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A magnetoelectric vibration converter with tunable resonance frequency

Magnetoelektrischer Vibrationswandler mit einstellbarer Resonanzfrequenz

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Abstract: Integration of smart materials to harvest energy from low vibration sources for powering wireless sensor networks has been of significant interest and still is. Owing to large magnetostriction and energy density of Terfenol-D, the use of piezoelectric/Terfenol-D composites exhibit great potential for the realization of vibration converters. In this work, a magnetoelectric vibration converter is presented. The interaction between the magnetic circuit and the magnetoelectric transducer is employed to tune the resonance frequency of the converter.

Keywords: Magnetoelectric converter, vibration energy harvesting, tunable frequency.

Zusammenfassung: Die Integration von Smart Materialien zur Energiegewinnung aus vibrationsarmen Quellen zur Versorgung drahtloser Sensornetzwerke war und ist von großem Interesse. Aufgrund der hohen magnetostraktion und der Energiedichte von Terfenol-D bietet der Einsatz von piezoelektrischen/Terfenol-D-Verbundwerkstoffen ein großes Potenzial für die Realisierung von Schwingungsumrichtern. In diesem Artikel wird ein magnetoelektrischer Vibrationsumrichter vorgestellt. Die Wechselwirkung zwischen dem Magnetkreis und dem magnetoelektrischen Wandler wird zur Einstellung der Resonanzfrequenz des Wandlers genutzt.

Schlüsselwörter: Magnetoelektrischer Wandler, Vibrationsenergiegewinnung, einstellbare Resonanzfrequenz.

1 Introduction

Extracting energy from ambient vibration to power wireless sensors and other electronic devices is well needed. The outstanding properties of laminate composites formed of magnetostrictive and piezoelectric layers make them interesting, not only as sensor elements, but also in energy

harvesting converters [1, 2]. Giant magnetostrictive materials, such as Terfenol-D can realize significant mechanical deformations higher than piezoelectric elements and can be therefore interesting for low amplitude vibration [3]. The main challenge hereby is to design a suitable energy converter, which can supply enough energy to wireless sensor networks or mobile electronic devices from a structure with low excitation frequency and low amplitudes [4]. In spite of numerous developed magnetoelectric (ME) converters, most of these devices operate still wide under their maximum possible output performance although diverse coupling architectures, magnetic circuit designs, and bonding techniques are adopted. On the other hand, most of developed ME converters generates maximum power when the resonant frequency of the generator matches the frequency of the applied vibration even in the presence of the nonlinear forces between the magnetic circuit and the ME transducer. Any difference between these two frequencies can result in a significant decrease in the harvested energy, which presents a big limitation for ME vibration converters and restricts their capability in real applications.

So far, different solutions have been developed to tune the resonance frequency of vibration converters to increase the bandwidth of the operating frequency [5, 6]. A possible solution is to use a generator array [6]. Based on this configuration, it is easy to add or remove a single cantilever and to adjust its resonance frequency. However, the setup requires a bulky volume, which is not suitable in most cases for wireless sensor systems.

Bandwidth widening can be achieved based on bistable or tristable nonlinear configurations [8, 9]. It is demonstrated that these configurations, which have two or three stable equilibrium states have better performance than the monostable configuration [10]. The main disadvantage of including nonlinear behaviour to ME vibration converter is the high complexity of the design while a limited improvement can be obtained due to the domination of the nonlinear magnetic forces between the magnets and the ME transducers [11, 12, 15].

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Another interesting method consists on introducing non-linearity using magnetic interactions [7] or to increase geometric nonlinearities in the converter design [16]. Non-linear effects can improve the energy generation and the frequency bandwidth of energy converters.

In this paper, a novel approach is proposed to broaden the frequency bandwidth of a magnetoelectric converter by tuning its resonance frequency. The proposed solution is based on the adjustment of the distance between the ME transducer and the magnetic circuit by means of a simple screw/nut system. The paper includes the finite element investigations, the design of the converter as well as experimental investigations, that demonstrate the validity of the proposed approach.

2 Finite element analysis

In order to study the magnetoelectric response in the laminate composite, a three-dimensional model, which can accurately predict the induced voltage in the piezo element as function of the excitation displacement of the magnetic circuit is developed. The model contains different interactions in the ME converter including magnetostriction and piezoelectricity. In order to validate the design, a series of demonstrators are designed and fabricated according to the simulation and optimization results. The proposed design is composed by a cantilever beam, a magnetic circuit with several magnet arrangements and a magnetoelectric transducer, which is formed by a piezoelectric PMNT plate bonded to two magnetostrictive Terfenol-D layers. In this design, external vibrations are converted to magnetic field changes acting on the magnetostrictive layers leading to deformations, which are transmitted directly to the piezoelectric layer.

The simulation model is presented in Fig.1. It consists of the three-layer magnetoelectric laminate composite, the magnetic circuit and an air domain is added to the model in order to eliminate the effect of the boundary condition outside of the modelling domain. The material properties used in the simulation are given in Table.1.

2.1 Approximate formula

The structure of the cantilever beam based converter is shown in Figure 2. For a cantilever beam having a rectangular cross section and fixed at one end with a concentrate mass on the other end, the natural angular frequency of the system, ω_c , can be determined using the

Fig. 1: Simulation model.

