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A Nonlinear Vibration Energy Harvester with Bandwidth Enhancement Excited by Fluid Flow

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Abstract: In this paper, a magnetically coupled piezoelectric energy harvester is proposed. A dual-mass system is fitted with a bluff body to harvest vortex-induced vibration (VIV) from a fluid flow in an open channel setup. Vortices formation behind the bluff body leads to utilizing vibration-based energy harvesting. Increasing the water velocity increases the overall output voltage and until a maximum at the natural frequency of the system when synchronization phenomena is observed. Broadband energy harvester is achieved by attaching magnets on the bluff body and is useful for increasing the harvestable range of variable flows. While conventional narrowband energy harvesters are still more superior when near to the natural frequency, the magnet coupling broadens the synchronization range of the harvesters by 35%. This proposed design made from 3D printed components can be used as a framework for compact energy harvesters and placed in multiple arrays inside pipelines to power wireless sensing devices.

Keywords: Vortex-induced vibration, Broadband energy harvesting, Synchronization, Piezoelectric.

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1. INTRODUCTION

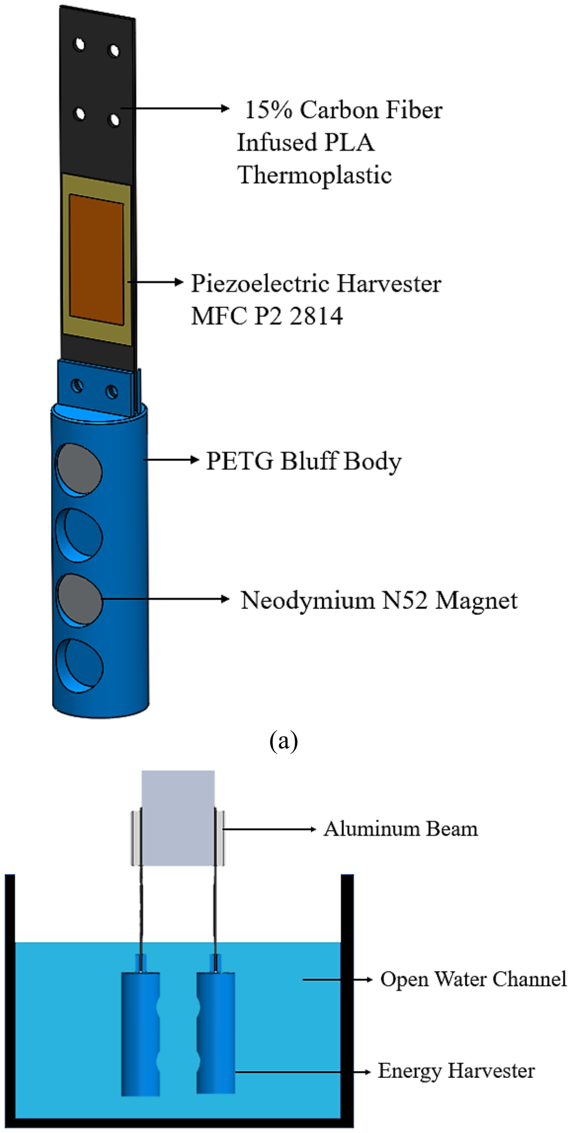
Vibration energy harvesting (VEH) is important for powering small devices as it utilizes the surrounding medium or applications in converting kinetic energy into electrical energy. Self-sustaining wireless devices have recently been shown to be viable with the addition of control systems and storage mechanisms [1]. Piezoelectric energy harvesting (PEH) is a well-researched topic, offering high performance, versatility and compactness at a competitive price [2]–[4]. Previous optimization work has provided parameter insights to maximize PEH [5]. The patches are usually attached to oscillating beams that generate charge when mechanically stressed. Electromagnetic generators are also employed in energy harvesting but are more bulky than PEH so are generally reserved for larger devices [6]. The addition of a bluff body allows for energy harvesting through flow-induced vibration of a fluid medium [7]. Vortex-induced vibration (VIV) is one of the widely adopted methods of VEH by taking advantage of periodic oscillations found in vortices [8]. Wang et al. [9] classifies flow-induced vibrations into different classifications of forced vibration modes such as fluttering, buffeting and galloping. The response of VIV has been shown to output large structural deformations during ‘synchronization’ or in the ‘lock-in region’ when the structural natural frequency matches the vortex shedding frequency [10]–[13]. Williamson & Govardhan outlined parameters for VIV harvesters by taking advantage of synchronization and vortex shedding modes [14]. Norberg [15] provided the collapsed data of VIV response in literature for various Reynolds Numbers and dimensions. Blevins [16] proposed mathematical models for the cylindrical bluff body response under the influence of VIV with robust agreement with experimental results. The adoption of vortex-induced vibration piezoelectric energy harvesting (VIVPEH) enhances energy harvesting by attaching piezoelectric beams to bluff bodies [17].

