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Energy Harvesting from Vibration of Structures-A Brief Review.

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Abstract. The shortage and high cost of energy in developing countries of the world has led to the search for other sources of electricity which are renewable and do not constitute to environmental hazards or pollution like fossil fuel. Also, the short life span of batteries which are used to power up important smart devices like the fire alarm makes searching for alternative sources all the more important. This has led to the recent interest in sustainable and renewable energy sources from water, sun, vibration, biological wastes etc. Harnessing energy from vibration amongst other renewable energy sources reduces fatigues in machineries, structures and control systems and effectively dissipates negative vibration energy from buildings, bridges, roads and various mechanical systems. This research paper provides a brief review on the current state of knowledge on the subject of harvesting energy from vibration. The review shows that harnessing renewable energy form vibration is feasible and has a great future.

Keywords: Vibration, Energy harvesters, Transduction mechanism, Piezoelectric vibration energy harvesters (PVEH).

1. Introduction

Energy shortage particularly in the developing countries, and the high cost of energy has led to the quest for finding alternative sources of energy. In addition to the subject of energy independence or renewability is also the concern of fossil fuel depletion and environmental hazards it poses. This quest has led to the recent interest in sustainable and renewable energy generation from air, water, sun and biological wastes [1,5-9].

Vibration reduces durability and causes damage or total failure of a structure or machine. Vibration reduces comfort, induces stress and bring about health related problems in humans. Vibration before now is usually dissipated as heat. The concept of vibration is useful in structural health monitoring and damage assessment of structures [2,3,4]. Vibration energy harvesting produces useful electrical energy which would have been otherwise dissipated as heat energy through the use of a transducer. The transduction mechanism may be piezoelectric, electromagnetic, electrostatic or hybrid systems [10-13]. 'Harvesting' is the conversion of an otherwise waste energy from vibration, collection and storage of the converted energy in an electric circuit. The simple vibration harvester system consists of a spring-mass system and a transducer which is used to convert the energy from vibration into electrical energy. The analysis of this simple system has been well studied using the Laplace or Fourier transforms, state space, transfer functions etc. An electric circuit is added to the spring-mass system to collect and store the converted energy. The interaction of the spring-mass system and the electric circuit is that of a 'shunt' damper. The influence of the electrical system on the natural frequency, the generated power and the conversion efficiency of the oscillator system is a measure of its coupling interaction. When interaction between the electric circuit and the spring-mass system produces little or no effect on the



natural frequency of the system, the coupling is said to be weak. However, if the interaction between the oscillator system and that of the mechanical damping has strong influence on the natural frequency of the system, the coupling is said to be strong. Performing non-dimensional analysis on the vibration parameters of a system during analysis makes it easily applicable to similar harvesters of different sizes, capacities or configurations by converting all variables and functions into dimensionless quantities, a process called ‘normalizing’.

2.0 Analysis of a single degree of freedom (dof) spring-mass system.

For the SDOF system with an unchanging source magnitude as a function of frequency as shown in fig.1.

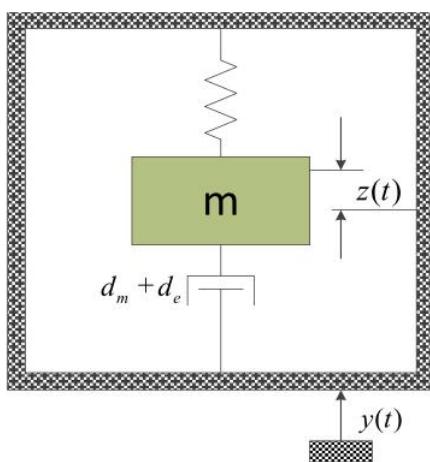


Fig. 1. Schematic diagram of a linear spring-mass system oscillator [14]

