Research Article

A Pressure-Based Electromagnetic Energy Harvester for Pipeline Monitoring Applications

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This work presents modeling, simulation, fabrication, and testing of a novel flow-based electromagnetic energy harvester (F-EMEH) for producing usable electrical energy from the pulsating fluid pressure levels within the pipeline. The power produced by the developed harvester can be effectively utilized for the operation of the wireless monitoring system of pipeline networks. The devised F-EMEH harvester consists of a stationary magnet positioned in the upper cap of the harvester and directly facing the wound coil that is fixed to a flexible latex membrane. The membrane along the coil when exposed to the pulsating fluid flow in the pipeline oscillates with respect to the stationary magnet. This relative motion of the membrane induced the voltage across the coil terminals. The harvester when applied to a pressure amplitude of 625 Pa generated an open circuit voltage of 1.2 V and a maximum load power of 18.6 μW when connected to 4.3 Ω load. Furthermore, when integrated to a voltage rectifier, an open circuit output of 4 V DC is achieved by the device at a pressure of 625 Pa. In addition, with the developed prototype, a 3.6 V, battery is charged up to 3.2 V within 30 min of duration. The voltage and power levels attained by the energy harvester can provide an easy solution for powering wireless sensor nodes mounted on a pipeline network for condition monitoring.

1. Introduction

Wireless sensor nodes (WSNs) have taken on immense significance in applications for condition monitoring in recent years. The WSNs have vast number of applications in the monitoring of physical and environmental conditions, such as machine health monitoring, traffic sensing and control, assets tracking, infrastructure condition detection, and monitoring of pipelines (carrying oil, water, and gas) [1–4]. Pipelines are typically subjected to extreme environment conditions like terrorist attacks, and similarly, corrosion may occur because of transportation of resources through the pipelines. This can destroy the infrastructure of these pipeline networks [5] The WSNs are key to monitoring oil and gas pipelines to detect any sort of malfunctioning. Such pipelines are usually located in remote and inaccessible locations; so, detecting any kind of defects is difficult in the piping system due to which the overall maintenance process is severely affected. Therefore, industries such as petrochemicals, petroleum, and natural gas are paying considerable attention to pipeline health, quality, and feasibility. Quality control and security of pipelines are very important to prevent any loss of natural resources or damage to the infrastructure of the pipeline [6]. Table 1 shows sensing and condition monitoring systems implemented on pipelines operated in different countries. These pipeline systems are available for oil and water transport purposes. Various monitoring systems such as water
control, fluid leak detection, and seismic monitoring system can be usually employed for surveillance of pipeline networks. Normally, in these systems, fluid pressure, flow velocity, flow discharge, and fluid leakage are sensed and monitored.

For regular supervision and surveillance of pipelines, sensors are utilized which facilitate in flow monitoring and moreover, help to detect any faults or damages in the pipeline and can also relay the desired information from the pipeline system to the control centre [9]. The arrangement of WSNs that are mounted on surveillance pipelines is shown in Figure 1. The network has a variety of detection terminals where WSNs are installed for the purpose of sensing and monitoring; these terminals are multifunctional, low-power WSNs, which consume less space and have longer life span. The WSNs transmit the information to the master sensor nodes, from where the information is then transferred to the control station with internet connection, and hence the information data is accessible worldwide.

The wireless sensor networks for pipeline sensing and detection provide secure, reliable, and speedy information across the pipeline network. Table 2 shows WSNs used for the condition monitoring of pipelines. It highlights various wireless monitoring systems which can be utilized for the surveillance and control objectives of pipelines. In addition, it details the usage of various WSN technologies to determine any sort of detection of certain physical parameters. Different pipeline monitoring systems based on WSNs are described for the detection of any malfunctioning and abnormalities in the pipeline networks.

Figure 2 shows the system layout of a WSN. The physical signals are received by the sensors and are transmitted to the transceiver through a signal processing circuit. The transceiver is a dual-purpose device, i.e., it receives data and also forwards it further to the operator. The entire data is stored in the memory unit, and in general, the overall operating system is controlled by the microcontroller. Moreover, the WSN utilizes a battery for its power consumption [14].

The power requirement of sensor nodes is fulfilled by batteries; however, the power stored in the batteries is insufficient to run WSNs for longer durations. Similarly, batteries are bulkier in size and furthermore, hazardous to the environment and require proper disposal. Therefore, for pipelines in distant places, the use of batteries in WSNs may restrict their applications. Energy harvesting from ambient sources will be the right option for empowering the WSNs in remote, deserted, and harsh environments. Energy harvesting is a method that extracts energy from available energy sources from the surrounding, such as vibration, wind thermal, and solar energy. Like other ambient energies, vibration energy from pulsating fluid could be easily utilized to harvest energy inside the pipelines for monitoring purpose of the WSNs. A substantial quantity of research has been carried out in literature to achieve considerable amount of electrical energy from vibrations originated by fluid flow to operate of WSNs.

