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RESEARCH ARTICLE

VIBRATIONAL CHARACTERIZATION OF IN-SITU STAIR PERFORMANCE USING ENERGY-HARVESTER DATA

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ABSTRACT

Vibration performance and energy harvesting potential of two in-situ stairs is evaluated using voltage output of an electromagnetic induction harvester prototype. First, the validation and benchmarking procedure is provided for a prototype electromagnetic induction harvester to assess 1) performance as a quantitative sensor for vibrations and 2) feasibility as a low-demand energy harvester. Secondly, the dynamic characteristics of two in-situ stairs are evaluated and compared to FEA and simplified analytical single-degree of freedom (SDOF) models. Lastly, the experimental dynamic response of the stairs is presented by using a single parameter: peak voltage response with the two-fold purpose of describing the performance and assessing the feasibility for energy harvesting. Using optimal mass and stiffness properties from previous research, the maximum voltage output under two time-history load cases reached 110mV per coil and was correlated to equivalent sinusoidal peak acceleration (ESPA) of 0.2% g for comparison to vibration criteria showing that both stairs are acceptable (< 1–2% g). Based on results, an improved harvester is being optimized for total power output, instead of only voltage.

INTRODUCTION

Both energy harvesting and vibration mitigation are well-developed fields that are increasingly being leveraged to produce novel devices for energy solutions. Examples of commercial energy harvesting devices include, Pavegen™ and Perpetuum™ that use live load vibrations to generate power. Some of these devices provide additional data like footfall and traffic patterns, but the primary use is to power ancillary sensors or systems. Additionally, structural health monitoring, remote sensor networks and in-situ sensors are becoming ubiquitous for monitoring and retrofit solutions to vibration problems. The rapid growth in these two distinct fields has prompted the authors to explore the feasibility of using energy harvesting devices to simultaneously scavenge power and characterize in-situ structural response. While significant work has been completed on identification of occupant traffic through sensing of structural vibrations [1, 2], this study explores using energy harvester output (voltage) to characterize structural performance and occupant behavior. Accordingly, the performance of a prototype magneto-induction floor harvester is presented as well as the method for benchmarking to the dynamic response of in-situ stair vibration excitations. Note that this research focuses on the feasibility of the dual-use of a harvester to assess in-situ vibrations while providing usable power, it does not focus on analysis and post-processing of vibration time-history responses or optimization of devices as the literature is replete with these [1-7]. Instead, a procedure for benchmarking of a prototypical harvester voltage output is presented along with the experimental data for energy harvesting feasibility case studies of two in-situ stairs. The device and procedure leverage fundamental energy harvesting concepts and applies them to meso-scale floor vibration applications by exploring the concept of peak voltage as a characteristically similar response metric to peak acceleration. As a result, the prototype harvester is validated for 1) feasibility as a low-demand energy harvester and 2) performance as a quantitative sensor for serviceability of floor systems. The tunable device is designed to accommodate coil arrays that allow wider bands of frequency optimization using scale-up methods. Due to improved structural optimization and development of new lightweight, long-span structural systems, occupant induced vibrations remains an area of on-going concern [7]. In addition to an initial design consideration, occupant induced vibrations also increasingly require retrofit solutions [4, 8]. Due to lighter and stiffer materials, system design or redesign is often governed by serviceability due to vibrations instead of strength or displacement [8, 9]. It has been well documented that fundamental floor frequencies near 7 Hz can be particularly disturbing to occupants and must be avoided [3, 10]. This issue has been addressed by introduction of additional design checks to supplement traditional design criteria for floors [3-4, 11-12]. Additionally, practicing engineers are increasingly looking at ways to address vibration via passive and active methods [13-15]. Recently, Love *et al.*,

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[8] presented case-studies for prediction and control of vibrations for multiple scenarios (lightweight pedestrian bridges, heavily loaded ballrooms and vibration-sensitive research laboratories). The dynamic properties for each case study are presented and analyzed for in-situ loading. Analysis for control, including TMDs, is presented in order to meet vibration criteria that may vary significantly depending on the structure and loading scenario. Similarly, Davis *et al*., [4] evaluated objectionable vibrations due to live loads and provided retrofit solutions. Both Love *et al*., [8] and Davis *et al*. [4] emphasize a procedure for analysis and summarize retrofit options with emphasis on the determination of natural frequencies vibration. Particular attention is given to determining the equivalent sinusoidal peak acceleration (ESPA) for comparison to criteria limits. Both studies focused on steel-framed structures and have similarities in both scope and method to Hanagan *et al*., [13]. While these three studies provide a good summative context for the fundamental methodology and the primary purpose of the prototypical device described herein (i.e., in-situ measurement of occupant based vibration of stairs), each of the preceding articles focused on using acceleration data from accelerometers to determine response not voltage from an energy harvester. Additionally, despite negative effects of vibrations, it remains impractical to eliminate floor dynamics completely through design, active or passive controls.

