

Fall 11-10-2018

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Recommended Citation

Aly Mousaad Aly, (2018) "Toward Building Resilient, Sustainable, and Smart Infrastructure in the 21st Century," EMI Technical Article, Dynamics, American Society of Civil Engineers (ASCE). http://images.message.asce.org/Web/AmericanSocietyOfCivilEngineersInc/%7B296acb26-90f7-4c4b-b125-e011f8878012%7D_Paper_Aly_v8.pdf?utm_campaign=EMI-20181112%20Newsletter&utm_medium=email&utm_source=Eloqua

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Toward Building Resilient, Sustainable, and Smart Infrastructure in the 21st Century

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Motivation

In recent years, as a result of significant climate change, stringent windstorms are becoming more frequent than before. Given the threat that windstorms bring to people and property, wind/structural engineering research is imperative to improve the resilience of existing and new infrastructure, for community safety and assets protection. The Windstorm Impact, Science and Engineering (WISE) research program at Louisiana State University (LSU) focuses on creating new knowledge applicable to the mitigation of existing and new infrastructure, to survive and perform optimally under natural hazards (Figure 1). To achieve our research goals, we address two imperious challenges: (i) characterization of realistic wind forces on buildings and other types of structures; and (ii) developing advanced control theory to accelerate the optimal tuning of smart structures, with the aim of developing novel probabilistic analytical methods to address the complex behavior and inherent nonlinearity in semi-active control, for multiple hazards.

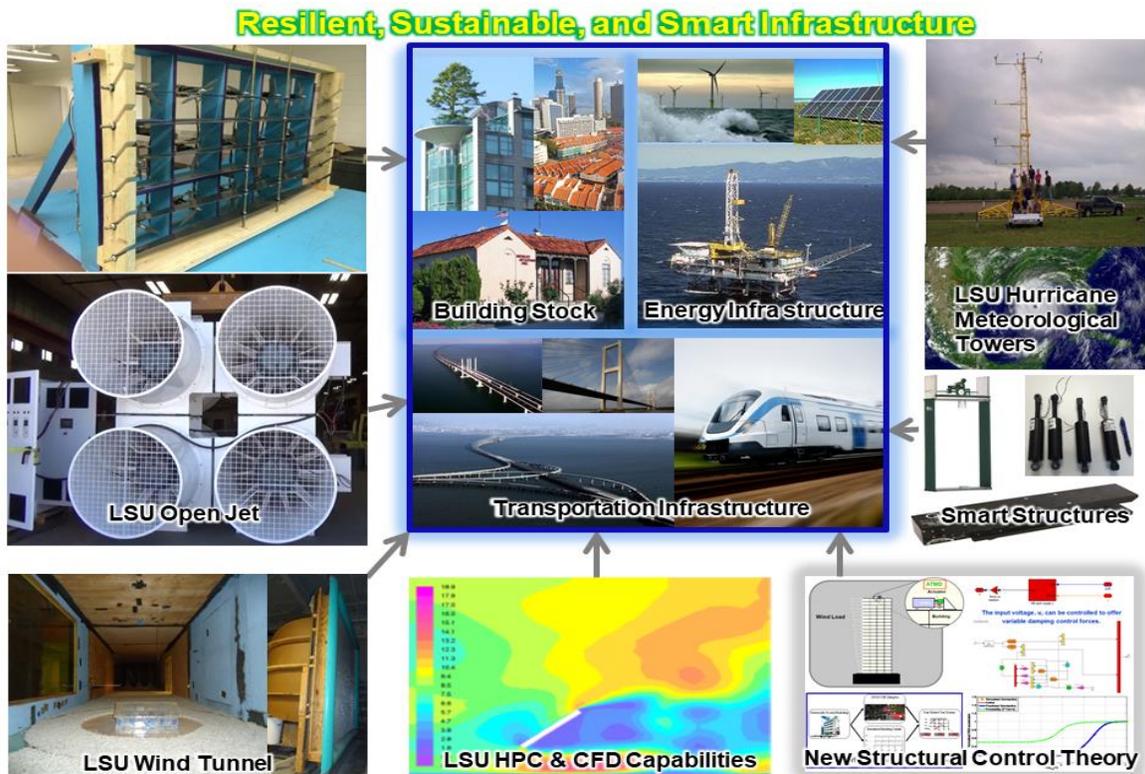


Figure 1 Long-term research goals of the LSU WISE research program – Building the more resilient community, to enhance public safety and reduce the huge cost of rebuilding due to natural disasters, is the core challenge of our research.

