t2fso + t7fso
Tso = t2so + t7so
Tsumso = Tsumso + tso

6. UNVIBRATED DRAFT

CS = cl
phisl = phis1
mus = tan(phisl)
betaf = pi/4.0 - phisl/2.0
areaf = b * dw / sin(betaf)
ws = mas1 * g

\[
kc = (\cos(betaf) - mus * \sin(betaf)) / (\sin(betaf) + mus \cos(betaf)) + \\
& (\cos(alphab) - mub \sin(alphab)) / (\sin(alphab) + mub \cos(alphab))
\]

In = bdsol * b * dw * vox ** 2 * sin(alphab) / sin(alphab + beta)
UDFl = ws / kc + (areaf * cs * 1000.0 + In) / (kc * (sin(betaf) + mus * \\
& cos(betaf)) + cad * areab * 1000.0 / (kc * (sin(alphab) + mub * cos(alphab)))

7. PRINTING RESULTS

write(60, 800) thetai, theta3, theta4, theta5, theta6
     format(x, f6.1, 4f10.4)
write(61, 810) thetai, w3, w4, w5, w6
     format(x, f6.1, 4f10.5)
write(62, 820) thetai, alpha3, alpha4, alpha5, alpha6
     format(x, f6.1, 4f10.4)
write(63, 830) thetai, xfl, xfo, xfr, vox, vfx, vfrx, vfry
     format(x, f6.1, 8f9.6)
write(64, 840) thetai, yfl, yfo, yfr, voy, vfy, vfry
     format(x, f6.1, 6f10.6)
write(65, 850) thetai, xg1, xgo, xgr, ygr, vox, vgx, vgrx, vgry
     format(x, f6.1, 8f9.6)
write(66, 860) thetai, ygo, yg1, ygr, voy, vgy, vgry
     format(x, f6.1, 6f10.6)
write(67, 870) thetai, t2ib, t7ib, t2stb, t7stb, t2fb, t7fb
     format(x, f6.1, 6f8.2)
write(68, 880) thetai, tib, tstb, tbf, t2b, t7b
     format(x, f6.1, 6f8.2)
write(69, 890) thetai, fo2, fo3, fo4, fo5, fo6, fo7
     format(x, f6.1, 6f10.3)
write(70, 900) thetai, shakb, Ifob, f12b, f14b, f17b
     format(x, f6.1, 5f10.2)
write(71, 910) thetai, DF, UDF1, dfv
     format(x, f6.1, 3f10.2)
write(72,920) thetai,t2iso,t7iso,t2stso,t7stso,t2fso,t7fso
920 format(x,f6.1,6f10.2)
write(73,930) thetai,tiso,tstso,tfso,tso,t2so,t7so
930 format(x,f6.1,6f8.2)
write(74,940) thetai,shakso,Ifoso,fos,h12so,h14so,h17so
940 format(x,f6.1,6f10.2)
write(76,960) thetai,afx,afy,af,agx,agy,ag
960 format(x,f6.1,6f10.2)

1000 continue

8. POWER AND RATIOS

UNVIBRATED DRAFT

\[ cs = c1 \]
\[ \text{phis} = \text{phis}1 \]
\[ \text{mus} = \tan(\text{phis}) \]
\[ \beta_{\text{af}} = \pi/4.0 - \text{phis}/2.0 \]
\[ \text{areaf} = b \times dw / \sin(\beta_{\text{af}}) \]
\[ \text{aa} = (\text{mub} \times \cos(\text{alphab}) + \sin(\text{alphab})) \times (\text{mus} \times \sin(\beta_{\text{af}}) - \cos(\beta_{\text{af}})) + (\text{mub} \times \sin(\text{alphab}) - \cos(\text{alphab})) \times (\text{mus} \times \cos(\beta_{\text{af}}) + \sin(\beta_{\text{af}})) \]
\[ \text{bb} = \text{ws} \times (\text{mus} \times \cos(\beta_{\text{af}}) + \sin(\beta_{\text{af}})) \]
\[ \text{In} = \text{bdsoil} \times b \times dw \times vox**2 \times \sin(\text{alphab}) / \sin(\text{alphab} + \beta_{\text{af}}) \]
\[ \text{Nb} = (-\text{In} \times \text{areaf} \times 1000.0 - \text{cad} \times \text{areab} \times 1000.0 \times (\text{mus} \times \sin(\text{alphab} + \beta_{\text{af}}) - \cos(\text{alphab} + \beta_{\text{af}}))) / \text{aa} \]
\[ \text{Fb} = \text{areab} \times \text{cad} \times 1000.0 + \text{mub} \times \text{Nb} \]
\[ \text{Fb} = \text{areab} \times \text{cad} \times 1000.0 \]
\[ \text{UDF} = \text{Nb} \times (\sin(\text{alphab}) + \text{mub} \times \cos(\text{alphab})) + \text{cad} \times \text{areab} \times 1000.0 \times \cos(\text{alphab}) \]

ANGULAR VELOCITY (Hz)
\[ \omega_2 = \omega_2/(2.0*\pi) \]
\[ \omega_7 = \omega_7/(2.0*\pi) \]

MEAN TORQUE AT THE INPUTS
\[ t_{2mb} = t_{2sumb}/37.0 \]
\[ t_{7mb} = t_{7sumb}/37.0 \]
\[ t_{2mso} = t_{2sumso}/37.0 \]
\[ t_{7mso} = t_{7sumso}/37.0 \]
\[ t_{mb} = t_{2mb} + t_{7mb} \]
\[ t_{mso} = t_{2mso} + t_{7mso} \]

MEAN DRAFT
\[ dfvm = dfvsum/37.0 \]
\[ dfm = dfsum/37.0 \]
DRAFT RATIO
DR=dfm/UDF

UNVIBRATED POWER
Nuv=UDF*vox/1000.0

VIBRATION POWER
Nv=abs(tmso)*abs(wi)/1000.0

DRAFT POWER
Ndf=dfm*vox/1000.0

TOTAL POWER
Nt=Nv+Ndf

POWER RATIO
PR=Nt/Nuv

print*, 'input speed : w2 =',ww2, 'Hz'
print*, 'mean torque (blade) : t2b =',t2mb, 'N.m'
print*, 'mean torque (soil) : t2s =',t2mso, 'N.m'
print*, 'Unvibrated draft : ',UDF, 'N'
print*, 'unvibrated power : ',Nuv, 'kw'
print*, 'Mean draft force : ',dfm, 'N'
print*, 'draft power : ',Ndf, 'kw'
print*, 'vibration power : ',Nv, 'kw'
print*, 'total power : ',Nt, 'kw'
print*, 'draft ratio : ',DR
print*, 'power ratio : ',PR
print*, dfvm,udf1

write(75,1100) VIBRATION
1100 format(4x,'MEAN TORQUE, POWER, DRAFT AND RATIOS - MOVEMENT: ',A12)
write(75,22) ecc2,ecc7,vr,vt,phase
write(75,1105)
1105 format("")
write(75,1110) ww2
1110 format(4x,'Input speed w2 : ',fB.2, ' Hz')
write(75,1120) w7
1120 format(4x,':f8.2,' Hz')
write(75,1130) t2mb
1130 format(4x,'Mean torque (blade) T2b : ',f8.2,' N.m')
write(75,1140) t7mb
1140 format(4x,' T7b : ',f8.2,' N.m')
write(75,1150) tmb
1150 format(4x,' Tb : ',f8.2,' N.m')
write(75,1160) t2mso
1160 format(4x,'Mean torque (blade-soil) T2so : ',f8.2,' N.m')
write(75,1170) t7mso
1170 format(4x,' T7so : ',f8.2,' N.m')
write(75,1180) tmso
1180 format(4x,' Tso : ',f8.2,' N.m')
write(75,1190) UDF
1190 format(4x,'Unvibrated draft : ',f8.2,' N')
write(75,1200) Nuv
1200 format(4x,'Unvibrated power : ',f8.2,' kW')
write(75,1210) dfm
1210 format(4x,'Mean draft force : ',f8.2,' N')
write(75,1220) Ndf
1220 format(4x,'Draft power : ',f8.2,' kW')
write(75,1230) Nv
1230 format(4x,'Vibration power : ',f8.2,' kW')
write(75,1240) Nt
1240 format(4x,'Total power : ',f8.2,' kW')
write(75,1250) DR
1250 format(4x,'Draft ratio : ',f8.2)
write(75,1260) PR
1260 format(4x,'Power ratio : ',f8.2)
end

**SUBROUTINES**

SUBROUTINE kinem(a,x)
This subroutine uses the Gauss-Jordan elimination method to solve a system of n equations
integer q,p,l,k,i,j,r,n,m
dimension a(4,5),b(5),temp(5),x(4),c(5)
real z,sum

n=4
m=n+1
q=1
p=1
l=2
k=1
j=1
c
10 if (a(q,p) .ne. 0.0) go to 50
   r=q+1
20 if (a(r,p) .ne. 0.0) go to 30
   r=r+1
   if(r .le. n) go to 20
   go to 50
30 do 40 p=q,n+1
   b(p)=a(q,p)
   a(q,p)=a(r,p)
   a(r,p)=b(p)
   continue
40
50 i=1
   p=q
55 if (a(i,j) .ne. 0.0) go to 60
   if (i .eq. n) go to 100
   i=i+1
   go to 55
60 z=a(i,j)/a(k,j)
c
do 90 j=1,n+1
   temp(j)=z*a(k,j)
   c(j)=a(i,j)-temp(j)
   if (j .gt. k) go to 80
   a(i,j)=0.0
   go to 90
80 a(i,j)= c(j)
90 continue
   if (i .ge. n) go to 100
   i=i+1
   j=q
   go to 55

c
100 if (q .ge. n-1) go to 110
   q=q+1
   p=p+1
   k=k+1
   l=l+1
   j=q
   go to 10
x(n)=a(n,m)/a(n,n)
do 160 i=n-1,1,-1
   sum=0.0
   do 150 j=i+1,n
      sum=sum+a(i,j)*x(j)
   continue
   x(i)=(a(i,m)-sum)/a(i,i)
160 continue
return
derend

