Electromagnetic Micro-power Generator for Energy Harvesting from Respiration

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Abstract—An electromagnetic energy harvesting mechanism is presented to convert the breath pressure into the electrical voltage. The generated power has application in providing energy for portable or wearable electrical devices. Changes in the breath pressure have been measured during normal respiration, and the proposed electromagnetic system has been simulated to find the best configuration of components. Also, a prototype has been built and tested. The experimental results will show that more than 3 µW can be harvested by using this generator.

I. INTRODUCTION

Energy harvesting from human body has a long history, however recent advances in extremely low-power potable or wearable electronic devices make human body power more interesting to supply their demanded power. Batteries as traditional source of electrical power have many disadvantages. They limit the space and mass of the system, must be replaced or recharged frequently, impose financial burdens on consumers, and most importantly have severe environmental impacts. Human body as a rich source of energy is a great alternative for batteries. Several methods have been reported in literature to harvest energy from human activities.

One of the first and well established human-powered mechanism is the auto-winding system built for mechanical or automatic watches that harvests energy from swinging arm [1]. Walking is another human activity that has even more associated energy. For example, considerable amount of power is available from heel strikes during brisk walk. Piezoelectric materials have been already employed in shoes in order to harvest energy from human walking activity [2]. This energy can also be harvested by mounting a mechanism at the knee and converting the kinematic motion of the knee through a generator [3]. This knee-mounted energy harvester is claimed to produce an average of 5 W of electricity, which is about 10 times that of shoe-mounted devices. The generation of power during human walking is not limited to shoe-mounted or knee-mounted generators. A suspended-load backpack which generates electricity from the vertical movement of carried loads during normal walking can generate up to 7.4 W [4]. In addition, a flexible human energy harvesting generator based on the Liquid Metal Magnetohydrodynamics Generator (LMMG) has been proposed and fabricated in [5]. Moreover, a thermoelectric generator that extracts energy from human tissue warmth has been developed for hearing prosthesis [6]. Electromagnetic induction as one of the most important method of generating electrical power, has been adopted to harvest energy from human activities too. For instance, a shoe-mounted rotary magnetic generator has been reported in [7], [8]. Also, a small spring magnet in a coil, oscillating with human body motion, is able to supply 2.5 mW of power [9].

Human breathing action can also be considered for energy recovery. During inspiration and expiration, the air flows in and out of respiratory system due to the pressure difference between lungs and the ambient air. The maximum breath pressure can reach to 2 % above the atmospheric pressure which corresponds to 1 W of power [10]. Some attempts have been done to tap this source of power. A PVDF microbelt for harvesting energy from respiration has been fabricated and tested in [11] with the output power in the range of nW−µW. Also, reference [12] has created a concept mask that converts wind energy provided by the wearer’s breath into electricity through the wind turbines.

The main advantage of the breath pressure as a source of power is its continuous presence even during sleep. However harnessing energy from breathing involves several disadvantageous. Increasing the effort to inhale or exhale the breath may ruin the user’s convenience. Additionally, most of breathing-based generators need breath masks that encumber the user. However, for some professionals such as military aircraft pilots, astronauts, or handlers of hazardous materials, such masks are already in place and for some others such as soldiers, mine workers or people who usually wear anti-pollutant masks may be of interest if the mask can be used as a source of power too.

In this paper an energy harvesting mechanism is proposed that is capable of producing energy from normal breathing. It is based on the electromagnetic induction due to relative movement of a circuit and a suspended magnet. Section II explains how this electromagnetic micro-power generator works. System modeling and optimization will be presented in section III. Section IV illustrates the experimental setup and discusses the results, and is followed by conclusion in section V.

II. ELECTROMAGNETIC POWER GENERATOR

The schematic representation of the electromagnetic mechanism is shown in Fig. 1. It is composed of a breath mask,
Fig. 1. Proposed system connecting tubes and energy harvesting module. The energy harvesting module is placed along the tube and consists of two fixed magnets out of the tube whose opposite poles are facing each other. Also, there is a free magnet inside the tube placed between the fixed magnets in such a way that it remains suspended due to the repulsive forces of them as shown in Fig. 2.

By flowing the air inside the tube, the free magnet starts moving. Therefore, it can induce a voltage on a coil wrapped around the outside of the tube. In fact, fixed magnets form a spring-like structure acting on the moving magnet, and the breath pressure applies an external force to move it. Displacements of the moving magnet change the magnetic field around the coil and induce voltage on it.

III. SYSTEM MODELING AND OPTIMIZATION

A. Modeling

According to Faraday’s law of induction, the induced voltage in a closed circuit is proportional to the time rate of change of the magnetic flux and can be calculated by,

\[ U = -N \frac{d\phi}{dt} \]  

whereby \( U \) is the induced voltage, \( N \) is the number of turns in the coil, \( \phi \) is the magnetic flux, and the negative sign demonstrates the harmony with Lorentz’s law. In the developed electromagnetic system, the free magnet moves along the \( x \)-axis and creates a time varying magnetic field at the coil position. Therefore, the rate of the change in the magnetic flux can be written in terms of the magnetic flux gradient \( (d\phi/dx) \) multiplied by the velocity of the magnet \( (dx/dt) \) \[9\].

\[ \frac{d\phi}{dt} = \frac{d\phi}{dx} \frac{dx}{dt} \]  

in which the position and velocity of the moving magnet is calculated by solving the following equation of motion.

\[ m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + F_m(x) = F_{in} \]  

where \( m \) is the mass of the magnet and \( c \) is the damping ratio. Also \( F_m \) and \( F_{in} \) are magnetic forces and input forces of breathing respectively. It should be notified that the induced voltage is measured in open-circuit setup, thus the current of the coil is considered to be negligible and consequently the corresponding electromagnetic force on the moving magnet is zero.