Recognizing this, the device presented herein allows relatively small amplitude vibrations (0.2% g) to be measured and harvested simultaneously for low demand building applications like active vibration control. Energy harvesting is the conversion of ambient environmental energy into electrical energy [16, 17] and while a detailed survey of energy harvesting and sensors is beyond the scope of this paper, recent work on the state of the technology is available by several authors [18-21]. Energy harvesting devices have been used extensively at both macro- and micro-scales and most of the devices at the micro-scale take advantage of piezoelectric effect, while macro-scale devices often use the principle of electromagnetic induction [18-22]. Harvesting kinetic energy to generate usable electric power is a well-known concept and behavior of both micro- and macro-devices has been studied by several authors [16, 17, 22]. However, the research and development of devices at the meso-scale for building applications like harvesting floor vibrations is a relatively new concept [23]. An electromagnetic kinetic energy harvester works by the principle of induction that arises from the relative motion of a conductor moving through a magnetic flux [24]. Induction is the production of an electromotive force across a conductor when it is exposed to a time varying magnetic field [25]. This principle inspires most forms of electrical power generation and is employs the concepts of Faraday's law and Lenz's law. These two relationships highlight the essential variables in device design: 1) that voltage output is dependent on the amplitude and velocity of the magnetic field's motion relative to a conductor and 2) a properly designed coil balances current and magnetic flux.

Recent preliminary experiments [26, 27] have investigated the feasibility of developing a meso-scale energy harvester and tuning to occupant induced floor vibrations. This was accomplished by validating numerical models to the author's previous floor vibration experimental data [13] and designing a device that was optimized for that fundamental frequency and modal response. The present work, discussed herein, takes experimental (shaker-table and in-situ) voltage output from the fabricated harvester and benchmarks those results to previously verified numerical modeling methods. Descriptions of numerical modelling methods are well known and have previously been discussed from the perspective of performance of constructed structural systems [13]. Detailed descriptions of the numerical models and methodology for the coupled structure-harvester system have been previously addressed by Raebel, Schultz, *et al*., [26, 27]. The numerical model of the structure is initially benchmarked to past experimental structural response provided by Hanagan, *et al*., [13] as measured using experimental protocols researched and developed by Raebel, *et al*. [28]. Then, the harvester is added to the model and compared to the current experimental results for the logarithmic decrement of a free vibration.

MATERIALS AND METHODS

Prototype Description: The prototype energy harvesting device is a simple magneto-induction system with a spring steel beam platform shown in Figure 1 that is readily idealized as a mass-spring system.

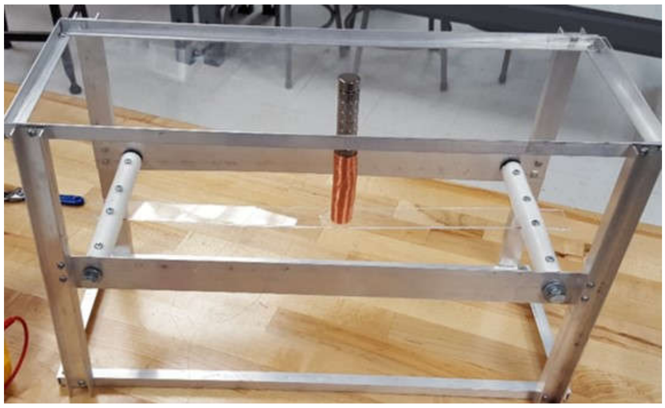

Figure 1. Energy Harvesting Prototype

The device is 254 mm long and consists of a simply supported spring steel beam with distributed point masses of 3 mm thick 13 mm diameter cylindrical Neodymium magnets. The system's fundamental frequency is tuned by adjusting stiffness via length of the beam. The well-known equation of motion for the system is readily formulated as: $my(t)''+dy(t)'+(F_m - mg)= -my_0(t)''$ where m is mass, d is damping, g is acceleration due to gravity, F_m can be approximated as shown by Zhang *et al*. [5]. Design of the coils used the well-known induction principles from Faraday's and Lenz's laws where the zero-to-peak electromotive force (EMF) is proportional to the time-varying magnetic flux through the coils [5]. The optimal mass and stiffness of the system were established by previous studies [26] and tuned for each of the stairs studied in this research.

Prototype Benchmark Studies

The prototype energy harvester was initially tested on a Quanser Shaker II shake table. Input to the shake table was programmed using MatLab, Simulink and WinCon, while data was recorded using LabVIEW. Multiple test cases were run on the energy harvester including: logarithmic decay, sinusoidal ground motion, heel drop and floor vibrations caused by walking histories measured as part of prior research initiatives [29].

