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Broadband Piezoelectric Vibration Energy Harvester Using Pole-Zero Cancellation Technique

극점-영점 상쇄 기법을 이용한 광대역 압전 진동 에너지 하베스터

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Key Words : Vibration Energy Harvester(진동 에너지 하베스터), Piezoelectric Materials(압전 재료), Broadband (광대역), Pole-Zero Cancellation(극점-영점 상쇄)

ABSTRACT

This paper presents a new design for a piezoelectric energy harvester with the potential to harvest vibration energy over a wide range of excitation frequencies, particularly beyond the resonance frequency. The piezoelectric vibration energy harvester employs the concept of pole-zero cancellation occurring in a lever type anti-resonant system. The experimental results show that the proposed energy harvester can provide the potential possibility of a broadband piezoelectric vibration energy harvester.

요 약

이 논문에서는 기존 외팔보 빔 형상을 가진 진동 에너지 하베스터의 작동 주파수 범위를 공진 주파수 이후로 확장하기 위해 새로운 형태의 진동 에너지 하베스터가 제시되었다. 압전 재료를 사용한 기존 외팔보 빔 형상의 진동 에너지 하베스터에 레버형 반공진 시스템에서 발생하는 극점-영점 상쇄 기법을 적용하여 작동 주파수 영역을 확장하였다. 간단한 이론적 해석 및 실험을 통해 제안된 광역 압전 진동 에너지 하베스터의 실현 가능성을 검증하였다.

1. Introduction

Although vibration-based energy harvesting based on piezoelectric materials is one of the most promising technologies as a potential replacement for primary battery sources in long-term, low-power autonomous sensory systems, there are only a few examples of commercial product available for energy harvesting because the power output of existing piezoelectric vibration energy harvesters (PVEHs) is not sufficient(1).

In addition, conventional vibration energy harvesters using only cantilever beam structure generally become inefficient when exposed to off-resonance or low frequencies because they are designed to tune to their resonant frequency. The power output degrades significantly when the ex-

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citation frequency of the ambient vibration deviates from the resonant frequency. Therefore, extending the feasible operating range for piezoelectric vibration energy harvesting is a major research issue(2).

Recent attempts to enable broadband PVEH have included active resonance frequency tuning for varying vibration frequency spectra(3), the design of multi-modal structure consisting of multiple beam arrays(4,5), and the use of a nonlinear vibration oscillator (e.g. the Duffing oscillator)(6~9). In particular, many studies have examined nonlinear bistable (buckling or snap-through) systems to address the aforementioned limitations of conventional beam structures(10~12), and true wide bandwidth vibration energy harvester based on piezoelectric transduction is examined(13). In addition, two flexible piezoelectric elements arranged in a bucked structure have been designed for harvesting over a broad range of ambient frequencies(14). Although previous studies have produced some promising findings, most broadband prototypes require better performance, simpler structures, and new operational principle.

This study proposes a new broadband piezoelectric vibration energy harvester that can generate electric power over a wide frequency range by simply including a geometric configuration such as a lever mechanism(Section 2). The new concept of a broadband PVEH is experimentally validated through laboratory tests(Section 3).

2. Broadband Piezoelectric Vibration Energy Harvester

The schematic diagram of the proposed broadband PVEH inspired by anti-resonant vibration isolator(15) is illustrated in Fig. 1(a). This configuration can be approximated by a linear lumped single-degree-of-freedom(1-DOF) mass-spring system by connecting a of negligible to the primary proof (tip) mass through a simple lever mechanism and by assuming that the cantilever beam dominantly vibrates only with the fundamental vibration mode because of the proof mass(Fig. 1 (b)). Then the constraint equation for z with respect to x and y and the Lagrangian function can be defined as follows:

$$L = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}m_s\dot{z}^2 - \frac{1}{2}k(x-y)^2 \tag{1}$$

Where $z = \alpha y - (\alpha - 1)x$, and $\alpha = \ell_1/\ell_2$. Here Hamilton’s principle yields the following equation of motion(15) :

$$(1+\mu(\alpha-1)^2)\ddot{x} + {\omega_O}^2 x = (\mu\alpha(\alpha-1))\ddot{y} + {\omega_O}^2 y \tag{2}$$

where $\omega_O = \sqrt{k/m}$, and $\mu = m_S/m$.