SUBROUTINE angle(ang,ay,ax)
real ang,ax,ay,pi
pi=3.141592
if(ax .lt. 0.0) then
   ang=pi+atan(ay/ax)
else if(ay .le. 0.0 .and. ax .gt. 0.0) then
   ang=2.0*pi+atan(ay/ax)
else if(ax .eq. 0.0 .and. ay .gt. 0.0) then
   ang=pi/2.0
else if(ax .eq. 0.0 .and. ay .lt. 0.0) then
   ang=-pi/2.0
else
   ang=atan(ay/ax)
endif
return
derend

SUBROUTINE torq(a,x)
integer q,p,l,k,i,j,r,n,m
dimension a(18,19),b(19),temp(19),x(18),c(19)
real z,ssum
n=18
m=n+1
q=1
p=1
l=2
k=1
j=1
if (a(q,p) .ne. 0.0) go to 50
r=q+1
20 if (a(r,p) .ne. 0.0) go to 30
r=r+1
if (r .le. n) go to 20
go to 50
30 do 40 p=q,n+1
    b(p)=a(q,p)
    a(q,p)=a(r,p)
    a(r,p)=b(p)
40 continue
50 i=l
p=q
55 if (a(i,j) .ne. 0.0) go to 60
    if (i .eq. n) go to 100
    i=i+l
    go to 55
60 z=a(i,j)/a(k,j)
do 90 j=1,n+1
    temp(j)=z*a(k,j)
    c(j)=a(i,j)-temp(j)
    if (j .gt. k) go to 80
    a(i,j)=0.0
    go to 90
80 a(i,j)=c(j)
90 continue
if (i .ge. n) go to 100
i=i+l
j=q
go to 55
100 if (q .ge. n-1) go to 110
q=q+1
p=p+1
k=k+1
l=l+1
j=q
go to 10
110 x(n)=a(n,m)/a(n,n)
do 160 i=n-1,1,-1
    ssum=0.0
do 150 j=i+1,n
  ssum=ssum+a(i,j)*x(j)
150  continue
  x(i)=(a(i,m)-ssum)/a(i,i)
160  continue
return
end
APPENDIX B

SETTINGS FOR THE MACHINE AND TRACTOR
<table>
<thead>
<tr>
<th>Test No</th>
<th>( r_2 ) mm</th>
<th>( r_7 ) mm</th>
<th>( v_{r_1} ) km/h</th>
<th>( w_1 ) Hz</th>
<th>( n_{\text{III}} ) rpm</th>
<th>( \phi ) deg</th>
<th>shift</th>
<th>( n_a ) rpm</th>
<th>( n_{\text{PTO}} ) rpm</th>
<th>( i_t )</th>
<th>( i_u )</th>
<th>( z_1/z_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>9.52</td>
<td>0.0</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>-</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td>1.061</td>
<td>1.067</td>
<td>16/15</td>
</tr>
<tr>
<td>02</td>
<td>3.0</td>
<td>13.9</td>
<td>-</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td>1.061</td>
<td>1.067</td>
<td>16/15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03</td>
<td>1.5</td>
<td>2.0</td>
<td>837</td>
<td>-</td>
<td>1260</td>
<td>526</td>
<td>1.591</td>
<td>1.60</td>
<td>24/15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>04</td>
<td>3.0</td>
<td>20.9</td>
<td>1253</td>
<td>-</td>
<td>1890</td>
<td>788</td>
<td>1.591</td>
<td>1.60</td>
<td>24/15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>12.7</td>
<td>0.0</td>
<td>2.0</td>
<td>7.0</td>
<td>420</td>
<td>-</td>
<td>2</td>
<td>1890</td>
<td>426*</td>
<td>0.986</td>
<td>1.00</td>
<td>15/15</td>
</tr>
<tr>
<td>06</td>
<td>3.0</td>
<td>10.4</td>
<td>626</td>
<td>-</td>
<td>1890</td>
<td>426*</td>
<td>1.469</td>
<td>1.467</td>
<td>22/15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>07</td>
<td>1.5</td>
<td>2.0</td>
<td>630</td>
<td>-</td>
<td>1260</td>
<td>526</td>
<td>1.198</td>
<td>1.20</td>
<td>18/15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>3.0</td>
<td>15.7</td>
<td>940</td>
<td>-</td>
<td>1890</td>
<td>788</td>
<td>1.193</td>
<td>1.20</td>
<td>18/15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09</td>
<td>9.52</td>
<td>12.7</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>0</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td>1.061</td>
<td>1.067</td>
<td>16/15</td>
</tr>
<tr>
<td>10</td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>0</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>90</td>
<td>1260</td>
<td>526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>90</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>180</td>
<td>1260</td>
<td>526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>180</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>270</td>
<td>1260</td>
<td>526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>( r_2 ) mm</th>
<th>( r_7 ) mm</th>
<th>( v_{r_i} ) km/h</th>
<th>( w_b ) Hz</th>
<th>( n_{III} ) rpm</th>
<th>( \phi ) deg</th>
<th>shift</th>
<th>( n_a ) rpm</th>
<th>( n_{PRO} ) rpm</th>
<th>( i_t )</th>
<th>( i_u )</th>
<th>( z_1/z_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>270</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.0</td>
<td>12.7</td>
<td>3.0</td>
<td>10.4</td>
<td>626</td>
<td>-</td>
<td>3</td>
<td>1890</td>
<td>426*</td>
<td>1.47</td>
<td>1.467</td>
<td>22/15</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td>2.0</td>
<td>7.0</td>
<td>420</td>
<td>-</td>
<td>3</td>
<td>1890</td>
<td>426*</td>
<td>0.986</td>
<td>1.00</td>
<td>15/15</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td>1.5</td>
<td>2.0</td>
<td>10.5</td>
<td>630</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td>1.20</td>
<td>1.20</td>
<td>18/15</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>3.0</td>
<td>15.7</td>
<td>940</td>
<td>-</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td>1.193</td>
<td>1.20</td>
<td>18/15</td>
</tr>
<tr>
<td>21</td>
<td>12.7</td>
<td>12.7</td>
<td>1.0</td>
<td>2.0</td>
<td>7.0</td>
<td>420</td>
<td>0</td>
<td>1890</td>
<td>426*</td>
<td>0.986</td>
<td>1.00</td>
<td>15/15</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td>2.0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>270</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td>3.0</td>
<td>10.4</td>
<td>626</td>
<td>270</td>
<td>3</td>
<td>1890</td>
<td>426*</td>
<td>1.47</td>
<td>1.467</td>
<td>22/15</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td></td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td></td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>9.52</td>
<td>9.52</td>
<td>1.0</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>270</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td>1.061</td>
<td>16/15</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>270</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>180</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>$r_2$ (mm)</th>
<th>$r_7$ (mm)</th>
<th>$v_{ri}$</th>
<th>$v_{oo}$ (km/h)</th>
<th>$w_b$ (Hz)</th>
<th>$n_{III}$ (rpm)</th>
<th>$ph$ (deg)</th>
<th>shift</th>
<th>$n_e$ (rpm)</th>
<th>$n_{pro}$ (rpm)</th>
<th>$i_t$</th>
<th>$i_u$</th>
<th>$z_1/z_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>180</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>90</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>90</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>0</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>0</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>12.7</td>
<td>9.52</td>
<td>1.0</td>
<td>2.0</td>
<td>7.0</td>
<td>420</td>
<td>0</td>
<td>2</td>
<td>1890</td>
<td>426*</td>
<td>0.986</td>
<td>1.0</td>
<td>15/15</td>
</tr>
<tr>
<td>38</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>2</td>
<td>1890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>2.0</td>
<td></td>
<td>180</td>
<td>2</td>
<td>1890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>270</td>
<td>2</td>
<td>1890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>3.0</td>
<td>10.4</td>
<td>626</td>
<td>270</td>
<td>3</td>
<td>1890</td>
<td>426*</td>
<td>1.47</td>
<td>1.467</td>
<td>22/15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td>3</td>
<td>1890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>3</td>
<td>1890</td>
<td>55</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>3</td>
<td>1890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>0.0</td>
<td>9.52</td>
<td>1.5</td>
<td>2.0</td>
<td>14.0</td>
<td>837</td>
<td>-</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td>1.591</td>
<td>1.60</td>
<td>24/15</td>
</tr>
<tr>
<td>46</td>
<td>3.0</td>
<td>20.9</td>
<td>1253</td>
<td>-</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>1.0</td>
<td>2.0</td>
<td>9.3</td>
<td>558</td>
<td>-</td>
<td>3</td>
<td>1260</td>
<td>526</td>
<td>1.061</td>
<td>1.067</td>
<td>16/15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>$r_2$ mm</th>
<th>$r_7$ mm</th>
<th>$v_{RL}$ km/h</th>
<th>$w_r$ Hz</th>
<th>$n_{III}$ rpm</th>
<th>ph deg</th>
<th>shift</th>
<th>$n_e$ rpm</th>
<th>$n_{III}$ rpm</th>
<th>$i_t$</th>
<th>$i_u$</th>
<th>$z_1/z_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td></td>
<td></td>
<td>3.0</td>
<td>13.9</td>
<td>836</td>
<td>-</td>
<td>3</td>
<td>1890</td>
<td>788</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>No Vibration</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
<td>3</td>
<td>1260</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>No Vibration</td>
<td>3.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
<td>3</td>
<td>1260</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>Skidding Resistance</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
<td>3</td>
<td>1260</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Skidding Resistance</td>
<td>3.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
<td>3</td>
<td>1890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C