The model of mechanical system governing equation which primarily helps to understand electrical energy harvested from vibration for both linear damping and stiffness alone is presented as [14]:

$$m\ddot{z}(t) + d_T\dot{z}(t) + kz(t) = -m\ddot{y} \quad 1$$

where m represents mass, d_T is the total damping due to the electrical and mechanical damping coefficients d_e and d_m respectively. The forcing function or force producing the vibration is harmonic and is given by $(-m\ddot{y})$ where $y(t) = Y_0 \sin \omega t$ and Y_0 is the amplitude of the source function. The particular solution of the model generally has the same frequency as the exciting force but with a different amplitude and phase difference. Thus, the particular solution is given by

$$\left. \begin{aligned} z(t) &= \chi \sin(\omega t - \phi) \\ z(t) &= \chi (\sin \omega t * \cos \phi - \sin \phi * \cos \omega t) \\ \text{let } p &= \chi * \cos \phi; \\ \text{and } q &= \chi * \sin \phi \end{aligned} \right\} 2$$

$$z(t) = p \sin \omega t - q \cos \omega t \quad 3$$

$$\left. \begin{aligned} \dot{z}(t) &= pw \cos \omega t + qw \sin \omega t; \\ \ddot{z}(t) &= -pw^2 \sin \omega t + qw^2 \cos \omega t; \\ y(t) &= Y_0 \sin \omega t; \\ \dot{y}(t) &= Y_0 \omega \cos \omega t; \\ \ddot{y}(t) &= -Y_0 \omega^2 \sin \omega t \end{aligned} \right\} 4$$

solving for p and q using method of undetermined coefficients and substituting equation 4 into 1, we have,

$$\begin{aligned} \ddot{z}(t) + \frac{d_T}{m} \dot{z}(t) + \frac{k}{m} z(t) &= -\ddot{y}; \\ (-pw^2 \sin \omega t + qw^2 \cos \omega t) + \frac{d_T}{m} (pw \cos \omega t + qw \sin \omega t) + \frac{k}{m} (p \sin \omega t - q \cos \omega t) \\ &= -Y_0 \omega^2 \sin \omega t \end{aligned} \quad 5$$

Further simplification yields,

$$\left. \begin{aligned} p &= \frac{-Y_0 \omega^2 (k - m\omega^2)}{(k - m\omega^2) + (wd_T)^2} \text{ and} \\ q &= \frac{-Y_0 \omega^3 d_T}{(k - m\omega^2) + (wd_T)^2} \end{aligned} \right\} 6$$

Substituting p and q into equation 3 and further simplification yields the solution of the mass relative displacement in the time domain as given below

$$z(t) = \frac{-\omega^2}{\sqrt{\left(\frac{k}{m} - \omega^2\right)^2 + \left(\frac{\omega}{m} d_T\right)^2}} * Y_0 \sin(\omega t - \phi) \quad 7$$

The ratio $\frac{q}{p}$ from equation 2a and equation 6 will yield the phase angle ϕ as given below;

$$\phi = \tan^{-1} \left(\frac{wd_T}{k - m\omega^2} \right) \quad 8$$

Performing non-dimensional analysis on equations 8 using the total critical damping coefficient and natural frequency of the undamped oscillation, $\omega_n = \sqrt{\frac{k}{m}}$ and $d_T = 2m\omega_n \zeta$

$$z(t) = \frac{1}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\left(\frac{\omega}{\omega_n}\right)\right)^2}} * Y_0 \sin(\omega t - \phi) \quad 9$$

The non-dimensional or normalized amplitude $\frac{\chi}{Y_0}$ is thus given as

$$\frac{\chi}{Y_0} = \frac{1}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\left(\frac{\omega}{\omega_n}\right)\right)^2}} \quad 10$$

2.1 Power generated by the single dof linear system.

The power developed by this linear mass/damper system is the ratio of the work done by the damper to the period of oscillation. The work done is defined as the energy absorbed by the transducer per cycle.

$$P_d = \frac{1}{T} \oint F_d \dot{z} \quad \text{where } F_d = d_T \dot{z} \quad 11$$

$$P_d = \frac{1}{T} \oint d_T \dot{z}^2 dt, \text{ but } \dot{z}(t) = \chi \omega \cos(\omega t - \phi); \quad 12$$