Table 1. Peak Values for Various Harvester Stiffness (k) and Mass (m)

k=0.1% of Floor Stiffness, *m*=1N			*k*=0.1% of Floor Stiffness, *m*=1N			*k*=0.1% of Floor Stiffness, *m*=1N		
Time (sec)	Displacement (mm)	Logarithmic Decrement (%)	Time (sec)	Displacement (mm)	Logarithmic Decrement (%)	Time (sec)	Displacement (mm)	Logarithmic Decrement (%)
1.87	0.07	1.56	1.87	0.11	1.47	1.98	0.35	2.66
2.10	0.06	2.03	2.10	0.10	1.18	2.81	0.30	1.96
2.46	0.06	0.41	2.29	0.09	0.82	3.87	0.26	3.26
2.69	0.05	0.32	2.69	0.09	0.04	4.80	0.22	2.45
3.04	0.05	0.04	3.16	0.09	0.39	5.74	0.19	2.40
3.27	0.05	0.66	3.40	0.09	1.25	6.68	0.16	1.98
3.63	0.05		3.74	0.08		7.63	0.14	
Damping (ζ) = 0.8%			Damping (ζ) = 0.9%			Damping (ζ) = 2.5%		

The energy harvester recorded voltage data in all three tests via a terminal board connected to the data acquisition board, NI USB-6210 M Series (powered by LabVIEW). Using LabVIEW, the voltage generated over time was plotted for various time-history inputs. Measurements were taken from a single coil, even though each beam can be equipped with multiple coils along the length. The single coil of one Neodymium magnet generated voltage peaks of approximately 20 mV. Adding a second magnet (simultaneously increasing flux and reducing frequency) resulted in voltage peaks of approximately 40mV. Tests conducted with up to four magnets achieved voltage peaks near 80mV. Similarly, the maximum voltage of 80mV was obtained from the walking time-history motion. After obtaining voltage results using the sinusoidal and walking time-histories, the device was subjected to a heel-drop time-history to provide a benchmark with numerical models previously described by Schultz *et al.*, [27]. By obtaining the experimental harvester response on the shake-table, the results can be seen to qualitatively match the numerical results and can be compared quantitatively via application of logarithmic decrement method. The results validate the FEA and show that if the harvester is tuned to the fundamental floor vibrations, the voltage response will be characteristically similar to acceleration. Total damping is the cumulative effect of internal and external sources leading to a decrease in the amplitude of an oscillation as a result of energy loss from the system due to resistive forces. In the case of this device, the internal damping sources are material damping and the external sources are the magnetic resistance in the coil to the motion of the magnets. Both sources can be shown to be negligible both theoretically and experimentally [5]. The logarithmic decrement, δ, is used to calculate the damping experimentally using the natural logarithm of the ratio of any two successive peak displacement amplitudes in the same direction. This can be described by Equation 1,

$$\delta = \ln[X(t0)/X(t1)], \tag{1}$$

where X(t0) and X(t1) are any two successive peaks on a logarithmic decay plot such as that shown in Figure 2 [30]. Equation 2 describes how the damping factor, ζ, of a system is estimated using δ,

$$\zeta = \delta/\{[(2\pi)^2 + \delta^2]^{0.5}\}, \tag{2}$$

Equations 1 and 2 utilize the displacement measurements of a system. However, as mentioned, the displacement curves for the device correspond to the voltage curves though time-derivatives of the displacement. Maximum voltage occurs at the point of maximum velocity of the magnet through a coil, which is related to zero displacement through the first time derivative.

For the (essentially undamped) system oscillating at its natural frequency, larger displacements correspond to an increase in velocity, and consequently, greater voltages. Therefore, in determining the logarithmic decrement, using the ratio of two successive voltage peaks instead of displacement peaks will calculate the same damping percentage. Table 1 shows the logarithmic decrement method as applied to the output of the numerical models. The testing procedure for logarithmic decay follows the methodology described for the sinusoidal and walking time-history signal testing. A single coil oscillated under free vibration after the beam was released from an initial displacement. The experimental data is benchmarked to the numerical model which is has previously been validated using past experimental results of an in-situ floor. Note that the damping results from the experimental harvester system shown in Figure 3 closely resemble the numerical results shown in Figure 2. Figure 2 and 3 show a typical section of the plot where logarithmic decrement would be calculated.

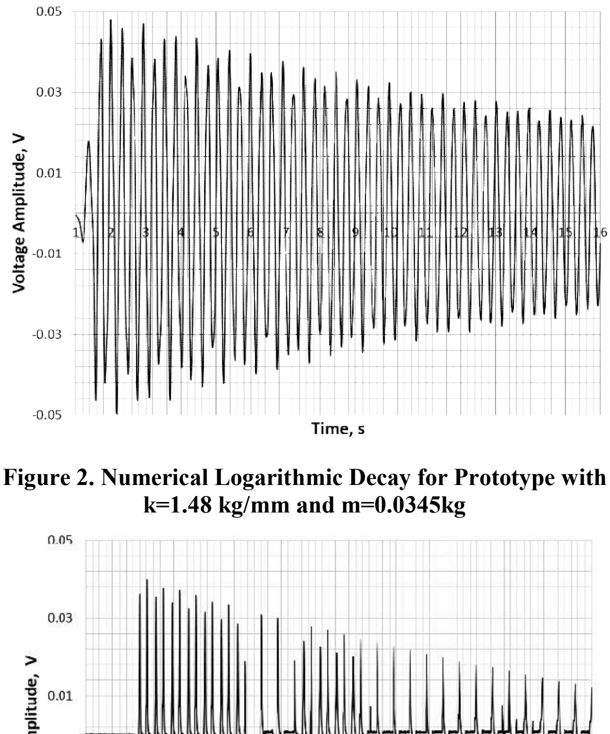

Figure 2. Numerical Logarithmic Decay for Prototype with k=1.48 kg/mm and m=0.0345kg

