CLOSED LOOP FREQUENCY TUNING OF A VIBRATION-BASED MICRO-GENERATOR

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Abstract: This paper presents a tunable electromagnetic vibration-based micro-generator with closed loop frequency tuning. Frequency tuning is realized by applying an axial tensile force to the micro-generator. A closed-loop frequency tuning system has been developed to control the tuning process so that the generator always operates at the ambient vibration frequency to make the entire process automatic. Experimentally the resonant frequency has been successfully tuned from 67.6 to 98 Hz when various axial tensile forces were applied to the structure. The generator produced a power of 61.6 to 156.6 μW over the tuning range when excited at vibrations of 0.588 m·s^{-2}.

Key words: frequency tuning, micro-generator, vibration energy harvesting, closed loop

1. INTRODUCTION

Vibration-based micro-generators, as a new source of energy, have received increasing levels of attention in the last decade. Mechanical energy from ambient vibrations is converted into electrical energy and this is often an attractive approach for powering wireless sensors. The majority of generators are based upon a spring-mass system with a characteristic resonant frequency. Theoretically, a vibration-based micro-generator produces maximum power when its resonant frequency matches the ambient vibration frequency [1]. Furthermore, to generate maximum power, devices are typically designed to have a high Q-factor. However, in this case, the output power drops dramatically if the ambient and device frequencies do not match. Most reported generators are designed to work only at one fixed resonant frequency [2]. This drawback severely limits the practical application of vibration-based micro-generators.

Generally, to date, there are two possible solutions to this problem. The first is to widen the bandwidth of the generator. However, wider bandwidth means a lower Q-factor, which reduces the maximum power generated. This can be compensated by making a generator larger in size but this is not always a practical solution. Bandwidth can also be widened by designing a generator consisting of an array of small generators, each of which works at a different frequency. Thus, the assembled generator has a wide operational frequency range whilst the Q-factor does not decrease [3][4]. However, this assembled generator must be well designed so that each individual generator does not affect the others. This makes it more complex to design and fabricate. Additionally, at a particular source frequency, only a single individual generator contributes to power output so the approach is volume inefficient. The second solution is to tune the resonant frequency of a single larger generator periodically so that it matches the frequency of ambient vibration at all times. Thus, the maximum power can be generated at various frequencies without reducing the Q-factor and with high efficiency per unit volume. Therefore, this second approach is a better choice to increase the working frequency range of a vibration-based micro-generator.

To maximize the useful power generated by the micro-generator, the tuning mechanism has to consume as little energy as possible to make self-powered resonant frequency tuning feasible. The period in which the system accumulates enough energy to perform tuning is called the duty cycle. It is therefore important to shorten the duty cycle in practical applications.

Attempts to tune the frequency of generators have been reported in the literature. Challa et al. [5] reported a tunable piezoelectric micro-generator, 50 cm^3 in volume, with a frequency range of 22 to 32 Hz with a tuning distance of 3 cm. The tuning was realized by applying a magnetic force perpendicularly on the cantilever of the generator. The generator produced 240 to 280 μW powers at 0.8 m·s^{-2} acceleration but the tuning mechanism had the unwanted side effect of varying damping over the frequency range. Leland and Wright [6] successfully tuned the resonant frequency of a vibration piezoelectric generator by applying axial compressive force directly on the cantilever using a micrometer. The tuning range is from 200 to 250 Hz. This device generated 300 to 400 μW at an acceleration of 9.8 m·s^{-2}. In both cases, frequency tuning was achieved manually.

In this paper, an electromagnetic micro-generator with closed loop frequency tuning is reported. The tuning mechanism is within a closed loop that is

controlled by a micro-controller, which makes it completely automatic. This tunable micro-generator has a tuning range from 67.6 to 98Hz. The generator produced a power of 61.6 to 156.6 µW over the tuning range when excited at vibrations of 0.588 m·s⁻².

2. THEORY

2.1 Resonant Frequency

An axial tensile load applied to a cantilever (Fig. 1(a)) increases the resonant frequency of the cantilever while an axial compressive load applied to a cantilever (Fig. 1(b)) decreases the resonant frequency of the cantilever.
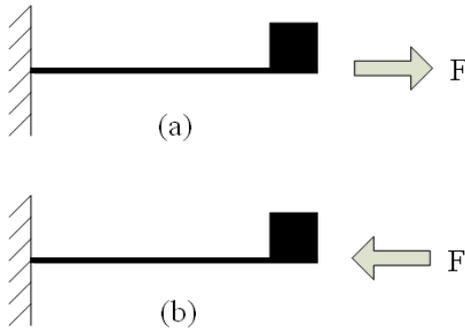
Fig. 1: Axial tensile (a) and compressive (b) load on a clamped-free cantilever.

An approximate formula for the resonant frequency of a cantilever with an axial load, f_r', is given by

$$f_r' = f_r \cdot \sqrt{1 + \frac{F}{F_b}} \qquad (1)$$

where f_r is the resonant frequency without load. F is the axial load. F is positive if the load is tensile and F is negative if the load is compressive. F_b is the axial load required to buckle the beam.