Substituting equation 12 into 11 and simplifying,

$$= \frac{d_T \chi^2 \omega^2}{T} \oint \cos^2(\omega t - \phi) dt;$$

$$P_d = \frac{\chi^2 \omega^2}{2} d_T \quad 13$$

Substituting $\chi = \frac{Y_0}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\left(\frac{\omega}{\omega_n}\right)\right)^2}}$ into equation 13

$$P_d = \frac{m\zeta Y_0^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\left(\frac{\omega}{\omega_n}\right)\right)^2} \quad 14$$

At resonance the maximum power is obtained and thus the exciting frequency matches that of the system i.e $\omega = \omega_n$

$$P_d = \frac{m\zeta Y_0^2 \omega^3}{4\zeta^2} \quad 15$$

The harvester power as seen from equation 15 is maximized only when the exciting frequency resonates with the same magnitude as that of the system. This is an obvious limitation of this system as the vibrating source in practice will normally have varied frequency. Researchers in trying to solve this have tried tuning the system's vibration to the source's dominant frequency which is only possible when the harvester is made to concentrate on just a particular predetermined frequency [9,15,16]. However, in most practicable cases, the source frequency is distributed over a range of frequency [17,18], hence the need to increase the frequency bandwidth or find a more suitable system became important. The application of nonlinear systems or multi-frequency system as a solution to the above problem was proposed by many researchers [17-22,48].

2.2 Methods of Transduction

Transduction is the process through which kinetic energy from vibration is converted into useful electrical energy which can be put to use or stored in an electric circuit. The methods are;

- Transduction through piezoelectricity
- Transduction through electromagnetism
- Transduction through electrostatics
- Hybrid methods.

2.3 Piezoelectric Transduction

Piezoelectricity is the simplest method of transduction in vibration-based energy harvesting owing to its ease of application. The piezoelectricity phenomenon was first described by [16,23-24]. The Currie brothers experimentally showed that crystals like tourmaline, quartz, topaz etc. conduct electricity

when stressed kinetically. The term piezoelectricity was coined from the Greek word ‘piezo’ translated to mean ‘to press’. Thus, Piezoelectricity is the electricity generated from certain crystals when placed under mechanical stress. The forward conversion of mechanical stress into electric charge by a piezoelectric transducer is known as the ‘direct piezoelectric effect’, while the opposite conversion is the ‘converse piezoelectric effect.’

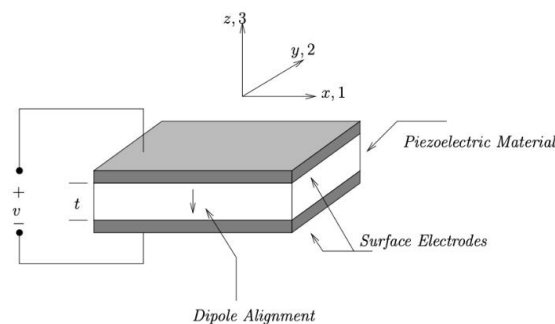


Fig. 2. The piezoelectric transduction schematics [25].

Fig.2 shows the method of piezoelectric transduction. The surface electrodes help to collect the converted energy for storage or immediate use. The piezoelectric constitutive equations are based on theory that the strain in the transducer is due to the resultant strains from the mechanical stress and that from the applied potential difference. The constitutive equations for both reverse and forward piezoelectric transduction are as derived in [3].

$$\left. \begin{aligned} T_{ij} &= c_{ijkl}^E S_{kl} - e_{kij} E_k \\ D_i &= e_{ikl} S_{kl} - \epsilon_{ij}^S E_k \end{aligned} \right\} 16$$

Where $ijkl$ takes the value 1,2 & 3, c_{ijkl}^E is the elastic coefficients matrix measured at constant field intensity, S_{kl} is the strain vector, e_{kij} is the strain constants matrix, E_k is the field vector, ϵ_{ij}^S is the matrix of the dielectric taken at constant stress, T_{ij} & D_i are the piezoelectric stress and electric displacement vectors [9,47].