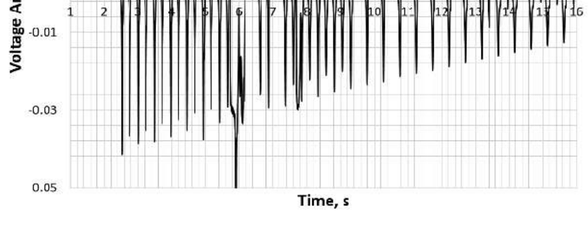

Figure 3. Experimental Logarithmic Decay for Prototype with k=1.48 kg/mm and m=0.0345kg

Peak X(t0) was measured to be 0.0398 V and peak X(t1) was measured to 0.0371 V. The resulting damping in the system found through the use of Equations 1 and 2 was determined to be approximately 1.0% damping. This is minimal, and agrees with the results expected from the authors' experience and from numerical analyses. The slight inconsistency in Figure 4 around time T = 6.0 sec was likely the result of slight contact between the magnets and the coils, but it is seen that the system recovered after a few oscillations indicating that it is an experimental variance not a systematic error.

Evaluation of In-Situ Vibration Performance

Having validated the FEA modeling procedure and calibrated the device on the shake-table, the harvester is used to assess the dynamic response of two different stairs known to meet existing vibration criteria specified by Murray [31] and AISC Design Guide 11 [3]. Problematic vibrations are usually observed in a single dominate mode of the structures lower natural modes that fall within the range of 7-10 Hz. Typically, in-situ vibration tests are conducted using accelerometers to measure the acceleration response due to live loading like a heel-drop. Here, the response is measured by the energy harvester, which reports peak voltage vs time that can be related to acceleration through Faraday's law.

The resulting response is converted from the time domain to a frequency spectrum and may be compared to vibration acceptability criteria. Stair 1 is a typical steel pan and concrete single flight stair located in a recreational facility. Stair 2 is located in an institutional facility and consists of longer spanning HSS stringers and was rectified to meet acceptable vibration levels with the installation of a tuned-mass damper (TMD). Both stairs have been modelled in previous studies with the relevant modal parameters such as frequencies, damping ratios and mode shapes being shown in Table 2.

Table 2. Dynamic Properties for In-Situ Stairs #1 and #2

	Stair #1	Stair #2
Total Mass (kg)	1961	8019
Effective Stiffness (kN/mm)	5.2	22.2
SDOF Frequency (Hz)	8.2	8.4
FEA Frequency (Hz)	9.87	8.7

RESULTS

Case Study #1

The first case study consists of a single straight flight of stairs from a mezzanine level to a second floor via HSS stringers on both edges supporting steel pan treads with 38mm concrete topping.

Figure 4 shows a section cut through the stair, illustrating the relationship between the stringer, steel pan, treads and riser. The stair consists of an HSS 304.8 mm x 101.6 mm x 6.4 mm stringer on each side of the stair with 6 mm steel pan treads and a 38 mm concrete topping slab. There are 19 treads spanning 5.2 m with a rise of 5.9 m. The stair frames into a steel-framed landing supporting a concrete slab over metal deck at the top and frames into a welded steel HSS frame at the bottom. There is a steel handrail with 9 – 19 mm rods and a 38 mm steel handrail running the length of the stair on each side.

