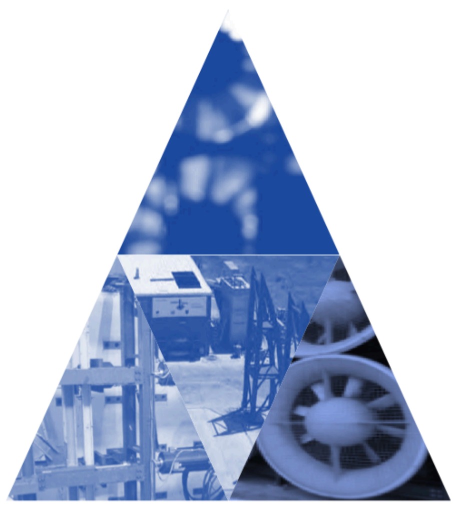
Multi-hazard Engineering Collaboratory on Hybrid Simulation (MECHS)

Committee on RTHS in Fluid-Structure Interaction (FSI) Applications

A Committee Report

November 2020



The Research Coordination Network in Hybrid Simulation for Multi-hazard Engineering is supported by a grant from the National Science Foundation (CMMI#1661621).

Executive Summary

Real Time Hybrid Simulation (RTHS) is a powerful technique that integrates physical experimentation with computational simulation. Typically, RTHS has been used in earthquake related studies to evaluate response of complex civil engineering systems. Recently, there have been several calls to further the development of RTHS for Fluid-Structure Interaction (FSI) engineering application. FSI research areas include, among several others, wind-structure interaction (e.g. aero-dynamic behavior), wind-induced vibrations (e.g. aero-elastic behavior) of slender structures, active wave absorption, advanced control for marine renewable energy (energy harvesting), behavior of marine structures (e.g. floating wind turbines, etc), and tsunami loading on structures. Thus, most recently, a committee on RTHS for FSI application has been established within the MECHS center. The committee brings together various expertise from FSI and RTHS fields in an attempt to expand HS/RTHS capabilities to the application of FSI engineering fields. The committee members will work together to identify the challenges and limitations, and develop guidelines for laboratory testing. The ultimate aim of the committee is to develop standards to maintain the quality of the conducted tests and to broaden the range of testing.

During the first meeting in March 2020, the committee members agreed to report the past and ongoing projects that relate to RTHS applications in FSI fields. Provided in this report is a list of a summary of eight ongoing projects from the committee members in the areas of wind, wave, tsunami applications. Each project provides a summary for the project overview, objectives, research methods, photos from the test, summary of the findings and lesson learned. The committee plans to provide more details about the ongoing and future projects as new findings arise. The committee also plan to hold a workshop to discuss the ongoing projects with interested researchers who would like to learn more about RTHS applications especially related to FSI applications.

RTHS-FSI COMMITTEE MEMEBRS:

Chair
Amal Elawady, Florida International University, USA (aelawady@fiu.edu)
Members
Shirley J. Dyke, Purdue University, USA
Oh-Sung Kwon, University of Toronto, Canada
Arindam Gan Chowdhury, Florida International University, USA
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James Ricles, Lehigh University, USA
Denis Istrati, University of Nevada, Reno, USA
Steven Wojtkiewicz, Clarkson University, USA
Pedro Fernandez-Caban, Clarkson University, USA
Thomas Michel Sauder, SINTEF, Norway
Pedro Lomonaco, Oregon State University, USA
Barbara Simpson, Oregon State University, USA
Wei Song, University of Alabama, USA
Jacob Waldbjørn, University of Denmark, Denmark
Amin Magahareh, Purdue University, USA
Brian Phillips, University of Florida, USA
Teng Wu, University at Buffalo, USA
Peter Thomson, University of Cali, Colombia, USA
Johnny Wilfredo Condori, Purdue University, USA
Sunny Sharma, Purdue University, USA

1. Real-Time Hybrid Simulation Enabled Damping System Assessment Using Scaled Aeroelastic Models of Tall Buildings

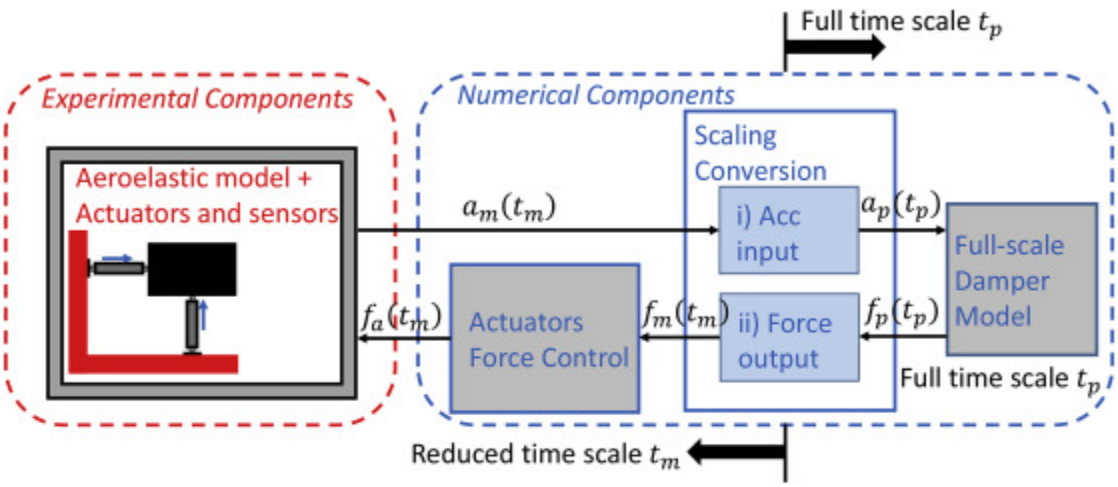
Project Team and Affiliations:

Wei Song (*The University of Alabama*)
Teng Wu (*University at Buffalo*)

Project Overview and Objectives

This project aims to develop a real-time aerodynamics hybrid simulation (RTAHS) framework that can offer improved response evaluation of a tall building integrated with an auxiliary damping system. Under the proposed RTAHS framework, the evaluation of wind-induced tall building response is achieved by interacting an aeroelastic model of the tall building with the numerical model of the full-scale damper via interfacing actuators during wind-tunnel tests.

Flowchart showing the Experimental and Numerical Sub-Structures



Experimental Details (e.g., Instrumentation) and Numerical Algorithms

The development of the proposed framework is still in its early planning stage. The experimental components include the aeroelastic model of the tall building under investigation, interfacing actuators, sensors, and other necessary hardware; the numerical components include the damper model, actuator force control algorithm, scaling conversion toolsets, and necessary time integration schemes.

Test Setup and Photos

In progress

Results

Multi-Hazard Engineering Collaboratory for Hybrid Simulation (MECHS) Committee on RTHS in Fluid-Structure Interaction (FSI) Applications

In progress

Challenges and Lessons Learned

In this early phase of the project, the challenges mainly include the following aspects:

- Experimental design of RTHS enabled wind tunnel tests
    - Appropriate design selections for the aeroelastic building model
    - Reliable interfacing mechanisms between experimental and numerical components in wind-tunnel testing environment
- Effective compensation algorithms for force control
- Development of scaling conversion toolsets
- Efficient and robust computational models for full scale damper model

As the project progresses, we will report the lessons learned from our experience.

Recommendations and Future Work

In progress

2. Real-Time Hybrid Model Testing of Floating Wind Turbines

Project Team and Affiliations:

Dr. Maxime Thys, SINTEF Ocean (project manager)
Dr. Valentin Chabaud, SINTEF Energy Research (original developer of the method, control system)
PhD cand. Einar Ueland, NTNU (cable-driven parallel robot)
Prof. Roger Skjetne, NTNU (supervision)
Prof Asgeir Sørensen, NTNU (supervision)
Prof Erin Bachynski, NTNU (floating wind turbine dynamics)
Mr. Lars Ove Sæther, SINTEF Ocean (instrumentation)
Mr Carlos Eduardo da Silva de Souza, SINTEF Ocean (wind turbine simulation and controller)
Mr Fredrik Brun, SINTEF Ocean (model design)
Dr. Øyvind Magnussen, SINTEF Ocean (control system)
Dr. Lene Eliassen, SINTEF Ocean (aerodynamics, wind field modelling)
Dr. Thomas Sauder, SINTEF Ocean (design of the empirical method, control system, fidelity)

Project Overview and Objectives

The objective of this setup is to study empirically the behavior of floating wind turbines under the combined action of waves, current and wind. The structural response of the tower and blades should be accounted for. The blade pitch controller and generator torque controller should be modelled. The generated data is used for calibration of numerical models, and system verification.