DATA
TABLE C1. MEASUREMENTS OF TORQUE IN THE LABORATORY AND RESULTS FROM THE SIMULATION

<table>
<thead>
<tr>
<th>Test No</th>
<th>$T_{ib}$ (Nm)</th>
<th>$T_{ia}$ (Nm)</th>
<th>$i_{33}$</th>
<th>$T_{bl}$ (Nm)</th>
<th>$T_{ba}$ (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>33.99</td>
<td>12.34</td>
<td>15/16</td>
<td>20.29</td>
<td>7.82</td>
</tr>
<tr>
<td>02</td>
<td>47.08</td>
<td>13.63</td>
<td>15/16</td>
<td>31.34</td>
<td>16.66</td>
</tr>
<tr>
<td>03</td>
<td>59.83</td>
<td>15.90</td>
<td>15/24</td>
<td>27.45</td>
<td>16.66</td>
</tr>
<tr>
<td>04</td>
<td>74.96</td>
<td>20.75</td>
<td>15/24</td>
<td>33.88</td>
<td>37.10</td>
</tr>
<tr>
<td>05</td>
<td>24.48</td>
<td>10.24</td>
<td>15/15</td>
<td>14.24</td>
<td>6.20</td>
</tr>
<tr>
<td>06</td>
<td>44.35</td>
<td>16.21</td>
<td>15/22</td>
<td>19.18</td>
<td>12.70</td>
</tr>
<tr>
<td>07</td>
<td>31.13</td>
<td>12.78</td>
<td>15/18</td>
<td>15.29</td>
<td>12.70</td>
</tr>
<tr>
<td>08</td>
<td>40.50</td>
<td>15.70</td>
<td>15/18</td>
<td>20.67</td>
<td>28.10</td>
</tr>
<tr>
<td>09</td>
<td>34.62</td>
<td>12.34</td>
<td>15/16</td>
<td>20.88</td>
<td>10.40</td>
</tr>
<tr>
<td>10</td>
<td>47.82</td>
<td>13.63</td>
<td>15/16</td>
<td>32.05</td>
<td>23.30</td>
</tr>
<tr>
<td>11</td>
<td>24.54</td>
<td>12.34</td>
<td>15/16</td>
<td>11.44</td>
<td>6.80</td>
</tr>
<tr>
<td>12</td>
<td>34.78</td>
<td>13.63</td>
<td>15/16</td>
<td>19.83</td>
<td>14.90</td>
</tr>
<tr>
<td>13</td>
<td>26.06</td>
<td>12.34</td>
<td>15/16</td>
<td>12.86</td>
<td>9.60</td>
</tr>
<tr>
<td>14</td>
<td>40.34</td>
<td>13.63</td>
<td>15/16</td>
<td>25.04</td>
<td>21.20</td>
</tr>
<tr>
<td>15</td>
<td>38.93</td>
<td>12.34</td>
<td>15/16</td>
<td>24.93</td>
<td>12.70</td>
</tr>
<tr>
<td>16</td>
<td>54.62</td>
<td>13.63</td>
<td>15/16</td>
<td>34.43</td>
<td>28.40</td>
</tr>
<tr>
<td>17</td>
<td>39.05</td>
<td>10.24</td>
<td>15/15</td>
<td>28.81</td>
<td>3.53</td>
</tr>
<tr>
<td>18</td>
<td>22.60</td>
<td>16.21</td>
<td>15/22</td>
<td>4.36</td>
<td>7.54</td>
</tr>
<tr>
<td>19</td>
<td>29.04</td>
<td>12.78</td>
<td>15/18</td>
<td>13.55</td>
<td>5.83</td>
</tr>
<tr>
<td>20</td>
<td>46.15</td>
<td>15.70</td>
<td>15/18</td>
<td>25.37</td>
<td>16.85</td>
</tr>
<tr>
<td>21</td>
<td>26.25</td>
<td>10.24</td>
<td>15/15</td>
<td>16.01</td>
<td>7.20</td>
</tr>
<tr>
<td>22</td>
<td>26.22</td>
<td>10.24</td>
<td>15/15</td>
<td>15.98</td>
<td>5.30</td>
</tr>
<tr>
<td>23</td>
<td>25.82</td>
<td>10.24</td>
<td>15/15</td>
<td>15.58</td>
<td>6.90</td>
</tr>
<tr>
<td>24</td>
<td>26.10</td>
<td>10.24</td>
<td>15/15</td>
<td>15.86</td>
<td>8.60</td>
</tr>
<tr>
<td>25</td>
<td>50.98</td>
<td>16.21</td>
<td>15/22</td>
<td>23.71</td>
<td>19.10</td>
</tr>
<tr>
<td>26</td>
<td>38.42</td>
<td>16.21</td>
<td>15/22</td>
<td>15.14</td>
<td>14.80</td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>$T_{th}$ (Nm)</th>
<th>$T_{tb}$ (Nm)</th>
<th>$i_{23}$</th>
<th>$T_{bl}$ (Nm)</th>
<th>$T_{bs}$ (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>47.15</td>
<td>16.21</td>
<td>15/22</td>
<td>21.10</td>
<td>10.70</td>
</tr>
<tr>
<td>28</td>
<td>52.32</td>
<td>16.21</td>
<td>15/22</td>
<td>24.62</td>
<td>15.90</td>
</tr>
<tr>
<td>29</td>
<td>28.12</td>
<td>12.34</td>
<td>15/16</td>
<td>14.79</td>
<td>11.40</td>
</tr>
<tr>
<td>30</td>
<td>49.24</td>
<td>13.63</td>
<td>15/16</td>
<td>33.33</td>
<td>25.30</td>
</tr>
<tr>
<td>31</td>
<td>34.40</td>
<td>12.34</td>
<td>15/16</td>
<td>20.65</td>
<td>8.90</td>
</tr>
<tr>
<td>32</td>
<td>12.53</td>
<td>13.63</td>
<td>15/16</td>
<td>--</td>
<td>19.40</td>
</tr>
<tr>
<td>33</td>
<td>25.30</td>
<td>12.34</td>
<td>15/16</td>
<td>12.15</td>
<td>6.60</td>
</tr>
<tr>
<td>34</td>
<td>33.32</td>
<td>13.63</td>
<td>15/16</td>
<td>18.46</td>
<td>14.00</td>
</tr>
<tr>
<td>35</td>
<td>25.35</td>
<td>12.34</td>
<td>15/16</td>
<td>12.20</td>
<td>9.50</td>
</tr>
<tr>
<td>36</td>
<td>38.52</td>
<td>13.63</td>
<td>15/16</td>
<td>23.33</td>
<td>21.20</td>
</tr>
<tr>
<td>37</td>
<td>28.71</td>
<td>10.24</td>
<td>15/15</td>
<td>18.47</td>
<td>6.80</td>
</tr>
<tr>
<td>38</td>
<td>34.16</td>
<td>10.24</td>
<td>15/15</td>
<td>23.92</td>
<td>5.50</td>
</tr>
<tr>
<td>39</td>
<td>23.65</td>
<td>10.24</td>
<td>15/15</td>
<td>13.41</td>
<td>6.50</td>
</tr>
<tr>
<td>40</td>
<td>28.35</td>
<td>10.24</td>
<td>15/15</td>
<td>18.11</td>
<td>7.90</td>
</tr>
<tr>
<td>41</td>
<td>41.03</td>
<td>16.21</td>
<td>15/22</td>
<td>16.92</td>
<td>17.50</td>
</tr>
<tr>
<td>42</td>
<td>39.45</td>
<td>16.21</td>
<td>15/22</td>
<td>15.84</td>
<td>13.90</td>
</tr>
<tr>
<td>43</td>
<td>36.70</td>
<td>16.21</td>
<td>15/22</td>
<td>13.97</td>
<td>10.50</td>
</tr>
<tr>
<td>44</td>
<td>42.76</td>
<td>16.21</td>
<td>15/22</td>
<td>18.10</td>
<td>14.80</td>
</tr>
<tr>
<td>45</td>
<td>49.99</td>
<td>15.90</td>
<td>15/24</td>
<td>21.30</td>
<td>5.68</td>
</tr>
<tr>
<td>46</td>
<td>56.64</td>
<td>20.75</td>
<td>15/24</td>
<td>22.43</td>
<td>12.65</td>
</tr>
<tr>
<td>47</td>
<td>30.35</td>
<td>12.34</td>
<td>15/16</td>
<td>16.88</td>
<td>2.76</td>
</tr>
<tr>
<td>48</td>
<td>34.36</td>
<td>13.63</td>
<td>15/16</td>
<td>19.43</td>
<td>5.68</td>
</tr>
</tbody>
</table>
**TABLE C2. RAW DATA FOR TORQUE (NM) AND DRAFT (N)**

