High-fidelity Modeling, Resilience Enhancement and Smart Sensing of Critical Infrastructures Exposed to Multi-hazard

Chao Sun, A.M. ASCE

Email: csun@lsu.edu, Phone: 225-578-8511

Department of Civil and Environmental Engineering, Louisiana State University

3240K Patrick Taylor Hall, Baton Rouge, LA 70803, USA

Research group webpage: http://faculty.eng.lsu.edu/cm/csun/

Google Scholar: https://scholar.google.com/citations?user=ZrsjbzoAAAAJ&hl=en

Motivation

Critical civil infrastructures (residential buildings, bridges, offshore wind turbines, oil/gas rigs, pipelines, power transmission/distribution systems, etc.) nowadays face serious issues of aging and are more frequently impacted by earthquake and windstorm induced multi-hazards including earthquakes, tsunamis, winds, storm surge/waves, flooding, and so on. The recent hurricanes (e.g., Hurricanes Harvey, Mike, Irma and Dorian) have caused tremendous structural damage to critical infrastructures and cost tens of billions of dollars. The combined loading effects and structural nonlinearity render the structural dynamic characteristics more complex than usual, which will inevitably undermine the structural performance, damage the structural integrity and cause huge loss of properties and lives. Unfortunately, characterization of the combined wind-wave-surge loading (especially the transient and variable nature) and the comprehensive failure mechanism of the critical infrastructures exposed to the combined loading, which is the foundation of building resilient infrastructures and communities, is not well understood currently. To achieve multi-hazard resilient infrastructures and communities,

