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Feasibility study of multi-directional vibration energy harvesting with a frame harvester

Hao Wu^a, Lihua Tang^{a,b}, Yaowen Yang^{a*}, Chee Kiong Soh^a

^a School of Civil and Environmental Engineering,
Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

^b Department of Mechanical Engineering,
University of Auckland, 20 Symonds Street, Auckland 1010, New Zealand

* Corresponding author, cwyang@pmail.ntu.edu.sg

ABSTRACT

Vibration energy harvesting using piezoelectric material is a promising solution for powering small electric devices, which has attracted great research interest in recent years. Numerous efforts have been done by researchers to improve the efficiency of vibration energy harvesters and to broaden their bandwidths. In most reported literature, harvesters are designed to harvest energy from vibration source with a specific excitation direction. However, a practical environmental vibration source may include multiple components from different directions. Thus, it is an important concern to design a vibration energy harvester to be adaptive to multiple excitation directions. In this article, a novel piezoelectric energy harvester with frame configuration is proposed to address this issue. It can work either in its vertical vibration mode or horizontal vibration mode. Therefore, the harvester can capture vibration energy from arbitrary directions in a two-dimensional plane. Experimental studies are carried out to prove the feasibility for multiple-direction energy harvesting using such harvester. The development of this two-dimensional energy harvester indicates its promising potential in practical vibration scenarios.

Keywords: energy harvesting; frame configuration; multiple-degrees-of-freedom system; two-dimensional vibrations

1. INTRODUCTION

Vibration energy harvesting using piezoelectric material is a promising solution for powering small electric devices, which has attracted great research interest in recent years. Typically, a vibration energy harvester converts ambient kinetic energy into electric energy through electrostatic, electromagnetic, or piezoelectric transduction mechanism [1-4]. No matter what mechanism was adopted, a vibration energy harvester is mostly resonance-based. To broaden the operating bandwidth, as well as to improve the efficiency, numerous efforts have been reported in the literature, such as nonlinear configurations and multi-model energy harvesting [5-12].

Most reported multi-model energy harvesters focus on harvesting energy from wider frequency range but only single excitation direction is concerned. However, a practical environmental vibration source may include multiple components from different directions [13-14]. For example, in Reilly *et al* [14], a Statasys 3D printer produces three frequency response peaks at 28 (1-axis), 28.3 (2-axis) and 44.1 Hz (3-axis) along different directions, and a washing machine undergoes resonance at 85.0 Hz for both 1 and 3 axes. Thus, it is an important concern to design a vibration energy harvester that can work with multiple excitation directions.

Few attempts were reported regarding multiple-direction energy harvesting. Bartsch *et al* [15] and Liu *et al* [16] developed similar electromagnetic energy harvesting device using a disk shape mass connecting with concentric circular springs. Zhu *et al* [17] developed a two-dimensional ultrasonic electrostatic harvesting device, with a central seismic mass suspended by 16 small beams attached to four corner anchors. Yang *et al* [18] studied a two-dimensional vibration energy harvester with magnetostrictive transducers, by using a circular cross-section cantilever rod to vibrate instead of rectangular cantilever beam. In this article, a piezoelectric energy harvester with frame configuration is proposed to address the issue for multiple-direction vibration energy harvesting, and experimental studies are carried out to validate it.

2. PROPOSED FRAME CONFIGURATION FOR 2-D ENERGY HARVESTER

This paper proposes a new frame-type piezoelectric energy harvester that can work with any orientation in a two-dimensional plane. Figure 1 shows a schematic drawing of the proposed harvester. Generally, it can be regarded as a beam (horizontal plate) supported by two walls (vertical plate). From simple structural analysis, it is known that: if the two walls are strong enough, the structure will be treated as a clamped-clamped beam that vibrates in vertical direction, or if the beam is stiff enough, the structure is a sway frame which deforms in horizontal direction. By adjusting the stiffness of the beam and walls, it can work either in its vertical vibration mode or horizontal vibration mode. And the natural frequencies for these two modes can be tuned easily by adjusting the structures parameters (length, thickness, and mass value). Therefore, the harvester can capture vibration from arbitrary direction in the two-dimensional plane by combining its two vibration modes. However, as the strain distributions on the frame are not with the same sign (as indicated in Figure 2), the piezoelectric materials on the frame should be segmented to avoid the cancellation.

