AN OPTIMIZED MAGNETOELECTRIC POWER GENERATOR FOR ROTATION ENERGY HARVESTING

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Abstract: This paper presents a magnetoelectric (ME) transducer based rotation energy harvester with optimized magnetic circuit. The harvester is composed of a cantilever beam, a magnetostrictive/piezoelectric laminate ME transducer, a cylinder magnet and a circular magnet. The cylindrical magnet is fixed on the free end of the beam and also functions as the tip mass of the cantilever. The ME transducer is placed in the hole of the circular magnet, which can produce an optimized bias magnetic field through the transducer. When the harvester is attached to a host structure rotating around a horizon axis, the alternation of the gravity component causes the beam to vibrate along its transverse direction. During vibration, the cylinder magnet moves relative to the ME transducer, which causes an alternating field applied through the ME transducer, and electrical power is generated. A prototype is fabricated and tested. The experimental results indicate that, due to the optimized magnetic circuit, the ME voltage coefficient of the transducer is distinctly improved, and a maximum output voltage of 118V is achieved at the second-order super-harmonic resonance, with a rotating rate of 636rpm.

Keywords: rotation energy harvester, magnetoelectric transducer, optimized bias magnetic field

INTRODUCTION

Over resent years, wireless sensor systems are receiving increasing interest since they offer greater flexibility, increased reliability and reduced costs compared with a weird infrastructure. A reliable power supply for these systems is naturally a critical requirement, and the majority of sensor nodes are reliant on batteries to date. Though the advancement in low power VLSI design and CMOS fabrication has reduced the power consumption of wireless sensor nodes to the order of μW to mW, batteries will still wear out with time, which impose a maintenance burden of recharging or replacement if a long sensor lifetime is required. For this reason, solutions that convert ambient energies, such as light, thermal and/or kinetic energy, into usable electrical energy have attracted much attention from many researchers. Of the various energy types, kinetic energy is particularly attractive for its abundance.

Kinetic energy is typically converted into electrical energy using electrostatic, electromagnetic or piezoelectric transduction mechanisms [1]. Recently, ME transducers have been applied successfully in kinetic energy harvesting. Due to the high energy density and high magnetomechanical coupling coefficient of the magnetostrictive materials, generators employing ME transducers can produce higher mechanical stress and accordingly higher power output than conventional piezoelectric generators. For instance, Huang et al. presented a vibration energy harvester employing Terfenol-D/PZT/Terfenol-D laminate transducer [2]. The harvester can generate a power of 1.2mW under an acceleration of 0.5g at a frequency of 30Hz. Previously we have also presented a ME transducer based vibration energy harvester with four rectangular magnets, fixing the ME transducer in the air gap between the magnets [3]. However, the electrical output performances of the ME transducers are highly dependent on their ME voltage coefficients which is dramatically effected by the bias magnetic field, which has not been taken into account in the previous works mentioned above. For example, in our previous design, the equivalent bias magnetic field applied through the transducer is about 1460Oe which is too large for an optimum ME voltage coefficient.

The subject of this paper is a ME transducer based rotation energy with optimized magnetic circuit. In the proposed harvester, the transducer is placed in the central hole of a circular permanent magnet, which generates an optimized bias magnetic field through the ME transducer, and consequently the ME voltage coefficient is obviously improved.

HARVESTER DESIGN

The schematic of the proposed rotation energy harvester is shown in Fig.1. The harvester is composed of a ME transducer, a cantilever beam, a cylinder magnet and a circular magnet. The transducer is a laminate structure made up of two Terfenol-D layers and one PMNT layer. The piezoelectric layer is polarized in its thickness direction (Y-direction), while the magnetostrictive layers are magnetized along their longitudinal direction (Z-direction). The ME transducer is fixed in the central hole of the circular magnet with a duralumin anchor and placed on a bracket which is screw-mounted with the frame of the harvester. The cylinder magnet is arranged on the free end of the cantilever with a tungsten plate clamping the beam on the other side, together they function as the tip mass of the cantilever beam. As shown in Fig.1, the magnets are magnetized in their axial direction (Z-direction), and so there is magnetic force between the adjacent magnetic poles.

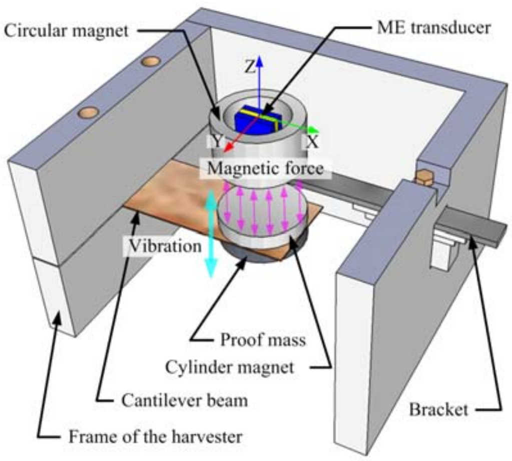

Fig.1:Schematic diagram of the proposed harvester.

