Electromagnetic Energy Harvesting

8. Electromagnetic Energy Harvesting **3 Lectures**

(a) Linear generators, physics mathematical models, recent applications

(b) Carbon captured technologies, cell, batteries, power consumption.

(c) Environmental issues and Renewable sources of energy, sustainability.

Let us make it clear in the beginning that it is only the topic 8(a) that is related to *Electromagnetic Energy Harvesting* whereas the other two topics are not directly related to it and can be studied independently. To avoid confusion we shall study the topics 8(b) and 8(c) separately in different study materials.

Introduction

Electromagnetic generators have numerous applications from the large-scale generation of power to smaller scale applications in cars to recharge the battery. They can also be used to harvest micro- to milli-Watt levels of power using both rotational and linear devices. Provided a generator is correctly designed and not constrained in size, they can be extremely efficient converters of kinetic energy into electrical. Attempts to miniaturise the technique invariably reduce efficiency levels considerably.

Basic Principle

The basic principle on which all electromagnetic generators are based is the Faraday's law of electromagnetic induction. The principle says that the induced emf in a circuit is proportional to the time rate of change of the magnetic flux linked with the circuit.

$$V = -\frac{d\varphi}{dt} \qquad (1)$$

Here V is the generated voltage or induced emf and φ is the flux linkage. In most generator implementations, the circuit consists of a coil of wire of multiple turns and the magnetic field is created by permanent magnets. In such case, the voltage induced in an N turn coil is given by:

$$V = -\frac{d\Phi}{dt} = -N\frac{d\varphi}{dt} \qquad (2)$$

Here Φ is the total flux linkage of the N turn coil and can be approximated as $N\varphi$ and in this case φ can be interpreted as the average flux linkage per turn.

In most linear vibration generators the magnetic field is produced by a permanent magnet that has no time variation and the motion between the coil and the magnet is linear i.e. in a single direction, say x-direction. We restrict our following analysis to this case and the voltage induced in the coil can then be expressed as the product of a flux linkage gradient and the velocity.

$$V = -\frac{d\Phi}{dx}\frac{dx}{dt} = -N\frac{d\varphi}{dx}\frac{dx}{dt} \qquad (3)$$

When the coil terminals are connected with a load resistance, the induced current in the circuit will flow in such a direction so as to oppose motion that causes the change in flux linkage. The source of vibration in the environment of the generator will work against this opposing electromagnetic force F_{em} to convert mechanical energy in electrical energy. The mechanical power dissipated in the process may be calculated as

$$P_m = F_{em}\frac{dx}{dt} \quad (4)$$

The amount of power so dissipated will be equal to the electrical power extracted from the generator. If R_L and R_C are load and coil resistances respectively and L_C is the coil inductance then the power dissipation in the coil and load is given by

$$P_{em} = \frac{V^2}{R_L + R_c + j\omega L_c} \quad (5)$$

Equating P_m and P_{em} we can write

$$F_{em}\frac{dx}{dt} = \frac{V^2}{R_L + R_c + j\omega L_c} \quad (6)$$

Since F_{em} is proportional to induced current and hence induced emf, which in turn is proportional to the velocity, we can express F_{em} as the product of an electromagnetic damping D_{em} and the velocity.

$$F_{em} = D_{em}\frac{dx}{dt} \quad (7)$$

Use of equations (3) and (7) in equation (6) gives rise to the following expression for electromagnetic damping as

$$D_{em} = \frac{1}{R_L + R_c + j\omega L_c}\left(\frac{d\Phi}{dx}\right)^2 \quad (8)$$

In order to extract the maximum power in the form of electrical energy, an important goal for the design of a generator is the maximisation of the electromagnetic damping, D_{em}. We can see from Eq. (8) that the maximum damping can be achieved by maximising the flux linkage gradient and minimising the coil impedance.

The flux linkage gradient largely depends on

i) The magnets used to produce the field
ii) The arrangement of these magnets and
iii) The area and number of turns for the coil.

The properties of typical magnetic materials will be reviewed in the sections to come.

At the low frequencies generally encountered in ambient vibrations (typically less than 1 kHz), the coil impedance is generally dominated by the resistance. The magnitude of the coil resistance depends on the number of turns and the coil technology. Common technologies for coil fabrication are

i) Wire-winding and
ii) Micro-fabrication.

The characteristics of these coil technologies are discussed in the sections below.

