Detection of Train Passages during Forced Vibration Testing of Bridge Structure using Energy Harvesting Technology

Paul Cahill[1], Raid Karoumi[2], Alan Mathewson[3], Andreas Andersson[2], Vikram Pakrashi[4]

[1] MaREI, Environmental Research Institute, University College Cork, Ireland and Dynamical Systems & Risk Laboratory, Civil, Structural and Environmental Engineering, School of Engineering, University College Cork, College Road, Cork, Ireland

[2] Division of Structural Engineering and Bridges, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden

[3] Heterogeneous Systems Integration Group, Microsystems Group, Tyndall National Institute, University College Cork, Cork, Ireland

[4] Civil, Structural & Environmental Engineering, School of Engineering, University College Cork, Ireland and Dynamical Systems & Risk Laboratory, Civil, Structural and Environmental Engineering, School of Engineering, University College Cork, College Road, Cork, Ireland

Email: p.a.cahill@umail.ucc.ie, raid.karoumi@byv.kth, alan.mathewson@tyndall.ie, v.pakrashi@ucc.ie

ABSTRACT: Through integration with civil infrastructure, smart systems have the potential to provide real time health monitoring of the host structure. Such systems can be designed so as to be power independent whilst monitoring the structure using energy harvesting technology. The use of piezoelectric energy harvesters is particularly attractive for such applications, due to the dynamics of the host structure being reflected in the voltage and power outputs of such harvesters. It is therefore possible to identify not only the nature of the host, but also the loading to which it is being subjected through the output of the energy harvester. This paper investigates the detection of train passages over a host bridge structure during full scale forced vibration testing using piezoelectric energy harvesters. A shaker unit is utilised to subject the bridge to controlled forced vibrations and the deployment of an energy harvesting device to the bridge for such testing is completed. Its performance during the dynamic testing is analysed and the time domain power output from the harvester during testing is provided, with host characteristics identified. Incident based events were identified from the energy output and corresponds with train passages which occurred during the forced vibration testing. The potential use of energy harvesters to identify event based incidents is discussed and future applications identified. This paper further establishes the potential applications of energy harvesting technology with civil infrastructure through full scale experimental validation.

KEY WORDS: Energy harvesting; Piezoelectric; Smart sensors; Bridge dynamics; Train-Bridge interaction.

1 INTRODUCTION

The integration of smart technology with civil infrastructure is a topic which is receiving increased attention in recent years. Such technology has resulted in the creation of Wireless Sensor Networks (WSN's), through which key infrastructure can be monitored remotely [1]. WSN's have the capacity to monitor the full dynamic response of a structure and obtain information such as strain and acceleration responses during operational conditions [2]. It is therefore possible to remotely monitor critical infrastructure, with applications including bridges, underground railways and tower structures being successfully integrated with WSN's [3]. A drawback with such networks currently is, however, the reliance on external, finite power supplies such as batteries, which limits the lifetime of the network. Should WSN's be made power independent, achievable through the integration of energy harvesting technology, they have the potential to monitor a structure over its entire lifespan [4].

There are many types of energy harvesting technologies which have the potential to power small scale electronics, including vibration, thermal, solar and micro fluid flow [5]. Of these, for applications relating to the monitoring of the dynamic response of civil infrastructure, vibration based energy harvesting is of particular interest and consists of three primary transduction methods, electromagnetic, electrostatic and piezoelectric [6]. Piezoelectric energy harvesting utilises materials which convert strain energy into electrical energy through the piezoelectric effect [7].

Research into the integration of piezoelectric energy harvesting technology with civil infrastructure has received some attention [8,9], however its full potential has yet to be realised. The problem of energy harvesting from bridge infrastructure has recently been formulated [10], with the use of different device configurations, namely a cantilever device and a surface-bonded patch device, being proposed [11]. Studies into the use of train loadings as a means of vibration excitation for both types of piezoelectric energy harvesters have also been conducted [12,13]. The validation of such harvesters with full scale infrastructure has not yet been fully achieved, with initial studies into the integration of the devices with a bridge structure being conducted [14]. Applications resulting from the energy harvested from structures have received limited attention, with the potential for damage detection [15] and weight-in-motion [16] being proposed. The use of piezoelectric energy harvesters with full scale infrastructure undergoing forced vibration testing has not been studied to date, in part due to the difficulties associated with such testing.

