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Magnetic tuning of a kinetic energy harvester using variable reluctance

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ABSTRACT

In this paper we present a new technique for tuning the resonant frequency of an energy harvester using a variable reluctance device which changes the strain in a cantilever beam to alter its spring constant. In order for energy harvesting devices to be able to operate reliably in many applications they must be able to generate energy as the input excitation frequency changes. Most harvesters are resonantly tuned mass-spring-damper devices and therefore it is important that their resonant frequency is tuneable during operation. Several mechanical methods have previously been demonstrated for accomplishing this task which operates by altering the stress in a cantilever beam by altering the distance between a fixed tuning magnet and a magnet on the moving cantilever. Here, we demonstrate a new actuation method for manipulating the stress in a beam. The actuation mechanism alters the magnetic reluctance between the cantilever mounted and the fixed magnet. The investigation has highlighted the importance of the design of the magnetic circuit and choice of materials in order to avoid eddy current damping and asymmetrical forces. The method presented here has demonstrated a maximum tunable frequency range of 11.1 Hz and may be more suitable for microfabrication than the previously reported techniques due to the reduced tuning force which makes microfabricated actuators feasible.

1. Introduction

Harvesting electrical energy from ambient vibrations remains the subject of considerable research interest [1,2]. Energy harvesting can provide a local power supply for autonomous wireless systems provided sufficient energy can be obtained from the range of vibrations present in the application environment. The majority of vibration energy harvesters are inertial systems based upon a spring-mass-damper with a characteristic resonant frequency that should be chosen to match a vibration frequency present in the application. This approach works well for any application where the excitation frequency is constant. For example, electrical machines supplied by mains electricity will typically exhibit vibrations at 50 and 100 Hz (or 60 and 120 Hz in the US) and demonstrate only small variations. However, in many applications the frequency of the environmental vibrations will change, for example in variable speed motors or in aeronautical applications where the mass of the fuel can affect characteristic frequencies in the airframe. In such applications it is desirable to have an adaptive harvester that can vary its frequency and track any changes that occur or a harvester that has a wide operational frequency range. Several techniques for achieving this have been demonstrated and are described in a review article by Zhu et al. [3]. Some typical solutions include mechanically tuning the resonant frequency of the energy harvester [4,5], electrically tune the resonant frequency of the energy harvester [6,7], using a nonlinear energy harvester [8,9] and using a bistable energy harvester [10,11].

This paper presents a new magnetic tuning mechanism which operates in the mechanical domain by modifying the effective spring constant of the system. Some of the previous work on altering the spring constant has used the attractive forces between two magnets [4,12] one was placed on the moving cantilever and the other was attached to an actuator which allowed the gap between the magnets to be adjusted. The magnetic force varies with the gap distance and this affects the tensile strain in the cantilever and therefore the resonant frequency. The new magnetic flux guide tuning mechanism presented here is a variation of this approach which may be more suitable for microfabrication. In this case, to affect changes in the magnetic tuning force, the position of a magnetically permeable moveable flux guide placed between the two tuning magnets is varied. This alters the amount of flux that flows between one tuning magnet and the other thereby altering the force between them. This in turn alters the tensile strain in the beam and hence the resonant frequency of the harvester. The concept is illustrated in Fig. 1. There are two ways in which the amount of flux from the fixed tuning magnet that reaches the magnet on the cantilever can be changed: either the reluctance between the two magnets can be modified directly (Fig. 1a) or the reluctance in the magnetic circuit between each end of the stationary magnet can be altered (Fig. 1b). In the first case, the reluctance path between the fixed

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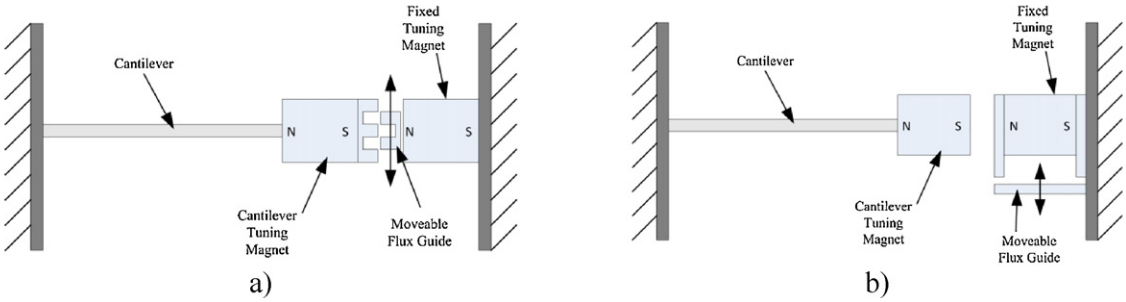
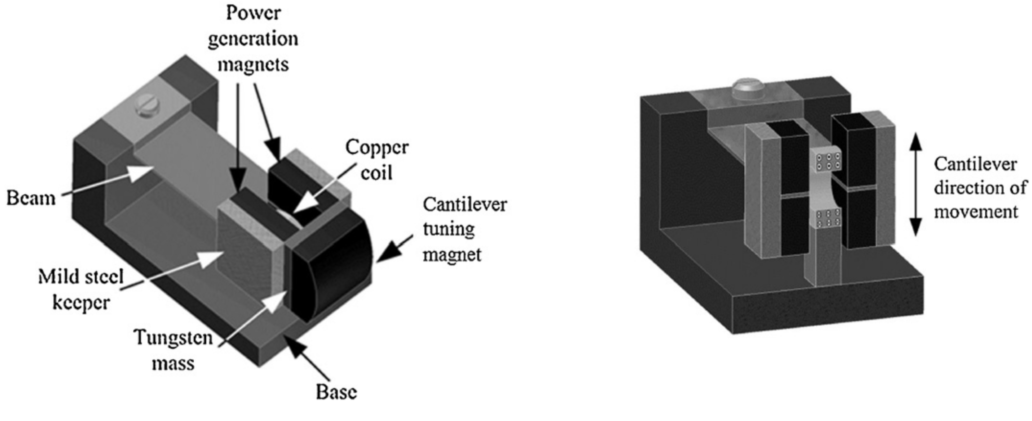


Fig. 1. Two possible configurations of harvester tuning mechanism with variable reluctance links.



a. Setup

b. Cross section view

Fig. 2. Tunable electromagnetic energy harvester.

and cantilever magnets is reduced through action of the flux guide located between them, meaning more flux from the fixed magnet flows to the cantilever magnet, increasing the resonant frequency of the beam. In the second case, the reluctance path between the poles of the stationary magnetic is reduced, pulling flux away from the cantilever magnet and reducing the resonant frequency of the beam. A practical solution to the moveable flux guide may exhibit both types of behaviour, depending on the exact geometry of the flux guide and its relative position with respect to the cantilever and fixed magnets.