Electromagnetic energy harvester was reported in [15] where a trapezium shaped bluff body is located in the center of flowing fluid and is responsible for generating Karman vortex street. A magnet attached to a stretchable doom-shaped membrane is exposed to the flow passage. In the internal frame of the unit, a magnet is fixed beneath the coil. The device size is 37.9 cm³. Inside the flow channel, the pressure variations cause the membrane to oscillate thereby the magnet moves with respect to the stationary coil, generating electric energy according to Faraday’s electromagnetic induction law. The output voltage of 20 mV_p-p and power of 1.77 μW is generated at a pressure of 0.3 kPa and driving frequency of 62 Hz. Sudhawiyangkul and Isarakorn. [16] presented an electromagnetic energy harvester which is able to provide WSNs with the power required for machine health monitoring. The device is operated at a flow velocity of 175 mm/s. The experimental results revealed the device maximum power density equal to 110 μW/cm³. A piezoelectric energy harvester [17] is made by Wang and Ko based on fluid flow vibrations. The harvester has a flow duct consisting of two glass pipes at the ends. A piezoelectric layer is

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Country</th>
<th>Average length (km)</th>
<th>Monitored parameters</th>
<th>Monitoring system</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water supply system</td>
<td>Goldfields pipelines (Australia)</td>
<td>530</td>
<td>Pressure, flow velocity</td>
<td>Water monitoring system</td>
<td>[5]</td>
</tr>
<tr>
<td>Oil transportation</td>
<td>Alaska (TAPS)</td>
<td>1280</td>
<td>Pressure, flow rate, deviation, flow rate balance, line volume balance</td>
<td>Seismic monitoring system, leak detection system</td>
<td>[7]</td>
</tr>
<tr>
<td>Water distribution</td>
<td>Saudi Arabia</td>
<td>4000</td>
<td>Pressure, flow rate</td>
<td>Water monitoring system</td>
<td>[8]</td>
</tr>
</tbody>
</table>

Table 1: Surveillance of pipelines operated in various countries.
ing electricity. At a making the cantilevers move back and forth thereby generating energy. The harvester is in contact with the three-dimensional piezoelectric energy harvester is reported by Sebastian et al. [19]. The harvester is made of a polydimethylsiloxane (PDMS) diaphragm secured to a polydimethylsiloxane (PDMS) diaphragm which is attached to the flow duct. The glass pipe provides way to the flow, and the fluctuations in pressure of the fluid surge hit the diaphragm. The diaphragm reaches the highest point at high pressure and the lowest point at minimal pressure. The experimental results showed that keeping the excitation frequency at 26 Hz and pressure 1.196 kPa and the output voltage and power of 2.2 Vp-p and 0.2 μW, respectively, is produced by the device. A piezoelectric-based power generation setup is devised by Feifei et al. [18] which creates a Karman vortex street by placing bluff bodies in a flow passage. The system hardware comprises a reservoir, a cylinder, and a polyvinylidene fluoride (PVDF) membrane. The PVDF film of the harvester is deformed in the vortex street, inducing electric field across the PVDF material. The electric power generated by this system is stored in an external memory. The coils are fixed with the iron cores which enhance magnetic flux. This setup is connected to a domestic water impeller. The coils are fixed with the iron cores which enhance magnetic flux. This setup is connected to a domestic water impeller.

![Figure 2: Schematic of a WSN.](image)

<table>
<thead>
<tr>
<th>Wireless monitoring system</th>
<th>Monitoring and control function of pipelines</th>
<th>Objective</th>
<th>Sensor nodes</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Framework for linear WSN</td>
<td>Oil, gas, and water pipelines</td>
<td>Networking and routing protocol</td>
<td>(i) Base sensor node (BSN)</td>
<td>[8]</td>
</tr>
<tr>
<td>PipeNet</td>
<td>Large diameter bulk-water pipelines</td>
<td>Detection and localization of any malfunctioning</td>
<td>(i) Intel mole sensor node (pressure, flow velocity, accelerometer sensors)</td>
<td>[10]</td>
</tr>
<tr>
<td>TriopusNet</td>
<td>Autonomous sensor deployment in water pipelines</td>
<td>Releasing sensor nodes from a centralized location, node placement in the inner surface of the pipeline</td>
<td>(i) TriopusNet node (water pressure sensors)</td>
<td>[11]</td>
</tr>
<tr>
<td>PipeTECT</td>
<td>Nondestructive monitoring of pipeline systems</td>
<td>Determine the variation in pressure of water weight caused by burst or any damage location</td>
<td>(i) Gopher (MEMS-based accelerometer)</td>
<td>[12]</td>
</tr>
<tr>
<td>SWATs: steam flood and water flood tracking system</td>
<td>Monitoring of steam flood and water flood pipelines</td>
<td>Detects and distinguishes significant abnormalities</td>
<td>(i) Single-node processing (pressure and temperature) (ii) Multinode collaboration (pressure and flow velocity)</td>
<td>[13]</td>
</tr>
</tbody>
</table>