The dynamic testing of bridge infrastructure provides major benefits for fields relating to bridge engineering. Such tests are important to determine key parameters of a bridge structure to be determined, including mode-shapes and damping ratios [17,18]. By experimentally obtaining such parameters, structural analysis of the bridge in question may be performed and allows for, amongst others applications, the [19]

- Enhancement of a database on the dynamical response of similar bridge structures, improving the prediction of the behaviour of new, similar structures.
- Ascertaining the condition of the bridge through the determining of critical parameters such as mass stiffness and damping.
- Theoretical modelling validation and updating.

The use of vehicle induced vibrations for structural analysis of bridge structures has been studied extensively, with the dynamic response of the bridge due to moving traffic loadings being monitored [20]. While such assessments are beneficial, issues do arise due to the presence of additional mass on the bridge structure in the form of the vehicle, which can influence the dynamical response of the bridge [21]. The use of ambient vibrations can resolve such issues [22], but it is through the use of external excitation devices that the most accurate experimental results can be ascertained [23].

Designs pertaining to external excitations devices utilised for the dynamical assessment of bridge infrastructure include vertical excitation using a dropped mass [24], an eccentric mass shaker for both horizontal [25] and vertical [26] excitation and a hydraulic shaker [27]. Such designs typically require the bridge to be closed to traffic for the duration of the testing process. It has therefore not been possible to date to detect both forced vibration loadings and traffic loadings simultaneously.

This paper investigates the detection of train passages using piezoelectric energy harvester integrated with a bridge structure undergoing dynamic testing. The theory of a cantilever based energy harvesting device is outlined, as is the design, construction and calibration of an experimental prototype. The application of the energy harvester to the host bridge structure is subsequently discussed and details of the excitation source for forced vibration testing provided. The results of the energy harvesters output during testing and the ability of the energy harvester to detect train events is determined. This paper illustrates further the potential applications that arise from the integration of smart technology with civil infrastructure.

2 PIEZOELECTRIC ENERGY HAVRESTING DEVICE

2.1 *Piezoelectric Energy Harvesting*

When integrated with a host structure, the acceleration response of the host provides the base excitation for the piezoelectric device and the electromechanical behaviour of the cantilever energy harvester is expressed by the coupled linear equations [10]

$$m_c\ddot{z}+c_c\dot{z}+k_cz-\theta V=-m_c\ddot{y}_b \tag{1}$$

$$\theta\,\dot{z}+C_p\dot{V}+\frac{1}{R_l}V=0 \tag{2}$$

Where m_c, c_c and k_c are the mass, damping and stiffness of the energy harvester respectively and z is the relative displacement of m_c, with over-dots denoting differentiation with respect to time. The base acceleration of the host is given by y_b and θ is the electromechanical coupling coefficient, V is the voltage, with C_p and R_l being the capacitance and resistance respectively. For this study, the base acceleration is provided by the host bridge which is undergoing two loading mechanisms. The first, and primary, loading mechanism is a sinusoidal loading applied at constant magnitude with varying frequency. The second loading is due to the passage of a train over the bridge. The response of the energy harvester through the analysis of the voltage output due to such loadings is herein determined experimentally to establish energy harvesting applications arising from a structure undergoing multiple loadings.

2.2 *Design and Construction of Piezoelectric Energy Harvesting Device*

When considering a bridge whose natural frequency is unknown for the deployment of the energy harvester, it is not possible to create an optimised solution. Such a solution would require that its fundamental frequency match that of the host bridge structure. As a result, for this study a non-optimised device is considered. The design of the harvester was completed with a natural frequency of 15*Hz* being considered. As such the dimensions of the cantilever device, including its length, L_1, width, w_1, and thickness, t, along with the tip mass, m_1, were determined so as to achieve this frequency. The cantilever was designed so as to be embedded within a rigid base, of length width and height L_B, w_B and h_B respectively, which is to be attached to the host bridge structure (Figure 1). Such a base is required to be of sufficient rigidity so as to prevent unwanted displacements and rotations at the base of the cantilever device. The active piezoelectric harvesting material is bonded onto a surface of the cantilever, with the cantilever substrate providing the necessary vibrations for energy harvesting.

