270-degree arc-shaped piezoelectric energy converter in uniflow fluid environment

Ying Gong\textsuperscript{1,2}, Xiaobiao Shan\textsuperscript{1*}, Zhengbao Yang\textsuperscript{2*} and Tao Xie\textsuperscript{1}

\textsuperscript{1} State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin 150001, China
\textsuperscript{2} Department of Mechanical Engineering (MNE), City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong SAR

shanxiaobiao@hit.edu.cn; zb.yang@cityu.edu.hk

Abstract. Energy harvesting in uniflow fluid environment aims at ambient energy that can be used in water environment for monitor equipment. In this paper, we focus on coupling both bending vibration and torsional vibration to gain better power generation. A novel structure of energy converter (arc-shaped) was designed and manufactured. Meanwhile the influence of vibrator with and without a pelvic fin was tested. Mathematical analyse due to vibration phenomenon and experimental result are reported. The 270-degree arc-shaped ring size piezoelectric ceramic is verified capable of producing an effective voltage over 10 V with the power of 0.5 mW.

Keywords: energy harvesting, arc-shaped; uniflow

1. Introduction
Energy harvesting has been in people’s sight for a long period of time [1-3]. Attention on energy harvesting never disappeared but yet still under development and not been put into use widely. With the rapid growth of the number and type of intelligent electrical apparatus, especially the smart and connected ones, the circumstance of energy harvesting seems changing [4-6]. Unlike the ordinary electric devices, intelligent electrical apparatus usually doesn’t need high power recharge energy [7]. Thus, the appearance of those apparatus drives low density energy harvesting nearer to the application area.

Researches on energy harvesting are widely oriented to various environmental energies like biochemical reaction, light energy (solar and artificial), mechanical energy, radio frequency waves and heat transfer energy [8-10]. Researchers in various fields are improving technology including photovoltaic [11], piezoelectric/triboelectric [12-15], thermal energy [16, 17], electrostatic [18] et cetera. The magnitude of energy varies with the size of the captor and the type of energy from \( \mu \text{W} \) to kW [19, 20] and have different application environments. In 2013, Lockwood et al. [21] proposed a method to generate electrical energy using osmotic pressure difference between salt water and fresh water. In 2015, Zi et al. [22] discovered the phenomena of pyroelectric–piezoelectric hybrid effect of PVDF and designed a hybrid battery for high efficiency energy-harvesting and self-powered sensing.
Energy transducers based on piezoelectric ceramics are widely studied these days and plenty of tests have been done [4], which mostly thanks to the piezoelectric properties of the ceramics. Among the piezoelectric ceramic transducers there are many energy harvesters which were designed to meet needs of different circumstance [23]. With improving attention to world climate change, marine float and hydrological monitoring equipment are being applied gradually. In the huge energy field of ocean and rivers, energy harvesting is the most ideal way for floatation and hydrological monitoring equipment to be self-sufficient [24]. Piezoelectric energy harvesting system can provide exactly what needed. In 2012, Erik Molino-Minero-Re et al. [25] presented a vertical cantilever-cylinder model and gain output of 0.31 µW in 0.1 m/s current. In 2015, Song et al. [26] reported numerical study of piezoelectric flag response in air flow for energy harvesting. Shan et al. [27, 28] gave a two-tandem oscillator and an eccentric oscillator model for uniflow fluid energy harvesting in 2016 and 2017. The output power of the two-tandem energy converter was 167.8 µW and 533 µW upstream and downstream correspondingly, while the eccentric converter gains an output capacity of 397.8 µW. With their work vertical oscillator energy convertor was optimized gradually. In 2012, Grouthier et al. [29] proposed vortex-induced vibrations in cables and they analysed the optimum efficiency and discussed the sensitivity. In 2014, Tanakaa et al. [30] carried out theoretical analysis and experimental verification of different dimensions based on the basic model of the forced vibration of the piezoelectric beam in air and water flow. In 2014, Xie et al. [31] designed a piezoelectric coupled energy harvester fixed on seabed to harvest wave energy. In 2015, Wu et al. [32] from the same team developed floating energy harvester with similar structure for wave energy harvesting. In order to increase the power density, in 2017, Yang et al. [33] made an assessment of the performance differences between 180-degree arc-shaped and plate shape piezoelectric elements using vibration exciter. The results show that arc piezoelectric elements have better performance than piezoelectric plates under the condition that only the piezoelectric property in the d33 direction is applied.