0.1 mW, voltage of 0.8 V is generated. The energy harvester [20] consisting of piezoelectric films utilizes waves coming from hydraulic systems to produce electric power. At 400 kPa pressure of the waves, output power of 1.2 mW is produced when the piezoelectric films oscillate. An electromagnetic energy harvester comprising of acrylic made flow channel and a 100 μm thick flexible diaphragm is fabricated by Wang et al. [21]. A magnet is attached to the diaphragm, where a coil is mounted in a separate housing above the magnet. The experiments obtained output power and voltage of 0.4 μW and 20 mVp-p, respectively, at pressure amplitude of 254 Pa and frequency of 30 Hz. Hoffmann et al. [22] fabricated a circular, axial flow-based energy harvester that utilized Faraday's law of electromagnetic transduction. The energy harvester comprises of a magnet of ring shape with three coils arranged in a star topology. The harvester implemented three-phase power generation concept which made use of domestic pipelines for converting water flow energy to electricity provided to power an intelligent metering network. The magnet is mounted on water meter impeller. The coils are fixed with the iron cores which enhance magnetic flux. This setup is connected to a domestic water pipeline for experimental depiction. At minimum flow rate of 3 l/min, power achieved is 2 mW, whereas at maximum flow rate of 20 l/min, 720 mW of output power is produced. To generate electrical power from fluid vibrations, a piezoelectric energy harvester [23] is designed. A piezoelectric membrane oscillates inside the acrylic made flow channel. After the testing, it was discovered that the system provided a 72 mVp-p and 0.45 mW of output voltage and power, respectively, at a pressure of 20.8 kPa and natural frequency of 45 Hz. Pobering et al. built an energy harvester [24] consisting of three cantilevers. Each cantilever contained a bilayered lead zirconate titanate (PZT). The piezoelectric cantilevers are positioned near the bluff body inside the fluid flow causing the cantilevers to oscillate. The resulting
turbulence makes the PZT layer vibrate in order to generate electric charges on the either sides. Output power and voltage achieved are 0.1 mW and 0.8 V, respectively. A reported piezoelectric energy harvester [25] is capable of generating electricity from vibrations induced by fluid flow. These vibrations cause up and down motion of the piezoelectric layer at a pressure of 0.3 kPa and frequency of 52 Hz, producing 120 mV peak and 0.7 nW as output voltage and power, respectively. A pneumatic energy scavenger utilized for harvesting device is presented in [27] that consists of a PDMS diaphragm attached to a flow passage. The Karman vortex street is created by placing the bluff bodies in the fluid’s way to generate variations in pressure. The device generated 14 mV and 0.59 nW output voltage and output power, respectively, under pressure of 70 Pa and excitation frequency of 872 Hz. Electromagnetic energy harvesting device is presented in [26]. The harvester consists of a PDMS diaphragm attached to a flow passage. The Karman vortex street is created by placing the bluff bodies to create flow vortices and generate vibrations, whereas a butterfly valve is used in the following work to generate pulses in the flow and the variation in the flow rate is caused with a help of a motor. The prototype is devised such that without any difficulty, it can be mounted inside the pipeline fittings; moreover, it can be easily integrated with the WSNs to meet their power demands. Besides, the magnet in the energy harvester is held fixed so that it can be conveniently installed in steel pipes. The operating theory of the fabricated device is based on Faraday’s electromagnetic induction law and the produced output which is dependent on the fluctuations produced in the pressure of the pipeline flow.

1.1. Device Architecture and Working Principle. Figure 3 depicts the working principle and device architecture of the flow-based electromagnetic energy harvester (F-EMEH). In the top housing of the harvester is a fixed magnet and a flexible membrane placed at the bottom of the harvester to which a wound coil is attached. The gap is kept low between the wound coil and the magnet. The coil oscillates under the fixed magnet in order can produce electrical energy. The harvester is supposed to be installed on a pipe where the fluid flow is pulsating, i.e., the notch of the tee inside which the energy harvester is placed. As the coil is attached to the membrane, it will oscillate in response to the fluid flow. The flexible membrane is robust enough to oscillate at high pressures without breaking. Since the fluid flow is increasing, simultaneously, there is decrease in the static pressure or the potential energy of the fluid thereby the membrane does not split. The pressure variations within the pipe permit the coil to vibrate in response to the fixed magnet which causes magnetic flux variation at the terminals of the coil. Consequently, according to Faraday’s law of electromagnetic induction, emf is generated within the coil terminals.

