MAXIMIZED FLUIDIC CIRCULATION BASED MICRO ENERGY HARVESTING DEVICE

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Abstract: We present an enhanced-capacity circulatory microfluidic energy harvesting device where the travel distance of an object is not limited within the tiny device size by taking an advantage of infinite circulatory loops, thus producing higher output power than conventional straight-channel devices. Previously reported micro hydraulic energy harvesting devices [1, 2] experienced unintended termination of fluidic flow, because of the limited length of the straight channel, quickly saturating the power production under large input force. To overcome this issue, we constructed a circular micro-fluidic channel with integrated microvalves (Fig. 1). The circular micro-fluidic channel is implemented in the PDMS substrate with the hydraulic amplification chamber structure, sphere magnets with polymer spacers in between, and coils around the channels. The fabricated device (1) extended the input dynamic range by 167% up to 4.7kpa, (2) enhanced the power output by 146%, respectively compared to the straight channel configuration, and (3) produced the max. instant power of 0.32µW under the input impulse pressure of 1.7kpa.

Keywords: Micro Energy Harvesting, Micro Fluidic, Hydraulic, Electromagnetic, Circular Channel.

INTRODUCTION

Micro-scale energy harvesting devices recently have attracted increasing attention as a potential alternative for the conventional battery because they ideally operate permanently, do not need replacement and prevent chemical wastes. However, their practical usages have not been prevalent because the produced amount of energy has been much limited with an average density of 100µW/cm^3 [1-4]. One of the main reasons is the fact that the micro-scale devices could not fully handle a large amount of input energy due to fragile structures or limited displacement ranges available in the tiny device. To obviate, first, the fragility of the micro structures and thus accommodate a large force, we previously presented a microfluidic energy harvesting device that *"de-amplifies"* the input force and simultaneously *"amplifies"* the flow distance through micro hydraulic principles [1, 2]. The developed device enhanced the input dynamic range and improved power output. However, the hydraulic device still suffered from a limited maximum input displacement that can be accommodated due to the restricted channel sizes.

To overcome this issue, we present a circular channel device that provides unlimited travel distances of a moving magnet along a circular loop and enables the significantly increased power generation especially under a high input deflection, as illustrated in Fig. 1.

Figure 2 illustrates the advantages of the developed circular channel configuration compared to the conventional channel device. As shown, straight channel traveling distance limited by the length of the channel, on the contrary, the circular channel provides limit-less traveling distance.

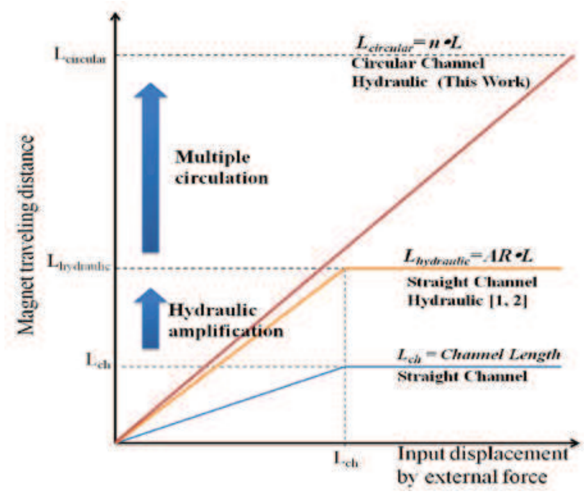

Fig. 1: Comparison of the fluidic flow travel distance, which is proportional to the output power output, among the conventional non-hydraulic, the previously developed hydraulic, and this circular channel hydraulic energy harvesting devices.

STRUCTURE

The circular channel energy harvesting device is comprised of four major elements: a pair of pressure chambers, a fluidic circulation channel, a set of serially- and alternatively-connected magnet/spacer, and multiple sets of coil turns, as shown in Fig. 3. The pair of pressure chambers provides the large surfaces that can easily bend under external input pressure or force.

