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Acoustic-Based Electrodynamic Energy Harvester for Wireless Sensor Nodes Application

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***Abstract*—An electrodynamic harvester for scavenging acoustic energy is reported in this paper. The working principle, fabrication and characterization of the harvester are discussed. The developed harvester consists of an Helmholtz resonator, flexible membrane, moving magnets and a fixed wound coil. The harvester is characterized under acoustic energy at different sound pressure levels (SPL's) and is subjected to both increasing frequency sweep (IFS) and decreasing frequency sweep (DFS). At resonance and under 120 dB SPL, the harvester produced a maximum load rms voltage of 315 mV at 66 Ω load resistance. The experimental results showed the maximum power delivered to load is 1503.4 µW at 120 dB SPL, that leads to a maximum power density of 191.4 µW/cm^3 for the developed harvester. The energy harvester is also characterized in open air with a large speaker as an acoustic source. Moreover, the harvester generated a load voltage of about 30 mV when subjected to the acoustical noise of a household electrical generator.**

***Index Terms*—acoustic energy, electrodynamics, energy harvesting, Helmholtz resonator, nonlinear response**

I. INTRODUCTION

In recent years, with the rapid development in technology, the application of wireless sensors has immensely increased. The wireless sensors play an important role in remote intelligent sensing systems, such as, mobile survey robots, structural health monitoring [1], tire pressure and temperature monitoring system and condition monitoring of aircraft engines [2]. For the conversion of wireless sensors into autonomous sensors the main problem associated is the power source [3], [4]. The power requirement of the wireless sensor node is obtained from a battery. The battery finite life limits the application of wireless sensor nodes for remote, embedded, hazardous and harsh environments [5]. In the last decade, energy harvesting from the wireless sensor's environment is employed to replace or supplement the battery power. The integration of micro energy harvester with wireless sensor will result in a long lasting autonomous sensor node. For the development of micro energy harvester, several ambient energies are available in wireless sensor's surroundings, such as, solar, wind, vibration and thermal. Likewise, these ambient energy sources, acoustic energy is also abundantly available in the surroundings of wireless sensor nodes. For wireless sensor nodes, the transduction of ambient acoustic energy into electrical energy is suitable for applications such as non-destructive health monitoring of machines (such as, turbines, rotary compressors, electrical generators and motors) and vehicles (automobiles and aircrafts). In the surrounding of the aircraft, the sound pressure level (SPL) above 80 dB is obtained over a frequency range of 20 Hz to 20 kHz [6]. In vehicles, such as automobiles, the SPL ranges from 70 dB to 90 dB over a frequency band that range from 1 to 100 Hz [7]. In the surrounding of the turbofan engines, the SPL of about 150 dB is obtained over a frequency range of 20 Hz to 20 kHz [8], [9]. Moreover, in automobiles without engine muffler, the SPL reaches up to 194 dB and its frequency is spread over a range of 1 to 20 Hz [10]. In car air conditioning system, acoustic energy exits, in supply duct, return duct and exhaust duct with SPLs that reaches up to 71.9, 65.1 and 47.7 dB respectively over a frequency range of 20 Hz to 20 kHz [11].

Several energy harvesters, utilizing acoustic or vibration energy, have been developed and reported in the literature. Most of the developed acoustic energy harvesters (AEH) are based on the principle of piezoelectricity [12]. Piezoelectric material, when subjected to compression, produces charge that is proportional to the applied load [13]. A micro-based acoustic energy harvester for aero-acoustic applications is reported in [8]. The developed acoustic energy harvester consists of an orifice, cavity, and a piezoelectric membrane. At SPL of 149 dB, a maximum output power density of 0.34 µW/cm2 is reported. However, with an improved design for the same energy harvester, output power density of 252 µW/cm2 is obtained. In order to enhance the performance of the acoustic energy harvester, a Sol-Gel fabrication technique is used to produce the piezoelectric membrane [14]. The maximum power produced by the harvester is 11 pW at 100 dB SPL and resonance frequency of 24.02 kHz. An acoustic energy harvester is produced by fabricating the piezoelectric membrane with a novel fabrication technique [15]. With the developed harvester, a maximum power of 140 pW is obtained at 100 dB and at resonance frequency of 16.7 kHz. Electric power harvested from acoustic energy using