Wire-Wound Coil Properties

A fundamental consideration in designing an electromagnetic energy harvester is the properties of the coil. The number of coil turns and the coil resistance are important parameters for determining the voltage and useful power developed by a generator. The number of turns is governed by the geometry of the coil, the diameter of the wire and the density with which the coil wire has been wound. Insulated wire of circular cross-section will not fill the coil volume entirely with conductive material and the percentage of copper within a coil is given by its *fill factor*. The copper fill factor depends on tightness of winding, variations in insulation thickness, and winding shape. Typically, the fill factor is an unknown value and has to be calculated. Ignoring insulation thickness the highest fill factors of up to 90% can be achieved.

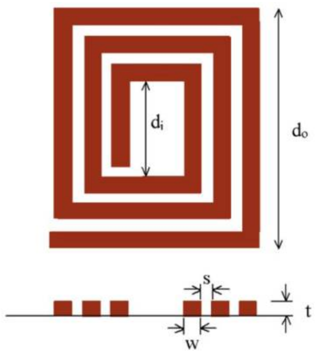
The type of wire used in the coil is clearly very important in defining the properties of the coil. In miniaturised electromagnetic energy harvesters, fine copper wire is desirable for minimising coil size while maximising the number of turns. The finer the wire the greater is resistance per unit length. Fine copper wire is typically insulated by thin polymer films. Different insulation materials offer different degrees of solvent resistance, operating temperature range and solder-ability.

The coil inductance can also be expressed as a function of the number of turns and the coil geometry. However, for a typical analysis, the inductance can be neglected as the resistive impedance of the coil is always significantly larger than the inductive impedance at frequencies less than 1 kHz. It can be shown that, for a constant number of turns, the coil resistance is proportional to the inverse of the coil dimension provided that the copper fill factor does not depend on the scaling. For a given dimension of the coil its resistance *depends on the square of the number of turns*.

Micro-Fabricated Coils

Micro-coils are are fabricated using photolithography techniques to define the coil pattern, most commonly on substrates such as silicon, flex substrates or printed circuit boards (PCBs). Such coils are used for a range of applications such as on-chip inductors, detection coils in sensors, or as a means of producing a magnetic field in actuators.

Micro-coils are fabricated by building up layers of planar coils, with each layer typically consisting of a square or a circular spiral coil. The technology which is used to fabricate the spiral coils generally limits the conductor thickness and the minimum spacing achievable between individual coil turns. Therefore, the minimum dimensions of the individual turn in the spiral will depend on the technology used for the fabrication.



For example, standard PCB technology may limit the spacing (S) between turns to greater than 150 μm for a thickness (*t*) of 35 μm, whereas a spacing (S) of 1–2 μm for a typical thickness (t) of 1 μm may be achievable for silicon-based micro-fabrication techniques. As a rough guide for silicon-based coil fabrication, the minimum spacing may be taken to be equal to the conductor thickness, although with more advanced techniques it is feasible to obtain aspect ratios of up to 10 between conductor thickness and minimum spacing.

For a single layer planar square spiral micro-fabricated coil (as shown in the figure) the coil resistance *depends on the cube of the number of turns*. This dependence of resistance on the cube of the number of turns proves to be the limiting factor for the use of micro-coils in vibration generators. The essential difference between the wire-wound coil and the micro-fabricated coil is that the wire winding is a 3D technology, whereas micro-fabrication is a 2D planar technology. If there existed a micro-fabrication technology, where the number of coil layers could be arbitrarily high, then the micro-fabricated coil resistance could approach *a dependence on the square of the number of turns*. However, in practice, micro-fabrication techniques are limited in the number of layers which can be practically achieved.

Magnetic Materials

The electromagnetic generators require magnetic fields. In case of small-scale low-power device the use of electromagnet is not suitable. The requirement in such devices is usually met by permanent magnets made from ferromagnetic or ferromagnetic materials.

The atoms of a ferromagnetic material exhibit a net magnetic moment. These atoms when grouped together in large numbers form magnetic domains. Within each domain the magnetic moments are aligned in a particular direction. In a block of the ferromagnetic material the domains are randomly aligned and hence there is no net magnetic field. When such material is magnetised, the domains become aligned in the same direction producing a strong magnetic field. Ferrimagnetic materials are subtly different to ferromagnetic in that they contain atoms with opposing magnetic moments. However, the magnitudes of these moments are unequal and hence a net magnetic field will exist. Ferrimagnetic materials are of interest since their electrical resistance is typically higher than ferromagnetic materials and therefore eddy current effects are reduced.

