An Electromagnetic Energy Harvester Based on Pressure Fluctuation in Kármán Vortex Street

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Abstract: A new electromagnetic energy harvester based on pressure fluctuation in Kármán vortex street is developed. It converts flow energy into electrical energy by fluid flow, vortex shedding from a bluff body and electromagnetic induction. A prototype of the energy harvester is fabricated and tested. Experimental results show that an output peak-to-peak voltage of nearly 20 mV is generated when the excitation pressure oscillates with an amplitude of 0.3 kPa and a frequency of about 62 Hz. By detecting the voltage drop across a matched load, the instantaneous power is determined as 1.77 µW under a pressure fluctuation frequency of 62 Hz and a pressure amplitude of 0.3 kPa in the Kármán vortex street.

Keywords: Electromagnetic; Energy harvester; Kármán vortex street.

1. INTRODUCTION

Development of wireless sensor networks for industrial process monitoring and control demands an economical source of energy without supply of fuel and replacement of finite power sources. By harvesting energy from the environment, miniature sensing/actuating devices can be self-powered in order to avoid the replacement of finite power sources. Sources of energy harvesting can be flowing water, rain, tides, wind, sunlight, and geothermal heat.

Our design of the electromagnetic energy harvester is based on the vibration induced by vortex shedding from a bluff body. The variation of the liquid pressure in the channel drives a polydimethylsiloxane (PDMS) flexible diaphragm with an attached permanent magnet into vibration. The vibration energy is converted to electrical energy by the Faraday’s law of induction. An electromagnetic energy harvester is shown in Fig. 2(a). Fig. 2(b) is an exploded view of the energy harvester. It consists of a flow channel with a trapezoidal bluff body placed at the center of the channel, a PDMS diaphragm bonded to the channel, and a permanent magnet glued to an acrylic bulge on top of the PDMS diaphragm. The permanent magnet is placed under a conducting coil.

Fig. 1. Operation of an electromagnetic energy harvester.

One approach to harvest energy is to convert mechanical energy of ambient vibration into electrical energy by electromagnetic induction [1-3]. We develop a new electromagnetic-energy-harvesting device based on vibration induced by Kármán vortex street. As illustrated in Fig. 1(a), a flow channel with a flexible diaphragm is connected to a flow source. A permanent magnet is glued to a bulge on top of the diaphragm and a coil is placed above the magnet. The pressure fluctuation due to vortex shedding from a bluff body drives the diaphragm into vibration. As shown in Fig. 1(b), the increase of the pressure causes the diaphragm to deflect in the upward direction. As the pressure increases to the maximum, the diaphragm reaches its highest position (see Fig. 1(c)). When the pressure drops, the diaphragm moves downward (see Fig. 1(d)). As the pressure decreases to the minimum, the diaphragm reaches its lowest position (see Fig. 1(e)). Thus, by connecting the energy harvester to a flow source, the oscillating movement of the diaphragm with an attached magnet under a coil makes the energy harvesting possible. The focus of this paper is on the investigation of energy extraction from magnet vibration induced by vortex shedding from a bluff body in a fluid flow. Fabrication of the energy harvester is described. Experimental setup to measure the pressure, displacement and output voltage of the device is reported. The experimental results are compared with the results of the analyses.

2. DESIGN

Our design of the electromagnetic energy harvester is based on the vibration induced by vortex shedding from a bluff body. The variation of the liquid pressure in the channel drives a polydimethylsiloxane (PDMS) flexible diaphragm with an attached permanent magnet into vibration. The vibration energy is converted to electrical energy by the Faraday’s law of induction. An electromagnetic energy harvester is shown in Fig. 2(a). Fig. 2(b) is an exploded view of the energy harvester. It consists of a flow channel with a trapezoidal bluff body placed at the center of the channel, a PDMS diaphragm bonded to the channel, and a permanent magnet glued to an acrylic bulge on top of the PDMS diaphragm. The permanent magnet is placed under a conducting coil.
which is guided around an inner housing. The inner housing of the coil is fixed by an outer housing.

Subsequently, an acrylic bulge is glued to the center of the PDMS diaphragm, and a magnet is glued to the top surface of the bulge. Finally, the inner housing with the coil wrapped around its exterior surface is placed inside the outer housing, which is then glued to the top surface of the acrylic blocks to complete the assembly steps. The distance between the top surface of the magnet and the bottom of the coil is 1 mm. Fig. 3 is a photo of an assembled energy harvester.

![Fig. 3. Assembled energy harvester.](image)

Fig. 2. (a) An assembled energy harvester. (b) Components of the energy harvester.

This harvesting of flow energy via the formation of Kármán vortex street behind a bluff body is related to the response of a flexible diaphragm to a periodical pressure variation of water in a flow channel. Flow past a bluff body creates an unstable wake in the form of alternating vortices and induces the periodic pressure variation [4]. The frequency at which the vortices are shed from the bluff body is given by the Strouhal number, St

\[
\text{St} = \frac{f H_1}{U_\infty}
\]

where \( f \) is the frequency of oscillating flow, \( H_1 \) is the height of the front side of the trapezoidal cylinder, and \( U_\infty \) is the free-stream velocity.

