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Vibration Energy Harvesting - A Case Study

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Abstract—**The study of energy harvesting technology is based on mechanical vibration. Recently, the study of the conversion of vibrational energy into electrical power has become a major field of research. Recent advances on ultra-low power portable electronic devices for low cost power supply are using conventional battery. However problems can occur when batteries die off because of their finite lifespan. In portable electronics, battery needs to be replaced when it dies replacement of the battery can become a tedious task because we do not know when the battery dies. People searched for more efficient portable power sources for advanced electronic devices. The critical long-term solution should therefore be independently of the limited energy available during the functioning or operation of such devices. Mechanical Energy Harvesting Systems may enable wireless and portable electronic devices to operate because they carry their own power supply that completely self-powered. Various types of vibration devices, piezoelectric materials and mechanical vibration rectifier harvestings are summarized. This report will investigates some of the research that has been performed in the area of vibration energy harvesting.**

***Index Terms*— Vibration Energy Harvesting**

I. Introduction

Energy harvesting (also known as power harvesting or energy scavenging or ambient power) is the process by which energy is derived from external sources (e.g., solar power, thermal energy, wind energy, salinity gradients, and kinetic energy, also known as ambient energy), captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks.

Energy harvesters provide a very small amount of power for low-energy electronics. While the input fuel to some large-scale generation costs resources (oil, coal, etc.), the energy source for energy harvesters is present as ambient background. For example, temperature gradients exist from the operation of a combustion engine and in urban areas, there is a large amount of electromagnetic energy in the environment because of radio and television broadcasting.

Vibration energy harvesting is an attractive technique for potential powering of wireless sensors and low power devices. While the technique can be employed to harvest energy from vibrations and vibrating structures, a general requirement independent of the energy transfer mechanism is that the vibration energy harvesting device operate in resonance at the excitation frequency. Most energy harvesting devices developed to date are single resonance frequency based, and while recent efforts have been made to broaden the frequency range of energy harvesting devices, what is lacking is a robust tunable energy harvesting technique. In this paper, the design and testing of a resonance frequency tunable energy harvesting device using a magnetic force technique is presented. This technique enabled resonance tuning to ± 20% of the untuned resonant frequency. In particular, this magnetic-based approach enables either an increase or decrease in the tuned resonant frequency.

II. Literature Review

Chongfeng Wei , Xingjian Jing; "A comprehensive review on vibration energy harvesting: Modelling and realization"; (2016) have concentrated on developing efficient energy harvesters by adopting new materials and optimizing the harvesting devices. The conversion efficiency from mechanical to electrical energy is a fundamental parameter to evaluate the energy harvesting performance of a harvesting device [1].

Xingtian Zhang , Hongye Pan, Lingfei Qi , Zutao Zhang, Yanping Yuan, Yujie Liu; "A renewable energy harvesting system using a mechanical vibration rectifier (MVR) for railroads"; (2017) concluded that the process was modelled and simulated, including the vehicle track contact, track vibration, the dynamic response of the MVR and an electromechanical analysis of the generator.The peak voltage of 58 V at 1 Hz with a displacement of 2.5 mm was close to being practically useful for supplying rail-side applications, such as safety devices and emergency repairs in areas lacking power, indicated that the proposed energy-harvesting system has potential as a renewable alternative energy source [2].

Madhav Ch, Shaikh Faruque Ali; "Harvesting Energy from Vibration Absorber under Random Excitations";(2016) concluded that the analytical results show the promise of broadband energy harvesting using the device combined with vibration reduction in the primary structure [3].

Hao Wanga , Abbas Jasima,, Xiaodan Chena; "Energy harvesting technologies in roadway and bridge for different applications: A comprehensive review"; (2017) concluded that Piezoelectric materials generate electric charges when subjected to mechanical stresses or change geometric dimensions when an electric field is applied. The voltage produced from piezoelectric material varies with time and results in an alternate current (AC) signal, which causes the direct and inverse piezoelectric effect, respectively [4].

III. Methodology

The history of energy harvesting dates back to the windmill and the waterwheel. People have searched for ways to store the energy from heat and vibrations for many decades. One driving force behind the search for new energy harvesting devices is the desire to power sensor networks and mobile devices without batteries. Energy harvesting is also motivated by a desire to address the issue of climate change and global warming. As the demand for clean and sustainable energy is increasing Energy Harvesting came into existence. To minimize the requirement of external power source and maintenance for electric device such as wireless sensor network, the energy harvesting technique based on vibrations has been a dynamic field of studying interest over past years.
The following are the benefits of Energy Harvesting:

- Long lasting operability
- No chemical disposal
- Cost saving
- Safety
- Maintenance free
- No charging points
- Inaccessible sites operability
- Flexibility
- Applications otherwise impossible

Vibration Energy Harvesting is the concept of converting the kinetic energy inherent in vibrations to electricity. It basically is as simple as it sounds. This is possible through different technologies, e.g. electromagnetic induction (used by ReVibe Energy) or piezoelectric fibres.

