

MICRO FLUIDIC ENERGY HARVESTING SYSTEM FOR HIGH FORCE AND LARGE DEFLECTION ACCOMMODATION

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Abstract: We report the development of a micro energy harvesting system that accepts high pressure inputs $>200\text{kPa}$ and sustains large deflection $>5\text{mm}$ and produces high electrical power, by utilizing microfluidic structures to disperse and accommodate such input ranges within fragile micro-scale devices. The system is comprised of two deformable chambers filled with fluid, and interconnected by multiple channels, which have permanent magnets and coils incorporated into their structures. When large-scale external force is applied, the proposed device hydraulically amplifies the energy into high speed fluid flow through multiple hydraulic micro channels in any desired direction, size, and locations, for robust power conversion. The generated flows move a train of magnets and electromagnetically produce electrical power. The successfully fabricated energy harvesting device produced electrical power of $268.96\mu\text{W}$, a power density of $1.18\text{mW}/\text{cm}^3$, by accepting an input pressure of $>200\text{kPa}$ and displacement of $>5\text{mm}$, while keeping the active device size of 227.75mm^3 .

Keywords: Energy harvesting, microfluidics, electromagnetics, MEMS, high pressure, high deflection, energy scavenging.

INTRODUCTION

Micro-scale energy harvesting has attracted a great deal of interest as it can potentially eliminate the need for batteries, their periodic replacement, and complex interconnections, thus making a system more compact, feasible and independent. However, previously developed micro energy harvesting devices [1-5] have produced only limited electrical power, which is insufficient to independently support typical electronic systems as of yet. One of the primary reasons is the focus on relatively weak and mild environmental sources due to the limited range of inputs (force and deflection) that a micro device can accommodate [2-4]. A few exceptions were reported [6,7], but have utilized rather large-sized devices that are not ideal for hand-held compact systems. Fundamentally micro-scale devices have limited input ranges due to their small mechanical structures and fragility. Thus, it would be desirable if a micro scale device could still accommodate and utilize such large-scale inputs while maintaining its advantageous small size.

In order to address this issue we present a micro hydraulic system that can be utilized to accommodate high force and large deflection into micro-domain for more efficient conversion. For this purpose the presented device has incorporated fluid dynamics by converting the applied forces into fluidic pressures to induce substantial emf (electromotive force) voltage in the coils. In addition, the device is designed such that phase matching between coils is utilized to amplify the power output.

In this paper we report the preliminary design, fabrication, testing, and optimization results of a hydraulic based micro energy harvesting device that enables the use of large mechanical input with micro-scale structures to produce electrical power.

SYSTEM DESIGN

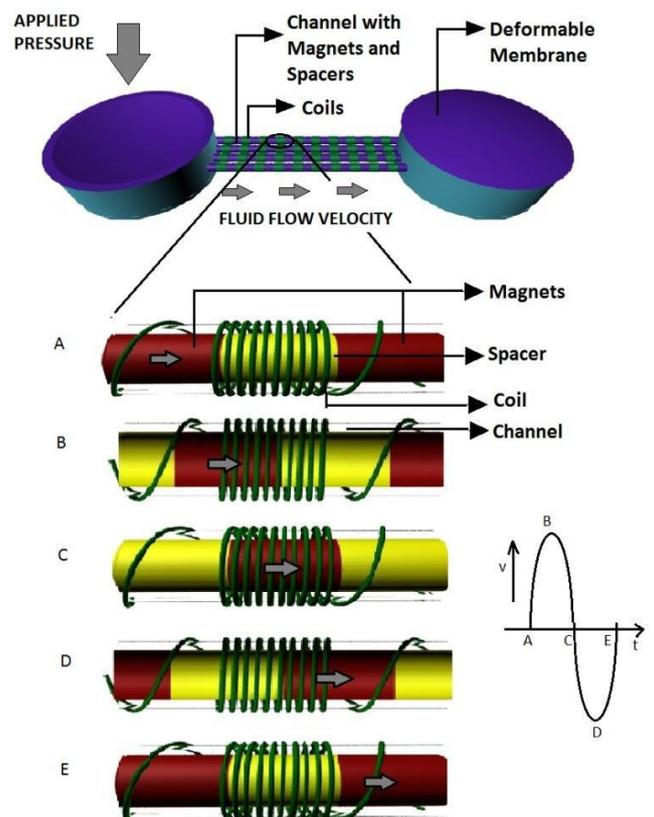


Figure 1: Illustration of the energy harvesting fluidic based system.(A-E)Depicts the movement of the magnets and spacer in the channel as fluid pushes on them. When the magnet moves from one end to the other end of the coil a complete sinusoidal voltage response is obtained due to induced emf.

