EUROSENSORS 2014, the XXVIII edition of the conference series

**An Electrically Tunable Low Frequency Electromagnetic Energy Harvester**

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**Abstract**

This paper reports the design, fabrication and experimental results of a low frequency electromagnetic energy harvester on FR4. The resonant frequency of the device is tuned electrically by using a generalized load (a capacitance in parallel with a resistance) instead of conventional resistive load. The device produces a maximum load power of 57 \(\mu\)W across 3310 \(\Omega\) resistive load at 37.5 Hz of untuned resonant frequency under 0.1g input acceleration. Later, the resonant frequency of the device is experimentally tuned up to 37 Hz successfully by changing the load capacitance from 0 to 10 \(\mu\)F. Though, this tuning comes with reduction in output power. It is observed that only 8.5% of the untuned maximum load power is obtained at the limit of the tuned range.

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Peer-review under responsibility of the scientific committee of Eurosensors 2014

**Keywords:** Low frequency, Electromagnetic Energy Harvester, Tuning, Generalized load;

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1. **Introduction**

Over the last decade or so, an intensive amount of research has been reported on conversion of kinetic energy from ambient vibrations into useful electrical energy [1-4]. In most of the earlier reported works, such a transducer system was modeled using a resonant spring-mass-damper system which normally operate at a particular resonant frequency and output drops as input vibration frequency is varied. As a result, a number of strategies have been adopted in literature to tune the resonant frequency of VEH. The concept of using a generalized load was first...
demonstrated by Cammarano et al [5]. Later, Zhu et al provided a more generalized model to investigate the influence of different parameters on the system performance [6].

2. Theory

The dynamics of a resonant Vibration Energy Harvester (VEH) is given by the second order differential equation:

$$m\ddot{z} + cz + kz = -m\ddot{y}$$  

(i)

Where m is the inertial mass, z(t) is the relative displacement of the inertial mass relative to the fixed frame, c is the total damping co-efficient (including both mechanical and electrical damping), k is the spring constant of the movable spring and y(t) is the input vibration applied to the frame. Using Laplace transformation and dividing throughout by γ (where γ is the electromagnetic coupling co-efficient), this equation can be written in the frequency domain as an equivalent circuital form:

$$\frac{m s^2}{\gamma}Z(s) + \frac{c s}{\gamma}Z(s) + \frac{k}{\gamma}Z(s) = -\frac{m s^2}{\gamma}Y(s)$$  

(ii)

Considering $V(s) = \gamma s Z(s)$ as the induced voltage, $I(s) = \frac{m s^2 Y(s)}{\gamma^2}$ as the input current, $C_m = \frac{m}{\gamma^2}$, $R_m = \frac{\gamma^2}{c}$ and $L_m = \frac{\gamma^2}{k}$ as respectively the equivalent capacitance, resistance and inductance of the mechanical system, Equation (ii) can be rewritten as:

$$V(s)\left(\frac{1}{R_m} + \frac{1}{s L_m} + s C_m\right) = -I(s)$$  

(iii)

Equivalent circuit of the electromagnetic VEH is depicted in Figure 1 where the mechanical system is represented as a parallel combination of $R_m$, $C_m$ and $L_m$ connected to a current source of generated current $I$. Open circuit induced voltage is obtained across the coil resistance $R_c$. The mechanical system is connected to a generalized load (containing both resistive and reactive parts). If we consider the mechanical system connected to a resistive load, then the resonant frequency is given by $\omega_n = 1/(LC)^{1/2}$. But adding a variable reactive element to the load gives the scope to tune the resonant frequency accordingly. By calculating the total impedance of the circuit and equating the imaginary part to zero, the modified resonant frequency of the system is found to be

$$\omega_r = \sqrt{\frac{2\mu}{R + X - \mu \omega^2_n}}$$  

(iv)

Where $R = (1+R_L/R_C)^2$, $X = C_L(\gamma^2/m)(R_L/R_C)^2$, and $\mu = R_L C_L$. It can be seen that the resonant frequency can be changed by adjusting the load capacitance $C_L$.

