# 2

# Vibration Energy Harvesting: Machinery Vibration, Human Movement and Flow Induced Vibration

Dibin Zhu
*University of Southampton*
*UK*

## 1. Introduction

With the development of low power electronics and energy harvesting technology, self-powered systems have become a research hotspot over the last decade. The main advantage of self-powered systems is that they require minimum maintenance which makes them to be deployed in large scale or previously inaccessible locations. Therefore, the target of energy harvesting is to power autonomous 'fit and forget' electronic systems over their lifetime. Some possible alternative energy sources include photonic energy (Norman, 2007), thermal energy (Huesgen et al., 2008) and mechanical energy (Beeby et al., 2006). Among these sources, photonic energy has already been widely used in power supplies. Solar cells provide excellent power density. However, energy harvesting using light sources restricts the working environment of electronic systems. Such systems cannot work normally in low light or dirty conditions. Thermal energy can be converted to electrical energy by the Seebeck effect while working environment for thermo-powered systems is also limited. Mechanical energy can be found in instances where thermal or photonic energy is not suitable, which makes extracting energy from mechanical energy an attractive approach for powering electronic systems. The source of mechanical energy can be a vibrating structure, a moving human body or air/water flow induced vibration. The frequency of the mechanical excitation depends on the source: less than 10Hz for human movements and typically over 30Hz for machinery vibrations (Roundy et al., 2003). In this chapter, energy harvesting from various vibration sources will be reviewed. In section 2, energy harvesting from machinery vibration will be introduced. A general model of vibration energy harvester is presented first followed by introduction of three main transduction mechanisms, i.e. electromagnetic, piezoelectric and electrostatic transducers. In addition, vibration energy harvesters with frequency tunability and wide bandwidth will be discussed. In section 3, energy harvesting from human movement will be introduced. In section 4, energy harvesting from flow induced vibration (FIV) will be discussed. Three types of such generators will be introduced, i.e. energy harvesting from vortex-induced vibration (VIV), fluttering energy harvesters and Helmholtz resonator. Conclusions will be given in section 5.

## 2. Energy harvesting from machinery vibration

In energy harvesting from machinery vibration, most existing devices are based on spring-mass-damping systems. As such systems are linear, these energy harvesters are also called linear energy harvesters. A generic model for linear vibration energy harvesters was first introduced by Williams & Yates (Williams & Yates, 1996) as shown in Fig. 1. The system consists of an inertial mass, *m*, that is connected to a housing with a spring, *k*, and a damper, *b*. The damper has two parts, one is the mechanical damping and the other is the electrical damping which represents the transduction mechanism. When an energy harvester vibrates on the vibration source, the inertial mass moves out of phase with the energy harvester's housing. There is either a relative displacement between the mass and the housing or mechanical strain.

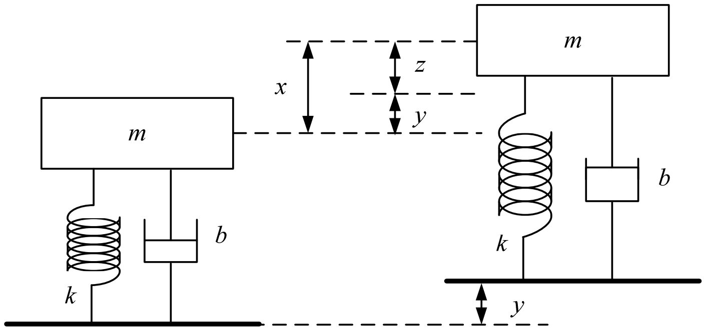


Fig. 1. Generic model of linear vibration energy harvesters

In Fig. 1, $x$ is the absolute displacement of the inertial mass, $y$ is the displacement of the housing and $z$ is the relative motion of the mass with respect to the housing. Electrical energy can then be extracted via certain transduction mechanisms by exploiting either displacement or strain. The average power available for vibration energy harvester, including power delivered to electrical loads and power wasted in the mechanical damping, is (Williams & Yates, 1996):

$$P(\omega) = \frac{m\zeta_T Y^2 \left(\frac{\omega}{\omega_r}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_r}\right)^2\right]^2 + \left[2\zeta_T \frac{\omega}{\omega_r}\right]^2} \tag{1}$$

where $\zeta$ is the total damping, $Y$ is the displacement of the housing and $\omega_r$ is the resonant frequency.

Each linear energy harvester has a fixed resonant frequency and is always designed to have a high quality (Q) factor. Therefore, a maximum output power can be achieved when the resonant frequency of the generator matches the ambient vibration frequency as:

$$P = \frac{mY^2\omega_r^3}{4\zeta_T} \tag{2}$$

or

$$P = \frac{ma^2}{4\zeta\omega_r} \quad (3)$$

where $a = Y\omega^2$ is the excitation acceleration. Eq. 3 shows that output power of a vibration energy harvester is proportional to mass and excitation acceleration squared and inversely proportional to its resonant frequency and damping.

When the resonant frequency of the energy harvester does not match the ambient frequency, the output power level will decrease dramatically. This drawback severely restricts the development of linear energy harvesters. To date, there are generally two possible solutions to this problem (Zhu et al., 2010a). The first is to tune the resonant frequency of a single generator periodically so that it matches the frequency of ambient vibration at all times and the second solution is to widen the bandwidth of the generator. These issues will be discussed in later sections.

There are three commonly used transduction mechanisms, i.e. electromagnetic, piezoelectric and electrostatic. Relative displacement is used in electromagnetic and electrostatic transducers while strain is exploited in piezoelectric transducer to generate electrical energy. Details of these three transducers will be presented in the next few sections.

### 2.1 Electromagnetic vibration energy harvesters

Electromagnetic induction is based on Faraday's Law which states that "an electrical current will be induced in any closed circuit when the magnetic flux through a surface bounded by the conductor changes". This applies whether the magnetic field changes in strength or the conductor is moved through it. In electromagnetic energy harvesters, permanent magnets are normally used to produce strong magnetic field and coils are used as the conductor. Either the permanent magnet or the coil is fixed to the frame while the other is attached to the inertial mass. In most cases, the coil is fixed while the magnet is mobile as the coil is fragile compared to the magnet and static coil can increase lifetime of the device. Ambient vibration results in the relative displacement between the magnet and the coil, which generates electrical energy. According to the Faraday's Law, the induced voltage, also known as electromotive force (e.m.f), is proportional to the strength of the magnetic field, the velocity of the relative motion and the number of turns of the coil.

Generally, there are two types of electromagnetic energy harvesters in terms of the relative displacement. In the first type as shown in Fig. 2(a), there is lateral movement between the magnet and the coil. The magnetic field cut by the coil varies with the relative movement between the magnet and the coil. In the second type as shown in Fig. 2(b), the magnet moves in and out of the coil. The magnetic field cut by the coil varies with the distance between the coil and the magnet. In contrast, the first type is more common as it is able to provide better electromagnetic coupling.

Electromagnetic energy harvesters have high output current level at the expense of low voltage. They require no external voltage source and no mechanical constraints are needed. However, output of electromagnetic energy harvesters rely largely on their size. It has been proven that performance of electromagnetic energy harvesters reduce significantly in micro scale (Beeby et al., 2007a). Furthermore, due to the use of discrete permanent magnets, it is difficult to integrate electromagnetic energy harvesters with MEMS fabrication process.

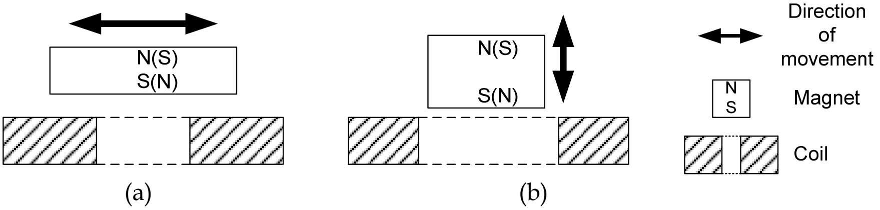


Fig. 2. Two types of electromagnetic energy harvesters

Fig. 3 compares normalized power density of some reported electromagnetic vibration energy harvesters. It is clear that power density of macro-scaled electromagnetic vibration energy harvesters is much higher than that of micro-scaled devices. This proves analytical results presented by Beeby *et al* (2007a).

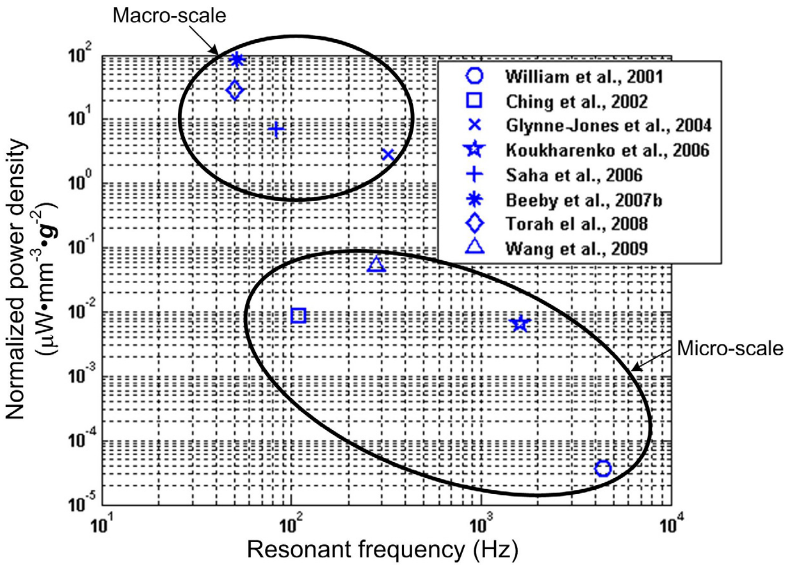


Fig. 3. Comparisons of normalized power density of some existing electromagnetic vibration energy harvesters

### 2.2 Piezoelectric vibration energy harvesters

The piezoelectric effect was discovered by Pierre and Jacques Curie in 1880. It is the ability of some materials (notably crystals and certain ceramics) to generate an electric potential in response to applied mechanical stress. In piezoelectric energy harvesting, ambient vibration causes structures to deform and results in mechanical stress and strain, which is converted to electrical energy because of the piezoelectric effect. The electric potential is proportional to the strain. Piezoelectric energy harvesters can work in either $d_{33}$ mode or $d_{31}$ mode as shown in Fig. 4. In $d_{31}$ mode, a lateral force is applied in the direction perpendicular to the polarization direction, an example of which is a bending beam that has electrodes on its top and bottom surfaces as in Fig. 4(a). In $d_{33}$ mode, force applied is in the same direction as the polarization direction, an example of which is a bending beam that has all electrodes on its top surfaces as in Fig. 4(b). Although piezoelectric materials in $d_{31}$ mode normally have a lower coupling coefficients than in $d_{33}$ mode, $d_{31}$ mode is more commonly used (Anton and Sodano, 2007). This is because when a cantilever or a double-clamped beam (two typical structures in vibration energy harvesters) bends, more lateral stress is produced than vertical stress, which makes it easier to couple in $d_{31}$ mode.