I. Characterization of Realistic Wind Forces on Buildings and Other Types of Structures. To address this challenge, the LSU WISE research program combines the benefits of state-of-the-art experimental/computational facilities to accurately reproduce the physics as well as aerodynamic phenomena inherent in atmospheric boundary layer (ABL) flows around buildings and other bluff bodies. The LSU WISE research group has access to experimental and computational facilities: small- and large-scale open-jet hurricane testing capabilities, boundary layer wind tunnel facility with high- and low-speed test sections, and High Performance Computing (HPC) resources for Computational Fluid Dynamics (CFD) simulations, with OpenFOAM for the simulation of ABL flow turbulence, employing advanced closures, such as the Reynolds Stress Model (RSM) and Large Eddy Simulations (LES) with realistic inflow fluctuations. This research mainly focuses on developing a hybrid mathematical-informatical holistic approach for dealing with scale issues in the simulation of wind flows around buildings, to ascertain correct evaluation of peak loads, with a potential to enhance/update design standards. The practical applications of this research include resilient and sustainable design of infrastructure for windstorms, such as, industrial buildings, residential homes, transportation infrastructure, and energy infrastructure.

II. Advanced Control Theory to Accelerate the Optimal Tuning of Smart Structures. To address this challenge, the LSU WISE research group developed novel control methods that enabled semi-active controller tuning under complex behavior and inherent nonlinearity, without simulations [1]. The recently developed control theory enables the evaluation of semi-active controllers' performance of multi-degrees-of-freedom systems, without significant computational effort. With this analytical probabilistic control theory, a wide range of controllers can be evaluated in a fraction of a second while optimum control parameters can be tuned to achieve different control objectives. The potential applications include semi-active vibration control in flexible structures under multiple hazard loads brought by wind, wave, and earthquakes.

Open-Jet Testing

For several decades, wind tunnels were employed to estimate wind forces on structures. The experimental characterization of wind loads on buildings and other types of structures requires scaling of the test object and flow, under the constraints of relevant dimensionless parameters (laws of similitude), to ensure the physics in the laboratory are representative of those at full-scale. Reynolds number and turbulence structure are two influential parameters that have been either underestimated or their exact role was neglected for decades. Wind loads on certain bluff bodies, like those with cylindrical shapes and rounded edges, may be significantly affected by the Reynolds number. However, the common belief that Reynolds number effects on sharp-edged structures are negligible is questionable these days for two reasons: (1) recent full-scale structural failure and the mismatch in data obtained from full-scale measurements and laboratory testing, and (2) the new capabilities of testing at higher Reynolds numbers such as those of open-jet facilities. In addition, an evidence that the Reynolds number affects aerodynamics of bodies with sharp edges was obtained from tests in pressurized wind tunnels [2,3].

In testing high-rise buildings, the ratio of the integral length scale of turbulence to the structural geometric scale in wind tunnel testing may be similar to full-scale. In testing of low-rise buildings and small-size structures, however, producing turbulence in the laboratory at reasonably large integral scales is a challenge. Testing low-rise buildings at smaller geometric scales is also a challenge because of the uncertainty in the flow velocity near the ground, and the difficulty to obtain high resolution pressure data, add to that the effects of interference with the sensors/instrumentation. At relatively large geometric scales, modelling the full turbulence

spectrum is difficult [4]. The lack of large scale turbulence (low frequency content) can significantly impact the flow fluctuation around the test objects and may underestimate the peak loads that cause failure at full-scale [5,6].

To further address the scale issues, the LSU WISE research team built two state-of-the-art open-jet facilities to permit aerodynamic/aeroelastic testing at larger model sizes, compared to their counterpart wind tunnel models, because of lower blockage effects, which enables better accuracy of testing with higher resolutions. While buildings with architectural features such as shingles, roof, tiles, balconies, and soffits are difficult to replicate in small-scale models, larger test models will capture the intricate flow separation, vortex generation, and flow re-attachment phenomena at higher resolution, which will improve accuracy.