<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th>Replication 2</th>
<th>Replication 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_s$</td>
<td>DF</td>
<td>$T_s$</td>
</tr>
<tr>
<td>01</td>
<td>45.23</td>
<td>4275.9</td>
<td>40.36</td>
</tr>
<tr>
<td>02</td>
<td>49.02</td>
<td>2185.8</td>
<td>53.69</td>
</tr>
<tr>
<td>03</td>
<td>68.43</td>
<td>3228.4</td>
<td>55.24</td>
</tr>
<tr>
<td>04</td>
<td>93.68</td>
<td>6605.6</td>
<td>84.48</td>
</tr>
<tr>
<td>05</td>
<td>60.86</td>
<td>2481.7</td>
<td>39.78</td>
</tr>
<tr>
<td>06</td>
<td>64.96</td>
<td>3690.2</td>
<td>63.86</td>
</tr>
<tr>
<td>07</td>
<td>44.98</td>
<td>4584.5</td>
<td>47.28</td>
</tr>
<tr>
<td>08</td>
<td>65.43</td>
<td>---</td>
<td>61.83</td>
</tr>
<tr>
<td>09</td>
<td>54.53</td>
<td>6106.7</td>
<td>43.04</td>
</tr>
<tr>
<td>10</td>
<td>53.86</td>
<td>5896.6</td>
<td>40.80</td>
</tr>
<tr>
<td>11</td>
<td>36.90</td>
<td>4159.1</td>
<td>41.81</td>
</tr>
<tr>
<td>12</td>
<td>51.10</td>
<td>8143.5</td>
<td>49.65</td>
</tr>
<tr>
<td>13</td>
<td>40.85</td>
<td>3868.1</td>
<td>40.53</td>
</tr>
<tr>
<td>14</td>
<td>58.95</td>
<td>4060.9</td>
<td>50.38</td>
</tr>
<tr>
<td>15</td>
<td>43.57</td>
<td>2878.1</td>
<td>44.72</td>
</tr>
<tr>
<td>16</td>
<td>52.98</td>
<td>3358.7</td>
<td>52.98</td>
</tr>
<tr>
<td>17</td>
<td>51.87</td>
<td>3654.0</td>
<td>53.81</td>
</tr>
<tr>
<td>18</td>
<td>34.96</td>
<td>3654.5</td>
<td>53.81</td>
</tr>
<tr>
<td>19</td>
<td>44.05</td>
<td>2302.3</td>
<td>34.91</td>
</tr>
<tr>
<td>20</td>
<td>45.61</td>
<td>4146.6</td>
<td>39.96</td>
</tr>
<tr>
<td>21</td>
<td>72.38</td>
<td>2020.6</td>
<td>81.87</td>
</tr>
<tr>
<td>22</td>
<td>53.04</td>
<td>1548.0</td>
<td>60.47</td>
</tr>
<tr>
<td>23</td>
<td>44.12</td>
<td>4089.7</td>
<td>46.12</td>
</tr>
<tr>
<td>24</td>
<td>48.30</td>
<td>3189.2</td>
<td>37.92</td>
</tr>
<tr>
<td>25</td>
<td>61.98</td>
<td>5000.4</td>
<td>80.33</td>
</tr>
<tr>
<td>26</td>
<td>19.96</td>
<td>---</td>
<td>66.44</td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th>Replication 2</th>
<th>Replication 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_s$</td>
<td>DF</td>
<td>$T_s$</td>
</tr>
<tr>
<td>27</td>
<td>76.34</td>
<td>4953.7</td>
<td>76.50</td>
</tr>
<tr>
<td>28</td>
<td>70.44</td>
<td>5783.3</td>
<td>87.46</td>
</tr>
<tr>
<td>29</td>
<td>38.82</td>
<td>5643.8</td>
<td>43.34</td>
</tr>
<tr>
<td>30</td>
<td>33.62</td>
<td>8283.9</td>
<td>42.20</td>
</tr>
<tr>
<td>31</td>
<td>49.31</td>
<td>4515.3</td>
<td>36.82</td>
</tr>
<tr>
<td>32</td>
<td>69.27</td>
<td>7505.7</td>
<td>41.03</td>
</tr>
<tr>
<td>33</td>
<td>34.24</td>
<td>4379.0</td>
<td>42.37</td>
</tr>
<tr>
<td>34</td>
<td>51.16</td>
<td>7430.2</td>
<td>89.10</td>
</tr>
<tr>
<td>35</td>
<td>36.64</td>
<td>1599.5</td>
<td>40.78</td>
</tr>
<tr>
<td>36</td>
<td>73.12</td>
<td>7669.2</td>
<td>68.00</td>
</tr>
<tr>
<td>37</td>
<td>88.22</td>
<td>3943.9</td>
<td>47.74</td>
</tr>
<tr>
<td>38</td>
<td>60.56</td>
<td>4141.8</td>
<td>66.89</td>
</tr>
<tr>
<td>39</td>
<td>45.30</td>
<td>3165.5</td>
<td>50.14</td>
</tr>
<tr>
<td>40</td>
<td>83.13</td>
<td>2943.7</td>
<td>40.01</td>
</tr>
<tr>
<td>41</td>
<td>68.51</td>
<td>3502.3</td>
<td>78.14</td>
</tr>
<tr>
<td>42</td>
<td>67.22</td>
<td>4940.7</td>
<td>68.04</td>
</tr>
<tr>
<td>43</td>
<td>68.60</td>
<td>7058.1</td>
<td>69.32</td>
</tr>
<tr>
<td>44</td>
<td>70.50</td>
<td>6135.4</td>
<td>57.13</td>
</tr>
<tr>
<td>45</td>
<td>47.24</td>
<td>3414.5</td>
<td>46.35</td>
</tr>
<tr>
<td>46</td>
<td>55.41</td>
<td>3747.8</td>
<td>56.82</td>
</tr>
<tr>
<td>47</td>
<td>31.79</td>
<td>4317.3</td>
<td>31.59</td>
</tr>
<tr>
<td>48</td>
<td>40.10</td>
<td>3017.6</td>
<td>36.41</td>
</tr>
<tr>
<td>49</td>
<td>5838.0</td>
<td>5636.7</td>
<td>5636.7</td>
</tr>
<tr>
<td>50</td>
<td>5014.3</td>
<td>4000.9</td>
<td>4000.9</td>
</tr>
<tr>
<td>51</td>
<td>5392.1</td>
<td>5198.1</td>
<td>5198.1</td>
</tr>
<tr>
<td>52</td>
<td>5257.4</td>
<td>4446.8</td>
<td>4446.8</td>
</tr>
</tbody>
</table>
TABLE C3. RAW DATA FOR DRAFT RATIO AND POWER RATIO