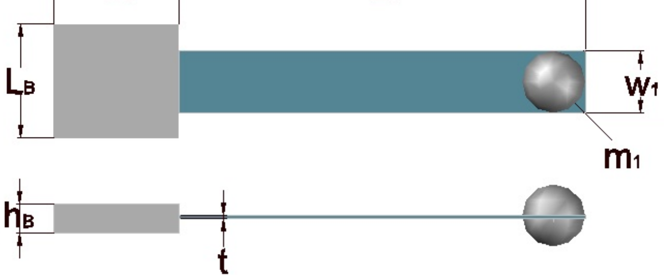

Figure 1. Illustration of cantilever energy harvester with embedment base

Following from the initial design of the energy harvester, the parameters of the experimental energy harvester were decided upon, with an aluminium substrate being chosen of thickness 0.0012*m*, length 0.1775*m* and width of 0.025*m*. Aluminium was chosen in part due to it being an electrical insulator and will therefore not influence the generated electrical energy. Onto the free end of the cantilever, a tip mass of 0.02*kg* was attached. The active piezoelectric material, in this case PolyVinyliDene Fluoride (PVDF), was bonded to the upper surface of the cantilever, resulting in the completed experimental cantilever energy harvester (Figure 2). While other piezoelectric materials, such as Lead Zirconate Titanate (PZT), offer more efficient energy harvesting potential, the polymer nature of PVDF results in a material which has a high mechanical strength while retaining excellent flexibility resulting in a material which is adaptable and easy to work with experimentally [28]. Upon the creation of the harvesting device, experimental calibration was subsequently performed.

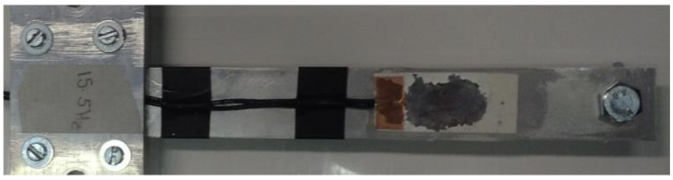

Figure 2. Experimental cantilever energy harvester with aluminium substrate and bonded PVDF energy harvester

2.3 *Calibration of Energy Harvesting Device*

For the experimental calibration of the energy harvester, the device was mounted onto an LDS Permanent Magnet Shaker (Figure 3), to which the input signal was supplied by a Diligent Inc. Analog Discovery waveform generator. Adjacent to the mounted energy harvester was placed a Microstrain G-Link LXRS wireless triaxial accelerometer, so as to provide a control for the applied vibration from the permanent magnet shaker.

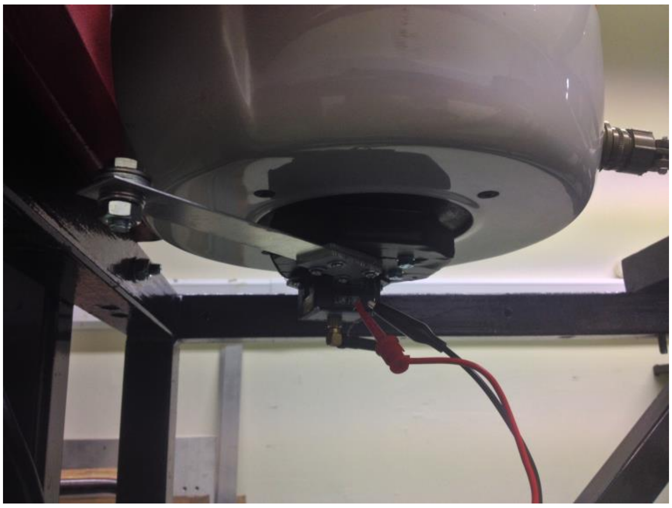

Figure 3. Cantilever energy harvester attached to permanent magnet shaker for provision of controlled base excitation

For the experimental calibration of the energy harvester, two different types of excitation were applied to the harvester. The first consists of an impulse load, to determine the natural frequency of the device experimentally. The second type of loading involves the application of a sweep sine load of constant amplitude and increasing frequency.

For the pulse load of 1*G* in magnitude, the voltage response of the device was measured under open circuit conditions (Figure 4(a)). From this measured voltage response, the natural frequency of the device was obtained through a fast Fourier transform (FFT). It was found that the experimental natural frequency of the device was 15.57*Hz* (Figure 4(b)), in contrast to a theoretical calculation of 15*Hz*. Following from the impulse response, the swept sine loading was subsequently applied to the energy harvesting device. A frequency range of between 1*Hz* and 40*Hz* was applied over a 120 second time period. While the ideal loading signal for this function would be a sine wave of varying frequency, this proved not to be possible using the Analog Discovery waveform generator. Instead, sinusoidal impulse loads were applied at increasing frequencies and a constant amplitude. It was for this reason

