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Optimal design and application of 3D printed energy harvesting devices for railway bridges

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ABSTRACT: In this paper, the authors investigate energy harvesting on railway bridges. The tuning frequency for the optimal design of cantilever based 3D printed energy harvesters is studied. An analytical model to represent the electromechanical behaviour of the device is presented for the estimation of the energy harvested from train-induced bridge vibrations. A genetic algorithm constrained to geometry and structural integrity is used to solve the optimisation problem. Additive manufacturing by 3D printing of the substructure of the harvester is considered to maximise the design flexibility and energy performance. Optimal device prototypes with PAHT-CF15 substructure are designed for a real bridge in the Madrid-Sevilla High-Speed line. Finally, the performance of energy harvesting is evaluated from in situ experimental data measured by the authors. The results allow quantifying the energy harvested in a time window of three and a half hours and 19 train passages.

1 INTRODUCTION

One of the major limiting factors in the implementation of sensor networks in monitoring applications on railway structures is the lack of a long-term and low-maintenance power supply. Most existing systems require battery changes, and difficulties of access and infrequent maintenance operations can limit their practical implementation. In this sense, piezoelectric energy harvesting is becoming an alternative to the electrical supply of sensors and nodes in remote areas (Wei & Jing 2017, Yildirim et al. 2017). Within the context of this work, many research have focused on the development of energy harvesters based on the piezoelectric effect to transform railway-induced vibrations into electrical energy to be used in small power devices and sensors. The most common typology is that of a bimorph cantilever beam. These systems have the ability to generate energy from environmental vibrations in a frequency range of 3–100 Hz (Sarker et al. 2019). The predominant frequencies of vibrations caused by rail traffic in the infrastructure are within the above range, making it possible to supply low-power devices and sensors. An important problem of energy collection systems is associated with the fact that the performance of the energy production device is limited to a very narrow operating frequency band around its resonance frequency (Erturk & Inman 2011). If the excitation frequency deviates slightly from the resonance condition, the output power is drastically reduced. This unsatisfactory situation is mainly due to the fact that the generator resonant frequency is often not tuned to the vibration frequency. However, compared to some applications, the energy harvesting of railway bridges is less sensitive to frequency effects, because the dynamic behaviour of the structure is mainly determined by the fundamental mode shape (Museros & Alarcon 2005), which is relatively constant. One of the objectives of this work is the estimation of the natural frequency of a bridge and the tuning of harvesting systems in railway bridges.

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2 APPROACH

The proposed approach considers that the energy harvester is attached to the bridge in a location defined by the coordinate x_b. This device is subjected to vertical vibration $z_b(x_b, t)$ induced by a train passage that travels at a speed V. The dynamic response of a bridge under the circulation of a rail convoy is complex and is affected by several factors. The most obvious and certain are the bridge properties, the geometric scheme of the train axles, and the speed of circulation V. Furthermore, there are other factors that are much more uncertain in determining the response of the bridge (Rocha et al. 2012), such as structural damping and various interaction mechanisms, the most relevant being vehicle-structure, track-structure, and soil-structure interaction effects. The dynamic response of a railway bridge due to train passage can be described by a stochastic process, assuming that the load has random amplitude described by a Poisson process (Zakęś & Śniady 2018).

The energy harvesting performance is closely related to the dynamic behaviour of the bridge during train passages (Romero et al. 2021), and maximum performance would be obtained when the harvester is tuned to the fundamental mode shape of the bridge. However, the performance of the energy harvester is limited to a narrow frequency bandwidth around the tuning frequency, and therefore the harvested energy is drastically reduced as a result of the detuning effect. Although the harvester device can be tuned to the natural frequency of the fundamental mode shape of the bridge, the uncertainties in the dynamic response affect not only the vibration levels but also the frequency content, making the choice of the tuning frequency more difficult.