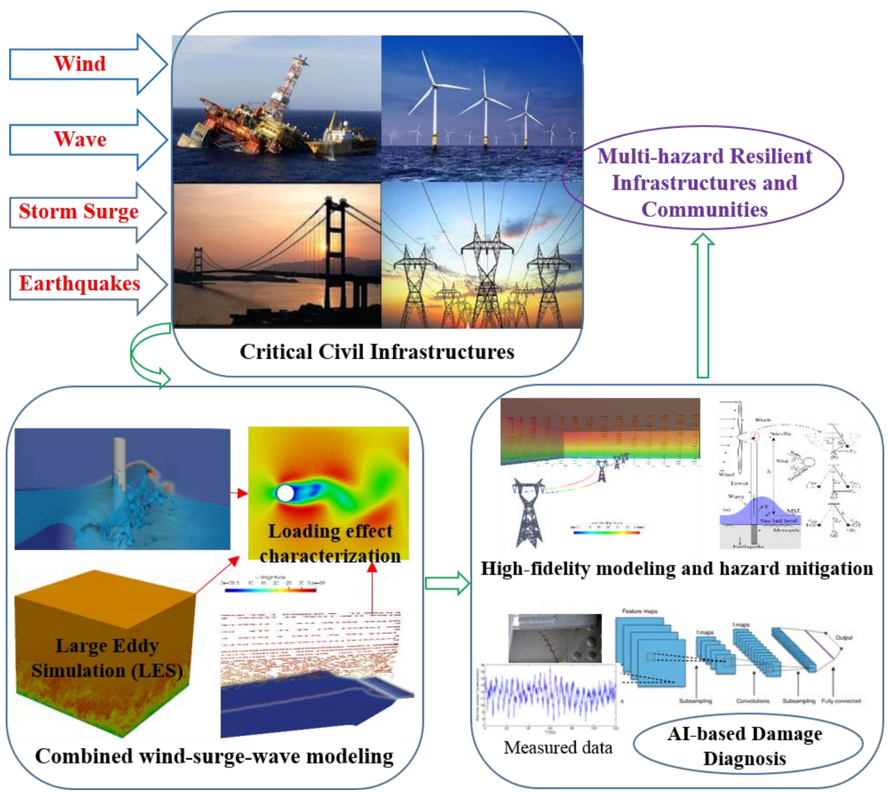

Figure 1 Overall research goals and methodologies of the CDSS lab at LSU

researchers at the Complex Dynamics and Smart Sensing (CDSS) lab at Louisiana State University focus their research effort on: 1) advancing the fundamental understanding of combined wind-wave-surge loading, and the complex behavior and failure mechanism of critical infrastructures, 2) physical vulnerability assessment of individual and community-level infrastructures, (3) resilience enhancement of critical infrastructures exposed to earthquake and windstorm induced multi-hazard, (4) smart sensing and damage diagnosis/prognosis of critical infrastructures to achieve secure operation and optimized management/maintenance. Figure 1 illustrates the overall long-term research goals and methodologies of the CDSS lab at Louisiana State University (LSU). Some completed and ongoing research projects are described as follows.

1. Characterization of combined wind-surge-wave loading on critical civil infrastructures

To design and build multi-hazard resilient civil infrastructures/communities, it is essential to understand and realistically characterize the combined wind-surge-wave loading through integrated high-fidelity computational modeling and laboratory testing. Currently, the researchers at CDSS lab at LSU are focusing on establishing high-fidelity computational models to understand and realistically characterize the combined wind-surge-wave loading. As shown in Figure 1, large eddy simulation (LES) is used to model the hurricane wind field. Open source code is also under development to model surge-wave flow using OpenFOAM. Characterization of the wind-surge-wave loading through laboratory testing will also be implemented via collaboration with the Natural Hazards Engineering Research Infrastructure (NHERI) experimental facilities. The established computational models will be used to fully understand the combined loading actions imposed on infrastructures and the complex performance and failure mechanism of target civil infrastructures, including residential buildings, offshore wind turbines, power transmission/distribution systems, bridges, offshore oil/gas platforms, etc.