Figure 1. proposed frame-type vibration energy harvester

Figure 2. Indication of strain distribution for the two different vibration modes

This frame harvester can be regarded as two single-degree-of-freedom (SDOF) models in two directions respectively, to evaluate the structure's natural frequencies. For the horizontal vibration mode, its equivalent stiffness can be calculated as

$$K_h = \frac{\frac{L_1 L_2^2}{EI_1} + \frac{L_2^3}{6EI_2}}{\frac{L_1^3}{6EI_1} \left(\frac{L_1 L_2^2}{EI_1} + \frac{L_2^3}{6EI_2} \right) - \frac{1}{8} \left(\frac{L_1 L_2}{EI_1} \right)^2} \quad (1)$$

Its equivalent stiffness for the vertical vibration mode is

$$K_v = \frac{\frac{L_1^2}{2EI_1} + \frac{L_1 L_2}{EI_2}}{\left(\frac{L_2^3}{48EI_2} + \frac{L_1^2 L_2}{4EI_1} - \frac{3L_1 L_2^2}{32EI_1} \right) \left(\frac{L_1^2}{2EI_1} + \frac{L_1 L_2}{EI_2} \right) - \left(\frac{L_1 L_2}{16EI_1} + \frac{L_2^2}{16EI_2} \right) \left(\frac{L_1^2 L_2}{4EI_1} + \frac{L_1 L_2^2}{4EI_2} \right)} \quad (2)$$

where E is the elastic module of the structure, $L_{1,2}$ are the length for wall and beam respectively, and $I_{1,2}$ are the moment of inertia for the wall and beam respectively (for simplistic, the moment of inertia is assumed uniform for the wall and beam).

In most cases of vibration energy harvesting, the Lumped mass is not very large, thus the distributed mass of the beam and wall cannot be ignored. For this frame harvester, the values of effective mass for the horizontal mode and vertical mode are different. In the horizontal mode, the effective mass should consist of the central mass and the mass of beam, and part of the mass of the two walls. While in the vertical mode, the mass of the walls barely contributes to the vibration, its effective mass is comprised with the central mass and part of the mass of the beam. These two effective mass can be written as

$$\begin{aligned} M_{eh} &= M_c + \alpha M_1 + M_2 \\ M_{ev} &= M_c + \beta M_2 \end{aligned} \quad (3)$$

where M_c is the value of the central mass, $M_{1,2}$ are the mass values for the walls and beam respectively, and the participation coefficients α and β can be calculated by integration of the kinetic energy based on its vibration mode shapes (e.g. for a uniform cantilever beam, its effective mass can be calculated as 33/140 of the mass of the cantilever.)

By using the two groups of equivalent stiffness and effective mass, two natural frequencies for the horizontal and vertical vibration modes can be roughly worked out as SDOF system,

$$\omega_{h,v} = \sqrt{\frac{K_{h,v}}{M_{eh,ev}}} \quad (4)$$

Thus, by adjusting such structural parameters, the two natural frequencies can easily be tuned close enough, or even the same. Therefore, the harvester can work in any orientation but with the same operation frequency.

3. EXPERIMENT STUDY

3.1 Experiment setup

Based on the schematic shown in Figure 1, a prototype for the proposed frame harvester is fabricated and installed on the shaker, as shown in Figure 3. Totally, 8 pieces of MFC patches (M-2814-P2, Smart Material Corp.) are attached on the aluminum frame substrate, to avoid the strain cancellation. The detail dimensions of the harvester are listed in Table 1. For the ease of data recording, the MFC patches are numbered as MFC-1 to MFC-8, starting from the root of the right side of the frame to another side (as indicated in Figure 3).

The shaker used in the experiment only vibrates in the vertical direction, which cannot change the orientation conveniently. Thus a circular plate is designed for the purpose of changing the orientation of the frame harvester. Part of the circular plate is fixed on the shaker, and another part can be rotated around its center, with the interval of 15 degrees. By rotating the circular plate, the orientation of the harvester can be tuned, while the base excitation from the shaker is

always in the vertical direction. This way, the vertical excitation of the shaker can be easily converted into the vibration with arbitrary direction for the harvester.

