A Design of the Two Architectures of Electromagnetic Vibration Energy Harvesting Devices

M. Maták, M. Gašparík, P. Šolek and M. Margetin

Abstract This paper presents two architectures of electromagnetic vibration energy harvesters. The first presented architecture of vibration energy harvester is comprised by a coil rotationally moving in magnetic field. Design goal is to produce the harvester capable of effective operation in wide range of frequencies and able to utilize vibrations from all directions in one plane. This architecture is capable of utilizing the low frequency vibrations as well. During the experiment, a peak voltage of approximately 1.2 V has been measured at 25 Hz harmonic excitation. The second architecture is comprised by cylindrical magnet moving inside the PMMA tube, along the axis of a coil wound around this tube. Magnetic mass of the harvester is suspended on magnetic springs on both sides. Ease of manufacture and customization of the harvester are emphasized in the design to allow fitting the parameters of the harvester to existing condition of vibration source.

Keywords Vibration energy harvesting · Electromagnetic induction · Energy scavenging

1 Introduction

Energy harvesting (or energy scavenging) is process of transformation of ambient energy into useful electric energy. In past decade, energy harvesting has become a viable source of power for low-powered systems. These systems include various

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sensors and devices operating in remote areas. Utilizing the energy from ambient sources greatly enhances usability of such devices by making them practically maintenance-free and fully autonomous.

Sources of ambient energy that can be artificially harvested an their respective available power densities are: solar energy—approximately 15000 μW/cm^2 (outdoor, sunny day), mechanical vibrations—375 μW/cm^3, fluid flow—380 μW/cm^3, temperature variation—40 and 1 μW/cm^3 for both acoustic and radio frequency energy [1, 2].

2 Electromagnetic Energy Harvesting Devices

The source of ambient mechanical energy can be either movement of industrial structure due to its operation, movement of human body or fluid flow. The frequency of mechanical motions depends on its source and in general can be considered less than 10 Hz for human movements and approximately 30 Hz for machinery vibrations [1].

From point of view of transduction mechanisms used to transfer the kinetic energy of vibrations to electricity, four options are available: piezoelectric, electromagnetic, electrostatic and magnetostrictive. According to various authors [3, 4], piezoelectric generators are best suited for microscale applications, while for situations where miniature dimensions are not necessary, electromagnetic generators are preferred because no smart materials are required and electromagnetic generators are robust and sturdy.

2.1 Principle of Operation

From point of view of mechanics, most vibration energy harvesters are 1DOF systems with base excitation (Fig. 1). From point of view of mathematics, the system is described by 2nd order differential equation.

$$M\ddot{z} + b\dot{z} + kz = -m\ddot{y} \tag{1}$$

Multiplying Eq. (1) by relative velocity $\dot{z}$ we get the flow of mechanical power in the system. In Eq. (2), the first member represents the change of kinetic and

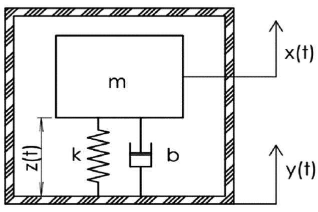

Fig. 1 Physical model of electromagnetic generator

potential energy, and the second member represents the power dissipated by the damper [5]. The members on the right side represent the power flow into system through spring and damper.

$$\frac{d}{dt}\left(\frac{m\dot{x}^2}{2}+\frac{k(x-y)^2}{2}\right)+b(\dot{x}-\dot{y})^2=b(\dot{x}-\dot{y})\dot{y}+k(x-y)\dot{y} \tag{2}$$

Damping in system is provided either by mechanical damping inherent to the structure and by electromagnetic damping, which occurs during transduction of mechanical energy to electric energy.

$$b=b_m+b_e \tag{3}$$

The expression $b\dot{z}^2$ in Eq. (2) represents all the power drawn from the system and only portion of it is available for transfer to electric power.

For harmonic excitation and steady state solution, we get following expression for the amplitude of relative displacement

$$Z=\frac{m\omega^2 Y}{\sqrt{(k-m\omega^2)^2+b^2\omega^2}}=\frac{r^2 Y}{\sqrt{(1-r^2)^2+(2\xi r)^2}} \tag{4}$$

The average power draw from the system is defined as

$$P_{av}=\frac{m\omega_0^3 Y^2\xi r^6}{(1-r^2)^2+(2\xi r)^2} \tag{5}$$

The maximum power draw from the system occurs at frequency ratio r defined as

$$r_{max}=\sqrt{2-4\xi^2-\sqrt{16\xi^4-16\xi^2+1}} \tag{6}$$

Maximum power draw from the system with given parameters occurs at frequency defined in Eq. (6). However, in design process, more important question is not the frequency ratio at which is the power output maximal for given generator, but the frequency ratio of harvester generating maximum power at given frequency of base excitation specific for the source. The generator should be tailored for the vibration source and not otherwise [3]. Using Eqs. (4) and (5) to redefine the average power P_{av} as a function of spring stiffness k, the r of the optimal generator is defined as:

$$r_{\max,k}=\sqrt{\frac{3}{1-2\xi^2+2\sqrt{\xi^4-\xi^2+1}}} \tag{7}$$

As Eqs. (6) and (7) show, the optimal generator for given frequency of source is operating at frequency ratio $r > 1$. A clear conclusion can be drawn from Eq. (5) that the higher angular frequency of the generator ω_n and larger amplitude of base excitation Y, the higher average harvested power. This means that it is much easier to get serious amount of power at higher frequency and therefore direct comparison of generator designs using only generated power as criterion is not always appropriate. Since machine vibrations occur at lower frequencies [6], it is important to present generator design capable of utilizing these vibrations effectively

