Performance Exploration of A Radially Layered Cymbal Piezoelectric Energy Harvester under Road Traffic Induced Low Frequency Vibration

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Abstract. A type of radially layered cymbal piezoelectric energy harvester is designed and fabricated. It is made of two cymbal metal caps, two axially polarized piezoceramic rings, one solid metal disk, one common metal ring and one drilled metal ring. The mechanical couplings in radial direction are finished by using extra strong epoxy. The mechanical couplings in axial direction are finished by using screw bolts. Subsequently, the force transferring coefficient of each cymbal metal cap is approximated through both theoretical calculation and experimental calibration. Aiming at matching the road traffic induced vibration frequencies that are predominantly ranging from 5Hz to 25Hz, the approximated analytical model of the harvester is established at frequencies below 30Hz. The model’s predictions agree reasonably with the measured data. Furthermore, the experimental results indicated that the harvester was able to generate a power of about 0.92mW across a 0.8MΩ resistor under the force of 500N at a frequency of 20Hz. The present work provides a new design concept for developing the novel cymbal harvesters used in roadway systems to harvest the traffic induced vibration energy.

1. Introduction
Energy harvesting from mechanical vibration using piezoelectric devices has attracted numerous research interests over the last few decades [1, 2]. Previous literatures have reported a large volume of structure forms of piezoelectric devices in various engineering applications, such as piezoelectric stack [3-7], piezoelectric patch [8-10], piezoelectric beam [11-13], piezoelectric drum [14, 15] and piezoelectric cymbal [16-18]. Comparing to other types of piezoelectric devices, piezoelectric cymbal transducer has a unique advantage in terms of mechanical force amplification mechanism of the cymbal metal endcaps, which can increase the radial stress applied to the piezoelectric element [19, 20]. Additionally, it also has reasonable energy conversion efficiency, medium stiffness and high durability under high loading level [18, 21]. These properties of cymbal transducer match well with the characteristics of pavement structure, such as medium stiffness, high stress, low frequency response and huge repetitions [22]. Owing to its excellent properties, piezoelectric cymbal transducer is a good candidate for harvesting energy from asphalt pavement.

A recent study has proved the feasibility of energy harvesting from asphalt pavement using traditional piezoceramic cymbal [17], which was formed by sandwiching a piezoceramic disk between two cymbal metal endcaps [23] using epoxy. The results indicated that a single piezoceramic cymbal can recover up to a power of 16 µW for the pass of one heavy vehicle wheel. This harvested power is far smaller than those reported in [24-26], whose power levels can reach up to 52mW or even 100mW.
Such an obvious difference is mainly caused by the mismatch of force frequency ranging from 4Hz [17] to 100Hz or 200Hz [24-26]. In addition, the embedded location will also induce a large deviation of the produced power. It is well known that the vertical stress component in the layered pavement structure decrease with the increase of depth [27]. To improve the harvesting efficiency, it is required that the harvester must be located as close as possible to the pavement surface while ensure that the harvester will not be damaged by the passage of vehicles. However, an earlier work has reported that the maximum bearing capacity of a 0.4mm thick steel cap is 70N [26], which limit the embedded location of the energy harvester.

Meanwhile, structural design of piezoelectric cymbal is a very important internal factor for the performance of the harvester. The past decades have witnessed great improvement in piezoelectric cymbal transducer. On the one hand, the cymbal metal endcaps have evolved from the traditional ones [19, 24-26, 28] to the slotted ones [29, 30] or the curved convex ones [31] for improving the force transferring efficiency. On the other hand, the piezoelectric element has been developed from the traditional one to unimorph (a piezoelectric/steel composite disk) [32] and bimorph (a piezoelectric/steel/piezoelectric composite disk) [20] for being used in the high load application, two-layer-stacked piezoelectric disks [28] for increasing the power output. However, most of these designs have their own disadvantages, such as lower force level, smaller power output, which limit the scope of applications.

This article attempts to develop a type of new piezoelectric cymbal harvester through combining the cymbal metal endcaps and the radially layered piezoelectric structure for energy harvesting in roadway systems. The rest of the paper is organized as follows. Section 2 describes the design details of the harvester, and establishes its approximate analytical model. Section 3 introduces the experimental setup. Section 4 analyzes and discusses the theoretical and experimental results, and compares the differences of energy harvesting properties between the present and previous work. Conclusions are drawn in Section 5.