Due to the fabrication defect, the harvester is not pure symmetric, and the structure is very sensitive to slight boundary change. Furthermore, it is difficult to tune the two natural frequencies to be exactly the same. Fortunately, from the primary analysis in the previous section, it is known that the difference of the effective mass for two vibration modes will be helpful for tuning the two natural frequencies. As the frame is already fabricated and installed, it is not possible to change its thickness and length, which means its equivalent stiffness for two modes have been already fixed. However, the two effective mass of different vibration modes are not with fixed ratio. By changing the value of the central mass, its two natural frequencies can still be adjusted. For example, the two natural frequencies are 40.5 Hz (horizontal mode) and 43.7 Hz (vertical mode) for the central mass of 9 grams, and they can be adjusted to 36.8 Hz (horizontal mode) and 37.2 Hz (vertical mode) for the central mass value of 14 grams. As the central mass is increased to 21 grams, the natural frequency of vertical mode (32.5 Hz) is tuned lower than that of the horizontal mode (34.4 Hz).

Figure 3. Experiment setup

Table 1. Dimensions for the prototype

Aluminum frame substrate		MFC patches	
Thickness	0.6 mm	Active length	28 mm
Width	20 mm	Active width	14 mm
Length (wall)	72 mm	Thickness	approx. 0.3 mm
Length (beam)	180 mm		

Therefore, the configuration of central mass value of 14 grams is chosen to harvest the vibration energy in multiple directions as the two natural frequencies are very close.

In the experiment, the harmonic vibration signal is generated by a function generator, and magnified by an amplifier, then drive the shaker to vibrate. An accelerometer is attached to the shaker, to monitor and control the base acceleration to be at same level during the experiment procedure. During the sinusoidal frequency sweep, the acceleration level is always kept at 2 m/s². The output responses are recorded using the data acquisition system (NI 9229).

4. EXPERIMENT RESULTS

4.1 Open circuit frequency response

First of all, the open circuit frequency response for each MFC patch is recorded in the experiment. To obtain the harvester's response under the excitations with different directions, the harvester is rotated in the two-dimensional plane for 15 degree each time. Due to the symmetric condition, the whole two-dimensional plane can be divided into 4 quarters which should have similar pattern in good symmetric condition. Thus, only one quarter of the plane is studied in the experiment, i.e., the harvester is orientated from 0 degree to 90 degree with 15 degree interval. Totally 7 groups of frequency responses for different directions are plotted in Figure 4. As can be seen in the graphs, the two natural frequencies of the harvester in two directions are almost the same. The resonance frequency for the vertical vibration mode (0 degree) is about 36.8 Hz, while for the horizontal vibration mode (90 degree) is 37.2 Hz. For the other orientations in-between, only one significant response peak is observed for most cases, locating at around 37 Hz.

Figure 4. Open circuit voltage response for different MFC patches in various orientations from 0 degree to 90 degree

From Figure 4, it can be observed that every piece of MFC patch can generate significant voltage output. At the orientation of 90 degree, the harvester is mainly vibrated in horizontal mode. According to the strain distribution from Figure 2, the two pieces of MFC near the root (MFC-1 and MFC-8) should have largest output, while the two pieces of MFC near the central mass (MFC-4 and MFC-5) perform smallest output. On the contrary, at the orientation of 0 degree, two pieces of MFC near the root of the wall (MFC-1 and MFC-8) produce smallest responses, while MFC-4 and MFC-5 generate significant outputs. Other than these, the other pieces of MFC can also generate significant output in different orientations. For the angles in-between 0-90 degrees, the vibration motion can be regarded as a combination of the two modes, cancellation and enhancement may happen to certain piece of MFC in certain direction. For example, at the angle of 45 and 60 degree, the cancellation is observed for MFC-6 and MFC-7 whose voltage outputs are reduced, while MFC-3 and MFC-2 have increased voltage responses because of the superposition of the two vibration modes. This can be easily observed in Figure 5, which presents the voltage change for the orientation changing from 0 to 90 degree at the same frequency of 37 Hz.

If the system is perfect symmetric, it can be predicted that the responses for each MFC patches should be just exchanged, for the angle from 90 to 180 degree. For example, in 165 degree, the responses of MFC-2 and MFC-7 should be same to that of 15 degree, but swapped with each other. Furthermore, at the orientation between 180 and 360 degree, their responses are exactly same as those between 0 and 180 degree.

