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A self-tuning resonator for vibration energy harvesting

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ABSTRACT

This work is concerned with developing a vibration-based energy harvester with a tunable natural frequency. The harvester is designed to automatically adjust its own natural frequency to match that of the imposed base excitation. The proposed device consists of a cantilever beam carrying a tip mass in the form of a magnet which is placed in close proximity to another magnet with opposite polarity that can move axially thereby adjusting the beam's natural frequency by mechanical straining. The system is designed to autonomously adjust the gap between the two magnets so as to achieve a harvester whose natural frequency matches that of the excitation. As such, the movable magnet is mounted on a motor-driven tray that undergoes linear motion and adjusts its position in accordance with the frequency of the support motion. The base motion frequency is detected by an electromagnetic means, wherein another magnet, fixed to the base, moves past a stationary coil generating an electric signal. The signal is conditioned through a microprocessor to detect its frequency and is then used to determine the favorable gap between the tuning magnets to achieve resonance from a lookup table. Based on the findings of this work, the natural frequency of the harvester is successfully tuned from 4.7 Hz to 9.0 Hz generating voltage per acceleration from 6.3 V/m/s^2 to 1.1 V/m/s^2, respectively.

1. Introduction

The recent years have witnessed a wealth of research on energy harvesting technologies wherein useful energy is extracted from ambient sources that are otherwise neglected. For maximum power output, vibration-based energy harvesters are usually designed to exhibit natural frequencies that match those of the excitation. As resonators normally possess high quality factors, a slight deviation from operation at resonance due to changes in the operating conditions or manufacturing errors leads to a substantial reduction in the output power generated. This has spurred interest into the design of devices that respond to a wide bandwidth to maintain an acceptable level of harvested power. In this context, the review papers by Tang et al. [1], Zhu et al. [2] and Ibrahim and Ali [3] on the techniques to increase the bandwidth of vibration-based energy harvesters are valuable.

Insight into the pertinent literature reveals that two main approaches have been adopted to address this issue. The first approach relies on widening the bandwidth of an essentially passive device, i.e. one whose design parameters are fixed. This is normally accomplished by designing harvesters that exhibit favorable dynamics to cope with variable-frequency excitation environments. Examples of these solutions include the use of nonlinearities [4,5], designs having multiple oscillators [6,7] and structures exhibiting multiple resonance frequencies [8–13] to harvest energy from a wide band of frequencies. The second approach relies on actively tuning the resonance frequency of a harvester, in response to the forcing environment, in order to attain resonance constantly. In this context, systems with manually [14] and automatically [15,16] adjustable natural frequencies have been proposed to improve the performance. While attempts to vary the natural frequency of an energy harvester by changing its length [17] or the center of mass of its inertial mass [18] have been reported, the most popular approaches depend on mechanical stiffening [14–16,19–21] wherein external forces are applied by actuators or magnets to strain the harvester, thereby altering its resonance frequency. A key component in self-tunable harvesters is the frequency sensing technique, which is usually employed as part of a control system to automatically adjust the natural frequency. Several approaches have been proposed in the literature, including maximization of the output voltage [15] and detection of the phase between the base acceleration and structural deflection [22].

This paper is concerned with the development of a low-cost self-tuning electromagnetic energy harvester combining both frequency detection and self-actuation. Frequency adjustment is attained through the use of permanent magnets that induce tensile forces on the resonator. Frequency sensing relies on using a

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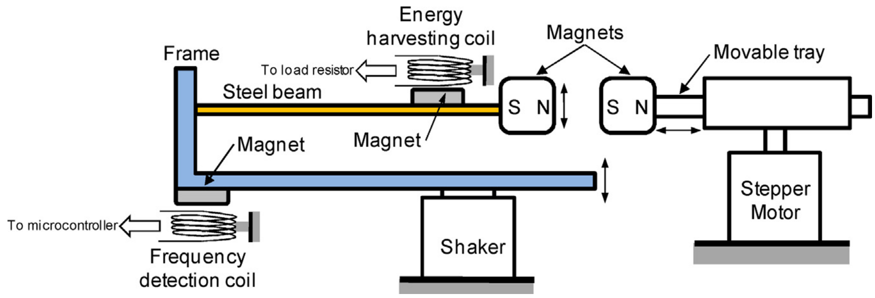

Fig. 1. Schematic illustration of proposed energy harvester.

microcontroller to measure the inverse of the periodic time of the incoming vibrations by an electromagnetic sensor. This information is utilized to give instructions to drive a linear actuator to tune the resonance frequency in an open-loop control algorithm. The remainder of this paper is organized into four sections. Section 2 outlines the proposed harvester design, together with the frequency sensing mechanism and gap calculation. Section 3 presents an experimental validation of the proposed algorithms, whereas Section 4 is dedicated to conclusions and recommendations.