In this work, due to the nature of the vibrations caused by rail traffic, the energy collected is processed statistically and represented by a stochastic process following a Gamma distribution $E \sim \Gamma(k, \theta)$ with mean $\mu_E = k\theta$ and variance $\sigma_E^2 = k\theta^2$, where k and θ are the shape and scale parameters, respectively. The mechanical energy is used as an estimate of the efficiency in the conversion of energy from the bridge vibration. A lumped mass model is used to represent the dynamic behaviour of the harvester. The properties of the system are given by the natural frequency ω, the mass m, and the damping coefficient c (Romero et al. 2021). The damping coefficient c is used to represent the energy transfer from the bridge vibration to the harvester system (Stephen 2006).

Then, the instantaneous power corresponds to the power absorbed by the harvester plus the kinetic energy and the mechanical energy in the system during the period T is a function of the velocity of the vibration:

$$E = c \int_0^T |\dot{y}(t)|^2 dt \tag{1}$$

where $y(t)$ denotes the vertical displacement of the lumped mass. The previous equation can be expressed in terms of the Fourier transform of the harvester velocity according to Parseval's theorem (Romero et al. 2021). Then, the displacement of the harvesting device is expressed in terms of the vertical displacement of the bridge and the frequency response function $H(\omega; \bar{\omega})$ of the harvester:

$$y(\bar{\omega}) = m\bar{\omega}^2 H(\omega; \bar{\omega}) z_b(x_b, \bar{\omega}) \tag{2}$$

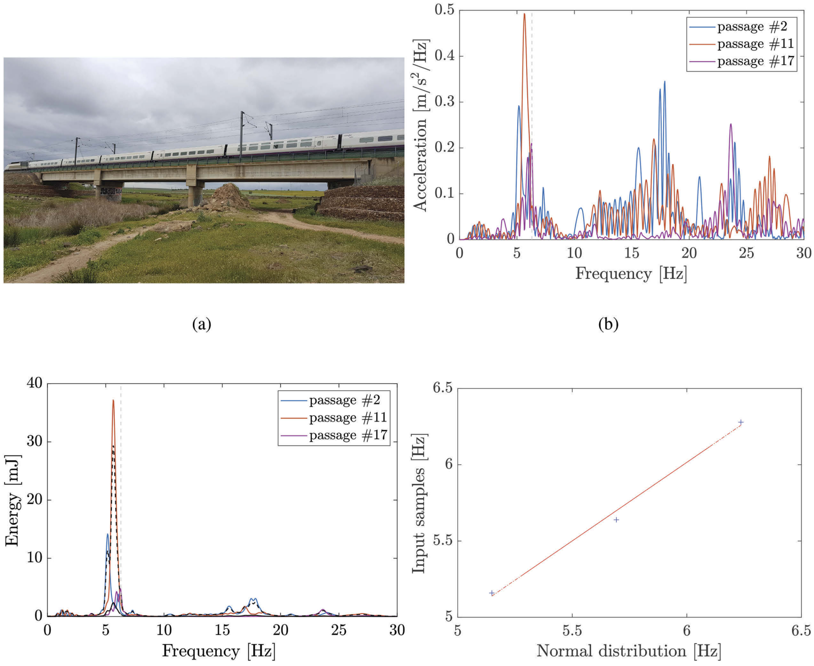
Thus, the energy collected becomes:

$$E = c \int_{-\infty}^{\infty} |\dot{y}(\bar{\omega})|^2 d\bar{\omega} = c \int_{-\infty}^{\infty} |\iota\bar{\omega} m\bar{\omega}^2 H(\omega; \bar{\omega}) z_b(x_b, \bar{\omega})|^2 d\bar{\omega} \tag{3}$$

where, the imaginary unit number is denoted by the Greek letter ι to prevent confusion with the subscript i used in posterior derivations.

Therefore, the tuning frequency needs to be selected following a statistics procedure. In this work, a stochastic process is proposed to find the tuning frequency.

