Mechatronics 49 (2018) 36–45

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Development and modeling of an electromagnetic energy harvester from pressure fluctuations☆

Hongliang Ren[a], Tao Wang[b,*]

[a] Department of Biomedical Engineering, National University of Singapore, Singapore 117575, Singapore
[b] Ocean College, Zhejiang University, Zhoushan 316000, China

ARTICLE INFO

Keywords:
Dynamic model
Electrical generation
Energy harvesting
Pressure fluctuation
Magnetic spring structure

ABSTRACT

This paper develops a miniature electromagnetic energy harvester, which can absorb gas pressure fluctuations in industrial piping or natural environment and then supply energy to electronic devices. The fabricated prototype mainly consists of a hermetic cylindrical housing with a gas inlet, a movable magnet suspended by a magnetic spring structure, and two fixed coils. The movable magnet in the middle of the housing is utilized as a piston on which the gas pressure directly acts. Taking mechanical, electromagnetic and fluidic dynamics into account, a mathematical model of the energy harvester is developed and simulated by combining finite element method and analytical equations. Experiments under various operating conditions are implemented to verify the model and evaluate the prototype's performance. The induced peak-to-peak voltage and output power are 2.41 V and 2.01 mW when the input peak-to-peak pressure and fluctuated frequency are 81.4 kPa and 20 Hz. The power density and normalized power density of the non-optimized prototype can reach 145.08 W m^{-3} and 0.0219 W m^{-3} kPa^{-2} respectively, which are comparable to existing harvesters for similar applications.

1. Introduction

Energy harvesting is an attractive technique for kinds of self-powered electronics and mechatronic systems. In recent years, the research reports on energy harvesting have kept increasing and the state of the art has been well introduced in [1] and [2]. Energy harvesters usually employ a transduction mechanism such as piezoelectric or electromagnetic type to convert ambient energy into expected electrical energy. For those typical applications such as monitoring devices [3], wireless network sensors and nodes [4], wearable robotics [5], as well as biomedical implants [6], being battery free always becomes one of their strong requirements.

Fluidic kinetic energy including both gas flow and liquid flow is one of the remarkable harvesting sources since they can be easily found in natural environment, industrial piping, and even human body. For steady flow, turbine generation is the most mature approach of energy harvesting [7]. Tan et al. presented a small-scale wind turbine generator to harvest wind energy for powering the remote sensor nodes of wildfire prediction [3]. Kim et al. developed a turbine-based electromagnetic energy harvester which could generate power at milliwatt level by using the blood flow from a cardiovascular system to drive an implanted medical device [6]. Tesla disc turbines are also employed in fluidic energy harvesting for their advantages of bladeless, easy manufacture and low noise [8,9]. Instead of turbine generation, another approach is to make the flow self-excited based on physical principles such as vortex [10,11], flutter [12,13], resonance [14], etc. and then harvest the flow-induced vibration energy with integrated transduction mechanisms.

Some situations are also existing where inherent pressure fluctuations are made as considerable sources for energy harvesting. Skow et al. designed and modeled an energy harvesting device by using piezoelectric stacks to generate low-power electricity from pressure fluctuation in hydraulic driven systems [15,16]. The similar pressure fluctuation can also be found in pneumatic driven systems with pulse width modulation (PWM) control or repetitive motion [17,18]. Ye et al. investigated the feasibility of energy harvesting in water distribution systems and the results showed that the generated power from water pressure fluctuation can reach milliwatt level [19]. Several groups reported analytical models and experimental validation about energy harvesting from pulsated blood pressure by using piezoelectric circular diaphragms [20–22]. Wang et al. studied both of piezoelectric and electromagnetic energy harvesters for water pressure fluctuation and the corresponding electrical power was at microwatt level [23,24].

It is noticed that the majority of the aforementioned energy

☆ This paper was recommended for publication by Associate Editor. M. Tavakoli.

* Corresponding author.
E-mail address: twang001@zju.edu.cn (T. Wang).

https://doi.org/10.1016/j.mechatronics.2017.11.008
Received 22 January 2017; Received in revised form 24 October 2017; Accepted 14 November 2017

harvesters for fluidic pressure fluctuation are piezoelectric type. In general, both of piezoelectric and electromagnetic types own their advantages but also have the limitations. The piezoelectric energy harvesters are easy to fabricate and integrate with microelectronic circuits, while they tend to have low output-current level and limited lifetimes [2,25]. The harvesters in [14] and [23] are electromagnetic type, but their output voltage and power density were relatively low. The main reason is that deformable diaphragms are utilized to absorb pressure fluctuation and make the attached magnets oscillatory, which results in limited magnet movements.

This paper proposes a novel scheme of electromagnetic energy harvesting for gas pressure fluctuation. It directly utilizes a movable piston-type magnet suspended by a magnetic spring structure to absorb pressure fluctuation. Taking mechanical, electromagnetic and fluidic dynamics into account, a mathematical model of the energy harvester is developed and simulated by combining finite element method and analytical equations. Experiments under various operating conditions are implemented to verify the dynamic model and evaluate the prototype's performance.

The rest of the paper is organized as follows. Prototyping and modeling are presented in Section 2. Results and discussion are presented in Section 3, and conclusions are drawn in Section 4.