### 3. FABRICATION AND EXPERIMENTS

#### 3.1. Fabrication

In order to verify the effectiveness of the proposed energy harvesting device, prototypes of the energy harvester are fabricated. The PDMS diaphragm is fabricated by a molding process in an acrylic mold. The walls, the top plate and the bottom plate of the flow channel are manufactured by a milling machine. First, the walls are glued to the bottom plate. Next, a trapezoidal bluff body is affixed to the walls. Then, the top plate of the flow channel with an embedded PDMS diaphragm is attached to the top surface of the walls.

![Fig. 4. A photo of the experimental setup.](image)

Fig. 4 is a photo of the experimental apparatus for testing of the fabricated device. The energy harvester is placed on an optical table for vibration isolation. From the bottom of a storage tank, an inlet pipe is run down to the inlet of the energy harvester. The water level in the storage tank is kept constant for a steady water flow at the inlet of the flow channel. Using gravity, water is forced into the inlet of the energy harvester. Tap water is pumped into the storage tank through a pump located in a recycle tank. An outlet pipe extending between the outlet of the energy harvester and the recycle tank provides a continuous supply of water.
Fig. 5 is a schematic of the measurement apparatus. The oscillating displacement of the magnet is measured by a fiber optic displacement sensor (MTI-2000, MTI Instruments Inc., US). The voltage induced by the coil is recorded and analyzed by a data acquisition unit (PCI-5114, National Instruments Co., US). The pressure in the flow channel is measured with a subminiature pressure sensor (PS-05KC, Kyowa Electronic Instruments Co. Ltd., Japan) embedded in the bottom plate of the flow channel, nearly 9 mm behind the bluff body and opposite to the flexible diaphragm. The pressure sensor is connected to a data acquisition unit (DBU-120A, Kyowa Electronic Instruments Co. Ltd., Japan).

The measured displacement history of the magnet is shown in Fig. 6(b). The measured open circuit voltage induced by the coil is shown in Fig. 6(c). The output peak-to-peak voltage is nearly 20 mV. The time history of the experimental results are considered typical of the measurements in a duration of 20 seconds. Figs. 6(d-f) are the power spectral density corresponding to Figs. 6(a-c), respectively, but are based on series of the measurements in the duration of 20 seconds. Fast Fourier transform is used to compute the power spectral density. It can be seen from Figs. 6(d-f) that there is one obvious peak value of 62 Hz. It is evident that the same peak values shown in Figs. 6(d-f) are caused by the pressure fluctuation in the flow channel. The low frequency noise, below 30 Hz, observed in Figs. 6(d-f) can be attributed to the fact that the flows of the experimental setup are always contaminated by ambient noise sources, and the geometry of the bluff body and the walls of the flow channel are not perfectly symmetric and smooth.

In order to evaluate the harvesting system, experiments on the electrical power output of the device are performed. A matched load can be connected to the device to maximize output power. The internal electrical resistance of the device is measured by a LCR meter (WK 4235, Wayne Kerr Electronics, Ltd., UK). The instantaneous power can be expressed as

\[ P = \frac{(\sqrt{2}V)^2}{R} \]

where \( R \) is the resistance value of the matched load and \( V \) is the root-mean-square value of the voltage drop across the matched load. By connecting the matched load of 38 \( \Omega \) to the device and detecting the voltage drop across the matched load, 5.8 mV rms, the instantaneous power is determined as 1.77 \( \mu W \). The output power of the device is relatively low, given the structure design of the flow channel, the bluff body, the diaphragm, the magnet and the coil. In order to obtain a higher output power of the energy harvester, the dimensions and structure of the device can be optimized.
5. CONCLUSIONS

An electromagnetic energy harvester based on flow induced vibration is developed. The energy is harvested from Kármán vortex street behind a bluff body in a water flow. The pressure oscillation due to the Kármán vortex street in the flow channel of the harvester results in a periodical displacement of the magnet placed under a coil and therefore the voltage generation. Prototypes of the energy harvester are fabricated and tested. The generated voltage and instantaneous power of the device are approximately 20 mVpp and 1.77 μW, respectively, when the pressure oscillates with an amplitude of nearly 0.3 kPa and a frequency of about 62 Hz.

Sources of pressure fluctuation of Kármán vortex street can be geophysical flows (ocean or river currents), blood flow in arteries, air flow in tire cavities, or fluid flow in machinery. The periodic vortex shedding behind a bluff body immersed in a steady stream causes a pressure oscillation in the stream. The energy harvesting from fluid flow in machines through pressure fluctuation in Kármán vortex street can power monitoring systems of machines. This approach could also be used for self-powering implantable and wireless devices in human bodies by converting the hydraulic energy of blood flow or flow of body fluid into electricity.

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