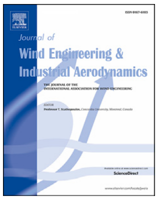
Journal of Wind Engineering & Industrial Aerodynamics 172 (2018) 441–452

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia



Optimal design of structures using cyber-physical wind tunnel experiments with mechatronic models

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ARTICLE INFO

Keywords:
Cyber-physical systems
Mechatronic
Optimization
Boundary-layer wind tunnel
Parapet
UFEF
NHERI

ABSTRACT

This paper explores the use of a cyber-physical systems (CPS) approach to optimize the design of rigid, low-rise structures subjected to wind loading, with the intent of producing a foundational method to study more complex structures through future research. The CPS approach combines the accuracy of physical wind tunnel testing with the ability to efficiently explore a search 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 physical changes to a mechatronic structural model. Because the model is undergoing physical change as it approaches the optimal solution, this approach is given the name “loop-in-the-model” optimization.

Proof-of-concept was demonstrated for a low-rise structure 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 adjusted using servo-motors to achieve a particular design. Experiments were conducted at the University of Florida Experimental Facility (UFEF) of the National Science Foundation's (NSF) Natural Hazard Engineering Research Infrastructure (NHERI) program.

1. Introduction

Boundary layer wind tunnels (BLWT) are the primary tool in wind engineering to characterize surface pressures on bluff bodies. BLWT modeling is valuable when studying new structures for which the simplified provisions of ASCE 7 are inadequate or too conservative (ASCE/SEI 7-10, 2010). While BLWT modeling has remained a standard for decades, it has not benefited from recent advances in computationally-based optimization techniques for structural design. These techniques are now efficient enough to be applied during live testing if the structure has the ability to morph, e.g., change aerodynamic shape. Metaheuristic algorithms such as particle swarm and genetic algorithms efficiently explore a complex solution space, providing new opportunities to study multi-variate and multi-objective optimization problems. These optimization algorithms have promise for delivering cost-effective design solutions for wind-sensitive structures. Moreover, the accuracy of the numerical optimization process can be improved by combining it with an experimental method such as BLWT modeling.

The goal of the study is to explore the use of cyber-physical systems (CPS) for optimal design in wind engineering. We demonstrate proof-of-concept for cyberinfrastructure-augmented BLWT modeling that produces optimal designs faster than purely experimental methods and with a higher degree of realism than purely computational methods. The approach is fully automated, with experiments executed in a BLWT, sensor feedback monitored and analyzed by a coordinating computer, and optimization techniques used to bring about physical changes to the structural model in the BLWT (see Fig. 1). Because the model is undergoing physical change as it approaches the optimal solution, this approach is given the name “loop-in-the-model” testing.

The building selected for the proof-of-concept was a low-rise structure with a parapet wall of variable height. The windward roof edges on low-rise structures cause a separation of the boundary layer and generate vortex flow with large suction loading that is particularly severe for oblique approaching wind angles. Changing the parapet height has a

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https://doi.org/10.1016/j.jweia.2017.11.013
Received 4 October 2017; Received in revised form 14 November 2017; Accepted 14 November 2017

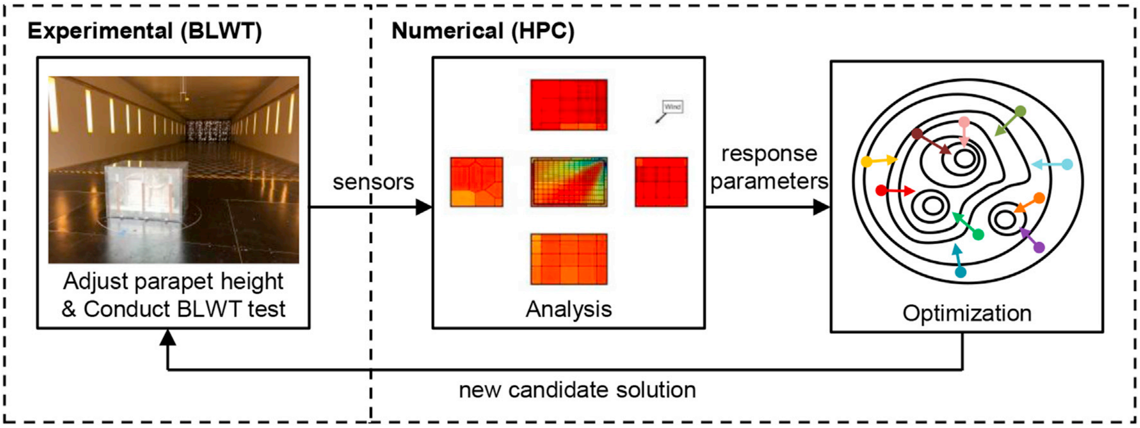

Fig. 1. Diagram of CPS framework for optimal design under wind loading.