2.3.1 Coupling Mode of Piezoelectric Transducers.

There are many coupling modes for piezoelectric transducers of which two are well documented in literature which are referred to as the ‘33’ and ‘31’ modes.

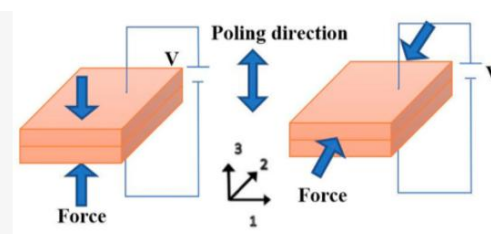


Fig. 3. Piezoelectric transduction modes [26].

The schematic diagrams in fig.3 illustrate the ‘33’ and ‘31’ coupling modes for piezoelectric transducers [26]. In the ‘33’ mode, the mechanical vibration and the resulting electrical voltage are poled in the 3 direction while the force producing the vibration is poled in the 1 direction for the ‘31’ mode. Although the mechanical to electrical coupling factor for ‘31’ mode is lower than for ‘33’ mode

[27], the '31' mode provides bigger deformation to input force ratio as a result of its slender structure making it a more suitable piezoelectric arrangement for energy harvesting. A one-degree freedom system of piezoelectric harvester connected to a single electrical load with a source vibration \dot{y} is shown in fig.4. The base vibration produces an output voltage through the piezoelectric transducer.

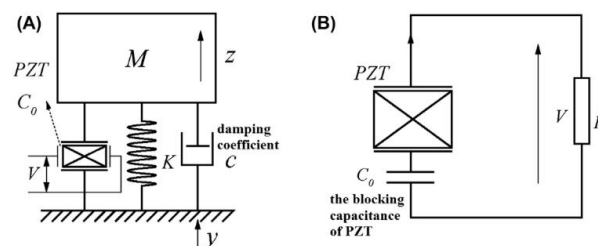


Fig. 4. Schematic diagram of 1dof PVEH system [10,11].

The model equation for a single degree freedom piezoelectric transducer connected to a single load resistor is given as;

$$\left. \begin{aligned} m\ddot{z}(t) + d\dot{z}(t) + kz(t) &= -h_{33}C_0v_L - m\ddot{y} \\ \alpha\dot{z}(t) &= \frac{v}{R_L} + C_0\dot{v} \end{aligned} \right\} \quad 17$$

If the relative displacement (z), voltage (V) and base excitation (y) are harmonic then the following mathematical relations hold.

$$\left. \begin{aligned} z &= Z(t) * e^{j\omega t} \\ y &= Y(t) * e^{j\omega t} \\ v &= V(t) * e^{j\omega t} \end{aligned} \right\} \quad 18$$

If ω is the angular frequency of the oscillator. Substituting equations 17 into 18 and simplifying, we get

$$\frac{Z}{\omega^2 Y} = \frac{m(1 + j\omega R_L C_0)}{(m + R_L C_0 c)\omega^2 - (c + d_T R_L C_0 + \alpha^2 R_L - m R_L C_0)j\omega + d_T} \quad 19$$

$$\frac{V}{\omega^2 Y} = \frac{-j\omega \alpha m R_L}{(m + R_L C_0 c)\omega^2 - (c + d_T R_L C_0 + \alpha^2 R_L - m R_L C_0)j\omega + d_T} \quad 20$$

Equations 19 and 20 gives the transfer functions between the relative displacement and voltage of the oscillator and its acceleration. The simulated results from equations 19 & 20 agrees with the experimental results from [7,28]. According to [11], the mean harvested power is expressed as

$$\frac{P}{\omega^2 Y} = \frac{1}{2R_L} * \left| \frac{v^2}{\omega^2 Y} \right| = \frac{1}{2} * \frac{\alpha^2 m^2 c R_L}{c \alpha^4 R_L^2 + 2c \alpha^2 R_L + (1 + \omega^2 C_0^2 R_L^2) c^2} \quad 21$$

