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Perspective microscale piezoelectric harvester for converting flow energy in water way

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ABSTRACT

This work proposes an energy harvester that captures the mechanical energy caused by water flow and converts into an electrical energy through the piezoelectric effect. A flexible piezo-film has been used as a transducer in the energy harvesting system and the kinetic energy of the water flow is produced by using the vortex induced vibration technique. When placing in water way the transducer is fluctuating in the vortex of the fluid flow, producing the kinetic energy of 44 μW at a low fluid velocity of 6.8 m/s and low frequency of 0.4 Hz. This configuration generates a corresponding open-circuit voltage of 6.6 mV at a matching load of 1 MΩ, leading to the maximum output power of 0.18 μW. An efficiency power conversion of the harvesting system was evaluated to be about 4.4 %. It is possible to use the proposed unit under gravitational force where there is a difference in the levels of the fluid no matter in water way or transporting parts such as petroleum pipes. However, rectifying the output voltage generated by the present micro generator is compulsory in order to feed small scale electronics and communication, for instance, wireless sensor networks. Furthermore, multiple arrays of the piezoelectric unit are also promising for delivering higher output power. Copyright © 2015VBRI Press.

Keywords: Piezoelectric; PVDF; energy harvesting; hydropower.

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Introduction

For many years there have been remarkable evolutions of self-powered devices such as airborne and stationary surveillance cameras, medical sensors, and wearable personal electronics **[1-3]**. These devices are conceived to work in a standalone manner, in particular, in rural places or in unmanned vehicles. While there is a decrease in powering various electronic components, there is an increase in developing microgenerators to provide sufficient electrical energy for those low power consumption devices. One of the most recent technologies is the piezoelectric power generator where a mechanical

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energy is captured and converted into an electrical energy through the piezoelectric effect. The most attractive advantage of the technique is that there is no combustion involved in the energy conversion process.

Among several ambient sources of mechanical energy such as vibration, human motion, wave's potential, or wind, it can be a vibrating structure, a moving object, and vibration induced by flowing fluid or gas (water or air). The energies are related to induced vibrations or movement to the piezoelectric film by fluid/gas flow with several techniques applied **[2]**.

Harvesting energy from fluid flow by flow induced vibration has been studied by several authors **[3]**. Well-known piezoelectric polymer films, i.e. polyvinylidene-fluoride (PVDF) have been used as "eels" for traveling vortices behind a bluff body to strain the piezoelectric elements. The flapping mechanical motion resembles that of a natural eel swimming, which can be converted into electrical power by harvesting.

Taylor *et al*. **[4]** studied the interaction between the hydrodynamics of water flow and the optimized resonance circuit. A year later, Techet *et al*. **[5]** presented the flapping frequency as a function of increasing flow speed and exposed a relation of strain energy density with different lengths of the eels**.** However, the output power of the membrane was not presented. Pobering and Schwesinger **[6]** presented two designs of a flattering flag and a piezo-bimorph generator, which is the place of the von Kármán's hydrodynamic instability. The maximum power density of the piezo bimorph configuration has been evaluated of around 68 W/m^3. Akaydin et al. **[7]** placed flexible piezo-electric cantilever beams inside a turbulence boundary layer which; here the experimental and the computational simulation results of voltage outputs that have been validated for a wake of a circular cylinder at high Reynolds numbers. All of them were performed in large scale envelopment, in a wave tank/river/ocean. An alternative system for harvesting water flow energy has been provided by the installation of a small scale pipe system. Wang et al. **[8]** presented the fabrication and demonstration of a proposed device, where a piezoelectric film oscillates on a flexible diagram due to vortices shed from the bluff body in a water flow channel. Indirect energy scavenging from fluid flow though unsteady vortices has been presented by Molino-Minero-Re et al. **[9]**; they used motion from a cylindrical bluff body that generated vortices and a cantilever holds the piezoelectric generators.

Not earlier than 2011, with the investigations described above, piezoelements were embedded in the media flow. However, we have not found any direct experimental evidence of a small scale ambient harvesting system. This work aims to harvest water flow energy by using a flexible piezo film and a vortex induced vibration (VIV) technique **[10]**. The proposed piezogenerator can be directly placed in water way and an advantage is that the absence of rotating elements and thus a maintenance free device is possible.