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piezoelectric materials and sonic crystals is reported by [16]. At resonance maximum power is produced under a load resistance of 3.9 kΩ. At 4.2 kHz resonance frequency and SPL of 45 dB, the device produced a maximum power of 40 nW. An acoustic energy harvester developed by [17] comprises of an electromechanical Helmholtz resonator (EMHR). To achieve higher efficiency, the piezoelectric membrane of the EMHR is coupled with an energy reclamation circuitry, in which a rectifier is connected to a fly back converter to improve load matching. At SPL of 161 dB, about 30 mW power is generated by the harvester. Acoustic energy harvester with improved performance is reported by [18]. For better performance the piezoelectric membrane is fabricated having dual top electrodes to utilize the different polarizations of charges on the surface of a vibrating piezoelectric (Lead Zirconate Titanate) diaphragm. The harvester having 25 Ω resistance produced a power of 42.5 pW at a resonance frequency of 4.92 kHz and at 100 dB SPL. Reference [19] reported on improved performances of piezoelectric AEH that utilizes different charge polarizations at the peripheral part and the center part of a piezoelectric diaphragm. The device having resonant frequency of 4.92 kHz when subjected to 100 dB SPL, generated power of 52.8 pW and 42.5 pW at optimum load of 25 Ω and 30 Ω resistances at the peripheral and center part of the piezoelectric diaphragm respectively. Another harvester was defined between the center and peripheral electrode, that generated a maximum power of 82.8 pW at an optimum load of 50 Ω resistance under the same SPL and resonant frequency. Simulation of an AEH is performed in COMSOL Multiphysics to forecast the operation of the harvester by [20]. The predicted results showed a power generation of 1.69 pW at 100 dB SPL under a resonant frequency of 3.5 kHz.

The acoustic energy harvesters reported in literature are based on piezoelectric transduction phenomenon. Up to author's knowledge, no acoustic energy harvester is developed that is based on the principle of electromagnetism. The electromagnetic-based acoustic energy harvester reported in this work, consists of a Helmholtz cavity, flexible membrane, permanent magnets and a fixed wound coil. When the harvester is subjected to an acoustic wave, the Helmholtz cavity magnifies the amplitude of the acoustic wave and results in membrane (magnets) motion relative to wound coil. The coil experiences the changing magnetic flux and an elective motive force (emf) is induced in the coil. The lower output impedance of the developed electromagnetic based acoustic energy harvester provides an edge over the piezoelectric acoustic energy harvesters. In comparison, the output impedance of the piezoelectric based energy harvesters is very high, therefore low output current is expected, however, in electromagnetic-based acoustic energy harvesters high output current will be available to power the autonomous sensors.

II. ARCHITECTURE AND WORKING MECHANISM OF THE ENERGY HARVESTER

The cross-sectional view and exploded view of the developed AEH are shown in Fig. 1 and Fig. 2 respectively.

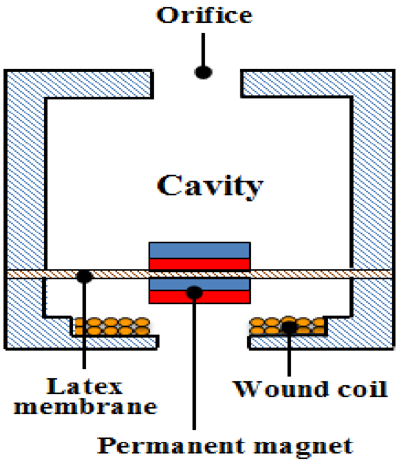

Figure 1. Cross-section of the developed acoustic energy harvester.

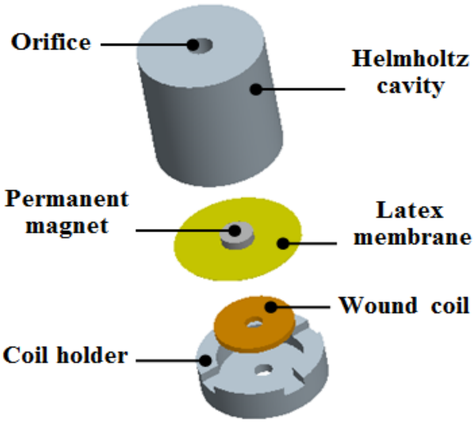

Figure 2. Exploded view of the developed acoustic energy harvester.