Figure 1 illustrates the proposed energy harvesting system. It is comprised of two chambers with deformable thin diaphragms on the top. The two chambers could be interconnected via multiple fluid channels located as shown, although the reported

results are from a single channel device. The chambers and the channels together form a completely fluid-filled system where the working fluid shuttles within the closed fluidic-loop.

Present inside the channels is a train of equally sized cylindrical permanent magnets and non-magnetic spacers. The train of magnets is aligned in the same direction for the enhanced signal generation. The ends of the channels are slightly tapered off so that the train of magnets and spacers are confined during the shuttling motions inside of the channel. Conductive coils are wound on the outer surface of the channel such that their length and space between coils is equal to that of the magnet length. They are connected in series so that a complete sinusoidal phase matched signal can be obtained.

OPERATION

Emf is induced in the coils as the fluid flows in the channel due to the application of force on the diaphragm. When an external force is applied on one of the diaphragms the resulting pressure is distributed evenly on the interior walls of the chamber. This creates a pressure difference between the two chambers, allowing the liquid to flow from the chamber under high pressure to the chamber under low pressure through the connecting fluidic channels. According to Pascal's principle, when force is applied to a confined fluid, an increase in pressure is transmitted equally to all parts of the fluid. Thus the pressure that is applied on the diaphragm is equal to the pressure that is experienced by the liquid column at the opening of the channels. As the same pressure is applied over a smaller cross-sectional area a larger force is produced in the channel leveraging the hydraulic amplification utilizing the geometric ratios between the chamber and the channel diameters, which results in high flow velocities in the channels.

The liquid that flows in the channels exerts a force on the train of magnets and spacers which are free to move within the channel. This movement varies the magnetic flux through the cross sectional area of the coils which are present on the exterior of the channels. This change in flux density induces an emf in the coil. By alternating the pressure applied on the two chambers, the magnets in the channels are actuated back and forth, continuously inducing emf in the coils. This electrical energy can be rectified and stored in a battery or capacitor for use in a complete system.

The magnets, spacers and coils are placed such that as the train of magnets and spacers move, all the magnets in the device enter and exit coils in the same time interval. Thus by having the coils connected in series the signals generated from each coil are superimposed and added up as they are in phase with each other. Thus the system is designed such that the maximum displacement of the magnets and spacers are twice the length of each individual coil to produce one complete sinusoidal signal.

FABRICATION

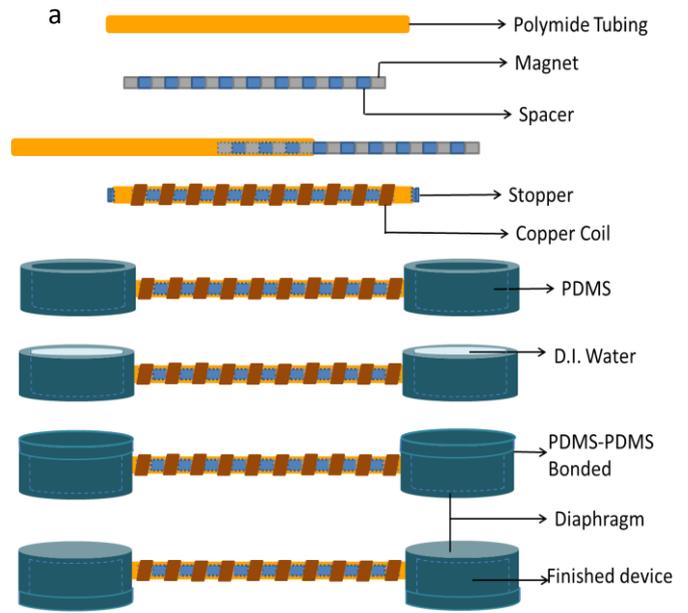


Figure 2: (a) Illustration of the device fabrication process. (b) Image of the fabricated device.