Perspective system

The fluid flow energy harvesting by vortex induce vibration is a highly nonlinear phenomena. The frequency of vortex shedding (*fs*) needs to approach the resonance frequency (*fr*) of the piezoelectric generator for obtaining the highest energy output. Many factors have an effect on that system such as a mean value of fluid flow velocity (*U*), the bluff body's height (*D*), and others. This article explores in the details of the concept as presented in **Fig. 1**. When the fluid flow is passing over a bluff body, the VIV has been generated by the vortex's shedding oscillation. The piezoelectric elastic film (like a flag) is oscillating. This behavior can be described by a mechanical spring mass vibration. The harvested electrical output from the piezoelectric convertor can be predicted by using an equivalent circuit model.

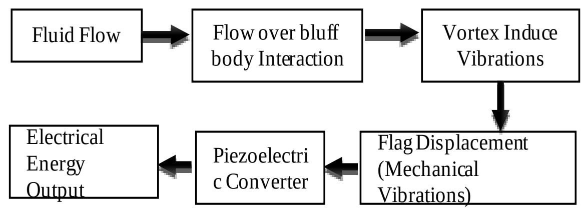

Fig. 1. Perspective model of fluid flow energy harvesting via VIV.

Vortex induced vibration

With fluid dynamics, the VIV method is a fundamental concept of a clean and renewable source of energy. Periodic oscillating flow over a stationary circular cylinder (bluff body) in a fluid at rest is characterized by the Reynolds number (Re). It can be expressed as the ratio of inertial forces and given by;

$$\mathrm{Re} = \frac{\vec{U} \cdot D_h}{\nu} \tag{1}$$

where ν is the kinematic viscosity and D_h is the hydraulic diameter. The parameter f_s for a cylinder is related to the Strouhal number (St), which is a dimensionless number as a function of Re, describing oscillating flow mechanisms by following equation **[11]**;

$$fs = \frac{\mathrm{St} \cdot A}{D} \tag{2}$$

where *A* is the flow channel area. The vortex shedding frequency is evaluated from the above equation on the rough assumption that St has a constant value of 0.21.

Consider the elastically supported rigid circular cylinder, the Kutta-Joukowski theorem can be used to determine the lift force (F_L) acting on the bluff body due to fluid flow. The fluid structure system can be treated as a mechanical sprig mass system with a fluid forcing function as given by eq. (3) **[12]**;

$$\ddot{Y}(t) + 2\varsigma\dot{Y}(t) + Y(t) = \frac{U^{*2}}{m^*} c_y(t) \tag{3}$$

Where,

$$m^* = \frac{2m}{\rho L D^2}; U^* = \frac{U}{\omega_n D}; 2\varsigma = \frac{b}{m\omega_n}; \omega_n = \sqrt{\frac{k}{m}} \tag{4}$$

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The related parameters constant m is a bluff body mass, m^* is the cylinder to fluid mass ratio, $Y(t)$ the displacement of cylinder oscillation, U^* the non-dimensional free velocity, $c_y = 2F_y/\rho DU^2$ the lift coefficient in y-direction, L the cylinder length, ω_n the natural frequency of system, ρthe fluid density, b the damping coefficient, and k is the spring constant. Assuming the quantity of lift acting on the beam structure and cylinder structure together, although the cylinder was fixed. The c_y also generated in periodicity and it is given by;

$$c_y(t) = C_y \sin(\omega t + \varphi) \tag{5}$$

Mechanical vibration

The energy harvester model can be equivalent as a damping mass-spring mechanical system by the degree of freedom (DOF) diagram as shown in **Fig. 2**. The seismic mass connected to movable body by a spring with a stiffness of k and the damper with coefficient of b. For the harvesting conversion, b is comprised of both the parasitic losses of b_p and electrical energy extracted by the transduction mechanism of b_e; $b = b_p + b_e$. This system consisted with seismic mass of m fixed on the moving body and the system is excited by an external force of $f(t)$ acting on with sinusoidal vibration, $Z(t) = Z \sin(\omega t)$. At the resonance frequency, there is a net displacement of $Y(t)$ between mass and frame, then the equation of motion of the seismic mass system can be described by **eq. (6) [13]**;

$$m\ddot{y}(t) + b\dot{y}(t) + k\,y(t) = m\ddot{z} = f(t) \tag{6}$$

where the excitation frequency of ω at the natural frequency of system ω_n and the damping factor of ξ are given by **eq. (7)**;