2.2 Architectures of Generators

The vast majority of vibration generators use the effect of resonance to get the maximum possible power output. This fact makes them inherently narrowband [3]. The use of nonlinear springs to widen the resonance bandwidth is common. Design intent of both presented architectures is to produce a generator with broad bandwidth and the ability to operate effectively at low frequency.

2.2.1 Architecture 1

The architecture 1 is an attempt to produce generator capable not based on resonance principle with the added benefit of being able to harvest energy equally from all directions in plane of the generator. It is in concept similar to generator presented in [7], but with different arrangement. The generator uses the movement of the coil in magnetic field and its layout resembles the hard disk drive actuator arm. The generator is depicted on Fig. 2b. Two variants of this architecture (marked as type 1 and type 2) have been assembled and tested, the only difference between them being the arrangement of the magnets.

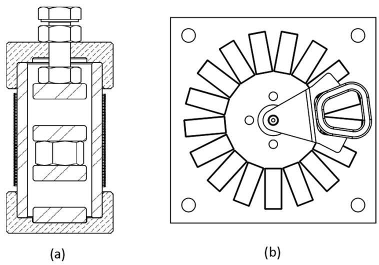

Fig. 2 Architectures 1 and 2 of proposed harvesters

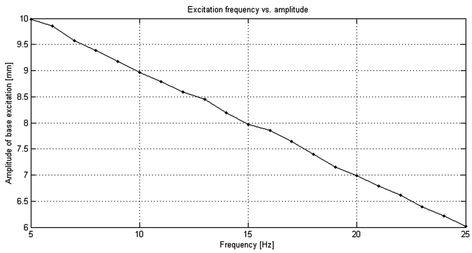

Fig. 3 Amplitudes of harmonic excitation

2.2.2 Architecture 2

The second architecture is a translational generator utilizing the motion of magnet inside the coil. The repelling force of neodymium magnets has been used as a nonlinear spring [8]. The generator has been designed with adjustable preload of magnetic springs and various configurations of inner magnets has been considered as well. Two samples (marked V1 and V2) with different dimensions and inner magnetic members has been assembled and tested. The layout of harvester is pictured in Fig. 2a.

2.3 Measured Results

Both architectures of generators have been tested on hydraulic actuator. Since our interest lies in low frequency range, the harvesters has been excited by harmonic signal with frequency range from 5 to 25 Hz. The measured data have been obtained using the NI myDAQ device. Measured physical parameter was voltage. The amplitudes of excitation are depicted in Fig. 3. Figure 4 shows the raw measured data for both architectures and variants. After processing the measured data using Matlab, average harvested voltages and powers have been calculated for both

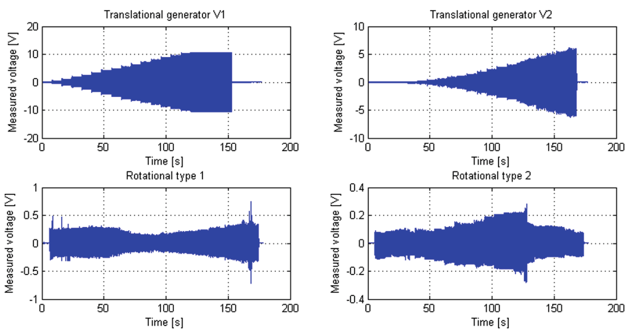

Fig. 4 Raw measured data

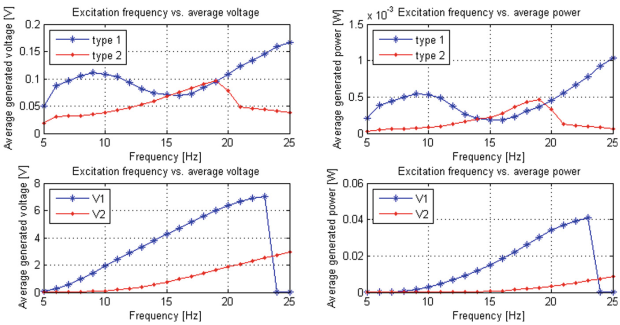

Fig. 5 Processed results for architectures 1 and 2

types of generators for both architectures. Average voltages and powers for architectures 1 and 2 are shown in Fig. 5.

3 Conclusion

As the measured results show, both harvesters of architecture 1 struggle to get usable voltage. On the other hand, architecture 2 has performed above expectations with V1 harvester even exceeding the voltage limit of NI myDAQ used to measure the output voltage. The results shown in this article are from initial testing, there is a solid potential for further growth.

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