2. Design and Modeling
As shown in Figure 1, a radially layered cymbal piezoelectric energy harvester is developed. The cymbal structure consists of two cymbal metal caps, two axially polarized piezoceramic rings, two metal rings and one solid metal disk. Two piezoceramic rings are connected in parallel electrically. A drilled ring casing is designed for the coupling with the cymbal metal caps. A hole was drilled in every metal cap to thread wires. The piezoelectric material used is PZT-5H and the outer casing is made of stainless steel. Their related properties are shown in Table 1 and Table 2. All rings are coupled radially with each other by using high strength epoxy. The upper and bottom metal caps were coupled with the outmost metal ring by bolting. The geometric parameters in Figure 2 are taken as $R_1 = 10\text{mm}$, $R_2 = 15\text{mm}$, $R_3 = 20\text{mm}$, $R_4 = 25\text{mm}$, $R_5 = 35\text{mm}$, $h = 5\text{mm}$, $h_m = 3\text{mm}$, $h_c = 8\text{mm}$, $R_{m1} = 8\text{mm}$, $R_{m2} = 25\text{mm}$, $\phi_{m4} = 3\text{mm}$, $\phi_{m5} = 4\text{mm}$.

![Figure 1](image_url). The radially layered cymbal piezoelectric energy harvester: (a) schematic and (b) prototype.
Table 1. Material parameters of PZT-5H

| Elastic constant   | Piezoelectric constant | Dielectric constant | Density  |
|--------------------|-------------------------|---------------------|----------|
| $E_{11}$ ($\times 10^{12}$ m²N⁻¹) | $d_{33}$ ($\times 10^{12}$ CN⁻¹) | $\varepsilon_{33}$ / $\varepsilon_0$ | $\rho_p$ (kgm⁻³) |
| 13                 | -4.29                   | -186                | 4500     | 7450     |

$\varepsilon_0 = 8.85 \times 10^{-12}$ Fm⁻¹, Permittivity of free space

Table 2. Material parameters of Epoxy

| Young’s modulus  | Poisson’s ratio | Density  |
|------------------|-----------------|----------|
| $E$ ($\times 10^{12}$ m²N⁻¹) | $\mu$ | $\rho_E$ (kgm⁻³) |
| 21               | 0.25            | 7930     |

Figure 2. Geometric dimensions of the symmetric upper parts.
(E: elastic material; P: piezoelectric material; ↑: polarized direction)

Similar to the earlier cymbal transducers [23, 25, 26], the proposed devices also utilized the advantage of the cymbal structure that an axial load is transferred to the radial stress via the cymbal metal caps onto the piezoelectric element in the key region ($R_i \leq r \leq R_4$), as shown in Figure 3. Under a pair of applied loads $F$, the radial stress is defined as

$$
\bar{\sigma} = 2 \frac{\chi F}{2\pi R_i h}
$$

(1)

where $\chi$ is the force transferring coefficient, which represents the force transferring capability of the cymbal metal cap. For the current cases, it is difficult to solve for this coefficient theoretically due to the complexity of the structure. Instead, the coefficient will be approximately obtained through experimental calibration.

Once the load transferring coefficient is determined, the next problem is to solve a layered piezoelectric/elastic composite structure subjected to a uniform radial stress, as shown in Figure 3(b). In the present work, an external mechanical force is considered as

$$
F(t) = F_0 e^{i\omega t}
$$

(2)

where $F_0$ is the force amplitude, $i = \sqrt{-1}$, $\omega = 2\pi f$ is the circular frequency, and $t$ is the time.
The transferring radial stress can be expressed as
\[ \bar{\sigma}(t) = \bar{\sigma}_0 e^{i\omega t} \]  
where \( \bar{\sigma}_0 = \frac{Z F_0}{2\pi R_h} \) is the amplitude of radial stress. Furthermore, the generated voltage across the resistive load \( R \) is also written as
\[ V(t) = V_0 e^{i\omega t} \]
where \( V_0 \) is the complex voltage amplitude across the resistor load \( R \).