The developed AEH consists of a Helmholtz resonator, a fixed wound coil placed in a coil holder and two Neodymium (NdFeB) permanent magnets mounted on a Latex membrane. The magnets and the fixed coil are held apart by small distance to allow the oscillation of permanent magnets over the fixed coil. The acoustic pressure is amplified by Helmholtz cavity to a much higher levels, when the harvester is subjected to an incident acoustic wave [21], [22]. The acoustic pressure inside the cavity causes the membrane (magnets) to oscillate on top of the fixed wound coil. Due to relative motion between the magnets and the coil a change in magnetic flux occurs, as a result an elective motive force (emf) is induced across its ends according to the Faraday's law of electromagnetic induction. To reduce the air damping of the harvester, air passages are provided in the coil holder.

III. FABRICATION OF THE ENERGY HARVESTER

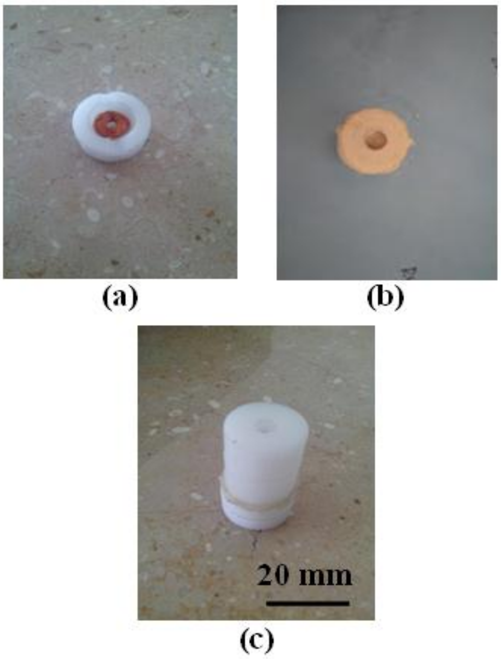

Figure 3. Photographic images of the energy harvester in various stages of the assembly: a) Coil placed in coil holder b) Suspension system fixed on coil holder c) Helmholtz cavity bounded on the suspension system.

Fig. 3 shows the fabrication of the energy harvester device. Commercially available Teflon rod (WS Hampshire Inc. Hampshire, Illinois, USA) of 31.75 mm diameter is used to fabricate the Helmholtz cavity and coil holder. Conventional machining operations are performed on this rod to fabricate the Helmholtz cavity and coil holder. For membrane Natural Rubber Latex (Kleengaurd gloves, Kimberly Clark Co., Dallas, Taxis, USA) is used because of its high flexibility, better resistance to punctures and the tendency to self-repair tiny holes [23], [24]. To develop the oscillating structure for the energy harvester device, two NdFeB magnets are self-clamped on either side of the Latex membrane. Copper wire of 80 μm diameter is used to develop the wound coil. With the help of manual winding equipment a coil of 3 mm thickness, 12 mm diameter and 11845 turns is produced. The different parts of the device is assembled and fixed with the help of Epoxy. First, the coil is placed in the coil holder as shown in Fig. 3(a). To fix the coil in the coil holder epoxy is used. Two NdFeB magnets are mounted on the membrane. The magnetic polar attraction of the magnets is utilized to firmly attach the magnets to the oscillating membrane. Using epoxy the suspension system consisting of two magnets and the membrane is bounded to the coil holder as shown in Fig. 3(b). Finally, the Helmholtz cavity is placed on the suspension system and is fixed with sub-assembly with the help of epoxy Fig. 3(c). Table I lists the dimensions and parameters of the assembled energy harvester device.

TABLE I. DIMENSIONS AND PARAMETERS OF THE DEVELOPED ACOUSTIC ENERGY HARVESTER

Description	Value
Harvester dimensions	25 mm x 20 mm
Magnet dimensions	1.60 mm x 6.35 mm
Magnet (NdFeB), B_r	0.3 T
Mass of each magnet	377 mg
Membrane thickness	100 μm
Membrane diameter	13 mm
Coil dimensions	3 mm x 12 mm
Coil resistance	66 Ω
Number of turns of coil	11845
Gap between magnet and coil	2 mm