![Figure 1: Equivalent Circuit of the Electromagnetic generator connected to a generalized load.](image-url)

3. Design and Fabrication of the Prototype

In this work, we have developed a novel Electromagnetic VEH structure using FR4 as the resonating spring material due to its suitable mechanical properties (Young’s Modulus - 22 GPa) for low frequency applications. The assembled prototype is shown in Figure 2(a). The novel spring structure is fabricated using Laser cutting technology on 0.2 mm thick FR4. The four spring configuration reduces the effective spring constant resulting in low frequency
operation. The length and width of each of the spring arm are 11.7 mm and 0.9 mm respectively. Oppositely polarized sintered NdFeB N35 magnetic arrangement including mild steel keepers is assembled to maximize the flux density. The dimensions of each of the NdFeB magnets are 8×4×2 mm³ whereas those of the mild steel blocks are 8×4.2×1.6 mm³. An enamelled copper wire wound coil having 6.5 mm outer diameter, 1.15 mm inner diameter and 1 mm thickness with 2500 turns was used to transduce the electrical voltage. The measured coil resistance ($R_C$) is found to be 697 Ω. The overall volume of the prototype is 2.3 cm³.

Figure 2: (a) Assembled prototype using FR4 as spring material. (b) Variation of RMS load voltage and average load power as a function of load resistance. The optimized load resistance is 3310 Ω.

4. Results and Discussions

The fabricated device was tested in a LDS V455 shaker using harmonic excitation. First, the device was tested with resistive load only and the corresponding variation of average load power and rms load voltage with load resistance is shown in Figure 2(b). It is seen that for an optimized resistive load of 3310 Ω, an average power of 57 μW and RMS load voltage of 0.43 V is obtained for an input acceleration of 0.1g. The untuned resonant frequency of the structure is 37.5 Hz.

Figure 3: (a) Theoretical variation of resonant frequency with load capacitance for different load resistance values. (b) Comparison between experimental and theoretical variation of resonant frequency with load capacitance at an optimized load resistance 3310 Ω.

Now, by using a generalized electrical load, the resonant frequency of the device has been tuned. A theoretical study based on equation (iv) is carried out first to show the variation of resonant frequency with the load capacitance for different values of load resistance keeping all the other parameters constant. The resonant frequency decreases with increasing load capacitance until a critical point is reached, after which the resonant frequency rises again. This critical value of capacitance becomes smaller with increasing load resistance. Also, the tunable frequency range widens with the higher values of load resistance. The experimental validation of this theoretical study is provided in
Figure 3(b). The capacitive load is varied using a variable capacitance decade box while the resistive load is maintained at its optimized value of 3310 Ω. It is seen that experimentally the frequency can be tuned up to 0.5 Hz, which is still not a large quantity.

Figure 4: Variation of RMS Load Voltage and Average Load Power at 0.1g with (a) load capacitance (b) resonant frequency.

Dependence of load voltage and maximum load power is shown from experiment in Figure 4(a). Both the load voltage and power remain same up to 500 nF of load capacitance after which they start falling, and become very small at large capacitance values. The variation of the above two mentioned quantities with resonant frequency are obtained by combining Figure 3(b) and 4(a), and plotted in Figure 4(b). Though the resonant frequency can be tuned by changing the reactive part of the generalized load, the output power and voltage falls down also with this change. The maximum output power at the edge (37 Hz) of tunable range is only 4.87 μW, which is 8.5% of its untuned value.

4. Conclusions

In this paper, we have reported a low frequency electromagnetic generator with FR4 as the resonating spring material. A four spring arrangement is used to achieve a resonant frequency of 37.5 Hz at which the device produces 57 μW of load power across a resistive load of 3310 Ω. The resonant frequency of this electromagnetic generator is tuned by using a generalized load (capacitance in parallel with a resistance). It is seen that, a tunable range of 0.5 Hz is obtained by varying the load capacitance from 0 to 10 μF. However, this tuning comes at the cost of drastic fall in output power and only 8.5% of the untuned maximum load power is obtained at the limit of the tuned range.

Acknowledgements

This work is financially supported by Science Foundation Ireland (SFI) Principal Investigator (PI) project on ‘Vibration Energy Harvesting’ grant no SFI-11/PI/1201.

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