2.4 Electromagnetic Transduction

Electromagnetic transduction is based on the discovery of Faraday in the year 1821. The law explains that if there is a change in the magnetic line of force or simply magnet flux of a magnet, then emf (ϵ) will be induced which could be used to perform an electrical work as stated by [29]. The induced emf

$$\text{is } \epsilon = -\frac{d\Phi}{dt} \text{ [29].}$$

Since emf is induced when there is a change in the magnetic flux of a conductor, electromagnetic transduction produces electric current by this flux change. To achieve a continuous change in the flux there must be relative positional translation between the coil and the magnetic mass. Figure 3 shows a 1dof electromagnetic vibration harvesting device connected to a load resistor. The source of vibration at the base through the connected string creates a relative displacement between the coils and the magnet thereby inducing current in the coils.

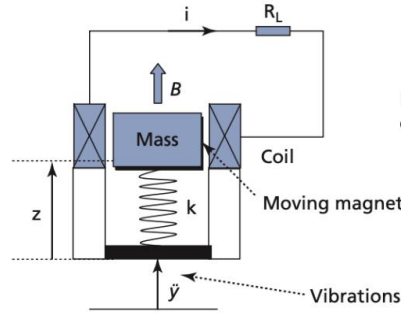


Fig. 5. Schematic diagram of single dof electromagnetic harvester [18].

The model equation for a single degree freedom of an electromagnetic transducer connected to a single resistive load is given as;

$$\left. \begin{aligned} m\ddot{z}(t) + d\dot{z}(t) + kz(t) &= -\frac{Bl}{R_L}V_L - m\ddot{y}(t) \\ V_L(t) + \omega_c V_L &= \frac{R_L}{L_e}Bl\dot{z}(t) \end{aligned} \right\} 22$$

Applying the Fourier transfer function for a harmonic excitation and transforming equations 22 into the Laplace domain where 's' is the Laplacian operator. The system's relative displacement and output voltage are given by;

$$\frac{Z}{Y} = \frac{-\frac{m}{L_e}(s + R_L)}{ms^3 + \left(\frac{mR_L}{L_e} + d\right)s^2 + \left(k + \frac{B^2l^2}{L_e} + d\frac{R_L}{L_e}\right)s + k\frac{R_L}{L_e}} \quad 23$$

$$\frac{V}{Y} = \frac{-\frac{m}{L_e}(BlR_L)s}{ms^3 + \left(\frac{mR_L}{L_e} + d\right)s^2 + \left(k + \frac{B^2l^2}{L_e} + d\frac{R_L}{L_e}\right)s + k\frac{R_L}{L_e}} \quad 24$$

The electrical power developed in the 's' domain by the one dof electromagnetic oscillator is as given below;

$$P(s) = \frac{Y_o^2}{2R_L} \left| \frac{-\frac{m}{L_e}(BlR_L)s}{\left(\frac{R_L}{L_e} + s\right)(-m\omega^2 + sd + k) + \frac{B^2l^2}{L_e}s} \right| \quad 25$$

An obvious limitation of most of the vibration energy harvesters is the need for high source frequency for effectivity. This is because the power developed from the linear harvesting device is directly proportional to the cube of the source frequency, which means that the harvested power is mostly insignificant for low frequencies. In addition, most of the ambient vibration sources have low frequencies (1-100Hz) [22,30-32,49]. [33] proposed the use of an electromagnetic generator that raises the low ambient frequency to a higher one. [22] confirmed the effectivity of ‘frequency up-conversion technique’ on microscale systems. Fig.6 explains the ‘frequency up-conversion’ approach through the schematic diagram.