IV. EXPERIMENTAL SETUP AND HARVESTER CHARACTERIZATION

The experimental setup for the characterization of the developed energy harvester for acoustic energy is shown in Fig. 4. The experiment setup consists of a power amplifier (Model A7-X, Kenwood, Japan), speaker, plane wave tube, function generator (Model GFG 8020H, GW Instek, New Taipei, Taiwan), microphone (Type CZ034A, Ringford products, Tsuen Wan, Hong Kong) and oscilloscope (Model GOS 6112, GW Instek, New Taipei, Taiwan). Function generator generates a sinusoidal signal of the desire frequency. Power amplifier amplifies this signal produced and gives it the speaker, which acts as an acoustic energy source. The acoustic energy produced by the speaker travels through the plane wave tube and impinges on the acoustic energy harvester. To measure the SPL of the incident acoustic wave, a microphone is fixed near the device. The signals from the energy harvester and microphone are analyzed using the oscilloscope.

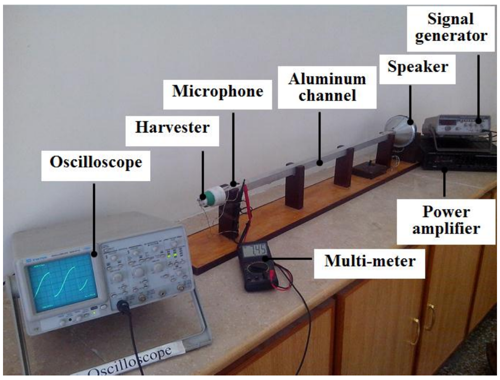

Figure 4. Experimental setup for the characterization of the developed acoustic energy harvester.

Fig. 5 shows the rms value of the load voltage as function of the frequency at various SPL's. A load resistance of 66 Ω, which equal to the internal resistance of the coil, is connected to the harvester and the device is subjected to an increasing frequency sweep (IFS) from 30 to 210 Hz and decreasing frequency sweep (DFS), back from 210 Hz to 30 Hz. The experimental results show that the behavior of the device is linear at low SPL, however, the harvester response is nonlinear at high SPL. The nonlinear response of the harvester is due to the nonlinear stiffness of the Latex membrane. The membrane stiffness is due to bending stresses and stretching. At low SPL the stretching is negligible and the membrane stiffness is only because of bending stresses that results in the linear stiffness of the membrane. However, at high SPL, stretching is considerable (and increases with increase in SPL) which induces excessive tensile stresses in the membrane that results in increasing the stiffness of the membrane [25], [26]. Under linear response, the harvester exhibits single resonant frequency (114 Hz) that shows the constant membrane stiffness in the linear regime of operation. However, at higher SPL the harvester response curve is tilted towards the higher frequency side. Moreover, the shift in the device resonant frequency, jump down (during increasing frequency sweep “IFS”) and jump up (during decreasing frequency sweep “DFS”) phenomena are also observed, which is due to the nonlinear stiffness of the membrane. Under nonlinear operation and subjected to 120 dB SPL, the harvester produced a maximum optimum load rms voltage of 315 mV at a resonance frequency of 144 Hz.

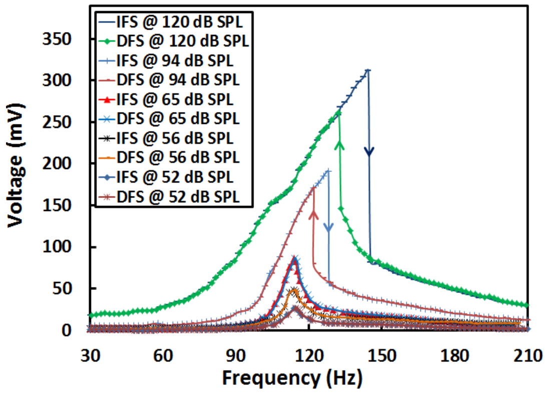

Figure 5. Optimum load voltage as a function of the frequency at various SPL.

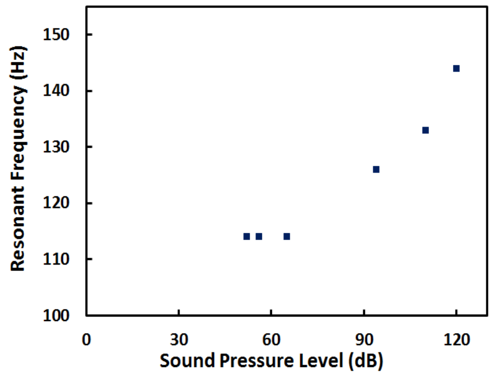

Figure 6. Resonance frequency shift with respect to increase in SPL.