The ratio of Laplace transform of input (y) to the Laplace function of output (x) yields following transfer function

$$H(s) = \frac{X(s)}{Y(s)} = \frac{\mu\alpha(\alpha-1)s^2 + {\omega_o}^2}{\left((1+\mu(\alpha-1)^2)\right)s^2 + {\omega_o}^2}, \tag{3}$$

where s is the complex variable. The roots of the numerator and denominator of the transfer function yield two resonant frequencies

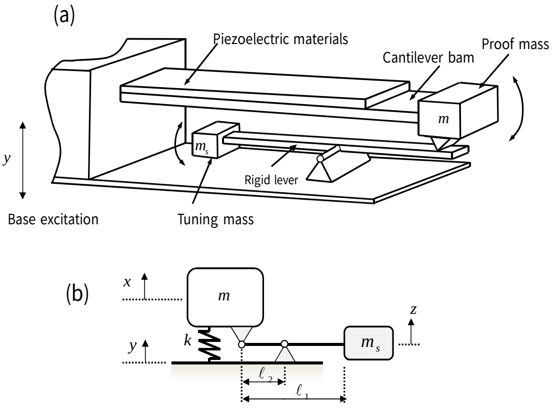


Fig. 1 (a) A schematic diagram of a broadband piezoelectric vibration energy harvester and, (b) An equivalent lumped spring-mass system (1-DOF) with a lever mechanism

$$\omega_Z = \frac{\omega_O}{\sqrt{\mu\alpha(\alpha-1)}}, \omega_P = \frac{\omega_O}{\sqrt{1+\mu(\alpha-1)^2}}. \qquad (4)$$

where ω_P is the resonant frequency associated with poles, and ω_Z is the anti-resonant frequency associated with zeros of the given system, respectively.

Note that the zero associated with the anti-resonant frequency is added to the system because of the lever. In addition, if $\mu = 1/(\alpha-1)$, then $\omega_P/\omega_Z = 1$, which implies that pole-zero cancellation can occur under certain excitation conditions. The frequency response function (FRFs, i. e., the transfer function) is uniform across all excitation frequencies, which allows for a new effective means for a broadband vibration energy harvester. To illustrate the pole-zero cancellation technique, the frequency response function for Eq. (2) is simulated (see Fig. 2). The viscous damping constant(c=0.01 N·s/m) was included to show the damped response. The auxiliary mass (m_S) is tuned to change the parameter μ, remaining constant α(=0.01 m/0.005 m), because the ratio of the primary mass to the tuning mass (μ) is a more sensitive parameter, and easier to change. With the removal of the tuning mass, the system becomes a conventional 1-DOF mass-spring system with a base excitation foundation, introducing a single peak (the resonant frequency of 16 Hz shown as a solid line in Fig. 2). The spring constant (k) is approximately estimated to be 100 N/m based on the bending stiffness of beams (0.095(L)×0.0173(W)×0.0005(t) m). In addition to a resonant frequency, an additional peak (an anti-resonant frequency of 19 Hz) is observed because of the zeros when the tuning mass is set to 0.0035 kg (the dotted line in Fig. 2). In general, this lever-type 1 DOF mass-spring-damper system can significantly reduce the amplitude of the transmitted vibration within the anti-resonant frequency range (i.e. a vibration isolator acting as a band-pass filter). On the other hand, the frequency response function flattens over a wide range of excitation frequencies (above 12 Hz in Fig. 2) because the poles and zeros cancel out as a result of the sufficient inertial forcing term when the tuning mass increases to 0.015 kg ($\mu \cong 1$, the phantom line in Fig. 2). Unlike in the case of the conventional 1-DOF system, the frequency response function shows no decrease beyond the resonant frequency.

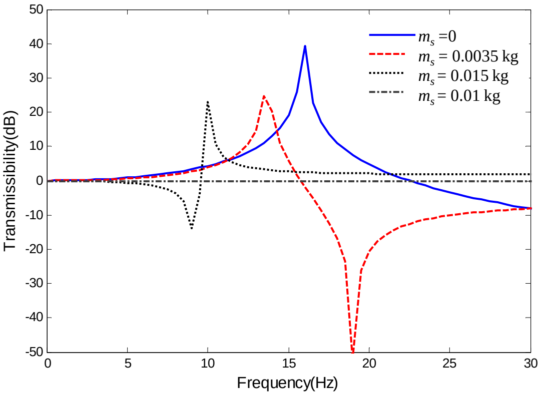
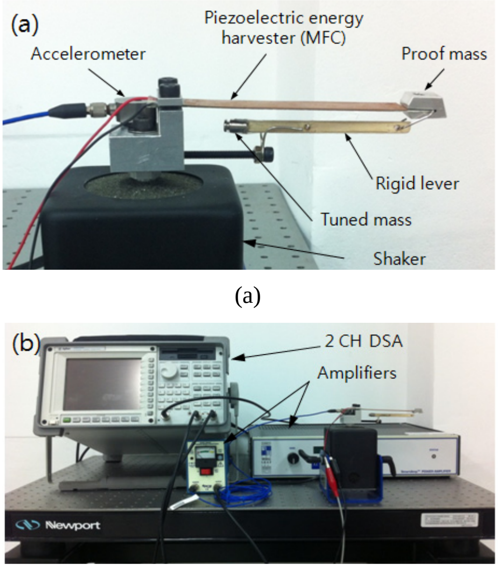