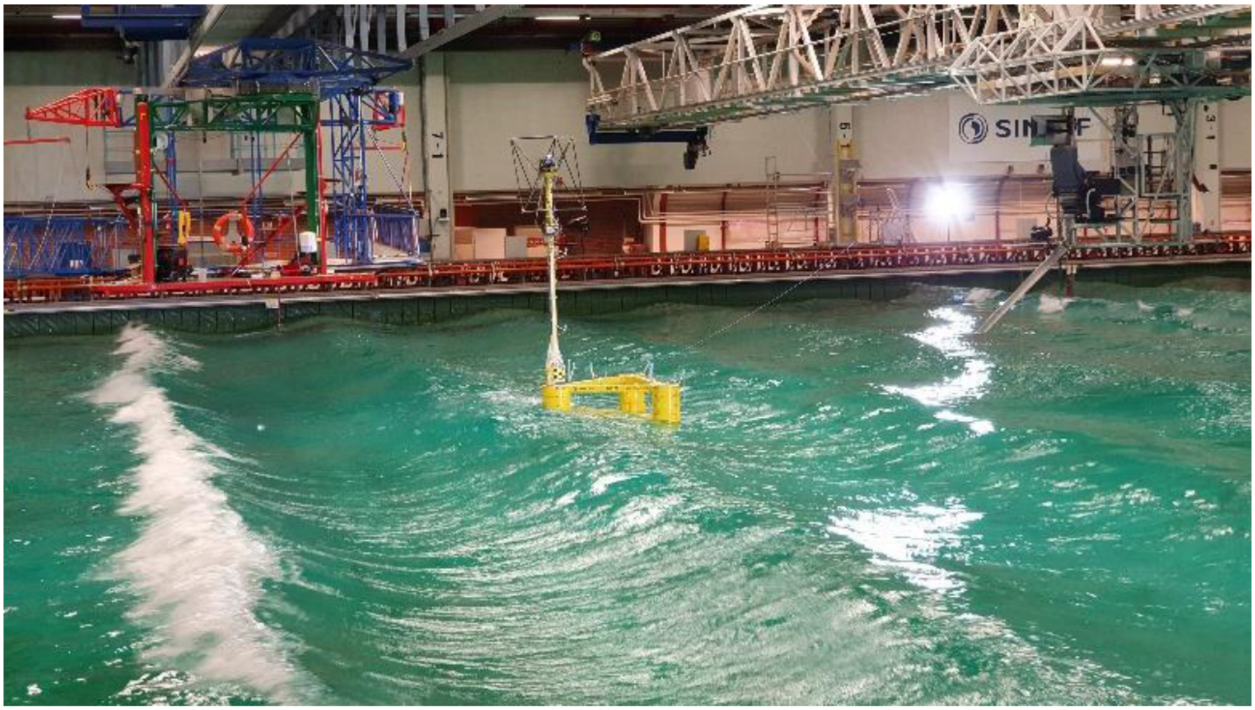
Flowchart showing the Experimental and Numerical Sub-Structures

The physical model of the wind turbine is located in SINTEF's ocean basin (80m x 50m) and subjected to wave and current loads. The rotor/nacelle of the turbine constitute the numerical substructure, subjected to a virtual wind field. The actual pitch blade controller used on field is used. Wind loads are calculated in real-time, fed with measurements in the basin (as well as observed values). Resulting wind loads are actutated on the model (NB: *load* control) using a cable-driven parallel robot consisting of 6 actuators.

Experimental Details (e.g., Instrumentation) and Numerical Algorithms

The wind field is generated with TurbSim (NREL software), and the wind loads are computed with by FAST (NREL software too). Instrumentation: mostly HBM and NI equipment.

Test Setup and Photos



Results

The setup enables studying the behavior of wind turbines in wave, wind and current (motions, tensions in the mooring system, internal structural loads.). Extreme events (gusts, gusts with change of direction) can be simulated with the present setup. Various control strategies (pitch blade) can be compared.

Challenges and Lessons Learned

Main lesson learned: always keep focus on the fidelity (how well we replicate the full-scale system's behaviour), and quantify how the control system influences the fidelity. Delays cause loss of fidelity, but they are other sources: calibration errors, biases, observer dynamics, etc…

Recommendations and Future Work

Our main challenge as of today is to standardize the setup, and make it more efficient (time and costs). We also extend the test method to bottom-fixed offshore wind turbines (higher natural frequencies than floating wind turbines).

3. Cyber-Physical Systems Approach to the Optimal Design of Structures for Wind Hazards

Project Team and Affiliations:

Brian M. Phillips (*University of Florida*)
Forrest J. Masters (*University of Florida*)
Pedro L. Fernández-Cabán (*Clarkson University*)
Michael L. Whiteman (*University of Maryland*)
Justin R. Davis (*University of Florida*)
Jennifer A. Bridge (*University of Florida*)

Project Overview and Objectives

Researchers at the University of Maryland (UMD) and the University of Florida (UF) pioneered a cyber-physical systems (CPS) approach to the optimal design of structures subjected to wind hazards. The approach combines the accuracy of physical wind tunnel testing with the efficient exploration of the design space using numerical optimization algorithms. The approach is fully automated, with experiments executed in a boundary layer wind tunnel (BLWT), sensor feedback monitored by a computer, and actuators used to bring about changes to a mechatronic building model as dictated by the optimization algorithm. The model undergoes physical changes in dynamics or aerodynamics as it approaches the optimal solution, accurately capturing the impacts of these changes on its response.

Flowchart showing the Experimental and Numerical Sub-Structures

Experimental wind tunnel testing provides unparalleled accuracy in the evaluation of buildings and bridges under steady wind loads, gusts, and complex wind-structure interaction. At the same time, computational optimization methods enable the rapid creation and evaluation of competing designs to best meet specified objectives (e.g., minimize weight or base shear) and satisfy constraints (e.g., drift and acceleration limits states). Advances in experimental cyber-infrastructure enabled the seamless integration of wind tunnel testing with computer-driven design and optimization to leverage the strengths of each component (see Figure 1). In the CPS approach, the use of scaled building models with physically adjustable properties (e.g., geometry, stiffness,

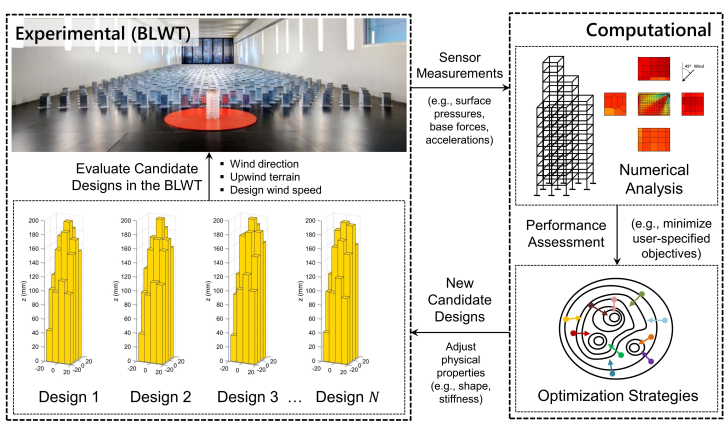


Figure 1. High-level flowchart of CPS framework for optimal design under wind hazards

damping) allows optimal designs to be attained faster than conventional methods and eliminates the need to reconstruct new models and perform additional wind tunnel tests. Mechatronic specimens connected to cyber-infrastructure greatly enhance the capacity of BLWT facilities.

Experimental Details (e.g., Instrumentation) and Numerical Algorithms

All experiments were conducted at the at the NSF-supported Natural Hazards Engineering Research Infrastructure (NHERI) experimental facility at UF. As part of the project, cyber-infrastructure was developed to connect the BLWT operations, specimen instrumentation, specimen actuation, data post-processing, finite element modeling, and heuristic optimization algorithms. The framework was first evaluated for a proof-of-concept low-rise building followed by a landmark tall building (see Figure 2). Model details are discussed below.

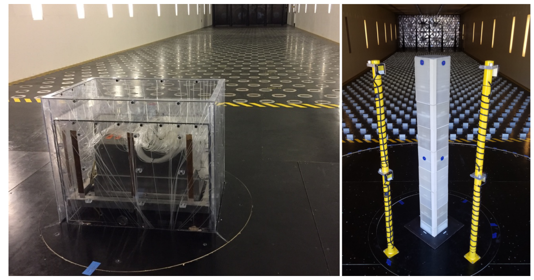


Figure 2. Low-rise pressure tapped model (left) and high-rise aeroelastic model (right).

Results

Proof-of-concept was demonstrated for a low-rise building model with a parapet wall of variable height. Parapet walls alter the location of the roof corner vortices, reducing suction loads on the windward facing roof corners and edges and setting up an interesting optimal design problem. In the BLWT, the parapet height was actuated using servomotors to achieve a design that minimized impacts on both components and cladding and the main wind force resisting system. Exploration of the design space was conducted in the BLWT using multi-objective heuristic optimization algorithms (Figure 3).

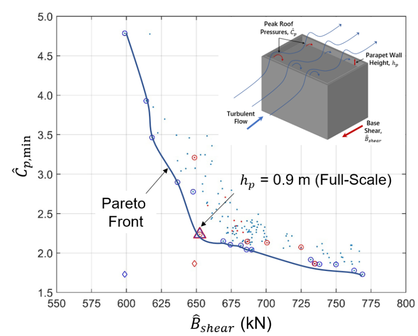


Figure 3. CPS multi-objective optimization of low-rise model.