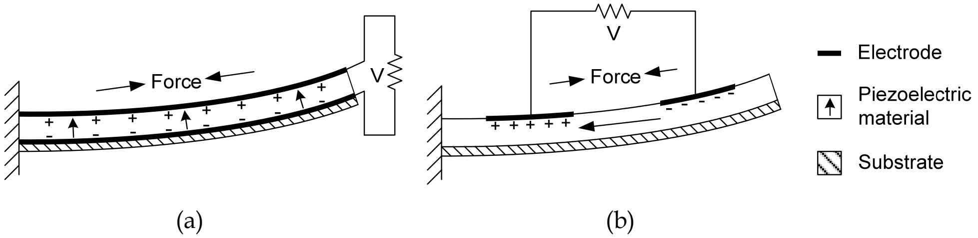


Fig. 4. Two types of piezoelectric energy harvesters (a) $d_{31}$ mode (b) $d_{33}$ mode

Piezoelectric energy harvesters have high output voltage but low current level. They have simple structures, which makes them compatible with MEMS. However, most piezoelectric materials have poor mechanical properties. Therefore, lifetime is a big concern for piezoelectric energy harvesters. Furthermore, piezoelectric energy harvesters normally have very high output impedance, which makes it difficult to couple with follow-on electronics efficiently. Commonly used materials for piezoelectric energy harvesting are $BaTiO_3$, PZT-5A, PZT-5H, polyvinylidene fluoride (PVDF) (Anton & Sodano, 2007). In theory, with the same dimensions, piezoelectric energy harvesters using PZT-5A has the most amount of output power (Zhu & Beeby, 2011).

Fig. 5 compares normalized power density of some reported piezoelectric vibration energy harvesters. It is found that micro-scaled piezoelectric energy harvesters have a greater power density than macro-scale device. However, due to size constraints in micro-scaled energy harvesters, the absolute amount of output power produced by the micro-scaled energy harvesters is much lower than that produced by the macro-scaled generators. Therefore, unless the piezoelectric energy harvesters are to be integrated into a micromechanical or microelectronic system, macro-scaled piezoelectric generators are preferred. Normalized power density of piezoelectric energy harvesters is about the same level as that of electromagnetic energy harvesters.

Efforts have been made to increase output power of the piezoelectric energy harvesters. Some methods include using more efficient piezoelectric materials (e.g. Macro-Fiber Composite), using different piezoelectric configurations (e.g. mode 31 or mode 33), optimizing power conditioning circuitry (Anton & Sodano, 2007), using different beam shapes (Goldschmidtboeing & Woias, 2008) and using multilayer structures (Zhu et al., 2010d).

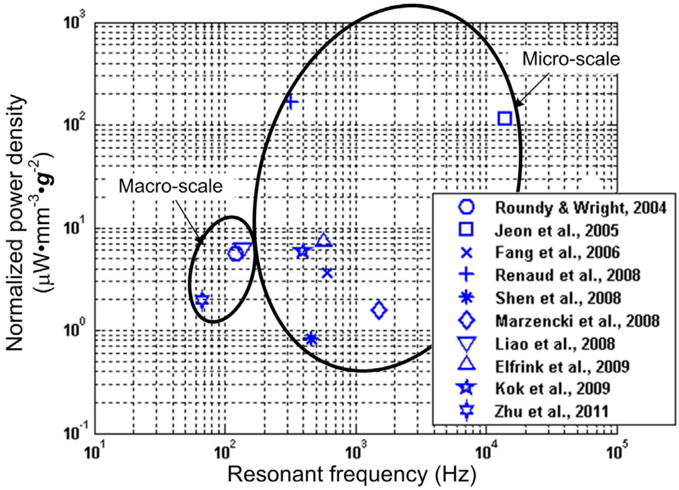


Fig. 5. Comparisons of normalized power density of some existing piezoelectric vibration energy harvesters

### 2.3 Electrostatic vibration energy harvesters

Electrostatic energy harvesters are based on variable capacitors. There are two sets of electrodes in the variable capacitor. One set of electrodes are fixed on the housing while the other set of electrodes are attached to the inertial mass. Mechanical vibration drives the movable electrodes to move with respect to the fixed electrodes, which changes the capacitance. The capacitance varies between maximum and minimum value. If the charge on the capacitor is constrained, charge will move from the capacitor to a storage device or to the load as the capacitance decreases. Thus, mechanical energy is converted to electrical energy. Electrostatic energy harvesters can be classified into three types as shown in Fig. 6, i.e. In-Plane Overlap which varies the overlap area between electrodes, In-Plane Gap Closing which varies the gap between electrodes and Out-of-Plane Gap which varies the gap between two large electrode plates.

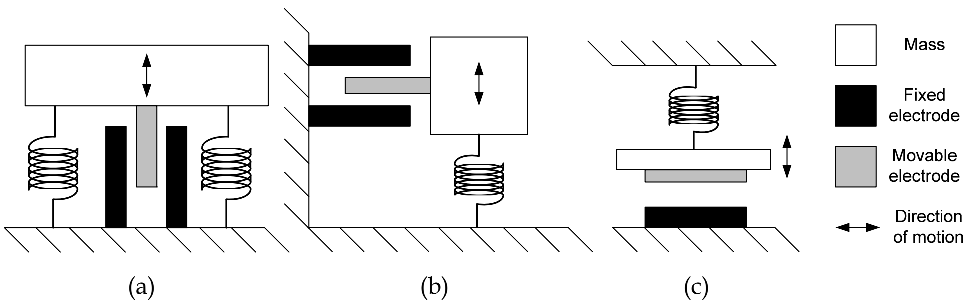


Fig. 6. Three types of electrostatic energy harvesters (a) In-Plane Overlap (b)In-Plane Gap Closing (c) Out-of-Plane Gap Closing

Electrostatic energy harvesters have high output voltage level and low output current. As they have variable capacitor structures that are commonly used in MEMS devices, it is easy to integrate electrostatic energy harvesters with MEMS fabrication process. However, mechanical constraints are needed in electrostatic energy harvesting. External voltage source or pre-charged electrets is also necessary. Furthermore, electrostatic energy harvesters also have high output impedance.

Fig. 7 compares normalized power density of some reported electrostatic vibration energy harvesters. Normalized power density of electrostatic energy harvesters is much lower than that of the other two types of vibration energy harvesters. However, dimensions of electrostatic energy harvesters are normally small which can be easily integrated into chip-level systems.

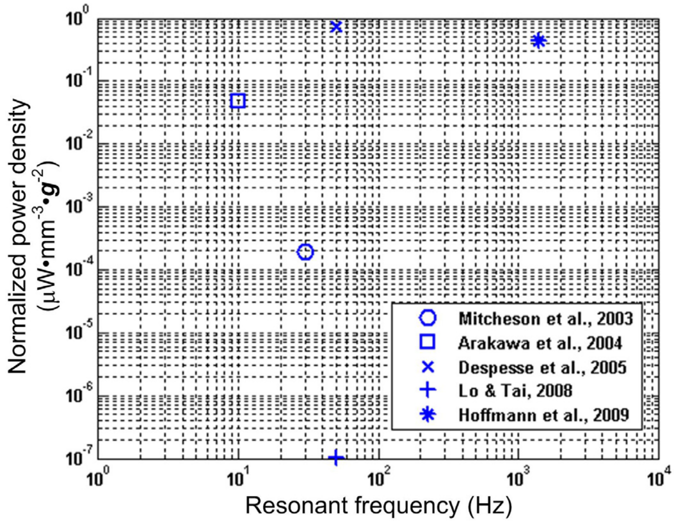


Fig. 7. Comparisons of normalized power density of some existing electrostatic vibration energy harvesters

### 2.4 Tunable vibration energy harvesters

As mentioned earlier, most vibration energy harvesters are linear devices. Each device has only one resonant frequency. When the ambient vibration frequency does not match the resonant frequency, output of the energy harvester can be reduced significantly. One potential method to overcome this drawback is to tune the resonant frequency of the energy harvester so that it can match the ambient vibration frequency at all time.

Resonant frequency tuning can be classified into two types. One is called continuous tuning which is defined as a tuning mechanism that is continuously applied even if the resonant frequency matches the ambient vibration frequency. The other is called intermittent tuning which is defined as a tuning mechanism that is only turned on when necessary. This tuning mechanism only consumes power during the tuning operation and uses negligible energy once the resonant frequency is matched to the ambient vibration frequency (Zhu et al., 2010a).

Resonant frequency tuning can be realized by mechanical or electrical methods. Realizations of mechanical tuning include changing the dimensions of the structure, moving the centre of gravity of proof mass and changing spring stiffness continuously or intermittently. Most mechanical tuning methods are efficient in frequency tuning and suitable for in situ tuning, i.e. tuning the frequency while the generator is in operation. However, extra systems and energy are required to realize the tuning. Electrical methods typically adjust electrical loads of the generator to tune the resonant frequency. This is much easier to implement. Closed-loop control is necessary for both mechanical tuning and electrical tuning so that the resonant frequency can match the vibration frequency at all times. As most of the existing vibration energy harvesters are based on cantilever structures, only frequency tuning of cantilever structures will be discussed in this section.

### 2.4.1 Variable dimensions

The spring constant of a resonator depends on its materials and dimensions. For a cantilever with a mass at the free end, the resonant frequency, $f_r$, is given by (Blevins, 2001):

$$f_r = \frac{1}{2\pi}\sqrt{\frac{Ywh^3}{4l^3\left(m + 0.24m_c\right)}} \tag{4}$$

where $Y$ is Young's modulus of the cantilever material; $w$, $h$ and $l$ are the width, thickness and length of the cantilever, respectively. $m$ is the inertial mass and $m_c$ is the mass of the cantilever. The resonant frequency can be tuned by adjusting all these parameters. However, it is difficult to change the width and thickness of a cantilever in practice. Only changing the length is feasible. Furthermore, modifying length is suitable for intermittent tuning. The approach requires an extra clamper besides the cantilever base clamp. This extra clamper can be released and re-clamped in different locations for various resonant frequencies. There is no power required to maintain the new resonant frequency. This approach has been patented (Gieras et al., 2007). However, due to its complexity, there is few research reported on this method.

### 2.4.2 Variable centre of gravity of the inertial mass

The resonant frequency can be adjusted by moving the centre gravity of the inertial mass. The ratio of the tuned frequency, $f_r'$, to the original frequency, $f_r$, is (Roylance & Angell, 1979):

$$\frac{f_r'}{f_r} = \sqrt{\frac{1}{3}\cdot\frac{r^2 + 6r + 2}{8r^4 + 14r^3 + \frac{21}{2}r^2 + \frac{2}{3}}} \tag{5}$$

where $r$ is the ratio of the distance between the centre of gravity and the end of the cantilever to the length of the cantilever.

