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Research Article

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A Review of Vibration Based Wide-Band Electromagnetic Energy Harvesters

Hamid Khan and Farid Ullah Khan

Abstract

Vibration based electromagnetic energy harvesters (VEMEHs) for powering wireless sensor nodes (WSNs) and low power devices has got enormous research interests as alternative source of power. One of the prime limitations to the application of these harvesters as a replacement to battery systems is their dependency on the limited range of operating frequencies. This paper highlights the current advancements in the area of wide-band VEMEHs. All such VEMEHs have been studied and reported based on their range of operating frequencies, frequency bandwidth, overall volume, output voltage, the value of available output power, power density and the level of vibrations these harvesters are subjected to. Moreover the reported VEMEHs are categorized on the basis of their operating mechanism i.e either resonant or non-resonant. The main focus over here is the operating range of frequencies and the frequency bandwidth where the harvester is capable of producing adequate amount of output power which could be used for operating remote WSNs. The reported VEMEHs include harvesters with a minute volume of 0.032 cm3 to as large as approx 1600 cm3. When compared on the basis of output voltage, the reported VEMEHs could produce output voltage from 0.13 mV to as high as 5700 mV. Similarly the reported VEMEHs are generating output power from 0.00096 μW to 74000 μW. The reported VEMEHs are having power densities in the range of 0.50 x 10-6 μW/ cm3 to1073 μW/ cm3. The power per acceleration of the reported VEMEHs is in the range of 16.012 x 10 -6 μW/g to 129824 μW/g. Moreover the reported VEMEHs are having power density per acceleration in the range of 0.500 x 10-6 μW/g.cm3 to 1877 μW/g.cm3. Based on the overall device's size and resultant output power, a 1 cm^3 harvester having an average power output of 0.75 μW to a harvester of 68.96 cm^3 with a peak output power of 74 mW have been reported in this literature. Comparison has been made on the basis of operating frequency range, frequency bandwidth, device size, output power, acceleration of operation, power per acceleration and power densities of the reported wide-band electromagnetic energy harvesters (EMEHs).

Introduction

The fast advancement and development in the field of mobile electronics and wireless sensors has led to the progress in several technologies. The applications of such wireless sensing electronics include environmental monitoring (like temperature, humidity and light), structural monitoring (like bridges and tall buildings), asset surveillance, industrial and medical machine monitoring, and military and aerospace equipment sensing [1]. These physical and environmental conditions are monitored with wireless sensor nodes (WSNs). A WSN mainly is composed of a sensor unit, signal processing and conditioning unit, micro-controller unit, on-board memory, transceiver and a power managing unit [2]. Some commercially offered sensors with their type, make and model, measurement range, working voltage, current and power level requirements have been listed in Table I. The temperature sensors are having power consumption in 13.8 μW to 247 μW range. The power utilization requirement of the reported pressure sensors is relatively high which is in the range of 3 mW to 240 mW. Similarly the acceleration sensors consume 0.45 mW to 72.8 mW range of power. The current requirement for temperature, pressure and acceleration sensors is in the range of 6 to 45 μA, 1 to 10 mA and 0.2 to 13.25 mA respectively. The operating voltage required for the temperature, pressure and acceleration sensors is in the range of 1.8 to 5.5 V, 3 to 24 V and 2.25 to 5.5 V respectively.

TABLE I Commercially available sensors

Temperature Sensors						
Manufactured By	**Model**	**Measurement Range (C°)**	**Required Voltage (V)**	**Current (μA)**	**Power (μW)**	**Ref.**
Texas Instruments	LMT85	-50 to 150	1.8 to 5.5	8.1	14.5 to 44.5	[3]
Microchip	MCP9701A	-40 to +125	3.1 to 5.5	6	18.6 to 33	[4]
Microchip	MCP9700	-40 to +150	2.3 to 5.5	6	13.8 to 33	[5]
Analog Devices	TMP35	+10 to +125	2.7 to 5.5	50	135 to 275	[6]
Sensirion	STS30	-40 to +125	2.7 to 5.5	6.6	17.8 to 36.3	[7]
Texas Instruments	TMP101	-55 to +125	2.7 to 5.5	45	121.5 to 247.5	[8]
Pressure Sensors						
Manufactured By	**Model**	**Range (Mpa)**	**Required Voltage (V)**	**Current (mA)**	**Power (mW)**	**Ref.**
Changzhou Leili	QYK	0.1 to 3.2	4.75 to 5.25	10	47.5 to 52.5	[9]
TE Connectivity	MS4525DO	1 to 150 psi	3.3 to 5.0			[10]
Micro Sensor Co., Ltd.	MPM286	0 to 3.5		2		[11]
Shanghai TM Sensor Co., Ltd.	Ns-P22	0 to 60	24	10	240	[12]
Dallas Semiconductors	DS18B20	-55 to +125	3 to 5.5	1	3 to 5.5	
Acceleration Sensors						
Manufactured By	**Model**	**Range (g)**	**Required Voltage (V)**	**Current (mA)**	**Power (mW)**	**Ref.**
Analog Devices	ADXL103/ ADXL 203	±1.7 / ±5 / ±18	5	0.7	3.5	[13]
Analog Devices	ADXL357	±10 / ±20 / ±40	2.25 to 5	0.2	0.45 to 1	[14]
Analog Devices	ADXL251	±60 / ±120 / ±240 / ±480	3.135	6	18.8	[15]
Texas Instruments	DRV-ACC16-EVM	±16	3.5 to 5.5	10	35 to 55	[16]
Microchip	MM7150	± 2	5.5	13.25	72.8	
STMicroelectronics	LIS3L02AL	± 2	3.3			[17]

Normally batteries are utilized for powering and operating these WSNs. These batteries have to be recharged and substituted as per necessity. Batteries deployed can either be rechargeable or non-rechargeable. Non rechargeable batteries can only be deployed only once and then need to be replaced. Rechargeable batteries can be recharged up to as many as 500 times. A rising number of wireless applications are demonstrating to be well-matched for energy harvesting devices which utilize rechargeable batteries for storing the energy harvested [18]. Nickel Cadmium (NiCd) batteries are

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well established and implicit but comparatively with low energy density. The NiCd batteries are employed for applications with requirements of high rate of discharge, extensive life and cheap to run. Main applications include biomedical equipments, video cameras and power tools. The NiCd batteries are environmental unfriendly because of containing toxic metals.

Nickel Metal Hydride (NiMH) batteries are having higher energy density in comparison to the NiCd batteries at the cost of lower life cycle. NiMH batteries do not contain toxic metals. Main applications of NiMH batteries consist of laptop computers and mobile phones.

Lithium Ion (Li-ion) batteries are the prompt emergent battery system. Li-ion batteries are used for applications with light weight and high energy density requirements. Applications of the Li-ion batteries consist of cell phones and notebook computers [18,19].

Consumer batteries do not perform well in extreme environments, therefore, the demand of energy harvesting from the ambient for powering the electronic devices in such circumstances arises. Consequently, self-renewable power supplies attract more interest for powering portable electronics and WSNs. The limited life time and continuous demand for replacement of power backups (batteries) of the remotely connected WSNs in many applications has resulted in looking for in-station availability of the alternate source of energy for powering these nodes [20].

This demand has led to the energy harvesting of ambient sources of energy, for example, solar, wind, thermal and mechanical vibrations as a replacement of batteries [21]. The power consumption level of small electronics usually lies in the range from few μW to mW and moreover, the sizes of such powering units need to be as tiny as to escort the core device. Similarly, the device used to power such small electronics needs to be operational indoor and outdoor in harsh weather environment. In such a situation, available mechanical vibrations and human moment is the most promising source to be converted to useful electrical energy [21, 22]. This is achieved using energy harvesters which convert the available ambient vibrations to useful electrical energy with the technique of vibration energy harvesting (VEH) [23]. Vibration based piezoelectric [24], electrostatic [25] and electromagnetic [26] energy harvesters are utilized for generation of energy from mechanical vibrations. In vibration based electromagnetic energy harvesting (VEMEH) electrical energy is produced by the coil and a permanent magnet's relative motion which induces voltage at the coil terminals when the coil faces the change in the magnetic flux density. The VEMEHs for powering WSNs have attracted researcher's interest because of the continual reduction in the size and high power production for these devices. Majority of the developed VEMEH simply function on the basis of resonance, which only work well when operated with limited bandwidth in the vicinity of their resonance frequencies. Unluckily, ambient vibrations enormously in the realistic circumstances are frequency-variant or entirely random with energy spread over a broad range of frequencies [24-26].

The vibration sources including oscillations from domestic household appliances, industrial machines, automobiles and bridges along with their vibration frequency range and vibration acceleration levels have been listed. The acceleration level of vibrations from household appliances ranges from 0.002 g (g = 9.8 m/s2) for refrigerator's casing to 0.653 g for kitchen blender's casing. The frequency range of these appliances is from as low as 1 Hz (lower frequency range of split AC's outdoor) to as high as 520 Hz (upper frequency range of window AC's backside). The acceleration level for automobiles ranges from 1.04 g (for Cargo trucks on highways) to 2.514 g (for Ford van on city roads). Similarly the frequencies of vibrations from these automobiles range from 0 to 500 Hz. The acceleration level of vibrations from reported bridges range from 0.0025 g (for Seoha grand bridge for light trains, South Korea) to 0.061 g (for Golden gate bridge for vehicles, San Francisco) while the frequency for these bridges is in the range of 0 to 80 Hz (for Xiangjiang grand bridge for high speed trains in Zhuzhou). (As seen in the table the highest acceleration of 2.514 g is obtained from Ford and the lowest acceleration of vibration is obtained from a household refrigerator with a value of 0.002 g. The associated frequencies from each source of vibration has also been mentioned in the table II.