It can be found from the above review that the development processing of piezoelectric based energy harvesting has encountered several challenges. The challenges are as follows:

- Material is vulnerable and limit the life span of the device [34].
- Low energy density.
- Turn voltage output mode from AC to DC to fit smart devices [10].
- Insufficient research on energy storage.
- The energy conversion rate of piezoelectric materials is not high enough.

In order to increase the energy conversion rate of piezoelectric materials, piezoelectric energy harvesting from the flow energy in both d33 and d13 direction becomes an innovative and bold idea. Therefore, this paper presents a new 270-degree arc-shaped piezoelectric energy harvester in purpose of a) exploring transforming vibration into DC, b) coupling both bending and torsional vibrations, c) increasing the utilization of space. Influences of a pelvic fin on the cylindrical oscillator will be analysed in the following sections.

2. Simulation analysis and experimental phenomena of the vibration

In this part, mathematical analysis and simulations are made for some phenomena in the process of experiment. First is the voltage asymmetry of the output voltage. Second is the fracture analysis of piezoelectric ceramics to verify the vibration mode. [Figure 1 illustrates a schematic diagram of experimental structure and an experimental photograph.

The spoiler cylinder and the fixture are designed to fit the curvature of the piezoelectric piece. And most of the spoiler cylinder is submerged in the water flow, and the rest of the structure is suspended above. Under the excitation of uniform and smooth water flow, the spoiler cylinder drives the piezoelectric ceramic to make elliptical motion at one end which can be seen as lateral swing. The
periodic deformation of the piezoelectric ceramic thus gives the output power. Due to structural asymmetry, lateral vibration will also exhibit an asymmetry.

![Experimental platform](image)

**Figure 1.** Experimental platform (a) Schematic diagram of experimental model and (b) Experimental photograph.

- **2.1 Voltage Asymmetry Analysis**

In the course of the experiment, for different velocity corresponding to motor frequency, the output voltage maintains asymmetric with respect to the x-axis. Considering the direction of polarization, it can be told that the radial inward vibration is stronger than the radial outward vibration. Figure 2 shows the original generation waveform of the prototype of piezoelectric ceramic.

To understand and explain the above phenomena, elastic mechanics was simulated in Comsol. Based on the assumption that the vortex induced oscillating force exerted on a cylinder is symmetrical. The simulation model is set up. The first and second principle strain is simulated in this case when the arc-shaped ceramic is exerted outward/inward force. Vertical motion is ignored here since it has no influence on the symmetrical characteristic. The results illustrated in figure 3 shows that the strain of a 270-degree arc-shaped piezoelectric ceramic is asymmetric when the same force (0.5 N) is exerted radial inward and outward. The figures below indicate that inward force brings greater strain than the outward force and leads to higher output voltage.

![Asymmetric vibration diagram](image)

**Figure 2.** Asymmetric vibration diagram and original voltage waveform corresponding to different water velocities.

According to the experimental phenomena, the peak value of the positive voltage is 1.4 times the peak value of the negative voltage, and the effective value of the positive voltage is 1.3 times the effective value of the negative voltage. Simulation result display that the outward deformation is 1.15 times the inward deformation. The simulation is basically consistent with the experimental results. The
gap should be due to the torsion phenomenon exist in the experiment but not considered here in the simulation. The asymmetry presents here is advantageous to solve the problem that the trapped energy is supplied to the DC storage element. Improve the structure and further expand the asymmetry to solve the AC-DC problem.

![Elastic mechanics analysis of the 270-degree arc-shaped piezoelectric ceramic when exerted](image)

**Figure 3.** Elastic mechanics analysis of the 270-degree arc-shaped piezoelectric ceramic when exerted (a) Inward force (b) Outward force.

### 2.2 Fracture Analysis

As is well known, piezoelectric ceramic is fragile. A slight overload in the experiment can results in fragmentation. While fragmentations during energy harvesting show different features from those generated during the installation processing. Figure 4 shows the fragments produced in different circumstances. As can be seen in figure 4, fracture edges produced in the installation are irregular and mostly with big angle while all of the fracture edges caused by energy harvesting progress has fractured angles at approximately 60 degrees. This proves the implementation of coupling both bending vibration and torsional vibration in the perspective of experiment.