2. Complex dynamics modeling and mitigation of offshore wind turbines

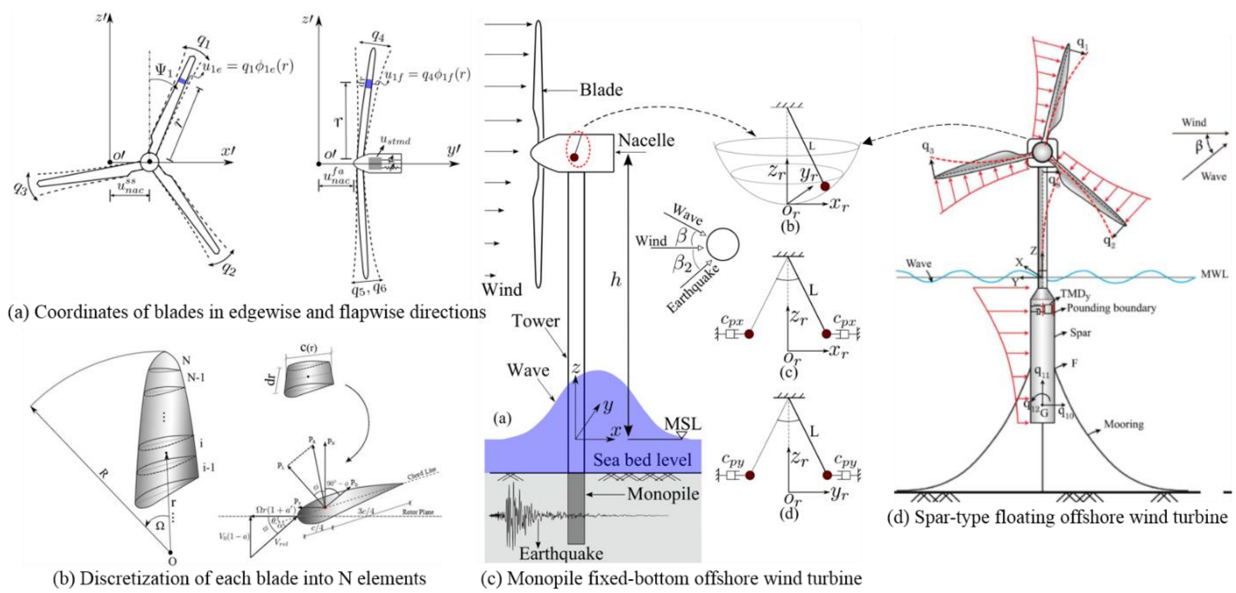

Figure 2 Analytical model establishment of offshore wind turbines with vibration mitigation devices. (a) Coordinates of blades in edgewise and flapwise directions; (b) Discretization of each blade into N elements; (c) Monopile offshore wind turbines with a three dimensional pendulum tuned mass damper installed in the nacelle; (d) Spar-type floating offshore wind turbine with a three dimensional pendulum tuned mass damper in the nacelle and two pounding tuned mass dampers in the floater.

Offshore wind farms (both fixed-bottom and floating types) are becoming increasingly attractive for wind energy production. However, the combined loading of wind, wave, current, earthquakes and ice renders the offshore wind turbines suffering from complex dynamics, which adversely influences power output and the structural integrity. To better understand the complex dynamics of offshore wind turbines, three-dimensional mathematical models of offshore wind turbines (fixed and floating types) have been established based on the state-of-the-art principles of aerodynamics, hydrodynamics and structural dynamics. The models have been validated through comparison with the open source program FAST [1-4]. In addition, to mitigate the excessive three dimensional vibrations of the offshore wind turbines, comprehensive vibration control strategies, including passive and adaptive control techniques have been developed and integrated with the established model of offshore wind turbines. Research results show that the passive three dimensional pendulum tuned mass damper and pounding tuned mass damper can mitigate the bi-directional/three dimensional vibrations of the offshore wind turbines [1, 5, 6]. With environmental or structural variations, the proposed semi-active/adaptive control method which tracks the variation and retunes the natural frequency and damping ratio in real-time can overcome the detuning effect and provide robust mitigation [3]. Figure 2 illustrates the research on offshore wind turbines in the CDSS lab.