TABLE IIVarious sources of vibrations along with their frequencies and accelerations

Source of Vibration	Frequency Range (Hz)	Dominant Frequency (Hz)	Maximum Acceleration (g)	Ref.
Small microwave oven		120	0.229	[27]
Bread maker		120	0.105	[27]
Clothe dryer		59	0.433	[27]
Casing of kitchen blender	40-250	216	0.653	[27]
Vacuuum cleaner		100	0.157	[27]
Notebook computer while reading CD		75	0.06	[28]
Casing of refrigerator		100	0.002	[28]
Windows Air-conditioner backside	10-520	120	0.234	[29]
Outdoor of split AC (old)	1-130	120	0.3	[29]
Outdoor of split AC (new)	1-130	17	0.06	[29]
Washing machine	10-100	11	0.238	[29]
Car engine compartment		200	1.22	[30]
Base of a 5HP 3-axis machine tool		70	1.02	[31]
Human walking		2–3	0.306	[31]
Wooden deck when people walking		385	0.132	[31]
Door frame as the door closes		125	0.306	[32]
Office building's HVAC vents		60	0.153	[32]
Cargo trucks on highways	10-500	10 to 20	1.04	[33]
Ford van (on city roads)	0-200	10 to 20	2.514	[33]
Honda light car	0-200	1 to 10	1.399	[34]
Golden gate bridge for vehicles (San francisco)	0-5	0 -1.5	0-0.061	[35]
Seoha grand bridge for light trains (South korea)	1 to 10	2 to 4	0.0025-0.018	[35]
Huanghe cable bridge for vehicles (China)	1 to2		0.015	[35]
Xiangjiang grand bridge for high speed trains (Zhuzhou)	1 to 80	40	0.0093-0.026	[35]

The harvester's peak output in case of a linear resonator is attained at its resonant frequency. The harvester's performance could be considerably deteriorated if there is a minor change in the excitation frequency [36]. Since most of the practical sources of vibration are frequency-varying or random in pattern, thus, enhancing the vibration energy harvester's bandwidth has turned out to be one of the most significant issues prior to the deployment of these harvesters in practice [36, 37].

The advancements in the last few years on this concern have been highlighted by this review. The review include a summary of vibration based EM wideband energy harvesting techniques, which covers the area of frequency tuning [38, 39], multimode and nonlinear techniques for EM energy harvesting [40,41], frequency up-conversion [42-45], spring less wide-band EM-EH [46-50], with consideration to their advantages and applications in different conditions.

II. WIDEBAND VIBRATION ELECTROMAGNETIC ENERGY HARVESTERS (VEMEHs)

II. (a) RESONANT VEMEHs

A frequency tunable (VEMEH) is reported by John Heit et al. [51]. The harvester has the capacity to adjust the resonant frequency in a broad range with an easy compacted mechanical adjustment by altering the stiffness of the structure. The whole arrangement is shown in figure 1 composed of two sets of N52 Neodymium magnets (6.35 mm^3) with a square coil in between, a control structure controlling the resonant frequency by controlling spring structure. By increasing the distance between the beams the stiffness of the spring structure is increased thus changing the frequency. The spring structure constructed from 0.1016 cm thick carbon steel has a resonant frequency which is tuned by control structure through the adjustment of the separation distance between the two beams. The peak output power at 0.2 g is 340 μW for the harmonic upsweeps. Moreover, the test results showed that the natural frequency is adjustable from 32 Hz to 85 Hz.

The frequency bandwidth of the device as estimated from the voltage against frequency plot is 5 Hz.

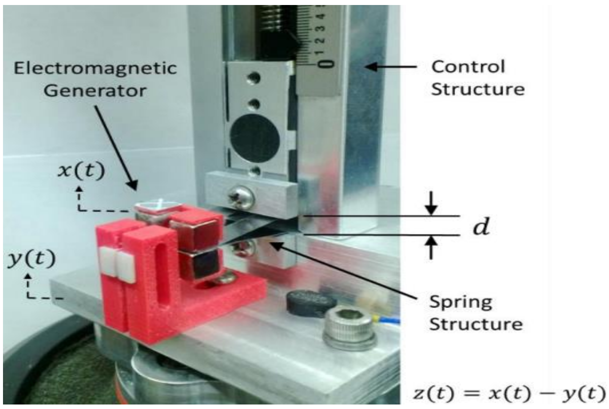


Figure 1: Frequency tunable EM energy harvester [51]

Takahiro Sato et al. [52] reported a non linear wide-band VEMEH suitable for random vibrations. Schematic diagram of the developed harvester is shown in figure 2. The device is composed of a fixed coil and magnets are firmly attached to the cantilever beam's free end. The ambient vibration causing displacing the magnets relative to the coil which changes magnetic flux and inducing EMF in the coil. The coil having the magnetic material inside results in directing the flux lines through the coil and thus increasing the magnetic flux across the coil. At the same time the strong attractive force (between magnets and magnetic material) acting on the magnets results in non-linear oscillations of the cantilever beam and thus entertaining a range of frequencies. Output power is observed to be larger than 0.1 mW over a whole frequency range of 20 Hz to 160 Hz.

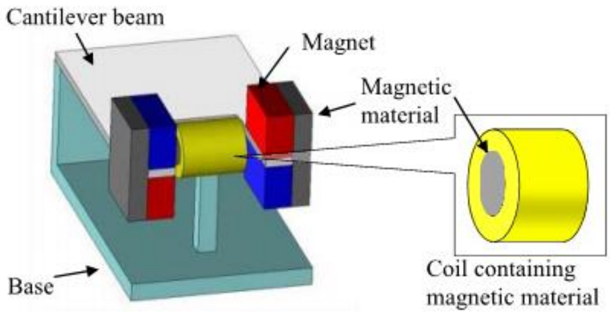


Figure 2: Schematic diagram of the EM harvester [52]

A non-linear VEMEH shown in figure 3 has been developed by Pranay Podder et al. [53] using a 300 μm thick folded, FR4 cantilever structure for low frequency applications. The folded cantilever structure's central portion is bonded at the base while the rest of the structure can freely oscillate due to external vibrations. In the harvester, a region of high magnetic flux gradient is produced through opposite oriented magnetic fields, for that purpose four NdFeB magnets (4 mm x 2 mm x 1 mm) are bonded on both sides of the slot of FR4 using epoxy. A wound copper coil (2500 turns) with inner and outer diameter of 1.15 mm and 4 mm respectively is positioned in the slot between the magnets. At the end of cantilever a magnet (NdFeB) of size 4 mm x 1mm x 1mm is placed facing a sixth NdFeB magnet (4 mm x 2 mm x 1 mm) placed in front of the magnet located at the cantilever's end, exerting repulsive force on each other and thus resulting the introduction of non-linearity into the system. By altering the gap in the two repulsing magnets results a varying non-linearity and increased bandwidth. The device is reported of generating a peak power of 19.3 μW at 1.5 g acceleration across a load of 1 kΩ with a wide bandwidth of 8 Hz.

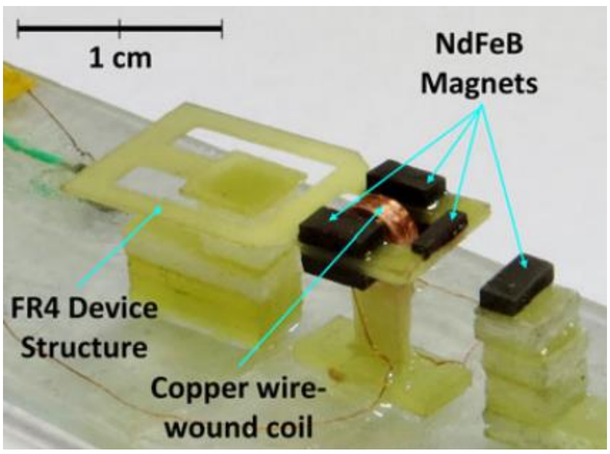


Figure 3: Fabricated prototype of the non-linear EM harvester [53]

A wideband VEMEH deploying a high permeability cantilever beam has been reported by X. Xing et al. [54]. The developed device consists of a 4.6 cm x 0.8 cm x 0.0254 cm high permeability cantilever beam with the free end vibrating inside a solenoid of size 4.4 cm x 3.2 cm x 4 cm. Two identical Samarium-Cobalt (SmCo) rectangular magnets each of size 2.2 cm x 1.3 cm x 0.2 cm with anti-parallel magnetization are located in close proximity of the beam as shown in figure 4. The induced vibrations oscillate the beam inside an inhomogeneous magnetic field formed by the anti-parallel magnetic moment resulting in reversal of magnetization in the beam by 180˚. This reversal of magnetization in the beam resulted in a maximum magnetic flux change in the solenoid and thus inducing a voltage in it. The developed harvester has a total volume of 68.96 cm^3 and generates 74 mW of maximum power which results in 1.07 mW/cm^3 of power density at 54 Hz frequency and 0.57 g vibration level. The device has an operational range of frequency from 30 Hz to 70 Hz with a wide bandwidth of 10 Hz (i.e 45.45 Hz-55.45 Hz).

