Title	Energy harvesting from train-induced response in bridges
Authors(s)	Cahill, Paul; Ni Nuallain, Nora Aine; Jackson, Nathan; Pakrashi, Vikram; et al.
Publication date	2014-09
Publication information	Journal of Bridge Engineering, 19 (9):
Publisher	ASCE Library
Item record/more information	http://hdl.handle.net/10197/10422
Publisher's statement	This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers. This material may be found at https://ascelibrary.org/doi/10.1061/%28ASCE%29BE.1943-5592.0000608
Publisher's version (DOI)	10.1061/(ASCE)BE.1943-5592.0000608

Energy Harvesting from Train Induced Response in Bridges

Paul Cahill[1], Nora Aine Ni Nuallain[2], Nathan Jackson[3], Alan Mathewson[4], Raid Karoumi[5] and Vikram Pakrashi[6]

Corresponding Author: Vikram Pakrashi, Lecturer in Structural Engineering, Dynamical Systems and Risk Laboratory, Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland.

Phone: 00353-(0)21-490-3862. Fax: 00353-(0)21-427-6648. Email: V.Pakrashi@ucc.ie[1]

---

[1] Paul Cahill. Dynamical Systems and Risk Laboratory, Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland.

2 Nora Aine Ni Nuallain. Department of Civil, Structural & Environmental Engineering, Trinity College Dublin, Dublin, Ireland.

3 Nathan Jackson. Microsystems Group, Tyndall National Institute, University College Cork, Cork, Ireland.

4 Alan Mathewson. Microsystems Group, Tyndall National Institute, University College Cork, Cork, Ireland.

5 Raid Karoumi. Department of Civil and Architectural Engineering, Royal Institute of Stockholm (KTH), Stockholm, Sweden.

6 Vikram Pakrashi. Dynamical Systems and Risk Laboratory, Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland.

Abstract

The integration of large infrastructure with energy harvesting systems is a growing field with potentially new and important applications. The possibility of energy harvesting from ambient vibration of bridges is a new field in this regard. This paper investigates the feasibility of energy harvesting for a number of trains considering their passage over a bridge. The power that can be derived from an energy harvesting device due to a train crossing a bridge for different speeds are compared against typical demands of small wireless devices and are found to be adequate for powering such devices. These estimates of harvested energy also relate to the individual signatures of trains. In this work, the modelled dynamic responses of a bridge traversed by trains are compared against full scale experimental analysis of train-bridge interactions. A potential application in structural health monitoring using energy harvesting has also been demonstrated and compared with laboratory experimental data. Consistent and monotonic damage calibration curves have been constructed using estimated harvested energy.

CE Database Subject Headings

Bridges; Smart Materials; Energy Methods; Monitoring;

Authors keywords

Train-Bridge Dynamics, Piezoelectric, Energy Harvesting, Structural Health Monitoring, Wireless Sensor Network, Experimental Data.

Introduction

With the current advances in microsystems, and the potential that they create for autonomous sensing systems, substantial consideration has been placed on the supply of power and the efficient use of such systems, particularly for wireless sensor networks. This requirement has resulted in significant investigations into the use of different energy harvesting techniques for the powering of wireless networks (Harb 2011), with much of the attention being focused on the use of vibration based electromagnetic, electrostatic and piezoelectric solutions (Beeby et al. 2006).

Of these energy harvesting techniques, devices based on the use of piezoelectric materials have proven to especially effective (Cook-Chennault et al. 2008; Sodano et al. 2004; Anton and Sodano 2007). Significant research has been carried out to date on the optimisation of the design of the piezoelectric energy harvesters, including cantilever based applications (Jackson et al. 2013a; Jackson et al. 2013b; Erturk and Inman 2008), a bimorph cantilever (Ajitsaria et al. 2007) and a dual-mass vibration harvester (Tang and Zuo 2011). With large differences in the physical properties of piezoelectric materials, which range from ceramics to polymers, identifying the most suitable for specific applications is essential (Vatansever et al. 2011).

The potential use of energy harvesting systems for civil infrastructure (Sazonov et al. 2009) has just recently begun to receive attention and the true potential for applications in the field of civil engineering has yet to be realised. A recent study (Ali et al. 2011) investigated the feasibility of using tuned piezoelectric energy harvesters as a method of powering microsystems through the parasitic harvesting of ambient structural vibrations from bridge infrastructure. Different methods of piezoelectric energy harvesting for bridges have also received attention (Erturk 2011).