This paper presents practical and simulation results from a comprehensive investigation into the variable reluctance tuning mechanism represented by the configurations shown in Fig. 1. Section 2 briefly describes the cantilever based energy harvester and Section 3 presents the simple case where a ferrite element (the flux guide) is positioned in a way that corresponds to Fig. 1b. Section 4 draws upon the results from the previous section and describes an improved system with increased tuning performance. Section 5 presents a different configuration where the flux guide is adjusted in a way corresponding to a hybrid behaviour between Fig. 1a and b. Section 6 discusses the results from experimental tests.

2. Energy harvester

The harvester used for testing the reluctance tuning device is of the electromagnetic type and follows the design presented in [13] with the addition of a tuning magnet fixed at the free end of the cantilever [4,14] as shown in Fig. 2. In this design, the power generation magnets are mounted on the cantilever beam and the coil is stationary relative to the generator frame. The beam is 0.14 mm thick, 14 mm long and 5 mm wide with a 2 mm × 5 mm slot at the free end to accommodate the coil. The magnetic circuit consists of four magnets, each of 1.5 mm × 3 mm × 5 mm, bonded to the top and bottom surfaces of the beam with two mild steel keepers for back iron. Tungsten is added to increase the mass of the harvester and the magnetic poles are aligned to maximise the magnetic flux through the stationary coil. The coil is attached to the base and centred between the magnets as shown in the cross section view in Fig. 2b. An additional tuning magnet is bonded to the tip end of the beam which is used in tuning the harvester, as shown in Fig. 2a. Table 1 summarises the materials and characteristics of the different components used in the harvester. All magnets, mild steel keepers and additional tungsten mass are glued to the beam with cyanoacrylate.

This harvester has been designed to operate at low frequencies (around 50 Hz) and low acceleration levels (around 0.6 m s^{-2} RMS) and occupies a total volume of 1120 mm^3, excluding the components associated with the tuning mechanism. The coil has an outer diameter of 4.9 mm, inner diameter of 1 mm and thickness of 1.3 mm. Three different coils were used during testing, two using 16 μm wire and one constructed from 25 μm wire giving 6000 and 2850 turns respectively. These coils result in different voltage output levels but, as expected, the power generated in the optimum load is comparable.

Table 1
Harvester components.

Component	Material
Magnet	NdFeB (flux density = 1.22 T)
Mass	Tungsten alloy
Keeper	Mild steel
Beam	BeCu
Base	Tecatron GF40
Coil	Copper

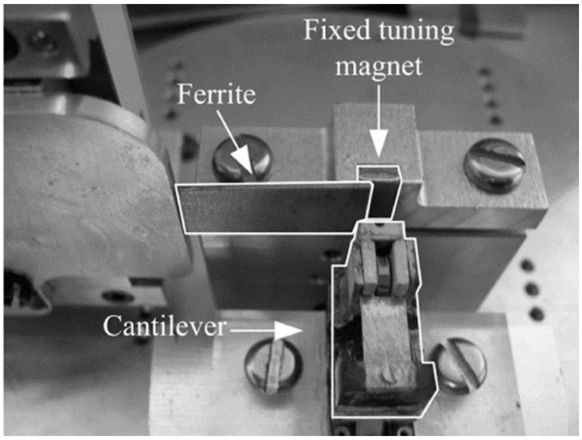


Fig. 3. First design of variable reluctance device using ferrite.

3. Design 1: magnetic tuning using a flux guide

The principle of the variable reluctance tuning approach is to affect changes in the magnetic tuning force by varying the position of a moveable magnetically permeable material which alters the amount of flux that flows between the stationary tuning magnet and the tuning magnet on the cantilever. The distance between the tuning magnets is fixed and the force between the two magnets depends upon the position of the flux guide. The variable gap tuning mechanism from [12] was modified so that both magnets remain at a constant separation, and a piece of ferrite with dimensions 30 mm × 15 mm × 1.5 mm slides between the tuning magnets as shown in Fig. 3. The fixed tuning magnet is 10 mm × 5 mm × 2 mm and has a flux density of 1.22 T. The ferrite was mounted on a single axis translation stage attached to a manual micrometre to allow it to slide in and out between the two tuning magnets. Note that in this case the moveable ferrite is able to modify the reluctance between both the fixed and stationary magnets as shown in Fig. 1a and between the north and south poles of the fixed tuning magnet as shown in Fig. 1b. Whether the behaviour of the system corresponds to one configuration or the other depends on the relative changes that can be made to the reluctance of each flux path. In this case, the flux guide acts more like the configuration of Fig. 1b and therefore the further the ferrite was moved out of the gap the more flux from the fixed tuning magnet reaches the cantilever magnet. This increases the effective stiffness of the beam, and thus the resonant frequency of the beam.

The amplitude of the cantilever's free end and the power generated were measured at different values of driving frequency for several different positions of insertion of the ferrite material into the gap. During the tests the system was excited with a constant value of RMS acceleration of $0.588\,\mathrm{m\,s^{-2}}$ (or 0.6 g where $1\,\mathrm{g} = 9.81\,\mathrm{m\,s^{-2}}$) and the harvester was connected to an optimal value of resistive load. Power was calculated based on the measured load voltage.

The power generated by a vibration-driven harvester operating without a constraint on the mass displacement, as was the case here, is proportional to A^2/ω, where A and ω are the magnitude and angular frequency of the driving acceleration respectively. Consequently, to allow fair comparison of output power of the generator being operated at different resonant frequencies, the measured power values are normalised to A^2/ω.

