Sensors and Actuators A 256 (2017) 1–11

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Temperature dependence of a magnetically levitated electromagnetic vibration energy harvester

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ARTICLE INFO

Article history:
Received 3 August 2016
Received in revised form 5 December 2016
Accepted 9 January 2017
Available online 12 January 2017

Keywords:
Electromagnetic
Energy harvesting
Magnetic levitation
Magnetic spring
Temperature effect

ABSTRACT

Electromagnetic vibration energy harvesters including magnetically levitated devices where opposing magnets are used to form the spring have been well documented. The strength of the magnets naturally has a large influence on the dynamic characteristics and output power of such harvesters. However, it can be affected by ambient temperatures which vary from applications to applications. This paper presents investigation into the performance of a magnetically levitated electromagnetic energy harvester under various ambient temperatures. Parameters investigated include magnetic flux density, resonant frequency, damping ratio, open circuit output voltage, velocity of the relative motion and the load resistance. Both simulation and experimental results show that these properties vary with ambient temperatures. The magnetic flux density reduces as the temperature increases which results in lower resonant frequency, lower relative velocity, lower open circuit output voltage and higher damping ratio. Varying resonant frequencies with temperature can lead to harvesters being de-tuned from the target vibration frequency. Decreasing magnetic field strength and increased damping ratios will also reduce output power even if the harvester's resonant frequency still matches the environmental vibration frequency. The power transferred to the electrical load will be reduced due to the variation in the optimal load resistance with temperature. This means the harvester is no longer matched to achieve the maximum harvested power. The specified maximum operating temperature of the magnets was found to lead to partial demagnetisation. When cycling from room to the maximum specified temperature, the magnetic field was initially found to fall but remained constant thereafter. Harvesters were found to operate beyond the specified maximum operating temperature of the magnet, but suffer from a reduced magnetic strength.

1. Introduction

In recent years, energy harvesters have been widely developed for various applications due to their ability to generate power from the ambient environment and overcome the limitations of batteries such as finite lifetime, issue of disposal, limited power density, and cost of maintenance [1]. One of the most common energy harvesters is kinetic energy harvesters that convert energy in the form of vibrations or environmental motion into electrical energy typically using electromagnetic, piezoelectric or electrostatic transduction mechanisms.

Electromagnetic transduction has been achieved by exploiting relative movement between permanent magnets and a coil, by varying flux gradients intersecting a coil or a combination of these. The velocity of the relative movement between the magnets and coils, the number of coil turns, and the strength of the magnetic field all affect the amount of electrical energy that can be generated [2]. The temperature effects have been considered in some of the reported electromagnetic transducers especially in the processes of design and fabrication. Glynne-Jones et al. [3] addressed the compatibility of working temperature and type of magnet to maintain strong flux density for a high degree of coupling. Neodymium-Iron-Boron (NdFeB) chosen for their electromagnetic generator in order to apply with the car engine which has a working temperature of up to 120 °C. Zorlu et al. [4] mentioned that the variation of the damping ratio with temperature has an influence on the analytical results of performance of the electromagnetic energy harvester proposed. The fabrication process of the electromagnetic energy

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http://dx.doi.org/10.1016/j.sna.2017.01.011
0924-4247/

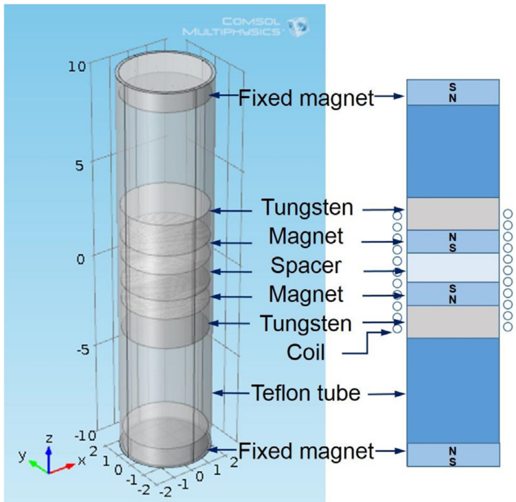

Fig. 1. Schematic of magnet levitated harvester [11].

harvester using buried NdFeB proposed by [5] was improved by maintaining process temperatures below 60 °C in order to avoid the demagnetization of the magnetic film which otherwise would cause deterioration in the performance of the final device. These papers highlight the importance of considering temperature when fabricating or using electromagnetic transducers, but to the best of our knowledge the effects of temperature on electromagnetic vibration energy harvesters have not been discussed in details.