2. Prototyping and modeling

2.1. Harvester structure

Fig. 1 shows the schematic of the proposed electromagnetic energy harvester for gas pressure fluctuation. It can be seen that the energy harvester mainly consists of a cylindrical housing, a movable magnet, two fixed magnets and two fixed coils. The housing is totally hermetic except for a gas inlet which is connected with the pipe or chamber where fluctuated flow exists. The movable magnet in the middle of the housing is used as a piston on which the gas pressure directly acts. On the one hand, a clearance between the housing and the movable magnet is required to make the magnet move freely. On the other hand, the clearance should be small enough so as to reduce leakage flow. The energy harvester employs a magnetic spring which has been exploited in vibration energy harvesting due to its extended lifetime in comparison with a physical spring [26]. The magnetic spring effect on the movable magnet is created by the two fixed magnets which locate at the top and bottom ends of the housing. The movable magnet has opposite magnetization direction with the fixed magnets so that it can be suspended by repulsive forces. The two fixed coils are arranged at the edge positions of the movable magnet to induce high electromotive force.

When gas pressure fluctuation is applied to the device, the movable magnet will start to oscillate because of the combined effect of magnetic repulsion and gas pressure. Moreover, the gas pressure in the inner chamber formed by the movable magnet and the housing will vary in operation and have an additional reaction on system dynamics. According to electromagnetic theory, the changing magnetic flux through the coils induces electromotive force as well as current when the coils are connected to electrical loads. In addition, the concept can be applied in a hydraulic system when a flexible seal such as bellow type is set between the movable magnet and the housing.

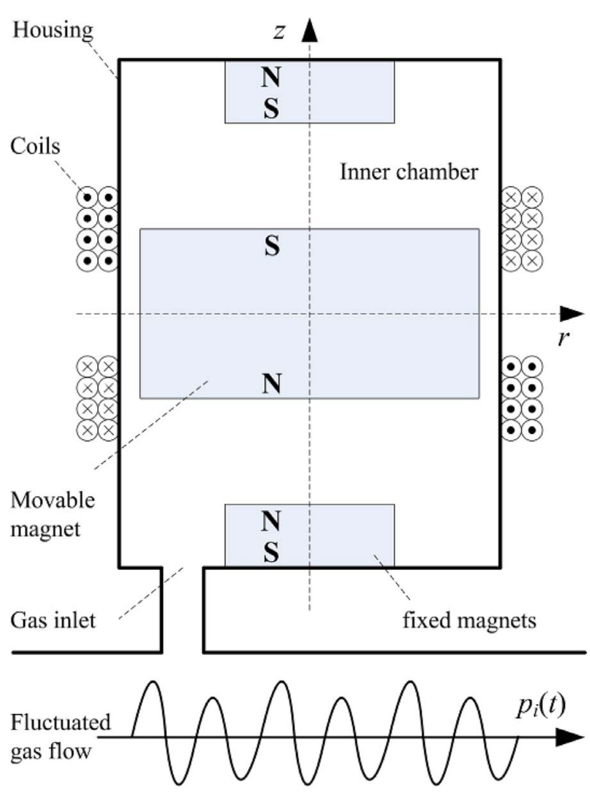

Fig. 1. Schematic of electromagnetic energy harvesting for fluctuated gas flow.

2.2. Prototype fabrication

A prototype of the energy harvester is fabricated as shown in Fig. 2. The prototype is nonoptimized and its dimensions are roughly estimated based on the expected output power and the reported power density in references such as [26] and [27]. The movable and the fixed cylindrical magnets adopt the material of sintered NdFeB and have the dimensions of ⌀15 mm × 10 mm and ⌀5 mm × 3 mm, respectively. The two coils have opposite winding directions and connect in series. The coils are wound uniformly by using copper wire with diameter of 0.1 mm and have 600 turns in total. The inner diameter, outer diameter and height of the coils are 18 mm, 21 mm and 5 mm, respectively. The housing is fabricated by 3d printing with the material of photopolymer resin. The outer dimensions of the housing are ⌀21 mm × 40 mm. There is a clearance of approximate 0.1 mm between the housing and the movable magnet. Some parameters of the harvester relevant with modeling in the following subsection are summarized in Table 1.

2.3. System model

Dynamic mathematical modeling is implemented to analyze the

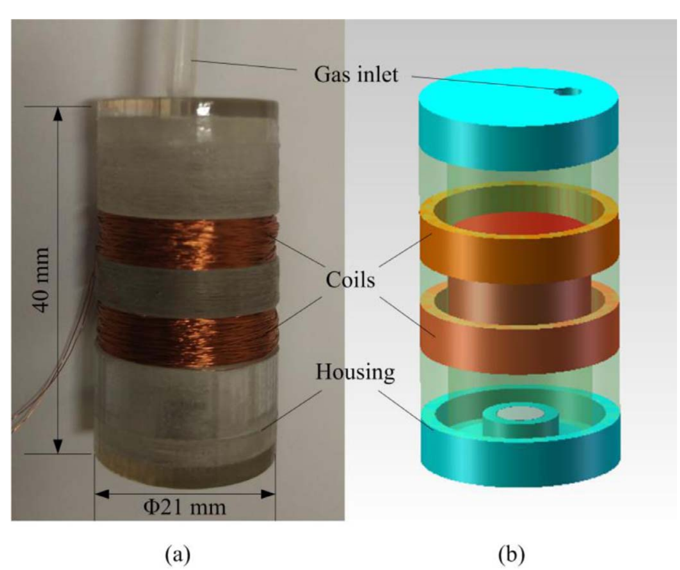

Fig. 2. Fabricated energy harvester. (a) Prototype picture. (b) 3d representation.