The relative position of the ferrite flux guide in the air gap is referred to as the tuning gap, T_g, as indicated on Fig. 4. The ferrite's initial position corresponds to a 0 mm tuning gap (fully inserted). In this position the fixed tuning magnet is fully covered by the ferrite as shown in Fig. 4a. The tuning gap can be adjusted from 0 to 9 mm, with partial removal of the flux guide shown in Fig. 4b where T_g is around 2 mm. The distance between the fixed and cantilever tuning magnets is called the magnet separation (M_s) is also shown in Fig. 4. In Fig. 4, the direction of movement of the harvester when excited is in the Z-plane, whilst the ferrite adjustment occurs in the Y direction.

3.1. Resonant frequency and power generation

During testing M_s was set at three different values: 4, 3 and 2 mm and the resonant frequency in each case, with the ferrite flux guide completely removed, was found to be 63.6, 69.6 and 78.1 Hz, respectively.

The ferrite was inserted and the tuning gap adjusted from 0 to 9 mm. The resonant frequency change and the resulting normalised power generated at resonance are shown in Fig. 5 and summarised in Table 2. There is a small change in resonant frequency when the tuning gap varies from 0 to 4 mm but as the tuning gap varies from 4 to 9 mm a larger increase in the resonant frequency is observed. For example, for a magnet separation of 2 mm the frequency changes by

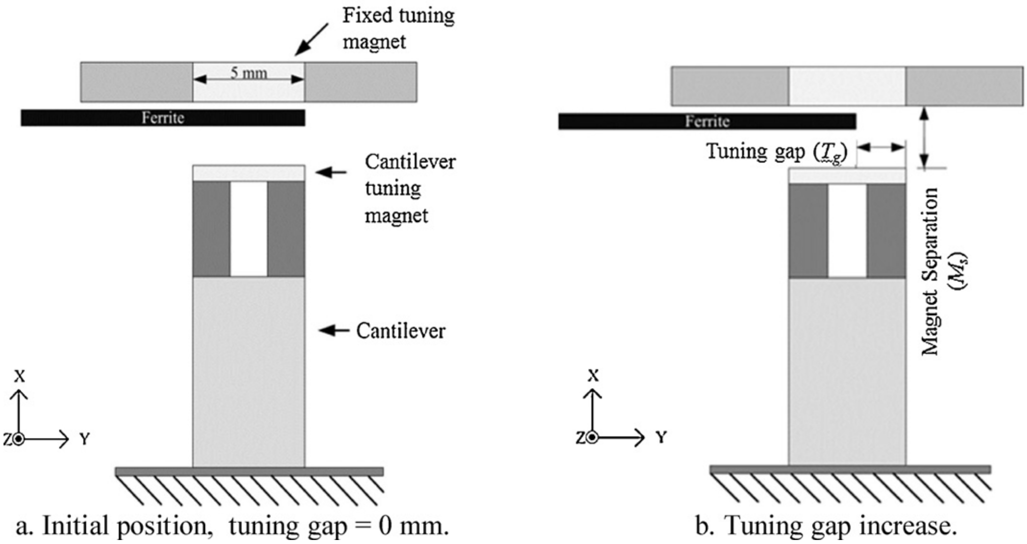


Fig. 4. Top view of electromagnetic tuning mechanism with ferrite.

Table 2
Resonant tuning range and power generation for the 1st design.

Distance between tuning magnets (mm)	Resonant frequency without ferrite (Hz)	Resonance frequency range using ferrite (Hz)	Maximum power (μW)	Maximum normalised power ($\mathrm{W\,s^3\,m^{-2}}$)
4	63.60	49.80–60.90	166.20	0.184
3	69.60	52.00–66.25	144.55	0.174
2	78.10	60.50–75.10	118.78	0.162

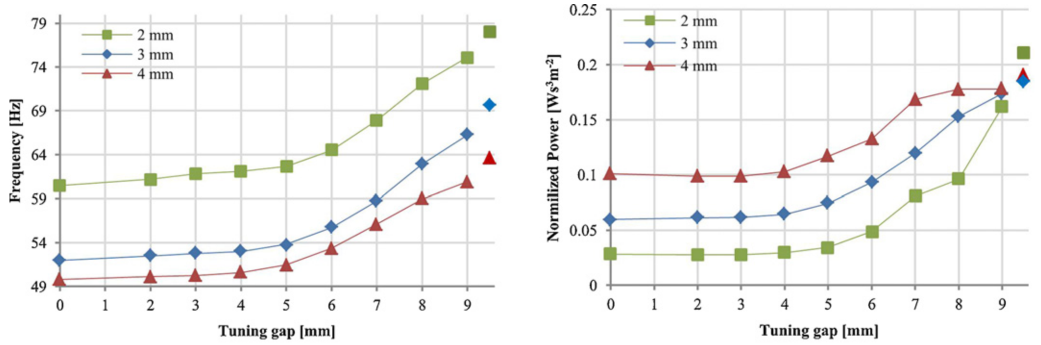
1.6 Hz from 0 to 4 mm and by 13 Hz from 4 to 9 mm. The 5 to 9 mm tuning gap is therefore the most practical range since it produces the largest change in frequency for the smallest displacement of the flux guide. The normalised power generated at resonance also increases with increasing tuning gap, finally reaching a value similar to the case where the ferrite has been completely removed. This indicates that the level of parasitic damping reduces as the moveable flux guide is withdrawn. Furthermore, as the magnet tuning distance reduces, the power generated falls from 165 μW for a 4 mm tuning distance to 65 μW for a 2 mm tuning distance, which indicates the parasitic damping increases as the tuning magnets get closer. The parasitic mechanical damping is dominated by eddy currents being formed in the moveable ferrite. The cantilever tuning magnet is moving relative to the static ferrite resulting in the formation of eddy currents which have a drag effect on the motion of the cantilever. The smaller the tuning gap and the shorter the distance M_S, the more pronounced the drag effect is. This effect can be clearly seen in Fig. 6 where the average Q-factor falls from 304 at 4 mm to 185 at 2 mm and can also be seen from the reduction in normalised power in Fig. 5b. The reduction in parasitic damping with increasing tuning gap is itself non-monotonic, leading to a non-monotonic curve in Fig. 5b. Another potential damping mechanism is the asymmetrical magnetic forces on the cantilever beam. The asymmetrical nature of the flux path results in an uneven flux distribution which produces a torsional moment on the cantilever that may also have a damping effect. The torsional moment from this simple flux guide arrangement also caused the power generation magnets on the harvester (Fig. 2) to collide with the coils and eventually cause the coil to break.

