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Experimental study of the variations in the electromechanical properties of piezoelectric energy harvesters and their impact on the frequency response function

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ABSTRACT

This work presents a comprehensive study of the uncertainties involved in the Frequency Response Function (FRF) of Piezoelectric Energy Harvesters (PEHs) based on experimental results. A proper experimental setup is designed facilitating the FRF identification for different PEHs. The test protocol consists in three test that quantify the aleatoric and epistemic uncertainties by the study of repeated measurements, variation in the mounting process, and variations in the electromechanical properties of the materials employed in the harvester. The experimental setup and the test protocol are tested employing two different bimorph-type harvesters identified as Model A and B. 20 harvesters corresponding to Model A and 10 to Model B are tested multiples times under the test protocol proposed. Results clearly indicate that the most important source of uncertainties deals with the variability of the electromechanical properties of the PEH, which is particularly greater than: (i) the noise on the measurements, (ii) the variations introduced by the clamping condition, and (iii) the dimensional variations in the geometry. The results are also compared with predictions performed by adopting a recent numerical framework to propagate uncertainties in PEHs. The present work is particularly important since it presents the experimental evidence of the variations in the electromechanical properties of PEH and their influence on the FRF. Additionally, the results not only validate the uncertainty propagation procedures previously proposed but also suggest that their use is mandatory to estimate the FRF. This work presents, to the best of the authors' knowledge, the first effort to experimentally quantify the uncertainties in PEHs.

1. Introduction

The piezoelectric energy harvesting from vibratory environments has been widely studied in the last decade. The devices usually employed to this purpose consist in cantilevered beams composed by a series of alternate layers of piezoelectric and elastic materials. Depending on the number of piezoelectric layers, the harvesters typically receive the name of unimorph or

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bimorph. The unimorph type corresponds to a single piezoelectric layer bonded to another layer that acts as support (usually referred as substructure layer) while the bimorph type consists in a substructure layer bonded to two piezoelectric layers, one at each side [1]. The energy harvesting is achieved by the deformation of the cantilevered beam induced by the vibratory environment (direct piezoelectric effect [1]). Since these devices offer high electrical power density, they become particular interesting to low-power electronics, especially for remote sensor applications [2].

Along the recent years, the researchers have been trying to model the Piezoelectric Energy Harvester (PEH) behaviour in detail. In general, the most relevant advances seem to go in particular directions: (1) proposing of adequate electromechanical coupling models [3–5], (2) optimization of PEHs for broad-band vibratory processes [6,7], (3) push the technology to a Micro-electro-mechanical systems (MEMS) [8,9] [10], and (4) development of efficient circuitry [11]. In that sense, the adequate modelling of PEH plays a determinant role for their prediction, optimization and design. Several models have been developed, but in particular two of them have been widely accepted and used in the scientific community: the analytical distributed parameter solution introduced by Erturk and Inman [4,12] and the finite element plate model introduced by De Marqui Junior et al. [13]. These models are particularly interesting since they have been ample tested showing an important level of accuracy.

Although the models available offer a good description of the physics involved in PEH, its accuracy relies in the complete knowledge of the electromechanical properties of the piezoelectric material together the geometrical characteristics of the harvester. In a recent work, Franco and Varoto [14] presented a design framework for PEHs but taking into account the uncertainties related to the geometrical parameters and the load resistance of the harvester. The results revealed that the incorporation of these uncertainties affects significantly the prediction of the PEH. On the other hand, Ruiz and Meruane [15] observed that the manufacturers typically report these electromechanical properties with variations close to ±20% of their nominal values. In that sense, the authors proposed a procedure to propagate these variations (all obtained from the literature) in order to identify the expected Frequency Response Function (FRF) and its corresponding confidence interval. The work conducted by Ruiz and Meruane presents one of the first efforts to describe the dynamic behaviour of PEHs assuming the electromechanical characteristic as uncertain parameters. As a result, the authors conclude that in order to obtain more robust predictions is mandatory to account the characteristic of the PEH as uncertain parameters or improve the manufacturing tolerance to decrease the variability in the PEH parameters. In other words, the accuracy in the prediction of the well-known deterministic models will be lost if the information related to the characteristic of the PEH is omitted. However, the study performed by the authors was conducted only through simulation; no experiments were performed at the time. Despite the extensive description of the effect of the uncertainties in the FRF of PEHs, there is still the need to perform an experimental characterization of these uncertainties. In particular, several questions are still open, e.g., how different really are the FRFs of many theoretically identical PEHs? Is it that difference greater than the repeatability error of one PEH? Is it really the nominal prediction as bad as the one anticipated (based on the available information about the variability of the electromechanical properties) by procedure presented by Ruiz and Meruane?

The work presented here specifically answers the previous questions by addressing the experimental characterization of the uncertainties in PEHs. A fair comparison between the variability obtained theoretically and by the experimental results requires a significant amount of measurements of different harvesters. For instance, it would be necessary to dispose and identify (experimentally) the FRF of a large number of harvesters (all of them having the same nominal values). Afterwards, the experimental dispersion of the FRF could be compared with the estimation offered theoretically by [15]. Note that the experimental measurement of only one harvester does not offer any relevant information for a validation since there is no information on how representative of the whole group is the harvester chosen. In that sense, the main contribution of this research deals with: (a) the design of a test protocol to quantify uncertainties in PEH; (b) the experimental identification of the uncertainty associated to the repeatability, imperfect mounting, and manufacturing process; and (c) the validation of the theoretical model for uncertainty propagation in PEHs proposed previously in [15].

2. Experimental procedure

2.1. Experimental setup

The experimental identification of the FRF in PEHs requires the direct measurement of the base acceleration together with the voltage generated by the piezoelectric layer. Then, the goal of the experimental setup is to find a configuration that allows the imposition of a controlled base excitation while the respective measurements are performed. The excitation is imposed by the use of an electromagnetic shaker, which requires an amplifier that can be controlled from a computer. The computer and the amplifier are connected by a data module that serves as signal generator and data processing unit (data acquisition). The PEH is attached to the electromagnetic shaker in such a way that a cantilevered condition is enforced (the clamp consists in two pieces joined by screws). The accelerometer is mounted on the top of the PEH base and its signal is sent to the data module. The voltage generated in the PEH is also sent to the data module to be analysed. Fig. 1 shows a picture of the experimental setup while Fig. 2 is a companion scheme for the clamped end of the PEH. Note that a proper mounting (Fig. 2) is designed to facilitate the installation and uninstallation of the PEH, the cantilever condition is obtained by locating the extreme of the PEH inside a socket where two bolts are tightened to clamp the harvester.