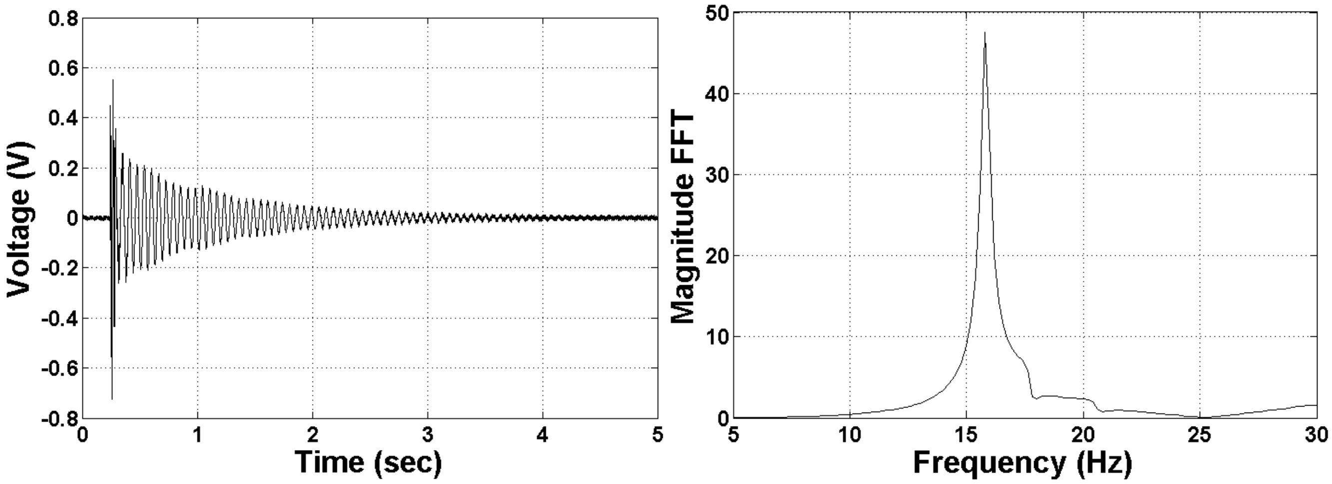

Figure 4. (a) Voltage response of energy harvesting device due to impulse load of magnitude 1*G* (b) Resultant FFT

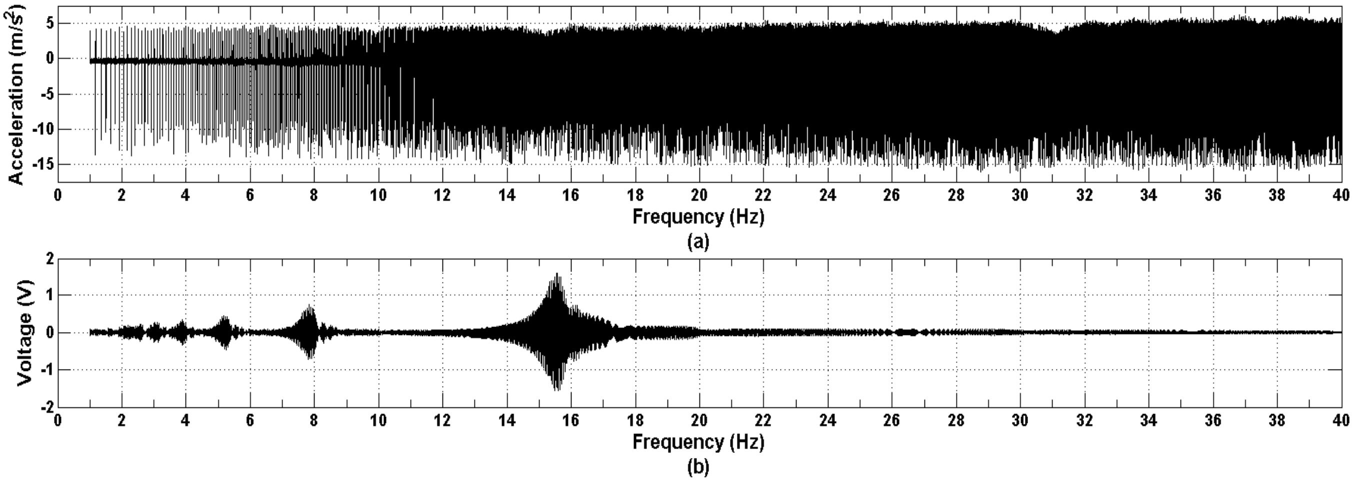

Figure 5. Swept sine loading of energy harvesting device including (a) Acceleration response with respect to loading frequency and (b) Measured voltage response of the energy harvesting device