4. Design 2: magnetic tuning with improved flux concentration

A second design was therefore investigated in order to provide a more even distribution of the air gap flux, thereby producing a more symmetrical tensile tuning force and preventing damage to the coil. This was achieved by incorporating a mild steel block situated 1 mm from the fixed tuning magnet leaving a gap into which the mild steel flux guide can be inserted as shown in Fig. 7. The sliding flux guide was mounted on a single axis translation stage with a manual micrometre that enabled its position to be adjusted to increase or decrease the tuning gap. As part of this experiment, the influence of the fixed tuning magnet's thickness was also investigated.

4.1. Resonant frequency and power generation

Results were obtained for distances between the cantilever tuning magnet and the mild steel block (hereafter referred to as the air gap length) of 2.5, 4.5 and 6.5 mm. Three fixed tuning magnets of 1, 3 and 5 mm thickness were tested for each air gap length



a. Resonant frequency

b. Power generated

Fig. 5. Resonant frequency and maximum power generated as tuning gap increases for three magnet separations. Unconnected marks correspond to the case were the ferrite has been completely removed.

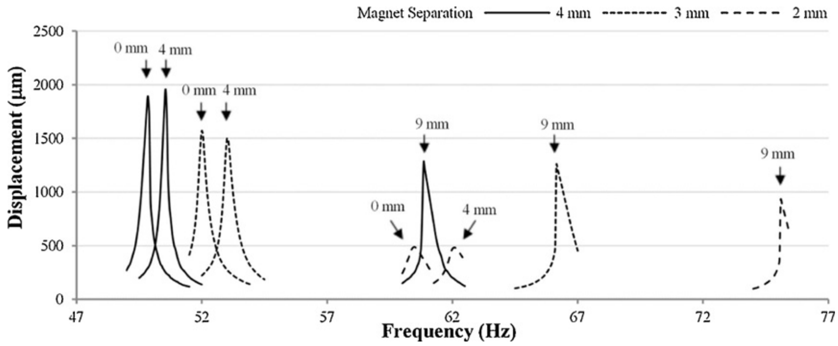
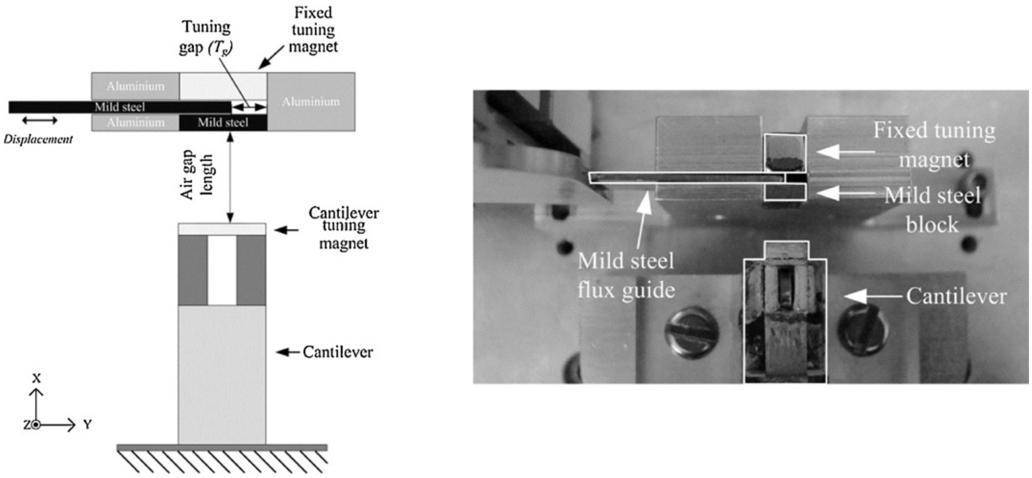


Fig. 6. Cantilever tip-end displacement for different magnet separations (shown with different line styles) and tuning gaps (labelled with arrows).



a. Schematic

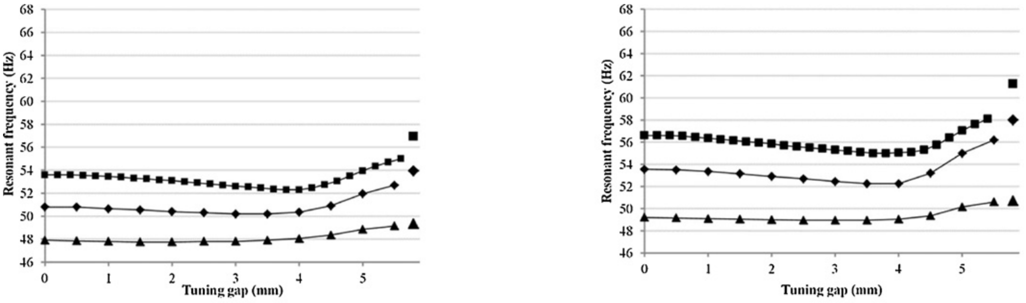
b. Photograph of setup

Fig. 7. Variable reluctance device second design, top view.

with the harvester connected to an optimal resistive load of 33 kΩ. Fig. 8 presents the variation in resonant frequency as the tuning gap increases. There is a non-monotonic response of the resonant frequency as a function of the tuning gap. For the 5 mm thickness magnet at a tuning distance of 6.5 mm, the frequency initially falls from 53.6 Hz to 52.3 Hz as the tuning gap increasing from 0 to 4 mm, and then increases from 52.3 Hz to 55 Hz as the tuning gap widens beyond 4 mm.

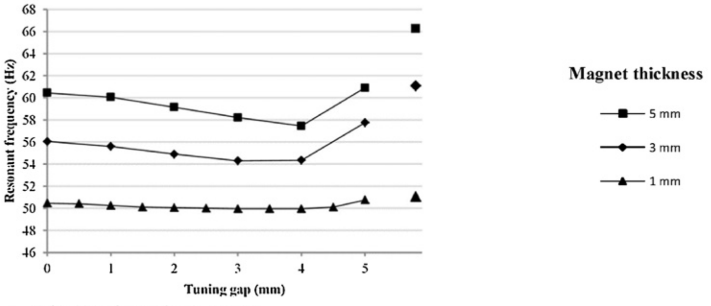
The reason for the non-monotonic behaviour exhibited in this experiment is due to the fact that the flux guide does not steer a monotonically decreasing flux away from the cantilever magnet as a the tuning gap increases. As the flux guide moves from a tuning gap position of 0–4 mm, the net flux from the fixed tuning magnet that flows to the cantilever tuning magnet decreases due to the flux guide steering more flux out of the gap and back to the rear pole of the fixed tuning magnet. However, when the tuning gap increases beyond 4 mm, less of the flux from the stationary tuning magnet is captured by the flux guide and, as the flux guide is further removed, an increasing amount of flux flows towards the cantilever tuning magnet increasing the resonant frequency, as was the case in the previous setup.