Further studies focused on tall building design, for which a 1:200 scale multi-degree-of-freedom (MDOF) aeroelastic model was created. The model was equipped with a series of variable stiffness devices (adjustable leaf springs) at the base to enable quick adjustments to the building's natural frequencies (Figure 4). The model's responses were monitored using accelerometers and displacement transducers. Multiple design problems were explored where the model's dynamics and aerodynamics were refined using heuristic optimization algorithms to minimize costs while satisfying acceleration and drift limits.

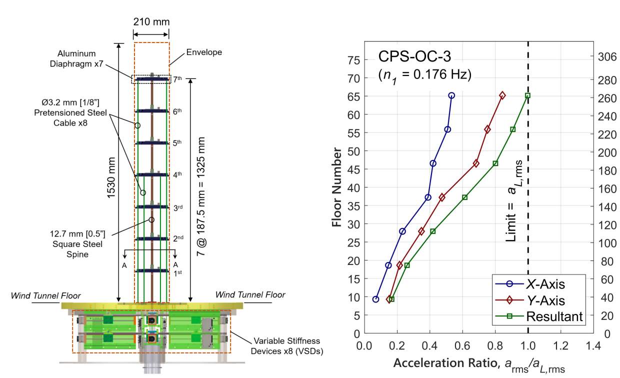


Figure 4. Aeroelastic model equipped with variable stiffness devices and (left) CPS optimization results considering floor acceleration limits (right).

Challenges and Lessons Learned

Although this project is complete, the PI and co-PI are continuing to explore the possibilities for cyber-physical testing in wind engineering. These include new specimen designs inspired by robotics and mechatronics and leveraging advances in hybrid simulation (hardware-in-the-loop testing) where the structure can be partitioned into numerical and experimental components.

Recommendations and Future Work

The use of cyber-physical systems for design optimization has many potential applications in other areas of hazard mitigation. The difficult to model portion of the optimization problem, e.g., wind load and response (as in this project), tsunami load, or material nonlinearities, can be captured through physical modeling. Iterative improvements in the design are sought using numerically-driven optimization algorithms, creating physical changes to the specimen and its performance

4. Aeroelastic Real-time Hybrid Simulation (AeroRTHS): Validation and Mitigation of Vortex Induced Vibration of a Tall Building Structure

Project Team and Affiliations:

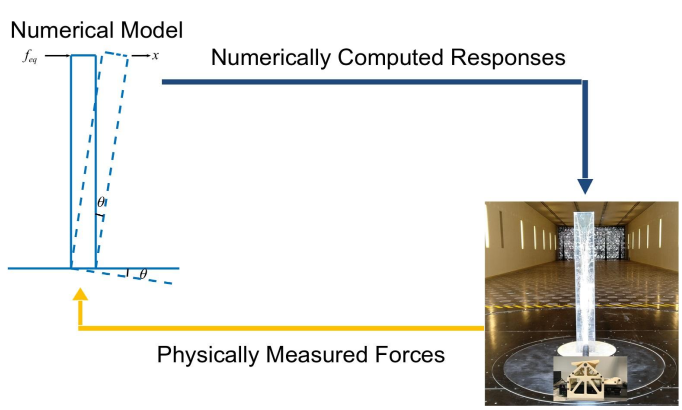
Prof. Richard E. Christenson (University of Connecticut)
Prof. Steven F. Wojtkiewicz (Clarkson University)
Jie Dong (Clarkson University)
Prof. Sergio Lobo-Aguilar (Universidad de Costa Rica)
Dr. Yuan Yuan (University of Connecticut)

*This is an NSF project: (CMMI-1732213 (UConn) and CMMI-1732223 (Clarkson))

Project Overview and Objectives

Due to large aspect ratios and flexible characteristics, modern structures are vulnerable to the effects of wind even at moderate levels. Conventional methods for wind studies often fail to accurately capture fluid-structure interaction. A new test method, called aeroelastic real-time hybrid simulation (aeroRTHS), aims to study aerodynamic vibrations of a structural building model in a wind tunnel. The aeroRTHS method captures the dynamic interaction between an aeroelastic structure and the wind loading to more accurately analyze sophisticated unstable wind phenomena such as vortex induced vibration and in doing so broadens the application of RTHS from earthquake engineering applications to wind engineering. The aeroRTHS tests were conducted in the boundary layer wind tunnel (BLWT) at the University of Florida NHERI EF. A 1 m tall rigid aeroelastic model with 7.3:1:1 aspect ratio is mounted on the single-axis Quanser shake table with a 3D printed pedestal which converts translational motion to rotation at the base of the scaled model. Multiple pressure sensors on both cross-wind surfaces of the model were instrumented to measure the envelope pressure loading. A further step of this aeroRTHS test was to numerically model passive tuned mass dampers (TMDs) in the numerical substructure. The TMD performance in suppressing vortex-induced vibration (VIV) was then investigated in the wind tunnel. Parameter studies were conducted by varying the natural frequency and damping ratio of numerical models and also by utilizing two different ratios of TMD to building superstructure mass.

Flowchart showing the Experimental and Numerical Sub-Structures



Experimental Details (e.g., Instrumentation) and Numerical Algorithms

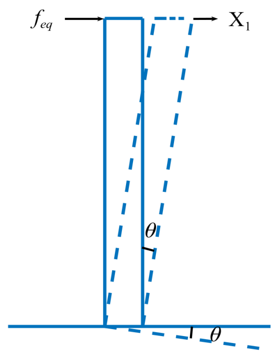
Physical substructure

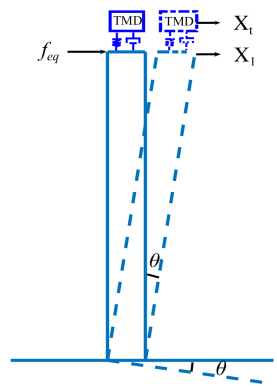
- Boundary layer wind tunnel (BLWT) at UF
- 128 pressure sensors
- Scanivalve pressure scanner
- 1-meter tall rigid physical building model
- 3D printed Quanser shake table transfer system

Numerical substructure

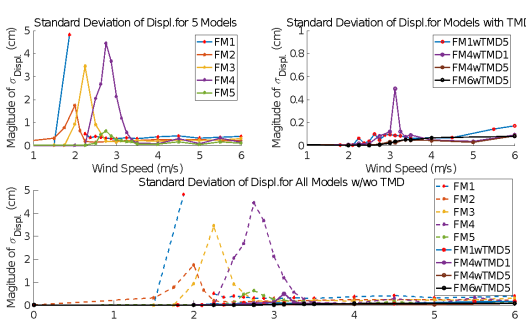
- Equivalent Force calculation algorithm
- Building and TMD equations of motion
- Newmark-Beta numerical integration algorithm

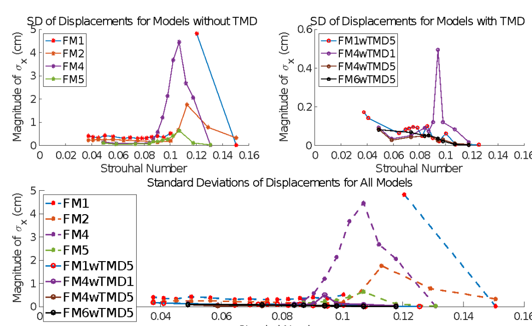
Test Setup and Photos





Results





1. The AeroRTHS method can be used to appropriately and easily tune natural frequency, and set the mass, stiffness and damping of a flexible building model.
2. Compensation of the transfer system and compensation and calculation of a single equivalent wind force from 128 pressure sensors conducted in the real-time of the wind tunnel test.
3. AeroRTHS captures the wind speed dependent phenomenon of vortex-induced vibration (VIV) and can provide further understanding of complex fluid-structure interaction in tall buildings.
4. AeroRTHS results demonstrate the feasibility of RTHS being extended to aeroelastic building models tested in a boundary layer wind tunnel.
5. The passive tuned mass damper is an effective way to attenuate cross-wind vibration in tall buildings with performance of various devices validated in a wind tunnel test.

Challenges and Lessons Learned

1. Actuation and compensation of a transfer system for use in RTHS testing in a BLWT to capture the first transverse bending mode of a slender building model.
2. Compensation of the dynamics of Scanivalve pressure transducers for use in RTHS.
3. Synthesis and utilization of 128 measured experimental signals (pressure taps) in RTHS.
4. Algorithm for simultaneously converting multiple wind pressure to a single equivalent wind force.

Recommendations and Future Work

Future work will be conducted in several directions:

1. Improved transfer systems for use in aeroRTHS testing.
2. Improved pressure measurements and synthesis for aeroRTHS applications.
3. Examination of scaling effects on aeroRTHS experimental setup.