that a short time period of 120 seconds was considered. Over a longer time period such impulses can be considered independent instead of being a continuous waveform, as achieved by the short time period chosen for this study. The magnitude of the loading was kept constant, with the wireless accelerometer being utilised for control, and the output voltage of the device was measured (Figure 5). The initial peak to peak loading magnitude at a frequency of 1*Hz* was measured at 18.7m/s² with a final loading magnitude of 21.2m/s² (Figure 5(a)). As can be seen in the voltage response of the energy harvesting device, such a drift has negligible impact on the energy harvesting output (Figure 5(b)). It is instead loading at the natural frequency of the device which has the most significant impact on the energy harvesting potential of the device, with a peak voltage of 1.59*V* being obtained at a loading frequency of 15.57*Hz*. Following the laboratory based calibrations of the energy harvesting device, the device was subsequently deployed with a bridge structure which was undergoing forced vibration testing while remaining open to traffic, presented in the following section.

3 DEPLOYMENT OF ENERGY HARVESTING ON BRIDGE STRUCTURE

3.1 Description of Host Bridge Structure

The bridge chosen for the deployment of the energy harvesters during forced vibrations was the Pershagen Bridge, Sweden. The bridge is a three span, 46.6*m* long, reinforced concrete slab bridge which carries two rail tracks. The central span is 18.8*m* in length and the two side spans both have lengths of 11.1*m*. An overhang exists between the side-spans and the abutments, which rest on backfill embankments. The structure is 11.9*m* width out to out and carries a 0.6*m* layer of ballast. Due to the existence of the overhangs and the backfill embankments, the structure is believed to exhibit some minor cantilever-like behaviour whilst undergoing the dynamic loadings from the train passages. It is therefore difficult to achieve a precise theoretical calculation of the natural frequencies and mode shapes, without key parameters being obtained during dynamic testing of the structure.

3.2 Assessment of Host Bridge under External Excitation

For the dynamic testing of the Pershagen Bridge, a hydraulic shaker designed by the Division of Structural Engineering and Bridges, KTH Royal Institute of Technology Sweden was utilized. It consisted of a hydraulic cylinder with an attached strut connecting it to the bridge structure, between which was placed a load cell. This allowed for the force, frequency and displacement of the applied load to be constantly monitored and maintained [29]. The design of the shaker unit is such that it is positioned under the bridge structure and provides vertical excitation to the bridge deck while the bridge is operational. The train tracks carried by the bridge can therefore remain open during the dynamic testing and trains passages across the bridge unaffected. With the deployment of the energy harvesting device onto the bridge structure, it is therefore the primary aim of this paper to investigate the potential of using the devices to detect train passages whist the dynamic testing is ongoing.

For the deployment of the energy harvesting device to the bridge structure, two primary considerations were taken into place. First, the device was to be mounted adjacent to an accelerometer, which would provide a base acceleration profile to which the device was subjected to during the testing. Secondly, the distance of the device from the location of the exciter was also considered, with the device being positioned adjacent to the exciters location to allow for maximum response during the dynamic testing.

3.3 Details of Dynamic Load Testing of Pershagen Bridge

The device was affixed at the chosen location on the top edge beam of the bridge, with the cantilever overhanging the bridge to prevent the device coming into contact with the bridge deck or other fixtures. The device was subsequently connected to a data acquisition unit and the response monitored at 100*Hz*. The dynamic assessment of the structure was achieved with load amplitude of 5*kN* between a frequency range of 3 to 50*Hz* being applied by the shaker unit. An initial preload of 15*kN* was applied so as to ensure that connection between the bridge structure and the shaker was maintained at all times. The loading was applied at a rate of 0.05*Hz* per second. The response of the accelerometer at the location of deployment was monitored, as was the voltage response of the device. From the responses of both, the existence of events due to the passage of trains were investigated, and the ability of the energy harvesting device to detect such train passages was determined.

