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High resolution operational modal analysis on a five-story smart building under wind and human induced excitation

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ABSTRACT

The Goodwin Hall Smart Infrastructure facility at Virginia Tech is a five-story "smart building" with an integrated network of 225 wired accelerometers. This study utilizes a subset of 117 sensors to perform Operational Modal Analysis (OMA) of the structure under wind excitation and establish a high-resolution benchmark modal characterization. Frequency Spatial Domain Decomposition and Stochastic Subspace Identification results are compared to validate the extracted modal parameters. Twelve structural modes were identified, including five high frequency local modes. These local modes are crucial features for structures with complex geometries and can generally be identified only with high density instrumentation. Through a parametric analysis and the use of standard deviation estimates, we determine that 50–60 min time series were optimal for high confidence on frequency and damping estimates. Furthermore, we employ standard deviation estimates to improve existing OMA automation methods. This enables continuous modal parameter extraction over a four-day period to understand the characteristics of the two main forms of ambient excitation: wind and human-induced. Although similar continuous analyses have been conducted on bridges, few of this kind exist for buildings. In general, we observe that modal participation of the three fundamental modes is closely tied to wind and human activity and that the confidence in frequency and damping estimates of these modes improves as the excitation increases. Slight decreases in natural frequency with increasing participation occur for several modes, agreeing with behavior observed in bridge monitoring studies. Finally, wind is seen to excite primarily in one direction, whereas humans induce even excitation in all directions.

1. Introduction

The Goodwin Hall Smart Infrastructure facility at Virginia Tech is a five-story "smart building" with an integrated network of 225 wired accelerometers. It is designed for occupant localization [1,2] and classification [3] as well as structural health monitoring (SHM) [4]. Its high sensor density and wired network provide high-resolution structural information at fast sampling rates. In the context of SHM applications, this makes it an excellent testbed for implementing continuous, long-term structural monitoring. This work first aims to describe the design of this unique smart structure, which has a higher accelerometer count than any other instrumented building in the literature. Second, it outlines the procedure for obtaining a benchmark, high-resolution modal characterization of the structure. Finally, the benchmark is used to continuously track modal data over a four-day period, demonstrating how two forms of excitation (wind and human-induced) affect the building response.

In the last twenty years, a number of instrumentation campaigns for bridges and buildings have arisen in order to tackle the challenges of infrastructure maintenance and natural hazards mitigation. Bridges, which are exposed to harsh environments and high loads, are typically extensively instrumented to monitor a variety of hazards, from sudden structural failure to long-term degradation. Some prominent examples of instrumented bridges include the 2nd Jindo Bridge in South Korea [5], the Tsing Ma Bridge in Hong Kong [6], the Tamar Bridge in the United Kingdom [7], the Confederation Bridge in Canada [8], and others [9–11]. Permanent instrumentation of buildings, on the other hand, has received significant interest primarily as a method of monitoring seismic response or validating structural models. Table 1 presents the Goodwin Hall instrumentation program and other extensively instrumented buildings in the literature in the context of several key features. The California Strong Motion Instrumentation Program (CSMIP) has permanently instrumented 170 buildings in the state for monitoring seismic response [12]. This includes the CalTech Millikan Library [13,14] and the UCLA Factor Building [15], which are listed in the table. In addition, many ambient vibration studies of buildings have

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Table 1
Goodwin Hall instrumentation in context of selected extensively instrumented buildings in literature.

Building name	Location	Stories	Height (m)	Year	Permanent?	No. of Accels.	Measured DoFs	Excitation method(s)
Goodwin Hall	**Blacksburg, VA**	**5**	**20**	**2016**	**Yes**	**225**	**117**[a]	**Ambient**
Millikan Library [14,23]	Pasadena, CA	9	44	1969	Yes	36	36	Ambient, Shaker
Factor Building [15]	Los Angeles, CA	15	66	2006	Yes	72	72	Ambient, Seismic
Provincial Admin. Bld. [16]	Bari, Italy	11	60	2011	No	13	13	Ambient (Wind)
Republic Plaza [17,24]	Singapore	65	280	1995	No	4	37	Ambient
Jurong Town Corporation Summit [17]	Singapore	31	141	2000	No	16	138	Ambient (Wind)
Heritage Court Tower [18,25]	Vancouver, Canada	15	43	1998	No	8	30	Ambient
One Wall Center [26,27]	Vancouver, Canada	48	137	2001	No	9	63	Ambient
Shanghai Tower [19]	Shanghai, China	128	632	2015	No	14	154	Ambient
Multi-function Building [20]	Shanghai, China	21	100	2015	No	14	34	Ambient
International Design Center [20]	Shanghai, China	25	100	2015	No	16	72	Ambient
St. Torcato Church [28]	Guimaraes, Portugal	1	50	2013	No	10	35	Ambient
Transamerica Pyramid [29]	San Fransisco, CA	48	257	1985	Yes	22	22	Ambient, Seismic
Pacific Park Plaza [29]	Emeryville, CA	30	89	1985	Yes	21	21	Ambient, Seismic
Imperial Norwalk Ctr. [29]	Norwalk, CA	7	29	1980	Yes	24	24	Seismic