As an example, Figure 1 shows the frequency content of the acceleration in a railway bridge in three different circulations. The fundamental mode of this bridge corresponds to the first longitudinal bending mode shape with natural frequency $f_{b1} = 6.3\,\mathrm{Hz}$. More details about the structure can be found in (Galvin et al. 2020). The three circulations are: *i*) Renfe S102 travelling at $V = 290\,\mathrm{km/h}$ (passage #2); *ii*) Renfe S012 at $V = 274\,\mathrm{km/h}$ (passage #11); and *iii*) Renfe S100 at $V = 290\,\mathrm{km/h}$ (passage #17). The passage numbers are in concordance with (Galvin et al. 2020). In all cases, the response presents peaks associated with the load (that is, the ratio of the train speed V to the bogie and axle distances and the corresponding harmonics) and to the lowest natural frequencies of the bridge. The peaks related to the fundamental mode shape were found in 5.16 Hz (passage #2), 5.6 Hz (passage #11) and 6.3 Hz (passage #17), that are in general lower than the natural frequency (marked by a vertical dashed line). Therefore, tuning the harvester is not trivial and the performance will be determined by the dynamic behaviour of the structure in forced vibration, in which the response associated with the fundamental mode shape can occur at frequencies lower than the natural frequency, as shown in Figure 1. A detuning higher than 1% can cause considerable power loss as shown in (Romero et al. 2021).



(a)

(b)

(c)

(d)

Figure 1. (a) General view of Jabalón HSL bridge. (b) Frequency content of the bridge acceleration at point A7 (see Galvin et al. 2020)) induced by different train circulations. The vertical line represents the first natural frequency of the bridge.

The proposed procedure considers the study of the scattering of the mechanical energy of different harvesters tuned from 1 Hz to 100 Hz to cover a wide range of frequencies, including the most fundamental frequencies of railway bridges. The mechanical energy is computed for each train passage using the experimental records of the bridge accelerations induced by 19 trains over the Tirteafuera bridge.

In order to verify the dispersion of the mechanical energy as a function of the excitation frequency to find the fundamental frequency of the bridge, a statistical analysis is carried out. The dynamic response of the device in the frequency domain is a complex random process in which the real and imaginary parts of the response follow a Gaussian distribution (Lombaert et al. 2014). Therefore, the modulus of the response is the absolute value of a circular bivariate

Gaussian random variable. The probability distribution of the latter follows the so-called Rayleigh distribution or, equivalently, the modulus of the dynamic response contribution, normalised by the squared standard deviation of the real and imaginary parts, follows a chi-square distribution with two degrees of freedom.

The proposed approach considers that the mechanical energy for each tuning frequency and excitation record follows a gamma distribution ($E(\omega_n \sim \Gamma(k, \theta))$, as the chi-square distribution with n degrees of freedom is a special case of the gamma distribution with the shape parameter $k = n/2$ and the scale parameter $\theta = 2$. The confidence intervals, standard deviation, and mean values of the mechanical energy can be derived from the cumulative distribution function, and the shape and scale parameters of the gamma distribution. The mean value of the mechanical energy for all train passages is computed as $\mu = k\theta$ and the standard deviation is $\sigma = \sqrt{k\theta^2}$.

Following, the results of an extensive experimental campaign are presented and the proposed tuning procedure is validated.

3 EXPERIMENTAL VALIDATION

An experimental campaign was carried out to assess the energy harvesting performance in a railway bridge in July-September 2022. The bridge under study belongs to the HSL Madrid-Sevilla. It is a single simply-supported span concrete bridge with three tracks. The deck is composed of a concrete slab of dimension 18m × 20.6m (length×width) resting on ten pre-stressed concrete I girders (see Figure 2). The slab carries two ballasted tracks with UIC gauge (1.435m) of high-speed lines separated from one ballasted track with Iberian gauge (1.668m) of a conventional line.

Figure 2. HSL bridge under study (38°43’33.06“N 4°5’20.05”W).

The main experimental campaign was carried out in September 2022 in order to characterise the dynamic properties of the structure along with the dynamic response of the bridge under railway traffic, the analysis of energy harvesting, and the validation of a harvester prototype in a relevant environment.