Structural health monitoring (SHM) for civil infrastructure elements, on the other hand, is a field in a continuous state of development and evolution (Chang et al. 2003; Catbas et al. 2008; Moaveni et al. 2009: Pakrashi et al. 2013). Modern advances in the development of smart sensors has suggested the potential for the creation of wireless sensor networks for use in the monitoring of infrastructure elements (Lynch and Loh 2006; Gangone and Whelan 2011). Lead Zirconate Titanate (PZT) sensors have been embedded within reinforced concrete elements and compared against traditional methods of detection, namely strain gauges and Linear Variable Differential Transformers (LVDT), under different loading conditions (Song et al. 2007). PolyVinyliDene Fluoride (PVDF) sensors have also been utilised for the wireless monitoring of tension conditions in cable stayed bridges (Liao et al. 2001). Structural health monitoring of bridge infrastructure has also received some attention, with a number of methods proposed to determine the condition of bridges (Brincker et al. 2003; Zhang et al. 2005; Sepe et al. 2005). One such method is using the dynamic response of train-bridge interaction and sensitivity analysis using stiffness variation for the detection of damage (Zhan et al. 2011; Shu et al. 2013). A Bridge Weigh-in-Motion (B-WIM) with accelerometers has also been implemented for the monitoring of actual traffic load (Karoumi et al. 2005; Liljencrantz et al. 2007; Liljencrantz and Karoumi 2009), but this is totally reliant on external power supplies. Consequently, evidence exists suggesting that the monitoring of train-bridge interaction under operational conditions may be beneficial for health monitoring of structures as the structure is not required to be closed for use.

This paper demonstrates that energy harvesting from vibration due to the response of train passages across bridges can provide sufficient power for small devices with low power demand. The additional advantage of this is that the harvested energy can be used for structural health monitoring. The levels of power which can be harvested from train-bridge dynamics under operational conditions have been investigated for:

- A range of passenger trains from international stock,
- A freight fleet from experimental data and
- A health monitoring system using the harvested energy as a metric.

Energy Harvesting From Train Induced Responses

Piezoelectric Energy Harvesting System

Significant research has taken place into the design and optimisation of piezoelectric energy harvesting systems, with emphasis being placed into the design of systems powered through the vibrations of the host structure (Erturk 2011). A limitation to the cantilever based energy harvester approach is the requirement to tune the harvester to the natural resonant frequency of the host structure to optimise energy harvesting potential (Ali et al. 2010). Potentially more effective is an energy harvesting system based on an adhesive patch which could be bonded to the host structure to generate power. This is achieved directly from the variation in the strain conditions from the surface to which it has been attached. It is envisaged that such an energy harvesting system could be used for multiple applications without the need for determining and tuning to the natural frequency of the host structure. Under such circumstances, it is important to assess the order of energy harvested from a certain system and assess the potential applications. For this paper, an adhesive patch energy harvesting system is evaluated for energy harvesting from bridge dynamics due the passage of trains and the potential applications of such a system identified and investigated.

Piezoelectric Materials

Due to the large variations in the nature of piezoelectric materials, as described previously, it is imperative to investigate different materials for their use as an energy harvester in these applications. Two commercially available piezoelectric materials of rectangular geometry, PZT and PVDF, were chosen for use as the basis of the energy harvesting system. PZT is the most commonly used piezoelectric material for energy harvesting due to its excellent piezoelectric properties. A drawback of PZT, however, is its brittle nature since it is a ceramic material. This can lead to difficulty in terms of the design, handling and durability of the energy harvesting systems and as a consequence, may render it be unsuitable for certain applications (Woo and Goo 2007). PVDF is a polymer which exhibits a high mechanical strength while retaining excellent flexibility (Vinogradov and Holloway 1999) and thus can be simply formed into different shapes. While it is not subject to the same physical limitations as PZT, its lower piezoelectric properties require higher strain conditions to produce a similar power output (Lin and Giurgiutiu 2006). The representative piezoelectric and physical properties of both energy harvesters considered in this paper are outlined in Table 1, including Youngs Modulus, E, the piezoelectric constant d_{31} and e_{33}, and the length, width and thickness of the materials, l, w and t respectively.

Modelling of Energy Harvester

In this work, energy harvesting systems are designed to be attached externally to the underside surface of the finite element model. The 31 mode, relating to the piezoelectric nature of the material whereby the material is poled in the vertical direction, 3, during its manufacture, and strain acts along the longitudinal direction, 1, is the mode of operation of the energy harvesting system (Anton and Sodano 2007). It is assumed that there is a perfect connection between the energy harvesters and the surface of the bridge and thus, almost identical strain conditions will act on both surfaces with no losses arising from an adhesive substrate. The model used for the calculation of the power output of the system is based on the piezoelectric principle for coupled electromechanical behaviour and the modelling of the voltage is obtained from Sirohi and Chopra (2000). The strain profile that acts upon the location at which the energy harvesters are to be positioned are evaluated and the potential voltage was subsequently calculated, (Eq.1), where ε is the evaluated strain averaged over the harvester length and C_p is the capacitance of the material, (Eq. 2). The power for each train passage was calculated from the root mean squared (RMS) of the generated voltage for the entire train passage, (Eq. 3), where R is the resistance, assigned a value of 100kΩ. The system would also incorporate an energy storage and power handling circuit which would be able to consistently provide power to the low power sensors and enable them to become autonomous wireless sensors. The design and modelling of the circuit is beyond the scope of this paper and, thus, no reduction in power due to losses through the circuit is assumed in this paper. Under operational circumstances, losses will not affect the order of the energy harvested since the extent of losses will be small, dependent on the circuit. Circuit losses range from 60 to 84% efficiency (Tabesh and Fréchette 2010), with some circuits reporting a 96% efficiency rate (Magno et al. 2013). Furthermore, the losses would be a consistent value over time and for each harvester, it can be expected that the losses would not influence the relative power output potentials between different trains, the feasibility of using the energy for devices with small power demand (Cook-Chennault et al. 2008) or potential applications in structural health monitoring (Farrar et al. 2006).