The magnetic field produced by a permanent magnet is typically denoted B and the magnetic field strength (and magnetising force) is denoted H. The terms B and H are linked by the equation $B = \mu H$. Here μ is the permeability of the magnetic material. A useful figure of merit for comparing magnetic materials is the *maximum energy product* BH_{max}, calculated from magnetic hysteresis loop of the materials. At this point in the loop, the volume of material required to deliver a given level of energy into its surroundings is a minimum. Another factor to be considered when comparing magnets is the Curie temperature. This is the maximum operating temperature the material can with withstand before the magnet becomes demagnetised.

Typically there are *four* types of magnet available: Alnico, ceramic (hard ferrite), samarium cobalt and neodymium iron boron. Each type is subdivided into a range of grades each with its own magnetic properties.

- **Alnico:** Stable with temperature and can be used in high-temperature applications (up to ~550 $\circ$C). It is inherently corrosion resistant and has a maximum energy product only surpassed by that of the rare earth magnets.
- **Ceramic** (hard ferrite): Low cost. Hard, brittle materials available in a range of compositions. The materials are mixed in powder form and then pressed and sintered to form the magnet geometries
- **Samarium cobalt**: Composed of materials from the lanthanide series within the rare earth group of elements. Exhibit much higher magnetic fields than Alnico or Ceramic materials. Good thermal stability, a maximum working temperature of around 300 $\circ$C and are inherently corrosion resistant. Fabricated using powder metallurgy processes.
- **Neodymium iron boron:** Composed of materials from the lanthanide series within the rare earth group of elements. Exhibit much higher magnetic fields than Alnico or Ceramic materials. Highest maximum energy product, Suffers from low-working temperatures and poor corrosion resistance. Fabricated using powder metallurgy processes.

The three most important properties of interest of magnet used in an inertial vibration energy harvesting application are: i) strength of the magnetic field, ii) the flux density and iii) the coercive force. The risk of corrosion or exposure to high temperature can be minimised easily by packaging the inertial energy harvester properly. Therefore, the strongest range of NdFeB magnets are the preferred option in the majority of cases since their use will maximise the magnetic field strength within a given volume. Also they have a high-coercive force and therefore the vibrations of the generator will not depole the magnets.

Scaling of Electromagnetic Vibration Generators

For vibration generators, it is of interest to understand how the power generated is related to the size of the generator and in particular in the case of the electromagnetic generator, how the power is limited by the interactions of the coils and magnets as the scale is reduced. In a vibration-powered generator, the available mechanical energy is associated with the movement of a mass through a certain distance, working against a damping force. Clearly, this will decrease with the dimensions as both the mass of the moving object and the distance moved is decreased. Generally, the damping force which controls the movement will consist of parasitic damping and electromagnetic damping. The electrical energy which can be usefully extracted from a generator depends on the electromagnetic damping, which as was shown earlier depends on flux linkage gradient, the number of coil turns, coil impedance and load impedance. These factors also depend on scale, so that typically as dimension decreases, the magnitude of the magnetic fields decrease and the quality of the coils decrease and hence the ability to extract electrical energy may be reduced.

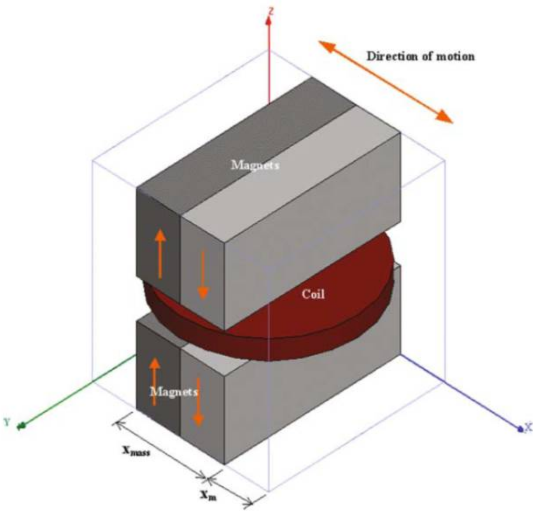


Fig. 2 Representation of the electromagnetic generator

In order to investigate how the power achievable from an EM generator scales with the dimension of the generator, an analysis is presented for an example electromagnetic generator structure shown in Fig. 2. This structure consists of a coil sandwiched between magnets, where the upper and lower magnets consist of two pairs, oppositely polarised. This opposite polarity creates a flux gradient for the coil in the direction of movement, which in this case, is in the *x*-direction.