The buckling load F_b is given by

$$F_b = \frac{\pi^2 \cdot E \cdot I}{4L^2} \qquad (2)$$

where E is the Young's modulus of the material of the cantilever, I is the area moment of inertia, L is the span of the cantilever.

Fig. 2 shows the change in resonant frequency of a cantilever with axial load. It shows that a compressive load is more efficient in frequency tuning than a tensile load. However, in the compressive case, the parasitic damping in the generator rises with increasing compressive load. In the tensile case the damping levels remain largely constant, i.e. the Q-factor increases with an increase of the tensile load, as expected given increasing frequency. Therefore, a tensile load is preferred in this application.
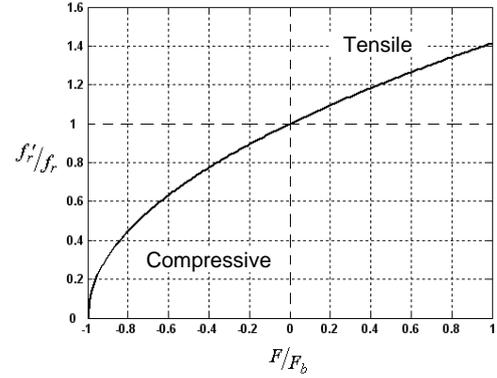

Fig. 2: Change in resonant frequency with axial load.

To minimize unwanted effects on the cantilever vibrations, contactless magnetic force is used to apply the axial load.

2.2 Output Power

Based on the model presented in [1], it is possible to predict the maximum power available within the vibration-based microgenerator, which is given by

$$P = \frac{m \cdot a^2}{4 \cdot \omega_r \cdot \zeta_T} \qquad (3)$$

where P, m, a, ω_r and ζ_T are maximum power, mass, acceleration, resonant frequency and total damping, respectively. Eq. 3 shows that the maximum available power within a micro-generator decreases with an increase of the resonant frequency for a constant acceleration and constant damping.

3. EXPERIMENTAL

3.1 Tuning Mechanism

Fig. 3 shows the schematic diagram of the tuning mechanism. The generator and the tuning mechanism are mounted on the same housing so that there is no relative displacement between them. The tuning force is provided by the attractive force between two tuning magnets with opposite poles facing each other. One magnet is fixed at the free end of a cantilever while the other is attached to an actuator and placed axially in line with the cantilever. The distance between the two tuning magnets is adjusted by the linear actuator. Thus, the axial load on the cantilever is changed. The areas where the two magnets face each other are curved to

maintain a constant gap between them over the amplitude range of the generator.
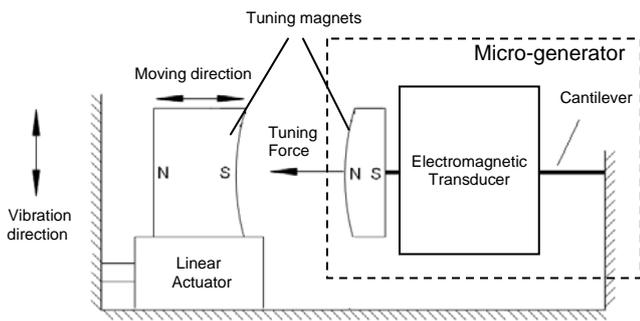

Fig. 3: Schematic diagram of the tuning mechanism.

3.2 Closed Loop Tuning System

The tuning process is controlled by a microcontroller (Fig. 4). The microcontroller detects the output voltage of the generator periodically and gives instructions to drive a linear actuator to adjust the distance between two tuning magnets (tuning force). Thus, the resonant frequency of the micro-generator is changed. When the output voltage reaches maximum, the microcontroller assumes the micro-generator is working at resonance and stops the tuning mechanism. It switches to sleep mode to save power. The microcontroller wakes up every duty cycle to monitor the output voltage and make a decision. The microcontroller and linear actuator will ultimately be powered by the micro-generator itself. In this test, they were powered by a separate power supply to initially evaluate tuning principles and algorithms.
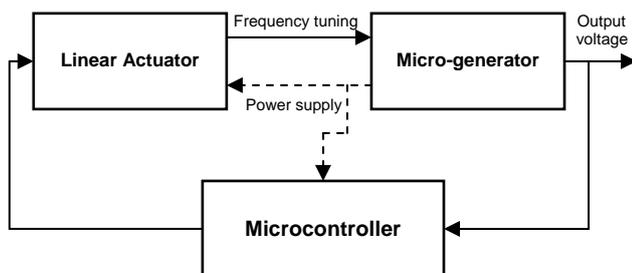

Fig. 4: Block diagram of the closed loop tuning system.

4. RESULTS AND DISCUSSION

To demonstrate the tuning principle, the generator was tested on a shaker table with a programmable resistance box and a PC with LabVIEW software collecting the data. This system is suitable for fully characterizing the generator over a wide range of acceleration levels, load resistances and frequencies.

