Performing structural assessment using acoustic measurements

A. Gonzaleez
Graduate Student, San Francisco State University, San Francisco, CA, USA

Z. Jiang
Associate Professor, San Francisco State University, San Francisco, CA, USA

ABSTRACT

Natural hazards, such as earthquakes, could be catastrophic. One challenge that society faces is how to provide a rapid and accurate evaluation of the structural damages after the events. Traditional visual inspection is useful, but it may not provide a subjective and consistent assessment. To overcome that, researchers have focused on designing and employing health monitoring systems on structures, in which various sensors are installed to obtain measurements to perform monitoring evaluations. Typically, either wired and/or wireless sensor networks are installed in these systems, where the deployment and operation costs are obstacles to their usage. This study attempts to use infrasound measurements obtained from microphones to identify low-frequency modal properties (e.g., natural frequencies and mode shapes) of structures. A two-story structural model subjected to ground excitations is utilized as a testbed to investigate feasibility. Various approaches are proposed to improve the signal-to-noise ratio of the microphone measurements. The results confirmed the possibility of using infrasound measurements as a means to perform non-contact and non-destructive structural health monitoring for civil structures.

1 INTRODUCTION

Natural hazards such as earthquakes frequently remind us how destructive they can be. The 6.3-magnitude 2011 Christchurch earthquake that struck the entire Canterbury region in South Island caused widespread damage across Christchurch (Wikimedia Foundation, 2022). There were 185 deaths as a result of the earthquake, and 6,659 major injuries (in the first 24 hours) (Australian Disaster Resilience Knowledge Hub, 2023). How to provide a speedy and subjective post-hazard structural safety and functionality assessment is crucial to the safety of the occupants and the prosperity of society as a whole.

Structural health monitoring (SHM) systems can be used to provide assessment in post-hazard events. Changes in structural modal properties and responses (e.g., natural frequency, mode shape, time-domain or frequency-domain responses, etc.) during their service life are strongly correlated to damage in structures

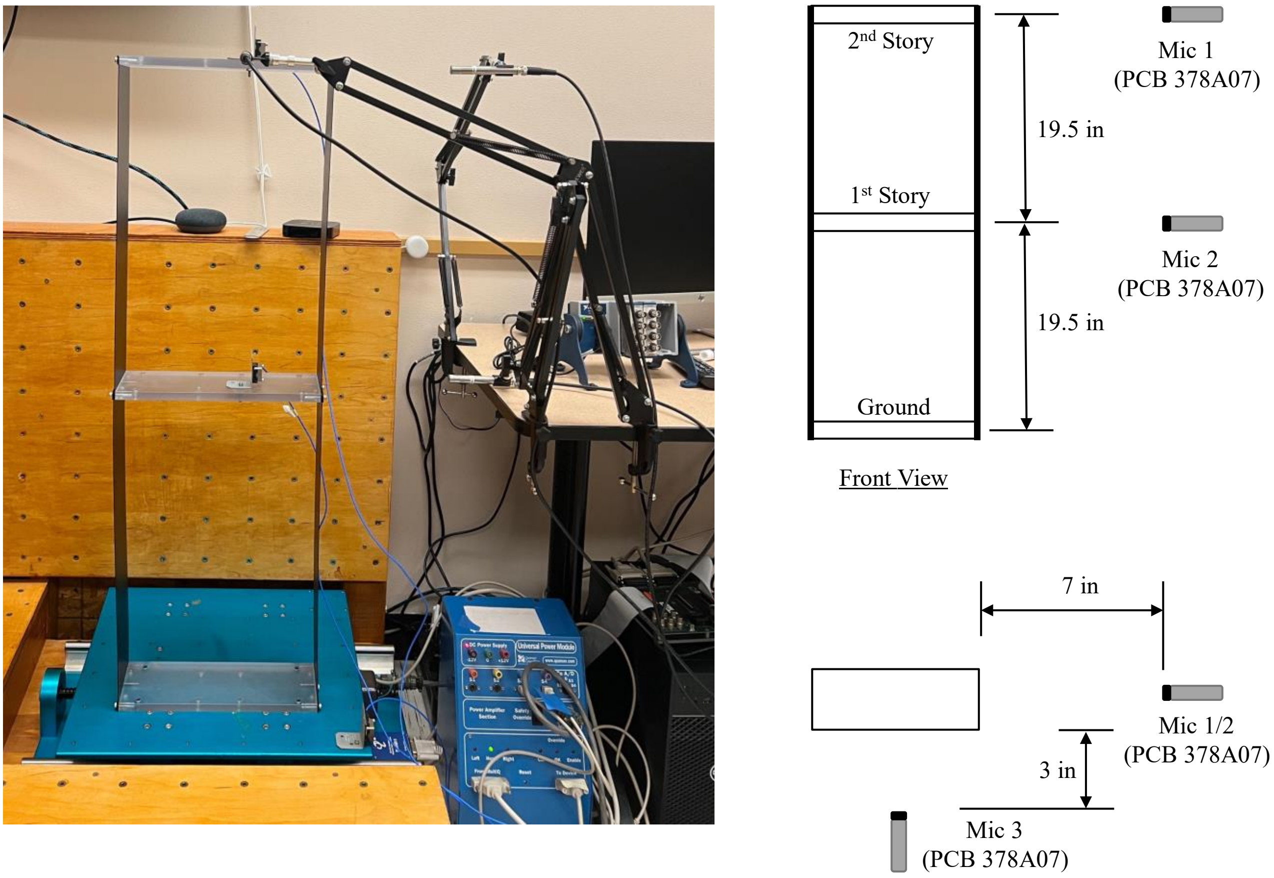
(Doebling et al., 1996; Fan and Qiao; 2011; Farrar and Worden 2006; Gomes et al., 2018; Hearn and Testa, 1991; Sirca and Adeli, 2012; Sohn et al., 2003). Among various matrices, modal frequency reflects the most basic dynamic performance and the shifts in modal frequencies or changes in structural mode shapes can serve as an indicator for structural damages (Carden & Fanning, 2004; Chang et al., 2003; Salawu, 1997; Shinh et al., 2009). To identify the modal frequency, SHM systems with sensors such as accelerometers, either wired or wireless, are typically deployed in structures to measure the structural response. For wired sensors, coaxial or multi-conductor cables are commonly used for reliably transferring measurements between sensors and the data acquisition system. While wires provide reliable communication, their installation and maintenance are expensive and labor-intensive (Celebi 2001; Lynch and Loh 2006). With the advancement of technology, wireless sensors and sensor networks have attracted interest in the community as they remove the need for wires between sensors and the data acquisition system and their associated cost and maintenance (Lynch 2006, Nagayama et al., 2009; Zimmerman et al., 2008). Although wireless sensors provide a promising alternative, challenges in current practice such as fault tolerance, bandwidth constraint, data transmission reliability, and sensor power consumption, are still under investigation (Bilstrup et al., 2003; Ou and Li, 2010).