The thickness of the tuning magnet affects the initial resonant frequency and the tuning range but has a negligible effect on the normalised power output. The maximum tuning range occurs for tuning gaps from around 4 mm to 5.5 mm which produces a maximum frequency change of 3.45 Hz (5 mm thick tuning magnet, 2.5 mm air gap length). Fig. 9 demonstrates that once again shorter the air gap lengths results in increased parasitic damping due to the generation of eddy currents. For a tuning gap of 0 mm, the normalised power falls from 157 μW to 31 μW as the air gap length reduces from 6.5 mm to 2.5 mm, whilst the frequency range increases from 2.95 Hz to 6.5 Hz. Increasing the thickness of



a. Air gap length: 6.5 mm.

b. Air gap length: 4.5 mm.



c. Air gap length: 2.5 mm.

Fig. 8. Resonant frequency variation for different tuning gaps for three different air gap lengths. Unconnected data points correspond to the case where the flux guide has been completely removed.

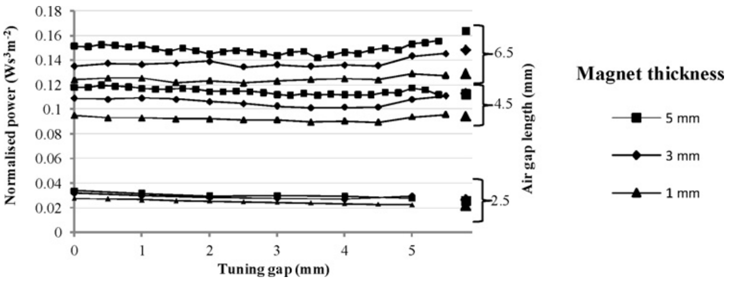


Fig. 9. Power generation at resonance for three different air gap lengths as the flux guide is removed. Unconnected marks correspond to the case when the flux guide has been removed completely.

the fixed tuning magnet reduced the parasitic damping by altering the flux path and reducing the magnitude of the eddy currents. Fig. 9 also shows that the normalised power generated at a fixed air gap length remains almost constant regardless of the tuning gap, suggesting that losses due to cantilever twist due to uneven flux distribution is negligible in this set up.

Table 3 presents a summary of the resonant frequency and power generation using this second flux guide arrangement. The achievable frequency range is less than that obtained with the first arrangement whilst power output is comparable in all cases except from the case where the air gap is set to 2.5 mm, which produces a much lower power output of around 30 μW. The normalised maximum power in the table corresponds to the case where the device is operating at resonance when the flux guide is completely removed.

4.2. Magnetic flux density

In order to investigate in more detail the non-monotonic relationship between resonant frequency, the magnetic flux density was measured in the centre of the air gap across the width of the cantilever as shown in Fig. 10, when the air gap length was set to 6.5 mm. The change in magnetic flux density matches the change in resonant frequency, i.e. the flux density decreases until the tuning gap reaches 4 mm before increasing as shown in Fig. 11.

A Comsol magnetic finite element analysis (FEA) was also used to show that the magnetic flux density along the width of the air gap is not uniform. In general, the predefined fine element size was used. Detailed meshing parameters are listed in Table 4. In areas of the most interests, e.g. tuning magnets, tuning gap and mild steels, the maximum element size was set as 0.1 mm.

The magnetic flux density was determined at 6 different points along the mid line of the air gap (Fig. 10) and the results are shown in Fig. 12. The non-symmetrical result between points *A* and *F* suggests that the force exerted on the cantilever is again not perfectly uniform (as was the case in the original flux guide setup) resulting in a torsional moment on the cantilever. However, this asymmetric force is less here than in the first case as the magnets did not strike the coil with this experimental arrangement.

The FEA shows that the magnetic flux lines flow through the flux guide back to the fixed tuning magnet, producing an asymmetrical flux density as shown in Fig. 13.

4.3. Force on flux guide

An important consideration for autonomous control of this system is the force required to move the flux guide. This force should

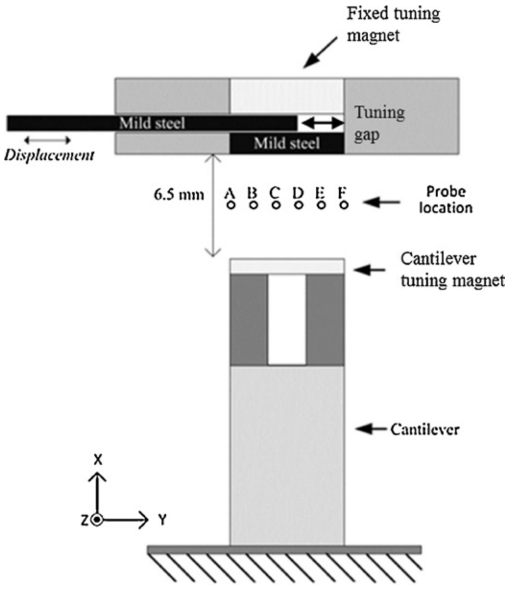


Fig. 10. Experimental setup for measurement of magnetic flux density showing the position of the probes.

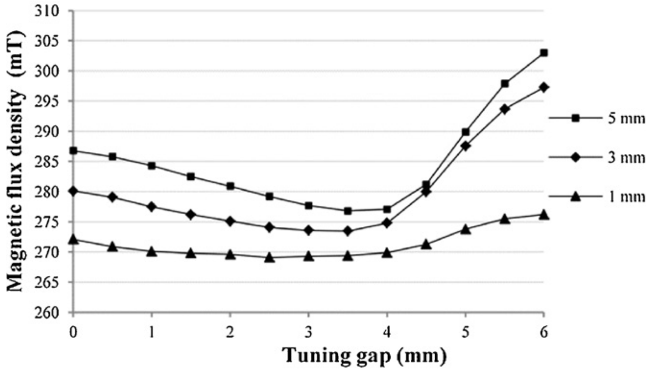


Fig. 11. Magnetic flux density variation as tuning gap increases for each magnet thickness.

