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Location Dependence of a MEMS Electromagnetic Transducer with respect to an AC Power Source

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Abstract. A MEMS, silicon based device with a piezoelectric layer and an integrated magnet is presented for magnetic to electrical transduction. The cantilever structure can be configured either as an energy harvester to harvest power from an AC power line or as an AC current sensor. The positioning of the transducer with respect to the AC conductor is critical in both scenarios. For the energy scavenger, correct positioning is required to optimize the harvested power. For the current sensor, it is necessary to optimise the sensitivity of the sensor. This paper considers the effect of the relative position of the transducer with respect to the wire on the resulting electromagnetic forces and torques driving the device. It is shown here that the magnetic torque acting on a cantilever beam with an integrated magnet and in the vicinity of an alternating electromagnetic field is a very significant driver of the cantilever oscillations.

1. Introduction

A major challenge to vibration based energy harvesting systems is achieving alignment in terms of resonance frequency between the source and the transducer. On the one hand, the inherently narrow bandwidth of the mechanical transducer makes matching to the source problematic. On the other hand, the stability of the source excitation can be unreliable and the amplitude very low. In the harvester application targeted here, the energy source is the AC electromagnetic field surrounding a current carrying mains conductor. The source signal frequency is therefore defined by the mains supply (50 Hz in Europe) and cannot, by regulation, deviate by more than $\pm 1\%$ [1]. In reality, the deviation is typically much less than that (<0.1 Hz). The stability of the vibration source means that energy harvested from an AC power cord is a truly viable source of power for wireless sensor nodes. In an extended application, the resonating harvester structure can act both as a energy source and as a proximity current sensor. For wireless sensor nodes with limited energy budget, the advantage of a passive AC current sensor is self-evident.

The positioning of the MEMS electromagnetic transducer is critical in both the harvester and sensor applications, as it defines the forces and torques acting on the cantilever magnet and thereby indirectly determines the power available for harvesting and/or sensitivity of the sensor. This paper presents the theory describing the driving forces and torques that act on a magnet in an alternating electromagnetic field. This effect has been studied for energy harvesting [2, 3] and for current sensing applications [4, 5, 6]. In prior work however, only the vertical force exerted by the field on the harvester was taken into account. In reality, the harvester is driven by a combination of torque components and the omission, in particular, of the magnetic torque


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in the these studies has rendered them inaccurate. In this work, all of the torque components driving the harvester are considered and the effect of their omission considered.

2. Theoretical Background

Consider a piezoelectric cantilever-type harvester, oriented such that the width of the beam runs parallel to a conductor carrying an alternating current. The axis of the wire is designated the z-axis. The beam length is aligned with the x-axis and its thickness with the y-axis as shown in Figure 1. In its first resonance mode, the cantilever will experience a maximum displacement in the y-direction at its tip. A permanent magnet, magnetized along the y-axis, and positioned near the cantilever tip will experience alternating electromagnetic forces that will cause the cantilever to oscillate with the same frequency as that of the AC signal in the wire. If the cantilever is designed such that this frequency matches its natural resonance, then mechanical amplification of the electromagnetic response will occur. A piezoelectric film disposed on the beam can then be used to convert the mechanical oscillations into an electrical output signal either for harvesting and/or sensing.

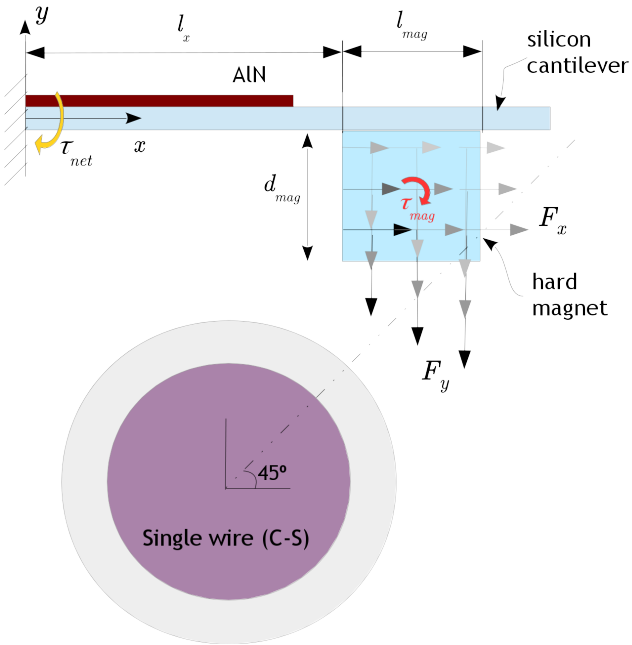


Figure 1. Schematic showing the lateral and vertical forces acting on a cantilever magnet that is in close proximity to a current carrying conductor.