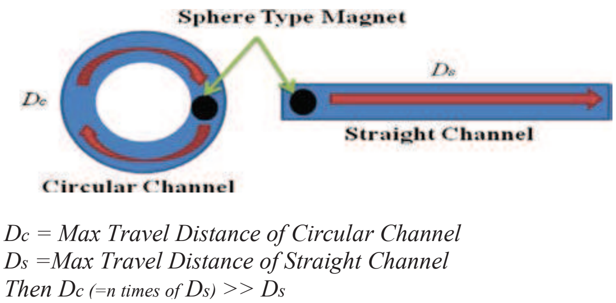

Fig. 2: Fluidic flow travel distance comparison between the circular channel and the straight channel.

Since the chambers are completely filled with an incompressible liquid (mineral oil) without bubbles, the bending of the membrane in one chamber drives the liquid to inflate the other chamber causing high-speed liquid flow though the fluidic channel. The fluidic circulation channel guides the produced fluidic flow to circulate in one direction with the help of integrated passive microvalves. Following the circulatory flow, the set of magnet and spacers rotate *without being restricted by the channel length*. The multiple sets of coil turns surround the circulatory channel and induce electrical voltage whenever passed by the set of magnet/spacers.

The pressure chambers are fabricated of flexible PDMS to easily induce the bending of a membrane, has the compact volume of 63x27x13mm^3, and is filled with mineral oil that has the low viscosity of 33.5cSt. The pair of the chambers is fluidically-interconnected to a circulatory channel through four uni-directional microvalves.

The uni-directional microvalve(4.5x4.5x6mm^3), consisting of a flip membrane(30um thick PDMS), only opens the path when a high pressure is applied onto the pressure chamber and passively regulates the fluid into one direction. The circular channel has a diameter of 36mm and a cross-section of 4.5x4.5mm^2. The cross-section is slightly larger by 1.32mm than the diameter of the magnet spheres to reduce the friction and facilitate their position displacement.

The magnet/spacer set is self-assembled through magnetic attraction among magnets. The utilized magnets are four grade-N42 Neodymium sphere magnets with a diameter of 3.18mm and three acrylic spacers with the volume of 3.18x3.18mm^3 fabricated by utilizing the CO2 laser cutting machine (Universal Laser Systems, PLS 6.15D) with a precision of 50μm. The coil sets consist of 12 groups with the separation distance of 3mm that is nearly identical to the diameter of the sphere magnets for higher voltage output through the phase matching [1, 2]. Each coil group has 20 turns of enamel coated copper magnet wire (0.12mm thick).

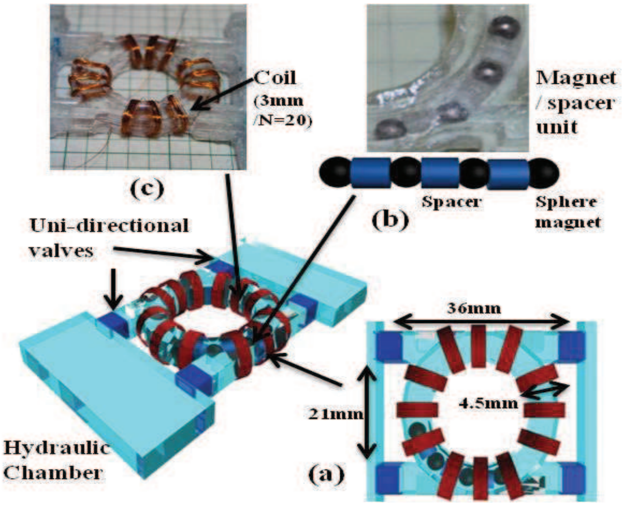

Fig. 3: Structure overview of circular fluidic channel energy harvesting device, (a) circular channel, (b) coil on the circular channel, (c) magnet/spacer unit

OPERATIONAL PRINCIPLE

The operation of the circular channel energy harvesting device starts with the acceptance of input force on one of the pressure chambers. The force bends the membrane of the pressure chamber and causes hydraulic the liquid inside through the fluidic channel to the other chamber. When initiated, the flow is pressurized until the pressure is sufficiently high to push the flip membrane and open the microvalve.