The breath gage pressure is measured using a differential pressure gage and is shown in Fig. 3 for three cycles of normal breathing. The positive values indicate expiration phase, while the negative values signify inspiration part.

Fig. 2. Structure of the electromagnetic energy harvesting mechanism

Fig. 3. Breath pressure

It is assumed that the magnet moves due to the pressure difference at its both sides. One side is connected to the breath pressure and another one is open to the free atmosphere. Consequently, the total force is obtained by

\[ F_{in} = \Delta PA \]
in which \( \Delta P \) is the breath pressure with respect to the atmospheric pressure as shown in Fig. 3 and \( A \) is the magnet cross section area. Now, Eq. 3 can be numerically solved by integrating and features to simultaneously solve the differential equation of motion and calculate magnetic fields and forces. The Simulink diagram of the system is illustrated in Fig. 4.

It solves Eq. 3 to find the position and velocity of the moving magnet. In this diagram, the module of "Magnetic Forces & Fields" takes the moving magnet position as an input and uses Comsol software to generate two output signals: \( F_m \) and \( d\phi/dx \). The first gives the total forces acting on the moving magnet according to the 3-magnet model configuration shown in Fig. 2 and the latter is the average of the magnetic flux at the coil considering its relative position to the moving magnet. The final output of the Simulink model is the induced voltage, \( U \), obtained by substituting Eq. 2 into Eq. 1.

### B. Optimization

Optimization is carried out to find the best distance between the given fixed magnets in order to achieve the maximum output voltage while other parameters are supposed to be fixed. The short distance between the fixed magnets, increases the magnetic forces and limits the moving magnet velocity while their long distances increase the range traveled by the moving magnets and take it far away from the coil position. Both situations decrease the output voltage. Therefore, there should be a particular distance between the fixed magnets that maximizes the induced voltage. To find this optimum value, the developed model is used to calculate the voltage versus the distance between the fixed magnets. The result is illustrated in Fig. 5 for the system whose parameters are presented in Table I.

Fig. 5 indicates that the best performance is obtained when the distance between two magnets is fixed around 40 mm. Also the maximum voltage would be 20 mV for this configuration.

### IV. Experimental Setup

#### A. Prototype

The prototype of the energy harvesting mechanism, based on the parameters presented in Table I was fabricated. The experimental setup includes the breath mask, energy harvesting module, tubes, an oscilloscope to monitor the induced voltage and a differential pressure transducer to measure the breath pressure. The experimental setup is demonstrated in Fig. 6(a). The breath mask is worn in such a way that tightly fit the area around the mouth and nose in order to minimize the air leak. Tubes transfer the air of breathing to the electromagnetic energy harvesting module as well as the pressure sensor. Since inhaling and exhaling of the air is done through the tube opening, most of the air flow passes the energy harvesting module and makes the suspended magnet move.

The generated voltage of the prototype and the output voltage of the simulation results are represented in Fig. 6(b). For both cases, the input breath pressure is exactly the same as shown in Fig. 3.
B. Results & Discussion

According to Fig. 6(b) simulation results are shown to be in close agreement with experimental measurements, however there are little differences in the amplitude of voltage peaks and the time at which they happen. For instance, the maximum voltage amplitude is $25 \text{ mV}$ for the experiment, while it is $20 \text{ mV}$ for simulation results. The following reasons are given for the observed differences.

- **Pressure:** There is a difference between the pressure at the position of the magnet and the pressure measured by the sensor due to the pressure gradient in the tube. Moreover, the gap between the moving magnet and tube wall creates a pressure distribution that makes the input force beyond the simple estimation presented by Eq. 4.

- **Energy Loss:** The approximate value of the viscous damping in Eq. 3 is another source of error. In addition there is an intermittent dry friction between the magnet and tube wall that has not been considered in the modeling.

In spite of the mentioned errors and limitations, the simulated model is quite successful in predicting the general behavior of the proposed electromagnetic energy harvesting mechanism as depicted in Fig. 6(b). The maximum generated power can be calculated by

$$W_{\text{max}} = \frac{V_{\text{max}}^2}{R}$$

where $R$ is the resistance of the coil and $V_{\text{max}}$ is the maximum generated voltage. Using this equation, the maximum generated power would be $3.1 \mu\text{W}$.

V. Conclusion

A magnetic-spring electromagnetic generator was developed in this paper to harvest energy from human respiration. The advantages of the proposed system are simplicity, reliability, and capability to work in off-resonance condition. The modeling of the system pointed out that the maximum energy recovery can be achieved when the distance between the fixed magnets is $40 \text{ mm}$ considering the normal breath cycle. The experimental results indicate that the maximum induced voltage of the prototype generator is $25 \text{ mV}$ which is equivalent to $3.1 \mu\text{W}$ of power, and is in a good agreement with simulation results. However, more power can be generated if the properties of the coil and the geometries of the magnets are also optimized.

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