![Fragments produced in (a) Installation process and (b) Energy harvesting progress.](image)

**Figure 4.** Fragments produced in (a) Installation process and (b) Energy harvesting progress.

To estimate the stress transmitted to piezoelectric ceramic via a vibrator, consider the piezoelectric voltage constant formula shown as

\[ g_{31} = \frac{U_{31}}{P} (V \cdot m/N) \]  

(1)
Where $U_p=U/b_c$ is the voltage gradient and $P$ is the corresponding strain. Since $g_{31}$ is $8.4 \times 10^{-3}$ (V·m/N) for PZT-5H, $P=2.38$ MPa. Figure 5 shows the simulation of maximum amplitude state in vibration, taking self-weight of the vibrator and water buoyancy into consideration. As can be seen in Figure 5, here torsion deformation exists simultaneously with bending deformation, and can’t be ignored. Compared to the simplified simulation in Figure 3, twisting significantly increases the magnitude of the deformation, thereby increasing the efficiency of energy harvesting.

![Figure 5. Bending torsional deformation coupling simulation.](image)

Here two phenomena in the experiment are analysed and explained with help of simulation and basic formula of piezoelectric effect. Due to the asymmetric arrangement of the vibrator, strain is not symmetrically produced and hopefully to increase asymmetry to form unidirectional current. Hence, the force mode obtained from the comparison of the experimental, simulation and mathematical results show that both the bending and twisting modes are significant for energy harvesting.

### 3. Energy harvesting experimental results and discussion

A prototype of energy harvester with an arc-shaped structure was fabricated, as shown in Figure 1. Processing by 3D printing process, the oscillator is made of resin material whose density is 1.16 g/cm³. The shrinkage of material is three parts per thousand. Captive elements are made of piezoelectric type PZT-5H and radially polarized. The dielectric constant $d_{33}$ is 300-600 pC/N, diverse individually. The basic model structure size data are listed in Table 1.

| Parameters                                      | Values       |
|-------------------------------------------------|--------------|
| Diameter of cylindrical oscillator, $d_o$ (mm)  | 10/12        |
| Soaking length of cylindrical oscillator, $l_o$ (mm) | 110          |
| Thickness of piezoelectric ceramic, $b_c$ (mm)   | 0.5          |
| Diameter of arc-shaped piezoelectric ceramic, $d_c$ (mm) | 30           |
| Height of arc-shaped piezoelectric ceramic, $h_c$ (mm) | 10           |
| Weight of cylindrical oscillator without fin, $m_o$ (g) | 13.4/19.4    |
| Weight of cylindrical oscillator with fin, $m_{of}$ (g) | 14.2/20.1    |
| Resistance of the NI 9215, R (kΩ)               | 200          |

The experiment was carried out on a uniflow artificial experiment platform. Regulating water speed by the frequency converter of the pump, after repeated measurements the relationship between the frequency and water speed can be to a primary curve. Figure 6 shows the relationship between the frequency and water velocity.
Figure 6. Relationship between the frequency and water velocity.

The above curve can be approximated to fit a straight line. It shows that there is a positive correlation between the water velocity and the motor frequency and their correlation coefficient is 0.991.

Using an NI data acquisition card and Labview, output voltage was extracted. Figures 7 and 8 show five sets of data from three piezoelectric ceramics. First three sets of data corresponded to one same ceramic with a cylindrical oscillator, a cylindrical oscillator with a fin facing the flow, a cylindrical oscillator with a fin along the flow. The last two sets of data belong to two ceramics which cracked due to increasing force became overload. Line 1-3 show that additional fin parallel to the direction of the flow will greatly reduce the effect of power capture to less than 1/10. Line 1 and line 4 show that individual difference of piezoelectric ceramic is a factor that can’t be ignored, as the peak value of voltage and power are similar the corresponding velocity shift. Line 1, 4, and 5 show that the size and gravity of the oscillator have influences on the captive performance of the model with diameter change from 10 mm to 12 mm. There is a significant increase at 66.7% in the effect of capture. While the captive element is also more vulnerable to damage which can be told by the left shift damage point.