Once induced into the channel, the flow follows the circular path and escapes to the other chamber through another microvalve connected to the other chamber until the pressure equilibrium is reached. Although some fluid escapes from the circular channel, the overall circulatory flow continues due to the momentum. Resultantly the travel distance, despite the tiny device volume, is not physically limited. This operation takes place in both directions alternatively between the pair of the chambers depending on the location of the applied force (Fig. 4).

As the circular flow carries a magnet set through the coils sets around the circular channel, the device generates electrical current by electromagnetic induction.

FABRICATOIN

The circular channel energy harvesting device was fabricated mainly by molding technique. First, two molds were fabricated respectively to build the cover and the channel & chamber substrates.

The mold was precisely fabricated onto the multiple layers of acrylic substrates (1.5 and 3mm to reach 4.5mm channel height). Each substrate of the mold was precisely patterned with CO2 laser cutting machine (Universal Laser System, PLS 6.15D).

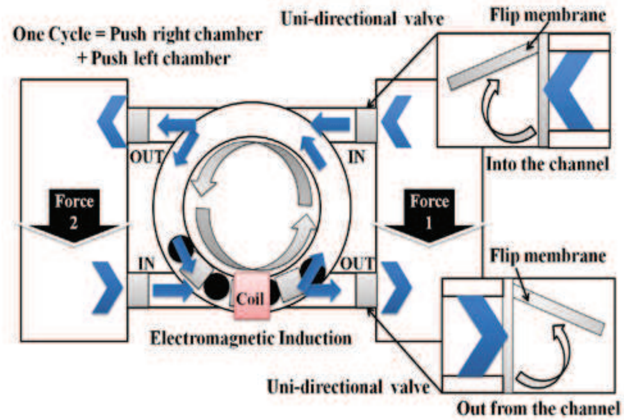

Fig. 4: Operational principle overview of circular fluidic channel energy harvesting device

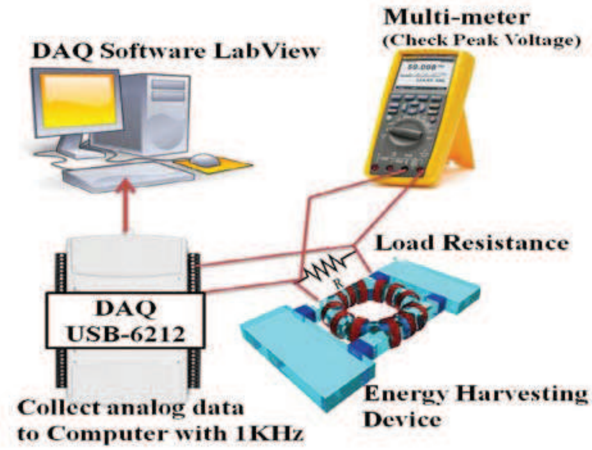

Fig. 5: Overview of experiment setup

These substrates were bonded with double sided acrylic-adhesive (3M, 200MP). Next, on top of the completed molds, uncured Polydimethylsiloxane (PDMS: Sylgard 184 Silicone Elastomer) base was poured and cured in a convection oven at 60^{o}C for two hours. Then, the fabricated PDMS substrates were permanently bonded by utilizing the PDMS-PDMS bonding technique where the 1:1 ratio mixture of the uncured PDMS and toluene was utilized. This type of bonding was known to tolerate the pressure of up 648kPa, which is sufficient for this work, and a reasonable sealing capability [2].

It is noteworthy to mention that a straight channel energy harvesting device was also fabricated in the same dimensions utilizing the same fabrication technique for comparison purposes.