<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th>Replication 2</th>
<th>Replication 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dftrat</td>
<td>Powrat</td>
<td>Dftrat</td>
</tr>
<tr>
<td>01</td>
<td>0.842</td>
<td>1.679</td>
<td>0.799</td>
</tr>
<tr>
<td>02</td>
<td>0.430</td>
<td>1.443</td>
<td>0.774</td>
</tr>
<tr>
<td>03</td>
<td>0.635</td>
<td>2.771</td>
<td>0.843</td>
</tr>
<tr>
<td>04</td>
<td>1.300</td>
<td>4.210</td>
<td>0.854</td>
</tr>
<tr>
<td>05</td>
<td>0.488</td>
<td>1.438</td>
<td>0.623</td>
</tr>
<tr>
<td>06</td>
<td>0.726</td>
<td>1.731</td>
<td>0.762</td>
</tr>
<tr>
<td>07</td>
<td>0.902</td>
<td>1.955</td>
<td>0.624</td>
</tr>
<tr>
<td>08</td>
<td>---</td>
<td>---</td>
<td>1.200</td>
</tr>
<tr>
<td>09</td>
<td>1.202</td>
<td>2.333</td>
<td>0.858</td>
</tr>
<tr>
<td>10</td>
<td>1.160</td>
<td>1.555</td>
<td>0.901</td>
</tr>
<tr>
<td>11</td>
<td>0.819</td>
<td>1.584</td>
<td>0.846</td>
</tr>
<tr>
<td>12</td>
<td>0.669</td>
<td>1.056</td>
<td>0.545</td>
</tr>
<tr>
<td>13</td>
<td>0.761</td>
<td>1.608</td>
<td>1.070</td>
</tr>
<tr>
<td>14</td>
<td>0.799</td>
<td>1.062</td>
<td>0.577</td>
</tr>
<tr>
<td>15</td>
<td>0.566</td>
<td>1.470</td>
<td>1.047</td>
</tr>
<tr>
<td>16</td>
<td>0.661</td>
<td>0.980</td>
<td>0.804</td>
</tr>
<tr>
<td>17</td>
<td>0.719</td>
<td>1.521</td>
<td>0.918</td>
</tr>
<tr>
<td>18</td>
<td>0.719</td>
<td>1.265</td>
<td>0.700</td>
</tr>
<tr>
<td>19</td>
<td>0.453</td>
<td>1.484</td>
<td>0.676</td>
</tr>
<tr>
<td>20</td>
<td>0.816</td>
<td>1.881</td>
<td>0.848</td>
</tr>
<tr>
<td>21</td>
<td>0.398</td>
<td>1.527</td>
<td>0.698</td>
</tr>
<tr>
<td>22</td>
<td>0.305</td>
<td>1.321</td>
<td>0.845</td>
</tr>
<tr>
<td>23</td>
<td>0.805</td>
<td>1.494</td>
<td>1.090</td>
</tr>
<tr>
<td>24</td>
<td>0.628</td>
<td>1.382</td>
<td>0.523</td>
</tr>
<tr>
<td>25</td>
<td>0.984</td>
<td>1.943</td>
<td>1.081</td>
</tr>
<tr>
<td>26</td>
<td>---</td>
<td>---</td>
<td>0.680</td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th>Replication 2</th>
<th>Replication 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dfrat  Powrat</td>
<td>Dfrat  Powrat</td>
<td>Dfrat  Powrat</td>
</tr>
<tr>
<td>27</td>
<td>0.975  2.155</td>
<td>1.037  1.707</td>
<td>0.754  1.736</td>
</tr>
<tr>
<td>28</td>
<td>1.138  2.228</td>
<td>1.094  2.446</td>
<td>0.910  1.953</td>
</tr>
<tr>
<td>29</td>
<td>1.111  1.916</td>
<td>0.629  1.527</td>
<td>0.305  1.034</td>
</tr>
<tr>
<td>30</td>
<td>1.630  2.326</td>
<td>1.292  2.164</td>
<td>1.613  2.819</td>
</tr>
<tr>
<td>31</td>
<td>0.889  1.911</td>
<td>1.049  1.813</td>
<td>0.377  1.115</td>
</tr>
<tr>
<td>32</td>
<td>1.477  2.909</td>
<td>1.379  2.228</td>
<td>1.439  1.864</td>
</tr>
<tr>
<td>33</td>
<td>0.862  1.572</td>
<td>0.973  1.852</td>
<td>1.295  2.432</td>
</tr>
<tr>
<td>34</td>
<td>1.462  2.520</td>
<td>---  ---</td>
<td>1.556  2.428</td>
</tr>
<tr>
<td>35</td>
<td>0.315  1.074</td>
<td>---  ---</td>
<td>---  ---</td>
</tr>
<tr>
<td>36</td>
<td>1.509  3.021</td>
<td>1.188  2.593</td>
<td>0.434  1.326</td>
</tr>
<tr>
<td>37</td>
<td>0.776  2.153</td>
<td>0.810  1.555</td>
<td>0.914  1.863</td>
</tr>
<tr>
<td>38</td>
<td>0.815  1.760</td>
<td>0.875  1.919</td>
<td>1.157  2.162</td>
</tr>
<tr>
<td>39</td>
<td>0.623  1.330</td>
<td>0.601  1.384</td>
<td>0.531  1.236</td>
</tr>
<tr>
<td>40</td>
<td>0.579  1.877</td>
<td>0.559  1.184</td>
<td>0.716  2.059</td>
</tr>
<tr>
<td>41</td>
<td>0.689  1.748</td>
<td>1.040  2.248</td>
<td>1.118  2.378</td>
</tr>
<tr>
<td>42</td>
<td>0.972  2.018</td>
<td>0.718  1.769</td>
<td>1.136  2.228</td>
</tr>
<tr>
<td>43</td>
<td>1.389  2.416</td>
<td>1.344  2.416</td>
<td>0.923  1.897</td>
</tr>
<tr>
<td>44</td>
<td>1.207  2.298</td>
<td>1.193  2.077</td>
<td>1.442  2.620</td>
</tr>
<tr>
<td>45</td>
<td>0.672  2.146</td>
<td>0.225  1.671</td>
<td>0.738  2.180</td>
</tr>
<tr>
<td>46</td>
<td>0.738  2.458</td>
<td>0.529  2.293</td>
<td>0.846  2.601</td>
</tr>
<tr>
<td>47</td>
<td>0.850  1.509</td>
<td>0.954  1.610</td>
<td>0.289  0.861</td>
</tr>
<tr>
<td>48</td>
<td>0.594  1.423</td>
<td>0.468  1.221</td>
<td>0.754  1.595</td>
</tr>
</tbody>
</table>
TABLE C4. RAW DATA FOR BULK DENSITY (KG/M³)

<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th>Replication 2</th>
<th>Replication 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho_0$</td>
<td>$\rho_1$</td>
<td>$\rho_2$</td>
</tr>
<tr>
<td>01</td>
<td>1022</td>
<td>845</td>
<td>1003</td>
</tr>
<tr>
<td>02</td>
<td>1151</td>
<td>789</td>
<td>845</td>
</tr>
<tr>
<td>03</td>
<td>1063</td>
<td>947</td>
<td>868</td>
</tr>
<tr>
<td>04</td>
<td>1038</td>
<td>796</td>
<td>918</td>
</tr>
<tr>
<td>05</td>
<td>1114</td>
<td>893</td>
<td>891</td>
</tr>
<tr>
<td>06</td>
<td>1185</td>
<td>770</td>
<td>821</td>
</tr>
<tr>
<td>07</td>
<td>1249</td>
<td>853</td>
<td>872</td>
</tr>
<tr>
<td>08</td>
<td>861</td>
<td>834</td>
<td>859</td>
</tr>
<tr>
<td>09</td>
<td>950</td>
<td>849</td>
<td>833</td>
</tr>
<tr>
<td>10</td>
<td>1089</td>
<td>705</td>
<td>815</td>
</tr>
<tr>
<td>11</td>
<td>1059</td>
<td>825</td>
<td>893</td>
</tr>
<tr>
<td>12</td>
<td>1012</td>
<td>897</td>
<td>848</td>
</tr>
<tr>
<td>13</td>
<td>1109</td>
<td>923</td>
<td>877</td>
</tr>
<tr>
<td>14</td>
<td>1143</td>
<td>850</td>
<td>938</td>
</tr>
<tr>
<td>15</td>
<td>1106</td>
<td>842</td>
<td>915</td>
</tr>
<tr>
<td>16</td>
<td>1155</td>
<td>927</td>
<td>910</td>
</tr>
<tr>
<td>17</td>
<td>1019</td>
<td>881</td>
<td>869</td>
</tr>
<tr>
<td>18</td>
<td>1111</td>
<td>879</td>
<td>861</td>
</tr>
<tr>
<td>19</td>
<td>1087</td>
<td>845</td>
<td>915</td>
</tr>
<tr>
<td>20</td>
<td>1123</td>
<td>828</td>
<td>829</td>
</tr>
<tr>
<td>21</td>
<td>1016</td>
<td>907</td>
<td>898</td>
</tr>
<tr>
<td>22</td>
<td>1004</td>
<td>921</td>
<td>908</td>
</tr>
<tr>
<td>23</td>
<td>1037</td>
<td>824</td>
<td>882</td>
</tr>
<tr>
<td>24</td>
<td>1212</td>
<td>874</td>
<td>950</td>
</tr>
<tr>
<td>25</td>
<td>1115</td>
<td>878</td>
<td>905</td>
</tr>
<tr>
<td>26</td>
<td>1055</td>
<td>897</td>
<td>943</td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th></th>
<th>Replication 2</th>
<th></th>
<th>Replication 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_0$</td>
<td>$p_1$</td>
<td>$p_2$</td>
<td>$p_0$</td>
<td>$p_1$</td>
<td>$p_2$</td>
</tr>
<tr>
<td>27</td>
<td>1090</td>
<td>835</td>
<td>877</td>
<td>1241</td>
<td>1008</td>
<td>868</td>
</tr>
<tr>
<td>28</td>
<td>1145</td>
<td>896</td>
<td>894</td>
<td>1149</td>
<td>967</td>
<td>948</td>
</tr>
<tr>
<td>29</td>
<td>1183</td>
<td>955</td>
<td>998</td>
<td>1159</td>
<td>842</td>
<td>760</td>
</tr>
<tr>
<td>30</td>
<td>997</td>
<td>824</td>
<td>963</td>
<td>998</td>
<td>918</td>
<td>964</td>
</tr>
<tr>
<td>31</td>
<td>1139</td>
<td>844</td>
<td>906</td>
<td>1217</td>
<td>920</td>
<td>931</td>
</tr>
<tr>
<td>32</td>
<td>1026</td>
<td>984</td>
<td>1004</td>
<td>1190</td>
<td>1146</td>
<td>1088</td>
</tr>
<tr>
<td>33</td>
<td>944</td>
<td>866</td>
<td>820</td>
<td>1132</td>
<td>949</td>
<td>807</td>
</tr>
<tr>
<td>34</td>
<td>1003</td>
<td>756</td>
<td>761</td>
<td>1148</td>
<td>846</td>
<td>926</td>
</tr>
<tr>
<td>35</td>
<td>1012</td>
<td>851</td>
<td>980</td>
<td>1072</td>
<td>931</td>
<td>941</td>
</tr>
<tr>
<td>36</td>
<td>992</td>
<td>885</td>
<td>823</td>
<td>1130</td>
<td>875</td>
<td>845</td>
</tr>
<tr>
<td>37</td>
<td>1039</td>
<td>951</td>
<td>790</td>
<td>994</td>
<td>753</td>
<td>893</td>
</tr>
<tr>
<td>38</td>
<td>1192</td>
<td>902</td>
<td>914</td>
<td>1030</td>
<td>918</td>
<td>834</td>
</tr>
<tr>
<td>39</td>
<td>1175</td>
<td>902</td>
<td>1054</td>
<td>1145</td>
<td>897</td>
<td>761</td>
</tr>
<tr>
<td>40</td>
<td>1055</td>
<td>972</td>
<td>960</td>
<td>1049</td>
<td>879</td>
<td>971</td>
</tr>
<tr>
<td>41</td>
<td>1074</td>
<td>854</td>
<td>966</td>
<td>1207</td>
<td>912</td>
<td>1047</td>
</tr>
<tr>
<td>42</td>
<td>1153</td>
<td>825</td>
<td>859</td>
<td>1054</td>
<td>935</td>
<td>850</td>
</tr>
<tr>
<td>43</td>
<td>1087</td>
<td>853</td>
<td>1067</td>
<td>1026</td>
<td>968</td>
<td>870</td>
</tr>
<tr>
<td>44</td>
<td>933</td>
<td>791</td>
<td>905</td>
<td>965</td>
<td>738</td>
<td>830</td>
</tr>
<tr>
<td>45</td>
<td>1127</td>
<td>943</td>
<td>899</td>
<td>1117</td>
<td>866</td>
<td>972</td>
</tr>
<tr>
<td>46</td>
<td>1074</td>
<td>799</td>
<td>836</td>
<td>1066</td>
<td>910</td>
<td>911</td>
</tr>
<tr>
<td>47</td>
<td>1027</td>
<td>912</td>
<td>799</td>
<td>1156</td>
<td>970</td>
<td>846</td>
</tr>
<tr>
<td>48</td>
<td>1177</td>
<td>918</td>
<td>935</td>
<td>1126</td>
<td>974</td>
<td>875</td>
</tr>
<tr>
<td>49</td>
<td>1213</td>
<td>905</td>
<td>950</td>
<td>1171</td>
<td>1022</td>
<td>897</td>
</tr>
<tr>
<td>50</td>
<td>1273</td>
<td>857</td>
<td>887</td>
<td>1119</td>
<td>965</td>
<td>1034</td>
</tr>
</tbody>
</table>
TABLE C5. RAW DATA FOR GEOMETRIC MEAN DIAMETER (MM)