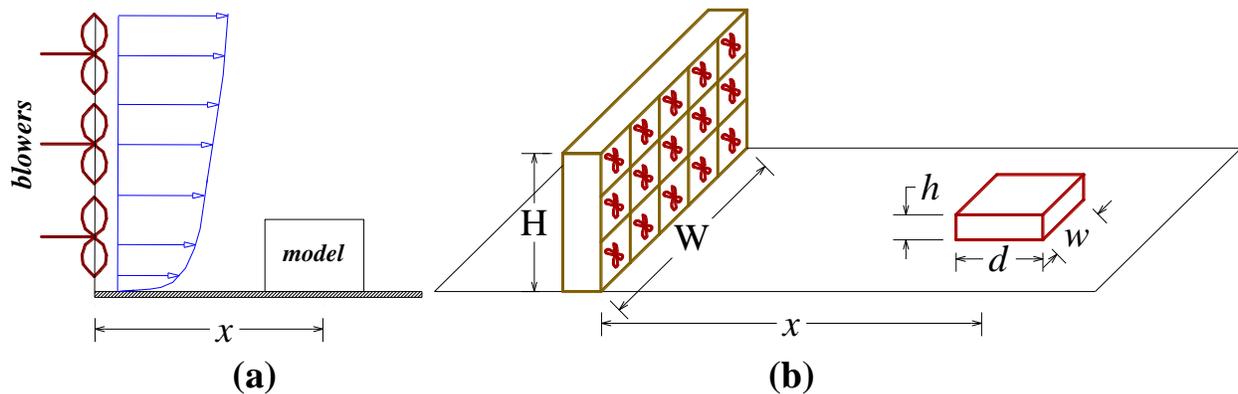


Figure 2 Open-jet testing concept: (a) 2-D sketch; and (b) 3-D representation. The test object's dimensions (d , w , and h), as well as the testing location (x) are the main parameters that depend on the size of the open-jet flow section (dimensions W and H), as well as the wind characteristics.

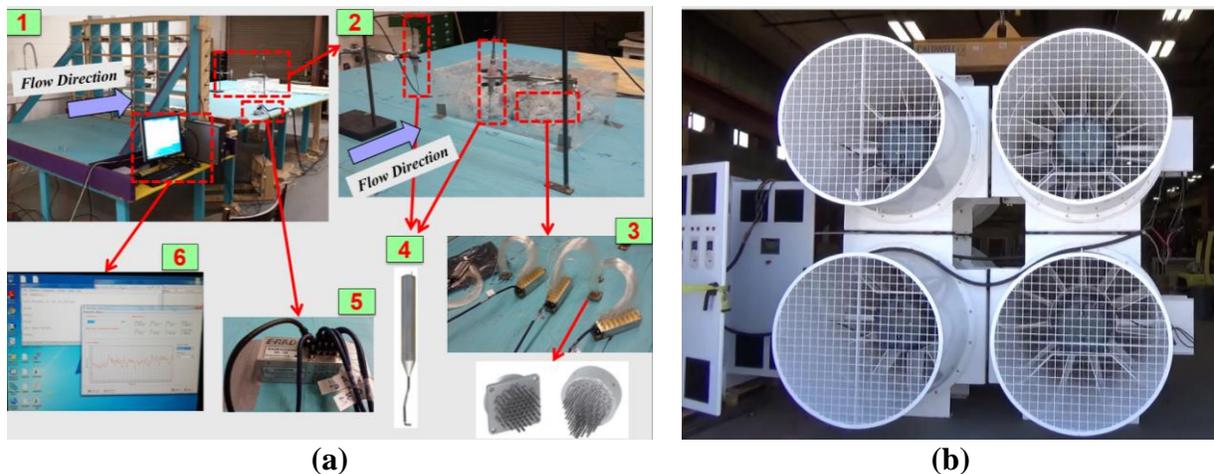


Figure 3 A new open-jet simulator at LSU: (a) small-scale with velocity and pressure transducers – 1. general view of the open-jet facility; 2. instrumented test building; 3. ZOC miniature electronic pressure scanning modules, and view of pneumatic connectors; 4. three-component velocity and static pressure measuring Cobra probe; 5. RADBASE data acquisition unit; 6. ScanTel and Turbulent Flow software installed on a computer for online recording and processing of flow and pressure data during testing, and (b) larger version of the LSU open-jet simulator.