$$V_P = \frac{d_{31}Eb}{C_p}\int_l \varepsilon dx \qquad \text{Eq. 1}$$

$$C_p = \frac{e_{33}lw}{t} \qquad \text{Eq. 2}$$

$$P = \frac{(V_{RMS})^2}{R} = \frac{\left(\sqrt{\frac{1}{T}\int_0^T V^2(t)\,dt}\right)^2}{R} \qquad \text{Eq. 3}$$

Train-Bridge Modelling

Train Models

Five international trains were chosen for the purposes of comparing the potential for energy harvesting from train passages over a bridge (Fig. 1). These are the Irish *071Loco* and *201Loco*, the French *TGV*, the German *I.C.E.* and the Japanese *Shinkansen* (Wang et al. 2003; Hagiwara et al. 2001). Each train was modelled with the same configuration as it would have under operational conditions, including the number of motorcars and carriages and the length and load of axles (Table 2). The *071Loco* and *201Loco* trains are powered by a single diesel motorcar, while the remaining are electric trains with locomotives located at both ends of the train. The *TGV* has a total of ten carriages, with the carriages connected to the motorcar being 21.9m in length and the remaining eight being 18.7m.

Modelling of Train Passage over Bridge

For the purposes of modelling the change in strain conditions of a bridge that arise due to a train passage, a three dimensional finite element sectional model of the bridge was created using Strand7 finite element analysis system (Strand7 2010). The double tracks model was created using 20 node hexahedral bricks (Fig 2) and has dimensions 10.6m in length and 10m in breadth. The train axle loads were modelled as point loads at distances determined by the individual axle spacing for each train as outlined previously, acting along a load path along the length of the track. A total of seven speeds, ranging from 40 to 160km/hr, were chosen for the purposes of this investigation. The models were analysed along the base surface at the mid-span of the support beams, the position at which the energy harvesting system are located. Single train passage and double train passage with trains travelling in opposite directions were considered.

For the purposes of comparison with the finite element model, a differential equation model for train passages over a bridge was created for a simply supported bridge. A beam model proposed by Fryba (2001) was used in this regard. The input values were obtained so as to be identical to the finite element model and the trains as described in previous sections. The model was then solved for all single passage cases and the harvested energy output for each model was calculated from the evaluated strain. Finite element and differential equation models were compared for dynamic strain responses for each train passage (Fig. 3) and a good correlation in the appearance of the dynamic strain response was found. However, the magnitudes of the responses obtained from the finite element model were higher than those of the comparable differential equation models. This response from the finite element models produced a 34.1%, 33.0%, 28.2%, 29.7% and 31.6% increase in the magnitude of the average strain for the *071Loco*, *201Loco*, *TGV*, *Shinkansen* and *I.C.E.* respectively, when compared to the differential equation counterparts. This is mostly due to the finite element model takes into account the non-centralised nature of the track and thus the transverse loading due to the train passages.

Results

Single Train Passage

All train models were analysed for passages of different speeds and the harvested energy levels were evaluated from the dynamic strain responses from the finite element and differential equation model (Fig. 4). The power outputs from the PZT energy harvesting systems are higher than that of its PVDF counterpart, again due to higher piezoelectric coefficients of PZT. It was found that the PVDF power outputs were approximately 52% of the PZT power outputs, which corresponds to PZT having a power figure of merit, a non-dimensional figure of the piezoelectric constant squared over the dielectric constant, which is double of PVDF. The finite element models produced a higher power output than the differential equation, which was expected during comparisons of the strain profiles. The finite element models show a small increase in the power outputs with increasing train speed, while there is a relatively higher increase from the differential equations. The *201Loco* was observed to have the highest potential of power output per train passage. From the finite element PZT model, the power harvested ranged from 382μW at 40km/hr to 397μW at 160km/hr, while ranging from 223μW to 363 μW from the differential equations. The *Shinkansen* was observed to have the lowest estimated power outputs, ranging from 197μW at 40km/h4 to 203μW at 160km/hr from the finite element PZT model. The differential equation model ranged from 112μW at 40km/hr to 163μW at 140km/hr. Each train is observed to have a signature power output which can be used to determine the identity of the train which has travelled over the bridge. This signature power output, and the subsequent potential of different trains towards energy harvesting, is consistent with existing investigations into the characterisation of different vehicles loading effect on bridges (Brady et al. 2006; O'Brien et al. 2009).

As shown even with a simplified differential equation model, the harvested energy for a single energy harvesting system for a single train passage is observed to be of the order of 100μW. The power requirement of an autonomous wireless sensor network in sleep mode requires on the order of 100's of nW (Magno et al. 2013) and typically requires approximately 100 μW (Torah et al 2008; Wang et al 2011) to operate in active mode. In structure health monitoring, the signal does not need to be transmitted after each passing train, but over an extended period of time. Hence, charge generated from each train can be stored and information transmitted periodically and through the highly routine nature of train networks, the time between cycles is highly predictable. Bridges which experience high levels of traffic and exhibit more dynamic behaviour would lend themselves to higher levels of harvesting. These are often the same bridges that require more attention in terms of monitoring. Consequently, a natural potential exists for the energy harvesters to be used as a monitor.