IV. Case Study

Piezoelectric materials are the most studied in the field of VEH as they generate charge when subjected to mechanical stresses or change geometric dimensions when an electric field is applied.

A. *Piezoelectricity*

Fig. 1. Piezoelectricity

Piezoelectricity is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics, and biological matter such as bone, DNA and various proteins) in response to applied mechanical stress. The word piezoelectricity means electricity resulting from pressure and latent heat. It is derived from the Greek πιέζειν piezein, which means to squeeze or press, and ἤλεκτρον ēlektron, which means amber, an ancient source of electric charge. Piezoelectricity was discovered in 1880 by French physicists Jacques and Pierre Curie.

B. *Piezoelectric Effect*

The piezoelectric effect converts mechanical strain into electric current or voltage. This strain can come from many different sources. Human motion, low-frequency seismic vibrations, and acoustic noise are everyday examples. Except in rare instances the piezoelectric effect operates in AC requiring time-varying inputs at mechanical resonance to be efficient. Most piezoelectric electricity sources produce power on the order of milli-watts, too small for system application, but enough for hand-held devices such as some commercially available self-winding wristwatches. In this device, the flow of pressurized hydraulic fluid drives a reciprocating piston supported by three piezoelectric elements which convert the pressure.

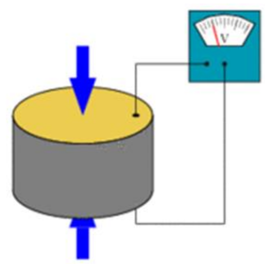

Fig. 2. Piezoelectric effect

C. *Piezoelectric Materials*

Fig. 3. Piezoelectric materials

The use of piezoelectric materials to harvest power has already become popular. Piezoelectric materials have the ability to transform mechanical strain energy into electrical charge.

Piezoelectric materials can be classified into the following categories:

- Single crystalline material (e.g., quartz),
- Piezoceramics (e.g., lead zirconate titanate [PZT]),
- Piezoelectric semiconductors (e.g., ZnO2),

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- Polymer (e.g., Polyvinylidene fluoride [PVDF]),
- Piezoelectric composites,
- Glass ceramics (e.g., $Li_2Si_2O_5$, Ba_2TiSiO_6).

Although piezoelectric materials have different piezoelectric and mechanical properties, the most common ones are polymers and ceramics. Polymer materials are soft and flexible, while ceramics are rigid. Polymer materials generate the lower energy than ceramics due to different dielectric and piezoelectric properties.

D. Working

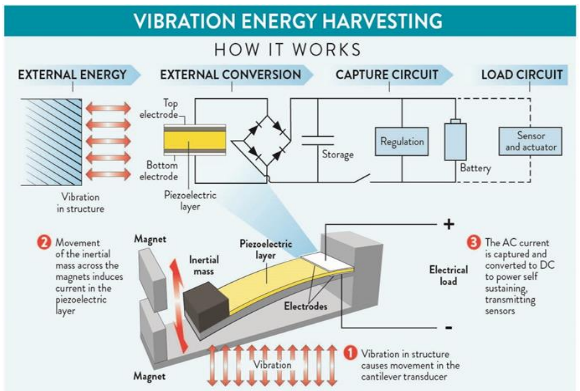

Fig. 4. Vibration energy harvesting

The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids. The latter may either be induced for ions on crystal lattice sites with asymmetric charge surroundings (as in $BaTiO_3$ and PZTs) or may directly be carried by molecular groups (as in cane sugar). The dipole density or polarization (dimensionality [C•m/m^3]) may easily be calculated for crystals by summing up the dipole moments per volume of the crystallographic unit cell. As every dipole is a vector, the dipole density P is a vector field. Dipoles near each other tend to be aligned in regions called Weiss domains. The domains are usually randomly oriented, but can be aligned using the process of poling (not the same as magnetic poling), a process by which a strong electric field is applied across the material, usually at elevated temperatures. Not all piezoelectric materials can be poled.

Of decisive importance for the piezoelectric effect is the change of polarization P when applying a mechanical stress. This might either be caused by a reconfiguration of the dipole-inducing surrounding or by re-orientation of molecular dipole moments under the influence of the external stress. Piezoelectricity may then manifest in a variation of the polarization strength, its direction or both, with the details depending on:

1. The orientation of P within the crystal;
2. Crystal symmetry;
3. The applied mechanical stress.
4. The change in P appears as a variation of surface charge density upon the crystal faces, i.e. as a variation of the electric field extending between the faces caused by a change in dipole density in the bulk. For example, a 1 cm^3 cube of quartz with 2 kN (500 lbf) of correctly applied force can produce a voltage of 12500 V.