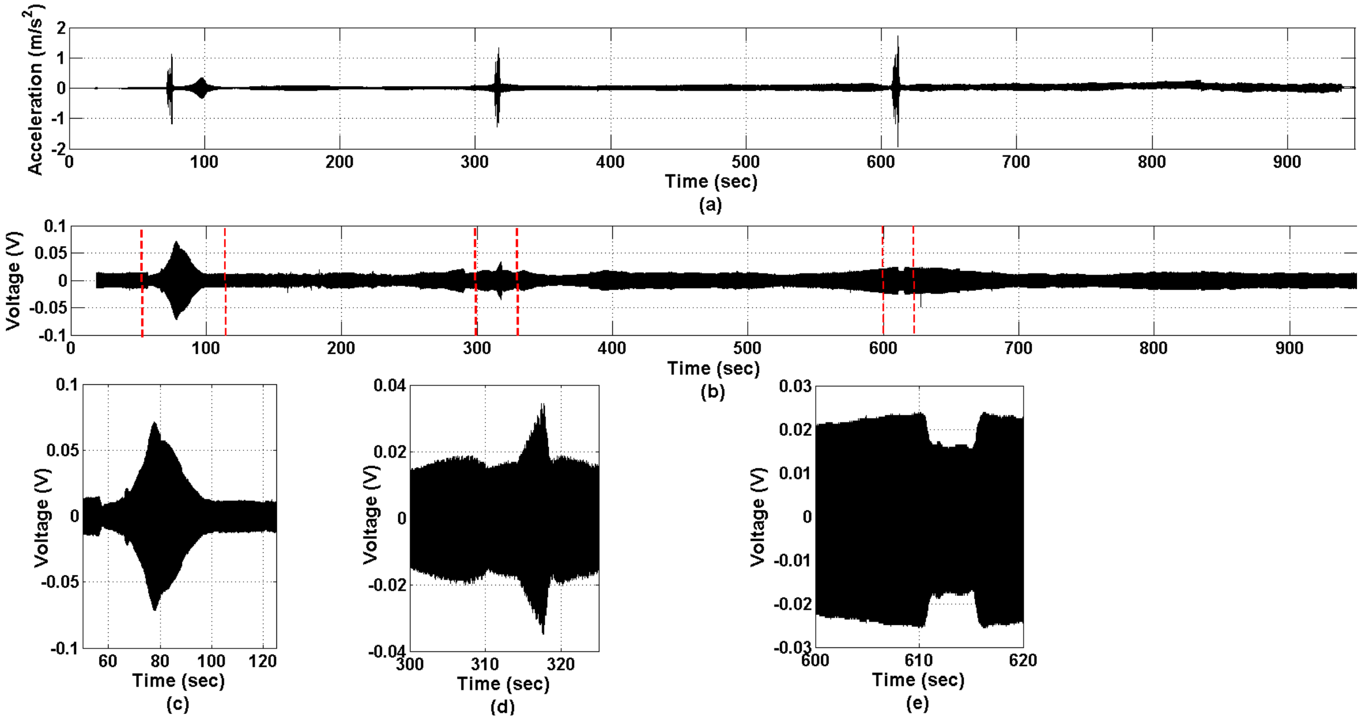

Figure 6. Response during dynamic testing of bridge structure with (a) Acceleration and (b) Measured resultant voltage of the energy harvesting device (c) Voltage response during Train 1 (d) Voltage response during Train 2 and (e) Voltage response during Train 3

4 EXPERIMENTAL ANALYSIS FROM ENERGY HARVESTING DEVICE FROM DYNAMICAL TESTING OF HOST BRIDGE STRUCTURE

The resultant acceleration and voltage output from the duration of the dynamic tests were obtained and compared (Figure 6). The testing occurred over a time period of over 15 minutes, during which time, three train passages were observed as having occurred. An examination of the acceleration response shows three distinct passages occurring at timestamps of 75 seconds, 314 seconds and 610 seconds (Figure 6(a)). A further acceleration incident is observed at the 95 second timestamp, which corresponds to the loading being applied at the fundamental frequency of the bridge, at 7.9*Hz*. An investigation of the voltage response of the cantilever energy harvesting device shows that the three train events do register a response (Figure 6(b)). The first train event occurs when the voltage response is at a maximum, due to the base excitation of the device being at a maximum harmonic loading condition. A closer inspection of the time at which the Train 1 passage occurs shows that the peak occurs during the voltage at time of 75 seconds (Figure 6(c)).

