Energy Conversion and Management 112 (2016) 246–253

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Feasible integration in asphalt of piezoelectric cymbals for vibration energy harvesting

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ARTICLE INFO

Article history:
Received 9 October 2015
Accepted 13 January 2016
Available online 23 January 2016

Keywords:
Energy harvesting
Piezoelectric
Cymbal
Vibrational Energy
Roads

ABSTRACT

Piezoelectric cymbals with 29-mm diameter and different configurations are fabricated and tested to determine the best conditions to optimize the conversion of mechanical to electric energy. Then, the ones with the best results are integrated directly in asphalt to evaluate their performance as vibration energy harvesters in roads, in a test bench designed to characterize these parameters. The main cymbal parameters and their integration in the asphalt are determined. For the first time, the electrical energy that can be obtained with the embedment of cymbals in asphalt is evaluated. Each single piezoceramic cymbal recovers up to 16 μW for the pass of one heavy vehicle wheel. An extrapolation of the energy transformed by the integrated cymbals in roads with high vehicle densities, such as in a peri-urban motorway, is approached. Energy densities in the range of 40–50 MW h/m^2 can be obtained at 100 m of road (use of 30,000 cymbals), which could account for more than 65 MW h in a year. All this with a relatively low cost for an emerging technology (less than 2 €/kW h). The conversion of wasted and unused vibrational energy in roads by piezoelectric cymbals is thus proved as a real possibility of energy harvesting.

1. Introduction

The search of new energy sources that combine good efficiency, profitability and being environmentally friendly is an open and attractive field in the R&D activities. Within this issue, there is an increasing interest in energy recovered from wasted or unused power, as in the case of vibrations. Different vibration sources exist in the environment [1]. The energy that they can generate depends on the characteristics of each one. Thus, there are studies in harvesting of wasted energy caused by human walk [2,3], railways [4], cars applications [5] or even in windmills, to increase the efficiency in wind energy harvesting [6]. In these applications, the transducer devices that convert the mechanical energy into electrical power often contain piezoelectric elements [7–11]. Specifically for energy harvesting in asphalt, some applications are nowadays in market. An example is the solution given by the Israeli company Innowattech [12]. They use different modules with piezoelectric elements to harvest the vibrational wasted energy from the asphalt.

In general, for energy harvesting in roads, the transducer must have some characteristic to assure the best integration. Thus, it must have high piezoelectric coefficients, and taking into account the asphalt pavement stiffness (1000–4000 MPa [13]), the transducer must have a stiffness coefficient within this range.

Several transducers have been proposed with this aim, as the multilayer stacks [14] (with the drawback of its high stiffness), the so-called RAINBOW (acronym of Reduced and Internally Biased Oxide Wafer, which is too brittle and not strong enough to endure the vehicle load) [15], the THUNDER (acronym of Thin Layer Unimorph Ferroelectric Driver and Sensor [16], with a very low stiffness about 1 MPa, far less than asphalt pavement) or the MFC (Macro-Fiber Composite) [17]. These ones are not in fact quite appropriate for these uses, as they are less effective in harvesting applications driven by stress as in the case of pavement asphalt.

A type of piezoelectric transducer with good characteristics to be used in these applications is the so-called piezoelectric cymbal. This device is a ceramic–metal composite built-up by a piezoelectric ceramic that is bonded, generally by an epoxy resin, to a truncated conical shaped metal end cap. The scheme of a piezoelectric cymbal is shown in Fig. 1a. The cavities of the metal end caps act as a mechanical transformer and amplifier of a portion of the incident

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http://dx.doi.org/10.1016/j.enconman.2016.01.030
0196-8904/