5. Coupled Aerodynamic and Hydrodynamic Hybrid Simulation of Floating Offshore Wind Turbines

Project Team and Affiliations:

Barbara Simpson (*Oregon State University*)
Bryson Robertson (*Oregon State University*)
Bryony DuPont (*Oregon State University*)
Ted Brekken (*Oregon State University*)
Pedro Lomonaco (*Oregon State University*)
Andreas Schellenberg (*Maffei Structural Engineering*)

Project Overview and Objectives

Floating, offshore wind energy is quickly becoming a viable source of affordable, renewable energy in the U.S. However, fluid-structure interaction and the fluid flow patterns around floating offshore wind turbines are complex and uncertain multi-physical phenomena. Significant uncertainties are related to the influence of dynamic effects on the turbine and sub-structure response, variability of the wave and wind loading, and modeling of the fluid flow and fluid-structure interaction effects.

Despite increasingly sophisticated computational models, physical aero- and hydro-dynamic experiments are still needed to verify said computational models of floating, off-shore wind turbines (FOWT) due to modeling uncertainties and computational limitations (i.e., in terms of simulation time, size, complexity, and resolution). However, de-coupled wave and wind experiments and computational models are the status quo. Although several large-scale facilities for hydrodynamic and aerodynamic testing exist in the U.S., the simulation of both wind and waves in experimental testing is inaccurate and complex due to a number of constraints, including: incompatible scaling laws between wind and waves and failure to generate wind that reasonably represents the atmospheric boundary layer in wave basins.

Wind tunnel and wave basin experiments often use scaled structural models due to size and capacity limitations of available experimental facilities. A model that is in the same gravity field and uses the same fluid as the prototype cannot fulfill both Froude and Reynolds scaling simultaneously unless the geometric scale is 1.0 (i.e., the model is full scale). This results in inconsistent scaling regimes for the wind (Reynolds) and wave (Froude) actions, making it incorrect to apply both physical wave and wind loading in scaled experiments.

Real-time hybrid simulation (RTHS) using numerical wind can partition an assembly so that one of the fluid is simulated numerically and the other physically. Thus, different scaling laws can be independently identified for wind and waves, mitigating these scaling constraints. This approach can alleviate the complexities associated with computational models (e.g., by physically representing the hydrodynamic phenomena near the free surface, higher-order wave loads, hydro-elasticity, slamming loads, viscous loads on slender structures like nets or risers, and wave-current interaction) while leveraging the additional sophistication gained through the coupled numerical model (e.g., wind effects, structural geometries, scaling effects, etc.).

Multi-Hazard Engineering Collaboratory for Hybrid Simulation (MECHS) Committee on RTHS in Fluid-Structure Interaction (FSI) Applications

The objective of this project is to implement real-time hybrid simulation (hydro-RTHS) to model simultaneous aero- and hydro-dynamic loads on floating offshore wind turbines. The outcome of this research will be a robust, modular, and extendable framework for hydro-RTHS testing of FOWTs with wind and wave loading, thus supporting innovative research and development related to offshore wind energy. The partitioning associated with the hybrid simulation framework mitigates scaling constraints by supplying different scaling laws to the physical and numerical sub-assemblies.

Flowchart showing the Experimental and Numerical Sub-Structures

Fig. 1 shows the partitioning between the numerical and physical sub-assemblies. The combined effects of wind and waves are represented by simulating the wind (and associated controls and structural dynamics) in a numerical model, enabling the study of simultaneous wave- and wind-structure response of FOWTs in a wave-only test facility. Herein, the assembly is partitioned into a physical sub-assembly (the wave, partial structure, and mooring lines) and a numerical sub-assembly (the remaining structure and wind). The physical and numerical sub-assemblies interact using actuators and represent the response of the complete assembly, including the wave- and wind-structure interaction. This coupling occurs in real time to be consistent with the rate-dependent behavior of the fluid-structure interaction.

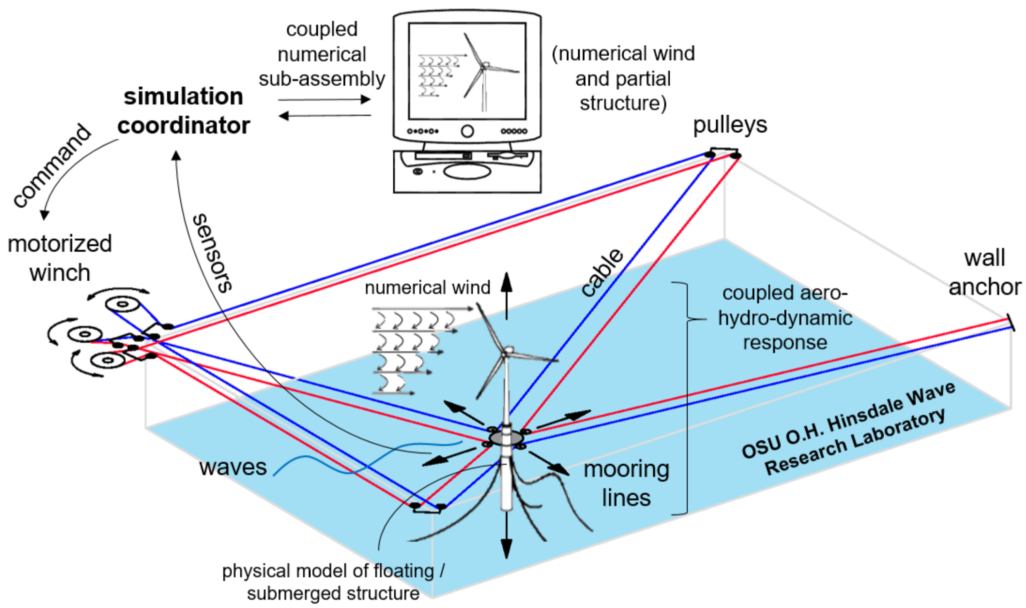


Fig. 1. Schematic of hydro-RTHS test
(actuation design is in progress and shown for illustrative purposes).

Experimental Details (e.g., Instrumentation) and Numerical Algorithms

Herein, the aerodynamic loads important to the structure will be applied to the physical model using an actuation system (the actuation system design is in-progress but an example cable-motor assembly is shown in **Fig. 1**). The measured response from the physical sub-assembly (wave actions and partial FOWT) will then be used to inform the state of the numerical sub-assembly (wind actions and remaining FOWT). The response of the complete assembly (wind-wave-FOWT) and subsequent commands will then be obtained by executing a step-by-step numerical solution of the governing equations of motion using OpenFAST considering the coupled hybrid physical-numerical assembly; see **Fig. 2**. An example schematic of the three-tier hybrid simulation architecture is shown in **Fig. 3** with the following components:

a. The finite element software for the numerical sub-assembly (i.e., response of the FOWT to the numerical wind) resides in the simulation host computer.

b. The controller and data-acquisition (DAQ) system controls and monitors the motion of the physical-assembly induced by the actuators and physical wave actions.

c. In between [a] and [b], the real-time target computer facilitates time synchronization between the simulation host-computer (which conducts the numerical time-stepping integration scheme) and controller (which runs in real time). This intermediate machine generates commands in real-time from the finite-element software that are sent to the controller.

Since [a], [b], and [c] are all collocated, SCRAMNet+ cards and fiber optics cables will be used to provide local high-speed connections to reduce communication delays and enable real-time communication among the simulation host computer, real-time target computer, controller, and controller/DAQ. Provided the numerical analyses can execute a time step fast enough due to small-scale similitude requirements, these connections make it possible to execute the simulation in real time.

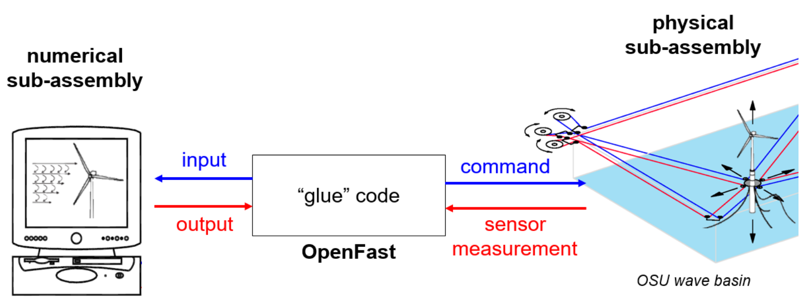


Fig. 2. Hydro-RTHS schematic.