The resonant frequency of the harvester during IFS, at low as well as high SPL’s is shown in Fig. 6. The shift in the resonant frequency of the harvester with the increase in incident SPL is associated to the nonlinear stiffness of membrane. Blow SPL of 56 dB is the linear regime of operation for the device. The harvester, resonant frequency (114 Hz) remains constant in this region. Whereas, nonlinear regime of operation is above 56 dB SPL and in this regime the resonant frequency changes from 114 Hz to 144 Hz for a an increase of SPL from 56 dB to 120 dB.

Fig. 7 and Fig. 8 respectively show the voltage and powered delivered to load as a function of load resistance at different SPL’s. Various load resistances were connected to the harvester and it is excited at 65, 94 and 120 dB SPL’s at 114, 126 and 144 Hz resonant frequencies respectively. From Fig. 7 and Fig. 8, it is evident that greater the load resistance, higher is the voltage across it and smaller is the current through it. The maximum power delivered to load is 1503.4 μW at 120 dB SPL and at a resonance frequency of 144 Hz. The power delivered to the load is maximum at load resistance of 66 Ω, which is identical to the coil resistance, thus satisfying the maximum power transfer theorem [27].

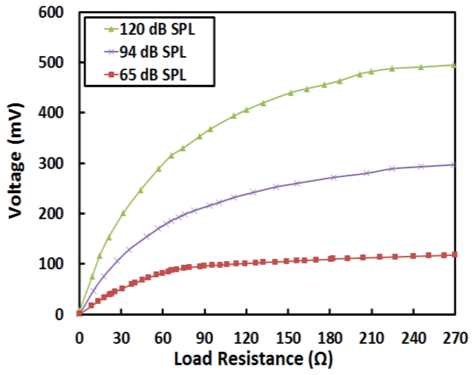

Figure 7. Load voltage as a function of load resistance at different SPL’s.

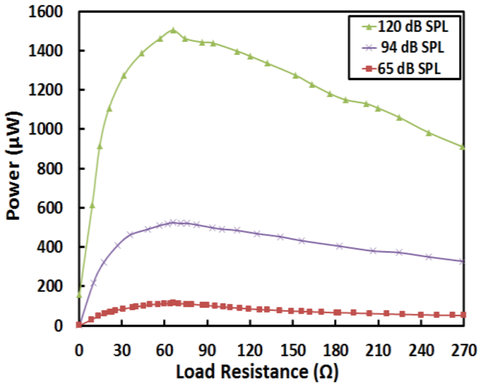

Figure 8. Power delivered to load at different SPL.

The resonant frequency of the harvester as a function of load resistance is shown in Fig. 9. The plots are obtained under the SPL’s of 94 and 120 dB. The resonant frequency slightly increases with the increase in the load resistance. At smaller load resistance, more current flows in the harvester’s coil that result in higher electrical damping and slightly lower resonant frequency of the harvester. However, at large resistance less current is permitted which results in lower value of electrical damping and slightly higher resonant frequency.

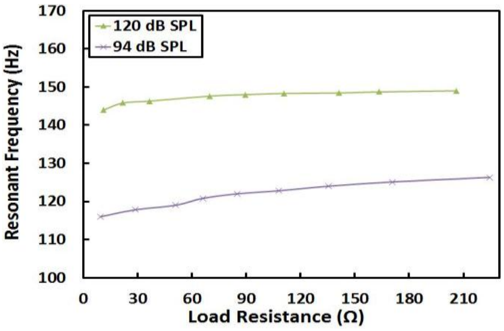

Figure 9. Resonance frequency shift with respect to increase in load resistance at different SPL.

The experimental setup for characterization of the harvester in open air is shown in Fig. 10. Instead of a square channel for sound propagation, a relatively big speaker is used as an acoustic energy source. Acoustic energy harvester and a microphone are firmly placed adjacent to each other in a moveable wooden stand.

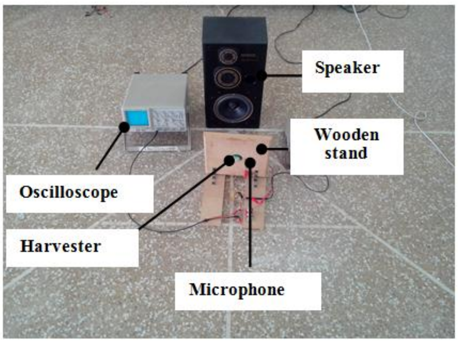

Figure 10. Experimental setup for the characterization of the developed harvester in open air.