Double Train Passage

After studying the effects of single trains on the models, the energy harvesting potential from double train passages was investigated (Fig. 5). For this, the finite element model was used exclusively and modelled with trains travelling in opposite directions. As previously found in the single passages, the PZT system produced a higher power output then the PVDF system. The highest figure of power produced was 588μW from PZT system and 307.1μW from PVDF system for the *I.C.E.* trains, traversing the model in opposite directions at a speed of 120km/hr. The *Shinkansen* again produced the lowest amount of power, ranging from 269μW to 285μW at speeds of 40 and 160km/hr respectively from the PZT harvesting system and 140μW to 149μW at speeds of 40 and 160km/hr respectively from the PVDF harvesting system.

As can be seen from the comparison of Fig. 4 and Fig.5, there is a considerable increase in power produced from passing trains when compared to single train passages. However, a double train passage does not result in a doubling of the power output. Instead it is dependent on the characteristics of the trains and their speed, with an increase in power output ranging 34 to 52%. This again is consistent with both theoretical and experimental investigations into the effects of vehicle loadings on bridges (O'Brien and Enright 2013; Brady and O'Brien 2006).

Energy Harvesting – Experimental Data

Full scale strain and acceleration measurements from train-bridge interaction were conducted at Skidträsk Bridge, located in Northern Sweden (Fig. 6). The bridge is a single span steel-concrete composite bridge which carries a single ballasted track, spans 36m and is 6.7m in width. The rails are supported by concrete sleepers, 0.65m apart, which lie on a 0.5m layer of ballast and a 0.5m layer of sub-ballast. The ballast layers lie on a reinforced concrete slab, ranging in depth of between 0.3 and 0.4m, supported through two steel beams.

Train Loading

Two different cases have been investigated for the purposes of determining the potential of energy harvesting from real-time train-bridge interaction. The first case is a single locomotive passing over the bridge at speeds ranging from 60 to 180km/hr. The locomotive is 10.4m long with two bogies, located 7.7m apart, with the two axles on each bogie a distance of 2.7m apart. The total load from the locomotive is 191.2kN. The second case considered for the purposes of this investigation is a loaded freight train, namely the *Steel Arrow*, a common iron ore freight train in Sweden. The *Steel Arrow* comprises of two locomotives and twenty six wagons, with the locomotives the same as in the first case. The wagons are a total of 10.4m in length, with two bogies 8.6m apart, with the bogie containing two axles 1.8m apart. The total load from each axle is 245.2kN. The train has a total length of 388m.

Monitoring System

The bridge was monitored by the Division of Structural Engineering & Bridges, KTH Royal Institute of Technology, Stockholm. Two monitoring systems, one permanent and one temporary, were installed on the bridge (Loireaux 2008). The permanent system consisted of four strain gauges measuring longitudinal strain on the main steel beams, two strain transducers measuring transverse strain on the concrete slab and three accelerometers measuring vertical bridge deck acceleration, all at varying points on the slab and steel beams. The temporary system consisted of four accelerometers installed on the sleepers and within the ballast. The speed of the passing trains was obtained from two optical laser sensors, placed a distance of 26.05m apart. The sensors output was used to determine the number of wagons of the train and the distance between two axles. This enabled the speed and length of the train to be determined through the distance between axles, bogies and wagons.

Comparisons with Modelling

Two computational models were created for comparison against the experimental data. The first is the differential equation model, which was referred to in the previous section. The second was a finite element model created using the LUSAS finite element analysis software (LUSAS 2012). A two dimensional simply supported beam model was created with five different cross-sections representing the variation in the Skidträsk Bridge. The elements used are ‘BEAM’ elements, which are 2 dimensional linear beam elements, at a mesh size of 0.1m. For both models, calibration was performed using actual properties and measurements of the Skidträsk Bridge. The experimental data, finite element model and differential equation model all correlated well (Fig. 7). The power output from the train and locomotive passages were then evaluated for the experimental data and corresponding differential equation model.

Results

Locomotive Passages

The potential power output obtained from a single locomotive passage was evaluated for speeds ranging from 61km/hr to 180km/hr (Fig. 8). Again, it was found that the PZT energy harvester generated more power when compared to its PVDF counterpart. For a single passage of the locomotive, a maximum of 1.55μW was produced at a speed of 118km/hr from the experimental based PZT harvester, with a corresponding model value of 1.31μW. From the same speed, the PVDF harvester produced 0.83μW and 0.7μW from the experimental and modelled data respectively. However, as the PVDF is less brittle than the PZT, the long-term reliability is believed to be significantly higher than PZT. Comparing the experimental power output with the finite element double track model bridge from the previous section, it can be determined that for energy harvesting, train passages are more efficient over short span bridges. While the energy harvested from a single train passage is relatively low for the locomotive passage, the energy harvested from multiple train passage can be stored to a predefined level which, when reached, is capable of powering a wireless communication device. With the highly timetabled nature of train networks, the system can be calibrated so as to act as a health monitoring tool.

