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A dual-purpose vibration isolator energy harvester: Experiment and model

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ABSTRACT

A new dual-purpose vibration isolator energy harvester device suitable for low frequency operation is presented in this work. The device features a combination of elastic and magnetic components to facilitate its dual functionality. The main purpose of the dual-purpose device is preventing vibrations from traveling through the isolated mass using magnetic and viscous dampers and elastic and magnetic springs. A secondary task is converting some of the kinetic energy contained in these oscillations into useful electric energy. Numerical and analytical models are developed and used to simulate the behavior of the device. The models are validated against measured data. Experiments demonstrate the ability of the device to, simultaneously, isolate the desired mass and harvest energy from unwanted free vibrations. The dual-purpose device attenuates oscillations higher than 12.5 [Hz] while, simultaneously, recovers 0.115 [mW] at 9.81 $m.s^{-2}$. The power produced by the dual-purpose device is significantly higher than the power recovered by its rival regenerative devices reported in literature. Moreover, results from model parametric study and experimental data show that the combined positive and negative stiffness elements in this device hold the promise for lower operating frequencies and higher output power. Initial results suggest that lowering the linear stiffness of the device can potentially lower the cut-off frequency to approximately 9 [Hz] while generating 1 [mW] electric power.

1. Introduction

Undesired vibrations and oscillations are the by-products from natural processes as well as human made structures and equipment. Examples of these vibrations include continuous or semi-continuous oscillations generated by highway bridges [1], human body motion [2], and moving vehicles [3–6]. On one hand, some of these vibrations may cause severe damage to structures or obstruct their operations [7]. On the other hand, these vibrations represent free and abundant form of kinetic energy [8,9]. As a result dealing with these vibrations has grown in two main directions: vibration isolation [10–12] and energy harvesting [13,14].

The literature on both vibration energy harvesting and vibration isolation is massive. Reviewing this massive literature is beyond the scope of this work. Nonetheless, energy from ambient vibrations has been successfully converted into useful electric energy via electrostatic [15,16], piezoelectric [17], and electromagnetic transducers [18–20]. Recent advances and approaches in energy harvesting have been reviewed in Ref. [13,14]. Similarly, active and passive vibration control systems

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have been developed and thoroughly investigated over the past few decades [21,22]. A typical vibration isolation system uses a spring and a damper to prevent these oscillations from traveling between the source of vibrations and the isolated mass [23]. Using this spring-mass-damper system the kinetic energy from these oscillations is suppressed and dissipated into waste heat that is conducted away to the surrounding.

Continuous improvement in electronics manufacturing has led to deployment of low-power sensors and gadgets [24–26]. Nowadays, onboard sensing units are installed on equipment and structures to monitor their health conditions including temperature, pressure, stress, strain, humidity, corrosion, etc [1,13,26,27]. Thus, there has been growing interest in using the energy from these oscillations as power source replacing or complementing traditional batteries used to operate onboard sensors [28–30]. For instance, Davis and McDowell built a passive regenerative vibration isolation device using post-buckled beam as spring element and piezoelectric film as power conversion unit [30]. Their results showed that experimental transmissibility of 2% and harvested power of 0.36 μW were achieved simultaneously. Similarly, Ali and Adhikari studied, theoretically, the performance of regenerative vibration absorber device supplemented with a piezoelectric stack for power recovery [31]. The study focused on modeling and design aspects of optimal design parameters using approximate fixed-point theory. Their study concluded that specific parameters of the energy harvester could lead to broadband harvesting combined with vibration absorption. In Ref. [32] the feasibility of integrating vibration absorber with piezoelectric stack for power generation under random excitations was investigated using probabilistic linear random vibration theory. Results from this theoretical study showed that the recovered power increases with increase in the mass of structure. Moreover, a dual-purpose device was developed to isolate micro vibrations and harvest energy from micro-jitters of a cooler during satellite on-orbit operation [7]. The dual-purpose device was able to isolate the desired mass and recovered 5.84 μW of vibration energy into electric energy. Also, a semi-active energy harvesting vibration suppression system using piezoelectric platform was proposed [33]. Tang and Zuo investigated the recovery of vibration energy from tall buildings using active tuned mass dampers and electromagnetic harvesters [34,35]. Furthermore, several studies investigated energy recovery from vehicle road interactions using regenerative vibration shock absorbers [36–39]. These studies focused on manufacturing of large scale regenerative hydraulic/pneumatic suspension systems that convert kinetic vibrational energy into hydraulic/pneumatic pressure and storing it in an accumulator [36–39]. This hydraulic power was then used to run a hydraulic motor. For instance, a macro-scale hydraulic-electromagnetic vibration absorber capable of recovering energy from vehicle interaction with road was investigated by Fang et al. [37]. While energy losses from pipelines were significant the device was able to recover energy from vibrations. The authors of the study denoted that the energy recovery efficiency of their device decreased as the excitation frequency increased. Recent progress on regenerative vibration suppression systems for vehicles was reviewed by Zhang Jin-qiu et al. [29].

The work presented here is focused on developing a unique dual-purpose vibration isolation energy recovery system shown in Fig. 1. While several studies were focused on coupling small scale piezoelectric energy harvesting units with vibration isolation [30], the work presented here targets the use of elastic and magnetic elements to achieve the dual functionality of the device. The main purpose of the dual-purpose device is preventing vibrations from traveling through the isolated mass using magnetic and viscous dampers and elastic and magnetic springs. However, a secondary task of the dual-purpose device is converting some of the kinetic energy contained in these oscillations into useful electric charge, instead of waste heat,

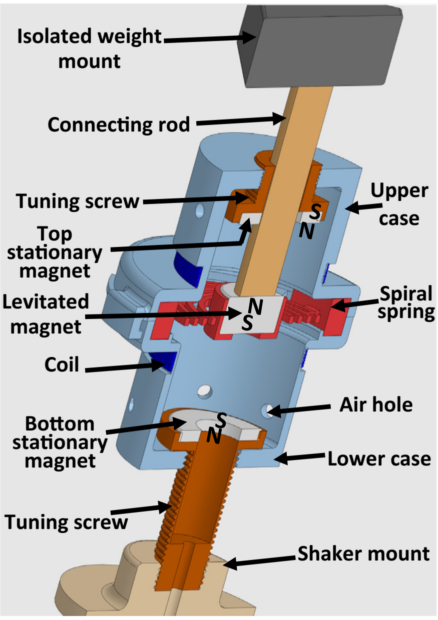

Fig. 1. Overall design of the dual purpose vibration isolator energy harvester.