The temperature dependence of the coercive fields in permanent magnets has been investigated by Hu et al. [6]. Magnets lose their magnetism when they are operated in an ambient temperature that exceeds their Curie temperature. It was also shown that the remanence and coercivity decrease with rising ambient temperature as characterised by the temperature-dependence equations presented by Calin et al. [7]. Luo et al. [8] highlighted that the effect of temperature should be considered alongside the grade of magnet used because the low Curie temperature of some magnets leads to a limited operating temperature range potentially close to room temperature that makes them unsuitable for many applications. Example specified temperature ranges for different types of applications include 0 °C to 70 °C for commercial, −20 °C to 85 °C for industrial, −40 °C to 125 °C for automotive and −55 °C to 125 °C for military. Typical temperature properties for a range of magnet materials are provided in Table 1.

Although the influence of temperature on magnetic properties has been widely investigated, characterization of electromagnetic energy harvesters under various ambient temperatures has not been well studied. The effects of temperature variations are an important consideration for all electromagnetic energy harvesters, and are especially relevant in the case of magnetically-levitated energy harvesters. Therefore, this paper studies the effects of temperature on the performance and fundamental properties of a magnetically-levitated energy harvester such as that shown in Fig. 1. The variation of magnetic flux density, the resonant frequency, damping ratio/quality factor, velocity of relative motion, open circuit output voltage and the optimal load resistance are all affected by temperature.

In this paper, the design and fabrication of the energy harvester used in the experiments are described. The theoretical background and the governing equations relating to magnetically levitated harvesters and magnetic characteristics are given in Section 3. A comprehensive set of experimental and simulation results are presented and discussed in Section 5.

2. Structure of the energy harvester

The harvester shown in Fig. 1 represents a standard configuration demonstrated in several devices in the literature [12–18], with some variations in the design and arrangement of the moving-mass components. Some of these harvesters were developed for harvesting energy from human movement which is characterized by low frequency high amplitude displacements [19,20]. The effect of temperature on the performance of such harvesters is least important in human applications due to the limited temperature range e.g. 0 °C–40 °C. In contrast, this magnetically levitated configuration has also been applied for harvesting energy from tyre deformation. The harvesters were developed to power a wireless sensor network attached at the inner surface of the tyre for measuring the interaction between the road and vehicle, i.e. pressure, temperature and acceleration [16,21]. The standard automotive temperature range is −40 °C to 125 °C and this is a real practical consideration since when traveling at a velocity of 100 km/h or when breaking from of 35 km/h tyre temperature can reach to 80 °C and 90 °C respectively [22,23].

The harvester studied in this work consists of two fixed magnets at the top and bottom of a Teflon tube. The tube contains a moving mass consisting of two magnets with a ferromagnetic spacer placed in between them in order to join the magnets together and concentrate the magnetic flux. In addition, the magnets have been aligned with like-poles facing each other as shown in Fig. 1. The magnetic flux density generated by the magnets at different temperatures was simulated by COMSOL as shown in Fig. 2. The voltage is induced in a stationary copper coil due to the variable and moving magnetic field that intersects it.

The interaction between the fixed and moving magnets results in nonlinear behaviour. The magnetic forces are nonlinearly varying with separation distance which results in a nonlinear magnetic spring. The properties of the magnetic spring are determined by the properties and strength of the magnets. Thermal demagnetization of the permanent magnets will reduce the performance of the harvester and change the dynamic behaviour of the magnetically levitated energy harvester. These effects will be explored using both simulations and experimental analysis and the results can be adapted for other types of devices.

3. Theoretical background

3.1. Magnet characteristics

The magnet chosen for this work is NdFeB magnet (hard magnetic material) which has a high magnetic strength and magnetic coercivity [24–26]. The characteristics of a magnetic material are shown by its hysteresis plot, which illustrates the ability of a magnetic material to retain its magnetization. The hysteresis behaviour of each magnetic material is indicated by magnetic parameters such as coercivity (H_c) and remanence (B_r). The ability of the magnet to resist demagnetization is indicated by the value of coercivity (H_c) with higher values meaning it is more difficult to magnetise or demagnetise the material [27]. The residual magnetisation after the removal of the external magnetic force used to polarise the magnet is denoted by the remanence (B_r) [28]. The higher the remanence, the larger the magnetic flux density (B) produced by the magnet, for example, described by Eq. (1) which is an estimate of the magnetic flux density, B, produced by a cylindrical magnet [29].

$$B(S) = \frac{B_r}{2}\left(\frac{(S+L)}{\sqrt{(S+L)^2+R^2}} - \frac{S}{\sqrt{S^2+R^2}}\right) \quad (1)$$

where S is the distance from a pole face on the symmetrical axis (m), L is the length of magnet (m), and R is the radius of magnet