The device was built using PDMS (Polydimethylsiloxane) molding technology (Figure 2). NdFeB neodymium rare earth, grade N52, Nickel plated, axially magnetized permanent magnets are used (0.8mm radius and 3.13mm in length). The spacers between the magnets are made of acrylic which was laser cut to the same dimensions as that of the magnets using laser cutting machine. The tubing for the channels is made of polyimide with an inner radius of 1.025mm and outer radius of 1.05mm. A train of 10 magnets with acrylic spacers between them are placed inside the channels. Coils are made of 57 μ m diameter insulated copper wire wound around the channel. Each coil has 40 turns. On either end of the channels acrylic laser cut nozzles are placed which confine the movement of the train of magnets and spacers within the channel. The deformable chambers are also made of Polydimethylsiloxane. Sylgard 184 base and curing agent were mixed in the ratio 10:1 and then poured into plastic molds and cured. The chambers were made in two parts, one forms the side walls and the top diaphragm of the chamber and the other part forms the bottom layer of the chamber. Holes are drilled into the walls of the PDMS chamber for making connections with the channels. The channels are inserted into the holes and bonded with

silicon glue. The channels are completely filled with D.I. water and the chambers are 3/4 filled with D.I. water so that the D.I. water does not interfere with the next bonding process. The two PDMS structures are bonded together using PDMS-PDMS bonding technology. Different PDMS-PDMS bonding technologies [8] were tested and the uncured PDMS bonding method proved to be the strongest which could sustain a pressure of up-to 200kPa for our device. After the bonding process a syringe was inserted along the interface between the channel and chamber wall on one side to remove the excess air bubbles and completely fill it with D.I. water. This opening was later sealed with silicon glue.

TESTING

Phase Matching

To test the principle of phase matching and for a proof of concept a cm-scale prototype was tested in two stages: a (1) Single coil, (2) Double Coil setup. The tubing used for the channels has a inner diameter of 4.18mm and a wall thickness of 1.11mm. The NdFeB magnets used are of 3.15mm diameter and 12.72mm length. The acrylic spacer is of the same dimensions as that of the magnets. A 40 turn copper wire (0.26mm diameter) coil is wound around the tube. As D.I. water flows through the channel the magnets are impelled forward and an induced emf on the coils was observed. For different applied pressure the voltage readings were taken for a single coil and a double coil setup.

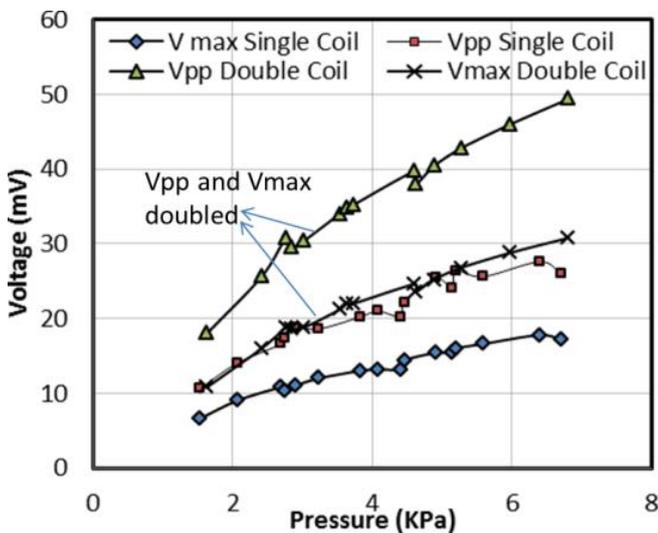


Figure 3: Voltage scaling due to phase matching with increase in the number of coils and magnets. Here Vpp is the peak to peak voltage and Vmax is the maximum voltage swing in the positive or negative direction.