<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th>Replication 2</th>
<th>Replication 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>01</td>
<td>9.4</td>
<td>8.8</td>
<td>10.9</td>
</tr>
<tr>
<td>02</td>
<td>11.4</td>
<td>8.0</td>
<td>7.4</td>
</tr>
<tr>
<td>03</td>
<td>15.4</td>
<td>11.3</td>
<td>11.2</td>
</tr>
<tr>
<td>04</td>
<td>8.3</td>
<td>9.6</td>
<td>9.2</td>
</tr>
<tr>
<td>05</td>
<td>11.8</td>
<td>11.0</td>
<td>12.5</td>
</tr>
<tr>
<td>06</td>
<td>13.2</td>
<td>11.4</td>
<td>11.5</td>
</tr>
<tr>
<td>07</td>
<td>9.5</td>
<td>8.5</td>
<td>9.5</td>
</tr>
<tr>
<td>08</td>
<td>6.7</td>
<td>7.5</td>
<td>6.8</td>
</tr>
<tr>
<td>09</td>
<td>8.0</td>
<td>7.3</td>
<td>8.1</td>
</tr>
<tr>
<td>10</td>
<td>10.0</td>
<td>8.3</td>
<td>23.5</td>
</tr>
<tr>
<td>11</td>
<td>8.3</td>
<td>7.6</td>
<td>9.0</td>
</tr>
<tr>
<td>12</td>
<td>7.4</td>
<td>10.4</td>
<td>7.5</td>
</tr>
<tr>
<td>13</td>
<td>10.3</td>
<td>8.6</td>
<td>13.8</td>
</tr>
<tr>
<td>14</td>
<td>6.6</td>
<td>11.3</td>
<td>10.2</td>
</tr>
<tr>
<td>15</td>
<td>7.6</td>
<td>8.4</td>
<td>5.7</td>
</tr>
<tr>
<td>16</td>
<td>7.7</td>
<td>10.0</td>
<td>10.9</td>
</tr>
<tr>
<td>17</td>
<td>8.1</td>
<td>10.8</td>
<td>16.8</td>
</tr>
<tr>
<td>18</td>
<td>10.0</td>
<td>9.8</td>
<td>8.3</td>
</tr>
<tr>
<td>19</td>
<td>12.7</td>
<td>16.0</td>
<td>10.5</td>
</tr>
<tr>
<td>20</td>
<td>10.8</td>
<td>10.0</td>
<td>41.0</td>
</tr>
<tr>
<td>21</td>
<td>12.0</td>
<td>9.8</td>
<td>10.6</td>
</tr>
<tr>
<td>22</td>
<td>8.3</td>
<td>9.0</td>
<td>8.9</td>
</tr>
<tr>
<td>23</td>
<td>9.0</td>
<td>7.1</td>
<td>8.7</td>
</tr>
<tr>
<td>24</td>
<td>9.7</td>
<td>7.8</td>
<td>7.8</td>
</tr>
<tr>
<td>25</td>
<td>8.1</td>
<td>9.7</td>
<td>7.3</td>
</tr>
<tr>
<td>26</td>
<td>7.9</td>
<td>9.2</td>
<td>7.2</td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th></th>
<th>Replication 2</th>
<th></th>
<th>Replication 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>28</td>
<td>11.4</td>
<td>16.5</td>
<td>13.0</td>
<td>15.3</td>
<td>7.7</td>
<td>8.1</td>
</tr>
<tr>
<td>29</td>
<td>10.6</td>
<td>8.0</td>
<td>11.7</td>
<td>8.5</td>
<td>18.8</td>
<td>18.8</td>
</tr>
<tr>
<td>30</td>
<td>13.0</td>
<td>11.9</td>
<td>12.0</td>
<td>14.7</td>
<td>16.1</td>
<td>18.8</td>
</tr>
<tr>
<td>31</td>
<td>9.5</td>
<td>27.5</td>
<td>13.5</td>
<td>18.4</td>
<td>10.8</td>
<td>18.8</td>
</tr>
<tr>
<td>32</td>
<td>15.0</td>
<td>12.0</td>
<td>8.4</td>
<td>11.5</td>
<td>14.2</td>
<td>16.7</td>
</tr>
<tr>
<td>33</td>
<td>7.4</td>
<td>7.4</td>
<td>8.8</td>
<td>7.6</td>
<td>20.2</td>
<td>20.2</td>
</tr>
<tr>
<td>34</td>
<td>10.7</td>
<td>8.1</td>
<td>7.8</td>
<td>8.8</td>
<td>23.5</td>
<td>20.5</td>
</tr>
<tr>
<td>35</td>
<td>10.4</td>
<td>8.4</td>
<td>10.6</td>
<td>9.0</td>
<td>13.5</td>
<td>19.6</td>
</tr>
<tr>
<td>36</td>
<td>10.6</td>
<td>8.2</td>
<td>8.4</td>
<td>10.0</td>
<td>9.8</td>
<td>12.7</td>
</tr>
<tr>
<td>37</td>
<td>12.2</td>
<td>9.6</td>
<td>8.8</td>
<td>11.2</td>
<td>23.0</td>
<td>22.0</td>
</tr>
<tr>
<td>38</td>
<td>13.3</td>
<td>13.3</td>
<td>6.3</td>
<td>8.6</td>
<td>16.5</td>
<td>22.8</td>
</tr>
<tr>
<td>39</td>
<td>23.0</td>
<td>16.8</td>
<td>9.8</td>
<td>9.5</td>
<td>21.0</td>
<td>18.5</td>
</tr>
<tr>
<td>40</td>
<td>9.4</td>
<td>8.2</td>
<td>11.2</td>
<td>12.3</td>
<td>17.3</td>
<td>19.0</td>
</tr>
<tr>
<td>41</td>
<td>8.4</td>
<td>7.7</td>
<td>10.5</td>
<td>11.5</td>
<td>20.8</td>
<td>29.2</td>
</tr>
<tr>
<td>42</td>
<td>10.1</td>
<td>10.8</td>
<td>10.1</td>
<td>8.3</td>
<td>14.8</td>
<td>16.0</td>
</tr>
<tr>
<td>43</td>
<td>10.6</td>
<td>9.2</td>
<td>8.7</td>
<td>11.7</td>
<td>17.2</td>
<td>16.0</td>
</tr>
<tr>
<td>44</td>
<td>10.8</td>
<td>10.1</td>
<td>15.3</td>
<td>8.0</td>
<td>30.5</td>
<td>19.0</td>
</tr>
<tr>
<td>45</td>
<td>8.1</td>
<td>9.7</td>
<td>12.7</td>
<td>12.1</td>
<td>22.8</td>
<td>21.3</td>
</tr>
<tr>
<td>46</td>
<td>11.2</td>
<td>11.6</td>
<td>9.4</td>
<td>10.5</td>
<td>19.2</td>
<td>21.5</td>
</tr>
<tr>
<td>47</td>
<td>8.2</td>
<td>8.2</td>
<td>11.5</td>
<td>13.9</td>
<td>19.5</td>
<td>21.5</td>
</tr>
<tr>
<td>48</td>
<td>8.5</td>
<td>8.5</td>
<td>18.3</td>
<td>9.0</td>
<td>14.8</td>
<td>16.0</td>
</tr>
<tr>
<td>49</td>
<td>7.7</td>
<td>6.2</td>
<td>10.4</td>
<td>10.6</td>
<td>17.0</td>
<td>33.0</td>
</tr>
<tr>
<td>50</td>
<td>12.0</td>
<td>7.7</td>
<td>7.5</td>
<td>7.5</td>
<td>12.7</td>
<td>12.7</td>
</tr>
<tr>
<td>Test No</td>
<td>Replication 1</td>
<td>Replication 2</td>
<td>Replication 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>01</td>
<td>4.70</td>
<td>4.88</td>
<td>4.45</td>
<td>5.95</td>
<td>4.12</td>
<td>4.74</td>
</tr>
<tr>
<td>02</td>
<td>4.39</td>
<td>3.80</td>
<td>4.24</td>
<td>3.89</td>
<td>4.55</td>
<td>4.72</td>
</tr>
<tr>
<td>03</td>
<td>6.54</td>
<td>5.26</td>
<td>5.75</td>
<td>4.46</td>
<td>4.44</td>
<td>5.29</td>
</tr>
<tr>
<td>04</td>
<td>4.05</td>
<td>3.92</td>
<td>4.27</td>
<td>5.10</td>
<td>4.90</td>
<td>4.74</td>
</tr>
<tr>
<td>05</td>
<td>4.95</td>
<td>5.13</td>
<td>5.95</td>
<td>5.00</td>
<td>4.90</td>
<td>5.15</td>
</tr>
<tr>
<td>06</td>
<td>4.98</td>
<td>4.85</td>
<td>4.03</td>
<td>3.44</td>
<td>5.56</td>
<td>4.24</td>
</tr>
<tr>
<td>07</td>
<td>3.58</td>
<td>4.46</td>
<td>4.74</td>
<td>4.78</td>
<td>5.35</td>
<td>5.03</td>
</tr>
<tr>
<td>08</td>
<td>5.08</td>
<td>4.41</td>
<td>4.00</td>
<td>4.81</td>
<td>4.03</td>
<td>3.69</td>
</tr>
<tr>
<td>09</td>
<td>4.20</td>
<td>3.75</td>
<td>4.05</td>
<td>3.70</td>
<td>4.81</td>
<td>3.92</td>
</tr>
<tr>
<td>10</td>
<td>4.26</td>
<td>4.05</td>
<td>5.71</td>
<td>5.81</td>
<td>4.74</td>
<td>4.41</td>
</tr>
<tr>
<td>11</td>
<td>3.86</td>
<td>3.80</td>
<td>4.10</td>
<td>4.88</td>
<td>4.17</td>
<td>3.97</td>
</tr>
<tr>
<td>12</td>
<td>3.79</td>
<td>4.52</td>
<td>4.41</td>
<td>3.75</td>
<td>5.68</td>
<td>4.46</td>
</tr>
<tr>
<td>13</td>
<td>4.84</td>
<td>3.37</td>
<td>4.12</td>
<td>5.00</td>
<td>3.60</td>
<td>4.12</td>
</tr>
<tr>
<td>14</td>
<td>3.57</td>
<td>3.97</td>
<td>4.03</td>
<td>3.50</td>
<td>4.03</td>
<td>3.86</td>
</tr>
<tr>
<td>15</td>
<td>3.48</td>
<td>3.82</td>
<td>4.03</td>
<td>5.71</td>
<td>3.83</td>
<td>4.17</td>
</tr>
<tr>
<td>16</td>
<td>3.50</td>
<td>4.08</td>
<td>4.03</td>
<td>4.20</td>
<td>3.97</td>
<td>3.72</td>
</tr>
<tr>
<td>17</td>
<td>4.57</td>
<td>4.18</td>
<td>3.73</td>
<td>3.82</td>
<td>4.48</td>
<td>5.56</td>
</tr>
<tr>
<td>18</td>
<td>7.41</td>
<td>6.67</td>
<td>4.48</td>
<td>4.72</td>
<td>7.09</td>
<td>5.00</td>
</tr>
<tr>
<td>19</td>
<td>4.95</td>
<td>4.78</td>
<td>4.31</td>
<td>4.31</td>
<td>6.80</td>
<td>8.47</td>
</tr>
<tr>
<td>20</td>
<td>3.97</td>
<td>4.26</td>
<td>7.87</td>
<td>7.20</td>
<td>4.61</td>
<td>4.39</td>
</tr>
<tr>
<td>21</td>
<td>4.72</td>
<td>4.27</td>
<td>5.13</td>
<td>4.72</td>
<td>6.29</td>
<td>4.59</td>
</tr>
<tr>
<td>22</td>
<td>4.44</td>
<td>4.22</td>
<td>4.33</td>
<td>4.44</td>
<td>4.52</td>
<td>4.78</td>
</tr>
<tr>
<td>23</td>
<td>3.85</td>
<td>4.26</td>
<td>3.88</td>
<td>4.00</td>
<td>4.81</td>
<td>5.08</td>
</tr>
<tr>
<td>24</td>
<td>4.74</td>
<td>3.83</td>
<td>4.29</td>
<td>4.00</td>
<td>4.41</td>
<td>4.48</td>
</tr>
<tr>
<td>25</td>
<td>3.40</td>
<td>4.22</td>
<td>3.80</td>
<td>3.77</td>
<td>4.57</td>
<td>5.29</td>
</tr>
<tr>
<td>26</td>
<td>4.08</td>
<td>4.26</td>
<td>3.33</td>
<td>3.62</td>
<td>4.20</td>
<td>3.62</td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>Replication 1</th>
<th>Replication 2</th>
<th>Replication 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>4.39</td>
<td>4.07</td>
<td>4.65</td>
</tr>
<tr>
<td>28</td>
<td>4.46</td>
<td>5.75</td>
<td>4.24</td>
</tr>
<tr>
<td>29</td>
<td>4.75</td>
<td>3.75</td>
<td>6.33</td>
</tr>
<tr>
<td>30</td>
<td>4.31</td>
<td>4.44</td>
<td>4.44</td>
</tr>
<tr>
<td>31</td>
<td>5.38</td>
<td>7.41</td>
<td>5.32</td>
</tr>
<tr>
<td>32</td>
<td>4.93</td>
<td>5.00</td>
<td>4.56</td>
</tr>
<tr>
<td>33</td>
<td>4.18</td>
<td>4.85</td>
<td>3.98</td>
</tr>
<tr>
<td>34</td>
<td>4.20</td>
<td>4.44</td>
<td>4.48</td>
</tr>
<tr>
<td>35</td>
<td>4.24</td>
<td>6.13</td>
<td>5.18</td>
</tr>
<tr>
<td>36</td>
<td>6.99</td>
<td>4.41</td>
<td>4.29</td>
</tr>
<tr>
<td>37</td>
<td>4.67</td>
<td>5.29</td>
<td>4.44</td>
</tr>
<tr>
<td>38</td>
<td>4.88</td>
<td>4.88</td>
<td>3.80</td>
</tr>
<tr>
<td>39</td>
<td>6.06</td>
<td>5.46</td>
<td>3.77</td>
</tr>
<tr>
<td>40</td>
<td>4.67</td>
<td>4.67</td>
<td>4.50</td>
</tr>
<tr>
<td>41</td>
<td>4.10</td>
<td>3.97</td>
<td>3.62</td>
</tr>
<tr>
<td>42</td>
<td>4.65</td>
<td>4.90</td>
<td>4.85</td>
</tr>
<tr>
<td>43</td>
<td>5.29</td>
<td>5.35</td>
<td>4.48</td>
</tr>
<tr>
<td>44</td>
<td>5.18</td>
<td>5.05</td>
<td>8.26</td>
</tr>
<tr>
<td>45</td>
<td>4.12</td>
<td>4.08</td>
<td>4.31</td>
</tr>
<tr>
<td>46</td>
<td>4.39</td>
<td>3.94</td>
<td>5.38</td>
</tr>
<tr>
<td>47</td>
<td>3.77</td>
<td>3.77</td>
<td>4.08</td>
</tr>
<tr>
<td>48</td>
<td>5.05</td>
<td>4.59</td>
<td>5.29</td>
</tr>
<tr>
<td>49</td>
<td>3.50</td>
<td>4.59</td>
<td>5.71</td>
</tr>
<tr>
<td>50</td>
<td>6.29</td>
<td>4.81</td>
<td>4.29</td>
</tr>
</tbody>
</table>
TABLE C7. MEASUREMENTS OF TORQUE IN THE FIELD TEST AND RESULTS FROM THE SIMULATION