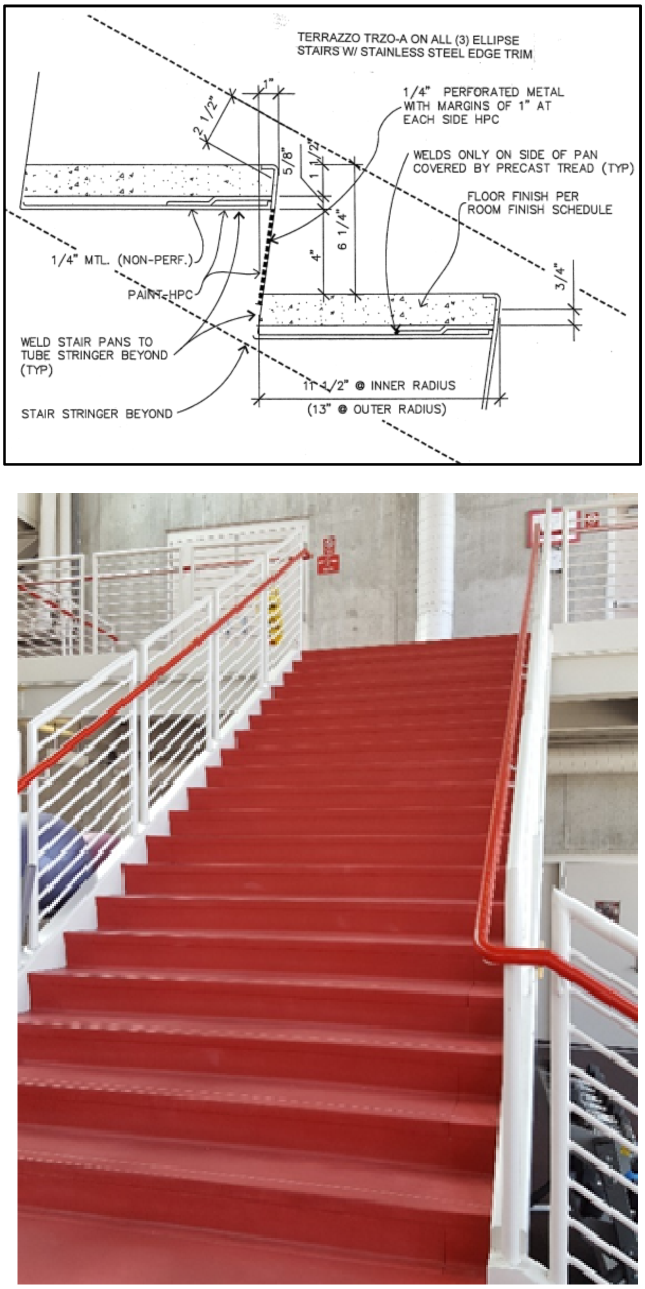

Figure 4. Stair #1 (a) Detail – Stair Pan Section (b) Picture of as-built Stair

Stair #1 was subjected to a heel-drop force measured separately using a force plate and the loading of a 92 kg person, as shown in Figure 5. The resulting voltages from the load cases are shown in as time-history responses in Figure 6. Figure 7 shows that the frequency content of the response to the heel-drop is in the range of 2 – 12 Hz. This range coincides with both the fundamental frequency of the floor and those frequency ranges that are especially problematic to human discomfort.

Finite element analysis (FEA) of Stair #1 was completed in Visual Analysis and checked in SAP2000 to determine the fundamental frequency and stiffness shown in Table 1, and the fundamental mode shape shown in Figure 8. The stair was modeled using higher-order beam and plate elements that account for shear strain compatibility and typical material properties for A992 steel and 21MPa concrete with 15% reduction in moment of inertia (to account for cracking/in-situ reduction in stiffness).

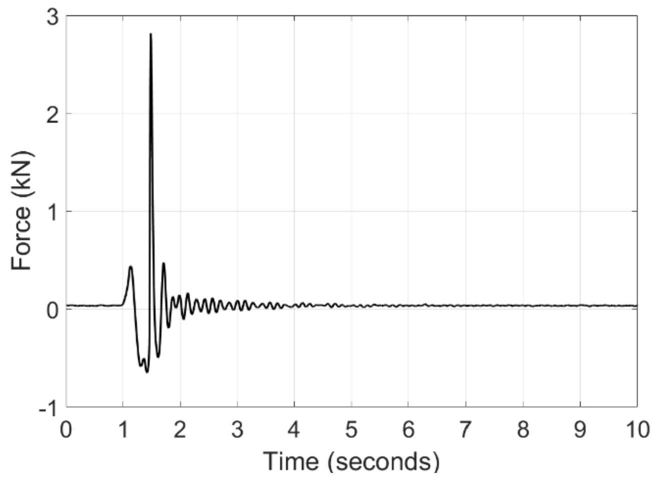

Figure 5. Applied Heel-Drop Force (92kg) Waveform for Stair #1

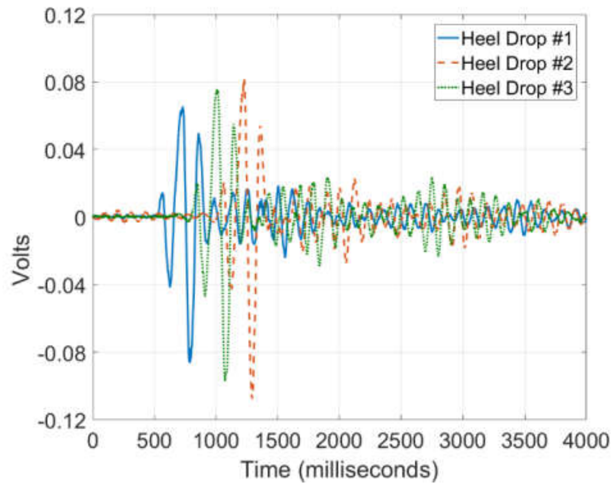

Figure 6. Measured Heel-Drop Voltage Time History for In-Situ Stair #1 Legend: Heel Drop #1, Heel Drop #2, Heel Drop #3