Broadband energy harvesting applications is usually implemented to capture a wider range of harvestable frequencies and increasing the harvested power [18]. Dauda et al. [19] investigated the broadband properties of piezoelectric beams by introducing nonlinear magnetic forces. Ali et al. [20] highlighted the piezoelectric plate properties in enhancing the energy harvesting properties. More recently, Hafizh et al. [21] improved on previous work by providing an alternative piezoelectric-electromagnetic design with bluff-body parameter optimizations.

In this paper, a compact vibration-based piezoelectric harvester collecting energy from a fluid stream is proposed. The harvesting mechanisms of piezoelectric and magnetic can be used to power monitoring and diagnostic systems for pipe flow applications.

2. PHYSICAL MODEL

The proposed design of the nonlinear vibration energy harvester is shown in Figure 1, which is submerged in water. The design specifications and parameters were expanded from work done by the author’s in creating a compact hybrid energy harvester [21]. An identical system is facing each other, and the magnetic field attached to both allows for the interaction. The whole system is made from 3D printed thermoplastic which allows for increased versatility in manufacturing and decreases the overall mass. 15% carbon-fiber infused polylactic acid (PLA) was used as the substrate for flexibility (compared to conventional aluminum and steel substrates) with the composite blend adding rigidity to prevent plastic deformation during deformation. The bluff body is made from polyethylene terephthalate (PETG) which provides that has good properties in water and does not break down at higher temperatures.



(a)

(b)

Figure 1. Proposed energy harvester: (a) Schematic of components; (b) Assembly of setup for Dual Energy Harvesters (DEH)

VIV oscillations causes the deflection of the substrate which can be modeled in Figure 2 and derived in Equations (1) – (3). The voltage output of the system is calculated in Equations (4) and (5). Vibration-based kinetic energy was converted to electrical energy using a piezoelectric macro fiber composite from smart materials: MFC-2814-P2 [22].

$$M_1\ddot{x_1} + C_1\dot{x_1} + K_1x_1 + \Theta_1V_1 = F_1 \qquad (1)$$

$$M_2\ddot{x_2} + C_2\dot{x_2} + K_2x_2 + \Theta_2V_2 = F_2 \qquad (2)$$

$$F(t) = F_{Fluid}(t) \pm F_{magnet} - F_{Piezo}(t) \qquad (3)$$

$$V_1(t)/R + C^s\dot{V}_1(t) - \Theta_1\dot{x}(t) = 0 \qquad (4)$$

$$V_2(t)/R + C^s\dot{V}_2(t) - \Theta_2\dot{x}(t) = 0 \qquad (5)$$

where M, C and K represent the equivalent mass, damping and stiffness of the system, respectively. Also, $\ddot{x}$, $\dot{x}$ and x represent the acceleration, velocity, and displacement, respectively. Here, Θ represents the electromechanical coupling of the piezoelectric patch when being deformed, C^s is the clamp capacitance, R the resistance and V is the measured voltage output.

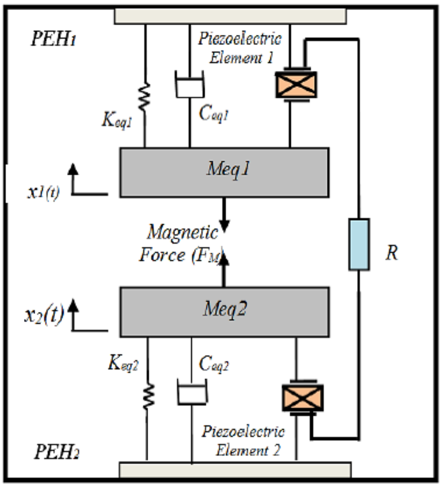


Figure 2. Equivalent Bluff Body Mechanical System of Two Magnetically Coupled Energy Harvester [19]

Because the magnet can be either attractive or repulsive, both instances can be evaluated and compared [19]. In this study, F_{magnet} looks at only the repulsive forces of the magnet on the energy harvesting. F_{Fluid} represents the transverse oscillations because of the bluff body [16]. F_{piezo} is the actuating effect caused by the accumulated charge on the piezoelectric patch [23]. Equations (6) and (7) represent the equations used to derive the forces. τ_0 is the permeability of the medium, m_1 and m_2 the moments of the magnetic dipoles and D_0 is the distance between magnetic tip mass and the fixed magnet.

$$F_{fluid} = \frac{\rho U^2 DL}{2}\left(C_{mv}\sin(\omega_v t) + C_{dv}\cos(\omega_v t)\right) \qquad (6)$$

$$F_{magnet} = \frac{3\tau_0 m_1 m_2}{2\pi}\left[x_1(t) - x_2(t) + D_0\right]^4 \qquad (7)$$

The water velocity to excite an elastically mounted cylinder is given by Equation (8) where the Strouhal Number (St) is approximated as 0.2 based on literature [14], [16]. Where f_n is the structural natural frequency, D is the diameter of the bluff body and U the water velocity.

$$St = f_n D/U \qquad (8)$$

3. EXPERIMENTAL SECTION

The experiment was carried out on an open channel research flume developed by Armfield, the setup and details are attached in Figure 3 and the material properties are shown in Table 1. Water is pumped into channel and velocity is adjusted through a shunt on the motor. Water level can also be varied through a gate just before the outlet and can be used to adjust the adequate water level to reach the bluff body

Table 1. Material and dimensional properties of energy harvester

Symbol	Description	Value	Unit
l	Substrate beam total length	70	mm
l_a	Active substrate beam length	55	mm
b	Substrate layer width	20	mm
t	Substrate layer thickness	0.95	mm
d	Cylinder bluff-body diameter	21	mm
h	Main bluff-body height	60	mm
ρ_{beam}	Substrate beam density	1300	kg/m^3
$\rho_{cylinder}$	Cylinder bluff-body density	1270	kg/m^3
ρ_{fluid}	Fluid density	999	kg/m^3
ρ_{piezo}	Active piezoelectric composite density	5400	kg/m^3
A_{2814}	2814-P2 piezoelectric active area	392	mm^2
A_{0714}	0714-P2 piezoelectric active area	98	mm^2
M	Equivalent system mass	0.0231	g
M_a	Added equivalent mass	0.0231	g
C_P	Clamp capacitance for piezoelectric transducer	–	F
Θ	Electromechanical coupling coefficient	–	NV^{-1}

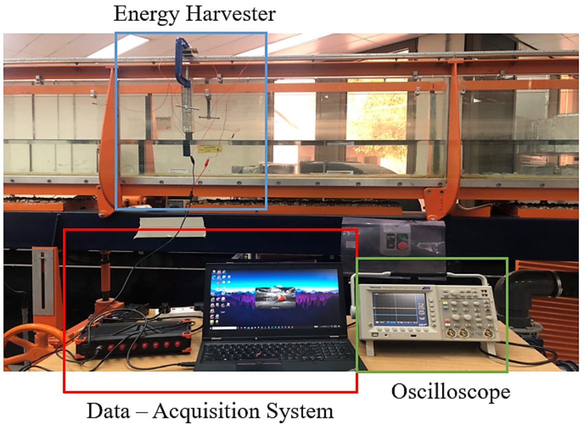


Figure 3. Experimental setup schematic of setup with DAQ

Vibration-based energy harvester's performance can be enhanced by harvesting near to the natural frequency (f_n) of the system. At this point, the bluff body oscillations reach a maximum and piezoelectric strain can be converted to voltage in large magnitudes. Table 2 shows the measured natural frequencies of the energy harvester in air and still water. The expected natural frequency in still water is calculated by taking the hydrodynamic effects of the water into account [21]. For the non-magnetically coupled normal dual harvester, $f_{nw,theoretical}$ was about 6% to 13% higher than the value of $f_{nw,experimental}$.

Table 2. Natural frequency of energy harvesters

	Normal Dual Harvester	Magnet Dual Harvester
Measured natural frequency in air ($f_{n,air}$)	8 Hz	9 Hz
Expected natural frequency in still water ($f_{nw,theoretical}$)	5.66 Hz	6.37 Hz
Measured natural frequency in still water ($f_{nw,experimental}$)	5 Hz	6 Hz
Water velocity corresponding to natural frequency (U_{fnw})	0.525 m/s	0.63 m/s

4. RESULTS AND DISCUSSION

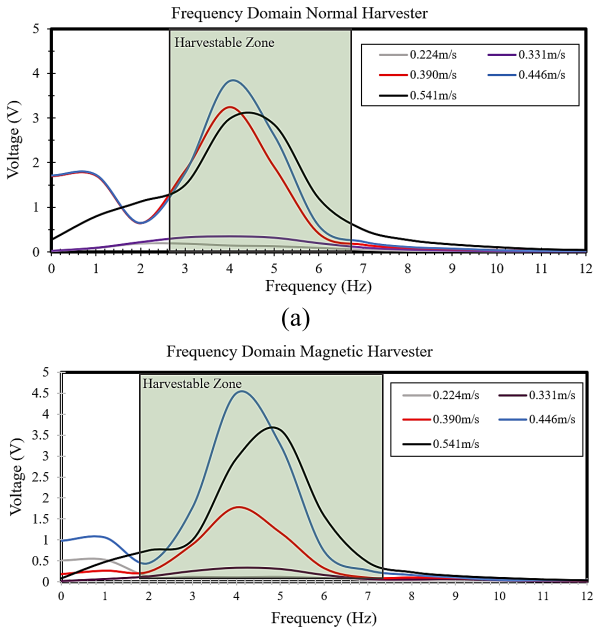
The experiment first measured the response of a single piezoelectric system, the Fast Fourier Transform analysis is shown in Figure 4. The harvester operates a low frequency, this is advantageous because lower mass ratio can help with VIV oscillations [11]. Since the energy harvester was designed for low frequency and first resonance point, the analysis only looked at a maximum of 12Hz.

Afterwards, the dual magnet coupled system is inserted into the water tank and the voltage output is recorded via DeweSoft Data Acquisition System and the water velocity is also recorded at each reading. Table 3 represents the root mean square voltage output of over the measuring range for a single energy harvester (SEH) and DEH. Only one value of SEH was taken for reference and the remaining study was performed on DEH configuration.

Table 3. Comparison between single and double energy harvesters

Water Velocity (m/s)	RMS Voltage Output (V)			Magnet Enhancement (%)
	SEH	Normal DEH	Magnet DEH	
0.200	0.170			
0.224		0.161	0.578	259%
0.331		0.367	0.247	-32.7%
0.390		0.56	3.92	600%
0.446		8.07	3.60	-55.4%
0.541		2.33	1.75	-24.9%

Table 3 shows that as the velocity increases, the amount of vibration also increases as more vortices is formed and is highest when close to the natural frequency. The main drawback of a narrowband energy harvesters can be seen when comparing a single harvester to the dual harvester where the performance is very limited. The reason for the lower RMS voltage in DEH compared to SEH at lower velocities could be due to vortex formation suppression. The addition of the magnet has improved the RMS voltage performance even at lower water velocities by 259% and 600% for 0.224 m/s and 0.39 m/s. Despite this, the normal dual harvester outperformed the magnet dual between 25-55% when close to resonance. The frequency performance is shown in Figure 4 through a Fast Fourier Transform (FFT). Here, the outlined harvestable zone is the area where efficiency for the energy harvester configuration is near to maximum. Normal harvester shown in Figure 4(a) has a narrow window for enhancing the performance whereas the magnetic harvester has a wider window and can be used for the design of variable flow velocities. Synchronization region of the energy harvester has been increased by 35% with the use of magnets placed 20mm apart.



(a)

(b)

Figure 4. Frequency Response of Harvesters; (a) Normal Harvester; (b) Magnetic Harvester

4. CONCLUSIONS

Overall, a magnetically coupled nonlinear vibration energy harvester was investigated with the following conclusions:

- Piezoelectric energy harvesting can be implemented in pipelines to power wireless sensing devices with the current macro fiber composites.
- The addition of magnetic nonlinear forces can enhance the energy harvesting properties at lower velocities by 600% and broaden the synchronization range by up to 35%.
- Narrowband piezoelectric energy harvesting is more superior for applications of fixed flow and designed to oscillate near the structural natural frequency.
- The use of 3D-printed materials to make compact energy harvesters can improve the accessibility and feasibility of harvesting energy.

Future work into the different configurations, magnets and including a rectifier system can further enhance the energy harvesting properties of the system. Enhancing the broadband properties by varying the magnet strength and orientation would also be part of additional work.

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