OVER RANGE PROTECTION FOR A TUNABLE KINETIC ENERGY HARVESTER

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Abstract: This paper describes the development and implementation of an over range protection mechanism which controls the displacement of a kinetic energy harvester when the environmental excitation amplitude increases beyond a maximum tolerable level. This prevents damage to the harvester's structure due to impact or excessive stress. The control of the displacement is achieved by adjusting the harvester's resonant frequency to a different frequency than that of the excitation, effectively reducing the mass displacement. This strategy increases the maximum tolerable level of acceleration by 257% from 2.75 $ms^{-2}_{(rms)}$ to 9.81 $ms^{-2}_{(rms)}$, in this implementation.

Keywords: energy harvesting, displacement protection.

INTRODUCTION

Kinetic energy harvesters are often designed with a high quality factor which multiplies the environmental excitation amplitude and hence increases their energy output [1]. They are typically optimized for a fixed known frequency and level of excitation, i.e. acceleration, although, the magnitudes of these cannot be guaranteed when the harvester is deployed. Attempts at tuning the frequency to overcome the limitations of fixed frequency operation have been surveyed in a recent review [2].

This paper presents two over range protection algorithms that prevent excessive displacement of an electromagnetic vibration-based energy harvester by adjusting its spring stiffness, and hence its resonant frequency, effectively maintaining the harvester's displacement within a finite range. This paper describes a new over range protection applied to a tunable energy harvester presented previously in [3]. It has an optimized tunable frequency range from 64 to 78 Hz. The tuning mechanism, previously employed to maintain resonance, is used here additionally, with a new algorithm, to protect the harvester from excitation levels beyond a tolerable maximum.

The importance of preventing excessive displacement of the harvester arises from the physical characteristics of the device, as well as the geometry of the package containing it. An excessive displacement could produce a constant physical impact between the harvester and the base, see fig. 1, or excessive stress in the spring element of the harvester that can lead to fatigue failure.

SYSTEM DESCRIPTION

The over range protection system consists of two main sections: the tunable electromagnetic harvester and the control system.

The tunable energy harvester converts kinetic energy into electrical energy with the added capability of adjusting its resonance frequency by altering its spring stiffness. The control system commands the adjustment of the tuning mechanism to either match the harvester's resonant frequency with the environmental excitation frequency or increase the difference between them when the displacement of the harvester reaches the maximum tolerable amplitude.

Tunable electromagnetic harvester

The tunable electromagnetic harvester follows the design presented in [4] which includes a tuning magnet fixed at the free end of the cantilever as shown in fig. 1. A second tuning movable magnet is mounted on a linear actuator. The tuning magnet poles have been arranged to create an attractive force between them. The axial tensile force exerted on the cantilever changes as the distance between the tuning magnets is modified. A reduction in the distance between magnets increases the tensile axial force on the cantilever, increasing the resonant frequency of the harvester. Conversely, increasing the distance between tuning magnets reduces the resonant frequency of the harvester. The movable magnet is operated using a bipolar linear actuator with a linear travel of 20 μm per step.

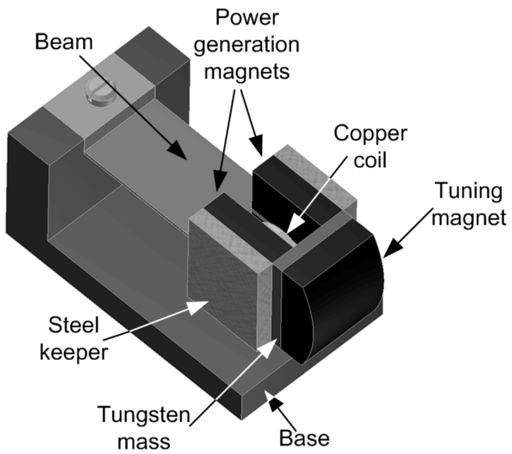

Fig. 1: Electromagnetic energy harvester with tuning magnet.

Control system

The change in the resonant frequency of the harvester is governed by the control system. In order to perform such adjustment, the tunable electromagnetic harvester includes three additional components: a microcontroller, an accelerometer and an actuator driver.