This approach was realized and reported by Wu *et al* (2008). The tunable energy harvester consists of a piezoelectric cantilever with two inertial masses at the free end. One mass was fixed to the cantilever while the other part can move with respect to the fixed mass. Centre of gravity of the inertial mass could be adjusted by changing the position of the movable mass. The resonant frequency of the device was successfully tuned between 180Hz and 130Hz. The output voltage dropped with increasing resonant frequency.

### 2.4.3 Variable spring stiffness

Another method to tune the resonant frequency is to apply an external force to change stiffness of the spring. This tuning force can be electrostatic, piezoelectric, magnetic or other mechanical forces. However, electrostatic force requires very high voltage. In addition, spring stiffness can also be changed by thermal expansion but energy consumption in this method is too high compared to power generated by vibration energy harvesters. Therefore, these two methods are not suitable for frequency tuning in vibration energy harvesting. In this section, only frequency tuning by piezoelectric, magnetic and direct forces is discussed.

Peters *et al* (2008) reported a tunable resonator suitable for vibration energy harvesting. The resonant frequency tuning was realised by applying a force using piezoelectric actuators. A piezoelectric actuator was used because piezoelectric materials can generate large forces with low power consumption. The tuning voltage was chosen to be ±5V resulted in a measured resonance shift of ±15% around the initial resonant frequency of 78 Hz, i.e. the tuning range was from 66Hz to 89Hz. A closed-loop phase-shift control system was later developed to achieve autonomous frequency tuning (Peters et al., 2009). Eichorn *et al* (2010) presented a piezoelectric energy harvester with a self-tuning mechanism. The tuning system contains a piezoelectric actuator to provide tuning force. The device has a tuning range between 188Hz and 150Hz with actuator voltage from 2V to 50V. These are two examples of continuous tuning.

An example of applying magnetic force to tune the resonant frequency was reported by Zhu *et al* (2010b) who designed a tunable electromagnetic vibration energy harvester. Frequency tuning was realised by applying an axial tensile magnetic force to a cantilever structure as shown in Fig. 8.

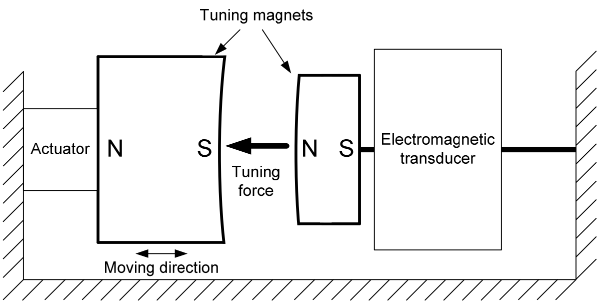


Fig. 8. Frequency tuning by applying magnetic force (reproduced from (Zhu et al., 2010b))

The tuning force was provided by the attractive force between two tuning magnets with opposite poles facing each other. One magnet was fixed at the free end of a cantilever while the other was attached to an actuator and placed axially in line with the cantilever. The distance between the two tuning magnets was adjusted by the linear actuator. Thus, the axial load on the cantilever, and hence the resonant frequency, was changed. The areas where the two magnets face each other were curved to maintain a constant gap between them over the amplitude range of the generator. The tuning range was from 67.6 to 98Hz by changing the distance between two tuning magnets from 5 to 1.2mm. The tuning mechanism does not affect the damping of the micro-generator over most of the tuning range. However, when the tuning force became larger than the inertial force caused by vibration, total damping increased and the output power was less than expected from theory. A control system was designed for this energy harvester (Ayala-Garcia et al., 2009). Energy consumed in resonant frequency tuning was provided by the energy harvester itself. This is the first reported autonomous tunable vibration energy harvester that operates exclusively on the energy harvester.

Resonant frequency of a vibration energy harvester can also be tuned by applying a direct mechanical force (Leland and Wright, 2006). The energy harvester consisted of a double clamped beam with a mass in the centre. The tuning force was compressive and was applied using a micrometer at one end of the beam. The tuning range was from 200 to 250 Hz. It was determined that a compressive axial force could reduce the resonance frequency of a vibration energy harvester, but it also increased the total damping. The above two devices are examples of intermittent tuning.

### 2.4.4 Variable electrical loads

All frequency tuning methods mentioned above are mechanical methods. Mechanical methods generally have large tuning range. However, they require a load of energy to realise. This is crucial to vibration energy harvesting where energy generated is quite limited. Therefore, electrical tuning method is introduced. The basic principle of electrical tuning is to change the electrical damping by adjusting electrical loads, which causes the power spectrum of the generator to shift.

Charnegie (2007) presented a piezoelectric energy harvester based on a bimorph structure and adjusted its resonant frequency by varying its load capacitance. The test results showed that if one piezoelectric layer was used for frequency tuning while the other one was used for energy harvesting, the resonant frequency can be tuned an average of 4 Hz with respect to the original frequency of 350 Hz by adjusting the load capacitance from 0 to 10 mF. If both layers were used for frequency tuning, the tuning range was an average of 6.5 Hz by adjusting the same amount of load capacitance. However, output power was reduced if both layers were used for frequency tuning while if only one layer was used for frequency tuning, output power remained unchanged.

Another electrically tunable energy harvester was reported by Cammarano *et al* (2010). The resonant frequency of the electromagnetic energy harvester was tuned by adjusting electrical loads, i.e. resistive, capacitive and inductive loads. The tuning range is between 57.4 and 66.5Hz. However, output power varied with changes of electrical loads.

## 2.5 Vibration energy harvesters with wide bandwidth

The other solution to increase the operational frequency range of a vibration energy harvester is to widen its bandwidth. Most common methods to widen the bandwidth include using a generator array, using nonlinear and bi-stable structures. In this section, details of these approaches will be covered.

### 2.5.1 Generator array

A generator array consists of multiple small energy harvesters, each of which has different dimensions and masses and hence different resonant frequencies. Thus, the assembled array has a wide operational frequency range whilst the Q-factor does not decrease. The overall power spectrum of a generator array is a combination of the power spectra of each small generator as shown in Fig. 9. The frequency band of the generator is thus essentially increased. The drawback of this approach is the added complexity in design and fabrication of such array and the increased total volume of the device depending upon the number of devices in the array.

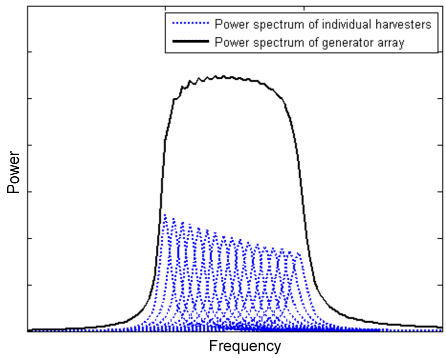


Fig. 9. Frequency spectrum of a generator array

Sari *et al* (2008) reported a micromachined electromagnetic generator array with a wide bandwidth. The generator consisted of a series of cantilevers with various lengths and hence resonant frequencies. Cantilevers were carefully designed so that they had overlapping frequency spectra with the peak powers at similar but different frequencies. This resulted in a widened bandwidth as well as an increase in the overall output power. Coils were printed on cantilevers while a large magnet was fixed in the middle of the cantilever array. Experimentally, operational frequency range of this device is between 3.3 and 3.6 kHz where continuous power of 0.5μW was generated.

A multifrequency piezoelectric generator intended for powering autonomous sensors from background vibrations was presented by Ferrari *et al* (2008). The generator consisted of three bimorph cantilevers with different masses and thus natural frequencies. Rectified outputs were fed to a single storage capacitor. The generator was used to power a batteryless sensor module that intermittently read the signal from a passive sensor and sent the measurement information via RF transmission, forming an autonomous sensor system. Experimentally, none of the cantilevers used alone was able to provide enough energy to operate the sensor module at resonance while the generator array was able to power the sensor node within wideband frequency vibrations.

### 2.5.2 Nonlinear structures

The theory of vibration energy harvesting using nonlinear generators was investigated by Ramlan (2009). Numerical and analytical showed that bandwidth of the nonlinear system depends on the damping ratio, the nonlinearity and the input acceleration. Ideally, the maximum amount of power harvested by a nonlinear system is the same as the maximum power harvested by a linear system. There are two types of nonlinearity, i.e. hard nonlinearity and soft nonlinearity as shown in Fig. 10. It is worth mentioning that output power and bandwidth depend the approaching direction of the vibration frequency to the resonant frequency. For a hard nonlinearity, this approach will only produce an improvement when approaching the device resonant frequency from a lower frequency. For a soft nonlinearity, this approach will only produce an improvement when approaching the device resonant frequency from a higher frequency. It is unlikely that these conditions can be guaranteed in real application, which makes this method very application dependent.

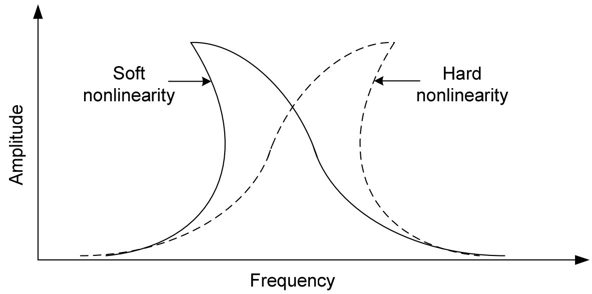


Fig. 10. Soft and hard Nonlinearity

Most reported nonlinear vibration energy harvester is realized by using a magnetic spring. Burrows *et al* (2007, 2008) reported a nonlinear energy harvester consisting of a cantilever spring with the non-linearity caused by the addition of magnetic reluctance forces. The device had a flux concentrator which guided the magnetic flux through the coil. The reluctance force between the magnets and the flux concentrator resulted in non-linearity. It was found experimentally that the harvester had a wider bandwidth during an up-sweep, i.e. when the excitation frequency was gradually increased while the bandwidth was much narrower during a down-sweep, i.e. when the excitation frequency was gradually decreased. This is an example of hard nonlinearity.

Another example of nonlinear vibration energy harvester is a tunable electromagnetic vibration energy harvester with a magnetic spring, which combined a manual tuning mechanism with the non-linear structure (Spreemann et al., 2006). This device had a rotary suspension and magnets as nonlinear springs. It was found in the test that the bandwidth of the device increased as magnetic force became larger, i.e. non-linearity increased.

A numerical analysis of nonlinear vibration energy harvesters was recently reported (Nguyen & Halvorsen, 2010). Analytical results showed that soft nonlinear energy harvesters have better performance than hard nonlinear energy harvesters. This is yet to be verified by experiments.

### 2.5.3 Bi-stable structures

Ramlan (2009) also studied bi-stable structures for energy harvesting (also termed the snap-through mechanism). Analysis revealed that the amount of power harvested by a bistable device is $4/\pi$ greater than that by the tuned linear device as the device produces a squarewave output for a given sinusoidal input. Numerical results also showed that more power is harvested by the mechanism if the excitation frequency is much less than the resonant frequency. Bi-stable devices also have the potential to cope with the mismatch between the resonant frequency and the vibration frequency.