For the observed second train event, a more definitive train detection is observed from the voltage output of the energy harvesting device compared to that observed from Train 1 (Figure 6(d)). The comparison of the voltage and acceleration responses shows agreement in both the start time and the duration of passage of Train 2. When comparing the final passage, that of Train 3, the passage of the train is evident in once again in the acceleration response. The event registers for the energy harvester however, there is a decrease in the voltage output, with Train 3 acting as a damper on the energy harvesting device (Figure 6(e)). The duration and timestamp of the passage correspond for both the acceleration and voltage responses. Of note is the influence of the environmental factors on the voltage output. It was noted that the wind conditions were blustery and influenced the results, with gust of winds causing the cantilever to vibrate and harvest energy. This is especially noticeable around the 600 second time period. The use of a wind shield would have prevented the wind from causing such interference.

As can be seen by the comparison of the acceleration and voltage response for the three identified train passages, the energy harvesting device has the potential to detect the passage of trains whist the host structure undergoes external excitation. While more work is required so as to utilise such detections for applications such as weight in motion (WIM) and other applications, this paper illustrates the ability of energy harvesters to detect events whist under different loading conditions. This is important when considering WIM and other applications, such as SHM, and should be further investigated as well as extended to other civil infrastructure applications.

5 CONCLUSIONS

This paper investigates the potential for utilising energy harvesting device for the detection of train loads whilst the host bridge structure undergoes dynamic testing. The design and fabrication of an energy harvesting device was presented. The use of impulse response testing and swept sine loadings to experimentally calibrate the energy harvesting device in a laboratory setting was investigated. The deployment of the device to a host bridge structure was outlined, as were details of the host, the external shaker and the dynamic testing procedure. The ability of the energy harvester to detect a train event during the forced vibration testing of the bridge was investigated. During such testing, three train passages were noted and were detected by both the accelerometer and by the energy harvesting device. The events which were easily identifiable in the acceleration profile of the forced vibration testing were found to be present in the voltage output of the energy harvesting device. More research is required to obtain accurately correlations between the acceleration and voltage response and also for further applications arising from the integration of energy harvesting technology with civil infrastructure elements. This paper demonstrates that such applications are possible and further advance the range of applications that can be achieved through the integration of smart technology with civil infrastructure elements.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from the Irish Research Council GOIPG/2013/482, Science Foundation Ireland TIDA Program and the FP7-PEOPLE-2013-IAPP-BridgeSMS Project.

REFERENCES

[1] Kim, S., Pakzad, S., Culler, D., Demmel, J., Fenves, G., Glaser, S. and Turon, M. (2007), ‘Health monitoring of civil infrastructure using wireless sensor networks’, in *6th International Symposium on Information Processing in Sensor Networks*, IEEE, 254-263.

[2] Gangone, M. V., Whelan, M. J. and Janoyan, K. D. (2011), ‘Wireless monitoring of a multi-span bridge superstructure for diagnostic load testing and system identification’ *Computer-Aided Civil and Infrastructure Engineering*, 26(7), 560-579.

[3] Spencer, B.F. and Yun, C.-B. (2010), ‘wireless sensor advances and applications for civil infrastructure monitoring’, Technical report, Newmark Structural Engineering Laboratory. University of Illinois at Urbana-Champaign, Champaign, Illinois, USA.

[4] Cahill, P., Jackson, N., Mathewson, A and Pakrashi, V. (2013), ‘PolyVinyliDene fluoride (PVDF) Material based energy harvesting from train and damaged bridge interaction’, *Key Engineering Materials*, 569-570, 335-341.

[5] Harb, A. (2011), ‘Energy harvesting: state-of-the-art’, *Renewable Energy*, 36(10), 2641-2654.

[6] Beeby, S. P., Tudor, M. J. and White, N. M. (2006), ‘Energy harvesting vibration sources for microsystems applications’, *Measurement Science and Technology*, 17(12), R175-R195.

[7] Priya, S. (2007), ‘Advances in energy harvesting using low profile piezoelectric transducers’, *Journal of Electroceramics*, 19(1), 167-184.

[8] Xie, X. D., Wu, N., Yuen, K. V. and Wang, Q. (2013), ‘Energy harvesting from high-rise buildings by a piezoelectric coupled cantilever with a proof mass’, *International Journal of Engineering Science*, 72, 98-106.

[9] Wischke, M., Masur, M., Kröner, M and Woias, P. (2011), ‘Vibration harvesting in traffic tunnels to power wireless sensor nodes’, *Smart Materials and Structures*, 20(8), 085014.

[10] Ali, S. F., Friswell, M. I., and Adhikari, S. (2011) ‘Analysis of energy harvesters for highway bridges’ *Journal of Intelligent Material Systems and Structures*, 22(16), 1929 – 1938.