Steel Arrow Passages

The estimated power outputs from single passages of the 388m long *Steel Arrow* train at varying speeds was found for speeds ranging from 65km/hr to 118km/hr (Fig. 9). The PZT harvester produced power outputs ranging from 24.1μW to 16.9μW at speeds of 65km/hr to 118km/hr respectively from experimental data and power output of 23.4μW and 16.1μW from the models. The PVDF harvester produced 12.8μW and 12.4μW from the same experimental conditions and 9μW and 8.6μW from the models. The values are lower than the finite element modelling considered in the previous section but significantly higher than that produced by a single locomotive. Apart from the difference in stiffness characteristics of the bridge considered in this paper, the *Steel Arrow* being a freight train may also be a contributing factor as the spacing between the axles are far smaller than the passenger trains previously investigated. Again, with multiple train passages and through storage and calibration, the potential use of the energy harvesters to power small, low powered devices for the purposes of health monitoring is confirmed.

Structural Health Monitoring Potential

The use of the energy harvesting adhesive patch system as a method for the detection of damage and the structural health monitoring of bridges was subsequently investigated. With the change in stress conditions created as a result of damage to the structure (Pakrashi et al. 2010, Perry and Koh 2008), there will be a subsequent change in the levels of energy harvested from the structure. As the harvested power is related to the RMS voltage and to the accumulation of dynamic responses filtered by electromechanical coupling over the period of the train passage, the use of an energy harvesting system for health monitoring is not dependent on individual measurements over time. This is an advantage since the ratio of undamaged to damaged energy harvesting potential is less affected by localised noise and is expected to be more robust due to the natural averaging that is carried out while energy is harvested.

The calibration of the energy harvesting system for use in health monitoring is dependent on a number of factors. These include the power generated from a single passage over the undamaged bridge, the storage capacity of the system, the power requirements for the wireless transmitter and the number of train passages over the bridge for a given period of time. Upon these parameters being determined, any damage to the bridge, be it instantaneous or gradual, would result in a change in the amount of energy harvested. This change in the energy harvesting levels can indicate the presence and position of the damage and through the factoring of this change against the undamaged levels, the magnitude of the damage can be determined, as outlined in the subsequent sections.

Modelling of Damage

The finite element model utilised in the previous sections for the determining of energy harvesting potential from train-bridge dynamics was employed for assessing the feasibility of structural health monitoring using the energy harvesting system. The *201Loco* train, travelling at 100km/hr, was chosen as an example to demonstrate how damage evolution and position can influence the energy harvested at a given device. Damage was modelled at two different locations, with varying Crack Depth Ratio's (CDR's) ranging from 0.05 to 0.20, in increments of 0.05. Each 0.05 CDR increment represents an increase of 40mm in the crack depth. Two crack widths were chosen, of width 400mm and 800mm, to investigate the relationship between increased width of damage and the effect on the energy harvesting system. A relatively localised damage is considered in this paper as opposed to diffused damage with larger influences on the global dynamics of the structure (Fig. 10). Consequently, successful application of SHM on this localised damage will ensure the potential of using energy harvesting for health monitoring in a wide range of damage situations.

Damage Detection

Structural health monitoring is a four step process with the detection of the presence of damage, the location of damage and the extent of damage respectively being the first three steps. The final step is the assessment of remaining service life and this is usually treated independently (Rytter 1993). The ability of the energy harvesting system to determine the presence, location and magnitude of the damage are investigated to determine whether it satisfies the first three criterion of SHM. The power harvesting profile from the model with localised damage was evaluated and compared against the power harvesting profile for an undamaged model, with the undamaged situation providing a benchmark. Using a monotonic descriptor of damage detection is typically considered to be a good method for estimating the extent of the damage extent (Pakrashi et al. 2007). The influence of the damage was determined through the modelling of the energy harvesting system as an array located along the bottom beam supports of the finite element model. The locations of the harvesting system and the grid spacing can be made commensurate with resolution at which damage effects need to be identified and the consequences of damage at a certain location. Such locations or spacing may be assessed from standard static analysis. At each chosen position, the influence of damage was determined through the normalised calibration of the harvested energy against the energy harvested from the undamaged model case (Fig. 11). The damage was introduced centred about the mid-span of the central support beam, with the solid line signifying the normalised power with damage of 0.8m width and the broken line representing the normalised power with damage of 0.4m width. The region closest to the damage experiences the largest variation in the normalised power harvested and the normalised power for the damage of width 0.8m is more significant when compared to its 0.4m width damage counterpart. The effect of the damage can be detected along the length of the beam, with the proximity of the energy harvester to the location of the damage being directly related to the change in the normalised power harvested (Fig. 11a). For the 0.8m wide damage for CDR = 0.20, at the location 3.9m from the edge of the damage the normalized power harvested was 0.97, compared to 0.70 at the location of 0.4m. For the 0.4m wide damage, again at CDR of 0.20, the normalized power was 0.98 at a location of 4.1m and 0.85 at a location 0.6m. At the location of damage, the normalized power increases dramatically (Fig. 11b). This ranged from 3.56 for damage width .8m and 2.50 for damage width 0.4m. This marked increase in the normalized power can be used to identify the magnitude to which the damage has developed to in the structure, due to the monotonic nature of the curves upon the introduction of damage to the structure. The ability of the energy harvesting system to detect damage at a non-symmetrical location was also investigated. Damages, again of widths 0.4 and 0.8m with CDR ranging from 0.05 to 0.20, were introduced centralised about the quarter-span located 2.65m from the support along the central support beam. The results of the quarter-span damage (Fig 12) are in keeping with that of the mid-span damage. The influence of the damage can again be detected through the reduction in the normalized power at locations situated along the length of the beam away from the position of damage (Fig. 12a), with the proximity to the damage location again being a critical factor. For damage of width 0.8m for CDR =0.20, the normalised power is 0.44 at a location .45m from the damage and for damage of width 0.4m for similar CDR, the normalised power is 0.68 at a distance of .65m. Due to the non-symmetrical location of the damage, between the support and the position of damage for both damage widths, there is an increase in the normalised power between CDR of 0.15 and 0.20. At the position of damage, there is a marked increase in the magnitude of the normalised power with increasing CDR (Fig. 12b). At the position of damage located closest to the support at a CDR of 0.20, the normalised power ranged from 48.51 for damage of width 0.8m to 37.74 for damage of width 0.4m. Again through the calibrated system, the magnitude of the damage can be determined, due to the quite monotonic nature of the normalised power harvesting curves once damage is detected. The presence, location and magnitude of the damage can be ascertained through the use of the energy harvesting system, thus satisfying the first three criteria of SHM.