Figure 5. Open circuit voltage response for all MFC patches versus angle of orientation at 37 Hz

4.2 Power output evaluation

Power output is an important concern to evaluate the performance of the harvester. In this study, variable resistors and rectifiers are used in the experiment to observe the power output of the frame harvester.

For every piece of MFC, its power output is evaluated by direct connection to a variable resistor, while keeping other MFC patches in open circuit condition. For different angles of orientation, the optimal resistor values for the MFC patches will be slightly shifted. However, as observed from all the experiment data, their optimal resistor values are always around the range of 100 k Ω to 120 k Ω . There are many cases for all the power evaluation for individual MFC patches, Figure 6 only shows one case.

Figure 6. Power evaluation for individual MFC patch

As indicated from the strain distribution pattern in Figure 2, it is apparent that there are different phase angles for different MFC patches in different vibration modes. Considering the superposition of the two modes in different directions, the condition will be even more complicated. Thus, the MFC patches cannot be directly connected to each other, to evaluate the overall power output. Therefore, in the experiment, 8 rectifiers are used to rectify the outputs of 8 MFC patches. The rectified outputs are connected in series and in parallel for overall power output evaluation, as indicated in Figure 7 and Figure 8, respectively.

The results for series connection are shown in Figure 7. It can be seen that, for different orientations, the overall optimal resistance for series connection is around 700 k Ω . The maximum of the overall power output is about 2.9 mw at 60 degree, while the minimum is about 1.8 mw at 15 degree. Thus, it can be concluded that this frame harvester can always provide significant power output with a base excitation from any direction in the two-dimensional plane.

Figure 7. Overall power output for series connection after rectified

Figure 8 shows the overall power output for parallel connection. In this condition, the optimal resistor value is about 20 kΩ. And the maximum power achieved is about 2.5 mw at 90 degree, while the minimum is about 1.6 mw at 0 degree. For all the power responses, resonance shifts due to the electromechanical coupling can be observed.

Figure 8. Overall power output for parallel connection after rectified

However, it is worth mentioning that, in the experiment, there is an inevitable voltage drop about 1 V in each rectifier, which sacrifices certain portion of power, especially for those MFCs having low outputs in specific directions, and thus reduces the overall power output. Therefore, more efficient rectifying interface for such frame harvester is highly desirable.

4.3 Other configuration with different mass

In previous sections, we provide the experimental study for the frame-harvester working in various orientations but with the same operation frequency (two natural frequencies are very close given the central mass of 14 grams). By changing the central mass, the two natural frequencies can be tuned to be separated from each other. Figure 9 shows the open circuit responses for the configuration in which the central mass is changed to 9 grams.

Unlike the previous configuration that provides only one significant response peak for different orientations, this configuration provides different frequency responses as the orientation is changed. As shown in Figure 9, the natural frequency for the vertical vibration mode (0 degree) is 43.7 Hz, while it is 40.5 Hz for the horizontal vibration mode (90 degree). For these two conditions, the harvester almost responds with single peak at their own resonances. However, at other orientations, the responses for those MFCs are the results of the superposition of two vibration modes. For example, at 45 degree, there are two response peaks located at the resonant frequencies of the vertical and horizontal modes. Such kind of configuration is valuable in the scenarios where the environmental vibration sources are not only with two direction components but also with broad bandwidth. The frame harvester in this case can serve as a broadband harvester for multi-directional vibrations, which definitely deserves further investigation.

Figure 9. Open circuit voltage response with central mass 9 grams

5. CONCLUSION

This paper proposes a piezoelectric energy harvester with a frame configuration for multiple-directional vibration energy harvesting. Experimental work is carried out to demonstrate the feasibility of using such frame-harvester subject to base excitations from various directions. When the system parameters are well-tuned, this harvester can consistently provide significant power output with excitations from any orientation with the same frequency. In addition, it can also be tuned to harvest vibration energy in two different directions with different working frequencies or to harvest broadband vibration energy in specific orientations. In summary, the proposed frame-based multi-dimensional vibration energy harvester in this study indicates its promising potential in practical vibration energy harvesting.

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