During the recordings, several RENFE trains (S100, S102, S103, S114, S130, R449, R599, Altaria and freight trains) crossed the bridges. Information that includes the axle schemes, coach distributions, the axle distances and axle loads, as well as more information in this regard, can be found in References (Galvin et al. 2020) and (Renfe).

3.1 *Setup*

A LAN-XI portable acquisition system from Brüel & Kjaer was used. Endevco model 86 piezoelectric accelerometers with a nominal sensitivity of 10 V/g and a lower frequency limit of approximately 0.1 Hz were used. An Ometron VH-1000-D laser vibrometer with nominal sensitivities 8.0064 V/m/s was used to measure the tip velocity of the harvester. The acquisition system fed the sensors (accelerometers). LAN-XI also performed the Analog/Digital conversion (A/D). The A/D was carried out at a high sampling frequency, which avoided aliasing effects. The acquisition equipment was connected to a laptop for data storage. The acquisition system was configured to avoid sensor overload. The recordings were decimated (to 256 Hz) to perform data analysis in the frequency range of interest. The response was filtered applying a third-order Chebyshev filter with high-pass frequencies of 1 Hz.

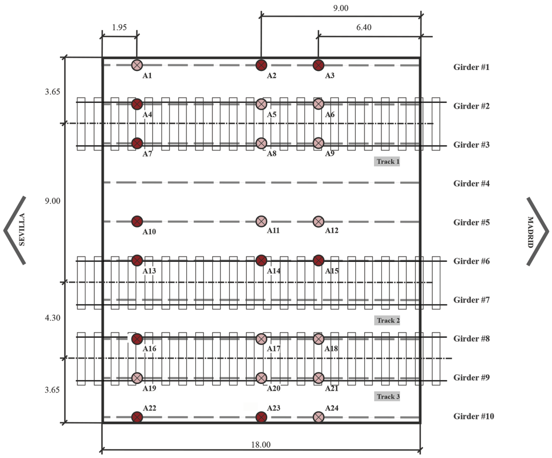


Figure 3. Scheme of the location of the sensors and experimental setup in HSL bridge over Tirteafuera River (38°43’33.06“N 4°5’20.05”W).

3.2 *Tuning*

In the first instance, vibration levels under operating conditions measured in July 2022 were used to estimate the tuning frequency. The measurement point $A14$ located in the girder #4 was chosen. The laser vibrometer was used to avoid the installation of the scaffolding system at this stage. A total of 19 train circulations were recorded between 10.20 and 13.50h. Table 2 summarises the train passages including the type of train, track number according to Figure 3, traffic direction and travelling speed.

The mechanical energy was estimated for harvesters with a damping ratio of 1% tuned in the frequency range 1–30Hz. The confidence intervals, standard deviation, and mean values of the energy were estimated from the shape and scale parameters of the gamma distribution over the frequency range. Figure 4 shows the computed results. It can be observed a predominant frequency around 8 Hz where energy reaches its greatest values. There are also significant values of the energy around 9.3 Hz, which is interesting to note.

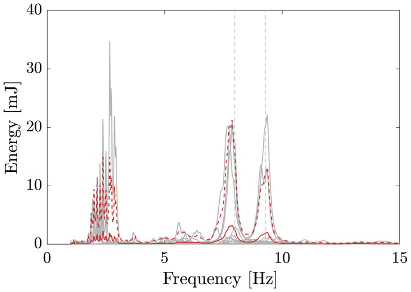
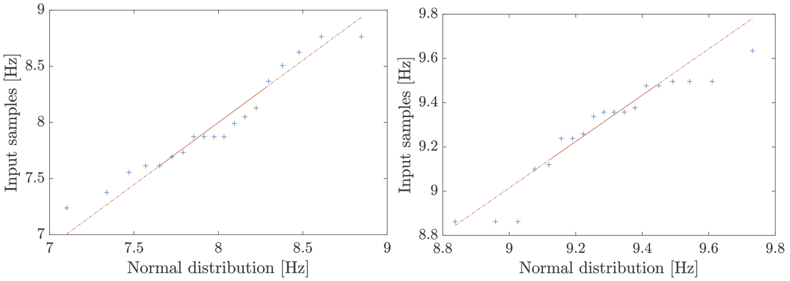


Figure 4. Mechanical energy for the bridge over the Tirteafuera River.

