Journal of Sound and Vibration 433 (2018) 385–424

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Energy harvesting with electromagnetic and piezoelectric seismic transducers: Unified theory and experimental validation

L. Dal Bo[*], P. Gardonio

Università degli Studi di Udine, DPIA, Via delle Scienze, 208-33100, Udine, Italy

A R T I C L E I N F O

Article history:
Received 22 September 2017
Received in revised form 28 February 2018
Accepted 13 June 2018

Handling Editor: D. J. Wagg

Keywords:
Vibration energy harvesting
Electromagnetic transducer
Piezoelectric transducer

A B S T R A C T

This paper presents a comparative simulation and experimental study on the principal features of time-harmonic vibration energy harvesting with electromagnetic and piezoelectric seismic transducers. The study is based on equivalent lumped parameter models and a consistent formulation of the constitutive electromechanical equations for the two transducers so that a unified energy formulation is derived for the two harvesters. The electromagnetic seismic transducer is formed by a moving ferromagnetic ring and coil assembly, which is elastically suspended on a core magnetic element. The piezoelectric seismic transducer is made of a piezoelectric beam laminate with one end clamped to a base block and the other free-end equipped with a tip block. The two seismic transducers are designed and built in such a way as they have similar weights and similar volumes of the base components, similar weights and similar volumes of the suspended components and about the same fundamental natural frequencies. Both transducers are connected to either a resistive-reactive or a purely resistive harvesting impedance load. The study shows that the peak vibration energy harvested with the two systems is heavily influenced by eddy current losses in the electromagnetic seismic transducer and dielectric losses in the piezoelectric seismic transducer. In general, the electromagnetic seismic harvester is characterised by a rather high damping effect that limits the peak value of the stroke and thus of the power harvested per unit base acceleration. Instead, the piezoelectric seismic harvester is characterised by a relatively smaller damping effect such that the peak value of the stroke and thus of the power harvested per unit base acceleration are comparatively larger. Nevertheless, when the harvested power per unit stroke of the seismic transducers is examined, the behaviour is inverted, also in case the electromagnetic transducer was not affected by eddy currents losses. Finally, in general, the electromagnetic harvester outperforms the piezoelectric harvester when it is operated at off resonance frequencies.

1. Introduction

The process used to convert ambient vibration energy into electric energy is generally known as vibration energy/power harvesting/scavenging. This approach has received growing attention in the last two decades, as a potential local source of

---

[*] Corresponding author.
E-mail address: dalbo.loris@spes.uniud.it (L. Dal Bo).

https://doi.org/10.1016/j.jsv.2018.06.034

energy to run low power consumption electronic components. As summarised in the books and articles listed respectively in Refs. [1–4] and [5–18] for example, several technologies based on different electromechanical transducers have been studied, which cover a vast range of energy densities, dimensions and weights of the harvesters. In most cases, the energy harvesters are formed by seismic transducers that effectively convert vibration energy into electrical energy [19–24]. These transducers are interfaced to electrical circuits, which, in general, are designed to accomplish three tasks [4,25–29]: firstly, maximising the energy absorption via the electromechanical seismic transducer, secondly, storing the absorbed energy into super-capacitors or small batteries and thirdly using the stored energy to activate low power electrical apparatuses. Often, the harvested electrical energy is used during short periods of time to run very low power consumption electrical circuits that, for example, implement control actions, condition monitoring functions, communication tasks, etc. In general, seismic harvesters can be used to effectively absorb energy from tonal or broadband ambient vibrations [1–3]. In the former case, the electromechanical seismic transducer is characterised by a dominant second-order response with a sharp resonance peak at the excitation frequency. Instead, in the latter case it is characterised by multiple second-order responses with closely-spaced resonance peaks that overlap and form a smooth and wide resonance crest in the frequency band of interest. Thus, the energy harvesters for tonal and brad band vibrations are based on the same operation principle, that is the single resonant or multiple-resonant response of the transducer at the frequency or frequency-band of interest. Often, more sophisticated seismic transducers exhibiting non-linear properties are used to widen the frequency-band of operation and to self-level the stroke of the transducer so as to maximise the power extraction for a wide range of frequencies [1–3,30–41] and amplitudes of the ambient vibrations [1–3,42–45]. Vibration energy harvesting systems provide tiny quantities of power that go from the order of milli-watts, for devices smaller than 1 kg, to the order of watts, for devices larger than 1 kg [11,23,24,46,47]. Several applications have been explored over the years [1–3,11]. For example, vibration energy harvesting devices have been implanted on the human body to power medical devices [7,8,11,20]. Clothes have been equipped with smart piezoelectric films to power low-energy electronic apparatuses [7,11,20]. Vibration energy harvesting systems have been mounted on transportation vehicles and industrial machinery to run condition monitoring devices [7,8,20,22,25,26]. Buildings and transportation infrastructures have been equipped with vibration energy harvesters to power condition monitoring devices and low power consumption electronic equipment [7,8,20,22,24]. Smart vibration harvesting structures have been set in air or water flows to extract energy from vortex-induced, aerodynamic flutter and turbulence phenomena and used to power condition monitoring devices [48–55].