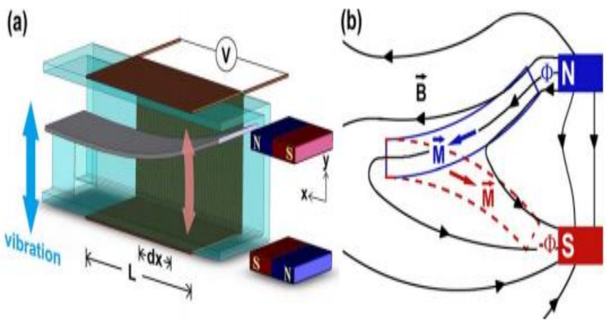


Figure 4: Schematic of the proposed harvester (a) with flux change (b) [54]

R. Paul and B. George [55] have developed a very low frequency VEMEH by deploying a spherical flipping magnet as shown in figure 5. The NdFeB spherical magnet (15 mm diameter) is housed (free to move) inside a bobbins. Two bobbins (one oriented vertical and another horizontal) are fabricated using Teflon and have V-groves and have an inner diameter of 16 mm. The vertical and horizontal bobbins each one is having a 42 gauge copper wire windings (300 turns) with a coil resistance of 52.5 Ω. The bobbins and the spherical magnet are located at the cantilever beam's free tip. Moreover, two cylindrical stationary magnets employed at top and bottom positions and the gap in between these the bobbins move due to vibrations. It is reported that due to the presence of these cylindrical magnets, even a very low frequency vibrations results in flipping the spherical magnet inside the bobbin. This flipping of the spherical magnet actually resulted in magnetic flux change in the coil and thus inducing voltage. The fabricated device is tested to operate within a range of frequencies from 0.25 Hz to 3.5 Hz. The frequency bandwidth of the harvester from the power as function of frequency plot is approximately 1.5 Hz (i.e 2-3.5 Hz). The developed harvester having a total volume of 3.59 cm^3 has a peak to peak open circuit output voltage of 3.5 V and an average output power of 1.66 mW which results in 445 $\mu W/cm^3$ of power density when operated at vibration of frequency 3.5 Hz.

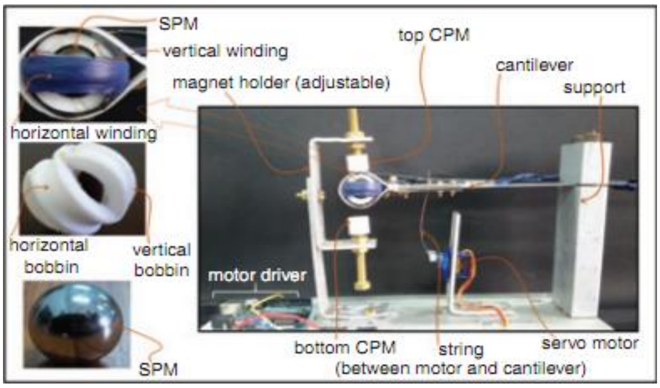


Figure 5: Experimental setup and the developed harvester [55]

Jinkyoo Park et al. [56] have reported a VEMEH in which both the coil and magnet are kept movable in response to the ambient vibrations. The developed prototype is shown in figure 6. The harvester is having a total of 11 cantilevers in which the 6 cantilevers carry permanent magnets which are attached to the cantilevers tips through magnet holder and having a fixed natural frequency of 6.8 Hz. The remaining 5 cantilever with the same geometry and stiffness carry coils with the same dimensions. The coil cantilever beams have different tip mass to alter the natural frequency of each coil carrying cantilevers from 7 Hz to 8.6 Hz and thus introducing asynchronous movement of the coil carrying cantilevers in the harvester. It is reported that the produced harvester is tested to be best suited for low frequency (below 5 Hz) and low acceleration level vibrations. The developed harvester is having a frequency bandwidth of 1.3 Hz. While testing on Nong-Ro Bridge (Korea) by adding more tip masses to coil carrying cantilevers and thus bringing their frequency range to the resonance frequency of the bridge (3 Hz) the device resulted in generating a maximum output power of 30 μW.

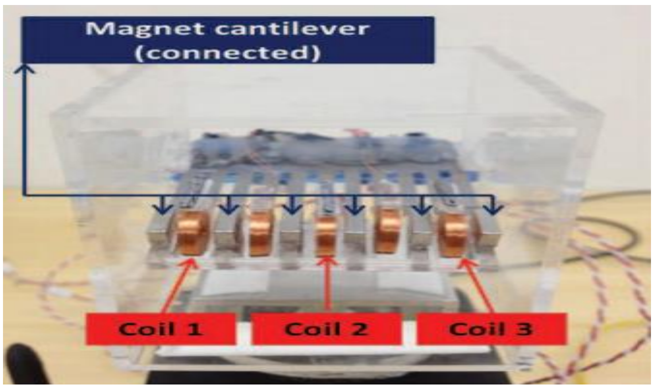


Figure 6: Prototype of the developed asynchronous phase shifted VEMEH [56]

A wideband VEMEH comprised of two major parts, a stator and a translator is devised by M. S. M. Soliman et al. [57].

The magnetic parts of the harvesters are housed by the stator, whereas the mechanical suspension and coil arrangement is carried by the translator. The device shown in figure 7 consisted of a cantilever beam (45.3 mm x 10 mm x 1.02 mm) carrying a seismic mass and a coil (160 µm, 22 turns with an area of 1 cm²) movable in a surrounded stationary magnetic field constituted by four permanent magnets each one of size 10 mm x 10 mm x 3 mm.

Moreover, the device carries a slider and an adjustable stopper movable along a track which varies the effective length of the beam and thus exhibits a wide band of the device's natural frequency. The device is operated at a constant acceleration level of 0.1 g at a frequency range of 90 Hz to 100 Hz and resulted in a maximum voltage of 19.5 mV. The frequency bandwidth of the developed harvester is estimated to be 1.4 Hz.

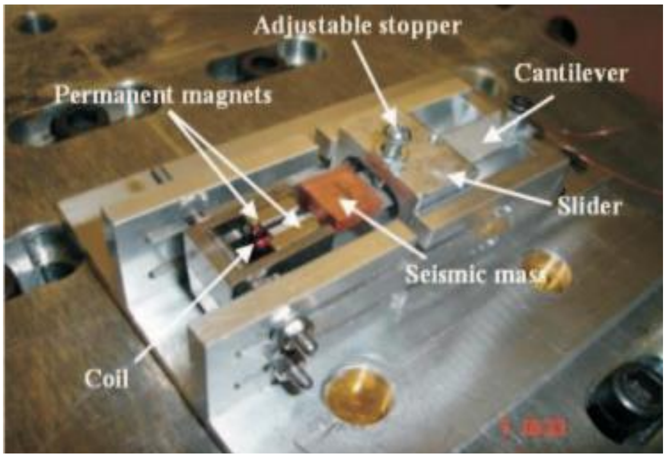


Figure 7: Photograph of the fabricated wide-band EMEH [57]

A fixed-fixed beam type VEMEH with three sets of magnets and coils (shown in figure 8) has been reported by Yang et al. [58]. The acrylic beam supports the three permanent magnets which are glued to it just upon the three sets of copper spiral bi layer planar coils (fabricated on both sides of FR4 substrate) in such a position that the applied vibrations results in inducing voltage in the coils. The device entertains three resonant frequencies thus enhancing the overall bandwidth as compared to a single magnet and coil arrangement. The resonant frequency of 369 Hz refers to the device's first mode of vibration, however, 938 Hz and 1184 Hz are the corresponding second and third mode of resonant frequencies of the harvester. The developed harvester is experimentally tested at vibration levels of 0.76 g for a frequency range of 0 to 1500 Hz. The maximum open circuit voltage from all the three coils connected in series is 0.2 mV at 0.76 g acceleration and 369 Hz frequency. The peak output power at first mode is reported to be 0.6 µW, however, a power of 3.2 µW is generated at the second mode of vibration. The frequency bandwidth for the first mode of vibrations as estimated from the voltage against frequency plot is 50 Hz (i.e 360-410 Hz) whereas for the second mode of vibration the frequency bandwidth is estimated to be 80 Hz (i.e 880-960 Hz).

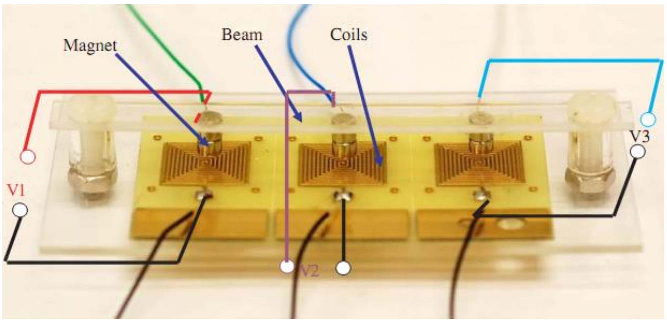


Figure 8: Photograph of the reported VEMEH [58]

For enhancing the frequency bandwidth, a VEMEH with fixed permanent magnet surrounded by an array of 35 different resonant frequency oscillating cantilevers has been produced by Sari et al. [59]. As shown in figure 9, a combination of different length cantilevers (parylene used as structural material) are patterned with coils. In the harvester to each cantilever an adequately small increment in the length is increased so that a wide range of frequencies is covered during operation. The coils and the central block magnet's relative movement results in inducing voltage in the coils. This device having a size of 14 mm × 12.5 mm × 8 mm is experimentally tested of generating a voltage of 10 mV in an operating frequency band of 4.2–5 kHz. The frequency bandwidth of the harvester is estimated from the output power against frequency plot to be 300 Hz (i.e 3350 -3650 Hz). Furthermore, it is reported that the reported VEMEH could generate a power of 0.4 µW.