The tuning frequency was obtained from the maximum peaks for each circulation around the frequencies 8 Hz and 9.3 Hz. Figure 5 shows the quantile-quantile plot for the energy peak frequencies and a normal distribution with mean the tuning frequency. The results show a great agreement with the normal distribution. The tuning frequencies $f_{t1} = 7.8\,\mathrm{Hz}$ and $f_{t2} = 9.28\,\mathrm{Hz}$ are obtained from the mean value in both cases.



(a)

(b)

Figure 5. Quantile-quantile plot for tuning frequencies (a) $f_{t1} = 7.8\,\text{Hz}$ and (b) $f_{t2} = 9.28\,\text{Hz}$.

3.3 *Manufacture*

An optimal tuning procedure has been performed to adjust the resonant frequency of the harvester to the tuning frequencies. Two energy harvesters tuned to the frequencies identified in the previous section have been manufactured with an optimal design. The pizoelectric patch selected for this application is the commercial DuraAct patch transducer P-876.A12 (PIceramic), composed of a piezoelectric layer covered by copper electrodes. The patch is embedded in a structure mechanically pre-stressed by a polymer surface, making it flexible. Patch dimensions are $L_p = 50\,\text{mm}$, $b_p = 30\,\text{mm}$, and $h_p = 0.2\,\text{mm}$. Additive manufacturing using FDM 3D printing has been selected for the substructure. Among the variety of 3D printing materials, a high temperature polyamide carbon fiber reinforced material (PAHT CF15) is selected. PAHT CF15 is often used to replace metals in some applications due to its high strength.

The material properties of the substructure were experimentally estimated according to the ASTM D638-14 standard (ASTM, 2014). The material properties obtained were: mean Young's modulus $E_s = 7.40\,\text{GPa}$ with a standard deviation of $s_E = 0.33\,\text{GPa}$; and tensile strength $\sigma_y = 94\,\text{MPa}$ with a standard deviation of $s_\sigma = 9.9\,\text{MPa}$. A safety factor $\gamma_G = 1.33$ was used to assess structural integrity in the optimisation procedure to account for the standard deviation of the tensile strength.

The design parameters of the harvester are the result of a constrained optimisation problem where the maximum power dissipated by a harvester tuned to the fundamental frequency of the bridge is sought subject to the structural integrity of the system and the imposition of geometry constraints. The constrained optimisation problem is solved using a genetic algorithm and provides optimal values of the design parameters, length (L_s) and thickness (h_s) of the substructure, tip mass (M_t) and optimal load resistance (R_l). Harvesters with a damping ratio of 1% have been considered.

The optimal design parameters for each harvester are collected in Table 1

Table 1. Optimal design parameters for designed prototypes.

Device	L_s[mm]	h_s[mm]	M_t[kg]	$R_l[k\Omega]$
Tirteafuera f_{t1}	106.7	0.94	0.09	664
Tirteafuera f_{t2}	90.9	0.73	0.076	552