EXPERIMENT

Testing of the circular channel energy harvesting device was conducted under three categories: First, the travel distance of the magnet/spacer unit was measured in the conventional straight channel device under various single impulse input force ranges from 0 to 8.0N and various initial position of magnet/spacer unit by capturing the positions of the unit utilizing a digital video camera. Second, the identical testing was performed on the circular channel device, and was compared to the data obtained from the straight channel device. Third, the output voltage was measured by incorporating an off-chip resistor in the optimal magnitude. Through these testing, the same input force condition of 2Hz, 4N was applied for 10sec. The output voltage was continuously acquired and recorded by utilizing a commercial recording device (National Instrument, USB-6212) through the Labview programmed software. Additionally, a multi-meter (FLUKE 287 Multi-meter) was connected in parallel to the load resistor to monitor the peak output voltages produced (Fig. 5).

RESULTS

The measured travel distances indicate that the circular channel device ensures a longer travelling distance of a magnet unit than a straight device by 54% beyond a critical pressure of 3.0N, as shown in fig. 7. Figure 6 shows the magnet/spacer unit positions under 3.0N of single impulse force for both the circular channel (top) and the straight channel (bottom). The bottom figure shows traveling progress by capturing the positions of the magnet/spacer unit on straight channel at different timing.

The measurement also indicates enhanced travelling capability in the circular configuration and the extended dynamic range of input pressure by 167% up to 4.7kpa. Figure 7 plots the measured travel distance under a wide range of input force between 0.27 and 8.0N. The measurement shows that the produced travel distance of the magnet units increases with the input force up to 3.0N in both configurations; however, is limited to 52mm in the straight channel while continues to increase to 56.3, 62, 69, 70, 75, and 80mm in the circular channel under 3.0 to 8.0N in 1.0N steps. This corresponds to 54% increase in power generation under the identical condition. The plot also implies that the gain through the circular configuration would continue in increasing if higher input forces are applied.

Figure 8 shows the voltage generation through the surrounding coils in the circular configuration under repeated input force of 4.0N at 2Hz over the period of 10sec. During 10sec, 10 harmonic cycles were produced. The measured maximum voltage output was 2mV, indicating the instant power generation of 0.32µW. Figure 9 shows the voltage generation under the same input conditions for the straight channel configuration. The maximum voltage of 1.2mV was measured, which corresponds to the instant power of 0.13µW.

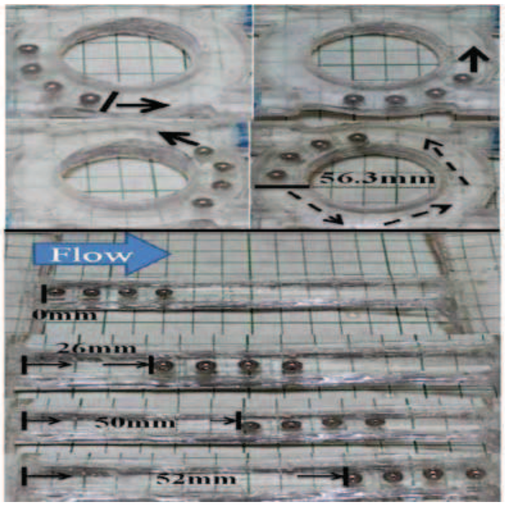

Fig. 6: Traveling distance comparison between circular and straight channel with 3N single impulse force.

Note that the maximum voltage from the straight channel configuration is lower than that from the circular configuration, because of limited travel distance interfere whole magnet/space unit to pass through all of coil sets.

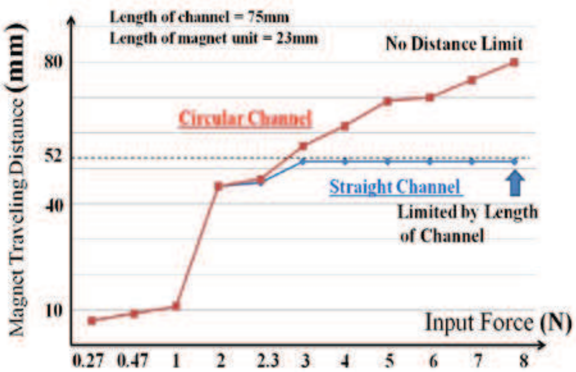

Fig. 7: Traveling distance comparison between circular channel device and straight channel device with various input force.