1.1 Aerodynamic loading

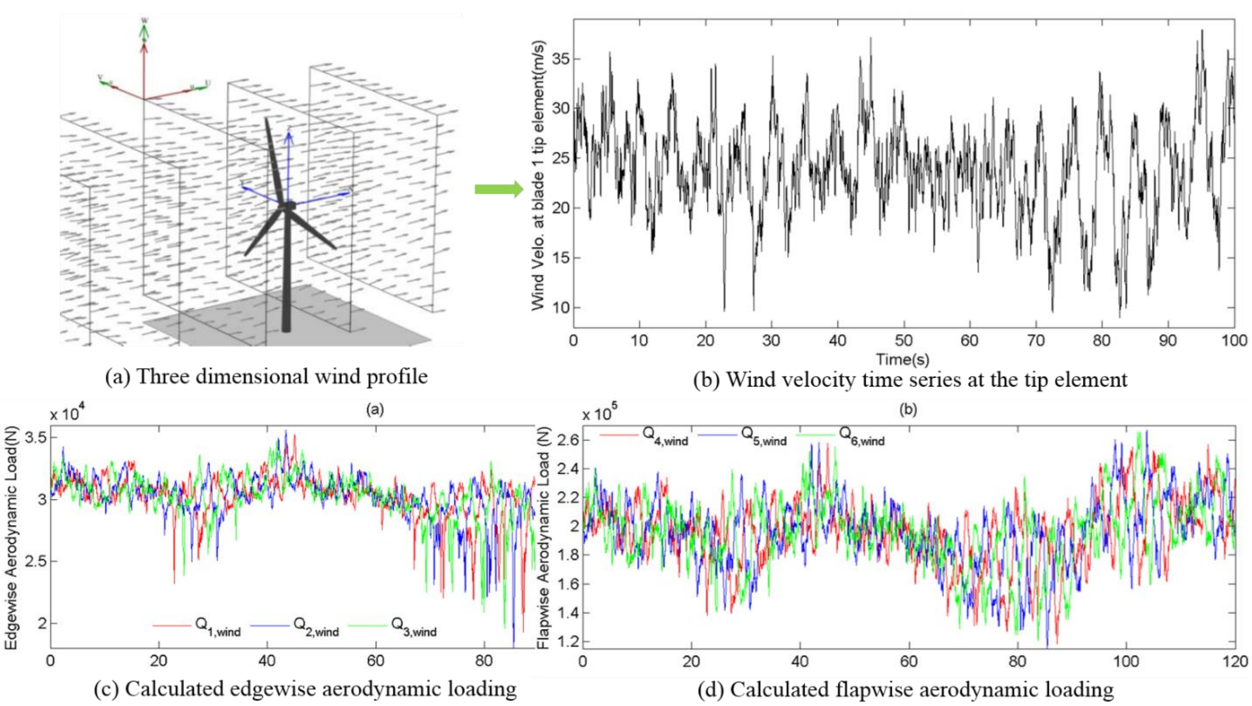

Figure 3 Calculation of aerodynamic loading. (a) Three dimensional wind profile; (b) wind velocity time series at the tip element of blade 1; (c) edgewise aerodynamic loading time series; (d) flapwise aerodynamic loading time series.

Figure 3 shows the key steps of calculation of the aerodynamic loading. First, a three dimensional wind field is generated using the open source program TurbSim [7]. Second, the generated wind field is mapped onto each element (shown in Figure 2(b)) of the rotating blades to determine the wind velocity time series at the element (Figure 3(b)). Then, the edgewise and flapwise aerodynamic loading acting on the three blades, as shown in Figures 3(c) and 3(d), is calculated using the Blade Element Momentum (BEM) method.

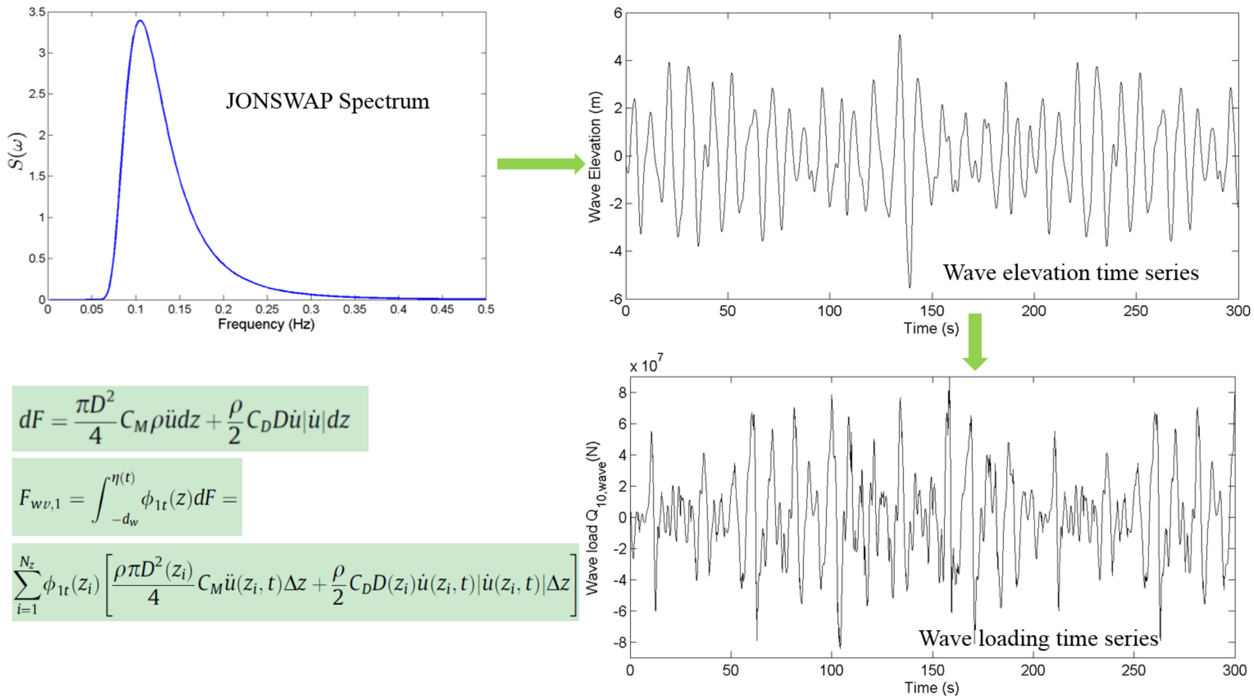

Figure 4 Calculation of hydrodynamic loading using Morrison equation and strip theory.