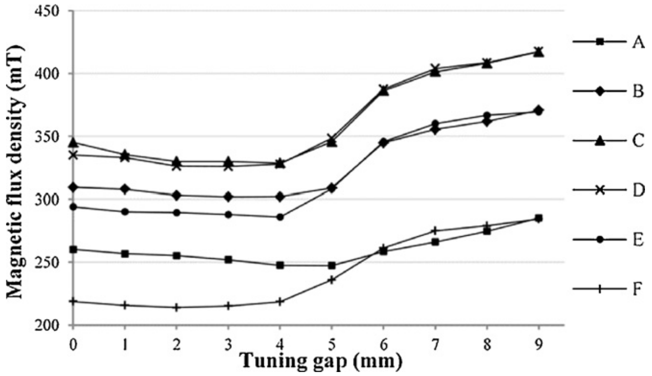


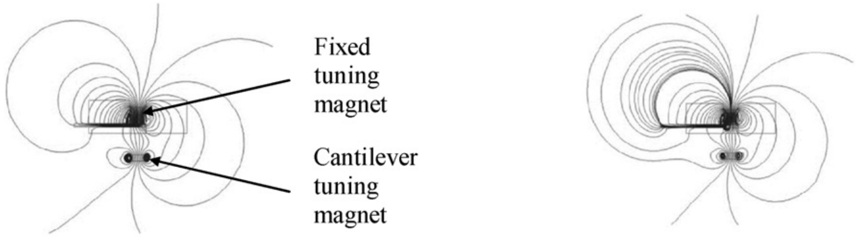
Fig. 12. Finite element analysis of magnetic flux density as tuning gap increases.

Table 3
Resonant tuning range and power generation for 2nd design.

Air gap length (mm)	Magnet thickness (mm)	Resonant frequency without flux guide (Hz)	Resonance frequency range (Hz)	Maximum power (μW)	Maximum normalised power (W s^3 m^{-2})
6.5	5	56.95	52.3–55.25	157	0.164
	3	53.95	52.7–50.2	152	0.145
	1	49.35	49.15–47.75	145	0.129
4.5	5	61.25	55.0–58.1	116	0.119
	3	58	52.25–56.2	112	0.109
	1	50.7	48.95–50.6	106	0.095
2.5	5	66.25	57.45–60.9	31	0.034
	3	61.1	54.3–57.75	31	0.032
	1	51.05	49.95–50.75	30	0.027

Table 4
Meshing parameters in Comsol.

Maximum element size (mm)	Minimum element size (mm)	Maximum element growth rate	Resolution of curvature	Resolution of narrow regions
4	0.5	1.45	0.5	0.6



a. 0 mm tuning gap

b. 4 mm tuning gap

c. 6 mm tuning gap

d. Flux guide removed

Fig. 13. Finite element analysis of magnetic flux density versus tuning gap for a fixed tuning distance of 6.5 mm, plan view.

be as small as possible to minimise the power consumption of the actuator used in an automatic tuning mechanism. The force on the flux guide was measured using a digital force gauge when the air gap length was 6.5 mm. The results are shown in Fig. 14. The force on the flux guide varies with the magnet size and, to a lesser extent, the air gap length. This force is dominated by the contact friction between the magnet surface and the flux guide and hence the larger the tuning magnet, the larger the attraction between the magnet and the guide and the larger the friction in the assembly. Ensuring a small air gap or introducing a thin low friction Teflon shim between the magnet and the guide would reduce the force considerably. For comparison, the maximum tuning force experienced by the moving magnet tuning arrangement described in Ref. [12] was less than 1 N.

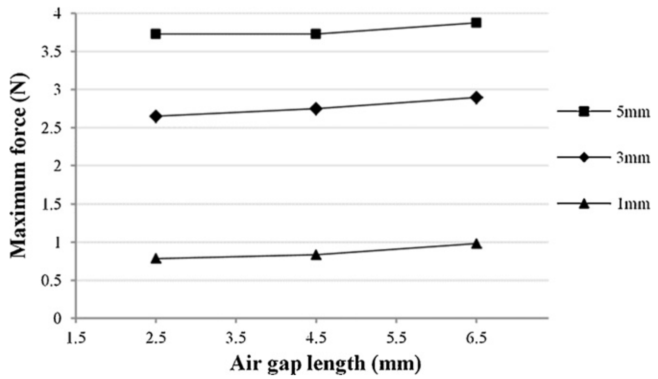


Fig. 14. Maximum force required to move flux guide for three different magnet thicknesses: 5, 3 and 1 mm.

5. Design 3: magnet tuning using vertical flux guide

A third magnetic flux guide design was proposed to further address the asymmetric magnetic flux in the *y*-plane to reduce the frictional force on the flux guide. The first modification made was a reduction in the size of the flux guide to 5 × 13 × 1 mm. Secondly, the orientation of the tuning arrangement was modified to move the flux guide in the vertical direction. This means that any non-uniform distribution of the magnetic flux is now in the vertical direction, which will cause no lateral displacement of the cantilever

Table 5
Resonant tuning range and power generation for the 3rd design.

Air gap length (mm)	Resonant frequency without flux guide (Hz)	Resonance frequency range (Hz)	Maximum power (μW)	Maximum normalised power (W s^3 m^{-2})
10	53.35	52.10–53.35	161.17	0.151
7	57.10	54.50–57.25	150.41	0.149
5	62.20	58.20–61.60	118.18	0.125
3	65.65	60.85–65.70	65.48	0.072

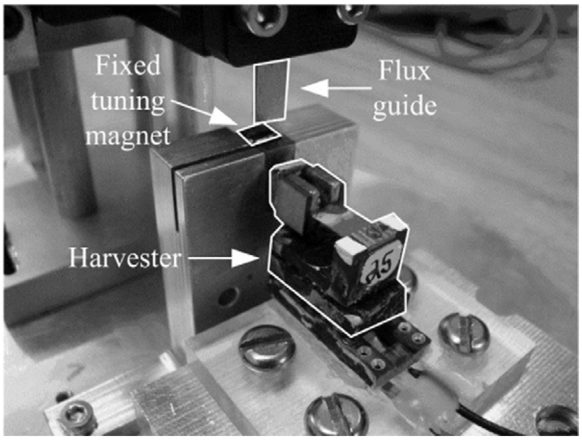


Fig. 15. Vertical magnetic flux guide.

and avoid contact between the cantilever and coil. In this experiment the flux guide was positioned directly in front of the fixed tuning magnet. The sliding mild steel was mounted on a single axis translation stage with a manual micrometre, as shown in Fig. 15.