E. Use

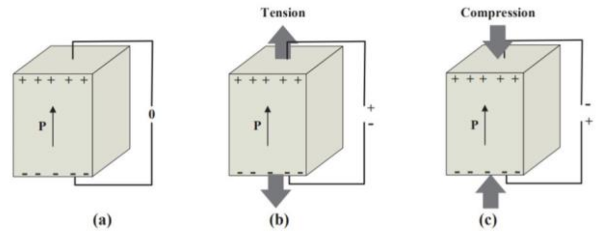

Fig. 5. Use

The device comprises a piezoelectric cantilever beam with a tungsten mass at its free end. By virtue of the piezoelectric property, the cantilever beam produces electrical energy when subjected to mechanical stress induced from vibrations. A tip mass is used to lower the natural frequency of the piezoelectric beam and increase the output power of the energy harvesting device. One potential application of such devices would be to harvest energy from low-level ambient environmental sources, which the literature suggests are typically under 100 Hz. For resonance frequency tuning, a magnetic force technique is proposed in which the applied magnetic force alters the effective stiffness of the device. Four permanent magnets are used: two magnets are fixed at the free end of the cantilever beam, while the other two magnets are fixed to the enclosure of the device at the top and bottom, vertically aligned with the magnets on the beam as depicted in figure 4. The magnets are placed such that attractive and repulsive magnetic forces can be applied on each side of the beam (the location of the attractive and repulsive magnetic forces can be interchanged with respect to their location). The cantilever beam is fixed on a clamp that can be vertically displaced using a screw–spring mechanism. With this mechanism the distance between the magnets can be controlled to alter the magnetic force that exists between the magnets on the beam and enclosure. The magnetic force from the magnet induces an additional stiffness on the vibrating element which in turn alters the resonance frequency of the piezoelectric beam. The additional stiffness induced from the magnetic force is positive for repulsive force and is negative for the attractive force, respectively. It is noteworthy that by applying either an attractive or repulsive magnetic force, the natural frequency of the beam can be tuned to higher and lower frequencies with respect to the un-tuned resonance frequency of the piezoelectric beam.

A piezoelectric cantilever beam with a natural frequency of 26 Hz is used as the energy harvesting cantilever, which is successfully tuned over a frequency range of 22–32 Hz to enable a continuous power output 240–280 µW over the entire frequency range tested. A theoretical model using variable damping is presented, whose results agree closely with the experimental results. The magnetic force applied for resonance frequency tuning and its effect on damping and load resistance have been experimentally determined.

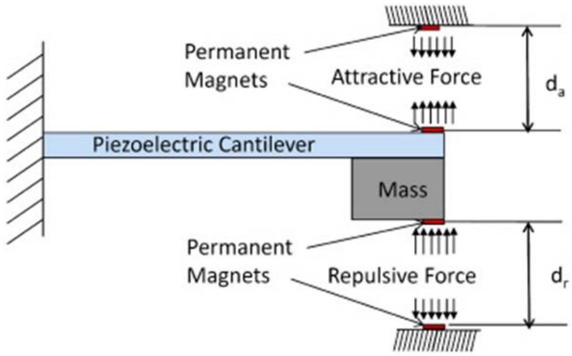

Fig. 6. The device

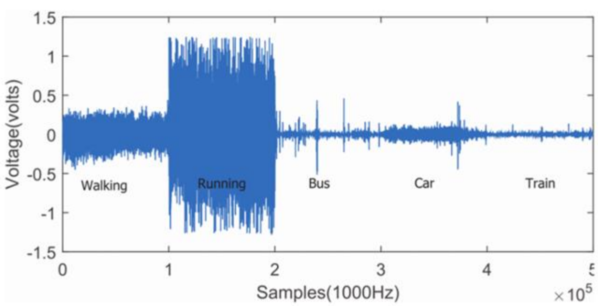

Fig. 7. Samples vs. Voltage

F. Applications

1. They are used to provide self-powered sensor units.
2. Electricity can be created from most of the vibrations.
3. They are used in:
   - *Trains:*

The vibrations on a train are not quite as consistent as with helicopters, but they are still pretty healthy, especially in the truck frame area where the vibration is not as damped. Train derailments and the desire to develop high speed rail solutions create a need for more and more sensors to ensure structural and system health. Wired power is a non-starter due to the amount of wiring needed and the harsh environment under a train. Batteries are not a good solution due to the temperature extremes they would be exposed to and cost of replacement. I've completed one project with the Federal Railroad Administration (FRA) where we designed a completely self-powered train brake force measurement device which was able to use a multi-hop wireless network to communicate the brake force data "up the chain" to the locomotive. The energy harvester was capable of providing adequate power for the system in this scenario.