[a] Number of degrees of freedom measured in this study.

been carried out through temporary network deployments, usually consisting of multiple roving sensor setups [16–20]. These multi-setup approaches typically measure a greater of degrees-of-freedom (DoFs), but are mostly intended to provide a one-time characterization for model updating purposes and not for monitoring structural condition and/or performance. Based on the comparison in the table, it is clear that the accelerometer count in Goodwin Hall large relative to its height (five stories). High measurement resolution enables the identification of high-order modes, which exhibit greater spatial complexity. It has been shown for smaller laboratory structures that high-order modes can be more sensitive to the presence of local defects, making them more desirable than low-order modes as features for SHM approaches [21,22]. For a majority of large civil structure tests, low sensor resolution typically limits modal identification to approximately five to eight modes, particularly for low-rise buildings.

Ambient vibrations from excitation sources such as wind or human-induced loading (HIL) are often used in lieu of forced vibration because large structures are difficult and expensive to excite globally through traditional methods, e.g. impact hammers or shakers [30]. Operational Modal Analysis (OMA) is the extraction of modal parameters (natural frequency, damping, mode shapes and modal participation) from ambient vibrations. The fundamental assumption of OMA procedures is that *all* ambient excitation can be modeled as uniform (broadband) random noise. However, recent advances wind and HIL excitation modeling have shown that such phenomena are better represented by time-varying Gaussian and deterministic components [31–33]. This raises questions about the validity of OMA assumptions and subsequent results.

In addition, a growing body of literature has begun to establish that the modal responses of bridges are sensitive to the source and amplitude of ambient excitation by conducting OMA over multiple days, months and years. The most commonly studied factors are wind, pedestrians, and vehicular traffic. Understanding the impact of each of these factors can facilitate the extraction of features that strongly linked to damage and other anomalies. Studies on the Tamar [7] and Hakucho bridges [34], deck acceleration magnitudes were positively correlated with wind speed measurements. Increasing deck accelerations were in turn correlated with decreasing natural frequencies of certain modes. This amplitude dependence of the bridge frequencies is evidence of nonlinear response, which is not surprising for complex civil structures. In the Tamar bridge case, wind effects were only observable for wind speeds above 25 mph. In the context of human induced excitation, Hu et al. [35] observed that the first two modes of the Pedro e Inẽs footbridge dropped in frequency by approximately 2% from low to high pedestrian activity. These modes occurred between 0.5 and 3 Hz, where pedestrian excitation energy is mostly concentrated due to natural human gait frequency. This study demonstrates that even pedestrian activity is enough to induce amplitude nonlinearities in large structures. Other studies also demonstrate similar structural changes due to vehicular traffic [36,37]. Despite these studies on bridges, no comparable work on buildings currently exists. As structural monitoring expands to buildings, it is important to establish whether such excitation induced behavior translates from bridges.

This paper begins with a description of the Goodwin Hall facility and the sensor selection methodology for OMA. It then covers the basic theory behind the OMA algorithms used throughout the study. The results establish high-resolution benchmark modal parameters of the building for high wind activity using sensitivity analysis as a basis for selecting the algorithms' parameters. The high resolution enables the identification of a larger quantity of modes relative to buildings of comparable size. Lastly, a novel adaptation of clustering approaches to automated OMA is presented, then employed over a four-day period to make inferences about the building behavior under wind and human-induced excitation conditions. Based on the excitation amplitude, the identified modal parameters exhibit behavior similar to those highlighted above for bridges. In addition, the direction of excitation (a deterministic component) is seen to have a large influence on modal contribution.

2. Methods

2.1. Virginia Tech Goodwin Hall facility overview

Goodwin Hall is a 160,000 sq-ft five-story classroom and laboratory building on the Virginia Tech Blacksburg campus. It has a steel, concentrically-braced frame with a limestone facade. An aerial view of the building can be seen in Fig. 1a. During construction in 2014, 136 sensor mounts were welded to the building frame, either on floor girders or columns. The mounts are blocks of stainless steel and are accessible from the floor below. Up to three accelerometers can be mounted to the steel with threaded studs in any desired uniaxial, biaxial, or triaxial configuration. A photo of a mounted triaxial configuration is shown in Fig. 1b. The number of axes that can be measured at a particular mount location is limited by the number of sensor cables wired to that location. At the time of testing, the building had 225 total accelerometers online.

The accelerometers are high-sensitivity PCB 393B04 accelerometers,[1] whose specifications are listed in Table 2. Each accelerometer is connected via coaxial cable to one of five data acquisition units (DAQs), VTI Instruments CMX-09 chassis equipped with EMX-

[1] http://www.pcb.com/products/model/393b04.