In order to achieve a fast and cost-effective structural assessment, the authors proposed to use infrasound measured by microphone sensors to capture the structural responses (Jiang et al., 2019). When an object is vibrating in the presence of air, the vibration will excite the air molecules around the surface of the object with vibrating frequencies and amplitudes depending on the source. These vibrating air molecules propagate to nearby air molecules through air, as a form of sound (Raichel 2006). Therefore, measuring sound pressure variation through microphones, for example, will provide information that can be used to backtrack the object vibration. Infrasound, typically considered below 20 Hz, is sound with frequencies below the audible range of the human ear, commonly between 20 and 20,000 Hz (Rossing 2007). With that, it is possible to use infrasound measurements to extract modal information of civil structures as the frequency range of infrasound aligns well with that of typical civil structures. This option will be a cost-effective alternative to the traditional SHM approaches given that 1) it does not require wires as transmit media, 2) no markers, paint or preparation on the surface of the structure is needed, 3) it is portable in nature, and 4) the microphone sensor is relatively inexpensive compared to the traditional accelerometers.

In the previous study, a single-degree-of-freedom structure was used to explore the idea and confirm the feasibility of using microphone measurements as a means to perform non-contact and non-destructive structural health monitoring evaluation. A parametric study was performed on various parameters such as the number of reference sensors and the amount of collected data to investigate their effects on identifying the fundamental frequency of the single-degree-of-freedom structure. This study builds upon the previous results and investigates the feasibility of using infrasound measurements obtained from microphones to identify low-frequency modal properties (e.g., natural frequencies and mode shapes) of a more complex structure. A two-story structural model subjected to ground excitations is utilized as a testbed. Various approaches are proposed to improve the signal-to-noise ratio of the microphone measurements.