Structural Health Monitoring – Experimental Data

Experimental data from a laboratory scale experiment on damaged beam and model vehicle interaction was considered next (Pakrashi et al., 2010). This entailed a model two-axle vehicle, with an axle distance of 0.11m, traversing a phenolic beam of length 0.91m. Damage was introduced in the form of an open crack located along the lower section of the beam, with CDR's of 0.167, 0.33 and 0.5. The vehicle was accelerated from a resting position by means of a string which was coiled around a motor located at the opposite side as the initial position. The response due to the bridge-vehicle interaction was recorded by means of two strain gauges, located at distances 4 and 6mm from the position of damage. The strain data was subsequently analysed and the normalised power harvesting for the varying CDR's was evaluated (Fig. 13). With increasing CDR, the normalised power increases, with proximity to the location of the damage being directly related to the magnitude, as was previously established in the finite element damage analysis.

Conclusions

This paper presents the feasibility of using train-bridge interaction for energy harvesting and proposes a possible application in structural health monitoring. Two difference piezoelectric materials, PZT and PVDF, were compared for energy harvesting purposes. Although PZT showed a significant increase in power generated, the brittle nature of the material is a potential reliability risk. Therefore the PVDF material is believed to be the better option at this time. Five international trains were chosen to determine their potential for energy harvesting from train-bridge dynamics. A three dimensional finite element model was created and compared against differential equation based models. Full scale testing data, along with calibrated finite element and differential equation models for train-bridge interaction were used and potential power output of the energy harvesting system were determined. Piezoelectric harvesting systems were observed to be appropriate for harvesting energy to support wireless sensors with low power demand. Important trains were observed to have individual signatures of energy harvesting and potential towards harvesting for bridge structures. Multiple crossings of trains do not produce double the amount of energy as compared to a single train passage. Train passages were found to produce power outputs up to 588μW for passenger trains, namely the *I.C.E.*, and 24.1μW for freight trains, the *Steel Arrow*, both from PZT based energy harvesting systems. Bridges with high dynamic responses, which are often identified as more in need of health monitoring than bridges with low dynamic responses, are more suited to energy harvesting from train passages over bridges. The use of energy harvesting systems for use in the structural health monitoring of train bridges was investigated. It was found that an array of energy harvesting systems have the potential for determining the location and the magnitude of damage throughout a bridge and compared against laboratory experiments. The extent of damage can be monotonically represented by the harvested energy.

References

Ajitsaria, J., Choe, S. Y., Shen, D., and Kim, D. J. (2007). "Modeling and analysis of a bimorph piezoelectric cantilever beam for voltage generation." *Smart Mater. Struct.,* 16(2), 447–454.

Ali, S. F., Friswell, M. I., and Adhikari, S. (2011). "Analysis of energy harvesters for highway bridges." *J Intel Mat Syst Str.,* 22(16), 1929–1938.

Ali, S. F., Friswell, M. I., and Adhikari, S. (2010). "Piezoelectric energy harvesting with parametric uncertainty." *Smart Mater. Struct.,* 19(10):105010 (9p).

Anton, S. R., and Sodano, H. A. (2007). "A review of power harvesting using piezoelectric materials (2003-2006)." *Smart Mater. Struct.,* 16(3), R1–R21.

Beeby, S. P., Tudor, M. J., and White, N. M. (2006). “Energy harvesting vibration sources for microsystems applications.” *Meas. Sci. Technol.,* 17(12) R175–R195.

Brady, S. P., O'Brien, E. J., and Žnidarič, A. (2006). “Effect of vehicle velocity on the dynamic amplification of a vehicle crossing a simply supported bridge.” *J. Bridge Eng.*, 11(2), 241–249.

Brady, S. P., and O'Brien, E. J. (2006). “Effect of vehicle velocity on the dynamic amplification of two vehicles crossing a simply supported bridge.” *J. Bridge Eng.*, 11(2), 250–256.