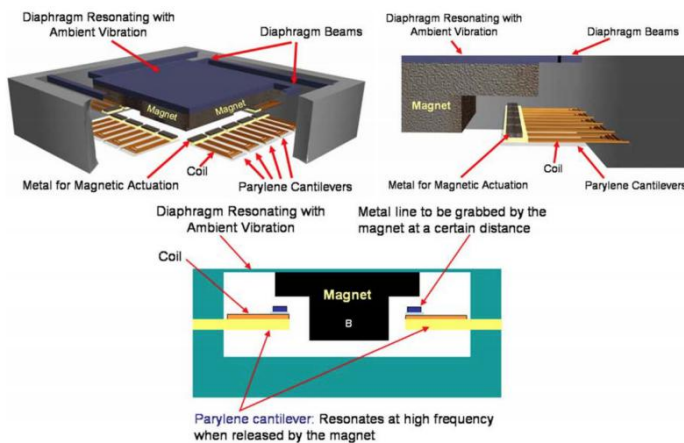


Fig.6. Proposed design for frequency up-conversion technique [22]

2.5 Transduction through Electrostatics

The electrostatic method of transduction uses the principle of production of voltage or current in a fixed charge or fixed voltage systems respectively when the capacitance between a parallel plate capacitance is varied. From elementary science the capacitance of a parallel plate capacitor, $c = \epsilon_m \frac{A}{d}$ where the dielectric of the medium of transduction is $\epsilon_m = \epsilon_r \epsilon_0$ where ϵ_r and ϵ_0 are the relative permittivity and that of free space. The energy stored in a charged capacitor is given as

$$E = \begin{cases} \frac{1}{2} QV \\ \frac{1}{2} CV^2 \\ \frac{1}{2} \frac{Q^2}{C} \end{cases} \quad 26$$

Substituting $c = \epsilon_m \frac{A}{d}$ into equation 26b, the electrostatic force in a constant charge electrostatic harvesting mechanism and 27b gives the electrostatic force for a constant charge system [9].

$$\left. \begin{aligned} F_e &= \frac{1}{2} \epsilon_m \frac{A}{d^2} V^2; \\ F_e &= \frac{1}{2} Q \frac{2d}{\epsilon_m A} \end{aligned} \right\} \quad 27$$

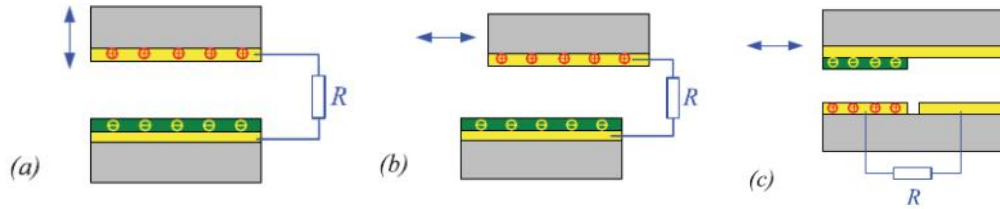


Fig.7. Configuration modes of an electrostatic based generator [9].

[34] proposed three different configurations of an electrostatic vibration harvesting mechanism (electret) based on the gap between the electrodes, the clear area of the overlap and a change of the counter electrode as seen in fig.7. The coupled electrostatic transducing model for the harvester proposed by [34] is;

$$\left. \begin{aligned} \ddot{x}(t) &= a_0 \sin(\omega t) - \omega_0^2 x - 2\xi_m \omega_0 \dot{x} + \frac{F_t}{m} \\ \dot{Q} &= \left(\frac{-d_{\epsilon_d} + g}{R\epsilon_0 \epsilon_d A} Q - \frac{d_{\sigma_d}}{R\epsilon_0 \epsilon_d} \right) \cdot \frac{A_0}{A_0 - \tilde{A}} \end{aligned} \right\} \quad 28$$

Where ω , is the source frequency, ξ_m is the damping factor, \tilde{A} is the resultant area of overlap.