In our experiments, the effective output voltage can reach up to over 10 V and positive peak voltage at around 15 V. The output power can reach up to 0.5 mW. Since without any substrate, the ceramics was very fragile, and the individual differences of the piezoelectric elements brought some inconveniences to the experiment. This experiment strictly followed the control variable method.

Figure 7. Output voltage of the converter corresponding to water velocity.
4. Conclusions
This paper presents a novel prototype of energy harvester in water flow energy harvesting. A 270-degree arc-shaped energy converter was designed, manufactured and tested. A concept of capture DC power is proposed based on the asymmetry of structure. Two modes of vibration including bending and torsion were successfully excited. Furthermore, the energy harvesting efficiency of this new 270-degree arc-shaped energy converter was distinctly improved by 40%. Additional fins in the parallel direction of flow were verified to weaken the effect of energy harvesting. The bigger oscillator helps improve the captive ability and weaken the strength of the system at the same time.

Acknowledgements
This work was financially supported by the National Natural Science Foundation of China (Grant No. 51677043 and No. 51875116).

References
[1] Perton M, Audoin B, Pan Y D, and Rossignol C, "Numerical analysis of bulk conical waves in anisotropic cylinders: application to stiffness tensor measurement," 2006, J. Ultrasonics, 44, pp. e859-e862.
[2] Lu X, Wang P, Niyato D, Kim D I, and Han Z, "Wireless networks with rf energy harvesting: A contemporary survey," 2015, J. IEEE Communications Surveys & Tutorials, 17, pp. 757-789.
[3] Sudevalayam S and Kulkarni P, "Energy harvesting sensor nodes: Survey and implications," 2011, J. IEEE Communications Surveys & Tutorials, 13(3), pp. 443-461.
[4] Yang Z, Zhou S, Zu J, and Inman D, "High-performance piezoelectric energy harvesters and their applications," 2018, J. Joule, 2, pp. 642-697.
[5] Boisseau S, Despesse G, and Ahmed B, "Electrostatic conversion for vibration energy harvesting," 2012, J. Physics, 6044(2), pp. 456-472.
[6] Marsic V, Zhu M, and Williams S, "Design and implementation of a wireless sensor communication system with low power consumption for energy harvesting technology," in 19th Telecommunications Forum (TELEFOR) Belgrade, Serbia, 2011, pp. 607-610.
[7] Chen D, "Smart grid and recent development of intelligent low voltage electrical apparatus " 2010, J. Low Voltage Apparatus,
[8] Lokhanded A C, Gurav K V, Jo E, He M, Lokhanded C D, and Jin H K, "Towards cost effective metal precursor sources for future photovoltaic material synthesis: Cts nanoparticles," 2016, J. Optical Materials, 54, pp. 207-216.

[9] Hannon M J, Griffiths J, and Vantoch-Wood A, "World energy resources 2016," London, EC3V 3NH, United Kingdom 2016.

[10] Global energy harvesting market, forecast to 2030 [Frost & Sullivan]. (2016 Apr 27). Available: https://store.frost.com/global-energy-harvesting-market-forecast-to-2030.html

[11] Polman A, Knight M, Garnett E C, Ehrler B, and Sinke W C, "Photovoltaic materials: Present efficiencies and future challenges," 2016, J. Science, 352, p. aad4424.

[12] You Y M, Liao W Q, Ye H Y, Zhang Y, Zhou Q, Niu X, et al., "An organic-inorganic perovskite ferroelectric with large piezoelectric response," 2017, J. Science, 357, pp. 306-309.

[13] Li F, Lin D, Chen Z, Cheng Z, Wang J, Li C, et al., "Ultrahigh piezoelectricity in ferroelectric ceramics by design," 2018, J. Nat Mater, 17, pp. 349-354.

[14] Liu Y, Chen W, Liu J, and Shi S, "A cylindrical traveling wave ultrasonic motor using longitudinal and bending composite transducer," 2010, J. Sensors and Actuators A: Physical, 161, pp. 158-163.

[15] Zhou S, Cao J, Erturk A, and Lin J, "Enhanced broadband piezoelectric energy harvesting using rotatable magnets," 2013, J. Applied Physics Letters, 102, p. 173901.