Figure 2 shows 2-D and 3-D sketches that explain the main concept of open-jet testing. The test model's dimensions (d , w , and h) as well as its location from the exit of the blowers (x) are parameters that depend on the size of the open-jet flow section (dimensions W and H) and the desired test flow characteristics. The distance (x) should be optimized to balance between the need for high wind velocity and fully developed turbulence characteristics – velocity spectra, profile, and turbulence intensity. The longer the distance x , the lower the wind speed that can be achieved in open-jet testing. However, a fully developed turbulence may be obtained at a longer distance (x). In addition, to reproduce realistic pressures on test objects, their size may depend on the open-jet size [6]. Figure 3 shows photographs of small- and large-scale open-jet simulators at LSU – Phase 1 of an intensive wind, rain and wave (WRW) testing facility [6,7].

The LSU WISE research team built a small-scale open-jet wind engineering testing facility (Figure 3-a). The small-scale open-jet was recently calibrated to generate wind velocity profiles that mimic wind characteristics over open and suburban terrain. With an adjustable planks mechanism, different wind profiles can be physically simulated. In addition, this lab has cobra probes, load cells, laser displacement sensors, and a 256-channels pressure scanning system. A Laser-Doppler Velocimetry measuring system is available, in addition to High Resolution Digital Photography capabilities for flow visualization. Also, six component sting balances, traversing systems, and computer with data acquisition units are available.

LSU is now building Phase 1 of a large wind and rain testing facility. Phase 1 permits generating wind flows at a relatively high Reynolds number over a test section of 4m x 4m (Figure 3-b). This will permit executing wind engineering experiments at relatively large scales. This facility strengthens the research capabilities of the WISE research program at LSU. The facility will enable researchers from LSU and the globe to test their research ideas, to expand knowledge leading to innovations and discovery in science, hurricane engineering and materials and structures disciplines, to build the more resilient and sustainable infrastructure. Potential applications include, but are not limited to, wind turbines, solar panels, residential homes, large roofs, high-rise buildings, transportation infrastructure, power transmission lines, etc.

Computational Fluid Dynamics

In addition to experimental testing, CFD is a potential tool for solving aerodynamic problems. CFD can provide qualitative/quantitative prediction of wind forces on bluff bodies by means of: (i) mathematical modelling, (ii) numerical methods, and (iii) software utilities – solvers, pre- and post-processing tools. CFD enables the prediction of wind flow and loads induced on buildings and other types of structures by performing numerical experiments in a virtual wind tunnel, without restrictions on model size and flow characteristics, when powerful computational capabilities and enhanced turbulence closures and wall treatment are properly employed, on a quality discretized computational domain (high quality mesh). The CFD study is usually carried out in three steps: (a) grid generation from a CAD geometry representative of the fluid domain surrounding a building/structure of interest, (b) boundary conditions set up with appropriate turbulence closure and solution of the governing equations, and (c) result visualization and validation. Experimental and full-scale data are still useful for CFD validation. The CFD user can benefit from several available software packages including commercial software such as STAR CCM + and ANSYS Fluent, as well as open source software such as OpenFOAM.