significant effect on these wind suction loads because it alters the location of the roof corner vortex, which mitigates extreme corner and edge suction loads with the tradeoff of increasing the downward roof loads in certain cases (Kopp et al., 2005a, 2005b, 2005c, 2005d). In this study, the model parapet height was adjusted automatically using servo-motors to create a particular design that is a "candidate" in the optimization framework. The building envelope was instrumented with pressure taps to measure the envelope pressure loading. The taps were densely spaced on the roof to provide sufficient resolution to capture the change in roof corner vortex formation. A modified particle swarm optimization (PSO) algorithm was implemented to achieve optimum parapet height which minimized suction on the roof and parapet surfaces. Experiments were conducted in the BLWT located at the University of Florida Experimental Facility (UFEF) of the National Science Foundation's (NSF) Natural Hazard Engineering Research Infrastructure (NHERI) program.

2. CPS optimization framework

CPSs link the real world with the cyber world, leveraging the capabilities of computers to monitor and control physical attributes (Al-Hammouri, 2012). Common components of CPSs include sensing, actuation, and communication systems for interfacing, computation for executing numerical models or algorithms, and a physical phenomenon of interest. The applications for CPS in civil engineering are diverse, including hybrid simulation (Shing and Mahin, 1984; Takanashi and Nakashima, 1987; Shing et al., 1996), online health monitoring and model updating (Song and Dyke, 2013), and decision-making frameworks (Lin et al., 2012). In civil engineering, experimental testing is essential to capture complex behavior for which numerical models are insufficient, e.g., strong nonlinearities, new devices and materials, and complex loads such as wind loads on bluff bodies. Physical models that capture these behaviors can be linked to numerical algorithms to create a versatile cyber-physical framework. Experimental testing has experienced a revolution through the use of CPS. Applications including the substructuring of physical systems and the substructuring of optimization algorithms are explored below.

In civil engineering, the first use of CPS as an experimental method began in earthquake engineering with what is now known as hybrid simulation (Hakuno et al., 1969; Shing and Mahin, 1984; Takahashi and Nakamura, 1987). Hybrid simulation is a type of hardware-in-the-loop (HIL) test where the structural system is separated into numerical and experimental components that are linked together through a loop of action and reaction using actuators and sensors. In this way, the entire structural system is evaluated with a cost savings through the numerical components and enhanced realism through the experimental components. Hybrid simulation traditionally uses an extended time-scale for the experimental components, capturing the quasi-static nonlinear behavior of the specimen while modeling damping and inertia numerically. The development of rate-dependent structural control devices such as base isolation bearings and fluid dampers spurred interest in expanding hybrid simulation to run both experimental and numerical components in real time. The first modern real-time hybrid simulation (RTHS) was conducted by Nakashima et al. on a SDOF system (Nakashima et al., 1992).

Fig. 2 shows an incomplete set of applications of CPS in civil engineering with a focus on experimental testing in earthquake and wind engineering. HIL testing has been developed for earthquake engineering in the form of hybrid simulation and RTHS. Similar HIL frameworks can be developed for wind engineering to study complex problems such as progressive failure and fluid-structure interaction, represented by the dashed boxes with X's under the *Hardware-in-the-Loop Testing* group in Fig. 2.

Another opportunity for CPS in civil engineering is a substructuring of the optimization process, shown in the *Cyber-physical Optimization* group in Fig. 2. Key to this framework is the numerical exploration of the search space coupled with the experimental creation and evaluation of a candidate designs. Experimental evaluation can take the form of either traditional testing methods (e.g., BLWT) or HIL methods (e.g., RTHS). The former is explored in this paper using a mechatronic specimen to explore candidate designs subject to accurate wind loading created using a BLWT. This application is termed "loop-in-the-model" optimization (LIMO) because the model is iteratively adapting toward an optimal configuration. The name is complementary to "model-in-the-loop" or "hardware-in-the-loop" testing, but instead of substructuring a physical system, a physical system's properties are iteratively adjusted through

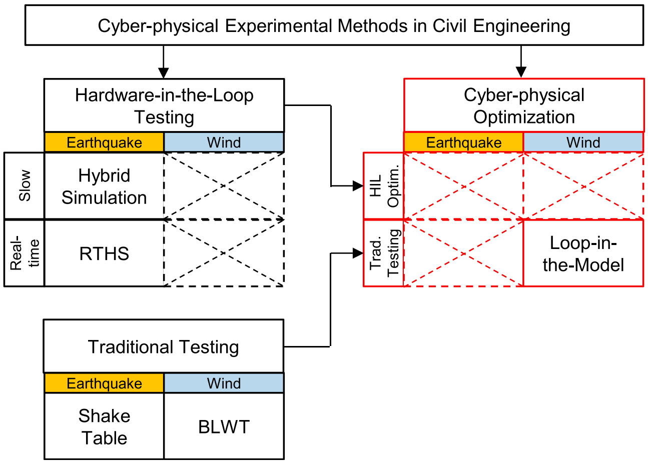

Fig. 2. CPS experimental methods in earthquake and wind engineering.