The microcontroller stores the control algorithms that command the operation of the tuning mechanism through the actuator driver. The accelerometer provides information on the environmental excitation to the microcontroller which is used to calculate the level of mistuning of the electromagnetic harvester, as presented in [3]. The actuator driver provides the power interface to operate the bipolar actuator.

Harvester displacement

The design of the tunable energy harvester allows a maximum vertical displacement at the free end of the cantilever of approximately 2.1 mm. This distance is measured from its horizontal position to its lower vertical position where it hits the base. Finite element simulations using static analysis in ANSYS predicts that a displacement of 18 mm is necessary to produce a stress in the cantilever equivalent to the yield strength of the material, and a displacement of 4.5 mm produces a stress equivalent to the maximum fatigue stress. Hence, the maximum displacement for this harvester is limited to 2.1 mm by its physical geometry not by the material employed on its construction.

HARVESTER DISPLACEMENT CONTROL

The harvester's power generation is proportional to the displacement of the mass; hence, the maximum displacement is desirable. However, an increase in the environmental excitation amplitude can produce an over range displacement of the cantilever producing physical contact with its base, and the potential risk of damage to the harvester.

The displacement of the cantilever can be expressed as function of the environmental excitation frequency (ω) and acceleration (a), the cantilever spring stiffness (k) and mass (m), and finally the damping coefficient (c), as described in Eq. (1) [5]. Hence, the displacement of the cantilever can be adjusted by modifying the spring stiffness with the existing tuning mechanism.

$$Z = \frac{m\,a}{\sqrt{(k - \omega^2 m)^2 + c^2\omega^2}} \tag{1}$$

The same tuning mechanism used for tuning the electromagnetic energy harvested is exploited to de-tune the harvester: tuning magnets and actuator.

Maximum acceleration

The first challenge is to establish the maximum environmental acceleration tolerable, which is defined as the acceleration value that produces a maximum displacement of 2 mm. This level of displacement prevents the harvester of impacting the base.

The harvester was connected in normal operation to a 5 stage voltage multiplier and storage capacitor to rectify and store the energy harvested. A variable resistive load was connected in parallel to the storage capacitor to draw energy from the capacitor maintaining a constant voltage simulating a load circuit. The environmental acceleration was gradually increased. The displacement at the tip end of the cantilever was measured using a laser vibrometer.

The voltage at the storage capacitor was varied from 2.6 to 3.2 V while maintaining the same environmental acceleration and the displacement was measured. 2.6 V is the minimum voltage required by the actuator to operate. The acceleration was then increased gradually until the maximum displacement of 2 mm was measured on the cantilever. The same test was followed at 64, 70 and 78 Hz. In every case, the harvester's resonant frequency was adjusted using the tuning mechanism to match the environmental excitation frequency.

The experimental results show that the maximum permissible acceleration level remains constant for the voltage range selected for a fixed frequency. The maximum acceleration level increases as the frequency increases; as shown in table 1. This is a result of the reduction in the environmental excitation amplitude due to the increase of frequency at a constant acceleration.

Table 1: Maximum permissible acceleration ($ms^{-2}{}_{rms}$).

Frequency (Hz)	Acceleration
64	2.75
70	3.14
78	3.73

Displacement control

As previously described, the over range protection systems relies on the same mechanism as used for tuning the harvester to match the environmental excitation frequency. To understand the detuning system a brief description of the tuning control is presented.

The tuning control algorithm contains a mathematical model relating environmental excitation frequency to the optimal position of the movable tuning magnet, which corresponds to its resonant frequency. Once the system measures a difference between the environmental excitation frequency and the resonant frequency of the harvester, the position of the movable tuning magnet is adjusted. Next, a fine tuning control compensates for errors between the model and the real harvester by adjusting the tuning mechanism to reduce the phase difference between the output signal from the harvester and the signal from the accelerometer. The harvester is at resonance when the phase difference is 0 sec.