For harmonic and steady vibration, the electrical and mechanical components for the plain stress problem can be written as [33]
\[
(u_{iE}, \sigma_{iE}, \sigma_{\theta E}, \phi_i, E_i, D_i) = [u_{iE}(r), \sigma_{iE}(r), \sigma_{\theta E}(r), \phi_i(z), E_i(z), D_i(z)] e^{i\omega t} \quad \text{for piezoelectric layer} \quad (5) \\
(u_{iE}, \sigma_{iE}, \sigma_{\theta E}) = [u_{iE}(r), \sigma_{iE}(r), \sigma_{\theta E}(r)] e^{i\omega t} \quad \text{for elastic layer} \quad (6)
\]
where \( u_{iE} \), \( \sigma_{iE} \), \( \sigma_{\theta E} \) and \( D_i \) are the radial displacement, the radial and tangential stress components, the axial electric field and electric displacement of the \( i \)-th piezoelectric layer, respectively. \( u_{iE} \), \( \sigma_{iE} \), and \( \sigma_{\theta E} \) are the radial displacement, the radial and tangential stress components of the \( i \)-th elastic layer, respectively.

The expressions of \( u_{iE}(r) \), \( \sigma_{iE}(r) \), \( \phi_i(z) \), \( D_i(z) \), \( u_{iE}(r) \) and \( \sigma_{iE}(r) \) can be written as
\[
u_{iE}(r) = A_{iE} f_1(r) + B_{iE} f_2(r) \\
\sigma_{iE}(r) = A_{iE} f_3(r) + B_{iE} f_4(r) + e_{31} \frac{V_0}{h} \\
\phi_i(z) = \frac{V_0}{h} \\
D_i(z) = A_{iE} e_{33} J_0(k_p r) + B_{iE} e_{33} k_p Y_0(k_p r) - \kappa_{33} \frac{V_0}{h} \\
u_{iE}(r) = A_{iE} f_5(r) + B_{iE} f_6(r) \\
\sigma_{iE}(r) = A_{iE} f_7(r) + B_{iE} f_8(r)
\]
where the functions \( f_1(r) \sim f_8(r) \) are the known functions defined in the previous work [33]. \( J_0(k_p r) \) and \( Y_0(k_p r) \) are the first and second kind Bessel functions, respectively.

As shown in Figure 3(b), this layered structure includes two mechanical boundary conditions and six continuous conditions, which can be expressed as follows
\[
\left\{ \begin{array}{l}
u_{iE} |_{r=0} = 0 \\
\sigma_{\theta E} |_{r=R_i} = \bar{\sigma}(t) 
\end{array} \right.
\]  

**Figure 3.** Force transferring mechanism.
\[
\left\{ \begin{array}{l}
\left. \mu_{pl} \right|_{i=R_{i-1}} = \left. \mu_{0} \right|_{i=R_{i-1}} \quad (i = 1, 2) \\
\left. \sigma_{pl} \right|_{i=R_{i-1}} = \left. \sigma_{0} \right|_{i=R_{i-1}} \\
\left. \mu_{pl} \right|_{i=R_{n-1}} = \left. \mu_{E(i+1)} \right|_{i=R_{n-1}} \\
\left. \sigma_{pl} \right|_{i=R_{n-1}} = \left. \sigma_{E(i+1)} \right|_{i=R_{n-1}} 
\end{array} \right\} 
\]

Substituting equation (11) into the first condition in equation (13) yields

\[ B_{i_1} = 0 \]

Substituting equations (7), (8), (11) and (12) into equations (14) and (15), and combining equation (16), the unknown constants \( A_{i_1} \), \( B_{i_1} \), \( A_{i_2} \), \( B_{i_2} \), \( A_{i_3} \) and \( B_{i_2} \) can be derived as the expressions of \( A_{i_1} \) and \( V_0 \). Furthermore, combining equations (8) and (13), we can obtain

\[ a_i^0 A_{i_1} + c_i^0 V_0 = \sigma_0 \]

where

\[ a_i^0 = a_i^0 f_i(R_i) + a_i^0 f_i(R_i) \]

\[ c_i^0 = c_i^0 f_i(R_i) + c_i^0 f_i(R_i) + \frac{e_{i1}}{h} \]