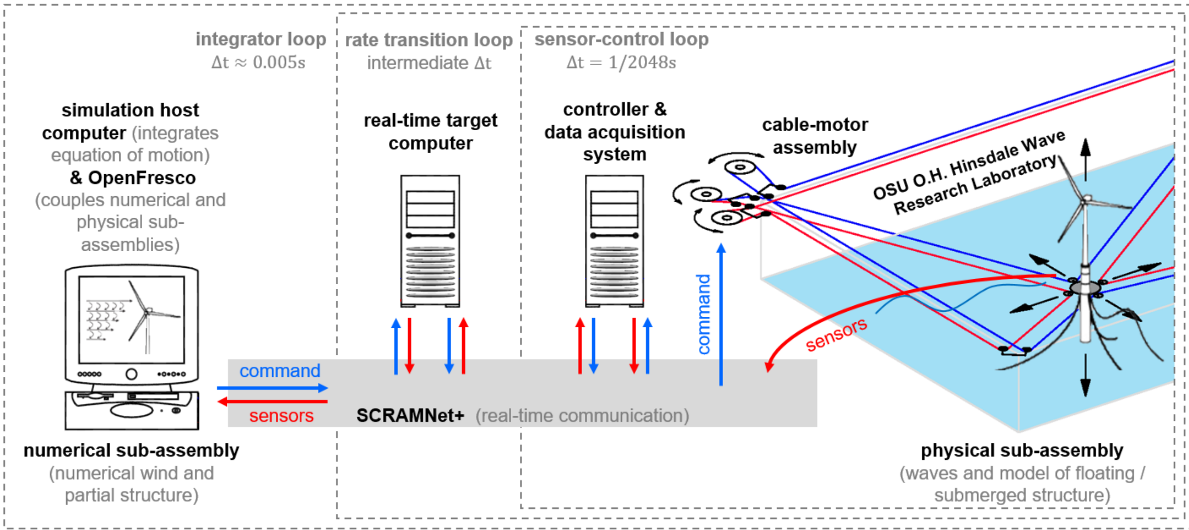


Fig. 3. Hybrid simulation three-tier architecture.

Test Setup and Photos

Test setup design is still ongoing. As of now, the project will conduct the hydro-RTHS tests using a semi-submersible type offshore platform at 1:50 scale. The specimen design will leverage NREL's campaign to validate numerical tools for the design of offshore wind systems. The OC5 (Offshore Code Comparison Collaboration, Continued, with Correlation) comparison will be used for model-scale validation (the OC5 project included small-scale experiments in the Maritime Research Institute Netherlands offshore wave basin for the DeepCwind floating semi-submersible wind turbine). Resource conditions for the wind and wave will be consistent with select locations (southern Oregon) on the west coast of the U.S.

Results

Expected testing to occur between Aug.-Dec. 2021.

6. Collaborative Research: Advancement in Wind Testing Methods using Hybrid Simulation Technology

Project Team and Affiliations:

James M. Ricles (Lehigh University)
Amal Elawady (Florida International University)
Arindam Chowdhury (Florida International University)
Peter Irwin (Florida International University)
Thomas Marullo (Lehigh University)
Liang Cao (Lehigh University)
Safwan Al-Subaihawi (Lehigh University)
Haitham Mohamed (Florida International University)
James Erwin (Florida International University)

Project Overview and Objectives

The NSF-Natural Hazard Engineering Research Infrastructure (NHERI) FIU Wall of wind (WOW) and Lehigh Real-Time Multi-Directional (RMTD) Experimental Facilities (EFs) are collaborating to advance Real-Time Hybrid Simulation (RTHS) for wind engineering applications. This collaboration combines the strengths of WOW large-scale wind testing with Lehigh's expertise in RTHS and computational capabilities to model the behavior of complex engineering systems under wind action.

The focus of this project is to analyze the aero-elastic behavior of a telecommunication tower mounted on the rooftop of a high-rise building. A 40-story building (170 ft x 107 ft x 544.5 ft) with a rooftop telecommunication tower of 131.25 ft height is selected for this study. The fundamental frequencies of the building are 0.17 Hz and 0.24 Hz in the two principle directions while the fundamental frequency of the telecommunication tower is 0.5 Hz in both directions. Thus, possible interactions between the two systems are expected where the building vibrations and deflections at the roof height can alter the aeroelastic response of the telecommunication tower and create unpredicted wind-induced vibrations and possible instabilities, which can significantly hinder their functionality. Such behavior cannot be investigated using typical finite element modeling or isolated wind tunnel testing. For the case of a high-rise building, the material and geometrical nonlinearity of the building is essential to better estimate the building behavior. Such nonlinearity cannot be considered in typical wind tunnel testing. Nevertheless, to obtain an accurate estimate of the wind-induced vibrations of flexible structures like the telecommunication tower, an aeroelastic simulation of the wind-structure interaction is necessary. The new RTHS capabilities will enable studies on the rate dependent nature of the wind-induced vibrations of flexible structures at large scales, which in turn will minimize scaling errors. This is particularly important to simulate aero-elastic behavior and instabilities caused by wind-induced vibrations. The numerical component of the RTHS can enable accounting for material and geometrical nonlinearities, which is not yet possible in typical wind tunnel testing.

Flowchart showing the Experimental and Numerical Sub-Structures

The project has three phases: (1) conduct wind testing at the WOW EF using a rigid wind tunnel model to obtain wind pressure measurements, which are used in a hybrid simulation framework as predefined wind loads applied to the building and tower (see Figure 1); (2) conduct RTHS using an aeroelastic model for the telecommunication tower (physical sub-structure) at the WOW EF and numerical model of the structural building system at Lehigh EF; and (3) validate the RTHS method by conducting physical experiments of the complete system to obtain the wind-induced dynamic response of the entire system and comparing the results with those of the RTHS.

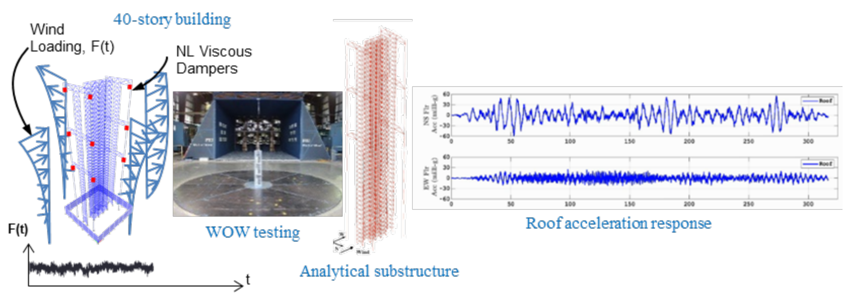


Figure 1: Phase I Hybrid Simulation Results Obtained by Lehigh, WOW EFs

Experimental Details and Numerical Algorithms

To date, the team has completed Phase 1, which included aerodynamic testing of a 1:150 scale rigid model for the building and the rooftop tower (see Figure 2). Pressure measurements were collected using six Scanivalve ZOC33 pressure scanners. The wind velocity profile was measured using six cobra probes devices. The test was conducted under a mean wind speed of 40 mph and varying wind directions.

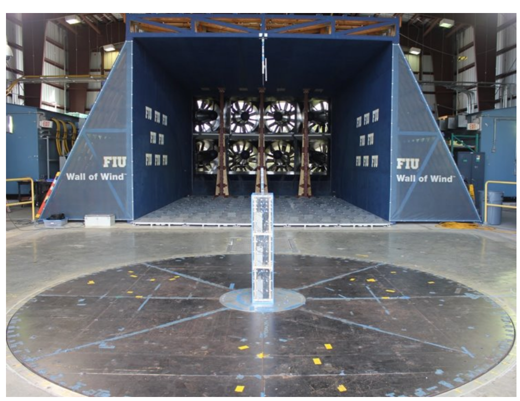
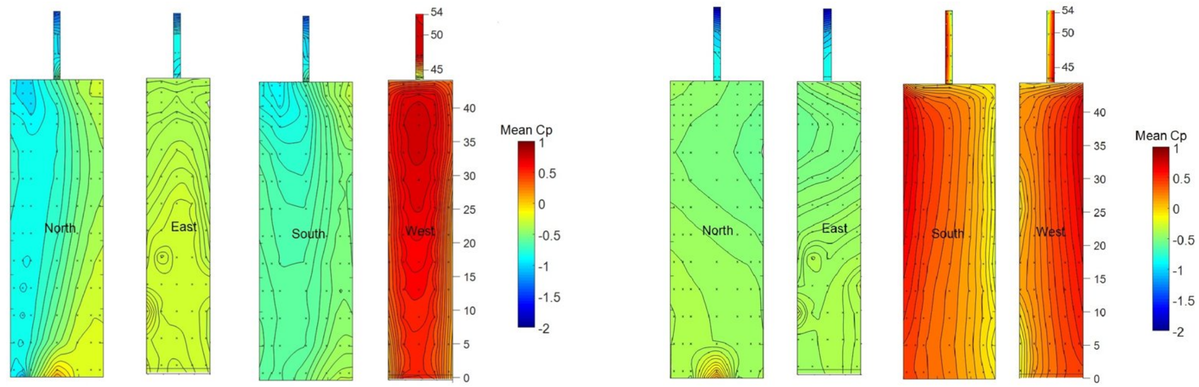


Figure 2: Aerodynamic Testing at the WOW EF

Results

Time histories of the roof accelerations obtained from the numerical model are shown in Figure 1. A sample of pressure coefficients from Phase 1 tests are shown in Figure 3.