ANALYTICAL MODEL

When the proposed rotation energy harvester is attached either off axis or on axis to a host structure rotating around a horizon axis, the harvester can be modeled as a hub-beam system that an elastic cantilever beam built in a rigid hub as shown in Fig.2. When the hub undergoes continuous rotation, the beam rotates along with the hub, and the tip mass causes the beam to vibrate along transverse direction (Z-direction) due to the alternation of the gravity component. The vibration of the cylinder magnet induces an alternating magnetic field applied on the transducer, which causes the ME transducer to generate electrical power. Previously, we have demonstrated that due to the coupling between the rigid motion of the hub and the elastic deflection of the beam, the equivalent stiffness of the cantilever tends to increase as the angular velocity grows, which is the so-called centrifugal stiffening effect. Here, due to the magnetic force between the magnets, there is an additional stiffness affecting the dynamic characteristics of the harvester, which is dependent on the mode of the magnetic force (i.e. repulsive or attractive mode).

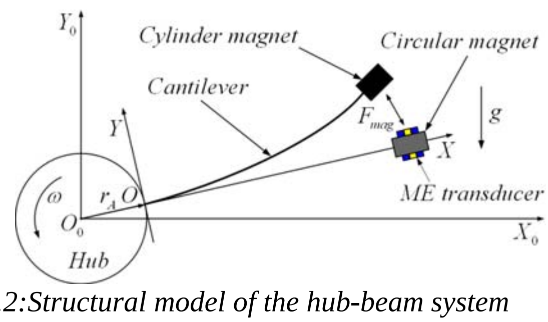

Fig.2:Structural model of the hub-beam system

FABRICATION

Fig.3 shows the photograph of the proposed energy harvester. The ME transducer is a sandwich of one PMNT layer ($12\times10\times1mm^3$) bonded between two Terfenol-D layers ($12\times10\times1mm^3$). The circular magnet is 10mm height, with an inner radius of 9mm and an outer radius of 10mm. The material of the bracket supported the ME transducer is duralumin which is hard enough to withstand the magnetic force, and so the ME transducer can keep static relative to the housing of the harvester during vibration. The cantilever is made up of beryllium bronze, and its length, width and thickness are 22mm, 16mm and 0.35mm, respectively. The cylinder magnet is 12mm height with a radius of 10mm. The total weight of the tip mass is 50g. In addition, the remnant flux density and relative permeability of the NdFeB magnets are 1.2T and 1.05, respectively.

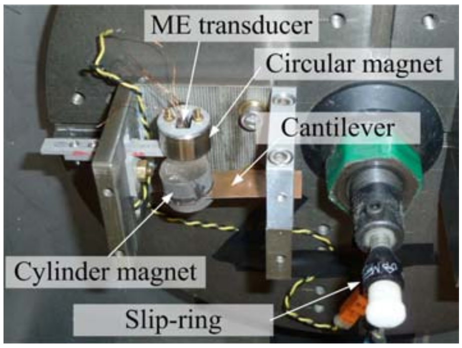

Fig. 3: Photograph of the proposed energy harvester

SIMULATION

In order to analyze the influences of the bias magnetic field on the ME voltage coefficient and accordingly the ME conversion output performances, the magnetic flux density, B, applied through the ME transducer must be determined, which is done by using the Ansoft's Maxwell 3D simulation software. Fig.4 illustrates the schematic diagram of the simulation model. The movement of the cylinder relative to the ME transducer is simulated by employing the 3D Field Simulator's transient solver.

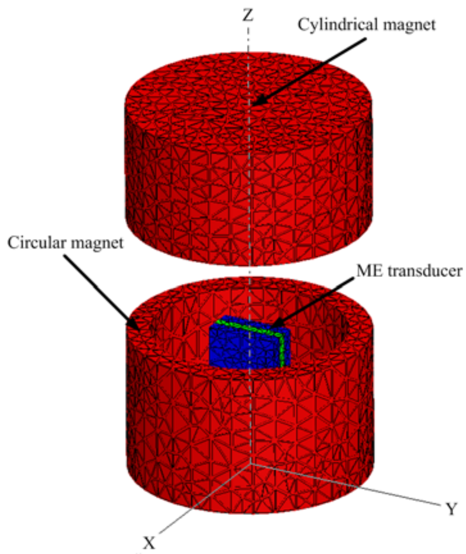

Fig. 4: Schematic diagram of the FEA simulation modal

Since the magnetized direction of the Terfenol-D layers is parallel to the z-axis, the magnetic field component along the z-axis direction causes much greater strain of the Terfenol-D layers than that parallel to the y-axis and x-axis direction do. Therefore, the induced magnetic flux density of the ME transducer B can be represented by the average magnetic flux density along the z-axis direction, and the influences of the magnetic field components along the y-axis and x-axis direction are ignored.