Additionally, the electrical condition can be expressed as

\[ V(t) = RI(t) \]

where, the electrical charge \( Q(t) \) and current \( I(t) \) can be expressed as

\[ Q(t) = \sum_{i=1}^{2} \int_{R_{i-1}}^{R_i} D_{i} rd \theta dr = (a_1^0 A_{i_1} + c_1^0 V_0)e^{i\omega t} \]

\[ I(t) = dQ(t)/dt = i\omega(a_1^0 A_{i_1} + c_1^0 V_0)e^{i\omega t} \]

in which

\[ a_1^0 = 2\pi \left\{ a_1^0 \left[ f_2(R_2) - f_2(R_1) \right] + a_1^0 \left[ f_10(R_2) - f_10(R_1) \right] \right\} \]

\[ c_1^0 = 2\pi \left\{ c_1^0 \left[ f_2(R_2) - f_2(R_1) \right] + c_1^0 \left[ f_10(R_2) - f_10(R_1) \right] \right\} \]

Then, equation (20) can be simplified as

\[ i\omega Ra_{i_1} A_{i_1} + (i\omega Rc_{i_1} - 1)V_0 = 0 \]

Combining equations (17) and (25) yields

\[ A_{i_1} = d_{i_1} \sigma_0 \]

where

\[ d_{i_1} = -\frac{i\omega Rc_{i_1} - 1}{i\omega Ra_{i_1} c_{i_1} - a_{i_1}^0 (i\omega Rc_{i_1} - 1)} \]

When \( R \rightarrow \infty \), the open circuit voltage \( V_{OC} \) can be obtained. an average power can be obtained as

\[ P = \frac{|V_{OC}|^{2}}{R} \]

where the subscript \( rms \) denotes the root mean square.

3. Experimental Setup
As shown in Figure 4, an experimental platform is set up to measure the energy harvesting performance of the fabricated cymbal harvester. This testing system consists of a low-frequency fatigue testing machine with a computer controller, a resistor control box and a digital oscilloscope. Prior to performing the experimental calibration, a static pressure of 1100N was first preloaded to clamp the specimen. Afterward, a sinusoidal mechanical load is applied to activate the harmonic vibration, and the resistor is adjusted through the resistor control box. When the generated AC signal observed in the oscilloscope is stable, the experimental data is saved into a flash drive.

![Experimental Setup](image)

**Figure 4.** Photograph of experimental setup.

4. Results and Discussion

Firstly, the force transferring coefficient $\chi$ was solved for several special examples. Taking $F_0 = 500N$, $f = 20, 25, 30Hz$, $R = 100M\Omega$, the measured output voltage amplitudes are 52.8V, 52.4V, 53.6V, respectively.

For a typical semi-rigid asphalt pavement, the vibration frequency caused by a moving vehicle is between 10Hz and 20Hz [34]. However, road traffic tends to produce vibrations with frequencies predominantly in the range from 5Hz to 25Hz [35]. In order to match this frequency range, the frequencies below 30Hz are focused in the following analysis and discussion.

Figure 5 presents the relationship between amplitude of output voltage and the value of the load resistor. It indicates that the output voltage amplitude increases with the increase in the load resistor. Under a force of 500N at 20Hz, the experimental open circuit voltage amplitude of 52.8V is generated. Further, Figure 6 plots the curve of output average power versus the load resistor. With the increase of the value of load resistor, the output average power reached an optimal value before slowly decaying. Under a force of 500N at 20Hz in the experimental setup, the optimal average power of about 0.92mW is generated across a resistor of 0.8MΩ. Subsequently, Figure 7 shows the output voltage as a function of the frequency of the applied force. It can be seen that the frequency of the applied force has slight effect on the open circuit output voltage.

In Figures 5~8, though qualitative agreement is found, there exists the difference among the predicted and experimental results, which may be caused by the following reasons: 1) a preloading was applied to clamp the specimens in the experiment, which was not considered in the approximate theoretical model and the simulation model; 2) the plain stress problem is assumed in the theoretical calculation, which cannot be satisfied in the actual situation.
Further, Table 3 compares the differences of energy harvesting properties between the present and previous work. It can be seen clearly that most of the traditional cymbal transducers [24-26] and the alternative designs [29, 30] can harvest more power (up to 100mW) under lighter forces (less than 70N) and higher frequencies (up to 200Hz). However, the harvested power is very small at the low frequencies [19, 31, 32]. A main reason is that the power decreases dramatically with the decrease of the force frequency [25]. In addition, most of them have the lower load bearing capacity [26]. The above factors will greatly reduce their energy harvesting efficiency in the pavement systems that have the characteristics of high stress and low frequency. To match the characteristics of the pavement systems, the present work attempts to develop a type of new piezoelectric cymbal harvesters through combining the cymbal metal endcaps with the radially layered piezoelectric structure. The results showed that the harvested power is in the level of 1mW at the low frequencies. However, it proved that this type of design is feasible, which provides a new design concept. The authors envisioned that the output power can be greatly increased by adopting the multilayered piezoelectric structure, which similar to the piezoelectric stack.