Ferrari *et al* (2009) reported a nonlinear generator that exploits stochastic resonance with white-noise excitation. A piezoelectric beam converter was coupled to permanent magnets creating a bi-stable system bouncing between two stable states in response to random excitation. Under proper conditions, this significantly improved energy harvesting from wide-spectrum vibrations. The generator was realized by screen printing low-curing-temperature lead zirconate titanate (PZT) films on steel cantilevers and excited with white-noise vibrations. Experimental results showed that the performances of the converter in terms of output voltage at parity of mechanical excitation were markedly improved.

Mann *et al* (2010) investigated a nonlinear energy harvester that used magnetic interactions to create an inertial generator with a bistable potential well. The motivating hypothesis for this work was that nonlinear behavior could be used to improve the performance of an energy harvester by broadening its frequency response. Theoretical investigations studied the harvester's response when directly powering an electrical load. Both theoretical and experimental tests showed that the potential well escape phenomenon can be used to broaden the frequency response of an energy harvester.

Erturk *et al* (2009) introduced a piezomagnetoelastic device for substantial enhancement of piezoelectric vibration energy harvesting. Electromechanical equations describing the nonlinear system were given along with theoretical simulations. Experimental performance of the piezomagnetoelastic generator exhibited qualitative agreement with the theory, yielding large-amplitude periodic oscillations for excitations over a frequency range. Comparisons were presented against the conventional case without magnetic buckling and superiority of the piezomagnetoelastic structure as a broadband electric generator was proven. The piezomagnetoelastic generator resulted in a 200% increase in the open-circuit voltage amplitude (hence promising an 800% increase in the power amplitude).

## 2.6 Summary

Eq. 3 gives a good guideline in designing vibration energy harvester. The maximum power converted from the mechanical domain to the electrical domain is proportional to the mass and vibration acceleration squared and inversely proportional to the resonant frequency as well as total damping. This means that more power can be extracted if the inertial mass is increased or energy harvesters can work in the environment where the vibration level is high. For a fixed resonant frequency, the generator has to be designed to make the mechanical damping as low as possible. For an energy harvester with constant damping, the generated electrical power drops with an increase of the resonant frequency.

However, as vibration energy harvesters are usually designed to have a high Q-factor for better performance, the generated power drops dramatically if resonant frequencies and ambient vibration frequencies do not match. Therefore, most reported generators are designed to work only at one particular frequency. For applications such as moving vehicles, human movement and wind induced vibration where the frequency of ambient vibration changes periodically, the efficiency of energy harvesters with one fixed resonant frequency is significantly reduced since the generator will not always be at resonance. This drawback must be overcome if vibration energy harvesters are to be widely applicable in powering wireless systems.

Tuning the resonant frequency of a vibration energy harvester is a possible way to increase its operational frequency range. It requires a certain mechanism to periodically adjust the resonant frequency so that it matches the frequency of ambient vibration at all times.

The suitability of different tuning approaches will depend upon the application, but in general terms the key factors for evaluating a tuning mechanism for adjusting the resonant frequency of vibration energy harvesters are as follows. First, energy consumed by the tuning mechanism must not exceed the energy generated. Second, tuning range should be large enough for certain applications. Third, tuning mechanism should achieve a suitable degree of frequency resolution. Last but not least, tuning mechanism should have as little effect on total damping as possible. Furthermore, intermittent tuning is preferred over continuous tuning as it is only on when necessary and thus saves energy.

It is important to mention that efficiency of mechanical tuning methods depends largely on the size of the structure. The smaller the resonator, the higher the efficiency of the tuning mechanism. Efficiency of resonant frequency tuning by adjusting the electrical load depends on electromechanical coupling. The better the coupling, the larger the tuning range. Mechanical tuning methods normally provide large tuning range compared to electrical tuning methods while electrical tuning methods require less energy than mechanical tuning methods.

Operational frequency range of a vibration energy harvester can be effectively widened by designing an energy harvester array consisting of multiple small generators which work at various frequencies. Thus, the assembled energy harvester has a wide operational frequency range whilst the Q-factor does not decrease. However, this array must be designed carefully so that individual harvesters do not affect each other, which makes it more complex to design and fabricate. In addition, only a portion of individual harvesters contribute to power output at a particular source frequency. Therefore, this approach is not volume efficient. Furthermore, non-linear energy harvesters and harvesters with bi-stable structures are another two solutions to increase the operational frequency range of vibration energy harvesters. They can improve performance of the generator at higher and lower frequency bands relative to its resonant frequency, respectively. However, the mathematical modelling of these energy harvesters is much more complicated than that of linear generators, which increases the complexity in design and implementation. In addition, there is hysteresis in non-linear energy harvesters. Performance during down-sweep (or up-sweep) can be worse than that during up-sweep (or down-sweep) or worse than the linear region depending on sweep direction. Therefore, when designing nonlinear energy harvesters, this must be taken into consideration. In contrast, energy harvesters with bi-stable structures are less frequency dependent, which makes it a potentially better solution.

In summary, some most practical methods to increase the operation frequency range for vibration energy harvesting include:

- changing spring stiffness intermittently (preferred) or continuously;
- adjusting electrical loads;
- using generator arrays;
- employing non-linear and bi-stable structures.

## 3. Energy harvesting from human movement

The human body contains huge amount of energy. The kinetic energy from human movement can be harvested and converted to electrical energy. The electrical energy produced can be used to power other wearable electronics, for example, a watch and a heart rate monitor. It can also be used to charge portable electronics, such as mobile phones, mp3 players or even laptops. Researches have been done to study movement of different parts of a human body. It was found that upper human body produces movement with frequencies less than 10Hz while frequencies of movement from lower human body are between 10 and 30Hz (von Buren, 2006). The first prototype of the electronic device powered by human movement is an electronic watch developed by SEIKO in 1986. Two years later, SEIKO launched the world's first commercially available watch, called AGS. Since then, more and more human-powered electronic devices have come to the market and researches in this area have drawn more attention (Romero et al., 2009). So far, two common types of human energy harvesters are energy harvesting shoes and backpacks.

### 3.1 Shoes

Energy harvesters in shoes are based on either pressure of the human body on the shoe sole or the kicking force during walking.

Kymissis *et al* (1998) studied energy harvesters mounted on sneakers that generated electrical energy from the pressure on the shoe sole. Output power of three types of energy harvesters was reported. The first energy harvesters had multilayer laminates of PVDF, the second one contained a PZT unimorph and the third one was a rotary electromagnetic generator. The PVDF and PZT elements were mounted between the removable insole and rubber sole. The PVDF stack was in the front of the shoe while the PZT unimorph was at the heel. The electromagnetic generator was installed under the heel. Experimentally, the three generators produced average power of 1.8mW, 1.1mW and 230mW, respectively.

Carroll and Duffy (2005) reported a sliding electromagnet generator placed inside the shoe sole for energy harvesting. This device extracted electrical energy from the kicking force during walking. The generator consists of a set of three coils with magnets moving inside the coils. Experimentally, this generator produced up to 8.5mW of power at 5Hz. A smaller set of three generators was also presented. This set delivered up to 230µW of power at 5Hz.

### 3.2 Backpacks

There are also two types of energy harvesting from backpacks. One utilises linear vertical movement of the backpacks to generate electrical energy and the other is based on stress on the strips of the backpacks.

Rome *et al* (2005) studied a backpack that converted kinetic energy from the vertical movement of a backpack to electrical energy. The backpack consisted of a linear bearing and a set of springs suspended the load relative to a frame and shoulder harness. The load could move vertically relative to the frame. This relative motion was then converted to electrical energy using a rotary electric generator with a rack and pinion. This system was demonstrated to generate a maximum power of approximately 7.37W. Although the backpack does generate significant power levels, the additional degree of freedom provided to the load could impair the user's dexterity and lead to increased fatigue.

Saha *et al* (2008) reported a nonlinear energy harvester with guided magnetic spring for energy harvesting from human movement. The average measured maximum load powers of the generator without top fixed magnets were 0.95mW and 2.46mW during walking and slow running condition, respectively.

Energy harvesting from a backpack with piezoelectric strips was reported by Granstrom *et al* (2007). The traditional strap of the backpack was replaced by one made of PVDF. PVDF was chosen due to its high flexibility and strength. In the test, a preload of around 40N was applied to the straps to simulate the static weight in the backpack while a 20N sine wave with a frequency of 5Hz was applied to simulate the alternating load in the backpack. Strips with PVDF of 28μm and 52μm were compared. Maximum power generated in these two strips was 3.75mW and 1.36mW, respectively.

Another backpack targeted straps as locations for piezoelectric generators was reported by Feenstra *et al* (2008). A piezoelectric stack was placed in series with the backpack straps. The tension force that the piezoelectric stack receives from the cyclic loading is mechanically amplified and converted into a compressive load. The average power output measured when walking on a treadmill with a 40lb load was reported as 176μW. The maximum power output for the device was expected to be 400μW.

### 3.3 Summary

Energy harvesting from human movement is quite different from energy harvesting from machinery vibration due to some special characters. First, human movement has low frequency (<30Hz) and large displacement (several mm or cm). Second, human movement is not sinusoidal. It is normally random. Therefore, resonant energy harvesters that are widely used in energy harvesting from machinery are not suitable for this application. Last but not least, energy harvesters to be worn on human body should have reasonable size and weight so that they will not affect normal human activity. Table 1 summarizes some reported energy harvesters from human movement.

## 4. Energy harvesting from flow induced vibrations

The turbine generator is the most mature method for flow energy harvesting. However, the efficiency of conventional turbines reduces with their sizes due to the increased effect of friction losses in the bearings and the reduced surface area of the blades. Furthermore, rotating components such as bearings suffer from fatigue and wear, especially when miniaturised. These drawbacks of turbine generators urges emergence of a new area in energy harvesting, i.e. energy harvesting from flow induced vibration. The flow here

| Generator type | Position | Operational principle | Output power (mW) |
|---|---|---|---|
| PVDF laminates | front of the shoe | Pressure | 1.8 |
| PZT unimorph | heel | | 1.1 |
| electromagnetic | heel | | 230 |
| electromagnetic | heel | Kicking force | 8.5 |
| nonlinear | backpack | Walking | 0.95 |
| | | Running | 2.46 |
| PVDF strip | | Preload: 40N<br>20N sine wave@5Hz | 3.75 |
| | | | 1.36 |
| Piezoelectric stack | | Walking | 0.176 |

Table 1. Comparisons of some existing energy harvesters from human movement

includes both liquid flow and air flow. There are three main types of energy harvester of this kind. They are energy harvesting from vortex-induced vibration (VIV), flutter energy harvesters and energy harvesters with Helmholtz resonators. Principles and reported devices will be presented in this section.

### 4.1 Energy harvesting from vortex-induced vibrations

Flow-induced vibration, as a discipline, is very important in our daily life, especially in civil engineering. Generally, scientists try to avoid flow-induced vibration in buildings and structures to reduce possible damage. Recently, such vibration has been investigated as an energy source that can be used to generate electrical energy. Two types of flow-induced vibration are studied so far: vortex-induced vibration and flutter.