(a) (b)

Figure 3: Measured mean wind pressure coefficients for (a) 0° winds; (b) 45° winds

Challenges and Lessons Learned

Part of the challenges encountered are related to aeroelastic modeling and testing of tall buildings include the complexity of matching the mode shape and mass distribution between the model and prototype. A careful and iterative aeroelastic design and testing plan are needed to achieve the targeted dynamic and aeroelastic behavior of the system. More discussion about challenges and lessons learned will be reported after the completion of Phases 2 and 3.

Recommendations and Future Work

The upcoming project phases (Phases 2 and 3) will constitute a step forward towards understanding the existing limitations. Two interconnected tasks will be conducted as follows: (1) RTHS where the building behavior will be simulated using FEM models that are coupled with an aeroelastic model of the rooftop tower; and, (2) conducting aeroelastic testing of the complete system to assess the dynamic behavior of the building with the rooftop tower. The results from the two sub-tasks will enable comparisons between the two methods and will ultimately answer research questions regarding the need for new RTHS frameworks in wind engineering fields.

7. Real-Time Hybrid Experimental-Numerical Simulation of Bridge Infrastructure Subject to Cascading Earthquake-Tsunami Hazards

Project Team and Affiliations:

Barbara Simpson (*Oregon State University*)
Pedro Lomonaco (*Oregon State University*)
Andreas Schellenberg (*Maffei Structural Engineering*)

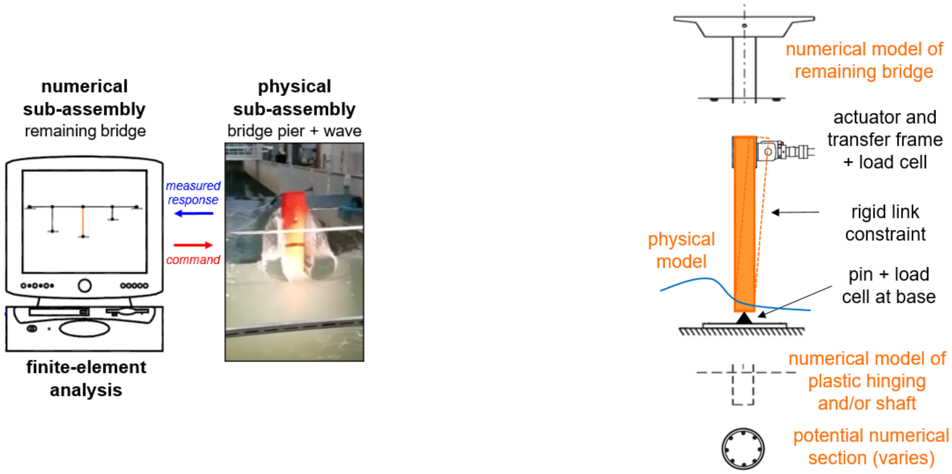
Project Overview and Objectives

Bridge strength can be significantly compromised when the bridge is subjected to cascading earthquake-tsunami scenarios. However, little data exists to support the simulation of bridges to both earthquake and tsunami loading. Test data under individual earthquake and tsunami hazards is available, but space is limited in wave facilities, necessitating small-scale structural models. Scaling laws then make it difficult to incorporate structural damage from previous seismic loading into hydrodynamic experiments. Although numerical models can be analyzed using full-scale bridge properties, few software can apply both seismic and tsunami loading (with structural damage) in a single analysis.

Real-time hybrid simulation (RTHS) – a testing technique that combines physical experiments and numerical models – can alleviate the aforementioned constraints by coupling the physical experiment with a numerical model. The objective of this work is to develop a hydrodynamic RTHS approach (termed hydro-RTHS) to study the vulnerability of bridges subjected to subsequent earthquake-tsunami loading. Hydro-RTHS will be used to virtually extend the Large Wave Flume at OSU, enabling holistic testing of a complete bridge subjected to numerical earthquakes and physical waves.

Flowchart showing the Experimental and Numerical Sub-Structures

Fig. 1 shows the partitioning between the numerical and physical sub-assemblies. A structural model representing a multi-span reinforced-concrete bridge, including abutments, will be used to simulate the bridge response. To study bridge pier response to cascading earthquake-tsunami loading, the hydro-RTHS approach partitions a bridge system such that: [i] the waves and bridge pier reside in a physical sub-assembly and [ii] the remaining bridge, including damage from seismic loads, resides in a numerical sub-assembly. Additionally, the mass, damping, and inelastic response of the bridge will reside in the numerical sub-assembly and the pier, wave loading, and fluid-structure interaction effects will reside in the physical sub-assembly. The effects of scour and soil-structure interaction at the base of the pier will also be included in the numerical sub-assembly for certain runs.



(a) (b)

Fig. 4. Schematic of hydro-RTHS test: (a) numerical and physical sub-assemblies; (b) numerical model of bridge pier with spring at base to model inelastic response or SFSI effects.

Experimental Details (e.g., Instrumentation) and Numerical Algorithms

The RTHS tests will use a cylindrical bridge pier specimen; see orange pier in **Fig. 1**, which is pinned at the base. Instrumentation and actuation at the interface between the numerical and physical sub-assemblies is shown in **Fig. 5**. These hydro-RTHS tests will be conducted using the three-tier testing architecture, including the controller and data-acquisition system, real-time target machine, and host machine housing the finite-element analysis, as shown in **Fig. 3**. The shared memory network, SCRAMNet+, and fiber optic cables connect the hybrid simulation nodes.

The damage states and residual displacements numerically induced by the earthquake will be retained as the initial state for physical testing in the wave flume. For each time step, the displacements, $\boldsymbol{X}^{i+1}$, are known from the finite-element analysis. The numerical and physical displacements, $\boldsymbol{X}_n^{i+1}$ and X_p^{i+1}, will be extracted from $\boldsymbol{X}^{i+1}$. The force at the interface of the sub-assemblies, f^{i+1}, due to the wave loading acting on the structure, $q_{wave}(\boldsymbol{x}, t)$, will be measured at a load cell located at the top of the pier. Resisting forces in the numerical sub-assembly, $\boldsymbol{R}_n^{i+1}$, (including potential plastic hinging or soil-foundation-structure (SFSI) interaction effects at the base of the pier) will be calculated using the virtual displacements, $\boldsymbol{X}_n^{i+1}$, and applied interface force, f^{i+1}. The forces, f^{i+1} and $\boldsymbol{R}_n^{i+1}$, will then be used to solve for the displacements at the next time step, $\boldsymbol{X}^{i+2}$. This process will be repeated for the remaining time steps.

In the numerical sub-assembly, a virtual spring will be included at the base of the pier to represent potential inelastic hinging and soil-structure interaction effects; see **Fig. 7**. The pier specimen in the physical sub-assembly will correspond to a rigid link between nodes 1 and 2 in the numerical sub-assembly. With this rigid constraint, rotational degrees-of-freedom in the pier are constrained to the translational degree-of-freedom at the top of the pier. Nodes 1 and 2 will rotate with the rigid element, imposing flexural deformations (which give rise to moments) in the spring at node 2 and at the ends of the elements in the bridge deck connected to node 1. Deformations in the spring then correspond to the rigid-body rotations induced by X_p^{i+1}.

Because the pier is idealized as rigid, the distributed load from the wave, q_{wave}, does not contribute to moment equilibrium at the ends of the rigid element (fixed end forces in the basic system) and only appears as nodal forces at nodes 1 and 2. In addition, the translational degrees-of-freedom at node 2 are constrained to the fixed boundary condition at node 3 and condensed out of the equations of motion. As such, the force arising from q_{wave} only needs to be measured at the load cell co-located with the nodal force at node 1, which materializes in the equations of motion as f^{i+1}. Thus, the moments in the spring are incorporated into the equations of motion when solving for the new lateral displacement at the top of the pier, X_p^{i+1}, and the resisting forces, applied loading, and reactions satisfy dynamic equilibrium. To validate this approach, a load cell will also be included to monitor the horizontal reaction force at the base of the pier.

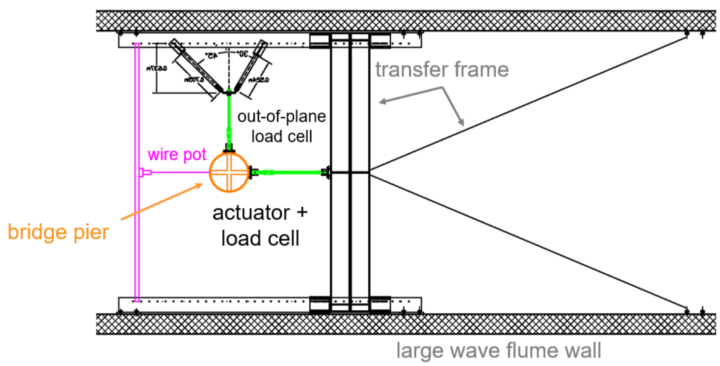


Fig. 5. Actuation and select instrumentation.