Figure 1 shows the x-axis and y-axis forces that act on a magnet positioned on a cantilever beam and in close proximity to a magnetic field source. If it is considered that it is torque rather than force that drives the electromagnetic transducer then it is the net torque acting at the beam anchor, τ_{net}, that is of interest when determining the cantilever response. τ_{net} is given by Equation 1

$$\boldsymbol{\tau}_{net} = \boldsymbol{\tau}(F_x) + \boldsymbol{\tau}(F_y) + \boldsymbol{\tau}_{mag} \tag{1}$$

where $\boldsymbol{\tau}(F_x)$ is the torque at the beam anchor resulting from the lateral magnetic force F_x; $\boldsymbol{\tau}(F_y)$ is the torque resulting from the vertical magnetic force F_y; and $\boldsymbol{\tau}_{mag}$ is the magnetic torque on a magnet in an electromagnetic field. Note that while the magnetic torque, $\boldsymbol{\tau}_{mag}$, acts through the center of the magnet, in a stiff beam it results in a moment about the anchor equal in magnitude to the moment about the magnet centre.

Prior work in this area analysed the response of the beam to the vertical force component, F_y, only. The contribution of the lateral force, F_x, was considered negligible and for thin magnets, this is indeed the case. The contribution of the magnetic torque, $\boldsymbol{\tau}_{mag}$, has not been considered at all previously and this omission is non-negligible. In the following, each of these torque components in Equation 5 is individually addressed and their impact on the mechanical response of the cantilever determined.

The net force on a magnetic dipole moment, $\boldsymbol{F_p}$, is given by Equation 2 [7].

$$\boldsymbol{F_p} = (\boldsymbol{p}\cdot\nabla)\boldsymbol{B} = \nabla(\boldsymbol{p}\cdot\boldsymbol{B}) \tag{2}$$

where $\boldsymbol{p}$ is the dipole moment and $\boldsymbol{B}$ is the magnetic field vector. A permanent magnet with magnetisation, $\boldsymbol{M}$, can be considered to have an associated dipole moment, $\boldsymbol{p_M}$, where $\boldsymbol{p}_M = \int \boldsymbol{M}dV$ and so the the total force on a permanent magnet in an electromagnetic field can be expressed by Equation 2 with $\boldsymbol{p} \rightarrow \boldsymbol{p}_M$.

$$\boldsymbol{F_{mag}} = \int_V \nabla\,(\boldsymbol{M}\cdot\boldsymbol{B})dV = \int_V \left[\boldsymbol{M}\cdot\frac{\partial\boldsymbol{B}}{\partial x}\right]\hat{\boldsymbol{i}} + \left[\boldsymbol{M}\cdot\frac{\partial\boldsymbol{B}}{\partial y}\right]\hat{\boldsymbol{j}} + \left[\boldsymbol{M}\cdot\frac{\partial\boldsymbol{B}}{\partial z}\right]\hat{\boldsymbol{k}}\;dV \tag{3}$$

If the source of the electromagnetic field is a very long, current carrying conductor aligned with the z-axis, then the magnitude of the field at any point has a spatial dependence only on r, the radial distance between the wire and the point, where $\boldsymbol{r} = x\boldsymbol{i} + y\boldsymbol{j}$. If we further assume that our magnet is magnetized in the y-direction only, Equation 3 reduces to

$$\boldsymbol{F_{mag}} = F_x\boldsymbol{i} + F_y\boldsymbol{j} = \int_V \left[M_y\frac{\partial B_y}{\partial x}\right]\boldsymbol{i} + \left[M_y\frac{\partial B_y}{\partial y}\right]\boldsymbol{j}\;dV \tag{4}$$

It is clear from Equation 4 that the magnet experiences force contributions in both the lateral and the vertical directions. These forces, F_x and F_y are proportional to the gradient of the y-component of the magnetic field, B_y, with respect to their respective axes. The absolute value of $\partial B_y/\partial y$ is shown in a contour log plot in Figure 2. The circular area in the centre, shown by a block yellow colour, represents the wire in which the field is constant. A plot of $\partial B_y/\partial x$ is the same as the plot of $\partial B_y/\partial y$ but rotated by 45°.