Fig.5 illustrates the FEA predictions of the magnitude and variation of B versus the separation between the magnets. When the magnetic force acts in the repulsive mode, the absolute value of the induced magnetic flux density of the ME transducer increase dramatically when the cylinder magnet moves towards the circular magnet, while the gradient of the B decrease rapidly as the separation increase.

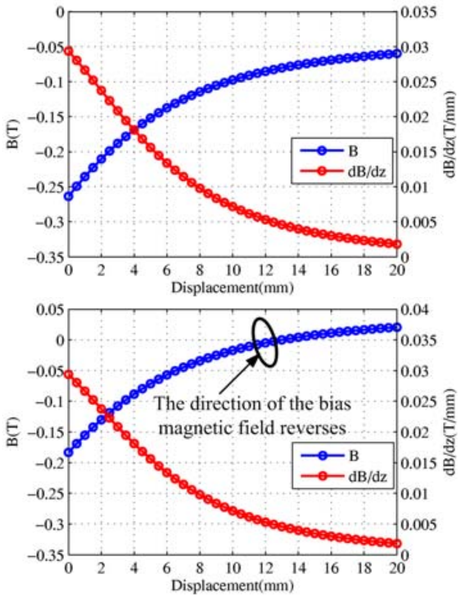

Fig. 5: Prediction of the magnitude and variation of B versus the separation between the magnets. Top: repulsive mode, bottom: attractive mode.

For the attractive mode case, since the magnetic fields generated by the two magnets are opposing to each other when being applied through the ME transducer, when the separation shifts from 20mm to 12mm, the absolute magnitude of B decrease slowly and achieves the minimum value finally. When the separation continues to decrease from 12mm to 0mm, the magnetic field generated by the cylinder magnet plays the major role, and consequently the absolute value of B increases rapidly.

EXPERIMENT

The experimental setup used for investigating the ME voltage coefficient is shown in Fig.6. The ME transducer is fixed at the central hole of the circular magnet, and together they are placed at the center of a long-straight solenoid which generates AC magnetic field. The cylinder magnet is fixed on the end of a aluminum pole, with one of the magnetic poles towards the circular magnet and the ME transducer, and so there is a bias magnetic field applied through the transducer in the longitudinal direction. The separation between the magnets is adjusted by using a translation stage. By applying the method presented in Ref.[4], the ME voltage coefficients under a given bias magnetic field at low frequency (2~100Hz) are measured.

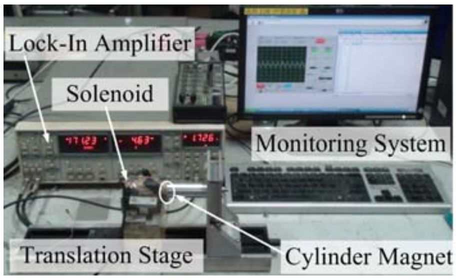

Fig.6: Experiment set-up for ME voltage coefficient

The experimental setup for the rotation energy harvesting is shown in Fig.7. The prototype is screw-mounted on a wheel which is driven by an AC servo-actuator. The wiring to the rotary assemble on the wheel is achieved using a slip-ring. The output voltage is measured and stored by a Tektronix TDS2022B digital storage oscilloscope.

Fig.7: Experiment set-up for rotation energy harvesting

RESULTS AND DISCUSSION

Fig.8 shows the measured ME voltage coefficients of the transducer versus frequency in the frequency range from 2Hz to 100Hz, with different separation between the magnets. For all the separation from 20mm to 2mm, regardless the mode of the magnetic force, the ME voltage coefficient first increases rapidly as the excitation frequency grows and then approximately acts as a constant α_V. For the repulsive mode case, the maximum value of α_V is 363.1mV/Oe. When the separation shifts from 20mm to 2mm, α_V decreases slowly and achieves a minimum value of 284.2mV/Oe, which is caused by the growing bias magnetic field. For the attractive mode case, when the separation shifts from 20mm to 11mm, α_V decrease rapidly as the equivalent bias magnetic field decrease. When the separation shifts from 11mm to 2mm, the direction of the effective bias magnetic field reverses, and α_V increases dramatically and finally achieves 350.4mV/Oe. In addition, the ME voltage coefficient of the transducer is also measured in our previous magnetic circuit, and the maximum value of α_V is 332.8 mV/Oe. It is clear that, due to the optimized magnetic circuit, α_V is improved.