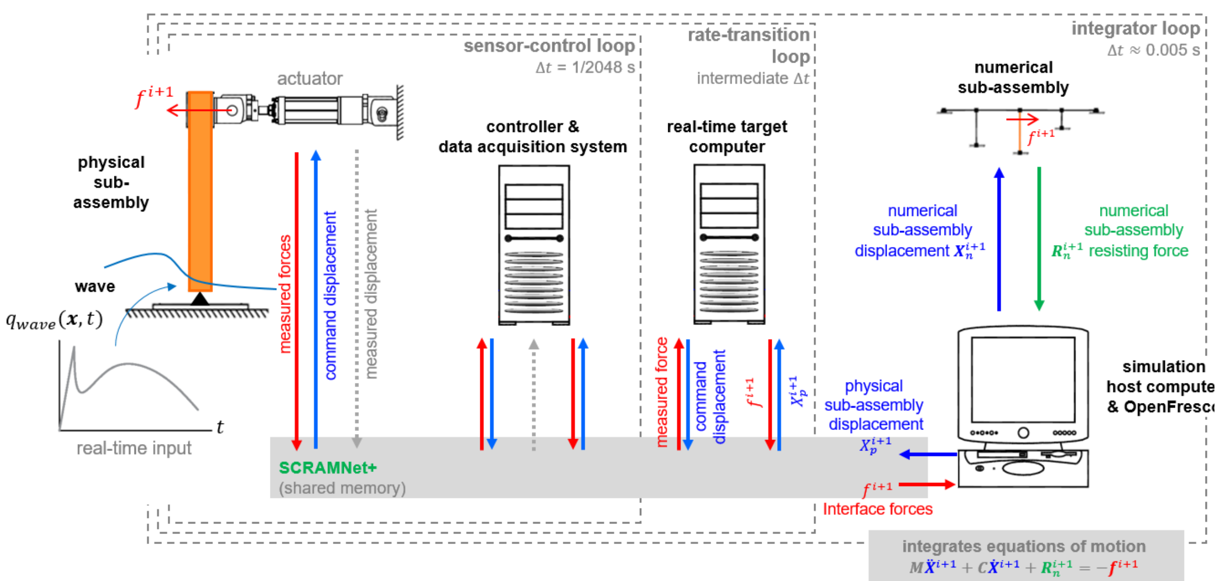
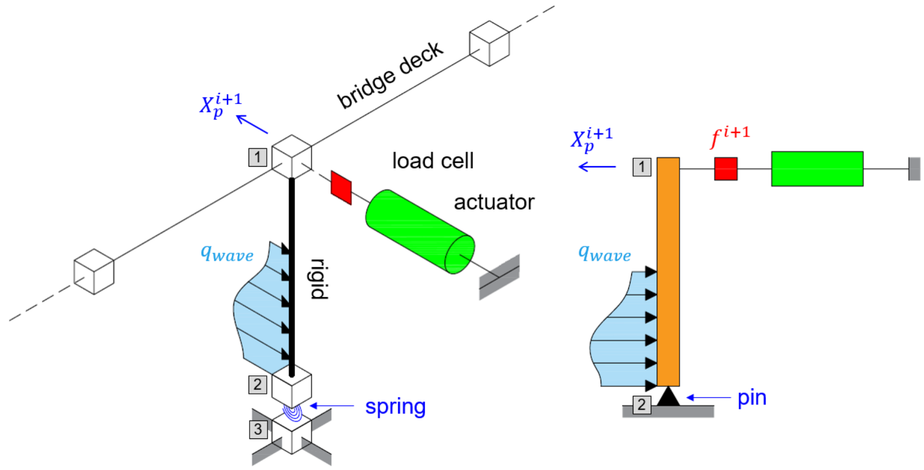


Fig. 6. Hydro-RTHS schematic.



(a) (b)

Fig. 7. Schematic of (a) wave and bridge assembly with actuator and load cell and (b) physical sub-assembly.

Test Setup and Photos

A three-dimensional schematic of the bridge pier specimen and its placement along OSU Large Wave Flume is shown in **Fig. 8** and **Fig. 9**, respectively.

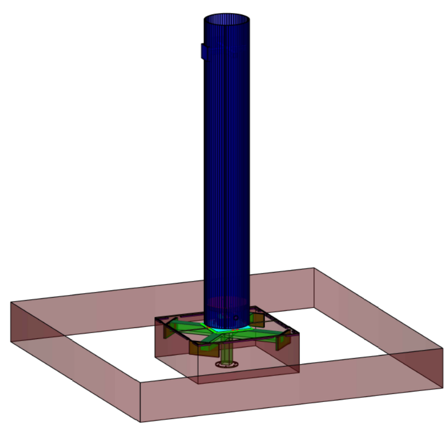


Fig. 8. Bridge pier specimen.

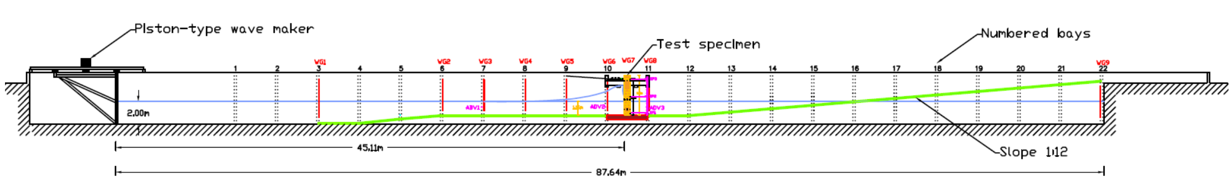


Fig. 9. Test setup in OSU Large Wave Flume.

Results

Expected testing to occur between Aug.-Dec. 2020.

8. Real-Time Aerodynamics Hybrid Simulation of a Flexible Bridge in a Multiple-Fan Wind Tunnel

Project Team and Affiliations:

Teng Wu (*University at Buffalo*)
Shaopeng Li (*University at Buffalo*)
Shivam Mishra (*University at Buffalo*)

Project Overview and Objectives

This project aims at developing a reliable framework for testing wind-sensitive structures under extreme wind events (e.g., downbursts and hurricanes). Specifically, an individually-controlled multiple-fan wind tunnel with deep reinforcement learning-based controller is utilized to generate the transient wind fields; real-time aerodynamics hybrid simulation (RTAHS) is used to enhance the conventional aeroelastic model tests. The proposed framework will be demonstrated using a long-span bridge example (sectional model) under downburst winds.

Flowchart showing the Experimental and Numerical Sub-Structures

It is noted that conventional boundary-wind tunnel using passive generation mechanisms cannot reproduce the extreme wind events that present transient features. An actively controlled multiple-fan wind tunnel has been constructed at University at Buffalo to address this issue (Fig. 1).

Figure 1. Actively controlled multiple-fan wind tunnel at University at Buffalo

Regarding the model test, it is known that conventional aeroelastic models for long-span bridges cannot accurately capture the structural dynamic properties due to the small scaling ratios. RTAHS is proposed to enhance the performance of conventional aeroelastic model test. As shown in Fig.

2, the whole structure is separated into two subsystems: the physical "skin" model capturing the aerodynamic properties and the virtual "skeleton" model capturing structural dynamic properties. The interactions of two subsystems are realized by a set of actuators, sensor and controllers (See "*Wu, T., Li, S. and Sivaselvan, M., 2019. Real-Time Aerodynamics Hybrid Simulation: A Novel Wind-Tunnel Model for Flexible Bridges. Journal of Engineering Mechanics, 145(9), p.04019061.*").

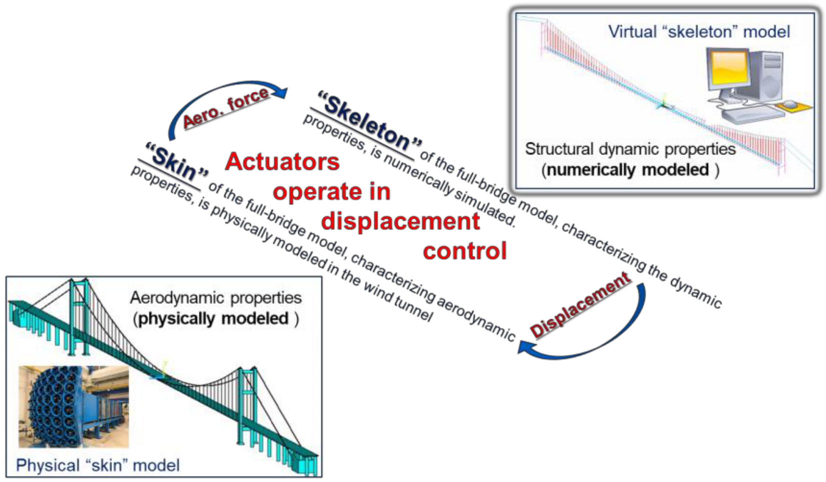


Figure 2. Proposed RTAHS of a long-span bridge in an actively controlled multiple-fan wind tunnel

Experimental Details (e.g., Instrumentation) and Numerical Algorithms

To accurately simulate the extreme wind fields in the multiple-fan wind tunnel, a novel control scheme based on deep reinforcement learning is proposed, which eliminates time-consuming hand tuning (Fig. 3). Regarding the RTAHS, a novel design is utilized where the controller design does not require the knowledge of the physical "skin" model (Fig. 4).