A 5 mm thick magnet was used as the fixed tuning magnet for all the tests in this arrangement. Experiments were performed for air gap lengths of 3, 5, 7 and 10 mm. Table 5 presents a summary of the resonant frequency and power generation using the third flux guide arrangement. The results show a similar performance change in the resonant frequency as with the second horizontal flux guide design. First, there is a slow reduction in the resonant frequency as the tuning gap increases, then a rapid increase towards the non-tuned resonant frequency, as shown in Fig. 16. Furthermore, the frequency range increases as the air gap length reduces. As with the previous designs, however, decreasing the air gap length increases the parasitic damping in the harvester which reduces the normalised power generated (Fig. 17). In summary, an air gap length of 10 mm produced a frequency change from 52.1 to 53.3 Hz as the ferrite moves from 9 to 13 mm. An air gap length of 3 mm increases the frequency range to 60.9–65.7 Hz. However, the power output and Q-factor reduce from 157 μW and 188 at 10 mm to 57 μW and 120 at 3 mm respectively.

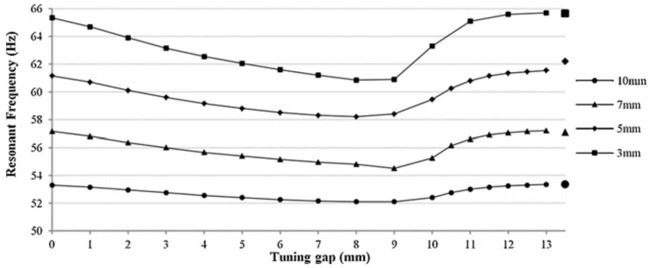


Fig. 16. Resonant frequency as the tuning gap increases for four different air gap lengths. Circular marks correspond to the case where the flux guide has been completely removed.

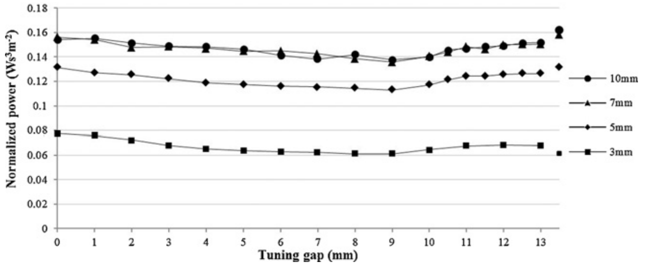
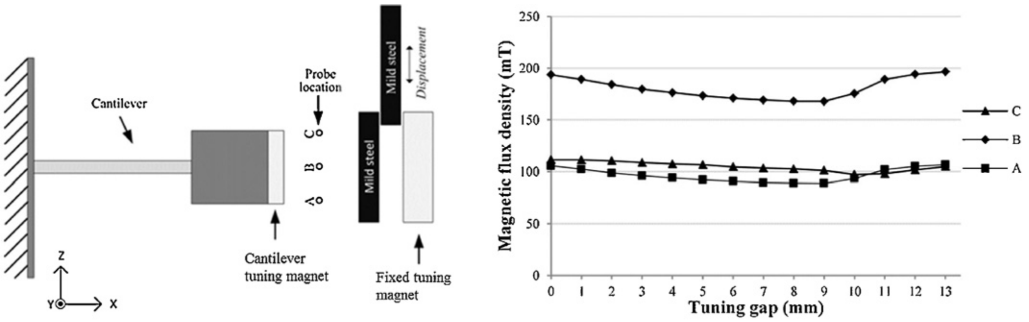


Fig. 17. Power generation as the tuning gap increases for four different air gap lengths. The unconnected data points correspond to the case where the flux guide has been completely removed.

5.1. Magnetic flux density

As in the previous design the air gap flux density is not uniform. In this case, the non-uniformity creates an additional force on the cantilever, pulling it downwards. As previously discussed, this does not cause a torsional moment on the beam and hence does not cause coil damage as the additional force acts in the *Z*-direction parallel to the movement of the cantilever. Fig. 18 shows the FEA of the magnetic flux density when the air gap length is 5 mm. The effect of the flux guide on the magnetic flux density is shown in Fig. 19. It is clearly shown in Fig. 19b that the magnetic flux density follows the path of the flux guide due to its lower reluctance than that of the air surrounding the harvester.



a. Probes position, side view.

b. Magnetic flux density.

Fig. 18. Finite element analysis of magnetic flux density as tuning gap increases.

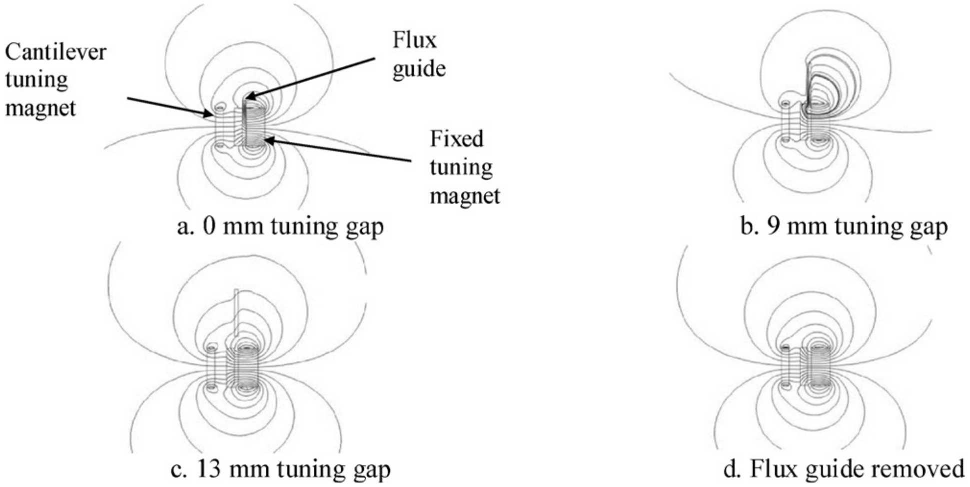


Fig. 19. Finite element analysis of magnetic flux density, viewed from the side.