The following assumptions are made in relation to the structure;

- The coil remains fixed while the magnets move in response to the vibration. Since the magnets generally have greater mass, *m*, than the coil, movement of the magnets is more beneficial than movement of the coil.
- A cubic volume, i.e. $x = y = z = d$ where *d* is the dimension of the device is assumed.
- Only the magnet and coil dimensions are included in the volume. Any practical generator must also include the volume of the housing and the spring. Since the housing and the spring can be implemented in many different ways, these are neglected for the present analysis. It is assumed that the spring can be implemented so as to allow the required movement of the mass at the frequency of interest.
- The movement of the mass in response to the vibrations is assumed to be sinusoidal and is well represented by the equations of motion for a mass–spring–damper system.

The frequency of the input vibrations is assumed to perfectly match the resonant frequency of the device.

For any practical device, the maximum displacement will be constrained by the volume, i.e. the peak displacement x_m is given by the difference between the external dimension *d* and the dimension of the mass x_{mass}. Therefore, a choice can be made to have a thin mass with a large displacement or a wide mass with a small displacement. In fact there exists an optimum ratio of peak displacement x_m to mass dimension x_{mass} which maximises the mechanical energy. The average power dissipated by the damping force of the mass is:

$$P_D = \frac{1}{T}\int_0^T F_D . U dt = \frac{(ma)^2}{2D} \quad (9)$$

However at resonance the damping, *D* controls the peak displacement, according to

$$x_m = \frac{ma}{D\omega} \quad (10)$$

So that the average power can be expressed as:

$$P_D = \frac{m.a.\ x_m\,\omega}{2} = \frac{\rho x_{mass}.\,y.\,z.\,(x - x_{mass})\omega}{4} \quad (11)$$

where in the second expression, the peak displacement of the mass is $x_m = (x - x_{mass})/2$, and the mass is expressed as the product of the density of the mass material ρ, and its dimensions, x_{mass}, y and z. Differentiating Eq. (11) with respect to x_m and equating to zero gives the optimum mass length for maximum power as:

$$x_{massopt} = \frac{x}{2} \quad (12)$$

From the point of view of the structure in Fig. 2, this implies that for a single magnet the *x*-dimension should be taken to be one-fourth of the overall dimension. These magnets are assumed to extend for the full *y*-dimension whereas along the *z*-dimension it is taken to be 0.4 times the overall dimension. This leaves the gap between the magnets as one-fifth of the overall dimension. The coil thickness is assumed to occupy half of the gap.

For the scaling analysis, it is assumed that as the dimension is reduced, all of the relative dimensions are retained. The scaling of the available power is then easy to calculate using Eq. (11). In order to do this, the total damping is set so as to limit the displacement to be within the volume.

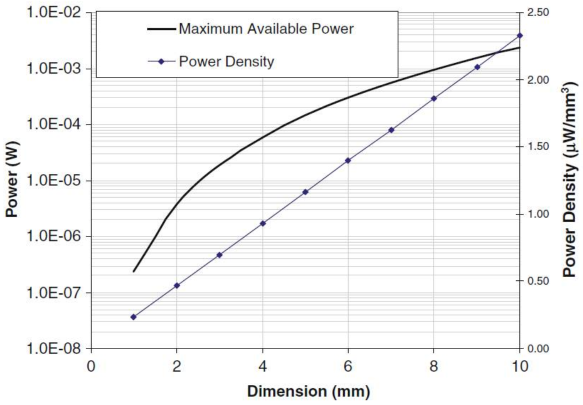


Fig. 3 plots an example of the scaling of the available power versus the dimension assuming a mass which is made from a sintered rare earth magnetic material, NdFeB, a vibration frequency of 100 Hz and a vibration acceleration level of $1 m/s^2$. This graph shows that the power available is proportional to the fourth power of the dimension, arising from the dependence on mass (proportional to cube of dimension) and displacement (proportional to dimension). The corresponding power density is linearly related to dimension.

The graph indicates a power density of approximately 2.3 μW/mm^3 (2.3mW/cm^3) for a device occupying a volume of 1 cm^3. It should be remembered that this analysis does not include the volume of the spring and housing, so that any real generators will necessarily have lower power densities. This graph represents simply the power dissipated by the damping force, but makes no assumption about how that damping force is achieved. Eq. (8) shows the magnitude of the electromagnetic damping depends on the magnet parameters and the coil parameters. The magnetic fields may decrease with dimension and the resistance of coils tends to increase. These effects place additional limits on the electrical power which can be achieved and are investigated in the following sections.

