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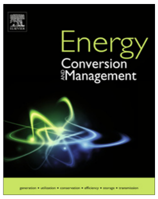

Modelling piezoelectric energy harvesting potential in an educational building

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ABSTRACT

In this paper, potential application of a commercial piezoelectric energy harvester in a central hub building at Macquarie University in Sydney, Australia is examined and discussed. Optimization of the piezoelectric tile deployment is presented according to the frequency of pedestrian mobility and a model is developed where 3.1% of the total floor area with the highest pedestrian mobility is paved with piezoelectric tiles. The modelling results indicate that the total annual energy harvesting potential for the proposed optimized tile pavement model is estimated at 1.1 MW h/year. This potential energy generation may be further increased to 9.9 MW h/year with a possible improvement in piezoelectric energy conversion efficiency integrated into the system. This energy harvesting potential would be sufficient to meet close to 0.5% of the annual energy needs of the building. The study confirms that locating high traffic areas is critical for optimization of the energy harvesting efficiency, as well as the orientation of the tile pavement significantly affects the total amount of the harvested energy. A Density Flow evaluation is recommended in this study to qualitatively evaluate the piezoelectric power harvesting potential of the considered area based on the number of pedestrian crossings per unit time.

1. Introduction

The increasing energy demand in the building sector, which results from the growth in population, enhancement of building services and comfort levels, together with the rise in time spent inside buildings, is a significant contributor to the overall energy use [1]. To minimize the impact of growing energy requirements by the building sector, integrating alternative energy sources is of paramount importance.

In the last few decades, a wide range of renewable energy sources has been considered as the possible solution, including but not limited to solar, wind and hydroelectric power [2,3]. Recently, there has been an increasing interest in the exploration of indoor energy harvesting sources. The indoor energy sources are believed to be an important component in the energy diversity and reliability when the weather related energy resources are minimal [4]. Inside a building, a range of harvestable ambient energy sources exist, e.g. waste heating, flowing water, electromagnetic waves and, particularly, vibration [5,6]. The vibration-based energy harvesting, termed as piezoelectric energy generation, has received the most attention due to its ability to capture the surrounding ambient energy and then directly convert the applied strain energy into usable electrical energy and the ease at which they can be integrated into a system [5,7–9].

The piezoelectric material in the piezoelectric system has several modes of operation. These modes are characterized by the piezoelectric strain constant d_{ij}, which is the strain to the electrical field [10]. The subscript i represents the direction of the applied electrical field, while the subscript j indicates the direction of deformation. When an electrical field is applied in the poling direction, normally along the vertical axis, the material contracts in the poling direction (3-axis) and extends in other directions (1 and 2-axis), as shown in Fig. 1. The deformation along the 1 and 2-axis is called the d_{31} effect, and the shape change along the 3-axis is defined as the d_{33} effect. These two effects predominate in the application of power harvesting. The piezoelectric materials are capable of generating power from the nano-Watt to the Watt range, depending on the piezoelectric materials and system designs [11–14].

The initial research driver in this field was the reduction in power requirement of small electronic components which would ultimately release the sensors used in remote passive and active monitoring applications from the constrain of complex cable wiring and periodic battery replacement [15–18]. Under this context, Roundy and Wright developed a piezoelectric generator as well as an analytical model for the design validation [19]. This generator

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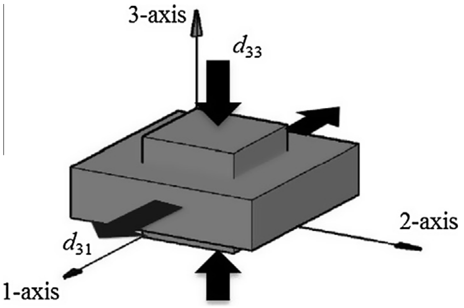

Fig. 1. Operation modes of piezoelectric material and its axis reference system.

had been successfully used to power up a radio transmitter from a vibrational source of 2.5 m/s^2 at 120 Hz. Similar piezoelectric generator was further proved to be functional in a much broader vibrational frequency from 40 Hz to 1000 Hz [20,21]. To extend the piezoelectric technology over micro-scale, relative energy storage devices were developed to accumulate a sufficient amount of energy to power the intended electronics [13,15].

In recent years, several attempts at the macro-scale application of the piezoelectric technology have emerged [22–25]. The piezoelectric floors have been trialed since the beginning of 2007 in two Japanese train stations, Tokyo and Shibuya stations. The electricity generated from the foot traffic is used to provide all the electricity needed to run the automatic ticket gates and electronic display systems [26]. In London, a famous nightclub exploited the piezoelectric technology in its dance floor. Parts of the lighting and sound systems in the club can be powered by the energy harvesting tiles [27]. However, the piezoelectric tile deployed on the ground usually harvests energy from low frequency strikes provided by the foot traffic. This working condition may eventually lead to low power generation efficiency.

In order to improve the power generation efficiency, a two-stage energy harvester design was suggested for the very low frequency vibration environment in the 0.2–0.5 Hz range [28], as shown in Fig. 2. This design contains two main components, a mechanical energy transfer unit linked with a vibration platform and secondary vibrating units composed of additional piezoelectric elements and vibrating beams fixed on one side. Ideally, when the initial impact effects on the platform, the mass attached on the mechanical energy transfer unit starts to vibrate in low frequency. The low vibration energy is then transferred to a much higher natural frequency vibration in the piezoelectric elements as the mass passes over and excites the piezoelectric beams.

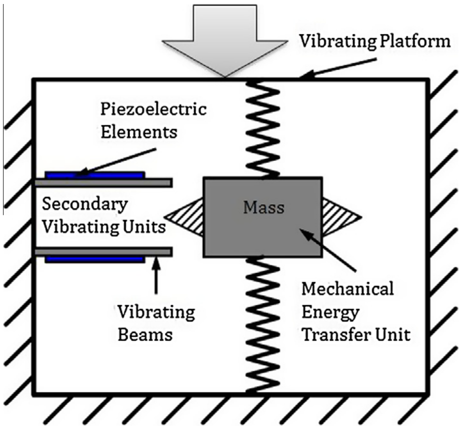

Fig. 2. Schematic of an enhanced piezoelectric energy generator based on the two-stage energy harvesting approach based on [28].

Based on the proposed design, a piezoelectric cantilever stream structure was adopted by Wu et al. [29]. In their research, the two-stage design is called the plucked method and the design was validated with experimental tests. It is claimed that the plucked method can enhance the efficiency of the energy harvesting system by 900% [29].

However, since the macro-scale piezoelectric technology has not yet been fully established, much uncertainty still exists about the actual energy harvesting efficiency of the commercialized piezoelectric tiles. There is a lack of information on energy harvesting potential of piezoelectric tiles when applied in buildings, and particularly in green buildings. In this work, a novel approach to estimate piezoelectric harvesters' power generating potential and their adaptability in buildings is developed. The analysis was conducted based on the data provided by a manufacturer of a commercial piezoelectric energy harvester to examine its adaptability in a central hub building at Macquarie University in Australia. In order to evaluate the full potential of this harvester, the high traffic areas inside the building were located by a mobility analysis approach. Based on the mobility pattern, a deliberate tiles deployment strategy was then selected. Along with modelling the amount of electricity converted from the footsteps, the energy generating potential of a possible improvement with plucked method was also determined. The study then proposes an evaluation indicator to calculate and predict the most efficient areas for tile deployment.

2. Methodology

2.1. Building description

The building considered for the piezoelectric power generation study in this research was a newly built library at Macquarie University, Sydney, Australia. The new library is a flagship building located in the center of the Campus, aiming for a Five-Star Green Rating under the criterion of the Green Building Council of Australia [30]. The building comprises of five stories, equal to a total of 16,000 m^2 in Gross Floor Area with capacity of 3000 seats available for students and 150 working staff.

The ground level of the library, as shown in Fig. 3, is the largest floor area in the building. Near the Main Entrance, there is a cafeteria providing food and drinks for the library users. Lobby meeting areas, including concourse spaces, are located after the main gates and the central cross area. They provide access to the exhibition spaces and the main collection section with open shelves. The lower ground floor and upper ground levels, 1, 2, 3 provide undergraduate and postgraduate students and research personnel collaborative learning spaces. With these features, the new library becomes a new hub for not only students but also staff members in the university. It makes the area the busiest spot on the Campus, making the library one of the target areas for deploying the piezoelectric tiles.

In order to facilitate students' learning, the library building is open seven days a week during the entire year, except for the third session period from 30 November to Tuesday, 24 December when the library is closed on Sundays. The library is also closed from 25 December to 1 January. The actual operating days of the library throughout the year, according to the library schedule, are 353 days.

2.2. Location of high traffic areas

The high cost of the piezoelectric power generation tiles ($3850/per tile) is the limiting factor in their deployment. For this reason, high traffic areas in the building should be identified in order to maximize the energy harvesting efficiency.