[16] Sales B C, Mandrus D, and Williams R K, "Cheminform abstract: Filled skutterudite antimonides: A new class of thermoelectric materials," 1996, J. Cheminform, 27(40), pp. no-no.

[17] Sootsma J R, Chung D Y, and Kanatzidis M G, "New and old concepts in thermoelectric materials," 2010, J. Angewandte Chemie, 48(46), pp. 8616-8639.

[18] Torres E O and Rincón-Mora G A, "Electrostatic energy-harvesting and battery-charging cmos system prototype," 2009, J. IEEE Transactions on Circuits and Systems I: Regular Papers, 56, pp. 1938-1948.

[19] Roundy S, Wright P K, and Rabaey J, "A study of low level vibrations as a power source for wireless sensor nodes," 2003, J. Computer Communications, 26, pp. 1131-1144.

[20] Park G, Rosing T, Todd M D, Farrar C R, and Hodgkiss W, "Energy harvesting for structural health monitoring sensor networks," 2008, J. Journal of Infrastructure Systems, 14, pp. 64-79.

[21] Lockwood D. Harvesting power when freshwater meets salty. (2013). Available: http://cen.acs.org/articles/91/web/2013/11/Harvesting-Power-Freshwater-Meets-Salty.html

[22] Zi Y, Lin L, Wang J, Wang S, Chen J, Fan X, et al., "Triboelectric-pyroelectric-piezoelectric hybrid cell for high-efficiency energy-harvesting and self-powered sensing," 2015, J. Adv Mater, 27, pp. 2340-7.

[23] Ulukus S, Yener A, Erkip E, Simeone O, Zorzi M, Grover P, et al., "Energy harvesting wireless communications: A review of recent advances," 2015, J. IEEE Journal on Selected Areas in Communications, 33(3), pp. 360-381.

[24] Cihar J, Grabs W, and Landwehr J, "Global terrestrial observing system establishment of a global hydrological observation network for climate report of the gcos/gtos/hwrp expert meeting," 2000, J.

[25] Molino-Minero-Re E, Carbonell-Ventura M, Fisac-Fuentes C, Manuel-Lázaro A, and Toma D M, "Piezoelectric energy harvesting from induced vortex in water flow," in Instrumentation and Measurement Technology Conference. IEEE, 2012.

[26] Song R, Shan X, and Xie T, "Numerical study of the aerodynamic response and energy harvesting of polyvinylidene fluoride piezoelectric flags in a uniform flow," 2016, J. Journal of the Chinese Chemical Society, 63, pp. 545-552.

[27] Shan X, Song R, Fan M, and Xie T, "Energy-harvesting performances of two tandem piezoelectric energy harvesters with cylinders in water," 2016, J. Applied Sciences, 6, p. 230.
[28] Shan X, Deng J, Song R, and Xie T, "A piezoelectric energy harvester with bending–torsion vibration in low-speed water," 2017, *J. Applied Sciences, 7(2)*, pp. 2076-3417.

[29] Grouthier C, Michelin S, and Langre E d, "Optimal energy harvesting by vortex-induced vibrations in cables," 2012.

[30] Tanakaa Y, Okoa T, HidemiMutsudaa, Popovb A A, Patelb R, and McWilliamb S, "Forced vibration experiments on flexible piezoelectric devices operating in air and water environments," 2014, *J. International Journal of Applied Electromagnetics and Mechanics, 45* pp. 573–580.

[31] Xie X D, Wang Q, and Wu N, "Energy harvesting from transverse ocean waves by a piezoelectric plate," 2014, *J. International Journal of Engineering Science, 81* pp. 41-48.

[32] Wu N, Wang Q, and Xie X, "Ocean wave energy harvesting with a piezoelectric coupled buoy structure," 2015, *J. Applied Ocean Research, 50* pp. 110-118.

[33] Yang Z, Wang Y Q, Zuo L, and Zu J, "Introducing arc-shaped piezoelectric elements into energy harvesters," 2017, *J. Energy Conversion and Management, 148* pp. 260-266.

[34] Zhu X, *Piezoelectric ceramic materials: Processing, properties, characterization, and applications*, 2010.