[11] Erturk, A. (2011) ‘Piezoelectric Energy Harvesting for Civil Infrastructure System Applications: Moving Loads and Surface Strain Fluctuations’, *Journal of Intelligent Material Systems and Structures,* 22(17), 1959 – 1973.

[12] Cahill, P. A., Nuallain, N. A., Jackson, N., Mathewson, A., Karoumi, R. and Pakrashi, V. (2014) ‘Energy Harvesting from Train-Induced Response in Bridges.’ *Journal of Bridge Engineering,* 10.1061/(ASCE)BE.1943-5592.0000608.

[13] Cahill, P., Jackson, N., Mathewson, A. and Pakrashi, V. (2014), ‘Comparison of piezoelectric materials for energy harvesting from civil infrastructure elements for use in health monitoring’, in ‘*Life Cycles of Structural Systems: Design, Assessment, Maintenance and Management. Proceedings 4th International Symposium on Life-Cycle Civil Engineering*, 16-19 November 2014’, CRC Press, Tokyo, 153–159.

[14] Peigney, M., and Siegert, D. (2013) ‘Piezoelectric energy harvesting from traffic-induced bridge vibrations’, *Smart Materials and Structures*, 22(9), 095019.

[15] Kaur, N. and Bhalla, S. (2015), ‘Combined Energy Harvesting and Structural Health Monitoring Potential of Embedded Piezo-Concrete Vibration Sensors’, *Journal of Energy Engineering* 141 (4) , 1–18.

[16] Kołakowski, P., Szelążek, J., Sekuła, K., Swiercz, A., Mizerski, K. and Gutkiewicz, P. (2011), ‘Structural health monitoring of a railway truss bridge using vibration-based and ultrasonic methods’, *Smart Materials and Structures* ,20(3), 035016.

[17] Salawu, O.S. and Williams, C. (1995), ‘Bridge assessment using forced-vibration testing’, *Journal of Structural Engineering*, 121(2), 161-173.

[18] Morassi, A. and Tonon, S. (2008), ‘Dynamical testing for structural identification of a bridge’, *Journal of Bridge Engineering*, 13(6), 573-585.

[19] Salawu, O.S. and Williams, C. (1995), ‘Review of full-scale dynamic testing of bridge structures’, *Engineering Structures*, 17(2), 113-121.

[20] Kwark, J., Choi, E., Kim, Y., Kim, B. and Kim, S. (2004). ‘Dynamic behaviour of two-span continuous concrete bridges under moving high-speed train’, *Computer & Structures*, 82(4-5), 463-474.

[21] Ülker-Kaustell, M. and Karoumi, R. (2011), ‘Application of the continuous wavelet transform on the free vibrations of a steel-concrete composite railway bridge’, *Engineering Structures*, 33(3), 911-919.

[22] Farrar, C. and James, G. (1997), ‘System identification from ambient vibration measurements on a bridge’, *Journal of Sound and Vibrations*, 205(1), 1-18.

[23] Cunha, A., Caetano, E., Magalhães, F. and Moutinho, C. (2013), ‘Recent perspective in dynamical testing and monitoring of bridges’, *Structural Control and Health Monitoring* 20(6), 853-877.

[24] Peeters, B., Maeck, J and Roeck, G. D. (2001), ‘Vibration-based damage detection in civil engineering: excitation sources and temperature effects’ *Smart Materials and Structures* 10(3), 518-527.

[25] Halling, M. W., Muhammad, I. and Womack, K. C. (2001), ‘Dynamic field testing for condition assessment of bridge bents’, *Journal of Structural Engineering*, 127(2), 161-167.

[26] Maragakis, E., Douglas, B., Chen, Q. and Sandirasegaram, U. (1998), ‘Full-scale tests of a railway bridge’ *Transportation Research Record: Journal of the Transportation Research Board*, 1624(98), 140-147.

[27] Farrar, C. R. and Jauregui, D. A. (1998), ‘Comparative study of damage identification algorithms applied to a bridge: I. experiment’, *Smart Materials and Structures*, 7(5), 704-719.

[28] Vinogradov, A. and Holloway, F. (1999), “Electro-mechanical properties of the piezoelectric polymer PVDF.”, *Ferroelectrics*, 226(1), 169-181.

[29] Andersson, A., Ulker-Kaustell, M., Borg, R., Dymen, O., Carolin, A & Karoumi, R. (2015). “Pilot testing of a hydraulic bridge exciter”, in *MATEC Web of Conferences*, 24, 02001.