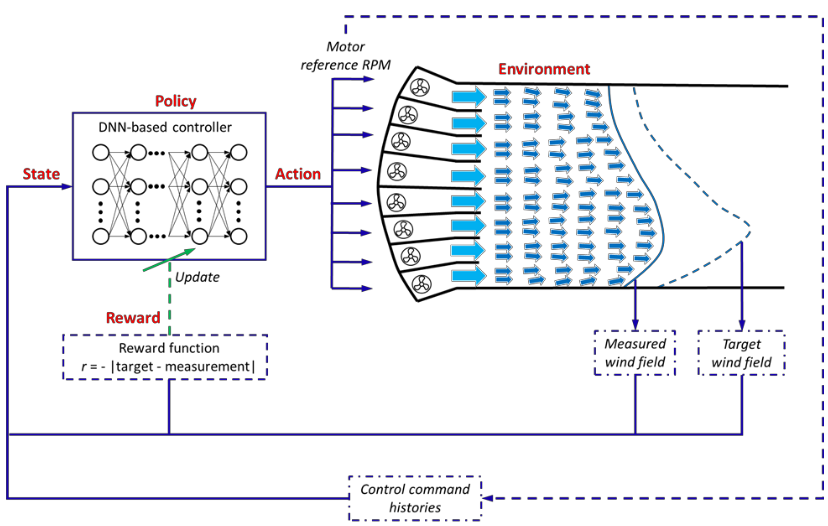


Figure 3. Deep reinforcement learning-based controller for the multiple-fan wind tunnel

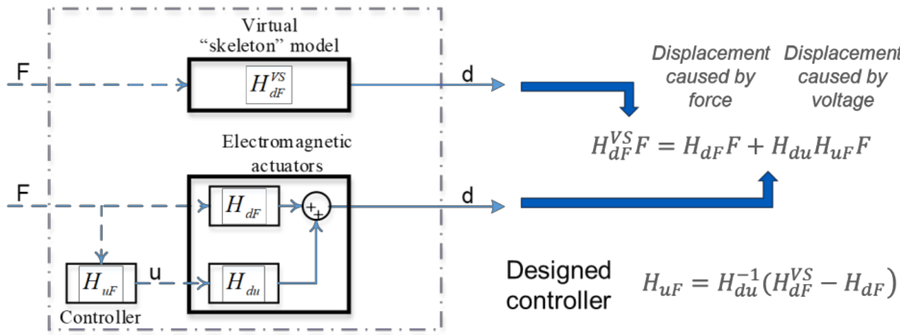


Figure 4. A novel controller design for RTAHS

Test Setup and Photos

The test setup for RTAHS of a sectional bridge deck has been built, which is shown in Fig. 5. The electromagnetic actuators used in the RTAHS have been tested (Fig. 6).

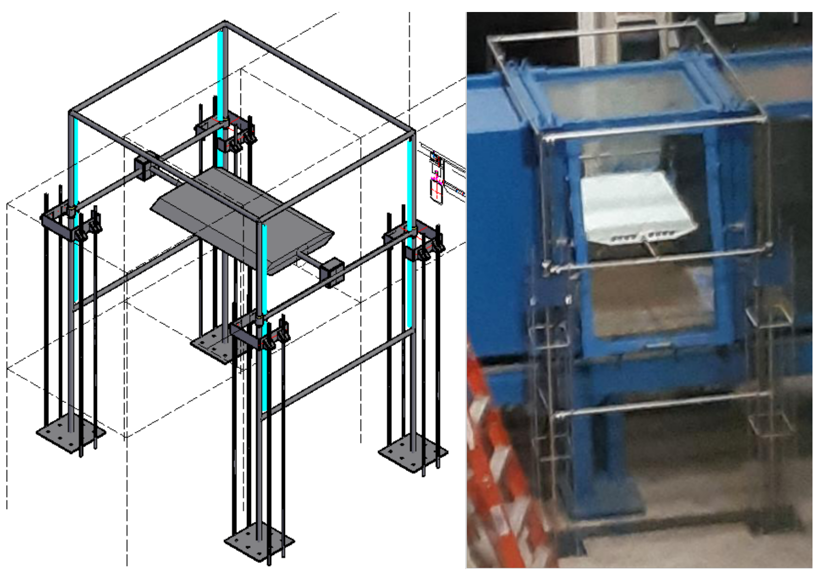


Figure 5. Conceptualized sectional model and frame (left) and constructed model and frame (right)

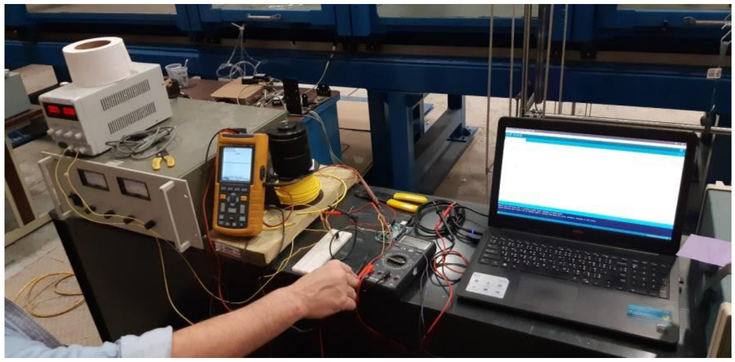


Figure 6. Electromagnetic actuator test

Results

The numerical simulations have demonstrated good performance of the deep reinforcement learning- enhanced multiple-fan wind tunnel to reliably generate transient winds (Fig. 7) and the designed novel controller to accurately achieve RTAHS (Fig. 8).

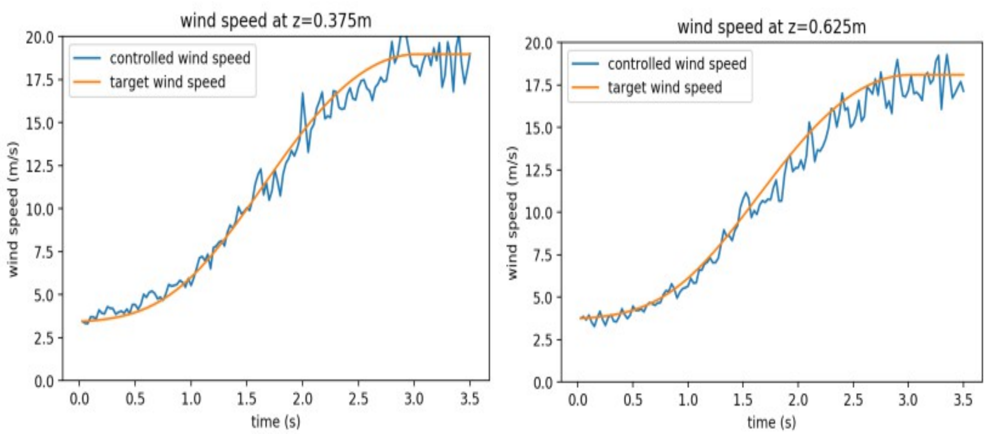


Figure 7. Simulated and target downburst wind fields

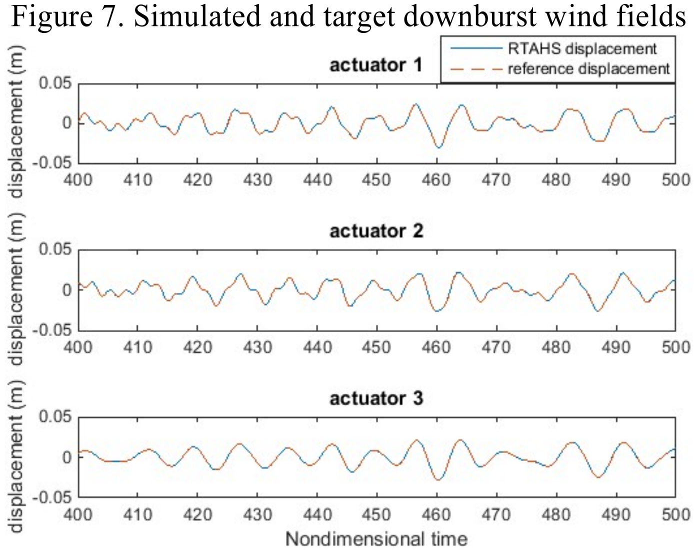


Figure 8. Controlled displacement follows well with reference displacement in RTAHS

7. Challenges and Lessons Learned

Extend the suspended sectional model to full-bridge aeroelastic model.

8. Recommendations and Future Work

The proposed framework will also be used to test other wind sensitive structures such as floating wind turbines and high-rise buildings.