Fig. 2 Simulation results for the frequency response functions(m=0.01 kg, α=2)

3. Experimental Validation

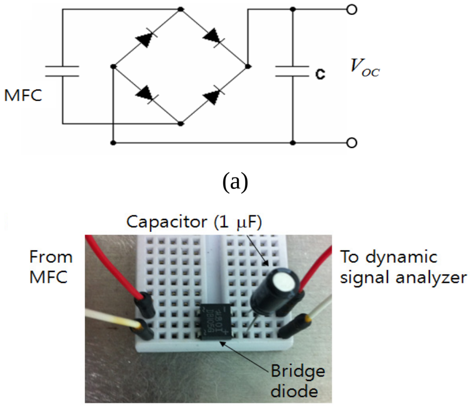
An experiment is conducted to validate the proposed design for broadband piezoelectric vibration energy harvesting. A prototype is fabricated based on a lever-type anti-resonant system (Fig. 1) and validated through a laboratory test, as shown in Fig. 3. A cantilever beam type piezoelectric harvester is first constructed using the macro fiber composite (MFC) from Smart Material Corporation® (Model: M8528P2, 0.09(L)×0.0173(W) m), and the glass-fiber reinforced plastic (GFRP) substrate plate (t=0.5 mm) from Composite Structure Technology®. Then MFC and GFRP are bonded using an Epoxy (model: 3M®DP460). To minimize the mass effect of the lever, it is made simply of lightweight wood, and pivoted at a fixed hinge connected to



(a)

(b)

Fig. 3 (a) The broadband piezoelectric vibration energy harvester and, (b) overall experimental set-up



(a)

(b)

Fig. 4 (a) Full-wave rectifying circuit (b) implementation of full-wave rectifying circuit

the base foundation, as well as to the proof mass. Accordingly, the rigid lever amplifies the input vibration force to provide a greater output force, which is frequently referred to as the leverage effect. The proposed harvester is excited harmonically using an electromagnetic shaker (model: Modal Shop 2007E). A generated sinusoidal signal is applied to the shaker through a linear amplifier. To measure the maximum output voltage, the open-circuit DC voltage without a resistive load from the harvester is measured by using a full-wave rectifying circuit with a bridge diode (model: Analog Device® DB105, voltage drop V_f=1.1 Volt), as shown in Fig. 4(b). The capacitive element of 1 μF is chosen for a smooth transient response.

To measure the frequency response function (FRF), the base acceleration is also measured using an ICP-type accelerometer (model: 355B02; PCB Piezotronics, Inc.) mounted on top of the shake. The voltages from the harvester and the voltage from the accelerometer are sampled with a sampling frequency of 400 Hz, and analyzed using a dynamic signal analyzer (model: HP35670A). While the proof mass of 0.01 kg is fixed to the end tip of the harvester, the tuned mass is adjusted manually by using small metal weights.

4. Results and Discussion

Multi-mode voltage frequency response functions are estimated using the AC output voltage (before rectifying) and the applied acceleration (an approximated root mean square (RMS) value of 1 m/s^2), as shown in Fig. 5. Although the sampling frequency is chosen to be sufficient for capturing some of the natural frequencies, only the fundamental vibration mode of interest is plotted for comparison with respect to the simulation results. The experimental result is generally consistent with the simulation results. The slight attenuation above 30 Hz in Fig. 5 is due to the exclusion of the higher modes. The voltage FRF for anti-resonant (m_s=0.0035 kg) and pole-zero cancellation (m_s=0.015 kg) slightly becomes reduced because of the reduced excitation force resulting from the attachment of tuned mass and lever. However, the voltage FRF for pole-zero cancellation (the phantom line in Fig. 5) shows no significant decrease