This paper is focussed on time-harmonic vibration energy harvesting with electromagnetic [1,2,56–59] and piezoelectric [1,3,58,59] seismic transducers, which, according to the literature, are the most common seismic transducers used in practical applications. The study presents both theoretical and experimental results taken on two prototype electromagnetic and piezoelectric seismic harvesters having: a) similar weights and similar volumes of the base components, b) similar weights and similar volumes of the moving components and c) about the same fundamental natural frequency, that is about 20 Hz. The first harvester, is formed by a moving ferromagnetic ring and coil assembly elastically suspended to a cylindrical core magnet via two spiral springs. The second harvester, is formed by a piezoelectric beam laminate with one end clamped to a base block and the other free-end equipped with a tip block. The work presented here builds up on refs. [60,61] and presents a unified energy formulation based on a common lumped parameter schematic for the two types of transducers, which allows a direct comparison of the electromechanical responses and energy absorption properties of electromagnetic and piezoelectric seismic vibration harvesters. The energy formulation is derived from constitutive electromechanical equations, written in a consistent form, for the electromagnetic and piezoelectric seismic transducers using Frequency Response Function (FRFs), [56–59]. The two constitutive equations are characterised by the input mechanical impedance FRF, the output electrical impedance FRF and the mechanical-to-electrical and electrical-to-mechanical transduction FRFs. The proposed unified formulation is used to: a) characterise the principal electromechanical properties of the two seismic transducers, b) derive the frequency-dependent optimal impedances of the harvesting electrical loads and c) derive the spectra of the power harvested by, and power input to, the two transducers with reference to harmonic base excitations. The constitutive equations and energy formulation are validated experimentally with measurements taken on the prototype electromagnetic and piezoelectric seismic harvesters. To fully characterise the two seismic harvesters, the time-harmonic response and energy harvested of the two seismic transducers is investigated in a wide frequency band comprised between 10 Hz and 1 kHz, which encompass the fundamental natural frequency of the two transducers at about 20 Hz and other natural frequencies due to higher order dynamics of the two transducers.

In contrast to classical formulations that can be found in literature [1,3,5–7], the constitutive equations for the piezoelectric seismic transducer are rewritten in such a way as they are consistent with the standard constitutive equations used for electromagnetic seismic transducers. Therefore, for the mechanical response, the spring-damper-mass modal parameters for the first flexural mode response of the composite beam transducer with the base and tip masses are reworked into base and seismic equivalent masses connected by equivalent spring and damper elements in parallel with a current controlled force source. Also, for the electrical response, the electric mesh is modelled in terms of a relative velocity controlled voltage source derived considering the contribution of the first flexural mode of the composite beam transducer with the base and tip masses in series with a capacitor that accounts for the capacitive effects of the two piezoelectric patches, which are connected in parallel. The lumped parameter elements are therefore derived from the exact analytical modal response of the composite beam transducer with the moving base mass and the seismic tip mass rather than the simplified formulae available in the literature. These expressions normally consider the bending stiffness derived from the static deflection of the cantilevered composite beam due to a concentrated transverse load at the tip and the equivalent seismic mass is obtained by expressing