Fig. 2: Schematic of the converter structure

approximate formula given in Equation 1 [13].

$$\omega_c = \sqrt{\frac{k_c}{M_t + 0.23m_c}} \quad (1)$$

where k_c is the stiffness of the cantilever beam. M_t and m_c are respectively the mass of the transducer and the cantilever beam (see Figure 2).

It has to be noted that the existence of the magnetic force resulting from the interaction between the magnetic circuit and the ME transducer creates an additional non-linear stiffness within the structure. In that case, the resonance frequency of the structure can be determined as a function of the beam stiffness and the stiffness associated with the magnetic force.

In the model under consideration, the influence of magnetic force is not taken into consideration in the calculation of the resonance frequency. The bending stiffness can be determined using Equation 2.

$$k_c = \frac{3E_c I_c}{l_c^3} \quad (2)$$

where E_c is the elastic modulus of the beam material, l_c is the length of the cantilever and I_c is the second moment of area about the neutral axis and is given by Equation 3

Table 1: Material properties used in the finite element analysis.

	Density in kg/m ³	Young's modulus in GPa	Poisson's ratio
Terfenol-D	9230	30	0.5
PMNT	8100	20	0.32

as a function of the width b_c and the thickness h_c of the beam.

$$I_c = \frac{b_c h_c^3}{12} \quad (3)$$

For instance, based on the approximate formula (Equation 1), the estimated theoretical resonance frequency of the converter with 0.2 mm thickness is about 25 Hz.

2.2 Modal analysis

In order to select the suitable thickness of the cantilever to obtain the first resonance frequency of the beam in the range of 20 Hz to 50 Hz (Frequency range for most of environmental vibration [14]), a modal frequency analysis is performed with a parametric sweep for the thickness of the beam. Another property of the simulation model is that it takes into consideration the two chamfers on the beam at the free end. The parametric sweep is performed for 3 thicknesses, which are 0.1 mm, 0.2 mm and 0.3 mm.

Results are presented in Table 2. As it can be seen, for the first mode, the natural frequency of the converter is 8.54 Hz, 23.36 Hz and 41.61 Hz respectively for 0.1 mm, 0.2 mm and 0.3 mm thicknesses. Therefore, the selected thickness of the beam is 0.2 mm.

Table 2: Modal analysis results. All values are in Hz.

	Thickness in mm		
	0.1	0.2	0.3
First mode	8.54	23.36	41.61
Second mode	75.57	190.41	319.69
Third mode	113.12	241.08	374.85
Fourth mode	323.04	700.47	1101
Fifth mode	368.46	750.03	1160.1
Sixth mode	659.99	1372.8	2155.7

3 Experimental investigations

3.1 Converter design

In this section, the design of the harvester is presented based on different results found by finite element investigations.

The magnetic circuit is composed of two rectangular magnets having the same magnetization direction along the horizontal axis. The dimensions of the used rectangular magnets are 6.3 mm × 3.2 mm × 3.2 mm. They are fixed to two supports, which are attached to the housing of converter. Additionally, the position of support relative to the ME transducer can be adjusted using a simple screw/nut system.

The ME transducer consists of one PMNT plate of length 12 mm, width 6 mm and thickness 1 mm bonded to two Terfenol-D plates of length 12 mm, width 6 mm and thickness 1 mm. magnetostrictive layers are magnetized in their length direction and the piezoelectric layers are polarized along their thickness direction. The three layer are bonded with a carbon nanotubes based epoxy resin to improve both electrical and mechanical properties of the transducers. Additionally, a brass cantilever beam with 50 mm length and 20 mm width and 0.2 mm thickness is used as shown in Fig. 3.

Fig. 3: Schematic of the magnetolectric vibration converter.

Fig. 4: Open circuit voltage output of the converter for different air gap widths; (red: 17 mm, blue: 16 mm, green: 15 mm).

3.2 Results

The converter is tested under harmonic excitation reproduced by an artificial vibration source. The magnetic forces between the transducer and the magnetic circuit were investigated experimentally. Tuning the resonance frequency of the ME converter is also addressed using a simple screw/nut system, which allows to control the relative position and therefore the magnetic forces between the magnetic circuit and the transducer. The influence of decreasing the air gap width, which is the separation distance between the two side of the magnetic circuit, is investigated. Fig. 4 shows the experimental investigation results for 1 mm harmonic vibration amplitude for different air gap widths, 17 mm, 16 mm and 15 mm. It can be seen the variation of the output voltage and of the resonance frequency of the converter, which is due to the additional magnetic stiffness created by the magnetic forces between the ME transducer and the magnetic circuit caused by changing the separation distance between them.

4 Conclusion

In order to harvest energy from real vibration profiles, the converter should be able to work for wide frequency band instead of resonant one. Non-linear forces presented in the ME converter can contribute to increase the working bandwidth of the converter. The resonance frequency of the converter can be tuned by adjusting the separation distance between these the magnets and the ME

transducer. This not only can improve the output energy of the converter but also can allow the use of the same design to harvest energy from different environmental vibration sources with different characteristic frequencies, which open new perspectives for the wide use of vibration converters to harvest energy from ambient sources.

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