$$\omega = \sqrt{\frac{k}{m}}\;;\quad \xi = \frac{c}{2\sqrt{km}} \tag{7}$$

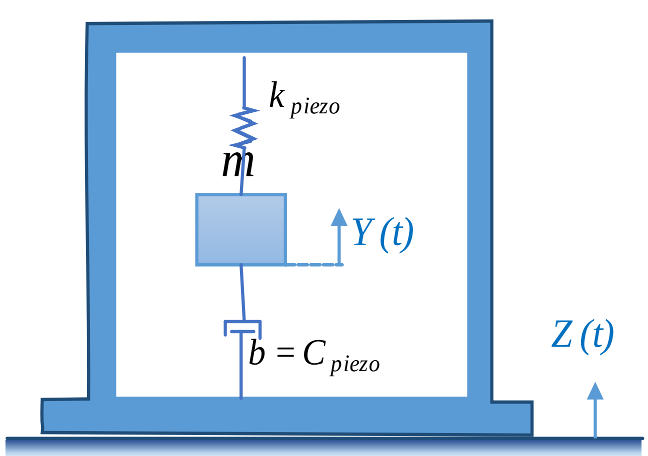

Fig. 2. Generic model of a piezoelectric energy harvester.

Equivalent circuit

The mechanical system can be described with an equivalent diagram with electrical components **[14]**. The inductance of L represents the seismic mass and inertia of the harvester, C_s is inversely proportional to a stiffness of k, C_p represents the static capacitance of the harvester, and R is the insulation leakage resistance of the harvester element, or its represents the damping coefficient of b. For the electric equivalent of a piezoelectric generator model can be described by applying Kirchhoff's current and voltage law, referring to **eq. (8a** and **b)** and **(8c)**, respectively **[15]**.

$$L\ddot{q}(t) + R\dot{q}(t) + \frac{1}{C_s}q(t) + U_{out}(t) = V(t) \tag{8a}$$

$$i = C_p \cdot \dot{U}_{out}\,;\quad U_{out} = U_{Cp} = \frac{1}{C_p}\int i \cdot dt \tag{8b}$$

$$U_{Cp} = V - U_{Cs} - U_{Lm} - U_R$$
$$= V - \frac{1}{C_s}\int i \cdot dt - L_m\frac{di}{dt} - R\frac{dV}{dt} \tag{8c}$$

The measurement of U value and the fluid flow rate (Q) is done by the relation given by **[16]**;

$$Q = \vec{U} \cdot A \tag{9}$$

The fluid flow power (P_{flow}) and the generated electrical power output ($P_{elec.}$) is expressed by;

$$P_{flow} = \frac{1}{2}\rho\, AU^3 \tag{10}$$

$$P_{elec.} = \frac{2V_{rms}^2}{R} \tag{11}$$

where ρ is the fluid density, R the load resistance and V_{rms} represents the root-mean-square value of a voltage drop across the load. The total efficiency conversion (η) of the harvester can be obtained by taking the output power from eq.(11) divided by the input power from eq.(10) as given by;

$$\eta = \frac{P_{elec}}{P_{flow}} = \frac{V_{rms}^2}{\rho RAU^3} \tag{12}$$

Materials and methods

Materials

The piezoelectric harvester unit and the schematics of the fluid flow energy harvesting system are shown in **Fig. 3** and **4.** The harvester consists of a flow channel, bluff body, piezoelectric film, and inlet/outlet covers. The size of the flow channel by length × width × depth is 26 mm × 36 mm × 146 mm, and was made from acrylic sheet series of Xhac-001 provided by Xinghua Manufacturer (RP.China),

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with its thickness of 8 mm. A 6 mm-high and 20 mm-wide rectangular bluff body with rounded edges was placed in the flow channel at the center height and 50 mm from the inlet boundary. A water proof laminated flexible piezoelectric PVDF film is from the LTD1-028K/L series manufactured by Measurement Specialties Inc., (U.S.A.) **[17]**. The properties of the material are presented in **Table 1**. The piezoelectric film was cleaved behind to the buff body. Inlet and outlet boundaries were each covered by rectangular cone with 50 mm in length and 10 mm of cavity diameter as shown in **Fig. 3**. All the ABS plastic accessories as bluff body and both inlet/outlet covered had been designed and manufactured by using a Makerbot replicator 2x experimental 3D printer (U.S.A.).

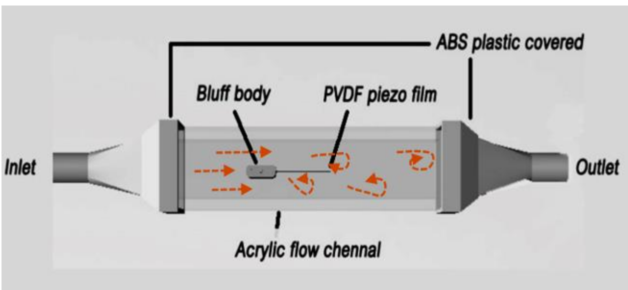

Fig. 3. Harvester unit.