#### 4.1.1 Principles

When a fluid flows toward the leading edge of a bluff body, the pressure in the fluid rises from the free steam pressure to the stagnation pressure. When the flow speed is low, i.e. the Reynolds number is low, pressure on both sides of the bluff body remains symmetric and no turbulence appears. When the flow speed is increased to a critical value, pressure on both sides of the bluff body becomes unstable, which causes a regular pattern of vortices, called vortex street or Kármán vortex street as shown in Fig. 11. Certain transduction mechanisms can be employed where vortices happen and thus energy can be extracted. Sanchez-Sanz *et al* (2009) studied the feasibility of energy harvesting based on the Kármán vortex street and proposed several design rules of such micro-resonator. This method is suitable both air flow and liquid flow.

Flutter is a self-feeding vibration where aerodynamic forces on an object couple with a structure's natural mode of vibration to produce rapid periodic motion. Flutter can occur in any object within a strong fluid flow, under the conditions that a positive feedback occurs between the structure's natural vibration and the aerodynamic forces. Flutter can be very disastrous. The worst example of flutter is the disaster of Tacoma Narrows Bridge that collapsed due to the aeroelastic flutter. However, such vibrant movement makes it an ideal source for energy harvesting. This method is normally only suitable for air flow as damping in liquid flow is very high, which makes flutter less likely to happen.

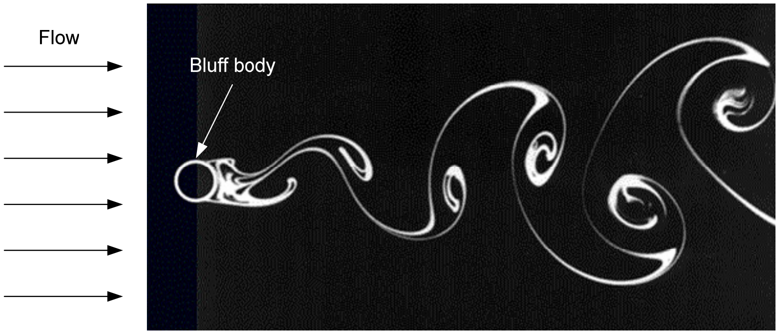


Fig. 11. An example of Kármán vortex street

#### 4.1.2 Energy harvesting in liquid flow

The most famous energy harvester based on Kármán vortex street is the 'Energy Harvesting Eel' (Allen & Smits, 2001; Taylor et al., 2001). Fig. 12 shows a schematic of the device. The 'eel' was a flexible membrane with PVDF on it. It is riveted a certain distance away behind a fixed bluff body. The vortices behind the bluff body caused the 'eel' to swing from one end to the other. Electrical energy can then be generated by the PVDF from such movement. However, no detailed test results were reported.

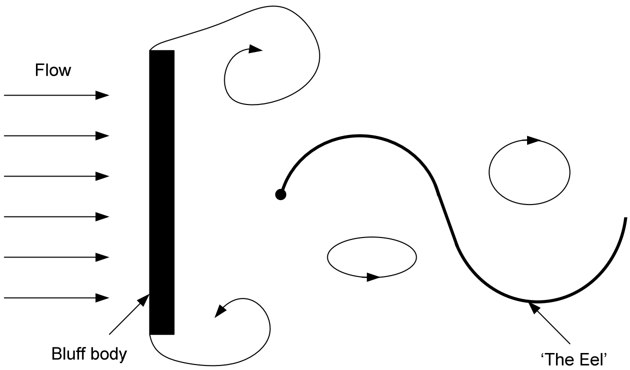


Fig. 12. Schematic of the 'Energy Harvesting Eel' (top view)

Wang and Pham (2011a) reported a small scale water flow energy harvester based on Kármán vortex street. The energy harvester had a flexible diaphragm on which a piezoelectric film (PVDF) was attached. There was a chamber below the diaphragm where the water flows. A bluff body iwas placed at the centre of the chamber. When the water flew past the bluff body, vortex street occurred. The diaphragm moved up and down with the vortices. The movement of the diaphragm bent the piezoelectric film and thus generated electrical energy. Experimental results showed that an open circuit output voltage of $0.12V_{pp}$ and an instantaneous output power of 0.7nW were generated when the pressure oscillated with amplitude of 0.3kPa and a frequency of 52Hz. Its active volume was 50mm × 26mm × 15mm. The active volume is defined as the product of the area of the diaphragm times the thickness of the device.

Similar devices without the bluff body were also studied by Wang *et al* (2010a, 2010b, 2011b). Both piezoelectric and electromagnetic transducers were used. Table 2 lists their test results.

| Transducer | Output power (μW) | Open circuit voltage (V) | Flow pressure (Pa) | Flow frequency (Hz) | Active volume (mm × mm × mm) |
|---|---|---|---|---|---|
| Electromagnetic (Wang, 2010a) | 0.4 | 0.01 | 254 | 30 | 900 × 600 × 400 |
| Piezoelectric (Wang, 2011b) | $0.45\times10^{-3}$ | 0.072 | 20.8k | 45 | 23 × 15 × 10 |
| Piezoelectric (Wang, 2010b) | 0.2 | 2.2 | 1196 | 26 | 50 × 30 × 7 |

Table 2. Comparison of Wang's work

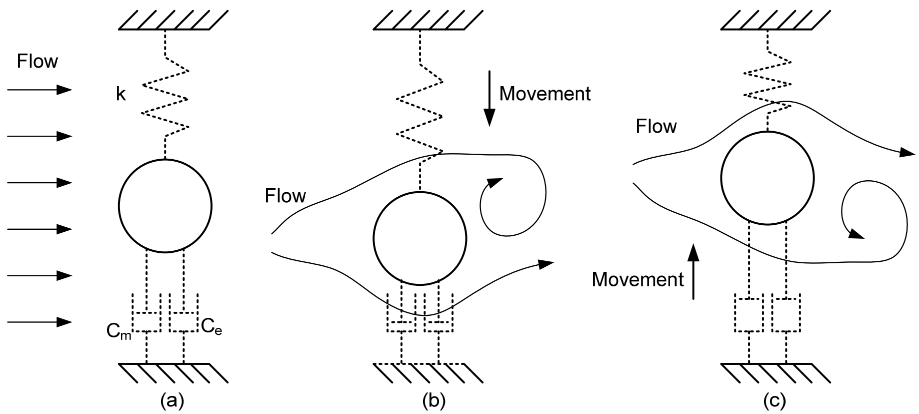


Fig. 13. Principle of VIVACE

Another type of energy harvesters in water based on Kármán vortex street is called Vortex Induced Vibration for Aquatic Clean Energy (VIVACE) (Bernitsas, 2006). The principle of this energy harvester is slightly different from that of the ones mentioned above. Instead of using the vortices created by a fixed bluff body, this energy harvester uses movement of the bluff body caused by the vortices it produces itself to generate power. When a flow passes a mobile bluff body, vortices are formed. The formation of a vortex alternately above and below the cylindrical bluff body forces an alternating vertical motion of the cylinder, the energy of which can be extracted (as shown in Fig. 13.). Note that the bluff body was designed to be restricted to have only one degree of freedom. Electromagnetic transducer was used to generator electrical energy. Multiple cylinders can be used to form arrays depending on applications.

Such devices are currently available only in large scales. Six different scales of VIVACE with power lever between 50kW and 1GW were reported so far. More work needs to be done to minimize it so that it can be used to power wireless sensor nodes. Barrero-Gil *et al* (*2010*) published a model for such energy harvesting method. Several design rules were summarized. Furthermore, the authors concluded that it is fairly straightforward to minimize such devices.

### 4.1.3 Energy harvesting in airflow

One method of energy harvesting based on Kármán vortex street, called flapping-leaf, has been reported by Li and Lipson (2011). The flapping-leaf energy harvester had the same principle as the 'energy harvesting eel' while it was only designed to work in airflow. The device consisted of a PVDF cantilever with one end clamped on a bluff body and the other end connected to a triangular plastic leaf. When the airflow passed the bluff body, the vortices produced fluctuated the leaf and thus the PVDF cantilever to produce electrical energy. The energy harvester generated a maximum output power of 17μW under the wind of 6.5m·s$^{-1}$. Dimensions of the PVDF cantilever was 73mm × 16mm × 40μm.

Dunnmon *et al* (2011) reported a piezoelectric aeroelastic energy harvester. It consists of a flexible plate with piezoelectric laminates which was placed behind a bluff body. It was excited by a uniform axial flow field in a manner analogous to a flapping flag such that the system delivered power to an electrical impedance load. In this case, the bluff body was in the shape of a standard NACA 0015 rather than a cylinder. The beam was made of 2024-T6 aluminium and an off-the-shelf piezoelectric patch was mounted close to the clamped end of the beam in the centre along the width of the beam. Experimental results showed that a RMS output power of 2.5mW can be derived under a wind of 27m·s$^{-1}$. The generator was estimated to have an efficiency of 17%. The plate had dimensions of 310mm × 101mm × 0.39mm and the bluff body has a length of 550mm. Dimensions of the piezoelectric laminate were 25.4mm × 20.3mm × 0.25mm.

Jung and Lee (2011) recently presented a similar electromagnetic energy harvester as VIVACE. Instead of operating under water, this device was designed to work under air flow. In addition, this device had a fixed cylinder bluff body in front of the mobile cylinder. These two cylinders had the same dimensions. It was found that the displacement of the mobile cylinder largely depends on the distance between the two cylinders and the maximum displacement can be achieved when this distance was between three and six times of the cylinder diameter. In the experiments, a prototype device can produce an average output power of 50-370mW under wind of 2.5-4.5 m·s$^{-1}$. Both cylinders had a diameter of 5cm and a length of 0.85m.

Zhu *et al* (2010c) presented a novel miniature wind generator for wireless sensing applications. The generator consisted of a wing that was attached to a cantilever spring made of beryllium copper. The airflow over the wing caused the cantilever to bend upwards, the degree of bending being a function of the lift force from the wing and the spring constant. As the cantilever deflects downwards, the flow of air is reduced by the bluff body and the lift force reduced causing the cantilever to spring back upwards. This exposes it to the full airflow again and the cycle is repeated (as shown in Fig. 14). When the frequency of this movement approaches the resonant frequency of the structure, the wing has the maximum displacement. A permanent magnet was fixed on the wing while a coil was attached to the base of the generator. The movement of the wing caused the magnetic flux cutting the coil to change, which generated electrical power. The proposed device has dimensions of 12cm × 8cm × 6.5cm. It can start working at a wind speed as low as 2.5m·s$^{-1}$ when the generator produced an output power of 470µW. This is sufficient for periodic sensing and wireless transmission. When the wind speed was 5m·s$^{-1}$, the output power reached 1.6mW.