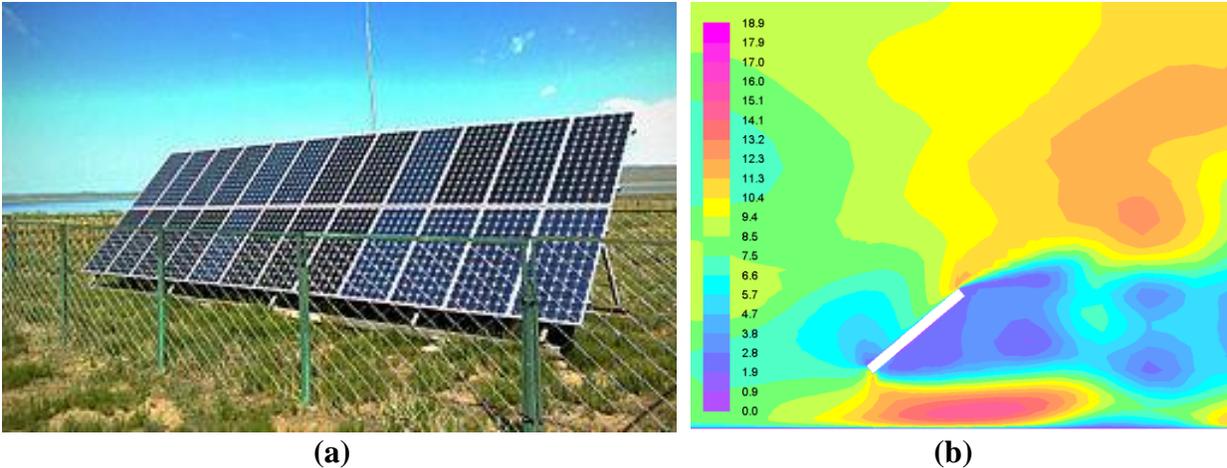


Figure 4 Ground-mounted solar panel CFD study: (a) prototype, and (b) LES computational simulation results of instantaneous flow velocity (m/s).

Over the past decades, CFD has been enjoying a renewed interest in solving aerodynamic problems involving wind flows over different types of structures [8]. When CFD was employed with realistic ABL characteristics and inflow turbulence, on a solar panel module (Figure 4), the results showed accurate prediction of wind loads. Furthermore, the CFD has a potential for conducting full-scale investigations, eliminating Reynolds number effects, and reproducing exact flow characteristics, especially the turbulence structure, provided that HPC resources are available, as well as proper near wall treatment and turbulence closures [5]. While experimental wind engineering testing remain a feasible tool, concurrent CFD studies provide additional opportunities to explain/augment physical simulation results, with a potential to explore full-scale physics. CFD is still a newcomer and additional research efforts are ongoing to permit executing the more efficient simulations [9].

Non-Simulative Tuning of Smart Dampers

In the dynamics of structures under multiple hazards, vibration control offers attractive means for protecting structures and inhabitants, as well as balancing between resilience and sustainability. A fundamental task related to the design of semi-active controllers to attenuate structural vibrations is the tuning of the parameters based on the physical properties (mass, stiffness, and damping), mitigation objectives, nature of excitation, etc. In addition, in a smart damping, the performance of the system to mitigate excessive vibrations is governed by the corresponding ideal active control force and the algorithm alerting the damping characteristics of the device.

While there are several studies on the advantages of employing semi-active dampers to attenuate vibrations in flexible structures, the controller tuning process is mainly based on numerical simulations, hindering the consideration of different families of controllers, to achieve controller tuning-based performance under varying loading patterns, for instance excitation due to multiple hazards. To address this challenge, the LSU WISE research team developed a novel control theory that enables the semi-active controller tuning, of multi-degrees-of-freedom systems, under complex behavior and inherent nonlinearity, without simulations [1]. According to the dissipative probability of the corresponding active control forces, a new concept of semi-active control gains was developed:

$$k_{s,i} = \frac{1}{2} G_{1,i} \{1 + \sin^2[\pi(P - 0.5)]\} \quad \& \quad i = 1, 2, \dots, m \quad (1)$$

$$\mathbf{k}_s = \text{diag}(k_{s,i}) \quad (2)$$

$$\omega_a = \sqrt{\text{eig}(M^{*-1}(\mathbf{K}_{m,a}))}; \quad \mathbf{K}_{m,a} = \mathbf{K}^* + \text{diag}(\Phi \mathbf{G}_1) \quad (3)$$

$$\omega_s = \sqrt{\text{eig}(M^{*-1}(\mathbf{K}^* + \mathbf{k}_s))} \quad (4)$$

$$c_{s1,i} = \frac{|G_{1,i}|}{\pi \omega_{s,i}} \{1 + \sin^2[\pi(P - 0.5)]\} \quad \& \quad i = 1, 2, \dots, m \quad (5)$$

$$c_{s2,i} = \frac{G_{2,i} \omega_{a,i}}{\pi \omega_{s,i}} \times \quad (6)$$

$$\left\{ \frac{\pi}{2} + \left[\sin[\pi(P - 0.5)] \times \sqrt{1 - \sin^2[\pi(P - 0.5)]} + \tan^{-1} \left(\frac{\sin[\pi(P - 0.5)]}{\sqrt{1 - \sin^2[\pi(P - 0.5)]}} \right) \right] \right\}$$

$$\mathbf{c}_s = \text{diag}(c_{s1,i} + c_{s2,i}) \quad \& \quad i = 1, 2, \dots, m \quad (7)$$

where, P is the dissipative probability of the corresponding optimal active control forces, G_1 and G_2 are the active gains, and \mathbf{K}^* is the generalized stiffness of the primary structure. Detail of this theory are available in Ref. [1].