5. Conclusion
This work explores a type of new radially layered cymbal piezoelectric energy harvester through combining the cymbal metal endcaps and the radially layered piezoelectric structure for energy harvesting from road traffic induced low frequency vibration. The experiment research combined with the theoretical analysis are used to investigate the effects of the load resistor, the amplitude and
frequency of force on the energy harvesting performance. The differences on energy harvesting properties between the present and previous work are also highlighted. Different from the previous cymbal designs, our designed cymbal structure includes two piezoceramic layers and three metal layers in radial direction. This design attempts to adopt the layered structural style similar to piezoelectric stack that is expected to improve the power output. Although the harvested power is in the level of 1mW at the low frequencies, this study proves that this kind of design is feasible, which provides a new concept to develop the novel cymbal piezoelectric energy harvesters for energy harvesting in roadway systems. In the future, a multilayered piezoelectric structure that similar to piezoelectric stack will be examined with the hope of enhancing the output power.

Table 3. Comparisons of energy harvesting properties between the present and previous work

| Type                      | Configuration                                                                 | Literature | Force  | Force frequency | Resistor | Harvested power |
|--------------------------|------------------------------------------------------------------------------|------------|--------|-----------------|----------|-----------------|
| Traditional cymbal transducer | A piezoelectric disk is sandwiched between two concave shaped metal endcaps | [24]       | 7.8 N  | 100Hz          | 400 kΩ   | 39mW            |
|                          |                                                                               | [26]       | 55 N   | 100Hz          | 400 kΩ   | 33mW            |
|                          |                                                                               | [25]       | 70 N   | 100Hz          | 400 kΩ   | 52mW            |
|                          |                                                                               |            | 70 N   | 200Hz          | 480 kΩ   | 100mW           |
|                          |                                                                               | [19]       | 50 N   | 2Hz            | 10 MΩ    | 1.2mW           |
|                          |                                                                               | [28]       | 2g acceleration | 166Hz   | 80 kΩ | 104.04µW      |
| Alternative designs      | Two curved convex steel discs                                                | [31]       | 24.8N  | 1.19Hz         | 2.6 MΩ   | 0.66mW          |
|                          | A circumferential slot between plane and conical surface of the cymbal metal endcaps | [30]       | 8.15N  | 120Hz          | 410 kΩ   | 1.4mW           |
|                          | 18-fringe radial slots in the cymbal endcaps edge                            | [29]       | 30N    | 120Hz          | 520 kΩ   | 14.5mW          |
|                          | 18-cone radial slots in the cymbal endcaps                                  | [29]       | 30N    | 120Hz          | 500 kΩ   | 16mW            |
|                          | Two-layer-stacked piezoelectric disks                                        | [28]       | 2g acceleration | 153Hz   | 40 kΩ | 141.61µW      |
|                          | Unimorph (A piezoelectric/steel composite disk)                              | [32]       | 1940N  | 1Hz            | 3.3 MΩ   | 121.2µW         |
|                          | A radially layered piezoelectric/metal disk with the drilled ring           | Present    | 500N   | 20Hz           | 0.8 MΩ   | 0.92mW          |