Two over range protection algorithms were evaluated and the results are presented in the next section. The first algorithm exploits the phase difference between the harvester and the environmental excitation acceleration. When the environmental acceleration reaches its maximum tolerable amplitude, this protection algorithm increases the phase difference by moving the tuning magnet thus detuning the harvester and reducing its displacement. The second algorithm modifies the position of the movable tuning magnet away from its optimal position, at which the harvester is at resonance, in proportion to the difference between the maximum acceleration tolerable and the current environmental acceleration.

EXPERIMENTAL RESULTS

This section presents the results from practical implementation of the over range protection algorithms.

Maximum acceleration

A mathematical expression describing the maximum environmental acceleration tolerable as a function of its period was developed based on the experimental results from table 1. The equation has been constrained to a first order polynomial, Eq. (2), to reduce the processing time of the microcontroller. The period is measured using the input voltage signal from the harvester.

$$Max.Accel.[bit\ count] = 420 - \frac{Period\ [\mu sec]}{64} \qquad (2)$$

The maximum tolerable acceleration is calculated by the microcontroller and compared against the peak acceleration measured from the accelerometer. The system normally operates at acceleration levels below the maximum tolerable, so adjusts the harvester's resonant frequency to match the environmental excitation frequency. The system enters protection mode when the environmental acceleration is higher than the maximum tolerable; then the harvester's resonant frequency is adjusted to reduce the harvester's displacement. The two protection algorithms were implemented and verified as follows.

Phase difference

The system enters protection mode as the environmental acceleration reaches its maximum tolerable. This algorithm adds and error or 40 μsec to the phase measurement for every 0.135 $ms^{-2}{}_{(rms)}$ of over acceleration.

The maximum environmental acceleration that can be reached using this algorithm is only 32% above the normal maximum tolerable acceleration, increasing from 2.75 to 3.63 $ms^{-2}{}_{(rms)}$ at 64 Hz, see table 2. This algorithm is constrained by the rapid change in phase difference from a negative to a positive maximum as the harvester's resonant frequency moves away from the environmental frequency.

Fig. 2 presents the displacement of the harvester (Δ line) as the acceleration increases. The second line (◊ line) presents the phase difference measured by the microcontroller. The harvester is considered to be at resonance when the phase difference is between ±100 μsec. The black arrows represent the points where the tuning mechanism is adjusted. Due to the non-linear response of the generator, the resonant frequency requires periodic adjustment as the acceleration increases. At 2.78 $ms^{-2}{}_{(rms)}$ the maximum tolerable acceleration is reached, the phase difference starts being adjusted internally. As the acceleration increases, the phase difference increases beyond -100 μsec, which, in normal operation, would cause an adjustment of the harvester's resonance. The phase difference value used by the tuning mechanism reads a lower value, restraining any further adjustment. The magnet remains in the same position, effectively limiting the displacement of the harvester.

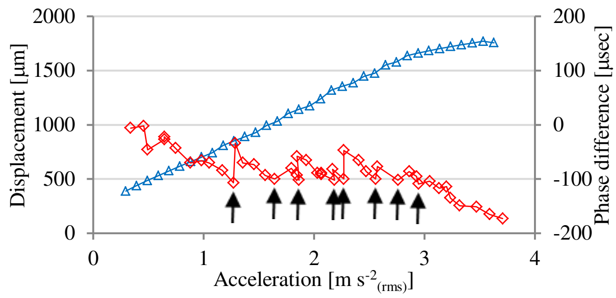

Fig. 2: Phase difference protection.(Δ) Harvester displacement, (◊) Phase difference, (↑) Adjustment of movable magnet.

Magnet position

The second protection algorithm was developed to increase the level of over range protection. This was based upon the known position of the movable magnet and its distance from the optimal position at which the harvester is at resonance. If environmental acceleration exceeds the maximum tolerable amplitude, the difference between the two magnets is increased by moving the movable magnet away from its optimal position.

For a system with a small damping ratio, such as the one presented here, the harvester's displacement is not uniformly affected when the movable tuning magnet is moved away from its optimal position. It has a greater effect on the cantilever displacement when the distance between the tuning magnets is small, while the effect is reduced as the distance increases.