Scaling of Electromagnetic Damping

From the Eq. (8) the electromagnetic damping may be written as:

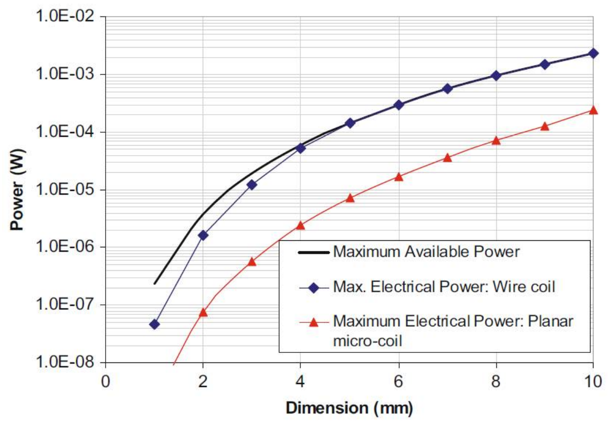
$$D_{em} = \frac{1}{R_L + R_c + j\omega L_c}\left(N\frac{d\varphi}{dx}\right)^2 \qquad (13)$$

This shows that the damping depends on the coil parameters and the flux linkage which both have a dependence on the dimension. The flux linkage depends on the gradient of the magnetic field and the area of the coil. Because the dimension of the gap between the magnets scales with the dimension of the magnets, the magnitude of the *B* field remains constant with scale reduction and hence the gradient of the field would actually increase. However, for a vibration generator, the parameter of importance is the gradient of the flux linkage with the coil, which of course depends on the area of the coil. Therefore, even though the flux density gradient is inversely proportional to dimension, the area of the coil will be proportional to the square of the dimension and hence the overall effect is for the flux linkage gradient to be directly proportional to dimension.

The coil parameters such as number of turns, resistance and inductance are not independent. For a fixed coil volume, the coil resistance and inductance depends on the number of turns. In the earlier section we have seen, the resistance of the wire-wound coil depends on the square of the number of turns assuming that the fill factor is constant. Whereas the resistance for a single layer micro-fabricated coil depends on the cube of the number of turns. From Eq. (13) one may therefore conclude that in the case of the wire-wound coil, the electromagnetic damping is independent of the number of turns but in the case of the micro-coil, the electromagnetic damping is inversely proportional to the number of turns.

It can be shown that for both kinds of coil with a constant number of turns, the coil resistance is proportional to the inverse of the scaling factor. Now considering that the flux linkage gradient is directly proportional to the dimension, and the coil resistance is inversely proportional to the dimension (for fixed *N*), it can be seen that the electromagnetic damping is proportional to the square of the dimension. Moreover, the analysis shows that the decrease in electromagnetic damping with scale cannot be compensated by increasing the number of turns. This is because for a wire wound coil the effect of any increase in the number of turns on EM damping is directly cancelled by an increase in coil resistance. For a planar micro-coil, the situation is worse as for this case, the effect of any increase in the number of turns results in a greater increase in the coil resistance, resulting in an overall decrease in damping. Thus, for a planar micro-coil, the highest EM damping would be achieved for a single turn coil.

It should, however, be noted that the voltage generated always depends directly on the number of turns, so that from a practical point of view a high number of turns may be required in order to obtain an adequate output voltage. For planar micro-coil implementations, this forces a design compromise between achieving high-EM damping and high voltage.



In an illustrative example, Fig. 4 shows significant difference between the power which can be extracted using the different coil technologies. Notice that in the case of the wire-wound coil technology, the fraction of the damping that can be supplied by EM damping decreases with dimension. Hence at smaller dimensions the electrical power is less than the available power. In the case of the micro-coil only a fraction of damping can be supplied by the EM damping at all dimensions.

Conclusions

Electromagnetic power generation is an established technology and the use of this transduction mechanism in small-scale energy harvesting applications is well researched. It is clear from the fundamental principles, and from the analysis of generators tested to date, that electromagnetic devices do not favourably scale down in size. Future applications for micro-scale vibration energy harvesters will be best served by piezoelectric and electrostatic transduction mechanisms that can more easily be realised using MEMS technology. However, where size is not a constraint and conventional discrete coils and magnets can be employed, electromagnetic generators provide the highest levels of performance achievable to date. Electromagnetic energy conversion relies only on relative velocity and change in magnetic flux to generate electricity and therefore an electromagnetic device will not be limited in amplitude by the fatigue strength of, for example, piezoelectric materials. In an electromagnetic generator, the design of the spring element can be chosen purely on the basis of the best spring material and will not be compromised by the inferior spring properties of a piezoelectric material. The high level of electromagnetic damping achievable also means these devices demonstrate the broadest frequency bandwidth over which energy can be harvested compared with other transduction mechanisms.

Bibliography

The content of this study material is taken from the book: