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Non-contact magnetic cantilever-type piezoelectric energy harvester for rotational mechanism

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ABSTRACT

In this work, a piezoelectric energy harvester excited by the magnetic force was proposed and developed for the rotational mechanism applications. The non-contact magnetic force was employed for exciting the piezoelectric cantilever vibration and avoiding power frictional loss. The different directions and configurations of magnetic force, attractive force and repulsive force, were designed and optimized for the piezoelectric energy harvesting system. The different exciting frequencies and duty ratios were carried out by the rotational mechanism for achieving the high power generation. When the exciting frequency approaches the natural frequency of piezoelectric cantilever beam and the duty ratio is larger, the highest power 1.23 mW was achieved by the alternate attractive and repulsive magnetic forces.

1. Introduction

Since the development of wireless sensors and low power devices, the portable and lasting energy source become an emerging and significant research topic. Various piezoelectric energy harvesters were developed by several vibrational energy sources such as heart [1], footstep [2], vehicle [3], and wind [4]. Considering the piezoelectric strain energy harvester and kinetic energy have attracted lots of concerns due to their advantages of compact size and power density. Most vibrating piezoelectric energy harvesting systems were designed and operated within a narrow bandwidth, resonant frequency region, for enhancing power generation efficiently. In order to achieve the portable miniature, microelectromechanical systems (MEMS) technology was employed for micro piezoelectric energy harvesting system [5]. However, most of these MEMS devices have a high natural frequency and this implies that it is difficult to operate in a near resonance state by outer environmental vibration. This limits the devices to obtain the maximum power generation efficiency from ambient vibration.

Researchers have proposed lots of strategies to realize broadband piezoelectric energy harvester for enhancing the energy efficiency, including tunable resonant frequency piezoelectric energy harvester [6], multi-impact energy harvester for low frequency excitation [7], bimorph cantilever system [8,9], and tunable bidirectional resonant frequency system [10]. Although, these strategies either increase the intricate design or reduce the energy density of a piezoelectric harvester, the provided nonlinear magnetic force has turn into a method for broadband energy harvester. The improved performance of piezoelectric energy harvester has been proved theoretically and experimentally [11–13].

The performance of the piezoelectric energy harvester depends on the exciting magnitude and frequency of the environmental vibration. The maximum generated power is obtained when the natural frequency of the harvester is matched with the exciting vibrational frequency. In this work, a piezoelectric energy harvester excited by non-contact magnetic force was presented and developed for rotational mechanism applications as shown in Fig. 1. The non-contact magnetic force was employed as the external exciting forces for reducing the power frictional loss. The different frequencies and duty ratios of the external magnetic impulse were measured and discussed. Besides, the magnetic force would widen the broadband of piezoelectric cantilever beam energy harvester. The different configurations of magnetic force were designed for optimizing the piezoelectric energy harvesting system.

2. Theoretic background

The piezoelectric energy harvester is composed of a piezoelectric cantilever beam and a magnet mass at the free end provided the exciting force. The harvested power was generated from the voltage difference of piezoelectric cantilever beam resulting from the strain of the piezoelectric cantilever beam. The larger strain and fast strain change

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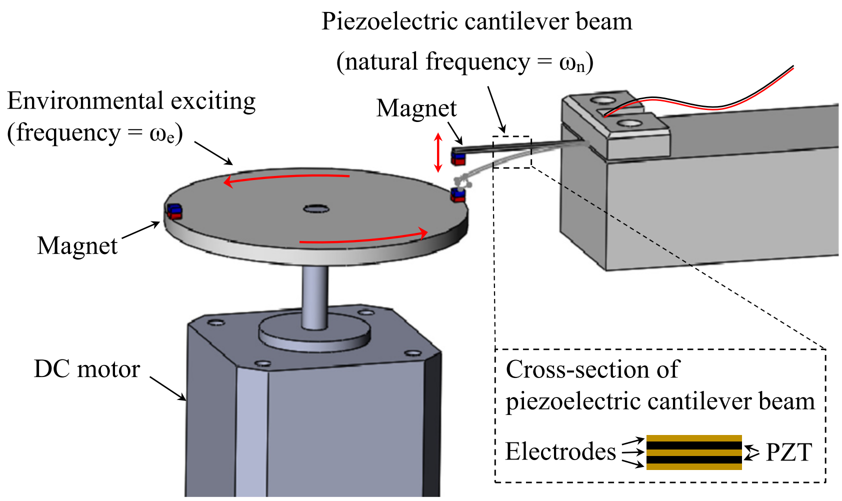

Fig. 1. Schematic of piezoelectric energy harvester excited by the non-contact magnetic force for the rotational mechanism applications.

rate will cause the larger voltage difference and power generation. Fig. 2 shows the setup of the piezoelectric cantilever beam model. The 1-DoF simple motion equation can be expressed as:

$$mx'' = F\delta\left(\frac{\omega_e t}{2\pi}\right) - cx' - kx \quad (1)$$

where x is the displacement of cantilever beam, m is the equivalent mass of the piezoelectric cantilever beam and the magnet, F is the magnetic force caused from the magnet, c is the damping coefficient, k is the equivalent spring constant, ω_e is the angular frequency of external magnetic force, and δ function is a step function represented the external magnetic force impulse.

In this energy harvesting system, the external force impulse is non-contact magnetic force (F_{mag}) depended on the distance of twos magnets. During the deflection of the piezoelectric beam, the magnetic force was changed rapidly. The magnetic force between any two cylindrical magnets can be expressed as [10]:

$$F_{mag}(d) = \left[\frac{B_r{}^2 A_m (l+r)^2}{\pi\mu_0 l^2}\right]\left[\frac{1}{d^2} + \frac{1}{(d+2l)^2} - \frac{2}{(d+l)^2}\right] \quad (2)$$

where B_r is the residual flux density of the magnet, A_m is the common area between the magnets, l is the length of the magnet, r is the radius of magnet, d is the distance between the magnets, and μ_0 is the permeability of the intervening medium. The magnetic forces were employed to tune the resonant frequency broadband of piezoelectric cantilever beam energy harvester. Besides, the magnetic force will change the damping ratio of the piezoelectric cantilever beam system. The motion equation can be rewritten as:

$$x'' + 2\xi\omega_n x' + \omega_n{}^2 x = \frac{F}{m}\delta\left(\frac{\omega_e t}{2\pi}\right) \quad (3)$$

where ξ is the damping ratio, ω_n is the harvester's natural angular frequency. In order to achieve the larger power generation, the displacement (x) and velocity (x') should be as larger as possible. If external exciting force frequency is close to the harvester's natural frequency, the system in the resonant motion has the larger power output. In this work, the magnetic force impulse was used as external exciting force. The impulse of external magnetic force results in piezoelectric cantilever beam vibration with its natural frequency for the larger power generation. Besides, the magnet on the free end of the piezoelectric cantilever beam was used to decrease the harvester's natural frequency. The natural frequency (f_n) of the piezoelectric cantilever beam with a magnet at free end is given by [12]:

$$f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m_m + m_p}} \quad (4)$$

where m_m is the magnet mass attached at the free end and m_p is the piezoelectric cantilever beam mass. The equivalent spring constant (k) is depended on the cantilever beam dimensions and elastic modulus.

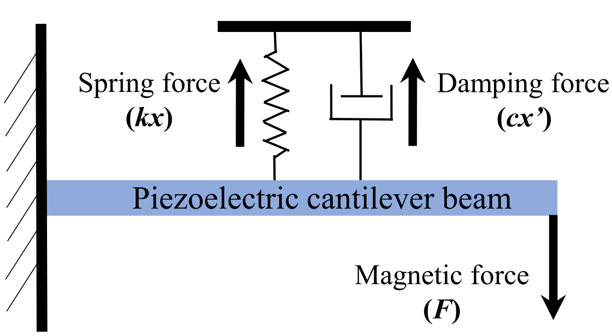

Fig. 2. Analytical model of the piezoelectric cantilever beam.

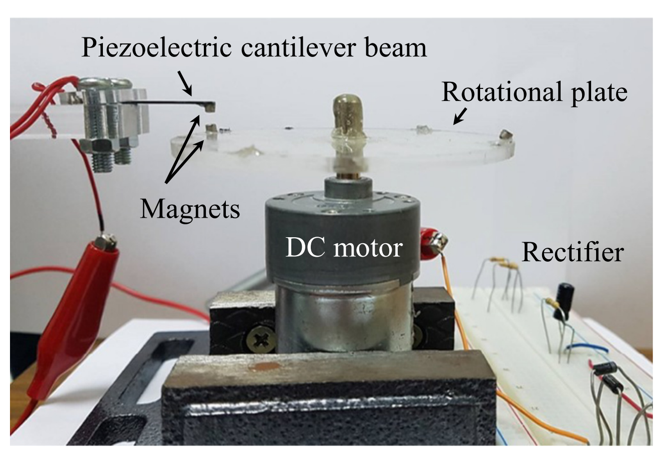

Fig. 3. The measurement setup of piezoelectric energy harvesting system.