1.2 Hydrodynamic loading

Figure 4 illustrates the key steps of calculation of the hydrodynamic loading. First, the JONSWAP spectrum is generated for target water depth, significant wave height and wave period. Second, the generated spectrum is used to generate the time series of wave elevation, water particle velocity and acceleration at desired locations. Third, the hydrodynamic wave loading is determined using Morrison equation and the strip theory.

It is noted that seismic loading is also determined and included in the offshore wind turbine model on which the details can be found in [1, 3, 6].

1.3 Equations of motion of the offshore wind turbines

With the calculated aerodynamic and hydrodynamic loading, the equation of motion of the offshore wind turbines (fixed and floating types) were determined using Euler-Lagrangian equation and shown as follows:

$$\widetilde{M}\ddot{\tilde{q}} + \tilde{C}\dot{\tilde{q}} + \widetilde{K}\tilde{q} = \tilde{Q}_{wind} + \tilde{Q}_{wv} + \tilde{Q}_{seismic} + \tilde{F} \tag{1}$$

$$\widetilde{M}\ddot{\tilde{q}} + \tilde{C}\dot{\tilde{q}} + (\widetilde{K} + \widetilde{K}_r)\tilde{q} = \tilde{Q}_{wind} + \tilde{Q}_{wv} + \tilde{Q}_{buo} + \tilde{Q}_{moor} + \tilde{F}_p + \tilde{F} \tag{2}$$

Where parameters $\widetilde{M}$, $\tilde{C}$ and $\widetilde{K}$ are the system mass, damping and stiffness matrices. Variables $\tilde{Q}_{wind}$, $\tilde{Q}_{wv}$, $\tilde{Q}_{buo}$ $\tilde{Q}_{seismic}$, $\tilde{Q}_{moor}$ are the generalized force vectors corresponding to wind, wave and buoyancy, seismic and mooring loadings. Details of the equation and associated parameters can be found in [1, 8]. Equations (1) and (2) are corresponding to fixed-bottom monopile and spar-type floating offshore wind turbines, separately. Complete Matlab codes have been developed to determine the loading and to solve for the responses of the offshore wind turbines under various loading scenarios.

1.4 Mitigation of the offshore wind turbines

A three dimensional pendulum tuned mass damper (3d-PTMD), as shown in Figure 5, is proposed to mitigate the bidirectional response of offshore wind turbines. A numerical search approach is utilized to obtain the optimized design of the 3d-PTMD. Based on results, the optimal design formula is proposed to minimize the root mean square (RMS) displacement of offshore wind turbine nacelle. Figure 5 shows the derivation of the optimal design formula of the 3d-PTMD. Based on the optimal design, performance of the 3d-PTMD is evaluated under misaligned wind, wave and earthquake loading. Figure 6 illustrates the comparison between the uncontrolled and controlled wind turbine. We can find that the 3d-PTMD can significantly mitigate the bi-directional response of the wind turbine nacelle under different misalignment angles. Furthermore, fatigue loading reduction of offshore wind turbines under realistic wind wave conditions is studied and compared with traditional TMDs. Results show that the 3d-PTMD can increase the offshore wind turbine fatigue life by more than 50% in comparison with traditional TMDs [9]. Meanwhile, to harness the kinetic energy of the pendulum rather than dissipating it into heat, linear electromagnetic energy harvesters are introduced to replace the viscoelastic dash pot. It is found that electric power in orders of magnitude of kilowatts can be harnessed [5], which will power the sensors for long-term online structural health monitoring (SHM) of offshore wind turbines as a self-powered SHM system.