2 EXPERIMENTAL SETUP

In this study, a two-story frame (2DOF) structure subjected to ground excitations was performed. The experimental setup is shown in Fig. 1. The microphone sensors used in this study included three PCB 378A07 free-field microphones and they were labeled as Mic 1, 2, and 3 respectively. Mic 1 and 2 were pointing at the masses of the 1st and 2nd story in the direction of the vibration, respectively. Mic 3 was pointing at the 2nd story in the direction perpendicular to the vibration direction (see Fig.1), which intended to capture the environmental noises in the room. Three PCB 3711B1110G accelerometers were attached to the ground level, 1st story, and 2nd story to provide a baseline to verify the microphone measurements. The ground excitation was produced by an earthquake simulator, Quanser Shake Table II, manufactured by Quanser Inc. (Quanser, 2023). The Shake Table II consists of a 46 cm x 46 cm top stage driven by a 400 W high-powered 3-phase brushless DC ball-screw motor, allowing it to achieve an operating frequency of 0–20 Hz, a ± 7.6 cm stroke and a peak acceleration ± 9.8 m/s with a payload of 11.3 kg. The microphone and accelerometer sensor measurements were collected using a 24-bits Crystal Instrument Spider-80Xi data acquisition system, running at 100 Hz sampling frequency. The sensor sensitivities, measurement ranges, and their associated properties are listed in Table 1.



Front View

Experimental Setup

Top View

Figure 1: Experimental Setup

Table 1. Sensor Specifications

Sensor	**Sensitivity**	**Frequency Range**
Microphone (PCB 378A07)	5.8 mV/Pa	0.13 Hz – 2000 Hz (±2 dB)
Accelerometer (PCB 3711B1110G)	200 mV/g	0 Hz – 1500 Hz (±10 %)

3 PRELIMINARY RESULTS AND DISCUSSION

During this study, tests were conducted by subjecting the 2DOF structure to sine sweep excitations with an amplitude of 0.2 cm and frequency varying from 0 to 10 Hz in 20 seconds. A system identification test was first performed to identify the natural frequency of the structure. The frequency response function between the input ground motions and the output from the accelerometers is shown in Figure 2. As can be seen from Figure 2, the 2DOF structure has fundamental frequencies of 1.51 and 4.35 Hz.

Figure 2: Natural Frequencies of the 2DOF Structure

To investigate if the measurements from the microphone sensors contain the modal information of the structure, the auto-power spectra of the measurements from Mic 2 are shown in Figure 3. It can be confirmed from the figure that the microphone measurements contain the modal information as the measurements from the traditional accelerometers. It is also observed that noises exist in the microphone measurements. Currently, various strategies such as the usage of filters (e.g., wiener filter), combining measurements from additional microphone sensors (e.g., Mic 3), and utilizing multiple trials, are being explored to better extract the modal information.

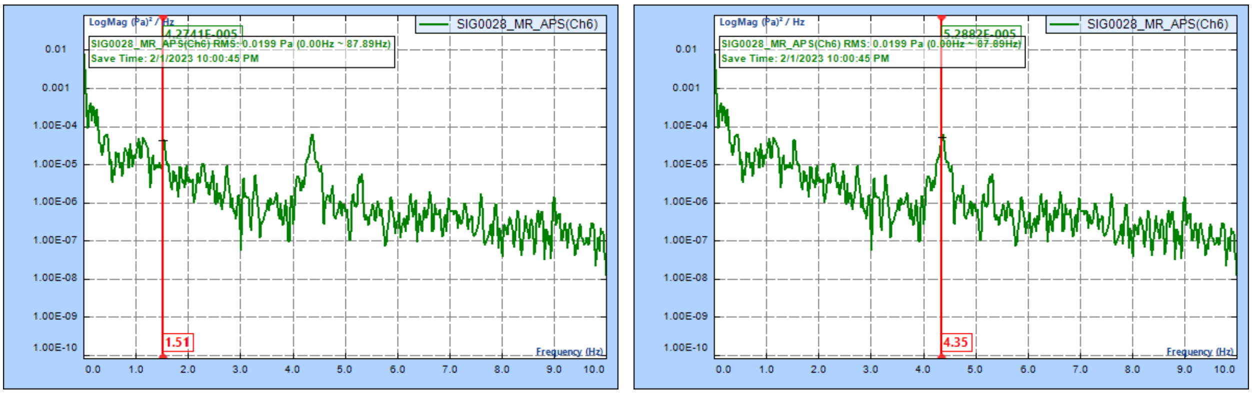


Figure 3: Measurements from Microphone Sensors

REFERENCE

Australian Disaster Resilience Knowledge Hub. (n.d.). Earthquake - Christchurch, New Zealand 2011: *Australian Disaster Resilience Knowledge Hub*. Christchurch earthquake, New Zealand 2011 | Disasters. Retrieved February 2, 2023, from https://knowledge.aidr.org.au/resources/earthquake-christchurch-new-zealand-2011/

Bilstrup, U., Sjoberg, K., Svensson, B., & Wiberg, P. A. (2003, September). Capacity limitations in wireless sensor networks. *In Emerging Technologies and Factory Automation, 2003.* Proceedings. ETFA'03. IEEE Conference (Vol. 1, pp. 529-536). IEEE.