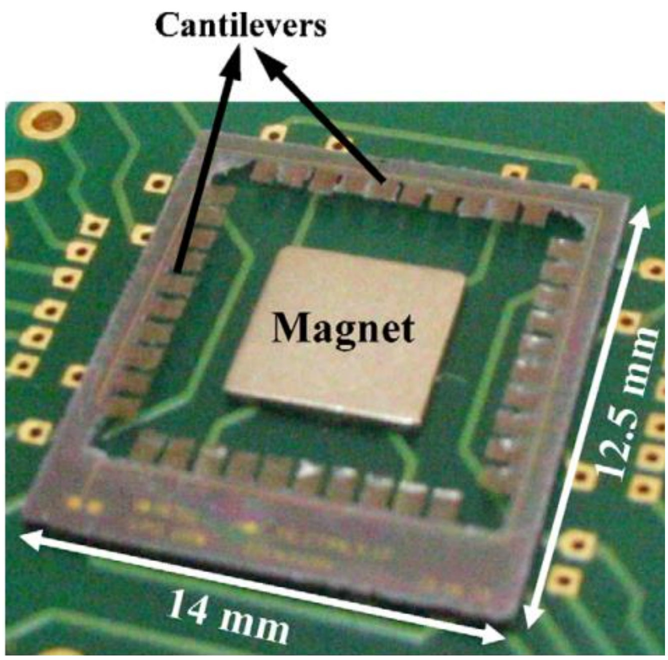


Figure 9: Photograph of the developed VEMH [59]

Liu et al. [60] has reported a VEMEH, which is basically an arrangement of three multi modal spring mass structures and a permanent magnet joined to the fixed-fixed beam. The VEMEH given in figure 10, is having three autonomous spring-mass structures which vibrates independently of each other during operation. In the harvester, folding springs are used to suspend the shuttle mass that carries the planar aluminum spiral coil. Nine resonant peaks are realized for the device in the range of frequency between 189 Hz to 662 Hz. For generating magnetic field and inducing voltage in the coils, two permanent magnets (cylindrical magnet of size 3 mm (diameter) x 2 mm (thickness)) are bonded to a fixed-fixed beam and are positioned just above the spring mass structure. The microfabricated spring-mass structure overall dimensions are 10 mm x 8 mm x 0.4 mm and is fabricated using the technique of double side deep reactive ion etching (DRIE) on a silicon on insulator (SOI) wafer. At an acceleration of 1g, the device open circuit output voltage is recorded to be in the range of 0.01 mV to 0.13 mV, however, the generated power is varying from 0.303 x 10-6 μW to 16.012 x 10-6 μW resulting in a power density of 0.010 x 10-3 μW/cm³ to 0.500 x 10-3 μW/cm³. The maximum frequency bandwidth as estimated from voltage as function of frequency plot is 10 Hz.

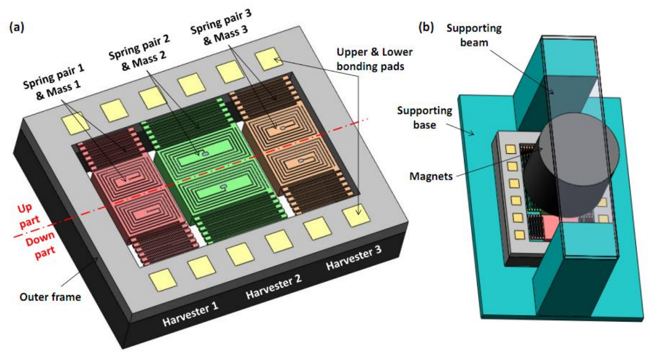


Figure 10: (a) 3D drawing of spring-mass structure of the harvester, (b) Reported VEMEH [60]

A multimodal (2DOF) VEMEH has been reported by Tao et al. [61], which is consisted of two sub systems. The primary subsystem generates power whereas the accessory subsystem is for tuning the frequency of the harvester. As shown in figure 11, the outer circular spring is used to support the primary mass, however, an inner spiral spring is used for suspending the accessory mass which in turn is used for tuning the first two resonant frequencies very close to each other's and at the same time maintaining comparable amplitudes. A cylinder shape permanent magnet is bonded onto an acrylic plate and is located exactly over the accessory mass of the spring-structure. In the device, the magnet (6mm x 5mm) is kept stationary. Moreover, a planar spiral coil is produced on the primary mass of the spring-structure. The prototype's fabrication involves the SOI wafer using double side DRIE. When the primary mass is vibrated relative to the fixed magnet by the exterior oscillations, it generates voltage across the coil's terminals. The device having a size of 14.5 mm × 14.5 mm × 430 μm when experimentally tested at 0.12 g acceleration level produced an output voltage of 3.6 mV at 326 Hz and 6.5 mV at 391 Hz resonant frequencies respectively. The device's maximum output power reported is 0.96 nW, however, the maximum value of normalized power density is mentioned to be 2.75 x 10-2 W/cm³/g. The device is provided with a forward frequency sweep from 300 Hz to 420 Hz and the frequency bandwidth from the voltage against frequency plot is estimated to be 2

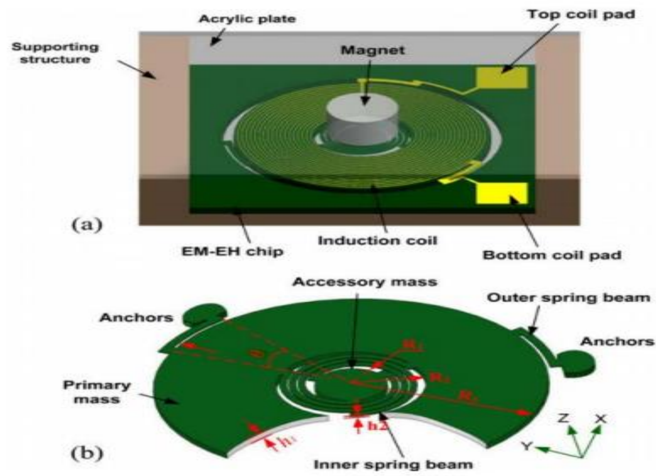


Figure 11: (a) 3-D schematic of the reported VEMEH, (b) Trimetric view of prototype [61]

A monostable very low frequency (less than 10 Hz) VEMEH has been developed by fan et al. [62], which consists of a tube with wrapped coil around it, two fixed magnet attached to tube's both ends and a magnet spring resonator inside the tube. As shown in figure 12, the central movable magnet is arranged in such a way that it is in attraction to both the end magnets thus introducing spring softening response and shifting the operating frequency to the lower side. Experiments show that under sinusoidal excitation the developed harvester is provided with a frequency range of 5 Hz to 25 HZ and at 0.8 g acceleration and 9 Hz frequency, the device generated 1.15 mW of power. The frequency bandwidth of the harvester as estimated from the frequency vs voltage plot is approximately 2 Hz (i.e 9-11 Hz). When excited by hand shaking, the harvester charged a capacitor (47 μF) from 0 V to 4 V in just 2 seconds. Moreover, it is reported that at the treadmill experimentation when the device is fasten on the leg in vertical position (shown in figure 13), the developed VEMEH produced around 0.5 mW of power during walking (4 to 6 km/hr). However, when the prototype is fasten on the leg in parallel position and tested during running (7 to 9 km/hr) it generated a power of 0.7 mW.

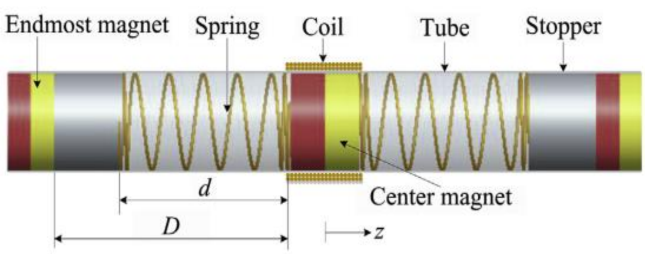


Figure 12: Schematic diagram of low frequency monostable VEMEH [62]

Figure 13: Developed prototype attached on arm vertically, on leg vertically and parallelly [62]

II. (b) NON-RESONANT VEMEHs

Iman Shahosseini et al. [63] have designed a VEMEH based on non resonant and wide-band frequency ambient vibrations. The harvester shown in figure 14 is comprised of two major parts. One part having a set of grade-42 NdFeB permanent magnets is aligned axially with same poles in front of each other. Second part is a series of alternately clockwise and counterclockwise copper wound coils (made from 34 AWG wire) so that the voltage levels induced in both coils are in phase. The coils are wound around thin Teflon tube (for reducing the coil-magnet gap to 1 mm). A 4 mm interface between the magnets is obtained by using aluminum shims. In contrast to a simple electromagnetic energy harvester where resonant repelling force is provided by either mechanical springs or pair of magnets, here coil is fixed to one end of the harvester and magnets through wire are connected to other harvester end. The developed prototypes with 4 mm long, 6 mm thick 60 Ω, and with 2 mm long 5 mm thick coil with 25 Ω were tested by subjecting to vibration through shaking table. The vertical up and down movement of magnets w.r.t stationary coils results in generating voltage. The EM energy harvester is tested to operate out of resonance frequency and the resultant power increased from 30 μW to 2.2 mW for a frequency range of 3 Hz to 12 Hz at vibration amplitude of 1 mm.