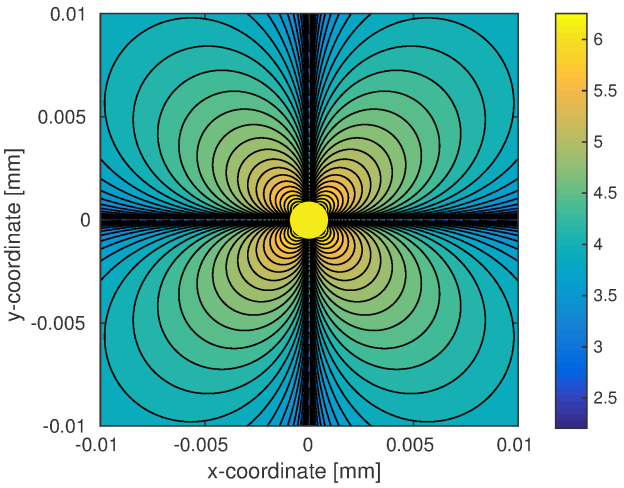


Figure 2. Contour plot showing the absolute value of the gradient with respect to y of the y-component of the $\boldsymbol{B}$ field.

From Figure 2, it appears that in order to optimize the vertical component of the magnetic force, the magnet should be positioned at 45° to the wire and indeed, this is the conclusion drawn by several authors who have considered this problem [3]-[6]. The x-component of the force acting on the magnet, F_x, is in most instances justifiably neglected since, although both F_y and F_x contribute to the total torque $\boldsymbol{\tau}_{net}$ at the beam anchor, the contribution resulting from the axial force component, $\boldsymbol{\tau}(F_x)$, will typically be much smaller than that from vertical force component, $\boldsymbol{\tau}(F_y)$, except where a very thick magnet is used and/or the magnet is positioned very close to the beam anchor.

The force described by Equation 4 is the force on a magnet in a non-uniform electromagnetic field. There are, however, an additional set of forces acting on the magnet that are not accounted for by Equation 4 and that act to rotate the magnet into the field generated by the wire. The torque resulting from these forces acts about the center of the magnet and is given by Equation 5.

$$\boldsymbol{\tau}_{mag} = \int_v \boldsymbol{M} \times \boldsymbol{B}\, dV \tag{5}$$

As with the lateral forces generated by the gradient of the field, the torque $\boldsymbol{\tau}_{mag}$ acts over the thickness of the magnet and its effect is therefore more prominent in thicker magnets. The magnitude of $\boldsymbol{\tau}_{mag}$ is much greater than $\boldsymbol{\tau}(F_x)$ however, and so even for relatively thin magnets, it cannot be omitted from calculations.

3. Results

Figure 3 plots the three torque components versus magnet thickness for a 1 mm square magnet positioned mid-way along the length of an 8 mm long cantilever beam. The cantilever thickness is 25 μm. It can be seen from the figure that $\boldsymbol{\tau}(F_x)$ is much less than $\boldsymbol{\tau}(F_y)$ and that, for a magnet less than 1 mm thick, can be justifiably neglected. The field-aligning magnetic torque component, $\boldsymbol{\tau}_{mag}$, however, is comparable in magnitude to $\boldsymbol{\tau}(F_y)$ and in fact, for a magnet thickness of approximately 2.5 mm, begins to dominate it.