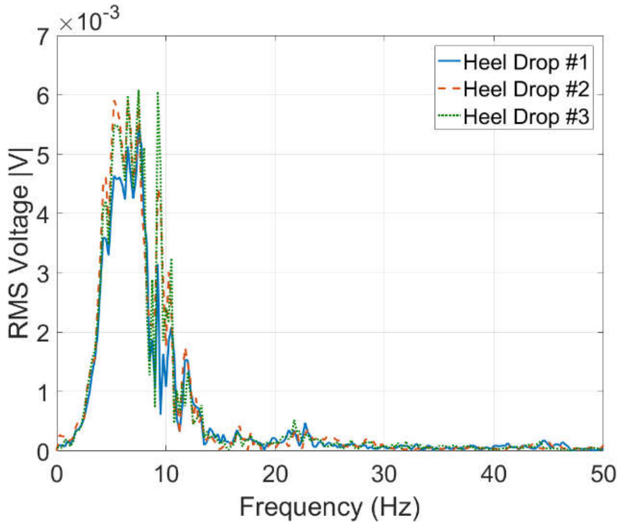

Figure 7. Measured Heal-Drop Voltage Frequency Spectra for In-Situ Stair #1 Legend: Heel Drop #1, Heel Drop #2, Heel Drop #3

The undeflected geometry and fundamental mode shape is shown in Figure 8 matches both the anticipated and observed in-situ response of Stair #1. Using the FEA, a representative load of 4.4 kN was applied at the mid-span of the flight to determine the stiffness as 5.17 kN/mm. Gravity takedown results in the mass of the stair as 1961 kg. Half the total mass (981 kg) is lumped at the mid-span and the system is solved as an undamped SDOF system. The resulting SDOF fundamental frequency is 8.22 Hz and is slightly lower than both the FEA frequency (9.87 Hz) and in-situ frequency (~10 Hz). The lower SDOF frequency result is likely due to several factors including: 1) assumption of zero damping while there is likely 1-2% based on previous studies, 2) assumption of 50% effective mass and 3) approximated stiffness using FEA static displacement.

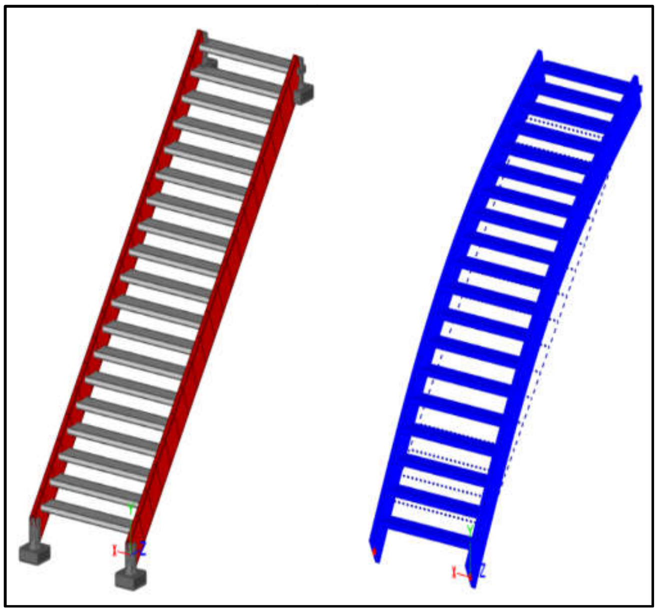

Figure 8. FEA of Stair #1 Showing Fundamental Mode Shape (9.87 Hz)

Case Study #2

The second stair consists of two exterior HSS 457.2 mm x 152.4 mm x 15.9 mm stringers and one interior HSS 203.2 mm x 152.4 mm x 6.4 mm stringer in the center. The stair has an overall height of 4.5 m and spans 7.5 m with a 2.17 m long intermediate landing located at the mid-span of the flight. For this study, the stair was instrumented between the second and third floors of the building. The treads are solid reinforced concrete with architectural finish and 6mm thick steel risers with a 7:11 tread spacing. Each side has a single 13 mm diameter stainless steel handrail and 9 mm thick fully tempered monolithic glass balustrades 927 mm tall. Initial performance with occupancy loading resulted in problematic vibrations and after analysis; a 2.3 kN tuned mass damper was added at mid-span of the flight. The stair and TMD can be seen in Figure 9. Stair #2 was subjected to a similar heel-drop force of a 92 kg person, as shown in Figure 5. The resulting voltages from the load cases are shown in as time-history responses in Figure 10 and Figure 11 shows the response frequency content in the range of 2 – 12 Hz. Note that Stair #2 response is within 1% of Stair #1 response and coincides with both the fundamental frequency of the floor and those frequency ranges that are especially problematic to human discomfort. Stair #2 was modeled using the same parameters and material options as Stair #1, resulting in the fundamental frequency, mode shapes and stiffness shown in Table 1. Similarly, the SDOF analysis is completed for Stair #2 by applying a representative load of 4.4 kN at the mid-span of the flight to determine the stiffness as 22.2 kN/mm. Gravity takedown results in the mass of the stair as 8019 kg. Half the total mass (4010 kg) is lumped at the mid-span and the system is solved as an undamped SDOF system.

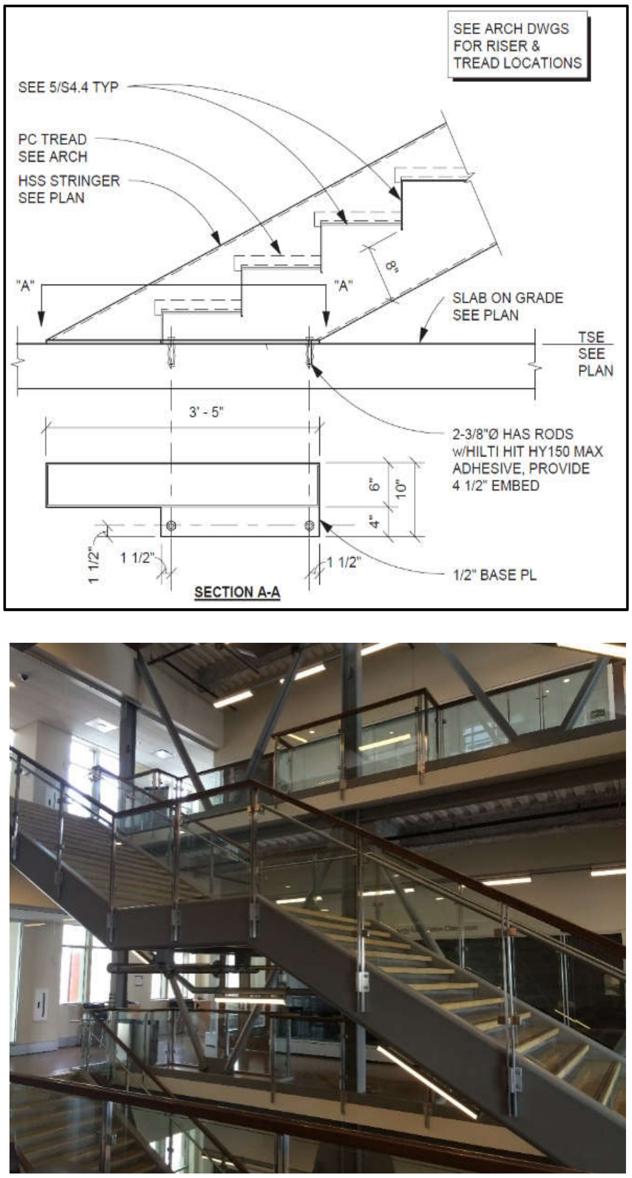

Figure 9. Stair #2 (a) Detail – Stair Pan Section (b) Picture of as-built Stair

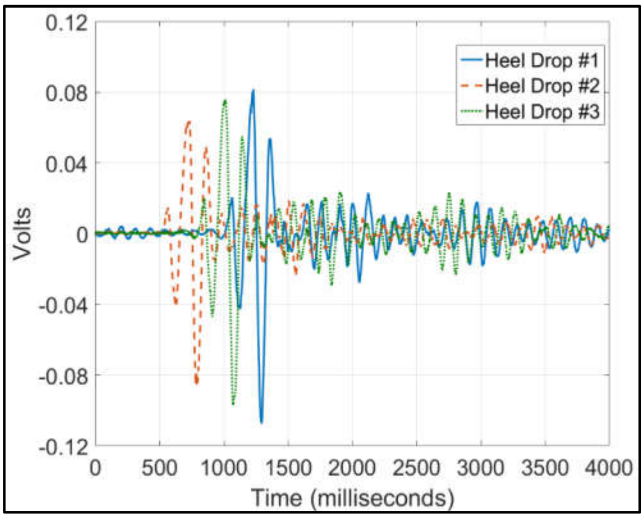

Figure 10. Measured Heel-Drop Voltage Time History for In-Situ Stair #2 Legend: Heel Drop #1, Heel Drop #2, Heel Drop #3

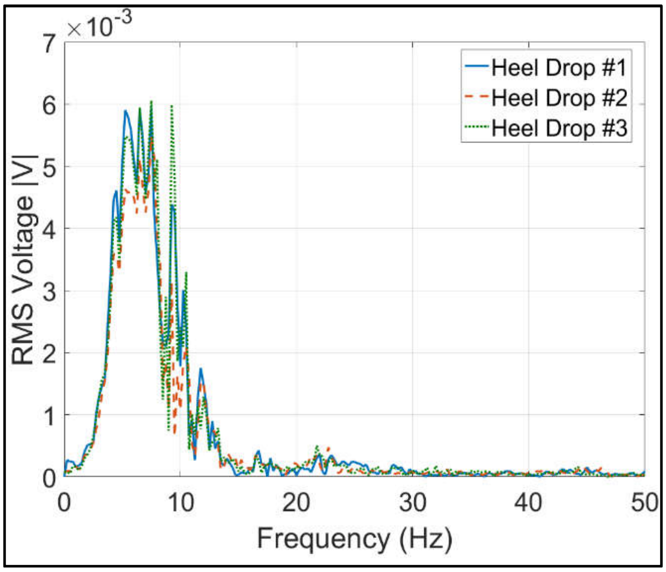

Figure11. Measured Heal-Drop Voltage Frequency Spectra for In-Situ Stair #2 Legend: Heel Drop #1, Heel Drop #2, Heel Drop #3

The resulting SDOF fundamental frequency is 8.4 Hz and is slightly lower than both the FEA frequency (8.7 Hz) and in-situ frequency (~10 Hz). Using the response history for the heel drop suites on both Stair #1 and Star #2, the equivalent sinusoidal peak acceleration (ESPA) is determined by converting the voltage to acceleration via numerical integration according to Faraday's law. Then, using the filtered waveform, the rolling root mean square is calculated and converted to ESPA using $(2)^{0.5}$. The results for this process are shown for Stair #2 in Figure 12 (results for Stair #1 are similar).