Brincker, R., Ventura, C. E., and Anderson, P. (2005). “Why output-only modal testing is a desirable tool for a wide range of practical applications.” *Proc. IMAC-21*, Florida, USA, pp. 265-272

Catbas, F. N., Gul, M., and Burkett, J. L. (2008). “Damage assessment using flexibility and flexibility-based curvature for structural health monitoring.” *Smart Mater. Struct.* 17(1):015024.

Chang, C. C., Flatau, A., and Liu, S. C. (2003). “Review Paper: Health Monitoring of Civil Infrastructure.” *Struct. Health Monit.*, 2(3), 257-267.

Cook-Chennault, K. A., Thambi, N., and Sastry, A. M. (2008). “Powering MEMS portable devices- a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems.” *Smart Mater. Struct.*, 17(4):043001 (33p).

Erturk, A., and Inman, D. J. (2008). “On mechanical modelling of cantilever piezoelectric vibration energy harvesters.” *J Intel Mat Syst Str.,* 19(11), 1311–1325.

Erturk, A. (2011) “Piezoelectric energy harvesting for civil infrastructure system applications: moving loads and surface strain fluctuations.” *J Intel Mat Syst Str.,* 22(17), 1959–1973.

Farrar, C. R., Park. G., Allen, D. W., and Todd, M. D. (2006). “Sensor network paradigms for structural health monitoring.” *Struct. Control Health Monit.,* 13(1), 210-225.

Fryba, L. (2001). “Rough assessment of railway bridges for high-speed trains.” *Engineering Structures.,* 23(5), 548–556.

Gangone, M.V., and Whelan, M. J. (2011). “Wireless Monitoring of a Multispan Bridge Superstructure for Diagnostic Load Testing and System Identification.” *Comput-Aided Civ In,* 26(7), 560-579.

Hagiwara, Y., Tanaka, M., and Ueno, M. (2001). “Evaluation of advantages of high-speed EMU in the case of the Series 700 Shinkansen highspeed train with IGBT applied traction system.” *Proc. World Congress Railway Research (WCRR) 2001*, Deutsche Bahn AG, Munich, Germany.

Harb, A. (2011). “Energy harvesting: state-of-the-art.” *Renew Energ.*, 36(10), 2641–2654.

Jackson, N., O'Keeffe, R., Waldron, F., O'Neill, M., and Mathewson, A. (2013a). "Influence of aluminium nitride crystal orientation on MEMS energy harvesting device performance." *J. Micromech. Microeng.,* 23(7):075014 (9pp).

Jackson, N., O'Keefe, R., O'Neill, M., Waldron, F., and Mathewson, A. (2013b). "CMOS compatible low-frequency aluminium nitride MEMS piezoelectric energy harvesting device." *Proc. SPIE 8763, Smart Sensors, Actuators, MEMS VI, 87631I.*

Karoumi, R., Wiberg, J., and Liljencrantz, A., (2005). "Monitoring traffic loads and dynamic effects using an instrumented railway bridge." *Engineering Structures.,* 27(12), 1813–1819.

Lam, H. F., Lee, Y. Y., Sun, H. Y., Cheng, G. F., and Guo, X. (2005). "Application of the spatial wavelet transform and Bayesian approach to the crack detection of a partially obstructed beam." *Thin Wall. Struct.*43(1), 1-21.

Liao, W. H., Wang, D. H., and Huang, S. L. (2001). "Wireless monitoring of cable tension of cable-stayed bridges using PVDF piezoelectric films." *J Intel Mat Syst Str.,* 12(5), 331–339.

Liljencrantz, A., and Karoumi, R. (2009). "Twim, A MATLAB toolbox for real-time evaluation and monitoring of traffic loads on railway bridges." *Struct Infrastruct E,* 5(5), 407-417.

Liljencrantz, A., Karoumi, R., and Olofsson, P. (2007). "Implementing bridge weigh-in-motion for railway traffic." *Computer and Structures*, 85(1-2), 80-88.

Lin, B., and Giurgiutiu, V. (2006). “Modeling and testing of PZT and PVDF piezoelectric wafer active sensors.” *Smart Mater. Struct.,* 15(4), 1085–1093.

Lorieux, L. (2008). “Analysis of train-induced vibrations on a single-span composite bridge.” M.S. Thesis, KTH., Stockholm, Sweden.

LUSAS Finite Element Analysis System. Finite Element Analysis Ltd., Version 14.7. (2012). (Computer Software.) LUSAS, Forge House, 66 High Street, Kingston upon Thames, Surrey, KT1 1HN, United Kingdom.

Lynch, P. J., and Loh, K. J. (2006). “A summary review of wireless sensors and sensor networks for structural health monitoring.” *Shock Vib. Dig.,* 38(2), 91–128.

Magno, M., Jackson, N., Mathewson, A., and Popovici, E. (2013). “Combination of hybrid energy harvesters with MEMS piezoelectric and nano-Watt radio wake up to extend lifetime of system for wireless sensor nodes.” *Pro., Int., Con., on Architecture of Computing Systems.,* VDE VERLAG GMBH, Berlin, Offenbach. (6pp)

Moaveni, B., Conte, J. P., and Hemez, F. M. (2009). “Uncertainity and sensitivity analysis of damage identification results obtained using finite element model updating.” *Comput-Aided Civ In*, 24(5), 320-334.