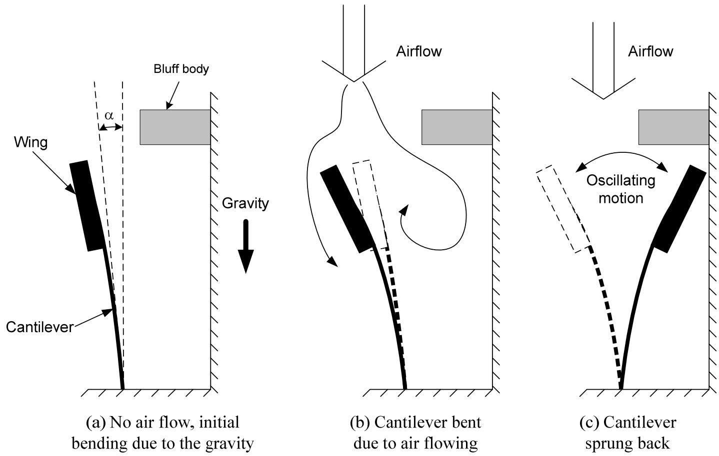


Fig. 14. Principle of the energy harvester in (Zhu et al., 2010) (transducer is not shown)

### 4.2 Flutter energy harvesters

The first flapping wind generator was invented by Shawn Frayne and his team in 2004, called Windbelt generator (Windbelt, 2004). The Windbelt generator uses a tensioned membrane undergoing a flutter oscillation to extract energy from the wind as shown in Fig. 15. Magnets are attached to the end of the membrane. They move with the membrane and are coupled with static coils to generate electricity. The company offer Windbelt generators of different sizes. The smallest Windbelt generator has dimensions of 13cm × 3cm × 2.5cm.

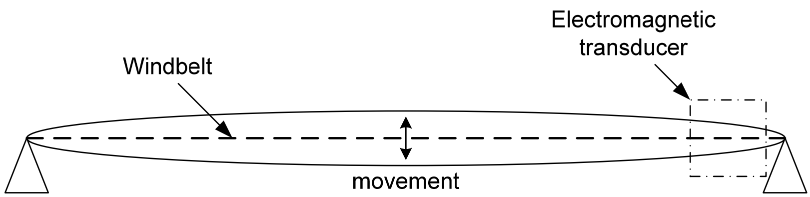


Fig. 15. Windbelt: airflow is perpendicular to this page

The minimum wind speed to make it work is 3m·s$^{-1}$, where an output power less than 100µW was produced. The generator can produce output power of 0.2mW, 2mW and 5mW under the wind of 3.5m·s$^{-1}$, 5.5m·s$^{-1}$ and 7.5m·s$^{-1}$ respectively (Windbelt, 2004).

Kim *et al* (2009) reported a small-scale version of the Windbelt generator. The generator had dimensions of 12mm × 12mm × 6mm. The generator was tested under the airflow with the pressure of 50kPa. It produced a voltage output with the frequency of 530Hz and the amplitude of 80mVpp.

Erturk *et al* (2010) investigated the concept of piezoaeroelasticity for energy harvesting. A mathematical model was established and a prototype device was built to validate the model. The generator had a 0.5m long airfoil vertically placed. Two PZT-5A piezoceramics were attached onto the two ends of the airfoil. Under certain airflow, the airfoil flapped and actuated the piezoceramics to produce electricity. An electrical power output of 10.7mW was delivered to a 100 kΩ load at the linear flutter speed of 9.3m·s$^{-1}$.

Li *et al* (2009, 2011) reported another type of flapping-leaf which works based on aeroelastic flapping. The device had a PVDF cantilever with its width direction parallel to the air flow. The leaf was placed to make the entire device like an 'L' shape as shown in Fig. 16. Different PVDF cantilevers were compared in the test. It was found that the optimum device generated a peak power of 615µW in the wind of 8m·s$^{-1}$.

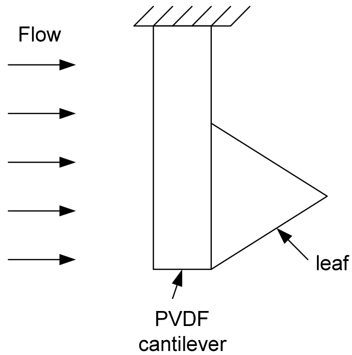


Fig. 16. Flapping-leaf based on aeroelastic flapping

St. Clair *et al* (2010) reported a micro generator using flow-induced self-excited oscillations. The principle is similar to music-playing harmonicas that create tones via oscillations of reeds when subjected to air blow. Output power between 0.1 and 0.8mW was obtained at wind speeds ranging between 7.5 and 12.5m·s$^{-1}$.

### 4.3 Energy harvesting with a Helmholtz resonator

#### 4.3.1 Principles

A Helmholtz resonator is a gas-filled chamber with an open neck (as shown in Fig. 17), in which a standard second-order (i.e. spring-mass) fluidic oscillation occurs. The air inside the neck acts as the mass and the air inside the chamber acts as the spring. When air flows past the opening, an oscillation wave occurs. Generally, the cavity has several resonance frequencies, the lowest of which is the Helmholtz resonance. The Helmholtz resonant frequency is given by:

$$f_H = \frac{v}{2\pi}\sqrt{\frac{A}{Vl}} \tag{6}$$

where $v$ is the speed of sound in a gas, $A$ is the cross sectional area of the neck, $l$ is the length of the neck and $V$ is the static volume of the cavity.

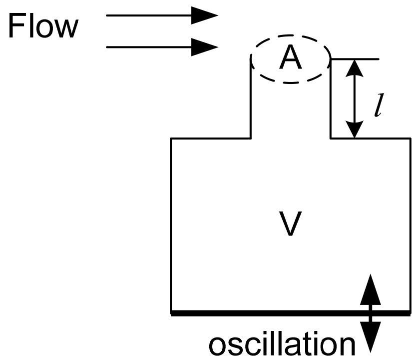


Fig. 17. Helmholtz resonator

### 4.3.2 Examples

Matova *et al* (2010) reported a device that had a packaged MEMS piezoelectric energy harvester inside a Helmholtz resonator. It was found that packaged energy harvesters had better performance than unpackaged energy harvesters as the package removes the viscous influence of the air inside the Helmholtz cavity and ensure that only the oscillation excites the energy harvester. Experimental results showed that the energy harvester generated a maximum output power of 2μW at 309Hz under the airflow of $13\text{m}\cdot\text{s}^{-1}$. Furthermore, it was found that a major drawback of the Helmholtz resonator is its strong dependence of their resonant frequency on the ambient temperature. This means that this kind of energy harvesters can only be used in the environments with stable temperature or the energy harvester must have a wide operational frequency range.

Kim *et al* (2009) presented a Helmholtz-resonator-based energy harvester with an electromagnetic transducer. The device has a membrane with a magnet attached at the bottom of the cavity. As the membrane oscillates due to the Helmholtz resonance, a static coil is coupled with the moving magnet to generate electricity. Two energy harvesters were fabricated and tested. The first one had dimensions of ϕ19mm × 5mm and a resonant frequency of 1.4kHz. It generated an open circuit voltage of $4\text{mV}_{pp}$ under the airflow of 0.2kPa ($5\text{m}\cdot\text{s}^{-1}$). The second device had dimensions of ϕ9mm × 3mm and a resonant frequency of 4.1kHz. It generated an open circuit voltage of $15\text{mV}_{pp}$ under the airflow of 1.6kPa.

Liu *et al* (2008) demonstrated the development of an acoustic energy harvester using Helmholtz resonator. It uses a piezoelectric diaphragm to extract energy. The diaphragm consisted of a layer of 0.18mm-thick brass as the substrate and a layer of 0.11mm-thick piezoceramics (APC 850). Experimental results showed an output power of about 30mW was harvested for an incident sound pressure level of 160 dB with a flyback converter. The cavity had dimensions of $\phi$12.68mm × 16.4mm.

### 4.4 Summary

Among these three types of energy harvesters from flow induced vibration, energy harvesters based on VIV and flapping energy harvesters are more suitable for practical application due to their reasonable output power level. Existing energy harvesters with Helmholtz resonators have very low output power and more work needs to be done to make this approach practical. In addition, all piezoelectric flow energy harvesters use PVDF as piezoelectric material due to its flexibility. However, piezoelectric coefficients of PVDF are low compared to those of other piezoelectric materials. Flexible piezoelectric materials with higher piezoelectric coefficients, for example Macro Fiber Composite (MFC), need to be investigated to improve output power of piezoelectric flow energy harvesters.

## 5. Conclusions

A vibration energy harvester is an energy harvesting device that couples a certain transduction mechanism to ambient vibration and converts mechanical energy to electrical energy. Ambient vibration includes machinery vibration, human movement and flow induced vibration.

For energy harvesting from machinery vibration, the most common solution is to design a linear generator that converts kinetic energy to electrical energy using certain transduction mechanisms, such as electromagnetic, piezoelectric and electrostatic transducers. Electromagnetic energy harvesters have the highest power density among the three transducers. However, performance of electromagnetic vibration energy harvesters reduces a lot in micro scale, which makes it not suitable for MEMS applications. Piezoelectric energy harvesters have the similar power density to the electromagnetic energy harvesters. They have simple structures, which makes them easy to fabricate. Electrostatic energy harvesters have the lowest power density of the three, but they are compatible with MEMS fabrication process and easy to be integrated to chip-level systems.

The linear energy harvester produces a maximum output power when its resonant frequency matches the ambient vibration frequency. Once these two frequencies do not match, the output power drops significantly due to high Q-factor of the generator. Two possible methods to overcome this drawback are tuning the resonant frequency of the generator to match the ambient vibration frequency and widening bandwidth of vibration energy harvesters.

The methods of tuning the resonant frequency include mechanical method and electrical method. The mechanical tuning method requires a certain mechanism to change the mechanical property of the structure of the generator to tune the resonant frequency. Thus, it requires more energy to implement while it normally has a large tuning range.

The electrical tuning method realizes resonant frequency tuning by adjusting electrical loads. This method consumes little energy as it does not involve any change in mechanical properties. In addition, it is much easier to implement than mechanical methods. However, this method normally has a small tuning range.

The suitability of different tuning approaches depends on the application but in general terms, the key factors for evaluating a tuning mechanism are:

- energy consumed by the tuning mechanism should be as small as possible and must not exceed the energy produced by the energy harvester;
- the mechanism should achieve a sufficient operational frequency range;
- the tuning mechanism should achieve a suitable degree of frequency resolution;
- the strategy applied should not increase the damping over the entire operational frequency range.

Energy harvesting from human movement is another important area in vibration energy harvesting. As human movement is random, linear energy harvesters are not suitable for this application. Broadband, non-linear or non-resonant devices are preferred. At the moment, the most common locations on human body for the energy harvesters are feet and upper body due to large displacement or force produced during movement. Up to date, some reported energy harvesters successfully produced useful amount of electrical energy for portable electronic devices. However, consideration needs to be taken to improve design of the energy harvesters so that they will not cause discomfort for human body. Furthermore, another potential solution to energy harvesting from human movement is to print active materials on fabrics, such as jackets and trousers, so that electrical energy can be generated while human body is moving.