With correct spacing between the magnets and the coils and with the coils connected in series it is seen that by doubling the number of coils the output voltage also doubled (Figure 3). Hence it is shown that by phase matching the coils the voltage increases proportionally to the number of coils present.

Scaled Down Version

To illustrate the complete feasibility of the device a scaled down version which is fabricated as stated above was tested. The DUT (device under test) had a single channel setup with a 10 magnet train and 10 copper coils built into it. Upon application of an external force on the diaphragm, the magnets are displaced through channels and an alternating sinusoidal electrical signal was obtained from the coils (Figure 4).

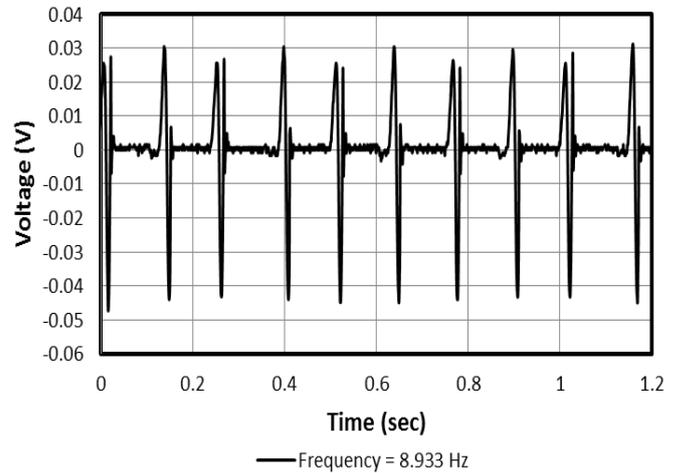


Figure 4: Sinusoidal voltage signal obtained due to emf induced in the coils. A constant pressure is alternately applied at a frequency of 8.933Hz.

Pressure Response

The fabricated device was tested for a wide range of input pressure. The DUT was set on a flat surface. External pressure was applied and measured using a CSD200 Chatillon dynamometer over an area of 18*15mm² on the diaphragm. A single actuation reading was taken at different input pressures. The output voltage was recorded across an optimum load on a Tektronix TDS 2024B oscilloscope and for different pressures the generated power response is graphed (Figure 5).

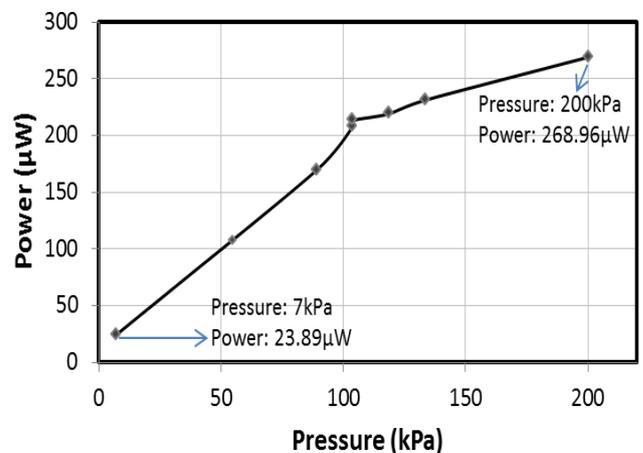


Figure 5: Power(rms) versus pressure results depicting a proportional increase in power with increase in pressure. The device under test is a single channel structure with 10 magnet-coil pair.

It is observed that the magnitude of power generated by the system is directly proportional to the pressure applied. As the applied pressure increases the output power increases linearly. But at higher end of the pressure range (~>130kPa) the rate of increase in the power generated gradually decreases and tends to reach a saturation point at much greater pressure. This is caused due to the limitation on the maximum speed at which the fluid and the magnets can travel within the confined space. The speed is limited by the resistance offered by the channel tubing, compressibility and viscosity of D.I. water and the confined space within which the magnets have to accelerate and reach its maximum speed. The device could resist pressures up-to 200kPa and at this pressure a power_{rms} of 268.96μW was generated which resulted in a power density of 1.18mW/cm³ for this configuration.