1.2. Mathematical Modeling of F-EMEH. Figure 4 shows the lumped parameter model of the fabricated F-EMEH. It is considered as single degree of freedom mass spring damper mechanism for the analytical modeling. The vibrating coil has a certain mass and thus has kinetic energy. Apart from that, the pipe provides resistance to air passage entering it. Because of its elasticity, the proof mass of wound coil is considered as a spring, whereas the flexible membrane has an area A, which is subjected to fluctuating pressure $P(t)$ inside the pipe causing a force $F(t)$. 
According to Faraday’s Law due to the motion between coil and magnet, a changing magnetic flux \( \Phi \) induces emf at coil’s terminals [28–30].

\[
V = -\frac{d\Phi}{dt}.
\]  
(1)

Simplifying equation (1) in terms of magnetic flux density \( B_x \) and velocity \( U \) of the coil (membrane),

\[
V = -U \int \frac{dB_x}{dx} \, dx.
\]  
(2)

Equation (2) can be simplified for a layer of wound coil by taking the area sum \( S_i \) of \( n \) number of turns of the coil individually:

\[
V_{\text{layer}} = -U \left( \frac{dB_x}{dx} \right)_{\text{layer}} \sum_{i=1}^{n} S_i,
\]  
(3)

where \( V_{\text{layer}} \) is the voltage generated due to one layer of the wound coil, and \( dB_x/dx \) is the gradient of magnetic flux density. The magnetic flux density, \( B_x \), through the top of the magnet and along the center line for a cylinder-shaped magnet [31–33]

\[
B_x = \frac{B_t}{2} \left( \frac{x + H_m}{\sqrt{(x + H_m)^2 + R_m^2}} - \frac{x}{\sqrt{x^2 + R_m^2}} \right)
\]  
(4)

is calculated by height of the magnet \( H_m \), the distance between coil and top surface of magnet \( x \), the remnant flux density \( B_r \), and the radius of magnet \( R_m \). The gradient of magnetic flux density is derived by taking derivative of \( B_x \) with respect to \( x \). Taking the number of layers of the coil as \( N_l \), the gradient of magnetic flux density can be computed as

\[
\frac{dB_x}{dx} = \frac{B_t}{2} \left[ \frac{R_m^2}{[(x + H_m)^2 + R_m^2]^{3/2}} - \frac{R_m^2}{[x^2 + R_m^2]^{3/2}} \right],
\]  
(5)

\[
\frac{dB_x}{dx} = \sum_{i=1}^{N_l} \left( \frac{dB_x}{dx} \right)_i = \sum_{i=1}^{N_l} \frac{B_t}{2} \left[ \frac{R_m^2}{[(x + H_m)^2 + R_m^2]^{3/2}} - \frac{R_m^2}{[x^2 + R_m^2]^{3/2}} \right]_i.
\]  
(6)

As the height of the coil is \( H_c \) with wire diameter \( d_w \), \( N_l \) could be modeled as

\[
N_l = \frac{H_c}{d_w},
\]  
(7)

whereas the distance between the coil and surface of magnet \( x_n \) for \( n \) layers (\( N_l \)) can be modeled as

\[
x_n = x + \frac{d_w}{2} + (N_l - 1)d_w.
\]  
(8)

The area sum of single layer coil with internal diameter \( d_i \)

\[
S_i = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} \frac{\pi}{4} (d_i)^2
\]  
(9)

is shown in Figure 5, and \( d_i \) is modeled as

\[
d_i = d_i + (2t - 1)d_w.
\]  
(10)

Substituting (10) in (9), \( S_i \) becomes

\[
S_i = \frac{\pi}{4} \sum_{i=1}^{n} (d_i + (2t - 1)d_w)^2.
\]  
(11)

The total voltage for multiple layers of the wound coil can be determined by replacing (6) and (11) in (3):

\[
V_T = U \sum_{i=1}^{n} S_i \left[ \sum_{i=1}^{N_l} \left( \frac{dB_x}{dx} \right)_i \right].
\]  
(12)
For this system, the maximum amplitude \[ [34, 35] \]

\[
X = \frac{x_o}{\sqrt{\left[1 - \left(\frac{\omega_d}{\omega_n}\right)^2 \right] + \left[2\xi_t \left(\frac{\omega_d}{\omega_n}\right)\right]^2}} \tag{13}
\]

of the membrane vibration relative to the magnet is calculated in terms of driving frequency \( \omega_d \), natural frequency \( \omega_n \), the static deflection of the membrane as \( x_o = F_o/k \), and the total damping \( \xi_t \), which is obtained by adding mechanical damping \( \xi_m \) and the electrical damping \( \xi_e \).
The magnitude of velocity \( U \), in (12), can be calculated by substituting (13) in \( U = X \omega_d \):

\[
U = \frac{F_o \omega_d}{k \sqrt{\left[ 1 - (\omega_d / \omega_n)^2 \right]^2 + \left[ 2 \xi_l (\omega_d / \omega_n) \right]^2}},
\]  

(14)

Further, simplification of (14) in terms of driving frequency \( f_d \), natural frequency \( f_n \), and also \( F_o = PA \) and \( k = m. f_n^2 \) is as follows:

\[
U = \frac{f_d PA}{2 \pi f_n^2 m \sqrt{\left[ 1 - (f_d/f_n)^2 \right]^2 + \left[ 2 \xi_l (f_d/f_n) \right]^2}},
\]

(15)

with applied pressure \( P \) to the definite mass, \( m \) of area \( A \), making it vibrate in the \( x \) direction. When the natural frequency and driving frequency become equal, the output of the device boosts, and

\[
U_{Res} = \frac{PA}{4 \pi f_n^2 m \xi_l}
\]