Energy harvesters from flow-induced vibration, as an alternative to turbine generators, have drawn more and more attention. Useful amount of energy has been generated by existing devices and the start flow speed has been reduced to as low as $2.5m\cdot s^{-1}$. However, most reported devices that produce useful energy are too large in volume compared to other vibration energy harvesters. Thus, it is difficult to integrate these devices into wireless sensor nodes or other wireless electronic systems. Future work should focus on miniaturise these energy harvesters while maintain current power level. In addition, researches should be done to further reduce the start flow speed to allow this technology wider applications.

## 6. References

Allen, J. J. & Smits, A. J. (2001). Energy harvesting eel, In: *Journal of Fluids and Structures*, Vol.15, pp. 629-640, ISSN 0889-9746

Anton, S. R. & Sodano, H. A. (2007). A review of power harvesting using piezoelectric materials (2003-2006), In: *Smart Materials and Structures*, Vol.16, pp.1-21, ISSN 0964-1726

Arakawa, Y.; Suzuki, Y. & Kasagi, N. (2004). Micro seismic power generator using electret polymer film, *Proceedings of PowerMEMS 2004*, 187-190, Kyoto, Japan, November 28-30, 2004

Ayala-Garcia, I. N.; Zhu, D.; Tudor, M. J. & Beeby, S. P. (2009). Autonomous tunable energy harvester, *Proceedings PowerMEMS 2009*, pp. 49-52, Washington DC, USA, December 1-4, 2009

Barrero-Gil, A.; Alonso, G. & Sanz-Andres, A. (2010). Energy harvesting from transverse galloping, In: *Journal of Sound and Vibration*, Vol.329, pp. 2873-2883, ISSN 0022-460X

Beeby, S. P.; Tudor, M. J.; White, N. M. (2006) Energy harvesting vibration sources for microsystems applications, In: *Measurement Science and Technology*, Vol.17, pp. 175-195, ISSN 0957-0233

Beeby, S.; Tudor, M.; Torah, R.; Roberts, S.; O'Donnell, T. & Roy, S. (2007). Experimental comparison of macro and micro scale electromagnetic vibration powered generators, In: *Microsystem Technologies*, Vol.13, No.12-13, pp. 1647-1653, ISSN: 0946-7076

Beeby, S. P.; Torah, R. N.; Tudor, M. J.; Glynne-Jones, P.; O'Donnell, T.; Saha, C. R. & Roy, S. (2007). A micro electromagnetic generator for vibration energy harvesting, In: *Journal of Micromechanics and Microengineering*, Vol.17, pp. 1257-1265, ISSN 0960-1317

Bernitsas, M. M.; Raghavan, K.; Ben-Simon, Y. & Garcia, E. M. H. (2006). VIVACE (Vortex Induced Vibration for Aquatic Clean Energy): A new concept in generation of clean and renewable energy from fluid flow, *Proceedings of OMAE2006 25th International OMAE Conference, Hamburg, Germany, 4-9 June, 2006*

Blevins, R. D. (2001). *Formulas for Natural Frequency and Mode Shape*, Krieger, ISBN 1-57524-184-6, Malabar, Forida, USA

Burrow, S. G. & Clare, L. R. (2007). A Resonant Generator with Non-Linear Compliance for Energy Harvesting in High Vibrational Environments, *IEEE International Electric Machines and Drives Conference*, pp. 715-720, Antalya, Turkey, May 3-5, 2007

Burrow, S. G.; Clare, L. R.; Carrella, A. & Barton, D. (2008). Vibration energy harvesters with non-linear compliance, In: *Active and Passive Smart Structures and Integrated Systems 2008, Proceedings of the SPIE*, Vol.6928, 692807

Cammarano A.; Burrow S. G.; Barton D. A. W.; Carrella A. & Clare L. R. (2010). Tuning a resonant energy harvester using a generalized electrical load, In: In: *Smart Materials and Structures*, Vol.19, 055003(7pp), ISSN 0964-1726

Carroll, D. & Duffy, M. (2005). Demonstration of wearable power generator, *Proceedings of the 11th European Conference on Power Electronics and Applications*, ISBN: 90-75815-09-3, ISBN: 90-75815-09-3, Dresden, Germany, September 11-14, 2005

Charnegie, D. (2007). Frequency tuning concepts for piezoelectric cantilever beams and plates for energy harvesting, *MSc Dissertation*, School of Engineering, University of Pittsburgh, USA

Ching, N. N. H.; Wong, H. Y.; Li, W. J.; Leong, P. H. W. & Wen, Z. (2002). A laser-micromachined vibrational to electrical power transducer for wireless sensing systems, In: *Sensors and Actuators A: Physical*, Vol.97-98, pp. 685-90, ISSN 0924-4247

Despesse, G.; Jager, T.; Chaillout, J.; Leger, J.; Vassilev, A.; Basrour, S. & Chalot, B. (2005). Fabrication and characterisation of high damping electrostatic micro devices for vibration energy scavenging, *Proceedings of Design, Test, Integration and Packaging of MEMS and MOEMS*, pp. 386–390, Montreux, Switzerland, June 1-3, 2005

Dunnmon, J. A.; Stanton, S. C.; Mann, B. P. & Dowell, E. H. (2011). Power extraction from aeroelastic limit cycle oscillations, In: *Journal of Fluids and Structures*, doi:10.1016/j.jfluidstructs.2011.02.003, ISSN 0889-9746

Eichhorn, C.; Tchagsim, R.; Wilhelm, N.; Goldschmidtboeing, F. & Woias, P. (2010). A compact piezoelectric energy harvester with a large resonance frequency tuning range, *Proceedings PowerMEMS 2010*, pp. 207-211, Leuven, Belgium, December 1-3, 2010

Elfrink, R.; Kamel, T. M.; Goedbloed, M.; Matova, S.; Hohlfeld, D.; van Andel,Y. & van Schaijk, R. (2009). Vibration energy harvesting with aluminum nitride-based piezoelectric devices, In: *Journal of Micromechanics and Microengineering*, Vol.19, No.9, 094005, ISSN 0960-1317

Erturk, A.; Hoffmann, J. & Inman, D. J. (2009). A piezomagnetoelastic structure for broadband vibration energy harvesting, In: *Applied Physics Letters*, Vol.94, 254102, ISSN 0003-6951

Erturk, A.; Vieira, W. G. R.; De Marqui, C. Jr. & Inman, D. J. (2010). On the energy harvesting potential of piezoaeroelastic systems, In: *Journal of Applied Physics*, Vol.96, 184103, ISSN 0021-8979

Fang, H. B.; Liu, J. Q.; Xu, Z. Y.; Dong, L.; Wang, L.; Chen, D.; Cai, B. C. & Liu, Y. (2006). Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting, In: *Microelectronics Journal*, Vol.37, No.11, pp. 1280-1284, ISSN 0026-2692

Feenstra, J.; Granstrom, J.; and Sodano, H. A. (2008). Energy harvesting through a backpack employing a mechanically amplified piezoelectric stack, In: *Mechanical Systems and Signal Processing*, Vol.22, pp. 721–734, ISSN 0888-3270

Ferrari, M.; Ferrari, V.; Guizzetti, M.; Marioli, D. & Taroni, A. (2008). Piezoelectric multifrequency energy converter for power harvesting in autonomous Microsystems, In: *Sensors Actuators A: Physical*, Vol.142, pp. 329–335, ISSN 0924-4247

Ferrari, M.; Ferrari, V.; Guizzetti, M.; Andò, B.; Baglio, S. and Trigona, C. (2009). Improved Energy Harvesting from Wideband Vibrations by Nonlinear Piezoelectric Converters, *Proceedings of Eurosensors XXIII*, Lausanne, Switzerland, September 6-9, 2009

Gieras, J. F.; Oh, J.-H.; Huzmezan, M. & Sane, H. S. (2007). *Electromechanical energy harvesting system*, Patent Publication Number: WO2007070022(A2), WO2007070022(A3)

Glynne-Jones, P.; Tudor, M. J.; Beeby, S. P. & White, N. M. (2004). An electromagnetic, vibration-powered generator for intelligent sensor systems, In: *Sensors and Actuators A: Physical*, Vol.110, pp. 344-349, ISSN 0924-4247

Goldschmidtboeing, F. & Woias, P. (2008). Characterization of different beam shapes for piezoelectric energy harvesting, In: *Journal of Micromachining and Microengineering*, Vol.18, 104013, ISSN 0960-1317

Granstrom, J.; Feenstra, J.; Sodano, H. A. & Farinholt, K. (2007). Energy harvesting from a backpack instrumented with piezoelectric shoulder straps, In: *Smart Materials and Structures*, Vol.16, pp. 1810-1820, ISSN 0964-1726

Hoffmann, D.; Folkmer, B. & Yiannos, M. (2009). Fabrication, characterization and modelling of electrostatic micro-generators, In: Journal of Micromechanics and Microengineering, Vol.19, No.9, 094001, ISSN: 0960-1317

Huesgen, T.; Woias, P. & Kockmann, N. (2008). Design and fabrication of MEMS thermoelectric generators with high temperature efficiency, In: *Sensors and Actuators A: Physical*, Vol.145-146, pp. 423-429, ISSN 0924-4247

Humdinger Wind Energy, LLC, http://www.humdingerwind.com/ (accessable on 13 May 2011).

Jungm, H.-J. & Lee, S.-W. (2011). The experimental validation of a new energy harvesting system based on the wake galloping phenomenon, In: *Smart Materials and Structures*, Vol.20, 055022 (10pp), ISSN 0964-1726

Kim, S.-H.; Ji, C.-H.; Galle, P.; Herrault, F.; Wu, X.; Lee, J.-H.; Choi, C.-A. & Allen, M. G. (2009). An electromagnetic energy scavenger from direct airflow, In: *Journal of Micromechanics and Microengineering*, Vol.19, 094010 (8pp), ISSN 0960-1317

Kok, S.-L.; White, N. M. & Harris, N.R. (2009). Fabrication and characterization of free-standing thick-film piezoelectric cantilevers for energy harvesting, In: Measurement Science and Technology, Vol.20, 124010, ISSN 0957-0233

Koukarenko, E.; Beeby, S. P.; Tudor, M. J.; White, N. M.; O'Donnell, T.; Saha, T.; Kulkani, S. & Roy, S. (2006). Microelectromechanical systems vibration powered electromagnetic generator for wireless sensor applications, In: *Microsystem Technologies*, Vol.12, No.11, pp 1071-1077, ISSN 0946-7076

Kymissis, J.; Kendall, C.; Paradiso, J. & Gershenfeld, N. (1998). Parasitic power harvesting in shoe, Digest of Papers. Second International Symposium on Wearable Computers, PP. 132-139, ISBN 0-8186-9074-7, Pittsburgh, Pennsylvania, USA, October 19-20, 1998

Leland, E. S. & Wright, P. K. (2006). Resonance tuning of piezoelectric vibration energy scavenging generators using compressive axial, In: *Smart Materials and Structures*, Vol.15, pp.1413-1420, ISSN 0964-1726

Li, S. & Lipson, H. (2009). Vertical-stalk flapping-leaf generator for wind energy harvesting, *Proceedings of the ASME 2009 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, Oxnard, California, USA, September 21-23, 2009