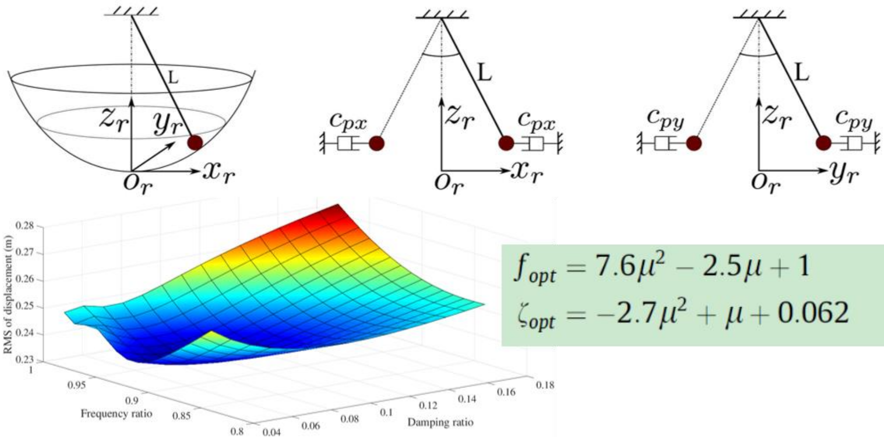

Figure 5 Optimal design of the 3d pendulum tuned mass damper.

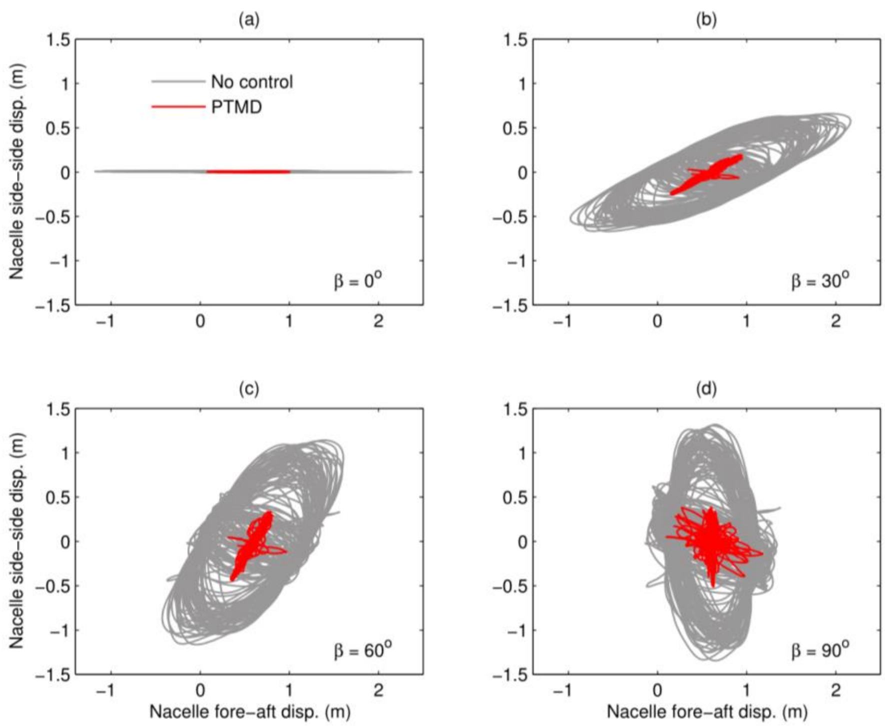

Figure 6 Bi-directional response mitigation of offshore wind turbines exposed to misaligned wind-wave loading. Parameter β denotes the wind-wave misalignment angle.

