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Finite element modelling and power estimation of multilayer energy scavengers

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Abstract

Converting vibration energy into electric energy via the piezoelectric effect is one of the most prominent small-scale energy scavenging concepts aimed at powering ubiquitous wireless sensor networks. Several analytical and numerical models, which have also been experimentally validated, have been proposed in literature to characterise the behaviour of cantilever vibration energy scavengers. A finite element coupled electromechanical model of a harmonically excited multilayer energy scavenging device is developed and investigated in this work by using the ANSYS® software. The intricate design of the device is based on off-the-shelf Midé Technology® Volture energy scavengers. The results of the modal and harmonic FEM analyses are experimentally validated via a suitable set-up employing two types of cantilevers as well as several tip masses and electrical resistances. It could hence be proven that numerical analysis is a reliable tool for predicting maximum available power outputs in the presence of electromechanical coupling effects.

Piezoelectric energy scavenging, finite element modelling, multilayer cantilever, electromechanical coupling effects, experimental validation

1. Introduction

Piezoelectric energy scavenging is a widely accepted concept of converting low-level kinetic energy found in the environment into small-scale electric power to be employed for powering ubiquitous autonomous wireless sensor networks or the Internet of things (IOT). Even though self-sustainability of miniature sensing and communication devices is a 'killer application' for the piezoelectric scavenging concept, this technology can be employed anywhere from medical implants to MEMS devices. In fact, devices employing this concept have gained lots of attention due to low resonant frequencies, easy integration into MEMS devices and large power outputs per device volume.

The often-considered design of piezoelectric energy scavengers is based on bimorph cantilevers consisting of three layers: a metallic substrate layer and two ceramic piezoelectric layers (with very thin interconnecting electrodes). The cantilever, whose eigenfrequency is tuned to the excitation by using a tip mass, is then placed in a vibrating surrounding and generates AC voltage across the electrodes [1-4]. In the last fifteen years, analytical models of piezoelectric bimorph cantilevers have been developed and experimentally validated [1-4]. On the other hand, Yang and Tang [5] have achieved excellent results with a simple finite elements model (FEM) for unimorph harvesters. However, commercially available cantilever piezoelectric scavengers often possess a quite different structure. In this work, an off-the-shelf piezoelectric scavenger consisting of seven different layers is hence numerically modelled in ANSYS® and the obtained results are experimentally validated.

2. Finite element model

ANSYS® is proven as an effective coupled-field FEM tool for simulating piezoelectric energy scavengers [5-8]. Combining the SPICE® software for the electrical domain and the ANSYS® software for the mechanical response of the device, produces the most accurate results [5, 7]. On the other hand, implementing the coupled electromechanical model solely in ANSYS® is still considered an appropriate and fast means of investigating the behaviour of the considered devices [5] and is hence adopted in this work. However, the cantilevers modelled in this work are based on off-the-shelf devices produced by Midé Technology®: Volture V21b (69.5 mm x 16.6 mm x 0.8 mm) and V25w (81 mm x 39.5 mm x 0.61 mm) [9]. Midé scavengers display an intricate structure differing considerably from the conventional bimorphs and consist of seven layers: two outer FR4 layers, two Cu electrodes, two layers of PZT-5A ceramic and an inner Cu-coated ESPANEX layer which also serves as the inner electrode (Fig. 1).

Figure 1. Layer structure of Midé Technology® scavengers: 1. FR4 layer, 2. Cu electrode, 3. piezoelectric layer, 4. ESPANEX layer

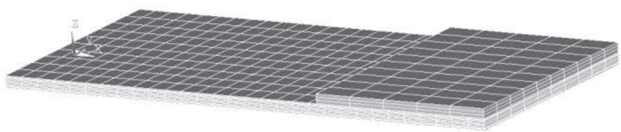

Figure 2. FEM structure of a Midé Technology® scavenger type V21B

These layers are modelled in the corresponding ANSYS® numerical model depicted in Fig. 2 with either block or tetrahedral elements: SOLID186 or SOLID 187 for piezoelectric layers and SOLID226 or SOLID227 for all other layers including the tip mass. Layers of epoxy glue are neglected in the model. On the other hand, the modelled electric circuit is composed of resistor elements CIRCU94, while the electrodes are simulated by coupling the nodes on the outer surfaces of the piezoelectric layers. The cantilever configuration is established by completely constraining the movement of the nodes at the clamped end.

An uncoupled modal analysis is performed first to confirm the correct mechanical coupling of the device. The excellent matching with well-established analytical results and experimental measurements could thus be proven [10]. Iterative harmonic and transient analyses with included geometric nonlinearities are performed next with preprogramed sinusoidal cantilever excitation profiles, while maintaining a constant excitation acceleration magnitude. The difference in the results obtained by linear harmonic and nonlinear transient analyses is unnoticeable in frequency calculations (< 0.1 %) and negligible in the estimation of the maximum output voltages (< 3 %).