Li, S.; Yuan, J. & Lipson, H. (2011). Ambient wind energy harvesting using cross-flow fluttering, In: *Journal of Applied Physics*, Vol.109, 026104, ISSN 0021-8979

Liao, Y. & Sodano, H. A. (2008). Model of a Single Mode Energy Harvester and Properties for Optimal Power Generation, In: *Smart Materials and Structures*, Vol.17, 065026, ISSN 0964-1726

Liu, F.; Phipps, A.; Horowitz, S.; Ngo, K.; Cattafesta, L.; Nishida, T. & Sheplak, M. (2008). Acoustic energy harvesting using an electromechanical Helmholtz resonator, In: *Journal of Acoustical Society of America*, Vol.123, Vo.4, pp 1983-1990, ISSN: 0001-4966

Lo, H. & Tai, Y. C. (2008). Parylene-based electret power generators, In: *Journal of Micromachining and Microengineering*, Vol.18, 104006, ISSN: 0960-1317

Marzencki, M.; Ammar, Y; & Basrour, S. (2008). Integrated power harvesting system including a MEMS generator and a power management circuit, In: *Sensors and Actuators A: Physical*, Vol.145-146, pp. 363-370, ISSN 0924-4247

Matova, S. P.; Elfrink, R.; Vullers, R. J. M. & van Schaijk, R. (2010). Harvesting energy from airflow with micromachined piezoelectric harvester inside a Helmholtz resonator, *Proceedings of PowerMEMS 2010*, Leuven, Belgium, November 30 - December 3, 2010

MicroBelt tech sheet, http://www.humdingerwind.com/pdf/microBelt_brief.pdf (accessable on 13 May 2011)

Mitcheson, P.; Stark, B.; Miao, P.; Yeatman, E.; Holmes, A. & Green, T. (2003). Analysis and optimisation of MEMS on-chip power supply for self powering of slow moving sensors, *Proceedings of Eurosensors XVII Conference*, pp. 48-51, Guimaraes, Portugal, September 21-24, 2003

Nguyen, D. S. & Halvorsen, E. (2010). Analysis of vibration energy harvesters utilizing a variety of nonlinear springs, *Proceedings of PowerMEMS 2010*, Leuven, Belgium, November 30 - December 3, 2010

Norman, B. C. (2007). Power options for wireless sensor networks, In: *IEEE Aerospace and Electronic Systems Magazine*, Vol.22, No.4, pp. 14-17, ISSN 0885-8985

Peters, C.; Maurath, D.; Schock, W. & Manoli, Y. (2008). Novel electrically tunable mechanical resonator for energy harvesting, *Proceedings PowerMEMS 2008+ μEMS2008*, pp. 253-256, Sendai, Japan, November 9-12, 2008

Ramlan, R. (2009). Effects of non-linear stiffness on performance of an energy harvesting device, *PhD Thesis*, University of Southampton, UK

Renaud, M.; Karakaya, K.; Sterken T.; Fiorini P.; Vanhoof, C. & Puers R. (2008). Fabrication, Fabrication, modelling and characterization of MEMS piezoelectric vibration harvesters, In: *Sensors and Actuators A: Physical*, Vol.145-146, No.1, pp. 380-386, ISSN: 09244247

Peters, C.; Maurath, D.; Schock, W.; Mezger, F. & Manoli, Y. (2008). A closed-loop wide-range tunable mechanical resonator for energy harvesting systems, In: *Journal of Micromechanics and Microengineering*, Vol.19, No.9, 094004(9pp), ISSN 0960-1317

Rome, L. C.; Flynn, L. & Yoo, T. D. (2005) Generating electricity while walking with loads, *Science*, Vol.309, No.5741, (September 2005), pp. 1725-1728, ISSN 0036-8075

Romero, E.; Warrington, R. O. & Neuman, M. R. (2009). Energy scavenging sources for biomedical sensors, In: *Physiological Measurement*, Vol.30, pp. 35-62, ISSN 0967-3334

Roundy, S.; Wright, P. K. & Rabaey, J. (2003). A study of low level vibrations as a power source for wireless sensor nodes, In: *Computer Communications*, Vol.26, pp. 1131-1144, ISSN 0140-3664

Roundy, S. & Wright, P. K. (2004). A piezoelectric vibration based generator for wireless electronics, In: *Smart Materials and Structures*, Vol.13, pp. 1131-1142, ISSN 0964-1726

Roylance, L. & Angell, J. B. (1979). A batch fabricated silicon accelerometer, In: *IEEE Trans. Electron Devices*, Vol.26, pp. 1911–1917, ISSN 0018-9383

Saha, C. R.; O'Donnell, T.; Loder, H.; Beeby, S. P. & Tudor, M. J. (2006). Optimization of an electromagnetic energy harvesting device, In: IEEE Transactions on Magnetics, Vol.42, No.10, pp. 3509-3511, ISSN 0018-9464

Saha, C. R.; O'Donnell, T.; Wang, N. & McCloskey P. (2008). Electromagnetic generator for harvesting energy from human motion, In: *Sensors and Actuators A: Physical*, Vol.147, pp. 248–253, ISSN 0924-4247

Sanchez-Sanz, M.; Fernandez, B. & Velazquez, A. (2009). Energy-harvesting microresonator based on the forces generated by the Karman street around a rectangular prism, In: *Journal of Microelectromechanical Systems*, Vol.18, No.2, pp. 449-457, ISSN 1057-7157

Sari, I.; Balkan, T. & Kulah, H. (2007). A wideband electromagnetic micro power generator for wireless Microsystems, *Proceedings of International Solid-State Sensors, Actuators and Microsystems Conference 2007*, pp 275-278, Lyon, France, June 10-14, 2007

Shen, D.; Park, J.; Ajitsaria, J.; Choe, S.; Wikle, H. C. & Kim, D. (2008). The design, fabrication and evaluation of a MEMS PZT cantilever with an integrated Si proof mass for vibration energy harvesting, In: *Journal of Micromechanics and Microengineering*, Vol.18, No.5, 55017, ISSN 0960-1317

Spreemann, D.; Folkmer, B.; Maurath, D. & Manoli, Y. (2006). Tunable transducer for low frequency vibrational energy scavenging, *Proceedings of EurosensorsXX*, Göteborg, Sweden, September 17-20, 2006

St. Clair, D.; Bibo, A.; Sennakesavababu, V. R.; Daqaq, M. F. & Li, G. (2010). A scalable concept for micropower generation using flow-induced self-excited oscillations, In: *Journal of Applied Physics*, Vol.96, 144103, ISSN 0021-8979

Taylor, G. W.; Burns, J. R.; Kammann, S. M.; Powers, W. B. & Welsh, T. R. (2001). The energy harvesting eel: a small subsurface ocean/river power generator, In: *IEEE Journal of Oceanic Engineering*, Vol.26, No.4, pp. 539-547, ISSN 0364-9059

Torah, R. N.; Glynne-Jones, P.; Tudor, M. J.; ODonnell, T.; Roy S. & Beeby S. P. (2008). Self-powered autonomous wireless sensor node using vibration energy harvesting, In: *Measurement Science and Technology*, Vol.19, 125202, ISSN 0957-0233

Mann, B. P. & Owens, B. A. (2010). Investigations of a nonlinear energy harvester with a bistable potential well, In: *Journal of Sound and Vibration*, Vol.329, pp. 1215–1226, ISSN 0022-460X

von Buren, T. (2006) Body-Worn Inertial Electromagnetic Micro-Generators, *PhD Thesis*, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland

Wang, D.-A. & Chang, K.-H. (2010). Electromagnetic energy harvesting from flow induced vibration, In: *Microelectronics Journal*, Vol.41, pp. 356–364, ISSN 0026-2692

Wang, D.-A. & Ko, D.-A. (2010). Piezoelectric energy harvesting from flow-induced vibration, In: *Journal of Micromechanics and Microengineering*, Vol.20, 025019 (9pp), ISSN 0960-1317

Wang, D.-A. & Liu, N.-Z. (2011). A shear mode piezoelectric energy harvester based on a pressurized water flow, In: *Sensors and Actuators A: Physics*, Vol.167, No.2, pp. 449-458, ISSN 0924-4247

Wang, D.-A.; Pham, H.-T.; Chao, C.-W. & Chen, J. M. (2011). A piezoelectric energy harvester based on pressure fluctuations in Kármán Vortex Street, *Proceedings World Renewable Energy Congress 2011*, Linköping, Sweden, 8-11 May 2011

Wang, P.; Dai X.; Zhao X. & Ding G. (2009). A micro electromagnetic vibration energy harvester with sandwiched structure and air channel for high energy conversion efficiency, *Proceedings PowerMEMS 2009*, pp. 296-299, Washington DC, USA, December 1-4, 2009

Williams, C. B. & Yates, R. B. (1996) Analysis of a micro-electric generator for microsystems, In: *Sensors and Actuators A*, Vol.52, pp. 8-11, ISSN 0924-4247

Williams, C. B.; Shearwood, C.; Harradine, M. A.; Mellor, P. H.; Birch, T. S. & Yates, R. B. (2001). Development of an electromagnetic micro-generator, In: *IEE Proceedings of Circuits Devices Systems*, Vol.148, pp. 337-342, ISSN 1350 -2409

Wu, X.; Lin, J.; Kato, S.; Zhang, K.; Ren, T. & Liu, L. (2008). A frequency adjustable vibration energy harvester, *Proceedings of PowerMEMS 2008+ μEMS2008*, pp. 245-248, Sendai, Japan, November 9-12, 2008

Zhu, D.; Tudor, M. J. & Beeby, S. P. (2010). Strategies for increasing the operating frequency range of vibration energy harvesters: a review, In: *Measurement Science and Technology*, Vol.21, 022001(29pp), ISSN 0957-0233

Zhu, D.; Roberts, S.; Tudor, J. & Beeby, S. (2010). Design and experimental characterization of a tunable vibration-based electromagnetic micro-generator, In: *Sensors and Actuators A: Physical*, Vol.158, No.2, pp. 284-293, ISSN 0924-4247

Zhu, D.; Beeby, S.; Tudor, J.; White, N. & Harris, N. (2010). A novel miniature wind generator for wireless sensing applications, *Proceedings IEEE Sensors 2010*, ISBN 978-1-4244-8170-5, Waikoloa, Hawaii, USA, November 1-4, 2010

Zhu, D.; Almusallam, A.; Beeby, S.; Tudor, J. & Harris, N. (2010). A Bimorph Multi-layer Piezoelectric Vibration Energy Harvester, *Proceedings of PowerMEMS 2010*, Leuven, Belgium, December 1-3, 2010

Zhu, D. & Beeby, S. (2011). Kinetic energy harvesting, In: *Energy Harvesting Systems: Principles, Modeling and Applications*, pp. 1-78, Springer, ISBN 978-1-4419-7565-2, New York Dordrecht Heidelberg London

Zhu, D.; Beeby S.; Tudor J. and Harris N. (2011) A credit card sized self powered smart sensor node, In: *Sensors and Actuators A: Physical*, Vol.169, No.2 pp. 317-325, ISSN 0924-4247