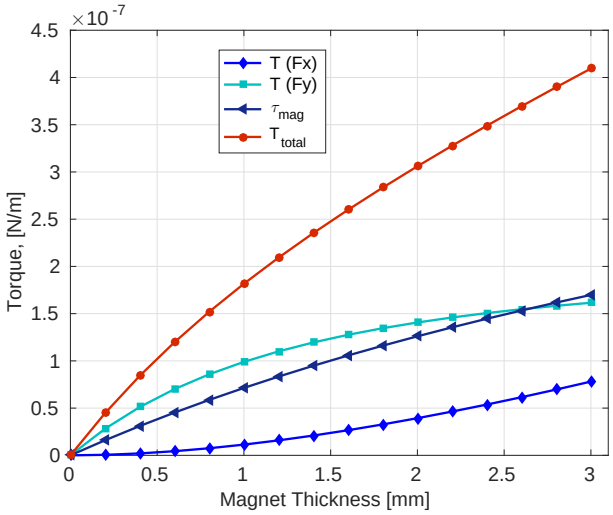


Figure 3. Plot of the three torque components acting at the beam anchor versus the magnet thickness. The cantilever was assumed to be 25 μm thick and 8 mm long. The magnet is a 1 mm x 1 mm square magnet. The net torque acting on the cantilever is shown by T_{total}.

Each of the three individual torque components that contribute to the displacement of the cantilever have a spatial dependence and their respective magnitudes varies as the magnet is

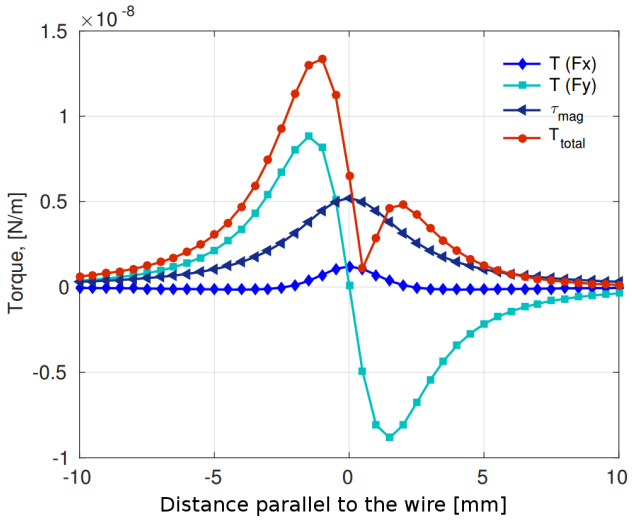


Figure 4. Torque generated at the anchor of a 8 mm long and 25 μm thick cantilever based harvester with 1 mm cube magnet located mid-way along the beam. A current of 1 A was used for the calculation and a gap of 2 mm between the magnet and the wire was assumed.

moved horizontally above the wire. Figure 4 plots $\boldsymbol{\tau}(F_x)$, $\boldsymbol{\tau}(F_y)$ and $\boldsymbol{\tau}_{mag}$ as the cantilever with its integrated magnet is passed over the current carrying conductor. The vertical component of the magnetic force is zero directly above the wire and increases to its maximum value as the magnet approaches the 45° axes, as indicated in Figure 2. The direction of the vertical force switches as the magnet passes the 90° line. By comparison, the horizontal component of the force and the magnetic torque are both at a maximum when the magnet is directly above the wire and the direction of these stays the same as the magnet passes over the wire. The result shows that, contrary to the conclusion drawn by Leland et al. [8, 4], positioning the magnet at 45° to the wire is not optimal in terms of maximizing displacement, nor indeed does locating it directly above the wire minimize displacement. The best location for the transducer will depend on the magnet dimensions and on its position on the cantilever.

4. Conclusions

The location dependence of an electromagnetic transducer with respect to its source, an AC power line, is analysed. The transducer is a silicon based MEMS cantilever with an integrated piezoelectric layer and with a permanent magnet disposed along its length. Placed in proximity to an AC current source, the cantilever oscillates with a frequency equal to that of the source and an electrical signal is generated across the piezoelectric capacitor. The position of the transducer with respect to the AC conductor is optimised here in order to maximise the tip displacement of the cantilever and consequently, the electrical output signal. Compared with previous work, where only the vertical component of the electromagnetic force is considered, here the horizontal component of the force is also considered as is the magnetic torque. It is found in particular, that the latter is a very significant driver of the cantilever oscillations and cannot be neglected for thick magnets.

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