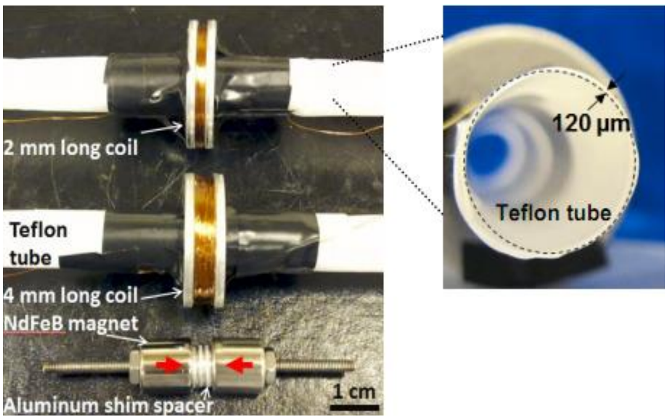


Figure 14: Developed prototype of harvester [63]

A VEMEH for scavenging non-periodic low frequency range of vibrations has been developed by Tzeno Galchev et al. [64]. A 3.175 mm diameter and 4.75 mm thick cylindrical magnet is positioned on the top of coil. In the harvester a coil of 2 mm width, 3.175 mm length and 240 Ω resistance is used. A grade N42, NdFeB, magnet (2.4 mm x 4.76 mm) bonded to a spring which is located on top of a plastic spacer (1mm x 1mm x 0.5 mm) makes the frequency increased generator (FIG) spring assembly. Latching and actuation is obtained by bonding another cylindrical magnet (1.15 mm diameter and 0.5 mm thick) on the other side of FIG spring.

A large inertial mass made of tungsten carbide is utilized for coupling the ambient vibration energy into the generator's structure and passing a part of this vibration energy to the two FIGs. Through electromagnetic induction this mechanical vibration energy is converted into electrical energy by FIGs. The two FIGs are placed on each sides of the inertial mass and are positioned to face each other. Moreover, for generating power, a magnet is attached to the FIG spring's bottom. For generating magnetic force and thus latching the FIG and inertial mass together, a smaller magnet is used on the top. Aluminum sidewall of 1 mm thickness is used for casing the generator. The developed parametric frequency-increased generator (PFIG) with an overall volume of 3.75 cm³(with internal volume of generator =2.12 cm³) which is shown in figure 15, is tested at input acceleration and frequency of 1 g and 10 Hz respectively and the generated power is having a maximum and average value of 163 μW and 13.6 μW respectively. Furthermore, it is reported that the device can be operated up to 65 Hz of frequency.

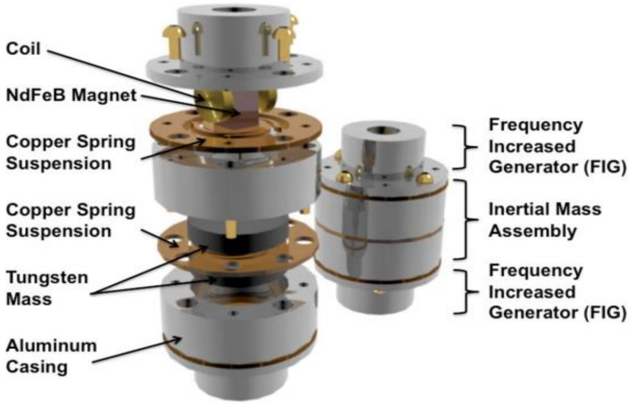


Figure 15: Prototype of the reported micro power generator [64]

A set of multi-dimensional harvesters have developed by Jeongjin Yeo et al. [65] to encounter a wide range of ambient vibrations. A common cylindrical and doughnut shaped harvesters with same volume, equal number of turns and equal number of wound coils and magnets have been developed and exposed to vibration through shaker in the entire three axis at three basic orientations of the vibration (0˚, 45˚ and 90˚). Each one of the two harvester prototypes has a total volume of 95.56 cm³ with 10 wound coils having 700 turns, each prototype carrying four cylindrical magnets (size 1.5 cm x 1cm) facing each other with similar polarity separated by rigid sponges. Coil solenoids are wound externally on the housing of both harvesters as shown in figure 16. Both the developed prototypes are tested with a range of frequency vibrations from 3 Hz to 100 Hz. The cylindrical harvester with a bandwidth of

25 Hz (i.e 20-45 Hz) as estimated from voltage as function of frequency graph is tested to have a maximum RMS voltage of 5.7 V at 30 Hz resulting in a maximum power of 19.03 mW; however, the doughnut shaped harvester generated a peak RMS output voltage of 5.4 V at 9 Hz frequency and is having a bandwidth of 2 Hz (i.e 8-10 Hz).

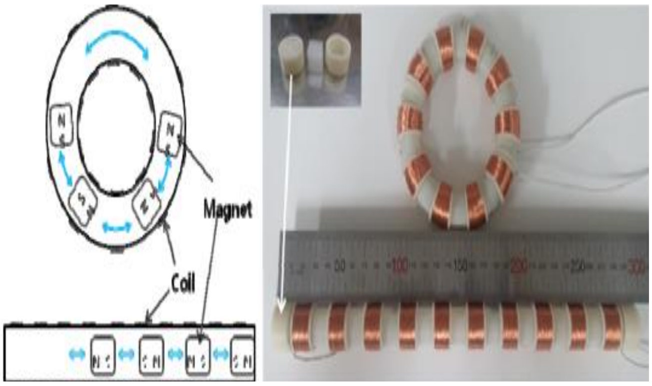


Figure 16: VEMEHs developed in [65]

A non-resonant and a wide band of frequencies harvester has been fabricated by Bin Yang et al. [66] as shown in figure 17. Harvester is produced by stacking five pieces of 2 mm thick FR4 substrates together having a 4 mm wide sealed cavity (hole) at the center and each substrate contains 12 layers of planar copper coils, each having 10 turns. Moreover, a Neodymium (Nd) cylindrical magnet (3 mm x 4 mm) resides in the central cavity and can move up-down freely due to vibrations. Furthermore, acrylic sheets are used for covering the whole package. In the harvester, the air damping is reduced by drilling small holes in the acrylic cover plate. The fabricated device is having total volume of 2.7 cm3. The fabricated energy harvester has been experimentally tested and it produced an output voltage of 9 mV from vibration at an acceleration of 1.9 g within frequency range of 40 Hz to 80 Hz. The harvester is operated within an operating frequency limits of 10 Hz to 300 Hz and is having a wide bandwidth of 40 Hz (i.e 40-80 Hz) which resulted in generating a maximum power of 0.4 μW.

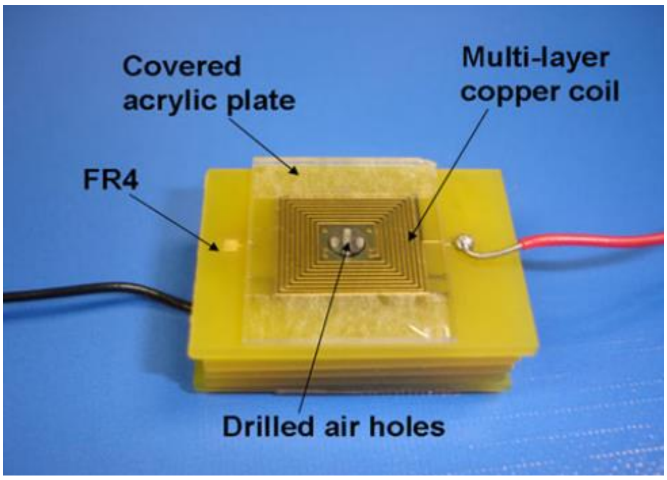


Figure 17: Fabricated wide band energy harvester [66]

S. Bradai et al. [67] have developed a non-linear wide-band VEMEH as shown in figure 18.

The developed harvester is operated in a frequency range of 10 Hz to 60 Hz and is having a frequency bandwidth of 20 Hz (i.e 25-45 Hz). As shown in figure 18, the developed harvester composed of a magnetic spring which is produced by placing a movable magnet between two fixed magnets (each magnet is NdFeB). Moreover, in the harvester, the additional stiffness is introduced by placing around the moving magnet, a ring magnet which results in increasing the output power as well. The device is compared with a simple EM converter through simulations and then confirmed through experimentation. The developed non-linear wide-band VEMEH is tested and it is reported to be able of harvesting 1.5 times more energy in comparison to a simple EM harvester when operated for a frequency ranging from 20 Hz to 35 Hz at 2 mm excitation amplitude and optimal load resistance of 33 Ω.

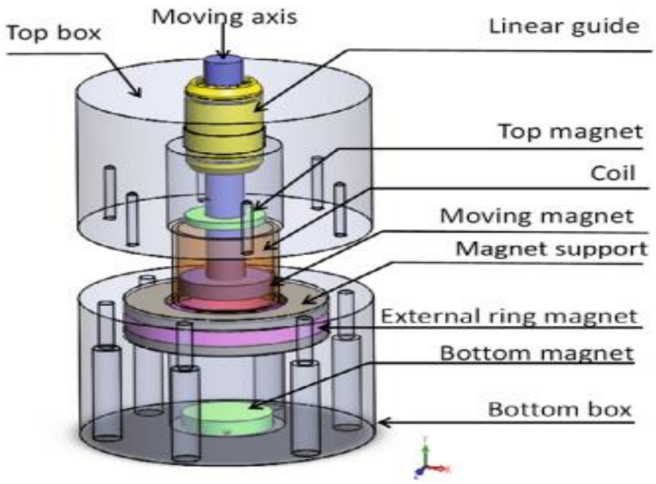


Figure 18: Schematic of the proposed VEMEH [67]

A two-degree-of-freedom (2-DoF) VEMEH is reported by fan et.al [68]. The harvester is produced by the alteration of a cylindrical housing wrapped with supplementary coils (1-DoF VEMEH). The 2-DoF VEMEH is achieved by the influence of magnetic coupling between the main VEMEH and the housing. Thus this magnetic suspension is useful for exploiting the ultra-low frequency excitations and for generating useful power. With an excitation of 0.5 g amplitude, the 2-DOF VEMEH is experimentally tested and at 7.5 Hz, it produced 2.58 mW peak power, which is reasonably better than (1.86 mW) generated by the 1-DoF VEMEH. The developed harvester is experimentally tested for a frequency range of 5 Hz to 25 Hz and from the plot of power as function of frequency, the frequency bandwidth is estimated to be 2 Hz (i.e 6.5-8.5 Hz). The operating bandwidth of the 2-DOF VEMEH is 9.1 Hz which is wider as compared to 3.6 Hz provided by the 1st counterpart. Both the developed prototypes of the energy harvester are shown in figure 19.

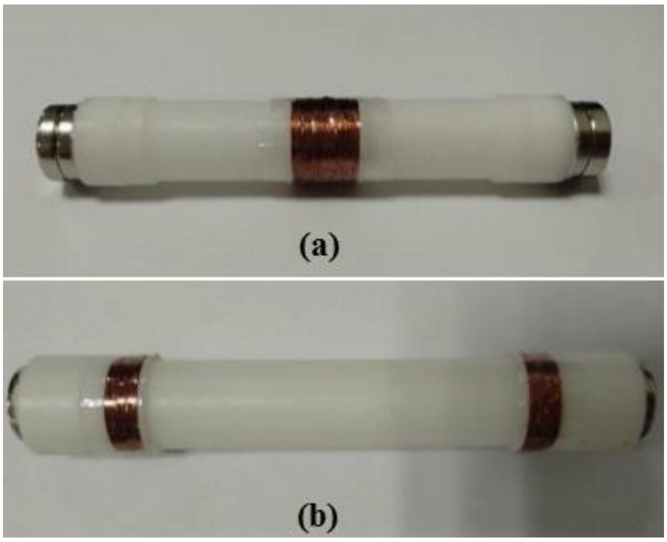


Figure 19: Prototypes of the fabricated wide-band VEMEH (a) 1-DoF (b) 2-DoF [68]

A non resonant VEMEH of miniature size for generating energy from low frequency and low acceleration levels has been developed by Zorlu et. al [69]. The developed device is comprised of a 2 mm x 2 mm cantilever beam, an NdFeB permanent magnet (2.5 mm x 0.5 mm) attached on an oscillator's shaker stage, a 40 layers dual level micro machined planar coil attached to the beam, and a polystyrene film mechanical barrier arm which is joined on the magnet's upper surface. Figure 20 shows the developed harvester. The applied vibrations caused the barrier arm to periodically engage, deform, and then release the cantilever beam which results in resonating the cantilever beam at its resonant frequency. The magnet and coil's relative displacement results in producing the voltage across the planar coil's terminals through electromagnetic induction.

The developed prototype has a total volume of 0.12 cm³ and 21.5 Ω coil resistance. At 0.8 g acceleration level and 10 Hz frequency the developed energy harvester is reported of generating an optimum RMS load voltage of 1.44 mV and 24 nW of power, ensuing a power density of 200 nW/cm³.

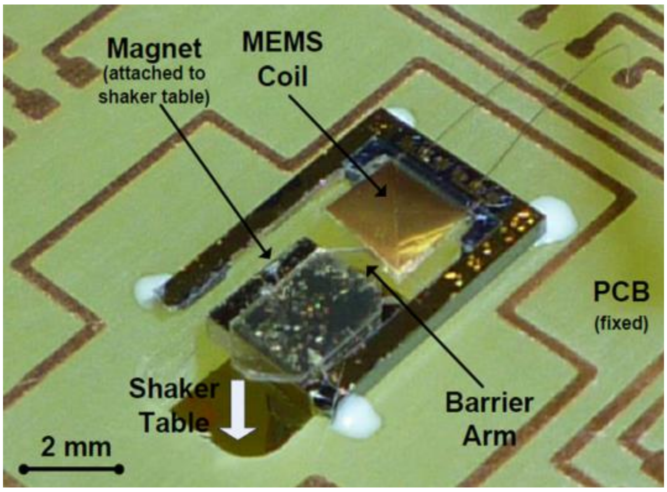
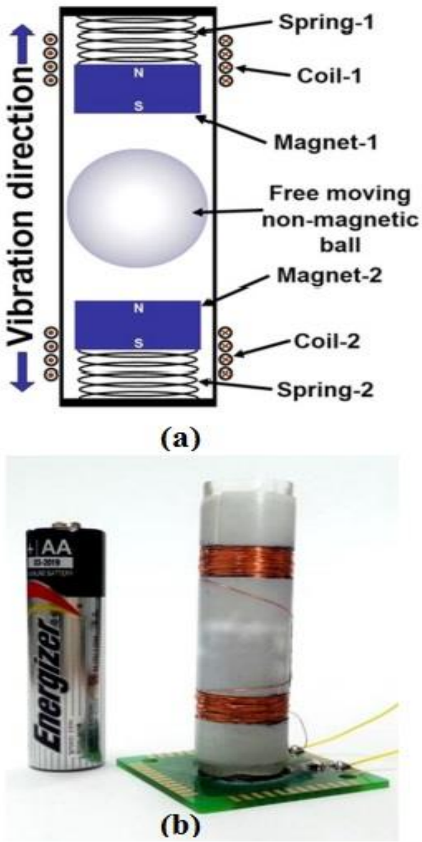


Figure 20: Photograph of the reported non-resonant VEMEH [69]

A non resonant frequency up-converted wide band VEMEH is developed by M. A. Halim et.al [70] for generating power from human body's movement. The fabricated VEMEH depicted in figure 21 comprised of a hollow acrylic cylinder, two helical steel springs, two acrylic end caps, two copper wound coils each of 200 turns, two permanent magnets (NdFeB) and a non metallic ball. Each spring carries a magnet connected to its one end while the spring's second end is fixed to end cap. The external movement or human motion results in moving the freely movable non-magnetic ball that hits the two magnets thus the magnet connected to the spring oscillates (relative the coil) at relatively high resonant frequency and results in voltage induction in the wound coil. The device having an overall volume of 6.75 cm³ when subjected to an external excitation of 1.53 g, 1.83 g, and 2.04 g generates an open circuit RMS voltages of 33.7 mV, 40.1 mV, and 45.3 mV, correspondingly for the operating frequency range of 14 Hz to 22 Hz. The developed harvester is experimentally operated for a frequency range of 12 Hz to 60 Hz and the frequency bandwidth is estimated to be 8 Hz (i.e 14-22 Hz). On the other hand, it is also reported that when operated from 23 Hz to 39 Hz, the device produced arbitrary voltages with declining trend. For relatively upper frequency ranging from 40 Hz to 60 Hz, the device produced very minute voltage because of the ball's non-prominent movement which is unable to complete its movement cycle and thus unable to hit the magnets.



Citation: *Hamid Khan et al. (2020) A Review of Vibration Based Wide-Band Electromagnetic Energy Harvesters. J Electr Eng Electron Technol, 9:4*

Figure 21: Reported prototype: (a) Schematic diagram (b) Developed non-resonant VEMEH [70]

A non resonant VEMEH has been reported by Li et al. ref [71] for car key remote controller's applications. The fabricated device shown in figure 22 is comprised of a cylindrical block magnet which can freely move inside a round cavity of 20 mm diameter. PCB fabricated multilayer copper planar coils are used to cover the two sides of the cavity. The relative movement between the copper coils and a magnet results in generating voltage across the coil's terminals. The planar copper coil has 4-layers produced using a standard FR-4 PCB fabrication technology with wire width of 100 μm and turn's thickness of 35 μm. The reported harvester having a height of 3.1 mm when vibrated using a z-axis polarized magnet produced 1.1 V of open circuit voltage at vibration amplitude and frequency of 100 mm and 3 Hz correspondingly. Moreover, it is also described that by increasing the magnet size with larger radius actually enhances the induced voltage in coils.

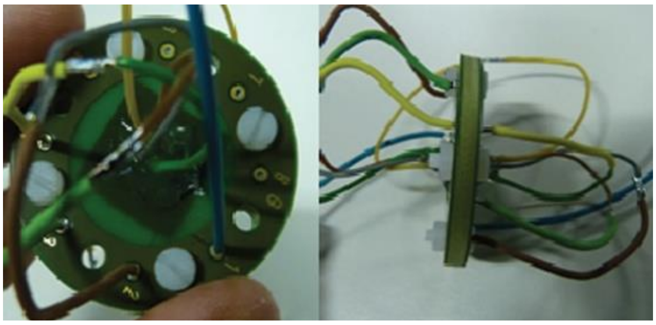


Figure 22: A non-resonant VEMEH developed [71]

For harvesting energy from human's body movement a VEMEH is developed by Bowers et al. [72] which is composed of a spherical cavity acting as device's casing as well as providing space for the freely movable spherical permanent magnet (NdFeB). The wound coil is produced by wrapping a 34-guage copper coil on top of the casing. Two prototypes have been developed ptototype-1 and prototype-2 as shown in figure 23. The wound coil in ptototype-1 is made at the spherical casing's equator, however, in prototype-2, two series connected wound coils are formed at the casing's hemispheres. 3-D rapid prototype print machine is utilized for fabricating the harvester's spherical casings. First two identical hemispherical parts are formed having flanges for holding the wound coils on the outer surface. Secondly, a permanent magnet is positioned inside the constructed hemisphere portion and the second hemisphere is afterward bonded on its top, and finally the wound coil is wrapped utilizing copper wire. The prototypes been characterized in human's walk and running activities are noted of producing more output voltage during running. The prototype-2 tested during running (as kept in trouser's pocket) is reported to produce more output voltage (680 mV) and better power density (0.5 mW/cm³) as compared to prototype-1 which produced only 350 mV resulting in a power density of 0.12 mW/cm³. The developed harvester is tested to be suited for low frequency operations in the range of 1 Hz to 10 Hz.

Figure 23: Developed VEMEH: (a) Prototype-1, (b) Prototype-2 [72]

A spring less VEMEH in cubic shape for converting the vibration in the entire three axes into useful electrical power is developed by Han et al. [73]. As shown in figure 24, a cube is formed by a combination of copper planar coils and a substrate in folded from. A permanent NdFeB magnet is placed within the cube which can freely move in all directions without any spring support thus allowing the device to harvest in all the directions. The fabricated harvester having an overall volume of 1 cm3 has an operating frequency range of 20 Hz to 100 Hz. The frequency bandwidth of the harvester from plot of voltage against frequency is estimated to be 3 Hz (i.e 25-28 Hz). When operated within the mentioned frequency range at 0.5 g acceleration, the highest value of voltage generated reached to 3.82 mV at 26.87 Hz with a peak power of 0.75 μW that resulted in the device power density of 0.75 μW/cm³.

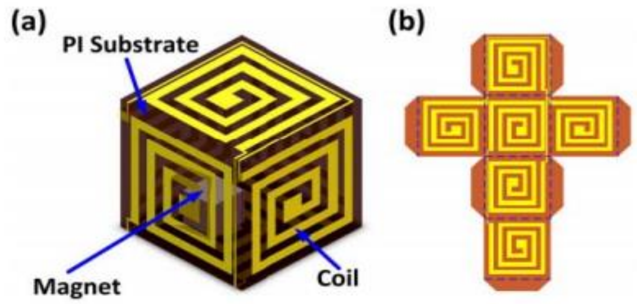


Figure 24: Developed VEMEH: (a) 3D drawing (b) Planar layout of cubic device [73]

III. COMPARISON OF THE REPORTED WIDEBAND VEMEHs

The VEMEHs reported in this review are mainly considered for their frequency and operating range of frequency where a particular harvester is able to produce adequate power for running a WSN. However beside frequency bandwidth, there are many other parameters linked with these harvesters on the basis of which these devices could be compared. These parameters include, the overall volume of the device, the acceleration level of vibration to which these VEMEHs are subjected, operating frequency range, output voltage, output power and resultant power density.

The reported harvesters are listed in Table III for the comparison on the basis of mentioned parameters reported for these devices.

Table III Comparison of the Reported Wide-Band VEMEHs

Type	Device Volume (cm³)	Acceleration (g)	Operating Frequency Range (Hz)	Frequency Bandwidth (Hz)	Voltage (mV)	Average Power Output (µW)	Power Density (µW/cm³)	Power / Acceleration (µW/g)	Power Density/ Acceleration (µW/g cm³)	Ref.
Resonant	1600[a]	0.2	32 - 85	5	260	340	0.21	1700	1.05	[51]
	---	---	20 - 160	140		100				[52]
	13.31[b]	1.5	10-50	8	150	19.3	1.45	12.86	0.96	[53]
	68.96	0.57	30-70	10	650	74000	1073	129824	1877	[54]
	3.59	---	0.25 - 3.5	1.5	3500	1660	445			[55]
	---	---	0.5 - 5	1.3		30				[56]
	675[a]	0.1	90 - 100	1.4	19.5					[57]
	3.4[a]	0.75	0-1500	80		3.2	0.941	4.26	1.24	[58]
	1.4	---	4200 - 5000	300	10	0.4	0.286		5.72×10^{-3}	[59]
	0.032	1	189 - 662	10	0.01 to 0.13	16.012×10^{-6}	0.50×10^{-3}	16.012×10^{-6}	0.500×10^{-3}	[60]
	0.091	0.12	300-420	2	3.6 & 6.5	0.00096	3.30×10^{-3}	0.008	27.5×10^{3}	[61]
	12.19[b]	0.8	5-25	2		1150	94.33	1437.5	117.91	[62]
Non-resonant	11.37[a]	5.67[c]	3 - 12	9	300	2200	193.7	388	34	[63]
	3.75	1	10 - 65		100	13.6	3.63	13.6	3.63	[64]
	95.56	---	3-100	25	5700	19030	199			[65]
	2.7	1.9	10-300	40	9	0.4	0.148	0.21	0.0778	[66]
	---		10-60	20	370					[67]
	---	0.5	5-25	2		2580		5160		[68]
	0.12	0.8	10		1.44	0.024	0.2	12.5	0.250	[69]
	6.75	2	12-60	8	45.4					[70]
	0.975[a]	3.62[c]	3		1100					[71]
	4	---	1 - 10		680	2000[b]	500			[72]
	1	0.5	20 - 100	3	3.62	0.75	0.75	1.5	1.5	[73]

[a]Estimated from dimensions provided

[b]Calculated from power density

[c]Calculated by $a = y(2\pi f)^2$

The reported harvesters have been categorized into resonant and non-resonant and then compared on the basis of their size and average output voltage as shown in figure 25. The device with the largest size of approximately 1600 cm³ is reported in [51] which is resonance based VEMEH and it produces an output voltage of 260 mV. Where the device produced in [60] is the one with the smallest size of 0.032 cm³ and could generate a maximum of 0.13 mV voltage. The maximum voltage of 5700 mV is produced by the VEMEH reported in [65] which is non-resonant type and it has a volume of 95.56 cm³. It is clear from figure 25 that most of the resonant VEMEHs are of larger size than non-resonant VEMEHs and that is mostly because of the presence of cantilever beam arrangement or spring in the resonant type devices.

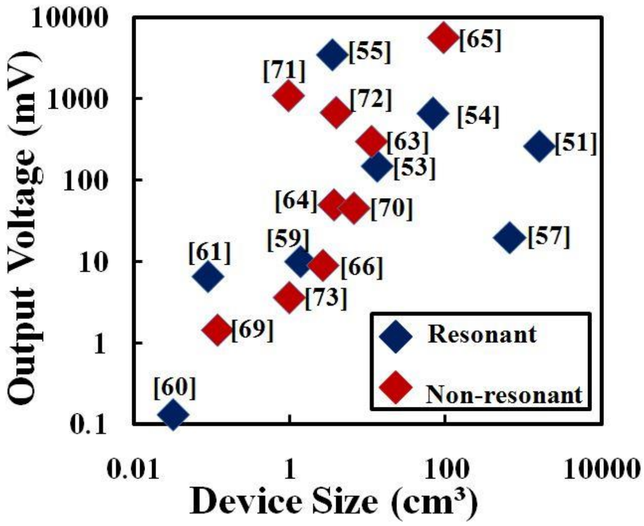


Figure 25: Voltage generated by reported VEMEHs as function of device volume

The comparison on the basis of output power and overall volume is shown in figure 26 where the reported VEMEHs are divided into resonant and non-resonant type. In the figure, the harvester reported by X. Xing et al. [54] is resonant device which is having an overall volume of 68.96 cm³ and could generate a maximum of 74000 µW output power that results in a power density of 1073 µW/ cm³.

Comparatively, the device reported in [60] is also a resonant device which generated a minimum amount of power (16.012 x 10-6 µW) with a power density of 0.50 µW/cm³.

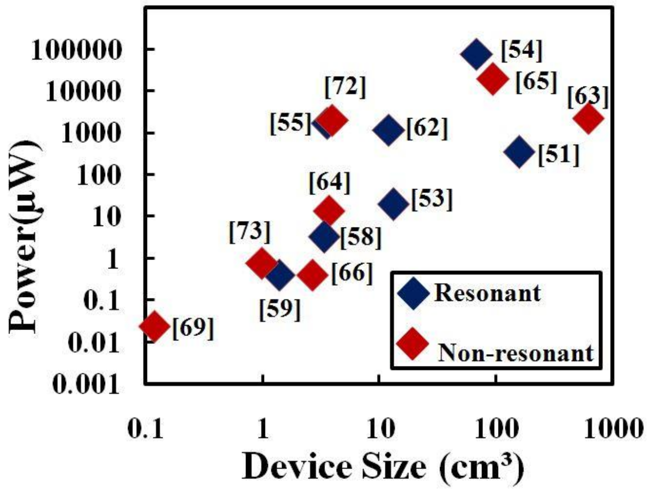


Figure 26: Power produced by reported VEMEHs as function of device volume

The graph between power density and acceleration is shown in figure 27. The device produced in [54] which is resonant type is offering the highest power density of 1073 µW/ cm³, while the lowest power density of 0.500 x 10-3 µW/ cm³ is reported by the device developed in [60]. Overall the power density of the resonant type VEMEHs is higher than that of non-resonant type VEMEHs.

Power per acceleration as a function of device size is shown in figure 28. The highest value of power per acceleration is 129824 μW/g which is offered by the harvester reported in [54] which is a resonant based device. The lowest value of power per acceleration is 16.012 x 10-6μW/g which is reported for the harvester in [60]. Again it is clear from the figure that the power per acceleration of the resonant VEMEHs is higher than that of the non-resonant VEMEHs. The higher value of power output for a lower acceleration level is contributed by the availability of cantilever beam arrangement or the presence of spring in such resonant devices. The non-resonant VEMEHs comparatively require higher values of acceleration amplitude to actually vibrate the harvesting device.

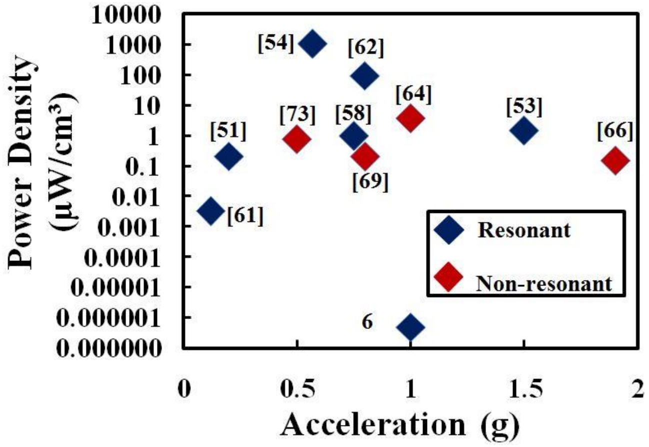


Figure 27: Power density of the reported VEMEHs as a function of acceleration

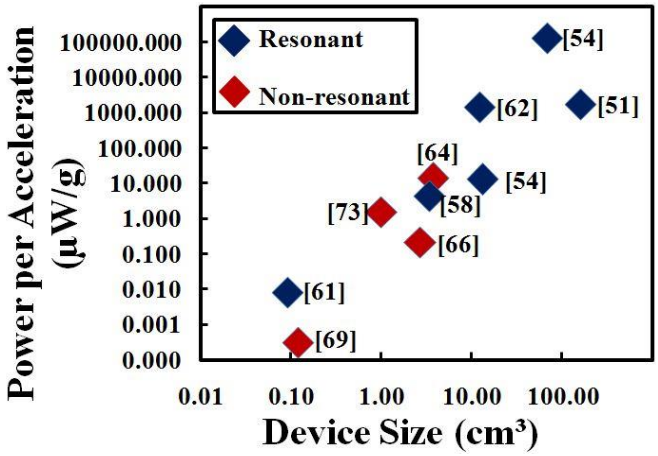


Figure 28: Power per acceleration of the reported VEMEHs as a function of device size

As the main focus over here for wide-band energy harvesting is the available bandwidth offered by the VEMEHs, so a comparison is made on the basis of the frequency bandwidth offered by each energy harvesting device and the output power. This comparison is shown in figure 29. The highest operating band of 300 is offered by the wide band VEMEH reported in ref [59] but the value of power obtained is only 0.4 μW. This highest frequency bandwidth is actually contributed by an array of 35 different resonant frequency oscillating cantilevers which results in an overall frequency band higher than other reported VEMEHs but the output power for this device is lower than others. The lowest value of frequency bandwidth which is 1.3 Hz is offered by the device presented in ref [56], however the maximum value of output power obtained from this device is 30 μW. The power as function of frequency bandwidth plot shows that on average the non-resonant VEMEHs are having wider frequency bandwidth as compare to the resonant VEMEHs.

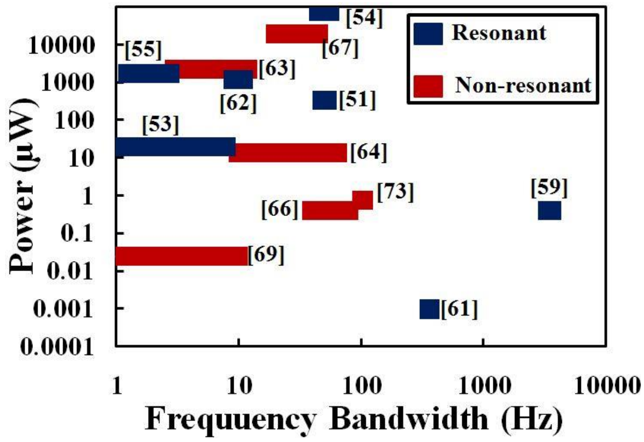


Figure 29: Output Power of the reported VEMEHs as a function of frequency bandwidth

Figure 30 shows the advancement in the power generating capability of the VEMEHs with respect to time. It is clear from figure 30 that with the passage of time the power generating capacity of the non-resonant VEMEHs is increasing as compared to the resonant VEMEHs. In 2008 the highest power of 680 μW is produced by the non-resonant VEMEH reported in ref [72].

Similarly higher values of generated power were recorded for the resonant VEMEHs in the year 2009, 2013 and 2016. For the years 2010 to 2012, 2014, 2015 and 2019 the non-resonant VEMEHs are dominating their resonant counterparts in term of power generating capability.

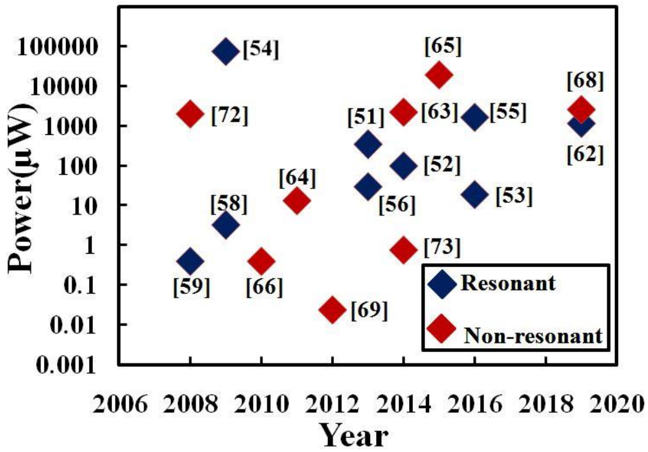


Figure 30: Output Power of the reported VEMEHs with respect to time

To have a better look at the advancement in the VEMEHs, the power density of the reported VEMEHs is plotted with respect to time. Normally in VEMEHs the key goal is to get a better power output for the reduced size of the harvester and thus have a better power density. Figure 31 shows such advancement in the resultant power densities of the reported VEMEHs with the passage of time. For the year 2009, and 2016 the power densities of the reported resonant harvesters are seen to be higher. However the non-resonant harvesters are seen to have higher power densities for the whole span of time and these power densities are noticed to be enhancing with time.

As mentioned earlier, the main focus in this review is to compare the developed harvesters on the basis of their frequency bandwidth besides their size, voltage and power output. So the frequency bandwidth of the reported VEMEHs is shown against time. Figure 32 shows that with the passage of time, there is an increase in the frequency bandwidth for both the resonant and non-resonant VEMEHs.

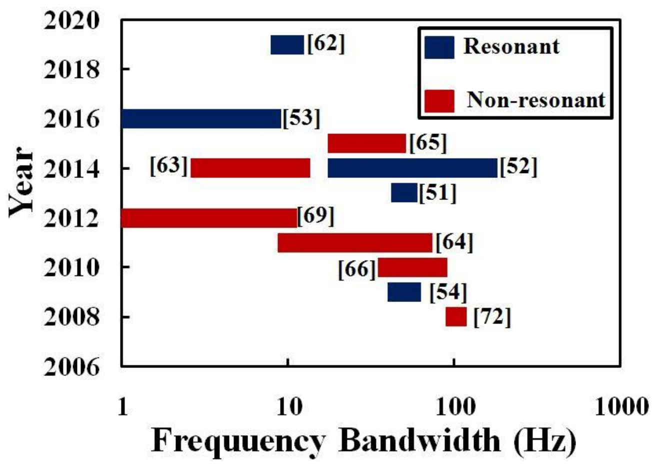


Figure 31: Power density of the reported VEMEHs with respect to time

IV. CONCLUSION

Vibration based electromagnetic energy harvester (VEMEHs) for powering remotely wireless sensor nodes as compared to its other counterparts (Electrostatic and Piezoelectric) have got vast research interest because of the simple structure and operating requirements. The main constraint for these devices is to produce a sufficient amount of power in their limited frequency bandwidth. The harvester to be able to continuously provide power to the connected WSN needs to be respondent to a wide band of ambient vibration frequencies and acceleration amplitude levels. A number of such developed and reported wide-band VEMEHs have been studied and analyzed based on their size, range of operating frequencies, frequency bandwidth, acceleration levels, output voltage, output power and power density. The reported VEMEHs have been shown with their overall volume ranging from 0.032 cm3 to 1600 cm3. Similarly the frequency bandwidth of the reported VEMEHs is 1.3 to 300 Hz. The power generated by the reported VEMEHs is in the range of 16.012 x 10-6 μW to 74000 μW resulting in a power density in the range of 0.500 x 10-3 μW/ cm^3 to 1073 μW/ cm^3. Most of the reported energy harvesters are capable of producing sufficient amount of power for energizing remotely connected sensor electronics. The reported harvesters consist of very lower frequency even starting from as low as 0.25 Hz of frequency with a bandwidth of 0.25 Hz to 3.5 Hz, while others even in the operating frequency range of 4.2 kHz to 5 kHz have also been reported. Based on the overall device size and resultant output power, a 1 cm^3 harvester with an average output power of 0.75 μW to a harvester of size 68.96 cm^3 with a peak output power of 74 mW have been reported in this literature. The comparison has been made on the basis of operating mechanism and the reported VEMEHs have been divided into two categories namely resonant VEMEHs and non-resonant VEMEHs. Comparatively the resonant VEMEHs are having larger size as compare to non-resonant VEMEHs. Similarly the output voltage and power output of the resonant type devices is higher than that of non-resonant type devices. However the frequency bandwidth of the non-resonant VEMEHs is higher than that of resonant VEMEHs. The year wise advancement in the power generating capability of the reported VEMEHs along with the resultant power density is also shown which illustrates that with the passage of time the power generation of the VEMEHs is enhancing while size is lowered thus resulting in better power densities. Most of the reported energy harvesters are capable of producing sufficient amount of power for energizing remotely connected sensor electronics.

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