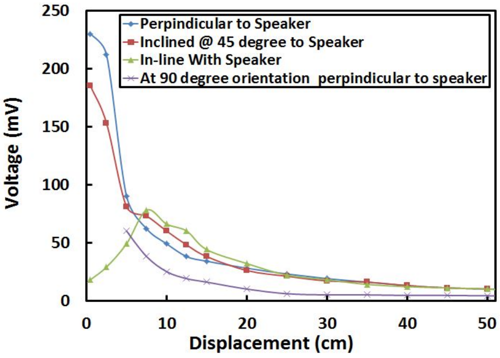

Figure 11. Open circuit voltage produce by developed harvester as a function of the displacement from the acoustic source at various directions and orientation

In order to verify the dependency of harvester on distance and orientation with respect to the acoustic source, the harvester is moved along three paths, perpendicular to the speaker, inclined at 45^o and in-line with the speaker. Fig. 11 shows the rms value of the open circuit voltage as function of displacement from the speaker along the three lines. At 94 dB SPL and resonant frequency of 116 Hz, a maximum voltage of 230 mV is produced when the device is placed on the perpendicular line and at a distance 0.5 cm from the speaker. The voltage generation decrease drastically as the harvester is moved away for the acoustic source. The voltage generation trends are similar when the harvester is moved along the perpendicular and 45^o inclined lines. However, when the harvester is moved in-line with respect to the speaker, the generated voltage increases and reaches a maximum value of 78 mV at distance of 7.5 cm. Beyond a distance of 7.5 cm, voltage generation decreases with the motion away from the speaker.

Fig. 12 shows the experimental arrangement for the harvester characterization under the acoustical noise of a household electrical generator (5000 kW). National Instruments® (NI, Austin, Texas, U.S.) data acquisition card (NI USB-6212) and NI LabVIEW Sound and Vibration Assistant is used to obtained the signals simultaneously from the microphone and the acoustic energy harvester.

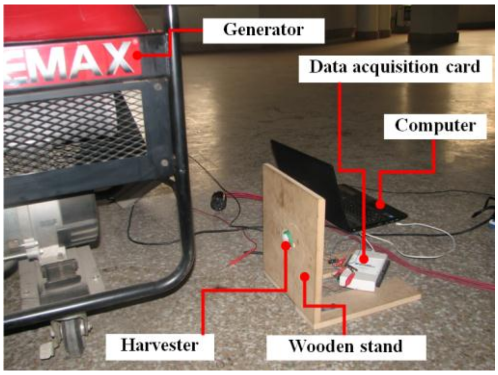

Figure 12. Experimental setup for harvester characterization under household electrical generator acoustical noise.

The output of the energy harvester when it is subjected to the acoustical noise of the household electrical generator is shown in Fig. 13. For this experiment the harvester is kept 30 cm away from the electrical generator. The SPL recorded at that distance ranges from 53 to 110 dB and is spread over a frequency range of 1 Hz to 2 kHz. The output response of the harvester is random, which was expected since the real acoustical noise is also chaotic and random. A maximum of about 30 mV load voltage is obtained when optimum load of 66 Ω is connected to the harvester.

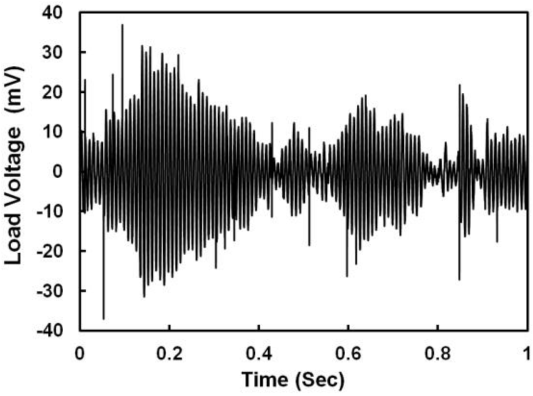

Figure 13. Time response of harvester under household electrical generator acoustical noise.