3. Smart sensing of civil and mechanical systems using emerging techniques

American Society of Civil Engineers (ASCE) gave a poor average grade of D+ on the current conditions of US infrastructure [12]. Based on the report, the national infrastructures are facing severe deterioration and aging issues that prevent the growth of the economy and development of communities. Hence, sensing and damage diagnosis/prognosis of critical infrastructures constitute a key step toward safe and resilient infrastructures and communities. Currently, the CDSS lab is developing smart sensing methodologies using emerging techniques, such as computer vision,

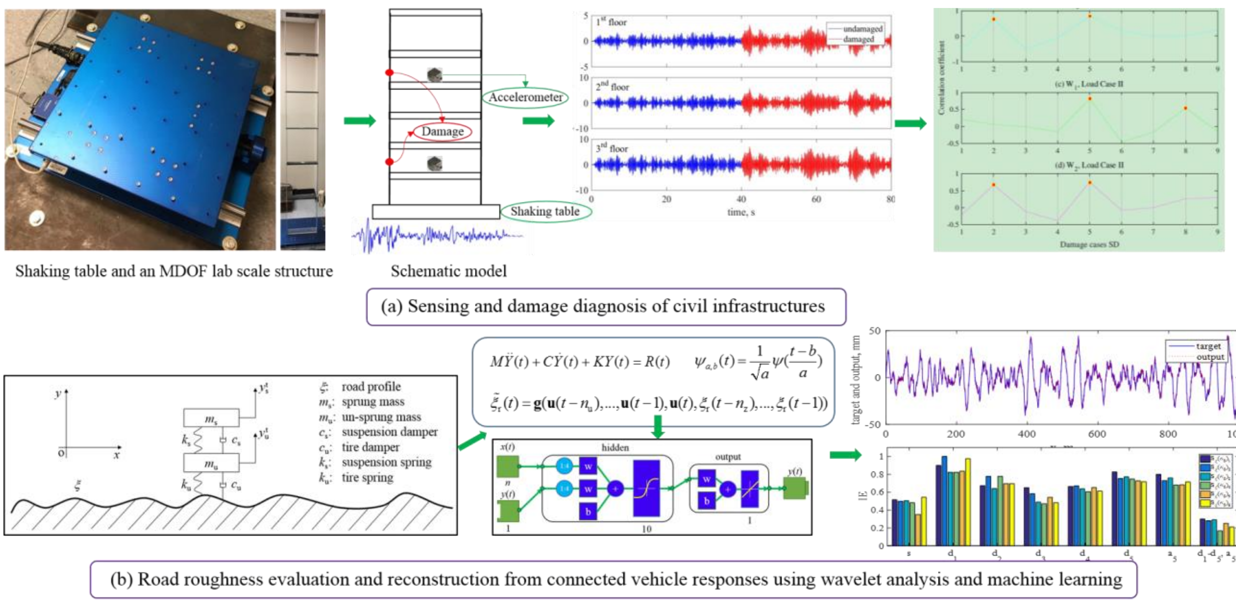

Figure 7. Smart sensing of civil infrastructures at CDSS lab

machine learning, advanced signal processing and data analytics to enable efficient and automatic damage diagnosis of critical infrastructures.

As an illustration, part of the work implemented in the CDSS lab on smart sensing of civil infrastructures is demonstrated in Figure 7. Figure 7 (a) shows an example of multi-site damage identification of a multi-story building model. Multi-site structural damage identification is challenging for data-driven structural health monitoring (SHM) methods due to the lack of data from damaged scenarios. To address this issue, constraint independent component analysis (cICA) was used to compact the damage information into the mixing matrix of cICA. Structural responses (acceleration and displacement) were recorded under intact and damaged scenarios. Results show that the proposed method can progressively locate the structural damage. Moreover, the method has the potential to identify multi-site damage using single-site damage data.

Figure 7(b) illustrates road roughness evaluation and reconstruction from connected vehicle responses using wavelet analysis and machine learning [10, 11].This research uses the wavelet decomposition of the vehicle inertial responses and a nonlinear autoregressive artificial neural network with exogenous inputs to reconstruct the elevation profile. The vehicle inertial responses are a function of both the vehicle suspension characteristics and its speed. The results demonstrate that applying the artificial neural network to the wavelet decomposed inertial response signals provides an effective estimation of the road profile.

