A first look at cybersecurity of structures under wind

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SUMMARY:
Controlling wind-induced responses is a challenging and fundamental step in the design of wind-sensitive structures. Passive design modifications, such as shape, stiffness, and mass tailoring, and passive control devices, such as dampers, have been demonstrated to mitigate aeroelastic responses effectively. However, further actions are required to fulfill design specifications under some demanding circumstances. Active countermeasures, such as active dampers or flaps, stand out as a smart alternative that allows extra control over wind-induced responses. To make this possible, structural control systems are required to handle the effect of these devices properly. However, as with any other cyber-physical system, these systems can be under the threat of cyberattacks. Changing the intended use of active countermeasures could result in severe structural damage or even the eventual collapse of the structure. This study takes a first look at the potential consequences of cyberattacks against wind-sensitive structures equipped with active countermeasures. Several kinds of cyberattacks, scenarios, and possible defenses are discussed. Furthermore, we conceptually introduce a new kind of cyberattack, the "wind-leveraged false data injection" (WindFDI), that can be specifically developed for wind-sensitive structures by taking advantage of the positive feedback between wind loads and the misuse of active control systems.

Keywords: cybersecurity, wind-induced responses, active structural control

1. INTRODUCTION

The accelerated growth of urban areas in the last decades has led to an unprecedented increase in the construction of tall buildings, long-span bridges, and other wind-sensitive structures. According to the CTBUH skyscraper center database (CTBUH, 2022), 79% of the buildings above 250 m have been built in the last decade (2010-2020), and this trend is expected to continue in the future. Increasing height leads to more slender, flexible, and low-damping structures, which make them more susceptible to earthquakes and wind loads. This has led to the adoption of dynamic modification systems as an effective alternative to control buildings' performance and improve human comfort. According to Lago et al. 2018, about 11% of tall buildings above 250 m worldwide are equipped with dynamic modification systems, and 97% of those have been equipped in the last three decades. This approach is prevalent in the US, where 25% of tall buildings are damped, and the percentage of damped tall buildings built in the last decade reached 42%. However, increasing their height and complexity requires advanced design strategies (Irwin, 2009), such as active mass dampers (AMD) (Kareem et al., 1999; Ricciardelli et al., 2000). Currently, 12% of damped buildings worldwide use AMD systems (CTBUH, 2022), and this trend is expected to grow as architectural requirements increase. Alternatively, the external shape can be used to improve tall buildings' response. This technique has evolved from experimental data-driven tailoring (Kwok et al., 1988) to CFD-based optimization (Elshaer et al., 2017). Moreover, Ding and Kareem, 2020, suggest that active adaptive façade systems can further improve the mitigation of wind-induced responses, highlighting the growing influence of active control systems in the field again.

Similarly, long-span bridges are another clear example of active control systems' capabilities to advance passive countermeasures' contributions in mitigating undesired wind-induced responses. Passive countermeasures have been successfully applied by adopting experimental-based tailoring strategies (Larsen and Wall, 2012) and numerical aero-structural optimization methods (Cid Montoya et al., 2022). The limits of passive countermeasures are discussed in Cid Montoya et al. 2022, where it was found that shape modification can improve the aeroelastic response up to a specific limit, and further improvements can be only achieved by introducing alternative modifications to the bridge design. In this context, active systems stand out as a promising alternative to alleviate wind-induced responses of long-span bridges, such as active mass dampers (Chang, 2020), active attachments (Kwon and Chang, 2000), and suction and jet mechanisms (Chen et al. 2020), which have proved to be very effective in research applications (Gao et al., 2021). Very recently, an adjustable wind barrier has been installed on the Xihoumen Bridge, which is automatically controlled by LSA2000 control platform and computer remote control technology (Yang et al., 2022), opening the way to the widespread use of active systems in bridges.