The power spectral density (PSD) of the output load voltage of the harvester is shown in Fig. 14. In the Sound and Vibration Assistant the RMS averaging is used to generate the PSD plot shown in Fig. 14. The PSD of the load voltage is optimum at the resonant frequency of the harvester. A maximum PSD value of 9.17x10^{-6} V^2/Hz is obtained at a frequency of 112 Hz.

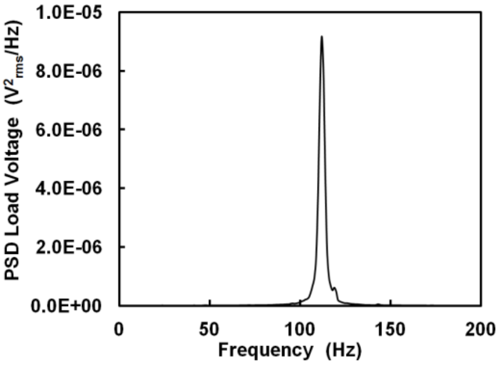

Figure 14. Power spectral density of harvester output under household electrical generator acoustical noise.

The output voltage of the developed acoustic energy harvester is in mV range (20 to 315 mV), however, because of the low resistance of the wound coil (66 Ω) high output current levels would be available for powering the micro sensors. The power generation capability of the developed harvester is better than most of the reported acoustic energy harvesters and is quiet enough to power most of the ultra low power sensors.

A comparison of the developed harvester is done with the reported acoustic energy harvesters and is shown in Table II. The size of the developed AEH is quiet comparable to the harvesters reported in literature. The AEH mentioned in [17] and [20] are generating more power than the developed energy harvester, however, the output impedance of these harvesters is in higher range. The output impedance of the developed AEH is lower than all reported energy harvesters except [18] and [19]. While comparing on the basis of resonant frequency, the resonant frequency of AEH reported in this work is lower than all of the acoustic energy harvesters.

TABLE II. COMPARISON OF THE DEVELOPED ACOUSTIC ENERGY HARVESTERS

Type	Device dimensions (mm)				SPL (dB)	F (kHz)	R (Ω)	P (μW)	Ref.
	Neck		Cavity						
	Diameter	Height	Diameter	Height					
Piezoelectric	2.39	3.18	6.35	16.1	149	13.57	1000	6 x10^{-6}	[8]
Piezoelectric	2.39	3.18	6.35	16.1	100	24	550	11x10^{-6}	[14]
Piezoelectric	-	-	-	-	100	16.7	75	14x10^{-5}	[15]
Piezoelectric	-	-	17.5	49	45	4.2	3900	40 x10^{-3}	[16]
Piezoelectric	2.42	3.16	6.34	16.4	161	2.64	20000	30 x10^{3}	[17]
Piezoelectric	-	-	-	-	100	4.92	25	42.5x10^{-6}	[18]
Piezoelectric	-	-	-	-	100	4.92	50	82.8x10^{-6}	[19]
Piezoelectric	0.1	0.18	1.2	1.02	100	3.5	1000	1.69x10^{-3}	[20]
Electrodynamic	2.5	4	6.5	16	125	0.143	66	1503.4	This work

V. CONCLUSION

A miniature acoustic-based electrodynamic energy harvester is developed and reported in this work. The harvester is characterized in laboratory as well as in real life environment, such as household electrical generator surrounding. In laboratory the performance of the harvester is analysed under varying sound pressure level (SPL) and frequency. The harvester exhibited linear as well as nonlinear response. The response of the harvester is linear when subjected to low acoustic energy levels, however, at high acoustic energy levels it exhibited nonlinear behaviour. Under nonlinear operation it produced a maximum of 315 mV load voltage at SPL of 120 dB and 144 Hz frequency. When connected to the optimum load of 66 ohm, it delivered a maximum power of 1503.4 μW to the load. When the energy harvester is tested in the surrounding of a 8.8 kVA household electrical generator it produced a maximum load voltage of 30 mV and a maximum spectral power density of 9.17x10^{-6} V^2/Hz under the acoustical noise level of 110 dB. The output power of the harvester is better than most of the other acoustic energy harvesters developed using piezoelectric material as a power producing element. The developed acoustic energy harvester is suitable to harvest energy for wireless micro sensors, for example, in turbofan engines, where the acoustic energy frequency band is from 20 to 20 kHz at about 150 dB SPL.

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