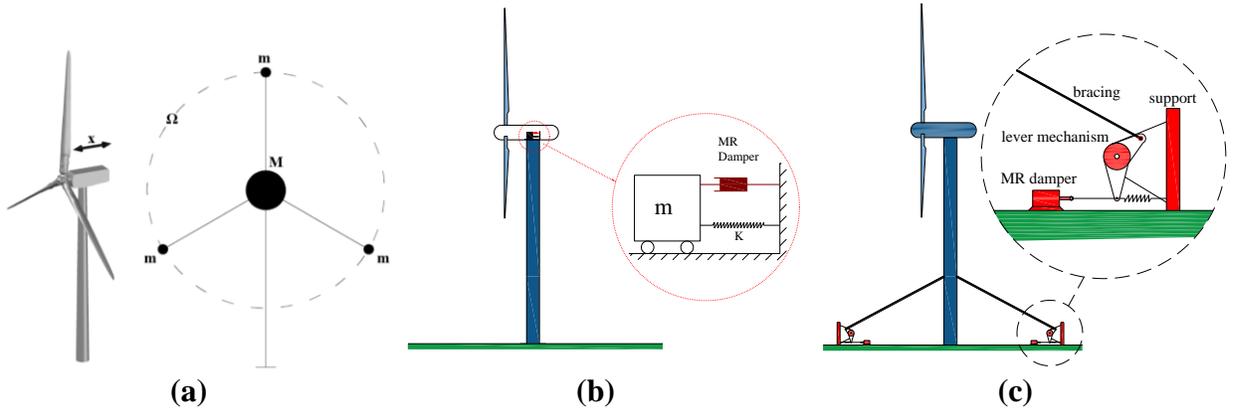


Figure 5 A sample study of modelling and control of a 5MW wind turbine: (a) wind turbine lumped mass model, (b) semi-active tuned mass damper (SATMD), and (c) external bracing with magnetorheological (MR) dampers benefiting a lever mechanism to enhance the performance [10].

With this new theory, a family of controllers can be studied, and their performance can be evaluated in a fraction of a second. This enables controller tuning to achieve optimum parameters for different design objectives. The potential applications of this control theory include vibration control in flexible structures under multiple hazard loads brought by, for example, wind, wave,

and seismic loadings. To show the potentiality of the new theory, we considered semi-active controller design in both onshore and offshore wind turbines in parked and operating positions, under wind, wave, and earthquake external forces, in addition to mechanical unbalance [1]. The Lagrangian approach was employed to model the wind turbine considering the blade/tower coupling. Two types of control systems are investigated: (i) semi-active tuned mass damper (SATMD) installed in the nacelle, and (ii) outer bracing with magnetorheological (MR) dampers (Figure 5) [1], [11]. The new control theory was employed to accelerate the tuning of the semi-active controllers subjected to multiple hazards (Figure 6). The results show that for the operating wind turbine, earthquake excitations lead to excessive vibrations for a long period. However, the properly tuned semiactive damping system improved the performance of the wind turbine by reducing the magnitude and duration of excessive vibrations. For the purpose of vibration control under multiple hazards, including wind and earthquake, the control system is immediately available, compared to, for instance, the classical slow responding tuned mass damper.

This new control theory reduced the design and performance evaluation time significantly. For instance, the CPU-time required for a single performance evaluation case considering specific weighting matrices, using a 2.5 GHz Intel Core i5-2400S processor PC, was about 3 hrs. This amount of time increases significantly for aggressive primary active controllers, which means that several days/weeks are needed to evaluate the performance of a family of controllers under certain loading excursions. This amount of simulation time can increase exponentially when the objective is to design semi-active controllers for multiple hazards, for different optimization objectives – e.g. minimizing displacement, velocity, acceleration, or all responses. The new analytical control theory reduced the total time to a few seconds for a wide range of controllers and optimization objectives.