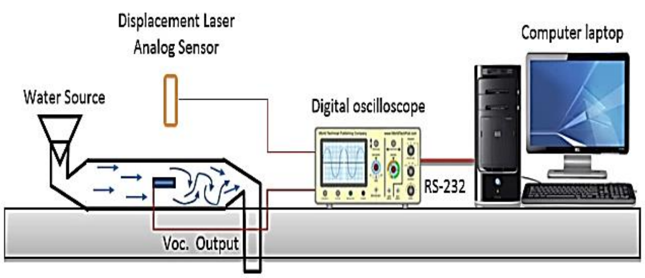

Fig. 4. Schematic diagram of the fluid flow energy harvesting setup.

Table 1. Summary of the PVDF film property.

Density kg/m^3	Young modulus x10^{9}N/m^2	Capacitance nF/cm^2 @1kHz	Relative permittivity ε_r	Piezo strain const. 10^9 C/N d_{33}	d_{31}	Piezo Coupling factor k_{31}	k_t
1,780	2-4	1.38	12-13	-33	23	12	14

Fig. 4 is a schematic diagram of the experimental apparatus for testing the fabrication device by ordinary tap water was used as the source supplying the fluid flow energy. Then water was running through an inch diameter PVC elastic tube. A Rota-meter (Fisher & Porter Co., model 10A3565, U.S.A.) was used for flow rate (Q) measurements and it was placed between the water supply and the harvester unit, joined together by PVC elastic tubes. After that the water passed the harvester unit, and finally it was released back to the sink. A digital oscilloscope (Tektronix, TPS 2014, P.R. China) was used at a 2,500 sample rate for 10.0 s measurements. Tip displacement film vibrations were taken for average amplitude of PVDF oscillation (A_{avg}) by using a CMOS Laser Analog Sensor (IA-030, Keyence, Japan) with an amplifier (IA-1000, Keyence, Japan) connected to an oscilloscope. All the measured data were collected by LABVIEW software via a USB to RS-232 cable. Spectral analysis and low passed filter function were carried out by using MATLAB-based FFT routine.

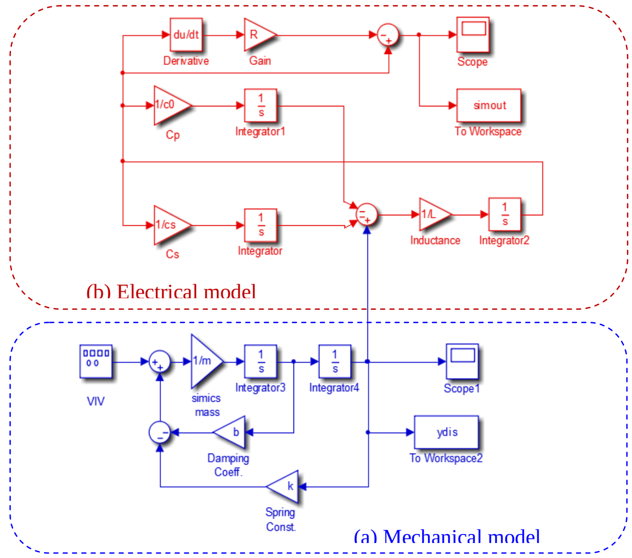

Fig. 5. MATLAB-Simulink of the combination of (a) mechanical vibration and (b) equivalent circuit models.

Table 2. Results of fluid flow characteristics and energy output on the VIV effect.

Q gallons /min	*Beam oscillation* f (Hz)	A_{avg} (mm)	*Flow characteristic* U m/s	Re	f_s (Hz)	*Electrical energy output* $V_{oc.}$ (mV)
0.6	-	2.86	3.8x10^{-5}	37.7	0.40	6.60

Methods

Water supply Q has been controlled by a ball value and fixed Uat 3.78×10^{-5} m^3/s. The corresponding frequency of f_s from a bluff body had been calculated by using **eq. (2)**.

Electro-mechanical systems can be modeled in the multi-purpose simulation environment MATLAB-Simulink. In this section, the fluid flow harvesting experiment setup is presents in **Fig. 5**. The flow characteristic information can be calculated by using **eqs. (9)-(12)** to obtain mechanical vortex shedding oscillation data. Assuming the amplitude of vortex shedding oscillation is 2/3 of D_h, and a flow condition with Reynold no. of 37.7, the $Q \approx 0.6$ gallons/min was obtained from **eq. (1).** The proper Simulink model of the combination mechanical vibration (red color) for the film oscillations and the equivalent circuit (blue color) for the voltage output were presented in **Fig. 5(a)** and **5(b)**.