3.4 *Modal identification*

The modal parameters of the bridge were identified from the ambient vibration data through an operational modal analysis using the Enhanced Frequency Domain Decomposition (EFDD) (Brincker et al. 2001). The EFDD technique is based on the decomposition of the power spectral density of the measured acceleration using singular value decomposition (SVD) (Tadeu et al. 2022). The natural frequencies of the structure are identified from the peaks of the singular value curves of the accelerations of ambient vibrations (Figure 6). The fundamental mode corresponds to the first longitudinal bending mode with natural frequency $f_{b1} = 8.14\,\text{Hz}$ and modal damping $\zeta_{b1} = 1.72\%$. It is interesting to note that there is some decoupling between high-speed and conventional tracks due to the difference in mass of both areas, since the frequency of the fundamental mode is associated with the first bending mode of the bridge in the high-speed track area and there is another frequency associated with the first bending mode of the bridge in the conventional track area at $f_{b2} = 8.65\,\text{Hz}$ with $\zeta_{b2} = 1.42\%$. In addition, an important peak is observed at $f_{b3} = 9.54\,\text{Hz}$ corresponding to the first transverse bending mode with modal damping $\zeta_{b3} = 0.5\%$, and a peak at $f_{b4} = 11.51\,\text{Hz}$ of the first torsional mode with modal damping $\zeta_{b4} = 0.78\%$. This frequencies are higher than the tuning frequencies obtained previously due to effect of the crossing train in the dynamic response of the bridge.

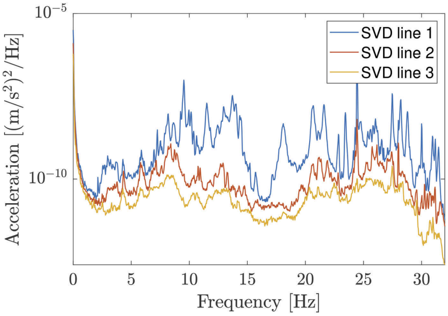


Figure 6. Singular Value Decomposition from ambient vibration.

Table 2 summarises the estimated energy collected with harvesters tuned to the tuning frequencies obtained with the proposed approach and harvesters tuned to the natural frequencies of the bridge. The results show that the energy generated in the case of harvesters tuned to the tuning frequency is much larger.

Table 2. Simulated Energy harvesting [mJ] in train passages recorded at Tirteafuera HSL Bridge (July 2022).

Passage	Train	Track	V [km/h]	E_{ft1} [mJ]	E_{ft2} [mJ]	E_{fb1} [mJ]	E_{fb3} [mJ]
1	S102	2	183.1	3.092	0.096	0.845	0.049
2	S102	3	200.6	0.317	0.012	0.328	0.008
3	S100	2	177.6	0.112	0.009	0.022	0.006
4	S114	2	221.0	0.003	0.018	0.006	0.011
5	S114	2	232.2	0.006	0.036	0.011	0.011
6	S103+S102-duplex	3-2	191.2	0.156	2.052	0.100	0.679
7	S114	3	197.7	0.228	0.005	0.080	0.003
8	S120	2	220.0	0.011	0.045	0.033	0.043
9	S120	3	220.0	0.006	0.033	0.010	0.022
10	S103	3	231.8	0.025	0.051	0.014	0.063
11	S100	2	168.6	0.004	0.127	0.005	0.186
12	R449	1	159.1	0.000	0.000	0.000	0.000
13	S114	3	198.0	0.131	0.010	0.032	0.015
14	S114	2	220.0	0.020	0.012	0.093	0.009
15	S100	3	176.8	0.012	0.015	0.005	0.022
16	S102	3	224.5	0.077	3.541	0.086	1.286
17	S102-duplex	2	176.4	1.911	0.191	0.570	0.191
18	S102	2	183.2	2.989	0.089	0.622	0.052
19	S100-duplex	2	184.4	0.071	0.040	0.065	0.020
			Total	9.173	6.380	2.927	2.676

4 CONCLUSIONS

The research presented here falls within the framework of the development of autonomous monitoring systems. A statistical procedure to estimate the tuning frequency of energy harvesters placed on railway bridges has been presented. A simplified lumped analytical model for the analysis of bimorph cantilever beams and an optimal tuning procedure have been followed. The analytical model allows us to study harvesters tuned to different frequencies with different lengths of substructure and PZT patches, which allows greater flexibility in the design. The performance of harvesters for a real bridge on the Madrid-Sevilla High-Speed line has been analysed. The energy collected by harvesters tuned to the frequencies obtained from the statistical process has been estimated, obtaining higher power levels than those tuned to the natural frequencies of the bridge.

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