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References

[1] Anton SR and Sodano HA 2007 *Smart Mater. Struct.* **146** R1.
[2] Erturk A and Inman DJ 2011 *Piezoelectric energy harvesting* (Chichester: Wiley).
[3] Feenstra J, Granstrom HA and Sodano HA 2008 *Mech. Syst. Signal Pr.* **22** 721-34.
[4] Jiang X, Li Y, Li J, Wang J and Yao J 2014 *Renew. Sustain. Ener.* **6** 043110.
[5] Wang JJ, Shi ZF and Han ZJ 2013 *J. Intell. Mater. Syst. Struct.* **24** 1626-36.
[6] Wang JJ, Shi ZF, Xiang HJ and Song G 2015 *Smart Mater. Struct.* **24** 105017.
[7] Zhao S and Erturk A 2014 *Sensor Actuat. A-Phys.* **214** 58-65.
[8] Erturk A 2011 *J. Intell. Mater. Syst. Struct.* **22** 1959-73.
[9] Xiang HJ, Wang JJ, Shi ZF and Zhang ZW 2013 *Smart Mater. Struct.* **22** 095024.
[10] Zhang ZW, Xiang HJ and Shi ZF 2016 *J. Intell. Mater. Syst. Struct.* **27** 567-78.
[11] Tang L, Zhao L, Yang Y and Lefeuvre E 2014 IEEE/ASME T. Mech. **20** 834-44.
[12] Yang Y, Zhao L and Tang L 2013 *Appl. Phys. Lett.* **102** 064105.
[13] Zhao S and Erturk A 2013 *Smart Mater. Struct.* **22** 015002.
[14] Wang S, Lam KH, Sun KWK, Chan HLW, Guo MS and Zhao XZ 2017 *Appl. Phys. Lett.* **90** 113506.
[15] Yuan T, Yang J, Song R and Liu X 2014 *Smart Mater. Struct.* **23** 125046.
[16] Leinonen M, Palosaari J, Juuti J and Jantunen H 2014 *J. Intell. Mater. Syst. Struct.* **25** 391-400.
[17] Moure A, Rodríguez MI, Rueda SH, Gonzalo A, Rubio-Marcos F, Cuadros DU, Pérez-Lepe A and Fernández J 2016 *Convers. Manage.* **112** 246-53.
[18] Zhao HD, Yu J and Ling JM 2010 *J. Ceram. Soc. Jpn.* **118** 909-15.
[19] Daniels A, Giuliano A, Zhu M and Tiwari A 2013 *Modeling, validation and design analyses of a piezoelectric cymbal transducer for non-resonant energy harvesting* (IEEE International Conference on Green Computing and Communications and IEEE Internet of Things and IEEE Cyber, Physical and Social Computing).
[20] Mo C, Jordan S and Clark WW 2012 *Bimorph piezoelectric cymbal design in energy harvesting* (ASME 2012 Conference on Smart Materials, Adaptive Structures and Intelligent Systems).
[21] Zhao HD, Ling JM and Yu J 2012 *J. Ceram. Soc. Jpn.* **120** 317-23.
[22] Zhao HD, Liang YH and Ling JM 2011 *J. Shanghai Jiaotong Univ.* **45** 62-66.
[23] Dogan A, Uchino K and Newnham RE 1997 *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **44** 597-605.
[24] Kim H, Batra A, Priya S, Uchino K, Markley D, Newnham RE and Hofmann HF 2004 *Jpn. J. Appl. Phys.* **43** 6178-83.
[25] Kim H, Priya S and Uchino K 2006 *Jpn. J. Appl. Phys.* **45** 5836-40.
[26] Kim H, Priya S, Uchino K and Newnham RE 2005 *J. Electroceram.* **15** 27-34.
[27] Huang RB, Niu YL, Zhao HD and Chang HB 2012 *China J. Highway Transp.* **25** 1-8.
[28] Tufekcioiglu E and Dogan A 2014 *Sensor Actuat. A-Phys.* **216** 355-63.
[29] Yuan J, Shan X, Xie T and Chen W 2009 *J Zhejiang Univ. Sci. A* **10** 1187-90.
[30] Yuan J, Shan X, Xie T and Chen W 2010 *J. Intell. Mater. Syst. Struct.* **21** 765-71.
[31] Palosaari J, Leinonen M, Hannu J, Juuti J and Jantunen H 2012 *J. Electroceram.* **28** 214-19.
[32] Mo C, Arnold D, Kinsel WC, Clark WW 2013 *J. Intell. Mater. Syst. Struct.* **24** 828-36.
[33] Wang JJ and Shi ZF 2013 *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **60** 2196-2203.
[34] Zhao HD, Qin L and Ling JM 2015 *Int. J. Transport. Sci. Technol.* **4** 17-28.
[35] Hunaidi O 2000 *Traffic vibrations in buildings* (Construction Technology Update: www.nrc-cnrc.gc.ca/ctu-sc/ctu_sc_n39).