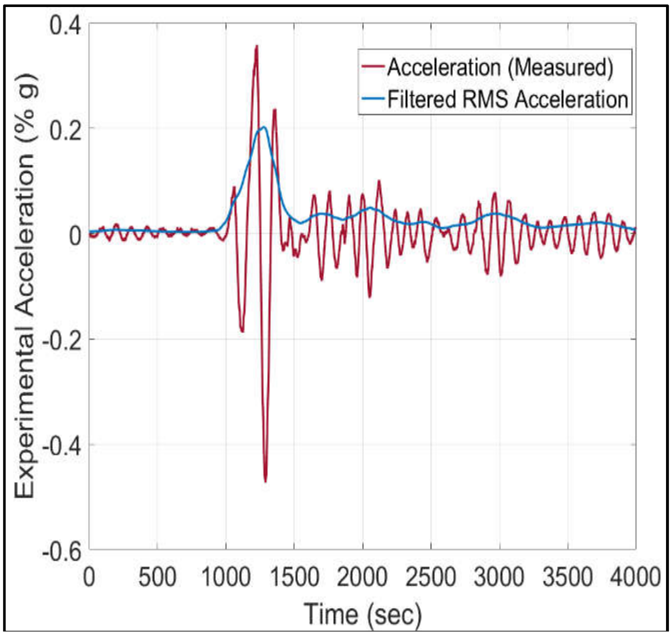

Figure 12. Stair #2 Acceleration Response for Heel Drop Legend: Acceleration (Measured), Filtered RMS Acceleration

The maximum acceleration of Stair #1 and Stair #2 are 0.2% g and 0.21% g, respectively. These values are significantly lower than the recommended peak acceleration of 1-2% g according to AISC DG 11 [3] shown in Figure 13.

Meanwhile, the voltage harvested from the stairs was 110 mV/coil with a total voltage of 220 mV for the current array.

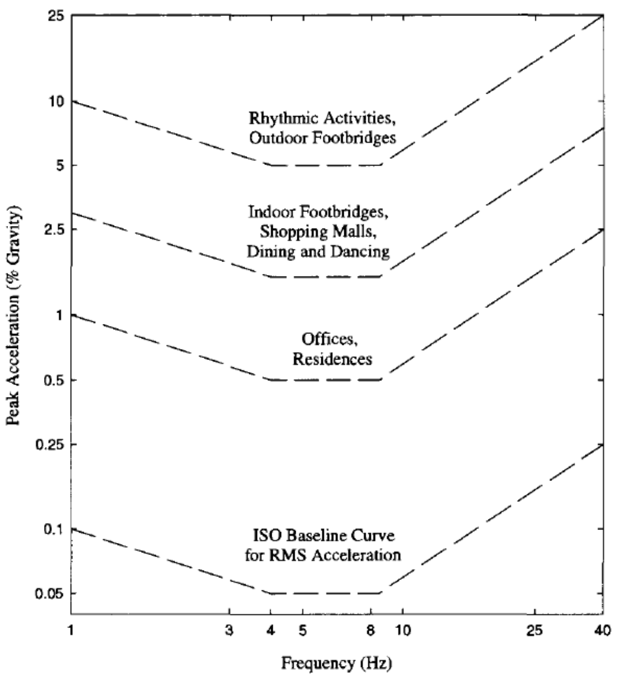

Figure 13. Recommended peak acceleration for human comfort for vibrations due to human activities [3]

DISCUSSION

Experimental voltage data for two in-situ stairs is presented and benchmarked to previous numerical studies. Initially, the harvester was tested on a Quansar II shake table for a range of excitations, which were then benchmarked to past studies and analyzed to verify the assumption of an "undamped" device with ~1% damping. Averaged damping results using the logarithmic decrement method indicated strong correlations between numerical, experimental and analytical predictions of damping and harvester displacement due to heel drop time-histories. Having validated the harvester, it was subject to heel drop and walking inputs on two in-situ stairs. The voltage response histories were converted to frequency domain using fast-fourier-transform waveform analysis and to accelerations via numerical integration and Faraday's law. The results for both stairs met the AISC DG 11 criteria (0.2% < 1 – 2%). The experimental results show that the device generates 220 mV per array and is able to convert the voltage data into meaningful acceleration data for evaluation of performance criteria against industry standards. The results indicate that energy harvesting devices are feasible for dual purpose harvesting/sensing when tuned to primary structural response and when internal damping is limited to 1-2%.

Additional work is needed to evaluate the impact of harvester improvements (broadband harvesting, voltage scale-up, multiple arrays of coils and non-linear step-up harvesting) and to look into optimizing the harvester for power output and not only voltage response. Results will be improved by the use of a full wave rectifier and signal averaging to create direct current. A second-generation device is underway to determine the impact of these considerations.

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