2. Harvester design

Fig. 1 shows a schematic illustration of the proposed energy harvester. A cantilever beam is mounted on a shaker. The beam carries a tip mass in the form of a permanent magnet that is attached to the beam tip. An opposite magnet is attached to a movable tray that is driven by a stepper motor through a rack and pinion mechanism. In this way, variable attraction forces can be applied to the beam to control its natural frequency. The beam is mounted on a rigid frame that is excited harmonically by a shaker. Two magnet-coil units (with fixed coils) are employed in the present design; one is responsible for energy harvesting (magnet attached on vibrating beam), whereas the second is utilized for detecting the frequency of base motion (magnet mounted on moving frame). As the shaker vibrates, the signal picked up by the frequency detection coil is conditioned and analyzed in real time by a micro-processor to identify the incoming frequency of base motion. This data is then used to drive the stepper motor to adjust the beam's natural frequency to match the excitation frequency, thereby ensuring resonance for a range of excitation frequencies.

The flow diagram shown in Fig. 2 illustrates how the stepper motor moves in response to the signal picked up by the frequency detection coil. For sinusoidal excitation, the signal picked up by the frequency detection coil is first fed into an operational amplifier in order to amplify and convert it to a square wave, which in turn is fed to a microcontroller. The microcontroller is responsible for detecting the frequency of the base motion and issuing the commands to move the stepper motor so as to match the harvester's natural frequency with that of the incoming vibrations. A description of the different subsystems and components constituting the frequency detection methodology is provided in the next section.

2.1. Frequency detection

Under harmonic base excitation, the signal picked up by the frequency detection coil will be a low-amplitude sine wave. The method proposed to sense the excitation frequency relies on measuring the period of the measured time-domain signal. This is conveniently accomplished by converting the resulting sine wave into a square wave and designing a positive-edge-triggered microcontroller circuit to measure the time between two successive cycles, from which the frequency can be determined by calculating the inverse of that time. The code developed for this purpose contains an infinite loop which instructs the device to keep measuring the frequency indefinitely, allowing the harvester to respond to continuously variable frequencies. The microcontroller chosen in this work is of the type PIC16F877A. As the output signal from the frequency detection coil will be in the order of milli-Volts, whereas the interrupt pin of the microcontroller needs a 2.4 V to operate, an operational amplifier of the type 741 is used to perform the dual functions of amplifying the signal and converting it to a square wave, as illustrated in Fig. 2.

2.2. Effect of magnetic forces on natural frequencies

In order to study the effect of the magnetic forces on the cantilever beam's natural frequencies, a finite element model of the beam is developed. The beam under investigation is modeled as an

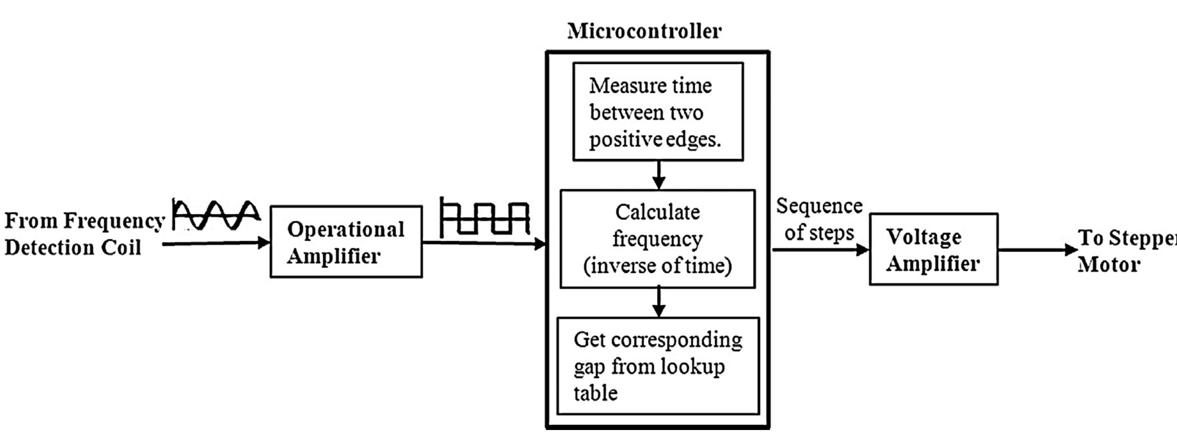

Fig. 2. Flow diagram of the frequency detection algorithm.