2. CYBER-PHYSICAL SYSTEMS AND VULNERABILITY TO CYBERATTACKS

All these wind-sensitive structures equipped with active countermeasures rely on the effective design and implementation of Cyber-Physical Systems (CPS). CPS include the network of processes, electronic devices, and communication and control mechanisms for mission-critical infrastructures such as the power grid, water plants, etc., and are an important asset to the economies of towns, states, and countries. In recent years, CPS have been transferring to electronic systems due to the vast opportunities available through the implementation and use of digital technology, such as the system's increased reliability, flexibility, resilience, and efficiency (Goff et al. 2014). While the benefits of these changes are unparalleled, cyberattacks at CPS are also unprecedented, which may lead to consequences ranging from power outages to homeland security breaches. In recent years, multiple attacks have occurred, including the Kyivoblenergo and the Prykarpattyaoblenergo attacks in 2015 (Whitehead et al. 2017) and the Ukrenergo transmission station attack in 2016. Moreover, there have been recent concerns that foreign actors may be already attacking CPS infrastructures in the US and Europe (Perlroth and Senger, 2018). Examples of past attacks to CPS can be classified into two groups: (1) attacks to Programmable Logic Controllers (PLCs), including Stuxnet, Triton, and Pipedream Toolkit (Dragos, 2022); and (2) attacks to Industrial Control Systems (ICS), such as Dragonfly and Crashoverride (Slowic, 2018). Active structural control systems are a group of CPS characterized by sensors and actuators able to modify the structure's response to its environment (Preumont and Seto, 2008). The first contribution dealing with cyberattacks to structural systems equipped with active control devices was recently published by Zambrano et al., 2021, where two cyberattacks were analyzed for structures equipped with earthquakes and wind mitigation active systems: (1) Denial of Service (DoS); and (2) False Data Injection (FDI). This study showed the potential of cyberattacks on civil engineering structures and buildings. However, it was not considered the potential damage increase by leveraging the effects of the natural hazard that the active control system is intended to mitigate. Indeed, daily winds can be effectively used to leverage the effects of cyberattacks, potentially leading to drastic damages or the eventual collapse of the structure. An example of the potential amplification of wind-induced responses due to the misuse of active flaps of a bridge deck can be seen in Sangalli and Braun, 2020. In the present study, we analyze the effects of the two attacks mentioned above, focusing on wind-sensitive structures, and expand the study to a new kind of cyberattack where the natural hazard, the wind, is used to increase the effect of the attack, defined as Wind-leveraged False Data Injection (WindFDI). Also, we discuss the attack planning depending on the available information about the structural system and wind conditions. This research effort aims to define criteria for designing and evaluating active control systems, focusing on their robustness for their intended use and resilience to cyberattacks.

3. KINDS OF CYBERATTACKS OVER ACTIVE STRUCTURES UNDER WIND

We consider three kinds of cyberattacks (see Table 1): (1) Denial of Service (DoS); (2) False Data Injection (FDI); and (3) Wind-Leveraged False Data Injection (WindFDI). The first two kinds of attacks have been applied in other fields (Zambrano et al., 2021), while the third one is described in this study for the first time as a new potential threat that can lead to the collapse of the structure.

Table 1. Summary of the main characteristics of the three cyberattacks considered in this study

Cyberattack	Characteristic	Description
DoS	Temporality	Under natural hazard
	Applicability	All active systems
	Effectiveness	Structural response without active system
FDI	Temporality	Always
	Applicability	Only active mass systems
	Effectiveness	Structural effect of moving mass
WindFDI	Temporality	Under frequent winds capable of amplify structural excitation
	Applicability	All active systems
	Effectiveness	Extreme amplification of wind effects. Potentially destructive.

On the other hand, three scenarios can be found depending on how the required information about the target is acquired to execute the cyberattack. This involves (1) the mechanical information of the structure, i.e., dynamic properties; (2) local wind data, including wind velocity, frequency of high wind events, turbulence, the influence of surrounding terrain and obstacles, etc.; and (3) aerodynamics and aeroelastic performance that enables the design of the attack. The availability of each data group changes how the attack should be planned to obtain the required information. Hence, cyberattacks can be classified into informed, uninformed, and hybrid, as in Table 2.

Table 2. Summary of the main characteristics of different cyberattacks scenarios

Cyberattack	Data	Knowledge
Informed	Structural dynamics	Available through FEM models
	Wind modeling	Available through accessible weather stations
	Aeroelastic performance	Aeroelastic models with enough information to plan attacks
Uninformed	Structural dynamics	Require hacking SHM system at the target
	Wind modeling	Require hacking weather stations at the target
	Aeroelastic performance	Require hacking SHM system at the target under wind conditions
Hybrid		Half way between informed and uninformed cyberattacks

Hence, the design of active systems should focus not only on their robustness in mitigating wind effects but also on limiting the ability of cyberattacks to damage the structure. This can be achieved by formulating a multi-objective optimization problem to balance these two goals: (1) maximize the mitigation capabilities of the active system; (2) minimize the impact on the structural integrity under cyberattacks. Moreover, to identify and eventually block ongoing cyberattacks, an external validation with parallel sensing systems should be implemented to minimize structural damage.

4. CONCLUDING REMARKS

This study first looks at an emerging challenge for the wind engineering community: the vulnerability to cyberattacks of active control systems for wind-induced response mitigation. The study analyzes the potential damage of active systems under cyberattacks and defines effective countermeasures by performing defensive strategies and recasting the design of active control systems. Developing and implementing active control systems that address this threat is essential.

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