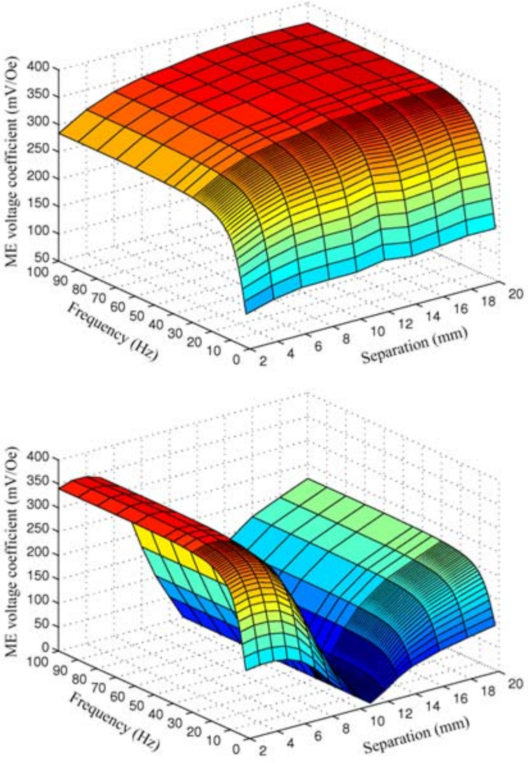

Fig.8: Measured ME voltage coefficient versus excitation frequency with different separation between the magnets. Top: repulsive mode, bottom: attractive mode.

Fig.9 illustrates the measured open-circuit output voltage versus rotation frequency with different initial separation between the magnets. For the repulsive mode case, the overall output voltage tends to be higher as the initial separation decrease, which is caused by the increasing gradient of B. However, due to the stiffening effect caused by the repulsive magnetic force, the vibration amplitude is small, and consequently the maximum output voltage in this case can only achieve 30V.

For the repulsive mode case, when the separation lies in the range from 11mm to 12mm, due to the poor ME voltage coefficient, the output voltage is low. When the separation shifts from 11mm to 8mm, due to the increasing α_V and gradient of B, the overall output voltage performance is improved. When the initial separation is 8mm, the maximum output voltage achieves 118V at the second-order super-harmonic resonance.

CONCLUSION

This paper presents a magnetoelectric transducer based rotation energy harvester with optimized magnetic circuit. The experimental results indicate that the proposed magnetic circuit can achieve large ME voltage coefficient and variation of the magnetic flux density at the same time, and the maximum output voltage is achieved at the second-order super-harmonic resonance, with proper initial separation between the magnets, when the magnetic force acts in the attractive mode.

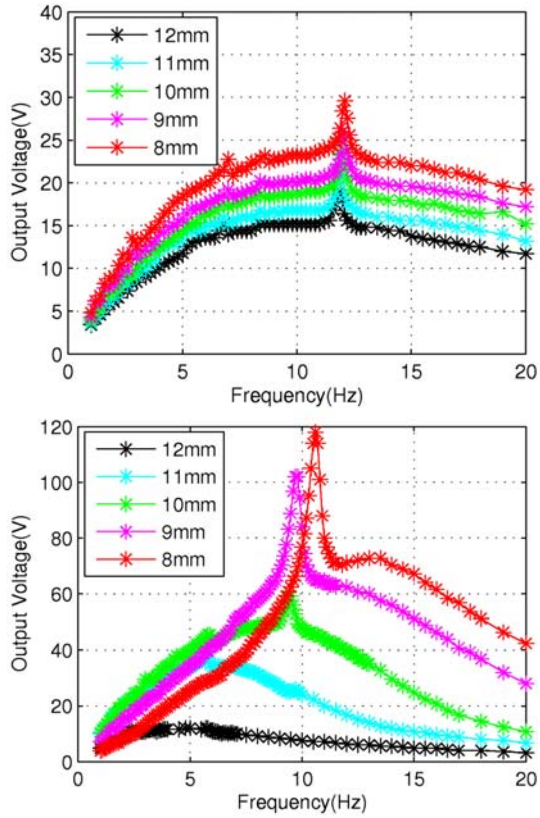

Fig.9: Open-circuit output voltage versus rotation frequency. Top: repulsive mode, bottom: attractive mode.

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