4.1 Resonant Frequency

The varying resonant frequency of the generator

with distance between the two tuning magnets is shown in Fig. 5. The resonant frequency increases as the distance between the two tuning magnets is decreased, i.e. when the tuning force is increased.
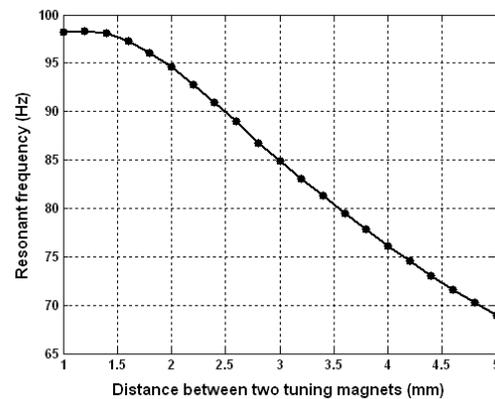

Fig. 5: Resonant frequency with variance of distances between two tuning magnets.

The resonant frequency was successfully tuned from 67.6 to 98 Hz when the distance between two tuning magnets was changed from 5 to 1.2 mm. It is found that, when this distance becomes very small (< 1.2 mm), the resonant frequency barely increases. The reason for this is that the force associated with the tension in the beam becomes much greater than the beam stiffness and the resonant frequency approaches that of a straight tensioned cable. The overall distance that the actuator covers is only 3.8 mm and the energy consumed in the tuning mechanism is 2.04 mJ·mm^{-1}. Table 1 compares experimentally the resonant frequency of the generator when the tuning was finished with the vibration frequency as it varied, which shows that the closed loop frequency tuning system is successful in tracing the ambient vibration frequency. The system was tested at the vibration with various frequencies and constant acceleration.

Table 1: Resonant frequency after tuning.

Ambient vibration frequency (Hz)	Resonant frequency of the micro-generator after tuning (Hz)
70	70.2
75	75.1
80	79.9
85	84.8
90	90.0
95	95.1
98	98.0

4.2 Power Output

Fig. 6 compares the maximum power at optimum load at different resonant frequencies when the micro-

generator is excited at a vibration of 0.588 m·s^{-2}. It is found that the maximum output power drops with the increase of the resonant frequency as predicted. However, when the two tuning magnets were less than 3 mm apart, i.e. when the resonant frequency is higher than 85 Hz, the output power decreased more than expected. The reason is that the restoring force caused by the tuning magnets is larger than the inertial force caused by vibration and, thus, increases total damping.
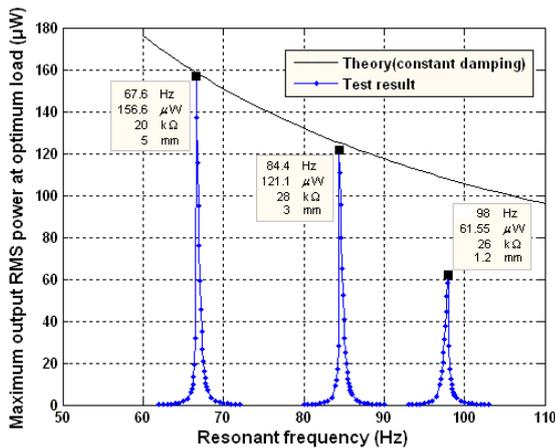

Fig. 6: Maximum output RMS power at optimum loads with variance of resonant frequencies of the micro-generator (excited at 0.588 m·s^{-2}).

4.3 Duty Cycle

The duty cycle of the closed loop frequency tuning system is proportional to the energy consumed by the actuator and is inversely proportional to the power generated by the generator and the efficiencies of the actuator and the generator.

This tuning method is passive tuning. The tuning mechanism consumes negligible energy when the micro-generator works at resonance. The average energy consumed from a change of vibration frequency being detected till the generator working at the new resonant frequency is 5 mJ. Assuming that the generator produces an average of 120 µW of power over the entire tuning range with an efficiency of 30% and the actuator has an efficiency of 60%, the average duty cycle would be approximately 230 seconds if all components of the system (i.e microcontroller, actuator) were powered from the micro-generator.

5. CONCLUSIONS AND FUTURE WORK

This paper has presented an electromagnetic micro-generator whose resonant frequency has been tuned by applying an axial tensile load using a pair of tuning magnets and a closed loop control system to match the ambient vibration frequency. A microcontroller was used to control a linear actuator to

adjust the distance between two tuning magnets and hence the tuning force.

The experiment results showed that the closed loop frequency tuning system has successfully traced the ambient vibration frequency and tuned the resonant frequency of the proposed micro-generator from 67.6 to 98 Hz by changing the distance between two tuning magnets from 5 to 1.2 mm respectively. The generator produced a power of 61.6 to 156.6 µW over the tuning range when it was excited at a constant vibration acceleration level of 0.588 m·s^{-2}. Importantly, it was found that 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 was increased and the output power was less than expected. It is estimated that the average duty cycle of this system is approximately 230 seconds.

The control system presented here was only able to detect the change in frequency of ambient vibration. If the amplitude and phase of the vibration change, the system may be triggered by mistake. A new control system consisting of additional sensors is currently being built. The sensors will be used to detect the ambient vibration for more accurate control. The duty cycle will be further shortened and a complete self powered tuning system will be demonstrated.

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