<table>
<thead>
<tr>
<th>Test No</th>
<th>$T_{te}$ (Nm)</th>
<th>$T_{ts}$ (Nm)</th>
<th>$i_{23}$</th>
<th>$T_{so}$ (Nm)</th>
<th>$T_{ses}$ (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>41.74</td>
<td>12.34</td>
<td>15/16</td>
<td>27.75</td>
<td>27.30</td>
</tr>
<tr>
<td>02</td>
<td>53.12</td>
<td>13.63</td>
<td>15/16</td>
<td>37.02</td>
<td>51.80</td>
</tr>
<tr>
<td>03</td>
<td>62.60</td>
<td>15.90</td>
<td>15/24</td>
<td>29.19</td>
<td>57.50</td>
</tr>
<tr>
<td>04</td>
<td>87.51</td>
<td>20.75</td>
<td>15/24</td>
<td>41.73</td>
<td>110.80</td>
</tr>
<tr>
<td>05</td>
<td>63.34</td>
<td>10.24</td>
<td>15/15</td>
<td>53.10</td>
<td>24.40</td>
</tr>
<tr>
<td>06</td>
<td>62.56</td>
<td>16.21</td>
<td>15/22</td>
<td>31.60</td>
<td>40.50</td>
</tr>
<tr>
<td>07</td>
<td>47.07</td>
<td>12.78</td>
<td>15/18</td>
<td>28.58</td>
<td>51.80</td>
</tr>
<tr>
<td>08</td>
<td>69.18</td>
<td>15.70</td>
<td>15/18</td>
<td>44.57</td>
<td>91.70</td>
</tr>
<tr>
<td>09</td>
<td>52.50</td>
<td>12.34</td>
<td>15/16</td>
<td>40.90</td>
<td>28.90</td>
</tr>
<tr>
<td>10</td>
<td>48.96</td>
<td>13.63</td>
<td>15/16</td>
<td>33.10</td>
<td>50.90</td>
</tr>
<tr>
<td>11</td>
<td>39.21</td>
<td>12.34</td>
<td>15/16</td>
<td>25.20</td>
<td>25.80</td>
</tr>
<tr>
<td>12</td>
<td>50.34</td>
<td>13.63</td>
<td>15/16</td>
<td>34.40</td>
<td>44.90</td>
</tr>
<tr>
<td>13</td>
<td>40.40</td>
<td>12.34</td>
<td>15/16</td>
<td>26.30</td>
<td>37.20</td>
</tr>
<tr>
<td>14</td>
<td>57.55</td>
<td>13.63</td>
<td>15/16</td>
<td>41.20</td>
<td>64.90</td>
</tr>
<tr>
<td>15</td>
<td>41.00</td>
<td>12.34</td>
<td>15/16</td>
<td>26.90</td>
<td>40.50</td>
</tr>
<tr>
<td>16</td>
<td>48.03</td>
<td>13.63</td>
<td>15/16</td>
<td>32.30</td>
<td>68.80</td>
</tr>
<tr>
<td>17</td>
<td>54.85</td>
<td>10.24</td>
<td>15/15</td>
<td>44.61</td>
<td>25.70</td>
</tr>
<tr>
<td>18</td>
<td>49.21</td>
<td>16.21</td>
<td>15/22</td>
<td>22.50</td>
<td>23.70</td>
</tr>
<tr>
<td>19</td>
<td>37.32</td>
<td>12.78</td>
<td>15/18</td>
<td>18.45</td>
<td>25.60</td>
</tr>
<tr>
<td>20</td>
<td>42.58</td>
<td>15.70</td>
<td>15/18</td>
<td>22.40</td>
<td>30.80</td>
</tr>
<tr>
<td>21</td>
<td>66.59</td>
<td>10.24</td>
<td>15/15</td>
<td>56.35</td>
<td>28.20</td>
</tr>
<tr>
<td>22</td>
<td>55.37</td>
<td>10.24</td>
<td>15/15</td>
<td>45.13</td>
<td>24.10</td>
</tr>
<tr>
<td>23</td>
<td>43.98</td>
<td>10.24</td>
<td>15/15</td>
<td>33.74</td>
<td>37.30</td>
</tr>
<tr>
<td>24</td>
<td>44.84</td>
<td>10.24</td>
<td>15/15</td>
<td>34.60</td>
<td>39.00</td>
</tr>
<tr>
<td>25</td>
<td>69.27</td>
<td>16.21</td>
<td>15/22</td>
<td>36.17</td>
<td>58.80</td>
</tr>
<tr>
<td>26</td>
<td>49.97</td>
<td>16.21</td>
<td>15/22</td>
<td>23.02</td>
<td>54.40</td>
</tr>
</tbody>
</table>