   - *Helicopters:*

All different types of sensors are needed on a rotor craft to ensure structural and component health. Systems such as the health and usage monitoring system (HUMS) benefit from as many sensors as possible. Running wires to all of these sensors is not only complex and costly but also adds weight, which for a helicopter world is at a premium. Due to all of these factors, helicopters are an ideal application.

   - *Industries:*
     - Process control sensors in industrial environments need reliable long life power supplies.
     - Most of the machinery vibrates at 50 or 60 Hz.
     - Very low level (10's of mG) vibrations, but very consistent and stable frequency:
     - Possibility of profit of thermal gradient.
     - Oil and gas
     - Chemical manufacturing
     - Waste water treatment
     - Food
     - Vibration Energy Harvesting works well and has been in use for several years.
4. They are used to eliminate the need of battery replacement and maintenance.
5. Biomedical uses.
   - Some novel uses for piezoelectric energy harvesting are starting to emerge.

Researchers at the University of Michigan have developed a device that harvests energy from the reverberation of heartbeats through the chest and converts it to electricity to run a pacemaker or an implanted defibrillator, hopefully obviating the need for periodic battery replacement. Research is also under way looking for ways to scavenge body heat, movement, and vibration to power other implantable devices. RF is already being used experimentally to recharge the batteries in pacemakers and implanted transcutaneous electrical nerve stimulation (TENS) devices. The patient sits in a chair that contains a low-frequency RF source whose output is received, rectified, and stored by the device.

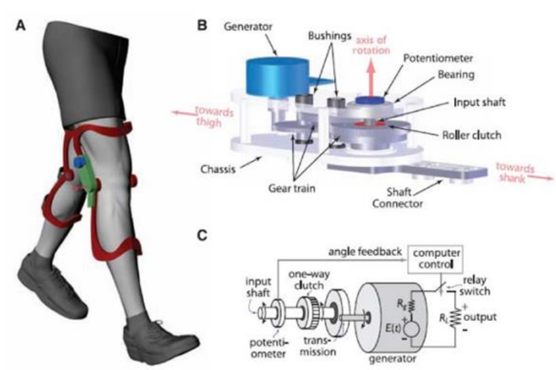

Fig. 8. Application (Example)

6. Architectural applications like, cantilever beams.

G. Limitations

- *High cost:*
  - Companies providing hard wired systems.
  - Non-biodegradable long-lasting lithium-ion chloride primary batteries.
- Needs steady vibrations.
- Dominating frequency.

The vibrational frequency range required to generate consistent energy is a very limited.

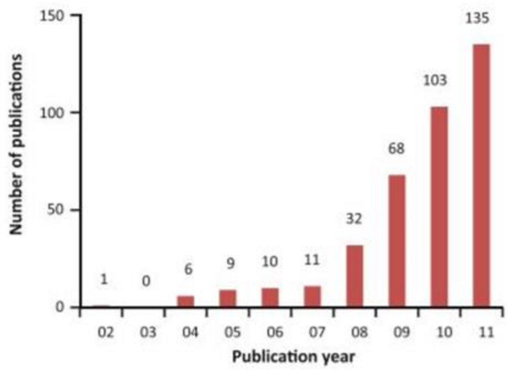

Fig. 9. Publication year vs. no. of publications

In addition, to realize vibrational energy harvesting devices as reliable power sources for MEMS-scale devices such as nano- and microrobotics requires an understanding of the lifetime stability and long-term performance of such devices.

V. Conclusion

The report summarizes studied of environmental friendly vibration energy harvesting of the conversion of vibrational energy into electrical power has become a major field of research. It illustrated various designs of vibration energy harvesting from ambient vibrations using electrostatics, piezoelectric and electromagnetic. Most of the harvesting circuits were developed based on the periodic or harmonic excitations. It may not be applicable to the piezoelectric vibration energy harvester designed to operate in random or broadband excitation circumstances. When compared with energy stored in common storage device, it has more improvement in term of sustainability, maintenance free and environmentally friendly. Efficient ways to convert environmental noise into electrical energy. Compared with the all about stating energy resources, less effort has been dedicated to developing sound energy harvesting methods. Since vibration energy harvesting is a clean, ubiquitous, sustainable energy source, it is great interest to study the mechanism generated by energy harvesting. In future work research efforts have also concentrated on harvesting energy such as airborne vibration and flow induced vibration or even from sources surrounding like acoustic, airdrop and heat into energy harvesting, which play a major role in greening world's energy supply. The future challenges to be addressed in the research field include improving the conversion efficiency and energy harvesting and storing circuits. Actually, one of the possibilities to recharge such batteries is to use energy harvested from the surrounding. The advantages of energy harvesting is not trying to replace batteries, but instead alleviating some of their drawbacks, especially in relation to the maintenance issue. This is a new alternative, efficiency, and renewable energy with lots of potential applications.

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