Results and discussion

The flow characteristics results of the VIV effect and electrical energy output have been summarized in **Table 2**. The obtained flow velocity value of this experiment occurred in Re≅37.7, which indicates a laminar flow steady

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state. The mechanical oscillations established by a pair of fixed vortices was generated in the wake of a bluff body corresponded to U=3.8×10^{-5} m/s. Oscillating frequency was not detected because of the vortex pair oscillations at upper and lower of film were canceled out, although the A_{avg} could be observed with 2.86 mm.

Using flow characteristic information, the f_s and $\mathbf{A_{avg}}$ in Table 2. applied to the VIV signal generator as shown in **Fig. 5**, the results of the tip displacement at the free end of the film oscillations obtained from the simulation are shown in **Fig. 6**. The results have been presented after applying a low passed filter the $V_{oc.}$ signals by the Fourier technique with MATLAB to take away the high frequency which might associate to electromagnetic radiation noise from other electronic devices. The filtered under 10 Hz signal was in good agreement with the simulation results as seen in **Fig. 7;** a comparison of the displacement oscillations of the film, which is corresponding to the filtered experimental signal from the simulation with 180 degree phase difference. Moreover, the frequency of $V_{oc.}$ experimental results in **Table 2** is agreeable to the calculated flow information of the VIV.

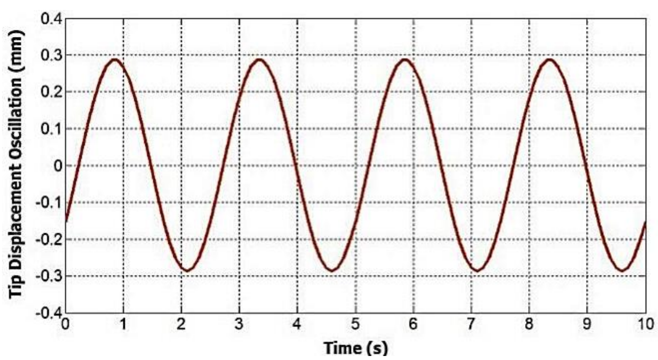

Fig. 6. Displacement of film oscillations at free end.

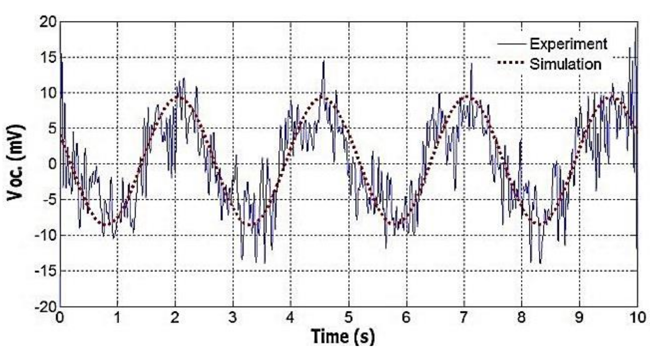

Fig. 7. Low passed filtered of $V_{oc.}$ signal with the results of MATLAB-Simulink.

Taking the common load R=1 MΩ for the PVDF **[18]**, the total conversion efficiency of the microgenerator was able to calculte by using **eq. (12)**. The regular flow pattern represented the maximum $V_{pp.}$ at Re = 37.7 which lead to the maximum P_{flow} = 44 μW and P_{elec} = 0.18 μW. These power values give the η≈4.4 %. This is the performance of a single piezo-generator. An increase in η can be developed by producing multiple arrays of the harvester, so that the $P_{elec.}$ is increased at a constant P_{flow}.

Conclusion

This work presents a micro-generator converting an energy from fluid flow into an electrical output based on the piezoelectric effect. A flexible PVDF has been used as a transducer in the energy harvesting system. Experiments need not perform at a resonance frequency but at a low oscillating frequency of 0.4 Hz and a tailored fluid velocity of ~6.8 m/s., producing the kinetic energy of of 44 μW. This unit generates a corresponding open-circuit voltage of 6.6 mV at a matching load of 1 MΩ, leading to the maximum output power of 0.18 μW. An efficiency power conversion of the harvesting system was evaluated to be about 4.4 %. It is possible to use the proposed unit under gravitational force where there is a difference in the levels of the fluid no matter in water way or transporting parts such as petroleum pipes. However, rectifying the output voltage generated by the present microgenerator is compulsory in order to feed small scale electronics and communication, for instance, wireless sensor networks. Furthermore, multiple arrays of the piezoelectric unit are also promising for delivering higher output power.

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