Carden, E. P., & Fanning, P. (2004). Vibration based condition monitoring: a review. *Structural health monitoring*, 3(4), 355-377.

Celebi M. (2001). Seismic Instrumentation of Buildings (with Emphasis of Federal Buildings). Technical Report, No. 0-7460-68170, *United States Geological Survey*, Menlo Park, CA, USA.

Chang, P. C., Flatau, A., & Liu, S. C. (2003). Health monitoring of civil infrastructure. *Structural health monitoring*, 2(3), 257-267.

Doebling, S. W., Farrar, C. R., Prime, M. B., & Shevitz, D. W. (1996). Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review. Report No LA-13070-MS, *Los Alamos National Laboratory*. Issued: May 1996.

Wikimedia Foundation. (2022, November 27). 2011 Christchurch earthquake. *Wikipedia*. Retrieved February 2, 2023, from https://en.wikipedia.org/wiki/2011_Christchurch_earthquake.

Fan, W., & Qiao, P. (2011). Vibration-based damage identification methods: a review and comparative study. *Structural health monitoring*, 10(1), 83-111.

Farrar, C. R., & Worden, K. (2006). An introduction to structural health monitoring. Philosophical Transactions of the Royal Society A: Mathematical, *Physical and Engineering Sciences*, 365(1851), 303-315.

Gomes, G. F., Mendez, Y. A. D., Alexandrino, P. D. S. L., da Cunha, S. S., & Ancelotti, A. C. (2018). A review of vibration based inverse methods for damage detection and identification in mechanical structures using optimization algorithms and ANN. *Archives of Computational Methods in Engineering*, 1-15.

Hearn, G., & Testa, R. B. (1991). Modal analysis for damage detection in structures. *Journal of structural engineering*, 117(10), 3042-3063.

Jiang, Z., Zhang, Z., & Maxwell, A. (2019). Extraction of structural modal information using acoustic sensor measurements and machine learning. *Journal of Sound and Vibration*, 450, 156-174.

Lynch, J. P., & Loh, K. J. (2006). A summary review of wireless sensors and sensor networks for structural health monitoring. *Shock and Vibration Digest*, 38(2), 91-130.

Lynch, J. P. (2006). An overview of wireless structural health monitoring for civil structures. Philosophical Transactions of the Royal Society A: Mathematical, *Physical and Engineering Sciences*, 365(1851), 345-372

Nagayama, T., Spencer Jr, B. F., Mechitov, K. A., & Agha, G. A. (2009). Middleware services for structural health monitoring using smart sensors. *Smart Structures and Systems*, 5(2), 119-137.

Ou, J., & Li, H. (2010). Structural health monitoring in mainland China: review and future trends. *Structural health monitoring*, 9(3), 219-231.

Quanser. Shake Table II. *Quanser Inc.* Retrieved February 2, 2023 from https://www.quanser.com/products/shake-table-ii/.

Raichel, D. R. (2006). The science and applications of acoustics. *Springer Science & Business Media*. New York.

Rossing, T. (2007). Springer Handbook of Acoustics. Springer Science & Business Media. pp. 747-748.

Salawu, O. S. (1997). Detection of structural damage through changes in frequency: a review. *Engineering structures*, 19(9), 718-723.

Shih, H. W., Thambiratnam, D. P., & Chan, T. H. (2009). Vibration based structural damage detection in flexural members using multi-criteria approach. *Journal of sound and vibration*, 323(3-5), 645-661.

Sirca Jr, G. F., & Adeli, H. (2012). System identification in structural engineering. *Scientia Iranica*, 19(6), 1355-1364.

Sohn, H., Farrar, C. R., Hemez, F. M., Shunk, D. D., Stinemates, D. W., Nadler, B. R., & Czarnecki, J. J. (2003). A review of structural health monitoring literature: 1996–2001. *Los Alamos National Laboratory*, USA.

Zimmerman, A. T., Shiraishi, M., Swartz, R. A., & Lynch, J. P. (2008). Automated modal parameter estimation by parallel processing within wireless monitoring systems. *Journal of Infrastructure Systems*, 14(1), 102-113.