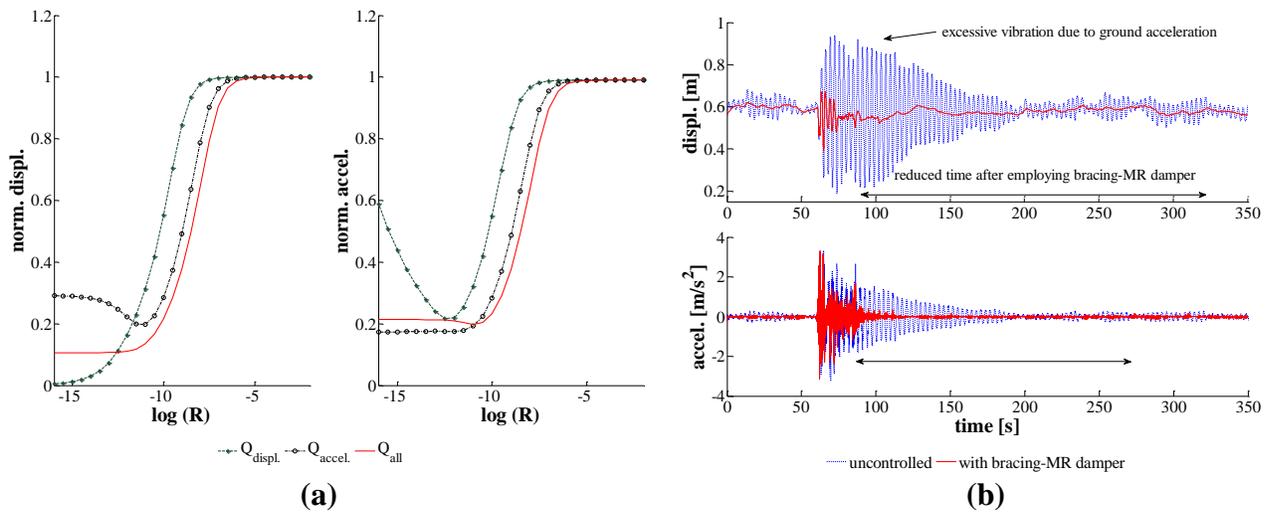


Figure 6 Results obtained by the proposed semi-active controller tuning theory: (a) effect of weighting the Q and R matrices to achieve desired control forces for certain optimization objectives – minimizing normalized root-mean square (RMS) displacement and acceleration; and (b) time histories of uncontrolled and controlled (employing MR dampers with outer bracing system) displacement and acceleration responses of the nacelle of an operating wind turbine under earthquake loading (El Centro horizontal component of ground acceleration).

Future Work, Novelty and Impact

Understanding the impact of windstorms including hurricanes, tornadoes, and other types of non-synoptic wind on the infrastructure is crucial for the building of resilient communities under current and future climate change effects. The available wind engineering tools may require novel testing and data processing protocols, in addition to more focus on full-scale computational fluid dynamic simulations, with realistic turbulence closures and proper near wall treatment, as well as more quantified data from full-scale that will enhance the understanding of wind impact on low-rise buildings. The quantification of wind loads considering climate change effects, interference effects, as well as uncertainties in the wind characteristics in the lower part of the atmospheric boundary layer is a challenging area of current interest. For flexible structures, the design for multi-hazard represent a challenge that requires the adoption and consideration of new control methods, theory, devices, and implementation techniques. This will yield more resilient and sustainable infrastructure such as high-rise buildings, towers, and long span bridges under the impact of wind and earthquakes, as well as wind turbines under wind, wave, and seismic excitation [9].

The research activities will provide knowledge useful for homeowners and insurance companies to deal more effectively with storms, for example, the results may assist officials and decision makers to fine tune design codes and give coastal residents options for making their dwellings more storm resistant. The goal is to build new structures and retrofit existing ones in innovative ways to balance resilience with sustainability, to better protect people, and reduce the huge cost of rebuilding after storms. This will broadly impact the wind/structural engineering research field and facilitate effective investments in the infrastructure industry that will result in more resilient and sustainable communities and contribute to economic growth and improve the quality of life.

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