O'Brien, E. J., and Enright. B. (2013). “Using Weight-In-Motion data to determine aggressiveness of traffic for bridge loading.” *J. Bridge Eng.,* 18(3), 232–239.

O'Brien, E. J., Rattigan, P., González, A., Dowling, J., and Žnidarič, A. (2009). "Characteristic dynamic traffic load effects in bridges." *Engineering Structures.,* 31(7), 1607–1612.

Pakrashi, V., Basu, B., and O'Connor, A. (2007). "Structural damage detection and calibration using a wavelet–kurtosis technique." *Engineering Structures.*, 29(9), 2097 – 2108.

Pakrashi, V., Harkin, J., Kelly, J., Farrell, A., and Nanukuttan, S. (2013). "Monitoring and repair of an impact damaged prestressed concrete bridge." *I.C.E. Bridge Eng*., 166(1), 16-29.

Pakrashi, V., O'Connor, A., and Basu, B. (2010). "A bridge-vehicle interaction based experimental investigation of damage evolution." *Struct. Health Moni.*, 9(4), 285–12.

Perry, M. J., and Koh, C. G. (2008). "Output-only structural identification in time domain: Numerical and experimental studies." *Earthquake Engng Struct. Dyn.*, 37(4), 517 – 533.

Rytter, A. (1993). "Vibration based inspection of civil engineering structures." Ph.D thesis, Department of Building Technology and Structural Engineering, Aalborg University, Denmark.

Sazonov, E., Li, H., Curry, D., and Pillay, P. (2009). "Self-Powered Sensors for Monitoring of Highway Bridges." *IEEE Sensors J*, 9(11), 1422-1429.

Sepe, V., Vestroni, F., Vidoli, S., Mele, R., and Tisalvi, M. (2005). "Train-Induced vibrations of masonry railway bridges." *Proc. EURODYN 6th, 1, pp. 161-6, Paris, France.*

Shu, J., Zhang, Z., Gonzalez, I., and Karoumi, R. (2013). "The application of a damage detection method using artificial neural network and train-induced vibrations on a simplified railway bridge model." *Engineering Structures.*, 52, 408-421.

Sirohi, J., and Chopra, I. (2000). "Fundamental understanding of piezoelectric strain sensors." *J Intel Mat Syst Str.*, 11(4), 246–257.

Sodano, H. A., Inman, D. J., and Park, G. (2004). "A review of power harvesting from vibration using piezoelectric materials." *Shock Vib. Dig.,* 36(3), 197–205.

Song, G., Gu, H., Mo, Y. L., Hsu, T. T. C., and Dhonde, H. (2007). "Concrete structural health monitoring using embedded piezoceramic transducers." *Smart Mater. Struct.*, 16(4), 959–968.

Strand7 Finite Element Analysis System. Strand7 Pty Ltd., Version 2.4.4., (2010). (Computer Software.) Suite 1, Level 5, 65 York Street, Sydney. NSW 2000.

Tabesh, A., and Fréchette, L. G. (2010). "A low-power stand-alone adaptive circuit for harvesting energy from a piezoelectric micropower generator." *IEEE Trans. Ind. Electron.,* 15(3), 840-849.

Tang, X., and Zuo, L. (2011). "Enhanced vibration energy harvesting using dual-mass systems." *J. Sound Vib.,* 330(21), 5199–5209.

Torah, R., Glynne-Jones, P., Tudor, M., O'Donnell, T., Roy, S., and Beeby, S. (2008). "Self-powered autonomous wireless sensor node using vibration energy harvesting." *Meas. Sci. Technol.,* 19(12), 8pp.

Vatansever, D., Hadimani, R. L., Shah, T., and Siores., E. (2011). "An investigation of energy harvesting from renewable sources with PVDF and PZT." *Smart Mater. Struct.,* 20(5):055019 (6p).

Vinogradov, A., and Holloway, F. (1999). "Electric-mechanical properties of the piezoelectric polymer PVDF." *Ferroelectrics*, 226(1), 169–181

Wang, J. F., Lin, C. C., and Chen, B. L. (2003). "Vibration suppression for high-speed railway bridges using tuned mass dampers." *Int J. Solids Struct.*, 40(2), 465–491.

Wang, W. S., O'Keeffe, R., Wang, N., Hayes, M., O'Flynn, B., Ó'Mathúna, C. S. (2011). "Practical wireless sensor networks power consumption metrics for building energy management applications." *Proc., 23rd European Conference Forum Bauinformatik 2011,* Construction Informatics, Cork, Ireland.

Woo, S-C., and Goo, N. S. (2007). "Identification of failure mechanisms in a smart composite actuator with a thin sandwiched PZT plate based on waveform and primary frequency analysis." *Smart Mater. Struct.,* 16(4), 1460–1470.

Zhan, J. W., Xia, H., Chen, S. Y., and De Roech, G. (2011). "Structural damage identification for railway bridges based on train-induced bridge responses and sensitivity analysis." *J. Sound Vib.*, 330(4), 757–770

Zhang, L., Brincker, R., and Andersen, P. (2005). "An overview of operational modal analysis: Major development and issues." *Proc. IOMAC 1, 2005, Copenhagen, Denmark*