5.2. *Force on the flux guide*

Due to the practical constraints of the experimental arrangement it was not possible to directly measure the force required to move the flux guide with sufficient accuracy. The magnetic force on the flux guide was therefore calculated using FEA. The force required in the *Z* direction to hold the flux guide in a fixed position is shown in Fig. 20.

Assuming a gap is maintained between the flux guide and the magnet and therefore friction can be ignored (e.g. due to the use of a Teflon coating), the force required to move the flux guide varies from 0.17 N to −0.94 N. This is simply the magnetic force which acts on the flux guide. This force is now comparable to the force in the moving magnet tuning mechanism described in [12].

6. Discussion

The influence of the magnetic flux on the resonant frequency of the harvester is a maximum when the tuning gap is varied from 4 to 9 mm for both the horizontal and vertical designs. Operating in this range gives the greatest change in frequency for the shortest distance moved by the flux guide which is an important consideration when using an automated actuator to control the flux guide position. The force required to vary the ferrite position is also a key parameter that affects the energy required to adjust the flux guide position. At present, this force is dominated by the friction between the ferrite and the jig which occurs due to the attractive force between the fixed tuning magnet and the ferrite.

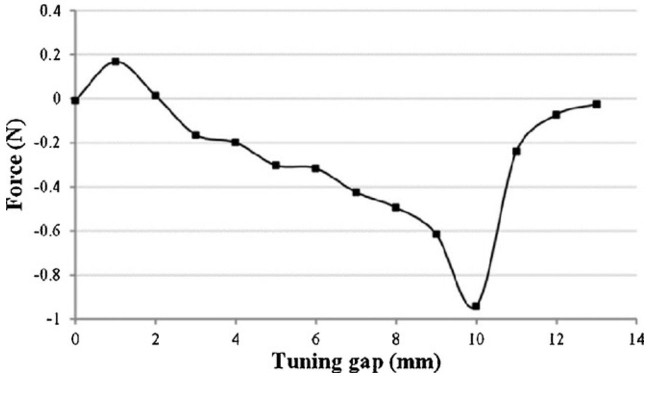


Fig. 20. FEA electromagnetic force exerted on flux guide metal in *Z*-axis.

The results also show a clear trade-off between the achievable bandwidth and the power output from the generator. In particular, reducing the magnet separation (configuration 1) or air gap length (configurations 2 and 3) to increase the frequency range reduces the power generated due to the increased parasitic mechanical damping on the cantilever. This arises from the proximity of the moveable ferrite, and other metal components used in the test rig, to the moving cantilever magnetic which causes losses due to eddy currents. Since the tuning mechanism used here relies on ferrous materials to provide the flux path, this loss mechanism will inevitably occur to some extent. Methods for reducing this effect are discussed in Section 7.

The largest frequency range is obtained in configuration 1 which, for a magnet separation of 4 mm, has a total frequency range of 11.1 Hz or 10.5 Hz if the tuning gap is limited to 4 to 9 mm. This arrangement has demonstrated the potential of this tuning approach and the frequency range achieved is similar to the moving magnet tuning mechanism described in Ref. [5] which achieved a 14 Hz range. However, the uneven forces applied to the cantilever damaged the coil. Configurations 2 and 3 do mitigate against this uneven force distribution but at the expense of the frequency range. At maximum air gap lengths, the frequency range reduces to 3 and 1.1 Hz respectively for configurations 2 and 3 respectively given the tuning gap range from 4 to 9 mm.

7. Conclusions

The use of a moveable magnetically permeable flux guide placed between two tuning magnets has been proven to modify the resonant frequency of a cantilever based energy harvesting generator. This work has provided valuable insight into the practical aspects of implementing this type of tuning mechanism and has highlighted three issues that must be considered. Firstly, whilst configuration 1 produced the largest change in frequency, it was not suitable for long term use due to the asymmetrical forces and wear on the coil. This device highlighted the potential for this tuning approach to introduce asymmetrical forces on the generator which could affect the level of mechanical damping and the reliability of the generator. Secondly, the reliance on the location of a ferrous flux guide which, in the designs presented here, is in close proximity to the moving cantilever tuning magnet results in the generation of eddy currents which damp the cantilever's oscillations. This is further compounded by the use of metal components in the test rig. Thirdly, in order to implement an automated version of this tuning mechanism an actuator would be required to position the moveable flux guide. The amount of power required by the actuator will depend in part on the force required to move the moveable flux guide. The magnetic forces and design of the test rigs presented here caused excessive friction which has exaggerated the required tuning force.

In order to minimise these effects several issues should be addressed. This type of tuning mechanism does not require the flux guide to be placed in line with the tuning magnets and therefore near the moving cantilever magnet. Alternative magnetic circuits that move the moveable flux guide away from the cantilever (such as that shown in Fig. 1b) should reduce eddy current damping and enable low or zero friction operation and provide more symmetrical forces on the beam. Non-conductive materials should be used in the rig where ever possible to prevent eddy currents. Also, if the design of the tuning rig results in sliding contact with the moveable flux guide then materials with a low coefficient of friction should be used. With respect to generator reliability, this tuning mechanism would work equally well with alternative transduction mechanisms such as piezoelectric. A piezoelectric cantilever, for example, will be relatively unaffected by the asymmetrical forces since the close proximity of coils and magnets is not required and impact can more easily be avoided.

Having demonstrated the feasibility of the moveable flux guide tuning mechanism, work is currently underway to develop flux guide designs that require smaller amplitudes of movement and would therefore use less power if positioned by an actuator [15]. This tuning principal is particularly well suited to a MEMS implementation using a micromachined actuator such as an electrostatic comb drive or piezoelectric actuator. A variable reluctance structure with a stationary magnet is more desirable for fabrication using MEMS techniques than a system with a movable magnet due to the difficulty of attaching a permanent magnet to a fragile moveable MEMS structure as a post process. The flux guide can be small and fabricated in a MEMS compatible material such as nickel, with the tuning magnet attached to a robust fixed structure in the MEMS device after MEMS processing. Work on such an approach is ongoing.

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