(16)

is the velocity at resonance. The output voltage can be obtained by substituting (16) in (12):

\[
V_{Res} = U_{Res} \sum_{i=1}^{n} S_i \left[ \sum_{l=1}^{N_l} \left( \frac{dB}{dx} \right)_l \right].
\]

(17)

When the energy harvester is connected to some resistive load \( R_L \),

\[
V_{Load} = \left( \frac{R_L}{R_L + R_C} \right) V_{Res}
\]

(18)

is the load voltage and the load power,

\[
P_{Load} = \frac{V_{Load}^2}{2R_L}
\]

(19)

depends on both the resistance of the load, \( R_L \), and that of the coil \( R_C \),

\[
R_C = \frac{\rho l_C}{A_C}
\]

(20)

can be found with the coil resistivity \( \rho_C \), the area of the coil \( A_C \),

\[
A_C = \frac{\pi d_w^2}{4}
\]

(21)

and length \( l_C \) for \( n \) number of turns of the coil:

\[
l_n = \pi [d_i + (2n - 1) d_w].
\]

(22)

The total length of the coil obtained for multiple layers shall be

\[
l_C = N l_n.
\]

(23)

1.3. Fabrication of F-EMEH. The F-EMEH fabrication steps are depicted in Figure 6. The assembled prototype has a cap of polypropylene random copolymer (PPRC) illustrated in Figure 6(a) showing the coil and magnet assembly. In the 22 mm height and 20 mm diameter dimensions, magnet was put in the cap by using RTV silicone sealant to stick it to the bottom as shown in Figure 6(b). The copper wire is used to fabricate the coil of 100 \( \mu \)m thickness. Using a customized manual wire winding kit, shown in Figure 6(c), a wound coil of 3 mm thick, outer diameter of 12 mm with 1400 turns is made. The fabricated wound coil is shown in Figure 6(d). The stretched latex membrane is placed on another cap like structure as shown in Figure 6(e) to which the fabricated wound coil is carefully pasted with the aid of RTV silicone sealant as shown in Figure 6(f). The PPRC cap is then placed upside down on the stretched latex membrane and modified in a way that the magnet is placed above the coil, and both are 3 mm apart. To take the coil output terminals from the harvester as shown in Figure 6(g), there was already a small opening created inside the PPRC cap. The other cap is detached from the opening of the PPRC cap after the membrane has fixed to it. Figure 6(h) illustrates the harvester’s top view. Finally, the extra excessive membrane is removed from the harvester’s cap. Figure 6(i) illustrates the energy harvester’s isomeric view.

2. Experimental Setup and Results

For the characterization of the energy harvester, experimental setup is built. Figures 7 and 8 represent the block diagram of the setup and the actual experimental setup, respectively. The electric blower of Bostiteng (model B9027) was the main source of airflow. And variable speed electric motor produces variations in flow. The electric motor (CM 12-E) has a disc attach to its shaft. The disc is located inside the pipe and is rotated to produce the pulsating flow. With the aid of a dimmer (speed regulator), the motor speed (disc) can be varied. The pressure variations occur by changing the speed of the motor, to test the response of the device at various amplitudes of pressure and flows. The F-EMEH is located in such a manner that the latex membrane is directly hit by the pressure of the flow, and it moves due to the air pulses. For the construction of experimental setup, an aluminum stand is made so as to hold the electric blower. The
blower is attached over an ordinary flexible plastic pipe to the polyvinyl chloride (PVC) pipe. The PVC pipe is extended with the aid of a tee which is also made of PVC. The developed prototype is placed in the opening of the tee. The PVC pipe with the harvester assembly is mounted on a wooden stand for support. At the bottom of the prototype, the latex membrane directly faces the fluid flow. The air blower provides the fluid medium. This air flow allows the latex membrane and consequently the coil to vibrate. As the magnet is fixed above the coil, the vibrations of the coil induce emf in it. The objective is to get the output of the fabricated prototype at different pressure amplitudes of the pulsating flow, and the rotating disc is mounted adjacent to the energy harvester within the PVC pipe. The spinning disk rotates with help of a motor mounted on the wooden stand for support.
stand. The disc functions butterfly valve as it rotates. The speed of the spinning disc can be varied by changing the motor rpm with the help of a dimmer. With the help of digital tachometer (photo type, model DT-6234B), the motor rpm is measured during testing. At slow speeds, the fluid flow pressure amplitude is small, similarly by increasing the motor speed the pressure amplitude of the flow rise. For sensing the increase in pressure, a pressure sensor MPX 5700 (NXP USA, Inc.) is utilized. The power is supplied via Aurdino Mega 2560 R3 to the pressure sensor. Anemometer (AR 856) is used for recording the pipeline flow velocities. The anemometer is placed on a separate wooden frame, facing the PVC pipe directly to measure the flow rate of the air pulses inside the pipe. The oscilloscope simultaneously measures and analyzes the output voltage signal from the device and the pressure sensor signal.

The test results are plotted for the harvester at various pressure amplitudes and motor speeds. Figure 9 displays the open-circuit output voltage of F-EMEH at several amplitudes of fluctuating pressure. Fluctuations in pressure range from 15 Pa to 625 Pa. The objective of the experiment is to calculate maximum output voltage of the energy harvester. The oscilloscope is used to determine the output AC voltage. The minimum output voltage of 0.02 V is generated by the device when the fluid pressure is minimum, i.e., 15 Pa. The device output is increased when the pulsating pressure is raised, thereby clearly demonstrating that the energy harvester output voltage is dependent on the amplitude of the pressure applied. The voltage generation increased to 1.2 V at maximum pressure of 625 Pa.

The open circuit output voltage is experimented as well as simulated. The analytical model for the prototype is simulated for the values given in Table 3. The output voltage (open circuit; both the experimental and simulated results) of the F-EMEH at various motor speeds is displayed in Figure 10. The motor speed is taken by changing frequency each time, which is displayed on the tachometer, and the corresponding output voltage is recorded. The minimum frequency is 38.3 Hz at which the voltage obtained is 0.3 V. By increasing motor rpm, output voltage increases. So, in this manner, the value of experimental maximum voltage is 1.2 V which is recorded at 107.5 Hz, whereas the simulated maximum output voltage is 1.3 V using the mathematical
model in equation (12). The graph clearly validates the experimental output.

The output voltage (open circuit) is observed at varying flow velocities while conducting the experiment. The anemometer is used to measure the velocities of pulsating flow. Figure 11 shows the output voltage of the energy harvester at different flow velocities. The air blower is calibrated with the motor controlling the spinning disc such that for the minimal flow speed of the fluid is 3.4 m/s. At minimum flow rate, the obtained output voltage is 0.05 V, whereas at maximum flow rate of 18 m/s, the maximum output voltage of 1.2 V is produced.

After the open circuit voltage was achieved, experiments were carried out to find the outputs of closed circuit by attaching (in series) variable load resistor with terminals of the output coil. Figure 12 illustrates the output voltage and output power produced versus load resistance. The prototype is experimented for a range of 0 to 220 Ω resistance. Experimental tests are carried out at various pressure levels; the output voltage exceeded 0.45 V when the pressure was 312.5 Pa at a resistance of 220 V. Similarly, at pressure amplitude of 437.5 Pa, the voltage reached 0.65 V, whereas at maximum pressure of 625 Pa, the voltage reached 0.88 V. The maximum open circuit voltage recorded was 1.2 V, whereas at the same pressure level, the load voltage production is 0.88 V at resistance of 220 Ω. This is due to the resistance offered by the resistor.

The graph in Figure 12 also displays the load power vs. load resistance, which is obtained experimentally. It can be concluded from the results that until the optimum load resistance of 4.3 Ω, the output power keeps on increasing. At this stage, the peak value of maximum power is obtained. For different pressures amplitudes, different response curves are obtained. The output power at a pressure of 437.5 Pa is 7.27 mW. And at the lowest amplitude of pressure, i.e., 312.5 Pa, peak value of load power is 5.13 mW. When the developed F-EMEH is connected to an optimum load of 4.3 Ω and subjected to an amplitude of 625 Pa of pressure, the maximum power achieved is 18.6 mW.

Figure 13 shows the frequency sweep ranging 35 to 400 Hz. The simulations are done using equation (12). As the graph indicates voltage as a function of frequency, peak values of voltage are obtained at resonance which takes place at a natural frequency of 130 Hz and damping ratio equal to 0.025. The voltage at resonance is simulated at various pressures. At maximum pressure of 625 Pa, the voltage at resonance is equal to 10.53 V. When the pressure is decreased to 437.5 Pa, the output peak voltage is 7.3 V and similarly, at minimum pressure of 312.5 Pa, the peak value obtained for voltage is equal to 5.2 V.

Figure 14 shows the simulations performed to obtain load voltage and load power at three different pressure amplitudes, i.e., 312.5 Pa, 437.5 Pa, and 625.0 Pa. The load voltage and load power produced as a function of load resistance are depicted in Figure 14. As the graph indicates voltage as a function of frequency, peak values of voltage are obtained at resonance which takes place at a natural frequency of 130 Hz and damping ratio equal to 0.025. The voltage at resonance is simulated at various pressures. At maximum pressure of 625 Pa, the voltage at resonance is equal to 10.53 V. When the pressure is decreased to 437.5 Pa, the output peak voltage is 7.3 V and similarly, at minimum pressure of 312.5 Pa, the peak value obtained for voltage is equal to 5.2 V.

Figure 15 shows the frequency sweep ranging 35 to 400 Hz. The simulations are done using equation (12). As the graph indicates voltage as a function of frequency, peak values of voltage are obtained at resonance which takes place at a natural frequency of 130 Hz and damping ratio equal to 0.025. The voltage at resonance is simulated at various pressures. At maximum pressure of 625 Pa, the voltage at resonance is equal to 10.53 V. When the pressure is decreased to 437.5 Pa, the output peak voltage is 7.3 V and similarly, at minimum pressure of 312.5 Pa, the peak value obtained for voltage is equal to 5.2 V.

Figure 16 shows the simulations performed to obtain load voltage and load power at three different pressure amplitudes, i.e., 312.5 Pa, 437.5 Pa, and 625.0 Pa. The load power is plotted against load resistance for each pressure amplitude, demonstrating the relationship between load resistance and output power. The data points are clearly defined, indicating the performance of the harvester under varying pressure conditions.
voltage is obtained using equation (18) which makes use of peak values of voltage, i.e., voltage at resonance. The simulations are carried for a range of 0 to 100 $\Omega$ load resistance. With the increasing load resistance, the output voltage also increases. At a pressure of 312.5 Pa, the voltage achieved is 5 V at a resistance of 100 $\Omega$. Similarly, at a pressure amplitude of 437.5 Pa, the voltage reached 7 V, whereas at maximum pressure of 625 Pa, the voltage reached 10 V. Figure 14 also displays the load power as a function of load resistance, which is simulated using equation (19). It can be concluded from the results that until the optimum load resistance of 4.3 $\Omega$, the output power keeps on increasing. And at 4.3 $\Omega$, the maximum power is obtained. For different pressures amplitudes, different response curves are obtained. At pressures of 312.5 Pa and 437.5 Pa, the load power is 799 mW and 1567 mW, respectively, whereas the maximum power simulated at 625 Pa of pressure is 3198 mW.

Figure 15 shows the graph of current vs. load resistance. At three separate fluid pressures, a number of load resistors are connected to F-EMEH, and electric current is measured through the load. From the experiment pattern, it is observed that the current generated at the coil terminals decreases as the resistance increases in accordance with ohms law.

A low voltage rectifier [36] is connected to the fabricated device. It can convert AC signals into DC voltage signals. The device is tested for the same conditions as the experimentation done for the AC outputs. Figure 16 represents the energy harvester’s open circuit DC voltage at various amplitudes of pressure. The graph clearly shows that the DC output voltage rises as the pressure increases. The output voltage recorded is 0.5 V at a minimum pressure of 156 Pa. Similarly, the energy harvester produced open circuit DC voltage of 4 V at maximum pressure amplitude of 625 Pa.

Figure 17 describes DC output voltage and DC load power against various loads. A variable resistor ranging from 1 to 100 $\Omega$ is be connected to the rectifier in series when conducting the experiment, the harvester is subjected to various
pressure levels, and output for DC voltage is recorded. This pattern shows that output voltage increases with an increase in load resistance. At pressure values of 312.5, 437.5, and 625 Pa, the DC load voltage obtained is 0.2, 0.34, and 0.6 V, respectively. These values of load voltage decreased in comparison to load voltage without rectifier, due to the impedance offered by the rectifier.

Figure 17 also displays the energy harvester’s DC load power versus the load resistance. To determine the device’s DC output power, the experimental data obtained from the previous experiment (DC load voltage vs. load resistor) is used. The plotted graph clearly shows that when the energy harvester is connected to a load resistance of 10 Ω, the maximum output DC power obtained is 3251.25 μW.

To examine the output of the fabricated device, two batteries charging experiment are performed. Initially, the DC output of the harvester is attached to two 1.2 V rechargeable batteries in series at the maximum pressure amplitude of 625 Pa. Charging the battery is monitored at different intervals of time. Initially, a battery of charge 0.05 V is connected to the system. As shown in Figure 18 (it is found that it was charged up to 1 V in 3 minutes (red curve), the battery voltage reached 1.4 V after another 3 minutes. The battery charging is investigated repetitively every three minutes. Finally, it is concluded that the battery is completely charged to approximately 2.2 V in 18 minutes.

Another experiment for battery charging was performed for 30 minutes (blue curve). In this experiment, there are total three rechargeable batteries. Each having charge capacity of 1.2 V, when connected in series, the total charge sums up to 3.6 V. Initially, the experiment is performed for every three minutes. Battery had an initial charge of 0.08 V and gained a charge of 2.8 V for the first eighteen minutes. There is a rise of 0.1 V after five minutes of the experiment; similarly, after a couple of minutes, the gained charge is very low. This means that the process of charging the battery is fast at startup and slows down gradually. The maximum charge of 3.2 V is achieved in 30 min.

Figure 19 shows the wireless transmitter and receiver units used for the pipeline pressure monitoring. To measure the pressure amplitude of the fluid in the pipeline and for wireless transmission, a pressure sensor (MPX5010DP), Arduino Uno (to process the pressure sensor data), and NRF24L01 module (for wireless communication) are used. Moreover, the pressure sensor data can be remotely monitored at the control room with the help of receiver unit.

To constitute the self-powered pipeline pressure monitoring system pulsating, the energy harvester,
rectification circuit, and power bank are integrated with a wireless transmitter unit as shown in Figure 19. The developed energy harvester will continuously charge the battery, and the battery will supply power to all the onboard components of the wireless transmitter unit.

2.1. Comparison of the Fabricated Energy Harvester with Flow-Based Energy Harvesters. A variety of parameters of the energy, that are based on vibrations induced due to the fluid flow, in the literature may be compared, such as maximum voltage, average power, maximum power density, internal resistance, input pressure, flow velocity, and the device size. Different physical parameters of the reported energy scavengers are presented in Table 4. The flow-based energy harvesters referred in Table 4 show that the output voltage of the energy harvesting devices varies from 14 mV to 1000 mV and 1456 \( \mu \)W of maximum power. The table clearly shows that the developed F-EMEH, i.e., this research work has capability of generating 1200 mV of open circuit output voltage and power of 18600 \( \mu \)W. This shows better performance of the fabricated device in comparison to the rest of electromagnetic energy harvesting devices. Both electromagnetic and piezoelectric energy harvesters are discussed in Table 4. While making comparison, it is observed that the electromagnetic scavengers can attain more power compared to piezoelectric based harvesters.

Figure 20 shows the voltage plot versus size of the device of flow-based energy harvesters discussed in Table 4. The output voltage for the reported energy harvester varies from 14 mV to 1200 mV. In the peak voltage, a piezoelectric power harvester obtained is 800 mV. However, a peak voltage of 1200 mV is recorded for an electromagnetic energy harvester [this work] with 24.73 cm\(^3\) device size. In comparison to this work, device in [26] is of larger size of 280.7 cm\(^3\) yet attained the minimum voltage of 14 mV. Thereby, it can be concluded that the output achieved by the developed prototype with respect to its size is adequate.

Figure 21 illustrates the output power vs. the device size generated by the related flow harvesters in Table 4. It is
noticed that the energy harvester reported in [20] has a small size and producing acceptable power but the device shown in [23] has smaller device size, $5.3 \times 10^{-3}$ cm$^3$, and generating a small amount of power. This is because of higher impedance of the system. The piezoelectric energy harvesters of a large size are reported in [25, 26] but still the output power generated is low because of its device design and greater impedance. The electromagnetic harvesters contrasted with piezoelectric energy harvester are generating more power. This is clearly indicated by the work shown in [15, 21, 27] and maximum power produced by this work.

Figure 22 characterizes the plot of power produced versus the internal resistance of the reported prototypes based on fluid flow. From the plot, the difference is clearly noticeable that maximum power is achieved in this research compared to the other related energy harvesting systems. It is because the built prototype’s lower impedance value was relative to the other related energy harvesters.

Figure 23 indicates the peak power achieved by the abovementioned harvesters versus the pressure levels. The plot shows the maximum output of 18600 $\mu$W at a pressure of 0.625 kPa is achieved by the device produced in this work. Although 20.8 kPa is a higher-pressure value, applied in [23], the output power obtained is only 0.00045 $\mu$W, that is, quite low. In addition, a higher pressure is applied to the system as big as 400 kPa as reported in [20]; however, the power produced by it is only 1200 $\mu$W.

Likewise, the power densities of the discussed energy harvesting systems are plotted against their internal resistance in Figure 24. It is obvious from the data points of harvesters [21, 25, 26] that those systems whose got a greater value of internal resistance have low power densities. The devices mentioned in [23, 27], however, indicate relatively higher densities of power when the internal impedances are high. The energy harvester power densities listed in Table 3 range from $1 \times 10^{-6}$ to 869.56 $\mu$W/cm$^3$. The fabricated F-EMEH has the lowermost internal resistance; hence, its power density is maximum compared to the rest of the energy harvesters.

3. Conclusion

The developed F-EMEH was successfully tested inside the lab. The prototype, with a volume of 24.73 cm$^3$, 1.2 V, open circuit output voltage was generated at maximum pressure of 625 Pa. At same pressure when connected to resistor, closed circuit voltage of 0.88 V and 18600 $\mu$W power was generated at optimum resistance of 4.3 $\Omega$ by the harvester. While carrying out the experiments, it was found that at the highest pressure, highest current of 53 mA was achieved. Similarly, the data extracted from the built prototype shows that the maximum DC power could be obtained from the system at 10 $\Omega$ of resistance. This shows that when the device is connected to the rectifier, the device resistance reached from 4.3 $\Omega$ to 10 $\Omega$. This is due to the added impedance of the rectifier. Therefore, the device provided 0.6 V and 3.25 mW of DC load voltage and power, respectively, due to the impedance of the rectifier. Here, the output of the device is reduced; this is because of most of power consumed in rectifier circuit. The current device is suitable for energy harvesting from fluid flow which can power wireless sensor nodes for condition monitoring of pipeline systems. This new concept gave the wireless devices a simple solution to attain power. However, by redesigning device parameters, such as gap and number of coil turns, the device will boost its power generation capabilities. Furthermore, the DC output of the energy harvester can be further enhanced by matching it to ultra-low power rectifier. Moreover, with integration with an appropriate impedance matching circuit, the F-EMEH output can be further optimized.
Data Availability

The data in Table 3 is used to support the findings of this research work that are included within the journal paper.

Disclosure

Publication charges would be paid by the authors.

Conflicts of Interest

Sadia Bakhtiar and all the co-authors declare that there are no conflicts of interest regarding the publication of this paper.

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