3.0 Applications and Trends of Harvesting Devices.

The conversion of ambient vibration from natural and man-made sources into useful electrical energy is a developing frontier of technology today. Many devices have been produced based on the varied recommendations from researches on the subject. The amount of useful electrical energy that can be harvested from vibration depends on the frequency of vibration, type of vibration, and the type and size of the harvesting device. The maximum power that can be harvested from a single dof linear generator irrespective of the method of transduction is given from equation 15 as,

$$P_d = \frac{mY_0^2 \omega^3}{4\zeta_T} \text{ where } \zeta_T = \zeta_m + \zeta_e$$

The power developed then is the addition of the extracted electrical energy by the harvester and the mechanical loss, which are given as follows;

$$\left. \begin{aligned} P_e &= \frac{m\zeta_e Y_0^2 \omega^3}{4\zeta_T^2} \\ P_m &= \frac{m\zeta_m Y_0^2 \omega^3}{4\zeta_T^2} \end{aligned} \right\} \quad 29$$

The maximum power then occurs when $\zeta_m = \zeta_e$; thus, according to [33].

$$P_d = \frac{mY_0^2 \omega^3}{16\zeta_m}; a(\text{max.}) = \omega^2 Y_0; Q_{OC}(\text{Open Cct } Q - \text{Factor}) = \frac{1}{2\zeta_m}$$

$$\left. \begin{aligned} &= \frac{ma^2}{16\omega\zeta_m} \\ P_d &= \frac{ma^2}{8\omega} \cdot Q_{OC} \end{aligned} \right\} \quad 30$$

There are a number of commercial devices that convert periodic source vibration into useful electrical energy such as the Vulture piezoelectric energy harvester element from Midé and Perpetuum electromagnetic based device in figures 8a & 8b.

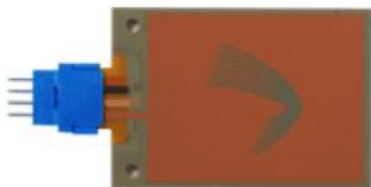


Fig.8a. Vulture PVEH element [45].



Fig.8b Electromagnetic VEH from Perpetuum [46].

3.1 Energy harvesting in buildings/Structures.

The use of batteries in microsensor devices will soon be replaced by harvester devices or will at least provide a worthy alternative since there will be zero maintenance costs as there won't be need for replacement. This translates to cleaner environment as there won't be nuisance from waste battery disposals. Otherwise waste energy from vibrations in buildings can be converted to power up important sensors like the fire alarm. Researchers are working to build an energy harvesting mat to be underlaid on the floors of school blocks or children's playground or even on a football pitch to harvest vibration energy. Energy harvesting devices are now used as sensors in bridges and roads.

3.2 Application to Biomedical Engineering.

Harvesting of energy on the motions of humans and not just on machineries or structures is receiving quite a lot of attention recently [35-38]. [36] developed a human motion energy harvesting backpack with adjustable frequency. [39] designed a wearable prototype energy harvester with particular focus on the knees due to the amount of negative work performed during swinging [40].

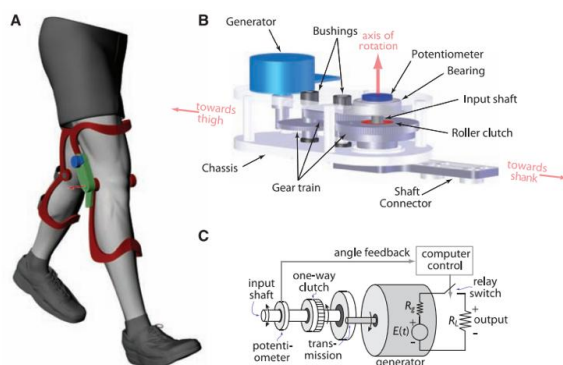


Fig.9. Biomedical energy harvester [39].

Fig. 9a shows an orthopedic customized knee brace (red) with an aluminum chassis (green) and an energy harvesting generator in blue. Fig.9b shows the schematic diagram of the gear train that does the conversion and fig.9c shows the smart feedback system connected to a potentiometer whose principal function is to determine when to generate power.