continued
<table>
<thead>
<tr>
<th>Test No</th>
<th>$T_{teo}$ (Nm)</th>
<th>$T_{t}$ (Nm)</th>
<th>$i_{23}$</th>
<th>$T_{so}$ (Nm)</th>
<th>$T_{sos}$ (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>77.73</td>
<td>16.21</td>
<td>15/22</td>
<td>41.94</td>
<td>36.40</td>
</tr>
<tr>
<td>28</td>
<td>75.12</td>
<td>16.21</td>
<td>15/22</td>
<td>55.23</td>
<td>41.50</td>
</tr>
<tr>
<td>29</td>
<td>39.10</td>
<td>12.34</td>
<td>15/16</td>
<td>25.10</td>
<td>38.60</td>
</tr>
<tr>
<td>30</td>
<td>43.04</td>
<td>13.63</td>
<td>15/16</td>
<td>27.60</td>
<td>66.50</td>
</tr>
<tr>
<td>31</td>
<td>40.57</td>
<td>12.34</td>
<td>15/16</td>
<td>26.50</td>
<td>35.70</td>
</tr>
<tr>
<td>32</td>
<td>43.60</td>
<td>13.63</td>
<td>15/16</td>
<td>28.10</td>
<td>62.60</td>
</tr>
<tr>
<td>33</td>
<td>44.80</td>
<td>12.34</td>
<td>15/16</td>
<td>30.40</td>
<td>25.90</td>
</tr>
<tr>
<td>34</td>
<td>60.79</td>
<td>13.63</td>
<td>15/16</td>
<td>44.20</td>
<td>45.60</td>
</tr>
<tr>
<td>35</td>
<td>38.71</td>
<td>12.34</td>
<td>15/16</td>
<td>24.70</td>
<td>28.90</td>
</tr>
<tr>
<td>36</td>
<td>61.74</td>
<td>13.63</td>
<td>15/16</td>
<td>44.80</td>
<td>50.90</td>
</tr>
<tr>
<td>37</td>
<td>65.59</td>
<td>10.24</td>
<td>15/15</td>
<td>45.11</td>
<td>27.60</td>
</tr>
<tr>
<td>38</td>
<td>63.93</td>
<td>10.24</td>
<td>15/15</td>
<td>53.69</td>
<td>24.10</td>
</tr>
<tr>
<td>39</td>
<td>46.88</td>
<td>10.24</td>
<td>15/15</td>
<td>36.64</td>
<td>35.50</td>
</tr>
<tr>
<td>40</td>
<td>69.74</td>
<td>10.24</td>
<td>15/15</td>
<td>59.50</td>
<td>37.50</td>
</tr>
<tr>
<td>41</td>
<td>76.05</td>
<td>16.21</td>
<td>15/22</td>
<td>40.80</td>
<td>56.20</td>
</tr>
<tr>
<td>42</td>
<td>68.62</td>
<td>16.21</td>
<td>15/22</td>
<td>35.73</td>
<td>52.80</td>
</tr>
<tr>
<td>43</td>
<td>66.98</td>
<td>16.21</td>
<td>15/22</td>
<td>34.62</td>
<td>37.00</td>
</tr>
<tr>
<td>44</td>
<td>67.93</td>
<td>16.21</td>
<td>15/22</td>
<td>48.50</td>
<td>41.30</td>
</tr>
<tr>
<td>45</td>
<td>46.60</td>
<td>15.90</td>
<td>15/24</td>
<td>19.20</td>
<td>27.00</td>
</tr>
<tr>
<td>46</td>
<td>56.25</td>
<td>20.75</td>
<td>15/24</td>
<td>22.20</td>
<td>34.10</td>
</tr>
<tr>
<td>47</td>
<td>31.10</td>
<td>12.34</td>
<td>15/16</td>
<td>17.60</td>
<td>24.50</td>
</tr>
<tr>
<td>48</td>
<td>39.07</td>
<td>13.63</td>
<td>15/16</td>
<td>23.85</td>
<td>27.10</td>
</tr>
</tbody>
</table>
The author was born in a rural community of Armenia (Q), Colombia on December 2, 1947. He started his elementary education in a rural school and finished his high school in the Colegio Rufino J. Cuervo, in 1966. He graduated with his B.S in Mechanical Engineering in 1972 at the Universidad Tecnologica of Pereira (Colombia). After graduation he worked for the Servicio Nacional de Aprendizage for three years. In 1976 he started working as an Instructor for the Universidad Nacional of Colombia on the campus of the Facultad de Ciencias Agropecuarias of Palmira (V). He pursued his MS in Agricultural Mechanization in Texas A&I University and graduated in 1984. He continued his career as a professor and became Head of the Department of Agricultural Engineering on the campus of Palmira for a two-year period in 1988. He enrolled for his Ph.D in Engineering Science at the Agricultural Engineering Department of Louisiana State University, in August 1991. Currently, he is a professor at the Facultad de Ciencias Agropecuarias. Apartado Aereo 237. Palmira (V), Colombia.
Candidate: Luis Arnoby Rodriguez Hurtado

Major Field: Engineering Science

Title of Dissertation: Simulation and Testing of a Vibrating Digger Blade for Root Crops

Approved:

[Signatures]

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

[Signatures]

Date of Examination: October 14, 1994