CONCLUSION

We have successfully fabricated a circular channel energy harvesting device that ideally eliminates the limitations of a micro-scale device by providing an infinite circular loop. The measurement results show that the travel distance was enhanced by 54% at the input force of 8.0N and implies further enhancement under higher input force. Resultant power output was increased by 146% in the circular configuration compared to the conventional straight channel configuration under the same operating condition. The fabricated circular configuration energy harvesting device produced a maximum power of 0.32μW at an instant impulsive force of 8.0N. The volume of the final device was 62cc.

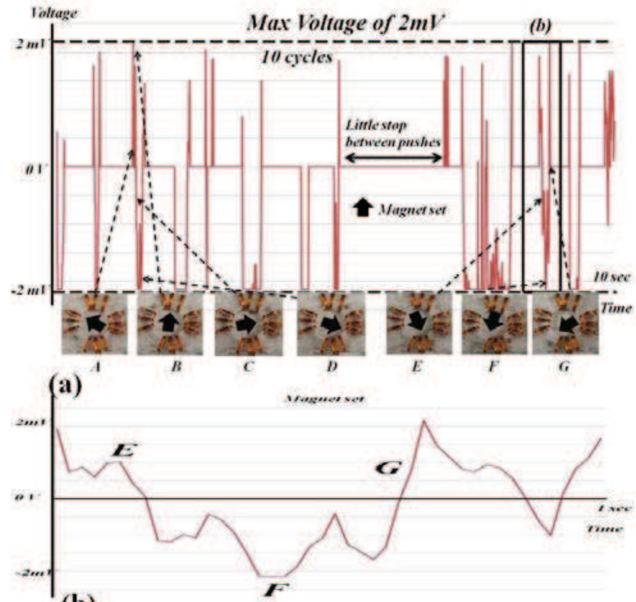

Fig. 8: Generated voltage of circular device (a) record for 10sec (b) view of one harmonic voltage signal during 1sec (4N applied).

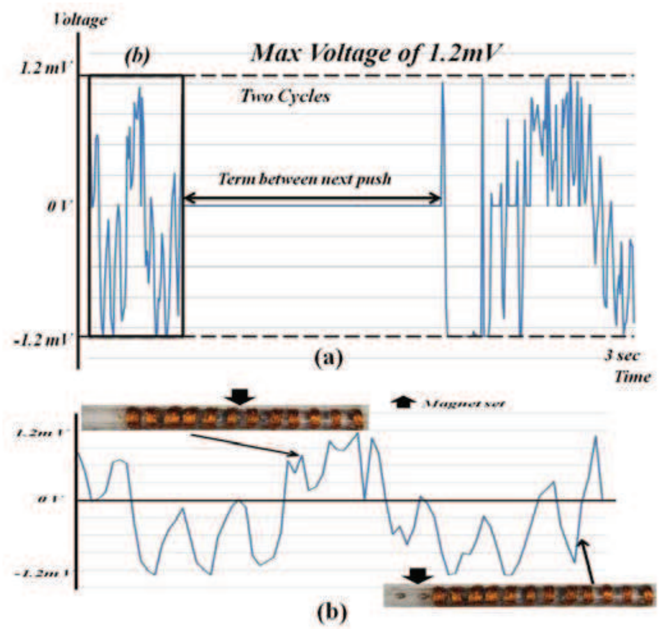

Fig. 9: Generated voltage of straight device (a) record for 3sec from 10sec record (b) view of one harmonic voltage signal during 1sec (4N applied).

REFERENCES

[1] *A. Bramhanand, M. Rahman, Y.C. Bae, H. Kim, HiltonHead'12, pp. 497-500, (2012)*

[2] *A. Bramhanand, and H. Kim, PowerMEMS 2011, pp. 74-77, (2011)*

[3] *S.H. Kim, C.H. JI, P. Galle, and F. Herrault, PowerMEMS 2008, pp. 133-136, (2008)*

[4] I. Sari, T. Balkan, H. Kulah, *MEMS 2009, pp.1075-1078,* (2009)