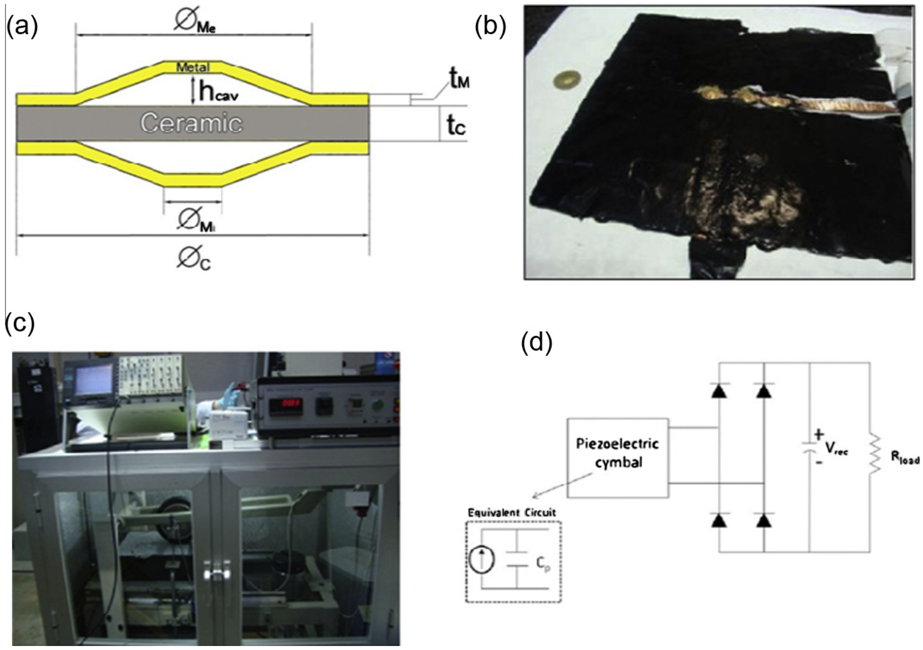

Fig. 1. (a) Schematic representation of a piezoelectric cymbal ceramic–metal composite, in which the different tested parameters are represented. The acronyms present in the panel (a) correspond to metal internal diameter ($\varnothing_{Mi}$); metal thickness (t_M); metal external diameter ($\varnothing_{Mi}$); ceramic thickness (t_C); ceramic diameter ($\varnothing_C$); and cavity heights (h_{cav}); (b) cymbals embedded in a 3-cm thickness mastic host layer made by bitumen and silica fillers; (c) experimental set-up with a wheel attached to a system that provides a weight that simulates the pass of a heavy vehicle that applies a stress of 0.9 MPa at a frequency of 4 Hz. The test wheel is composed by a 5 cm wide solid tire and 2 cm thickness, whose movement frequency is 42 passes per minute and the distance run is 23 cm in each direction. It ensures a complete overpassing of the cymbal area; (d) full wave rectification circuit with a full wave rectifier in the input and an output capacitor for storing the generated electrical energy of the cymbal transducer. This circuit needs a threshold voltage (2.5 V) to work and have an output electrical signal. The energy transformed by the cymbal was then measured in a resistive load of 1 MΩ.

axial stress in the radial stresses of opposite sign [18]. The actual piezoelectric coefficient d_{33} is in fact an effective d_{33}^{eff} coefficient calculated as:

$$d_{33}^{\text{eff}} = d_{33} - Ad_{31} \tag{1}$$

with d_{31} having negative values. Thus, A is an amplification coefficient with values in the range of 10–100. As a result, the piezoelectric cymbal has a transducer rate much higher than the corresponding piezoelectric ceramic, and also higher than other configurations as the multilayer stack [18]. The cymbal piezocomposites have unique piezoelectric properties resulted for both the charge and the displacement amplification, the ability to tailor the desired properties by the choice of the cap and driver materials, the simple design, the easiness of fabrication and their low cost [19]. The piezoelectric activity of a cymbal is influenced by its design. It depends on several parameters as the thickness and diameter of the ceramic, the design of the truncated conical end caps or the chosen metal [20,21]. An expression is often used for the effective d_{33}^{eff} coefficient, which is found to depend on several cymbal parameters [22]:

$$d_{33}^{\text{eff}} = -d_{31}\frac{\Phi_{\text{Me}}(\Phi_{\text{Me}} - \Phi_M)}{2h_{\text{cav}}(t_c + 2t_m)} + d_{33} \tag{2}$$

Thus, the adequate choice of the cymbal design is essential to optimize the conversion of the mechanical into electrical energy.

A main difficulty for the cymbals in harvesting applications in asphalt is their integration. It has to be done at conditions that allow the conversion of the maximum possible energy without losses. The cymbals must be embedded in the asphalt in a fixed position but they cannot be clamped. The position is also critical for the performance of the piezoelectric harvesters. The asphalt is built up by different layers where the cymbals can be placed. The pressure applied by the vehicles is high, so the asphalt must also act as a protective layer for the cymbals. They must be located as close as possible to the surface without being damaged. In this way, they must take advantage of the maximum pavement deformation where the applied force is the highest [13]. The electrical connections must also ensure that the energy transformed by the cymbals can be harvested with the minimum losses. All these features must be fulfilled by a process that is compatible with the one employed nowadays for road construction, so it does not mean an increase in the process cost.

In this work, piezoelectric cymbals have been integrated in asphalt and characterized in a test bench that simulates car passing conditions (wheel-track test) for the first time. They are characterized in a first stage at laboratory conditions to determine the cymbals characteristics (height and metal cap thickness) that give the best properties. With the results obtained, the energy that can be harvested by cymbals embedded in asphalt as a function of the vehicle number passing onto a fixed road length is calculated and compared with other technologies. It should be emphasized that the energy density obtained by this pioneer technology (40 MW h/m^2) is in the order of the ones obtained by other alternative energy sources already in used, with a lower environmental impact.

2. Experimental procedure

2.1. Cymbal preparation

Piezoelectric cymbals with a similar design to the one shown in Fig. 1a are fabricated with commercial PZT ceramics (Noliac NCE51 and PiCeramics PIC 141) as piezoelectric components bonded by epoxy (EPO-TEK® 353ND-T) to end brass caps. The piezoelectric coefficients of each ceramic are shown in Table 1. The cymbal design can modify its piezoelectric activity. Several works have studied the influence of different parameters (metal and