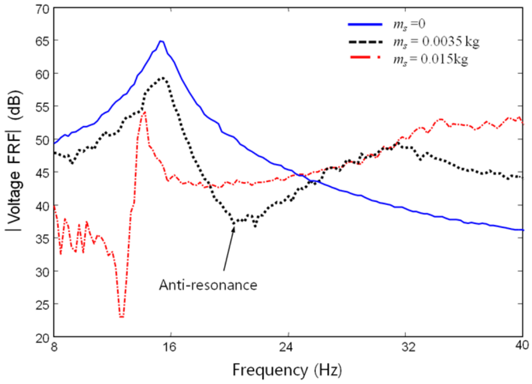


Fig. 5 Experimental results for the frequency response functions (m=0.01 kg, α=2)

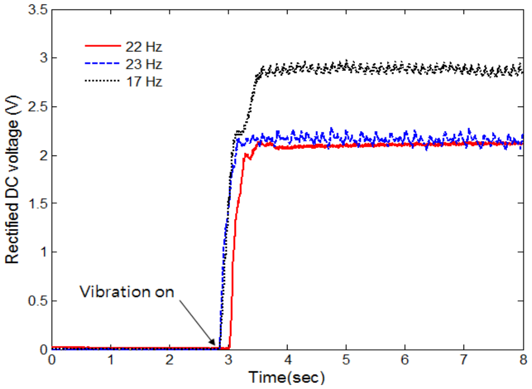


Fig. 6 Steady-state open-circuit DC voltages with respect to different excitation frequencies: PVEH using pole-zero cancellation (m_s=0.015 kg)

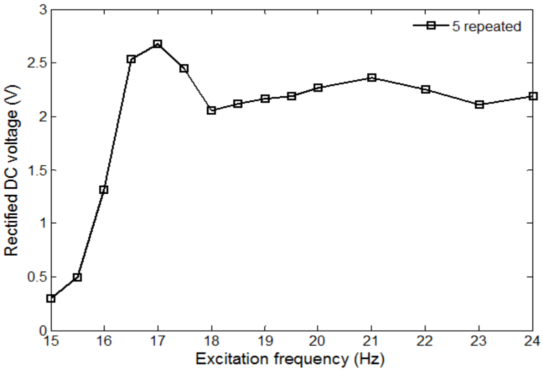


Fig. 7 Broadband vibration energy harvesting performance of the proposed PVEH

beyond the resonant frequency, which is consistent with the simulation results. In the case of pole-zero cancellation, the anti-resonant frequency disappeared, and the voltage FRFs can be more uniformly distributed, ranging from 15 Hz to 40 Hz, at the expense of peak value at the resonant frequency.

To demonstrate the wide bandwidth of the proposed harvester using pole-zero cancellation, the output AC voltage is rectified to a DC voltage with the rectifying circuit. When vibration is on around 3 second, the open-circuit DC voltages with respect to different excitation frequencies are illustrated, as shown in Fig. 6. The measured DC voltages reach their steady-state values of 2.8 V at 17 Hz (resonant frequency), 2.2 V at 23 Hz, and 2.1 V at 22 Hz, respectively. These steady-state values as a function of the excitation frequencies are averaged by using 5 measured data, as shown in Fig. 7. The trend of the frequency response curves is nearly consistent with the multi-mode voltage frequency response functions (the phantom line in Fig. 5). The average power output capability of the proposed broadband harvesters can be measured using the following equation$^{(10)}$.

$$P_{avg} = \frac{C \cdot V^2}{2\Delta t} \tag{5}$$

where C is the capacitance (1 μF in this study), V_p is the peak-to-peak open-circuit voltage of the piezoelectric harvester, and Δt is the time interval required to reach the steady-state open-circuit voltage. The average output power is approximately estimated to be 13~15 μW over excitation frequency between 18 Hz and 24 Hz, which can suggest that the proposed PVEH using pole-zero cancellation possesses wide operating range.

5. Conclusion

This paper proposes new broadband PVEH based on the pole-zero cancellation technique to extend the operating frequency range. Pole-zero cancellation is successfully produced using a lever type anti-resonant configuration with the tuning mass. In comparison to the conventional cantilever beam-type harvesters, the proposed PVEH offers a simple but effective way to generate electric power over a wide range of frequencies (i. e., between the fundamental and second natural frequencies). The results suggest that the proposed harvester can potentially provide a simple means to overcome the limitation of conventional PVEHs (narrow operating range).

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