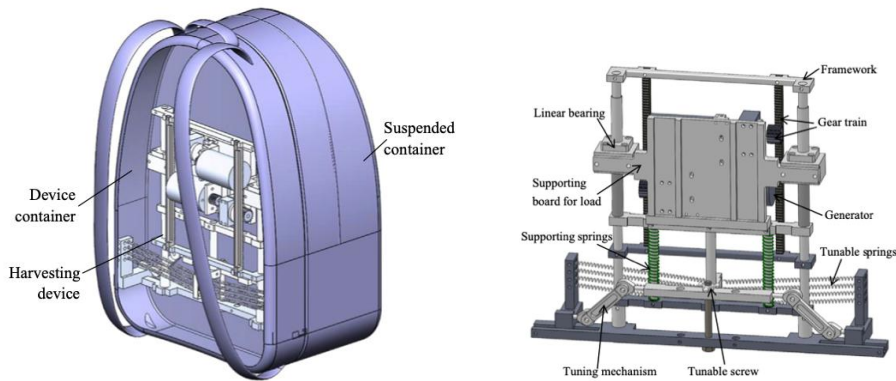


Fig.10. Energy harvesting based back-pack [36].

Prosthetic ankles & knees which use batteries are limited in effectiveness due to obvious limitation on working life [41,42] hence a near future overhaul of batteries for energy harvesters. [36] developed, and analyzed a model of a wearable back-bag that harvests kinetic energy from the motion/activity of its wearer.

3.3 Application to Automobiles

The chassis of moving vehicles undergo so much vibrations especially on wicked roads like the one in Ota, Ogun state. So, it is imperative that this waste energy which would otherwise cause damage to the car be converted into useful energy.

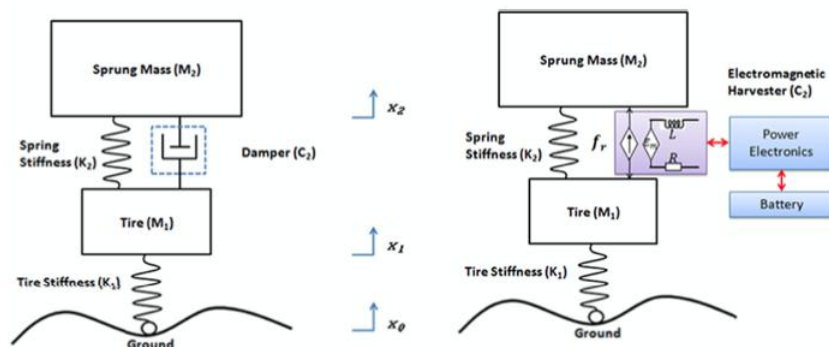
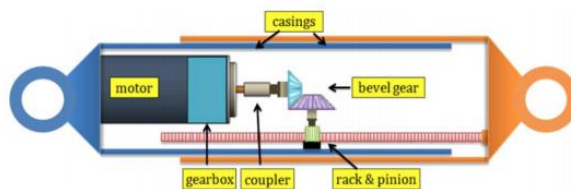


Fig. 11. Viscous damper & electromagnetic based harvester for a car model [35].

The vibrations from the chassis of the quarter-car model by [43] was converted into useful power by an electromagnetic based damper which was used in replacement of the conventional viscous damper. Their experimental results which was in close consonance with their mathematical model showed between 100 to 400W power harvested for a middle-sized passenger car on good classes B & C



roads
Fig.12. A regenerative electromagnetic shock absorber [44].

The regenerative model proposed by [44] is an electromagnetic based shock absorber. They achieved a maximum energy efficiency of 56% under a frequency of 0.5Hz connected to a 94ohm resistor.

4. Conclusions

Scavenging for energy from vibration is an alternative and renewable source of energy which does not constitute environmental pollution. This source of energy will soon replace batteries in sensor devices and will provide a wide application for use in smart homes. There are wide applications of this energy source and a yet developing frontier of applications due to the huge research interest it has attracted over the recent years.

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