4. Long-term research goal, novelty and impact

The long-term research goal of the CDSS lab at Louisiana State University is to create multi-hazard resilient and sustainable civil infrastructures and residential communities threatened by manmade and/or natural hazards, and changing climate conditions. The research effort will be focused on advancing the fundamental understanding of the combined wind-surge-wave loading actions (especially the transient and variable nature of the loading) imposed on critical civil infrastructures (residential buildings, offshore wind turbines/oil gas platforms, power transmission/distribution systems, bridges, etc.) through integrated high-fidelity computational modeling and experimental study. The complex dynamics/performance and comprehensive failure mechanism of the infrastructures exposed to extreme single and/or multi-hazard will be studied systematically. Meanwhile, hazard mitigation strategies will be developed to protect the critical infrastructures from damage when impacted by extreme hazards. To timely detect damage occurred to the aging infrastructures, smart sensing methodologies on the basis of emerging technologies will be developed to implement online damage diagnosis/prognosis for old and newly-built infrastructures. In addition, outreach activities (currently ongoing) on educating local k-12 students, inhabitants and community management officers will be implemented to enhance their preparedness and the safety culture about earthquake and windstorm induced multi-hazard.

It is expected that the research data and outcomes will enhance the fundamental understanding on windstorm induced combined wind-surge-wave loading effects. Current design codes and provisions on loading are expected to be improved on the basis of the new findings, which is the foundation to design and build multi-hazard resilient infrastructures and communities. Furthermore, the public safety culture and the quality of community management will be improved to achieve multi-hazard resilient residential communities.

Reference

[1] C. Sun, V. Jahangiri. Bi-directional Vibration Control of Offshore Wind Turbines Using a 3D Pendulum Tuned Mass Damper. *Mechanical System and Signal Processing*, 2018, 105: 338-360.

[2] C. Sun. Mitigation of Offshore Wind Turbines under Wind-wave Load: Considering Soil Structure Interaction and Damage. *Structural Control and Health Monitoring*, 2018 25(3): 1-22.

[3] C. Sun. Semi-active Control of Offshore Wind Turbines under Multi-Hazards. *Mechanical System and Signal Processing*, 2018, 99: 285-305.

[4] J. M. Jonkman, M. Buhl, FAST User's Guide. National Renewable Energy Laboratory, Technical Report, NREL/EL-500-38230, Golden, CO, 2005.

[5] V. Jahangiri, C. Sun. Integrated Bi-Directional Vibration Control and Energy Harvesting of Monopile Offshore Wind Turbines, *Ocean Engineering*, 2019, 178: 260-269.

[6] V. Jahangiri, C. Sun. Performance Evaluation of a 3D-PTMD in Offshore Wind Turbines under Multiple Hazards and Damage, *Smart Structures and Systems*, 2019, 24(1): 53-65.

[7] B. J. Jonkman, L. Kilcher, TurbSim User's Guide: Version 1.06.00, Technical Report, National Renewable Energy Laboratory, Golden,CO, 2012.

[8] V. Jahangiri, C. Sun. Space Vibration Control of Spar-type Offshore Wind Turbines Using Multiple Tuned Mass Dampers (under review).

[9] C. Sun, V. Jahangiri. Fatigue Damage Mitigation of Offshore Wind Turbines under Real Wind and Wave Conditions, *Engineering Structures*, 2019, 178:472-483.

[10] Z. Zhang，C. Sun, R. Bridgelall, M. Sun. Road profile reconstruction and evaluation using connected vehicle responses and wavelet analysis. *Journal of Terramechanics*, 2018，80：21-30.

[11] Z. Zhang, C. Sun, M. Sun, R. Bridgelall. Application of a Machine Learning Method to Evaluate Road Roughness from Connected Vehicles. *Journal of Transportation Engineering, Part B: Pavements*, 2018, 144(4): 04018043.

[12] https://www.infrastructurereportcard.org/