3. Experimental validation

In order to validate the coupled electromechanical FEM results, a suitable experimental set-up is employed (Fig. 3). Midé cantilevers are thus clamped to an electromagnetic shaker and harmonically excited in frequency intervals close to their first eigenfrequency (± 3 Hz). The acceleration amplitude is kept constant via a closed-loop system based on the signal obtained from an accelerometer mounted on the shaker. Data on the response of the scavengers, measured by using a laser vibrometer, is acquired by employing a National Instruments PXI-1042 data acquisition system. Two different cantilevers with three different tungsten tip masses (2.4 g, 4.8 g and 7.2 g for the V21b cantilever, and 7.8 g, 15.6 g and 23.4 g for the V25w cantilever) are used. Twelve different electrical resistance values (0 kΩ to 651 kΩ) are employed as electrical loads; simple resistors connected in series with scavengers' electrodes are used.

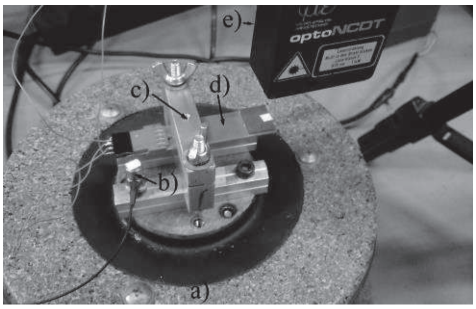

Figure 3. Experimental set-up: a) MB Dynamics shaker, b) Bruel&Kjaer 4375 accelerometer, c) cantilever clamping, d) Midé V21B scavenger, e) Micro-Epsilon Meßtedchnik optoNCDT 1605 laser vibrometer

4. Analysis of obtained results and outlook

The FEM results, obtained by using both harmonic and transient analyses, are compared in Fig. 4 and Fig. 5 with acceleration normalized experimental results. It can thus be observed that, in terms of eigenfrequency values, coupled electromechanical dynamic responses obtained numerically and experimentally are in excellent agreement, with an average error smaller than 2 %. In fact, the FEM model clearly allows predicting correctly the frequency shift due to the backward piezoelectric coupling effects postulated in [3]. This hardening effect, implied by the fact that the electric field generated in the piezoelectric material (in electromechanical terms equivalent to a transformer) influences the mechanical response, can be better observed in Fig. 5. A rise in the ratio of the mere mechanical (uncoupled) eigenfrequency ω_1 and the coupled electromechanical eigenfrequency ω, versus the values of the electrical loads R_l, is hence clearly visible.

However, a good agreement of numerical and experimental results on the respective output voltage magnitudes (with relative errors ≈ 10 %) is achieved only for low resistances loading the scavengers (Fig. 4). Discrepancies in output voltages become more prominent (errors > 30 %) for electrical loads higher than R_l ≈ 100 kΩ. Nevertheless, this is not detrimental since piezoelectric energy scavengers are generally loaded with devices whose resistances rarely exceed the kΩ range.

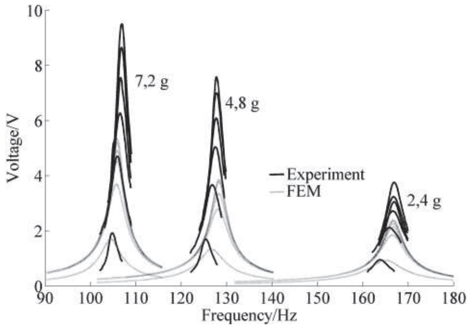

Figure 4. Comparison of experimental and numerical results for 12 electrical resistances and 3 tip masses for Midé scavengers type V21B

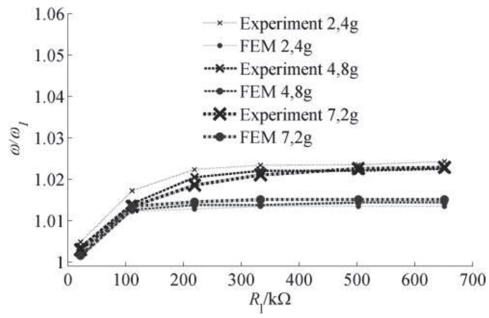

Figure 5. Comparison of numerical and experimental results of the electromechanical hardening effect for V21B Midé scavengers with three tip masses

It can thus be concluded that ANSYS® FEM modelling can be used as a reliable engineering tool to predict the maximum obtainable voltages (and respective output power levels) of commercially available multilayer piezoelectric scavengers in the presence of electromechanical coupling effects.

In future work the authors plan to explore the 'plucking' method of repetitive impact excitation at the free end of cantilever scavengers by employing the same FEM approach.

Acknowledgements

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