This effect can be observed in fig. 3 where the over range protection has been implemented. The first line (Δ line) presents the case when the magnet position is adjusted by 20 μm, or one step in the actuator, every time the difference between the maximum tolerable acceleration and the environmental acceleration increases by 0.265 $ms^{-2}{}_{(rms)}$; starting from the maximum tolerable acceleration of 2.97 $ms^{-2}{}_{(rms)}$.

The second case (◊ line), the magnet is adjusted at a different rate depending on the acceleration level. After the maximum tolerable environmental acceleration has been reached, the magnet is adjusted 20 µm every 0.265 $ms^{-2}_{(rms)}$ until the acceleration level reaches 5.12 $ms^{-2}_{(rms)}$. Then the magnet position is adjusted 20 µm every 0.765 $ms^{-2}_{(rms)}$. These tests were performed maintaining a constant environmental frequency of 64 Hz.

The maximum acceleration that the protection system can control is limited by the acceleration range of the accelerometer, which is 9.81 ms^{-2}. This limit can be observed on fig. 3 where, around this acceleration value, the displacement starts increasing for both cases. Beyond this acceleration the system is unable to differentiate any further increase in acceleration.

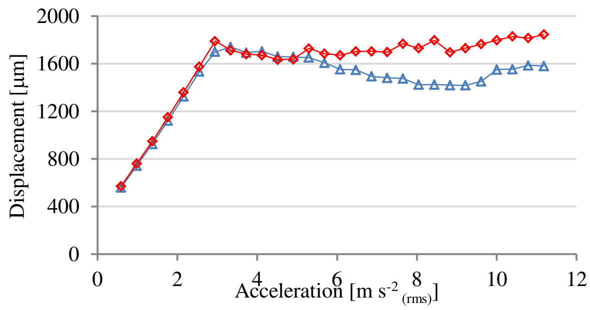

Fig. 3: Over range control using magnet position, (Δ) uniform rate, (◊) Double slope rate.

Fig. 4 shows the effect of the over range protection based on the magnet position algorithm at different environmental frequencies and accelerations; the vertical axis corresponds to the displacement of the harvester. The over range protection doesn't intervene in the adjustment of the tuning mechanism until the acceleration reaches the maximum tolerable acceleration. During the initial range, the displacement increases as the acceleration increases. After the maximum tolerable acceleration is reached, the over range protection starts adjusting the position of magnets thereby controlling the displacement.

The maximum over range protection range occurs at 64 Hz were the maximum acceleration tolerable increases from 2.75 to 9.81 $ms^{-2}_{(rms)}$, or 257%, using the magnet position protection algorithm.

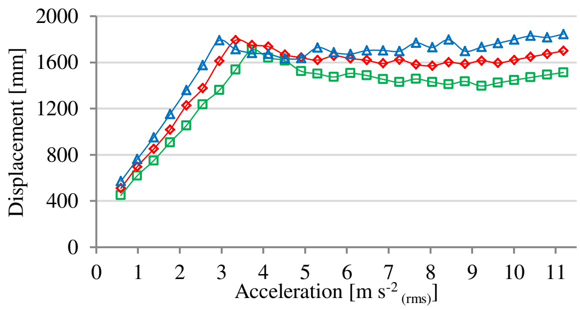

Fig. 4: Magnet position over range protection. (Δ) 64 Hz, (◊) 70 Hz and (□) 78 Hz.

Comparison

Table 2 presents a comparison between the two algorithms proposed here. 9.81 ms^{-2} is considered to be the maximum acceleration controllable because beyond this value the system can't recognise any further increase in acceleration. However, this limit can be easily expanded by integrating an accelerometer with a higher range.

Table 2: Maximum acceleration ($ms^{-2}_{(rms)}$).

Frequency (Hz)	Phase difference	Magnet position
64	3.63	9.81
70	3.92	9.81
78	4.32	9.81

CONCLUSION AND FUTURE WORK

This paper has presented the implementation of an over range protection mechanism that adjusts the harvester displacement when the acceleration increases beyond a maximum tolerable.

Two algorithms have been proposed. The second algorithm based on the magnet position offers a higher range of acceleration protection, with a 257% increase in the maximum acceleration that the harvester can withstand.

The system is currently being further optimized to increase the range of acceleration by using an alternate accelerometer.

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