OPTIMIZATION

Further optimization of the device design can prove to yield greater power. From Faraday's law the induced electromotive force in any closed circuit is equal to the time rate of change of the magnetic flux through the circuit.

$$\varepsilon = \partial\Phi/\partial t \quad (1)$$

The magnetic flux is given by the vector dot product of the magnetic field (B) and the cross-sectional area (A) of the normal surface. Since these two vector parameters are directionally parallel to each other the magnetic flux is given by

$$\Phi = B * A \quad (2)$$

The rate of change of the magnetic flux in our system is directly proportional to the flow velocity of the liquid in the channels. Thus the time over which the magnetic flux changes is given by the time taken by the fluid to push the magnets by a distance that is equal to twice the length of that of the magnet. Hence the emf generated by the system per coil turn is given by

$$\varepsilon = \frac{BAv}{2x} \quad (3)$$

Where x is the length of the magnet and v is the flow velocity. From equation (4) it is observed that for a given velocity the emf is directly proportionally the ratio of the cross-sectional area of the magnet to the length of the magnet. Therefore, as long as this ratio is maintained or increased as we scale down the system size the emf induced will be the same or increases.

Also, as the magnet size is scaled down by a factor of k the magnetic field scales down at a rate of 1/k [9]. But as the device size is reduced the magnets in the adjacent chambers are brought in closer proximity to each other, thus the magnetic field strength around each magnet increases by a factor of k [9] due to the interaction between magnets at the scale. Thus the fluidic based energy harvesting system can be scaled down further and still be capable of producing power in the μW range.

The results shown here are only for a single channel with ten coils. The power output can be further increased in two ways. As stated in the system design, by having multiple channels in parallel between the chambers the power output can be proportionally scaled. Here the voltage induced in each coil is summed as long as the coils are connected in series. Another way of increasing the power is by having multi-layered coils which are wound in the same direction to ensure the voltages generated are in phase. A greater increase in the power density can be obtained from the latter method.

CONCLUSION

An efficient fluidic based energy harvesting system was successfully constructed. By the use of fluid dynamics it is shown that the device can handle high deflection force inputs and generate electrical power from it. The device also generated high output at low frequency force applications and demonstrated the effect of phase matching which amplified the output response. The experimentally measured power_{rms} is 268.96μW, power density of 1.18mW/cm³ for an active device volume of 227.75mm³.

REFERENCE

- [1] Kulah H and Najafi K, "An electromagnetic micro power generator for low-frequency environmental vibrations Micro Electro Mechanical Systems" 17th IEEE Conf. on MEMS, 2004.
- [2] D.A. Wang and K.H. Chang, "Electromagnetic energy harvesting from flow induced vibration", *Microelectronics Journal* 41, 2010.
- [3] Seong-Hyok Kim, Chang-Hyeon Ji, Preston Galle, Florian Herrault, Xiaosong Wu, Jin-Ho Lee, Chang-Auk Choi and Mark G. Allen, "An electromagnetic energy scavenger from direct airflow", *Proc. of PowerMEMS*, 2008.
- [4] C.R. Saha, T.O'Donnell, N. Wang and P. McCloskey, "Electromagnetic generator for harvesting energy from human motion" , *Sensors and Actuators*, 2008.
- [5] Ching N N H, Wong H Y, Li W J, Leong P H W and Wen Z, "A laser-micromachined vibrational to electrical power transducer for wireless sensing systems", *Sensors Actuators A* 97–98, 2002.
- [6] Kymissis J, Kendall C, Paradiso J and Gershenfeld N "Parasitic power harvesting in shoes" *Proc. 2nd IEEE Int. Conf. Wearable Computing*, 1998.
- [7] Shenck N.S. and Paradiso J.A., "Energy scavenging with shoe-mounted piezoelectrics" *IEEE Micro*. 21, 2001.
- [8] O.Cugat, J.Delamare, and G.Reyne, "Magnetic micro-actuators and systems(MAGMAS)" ,*IEEE Trans. Magn.*,vol. 39,no. 6, 2003.
- [9] Mark A Eddings, Michael A Johnson, and Bruce K Gale, "Determining the optimal PDMS–PDMS bonding technique for microfluidic devices", *J. Micromech. Microeng.* 18, 2008.