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Modeling of vibration energy harvesting system with power PZT stack loaded on Li-Ion battery

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ABSTRACT

Harvesting of mechanical energy generated by the moving cars and trains is a vigorous field of researches because such harvested energy can supply the electric and electronic devices with low power consumption. For instance, the energy harvesting systems that are based on the PZT stack transducers can be effectively used for lighting the road sections at night or in tunnels, which are located far from the power electric networks. An essential feature of PZT stack transducers is their very big electric capacitance that has a decisive influence on the harvested electric energy flow to the load. Another important feature of such systems that are installed under highway's pavement is the impossibility to instantaneous use the harvested electric energy because of its random dependence on mass, speed of moving transporter, and traffic intensity. Hence, the harvested electric energy should be stored in some storage device for subsequent use. The main purpose of the present work is matching the parameters of PZT stack with Li-Ion battery that is destined for the energy supply of LED lamps. From the use of experimental data and finite-element (FE) models of PZT stacks with various numbers of layers, we construct the lumped symbolic model of random vibration energy harvesting circuit, which incorporates a model of the battery dynamics. Finally, we compare the efficiency of the different PZT stack designs at the given mechanical vibration parameters and characteristics of the battery.

Introduction

The challenge of renewable energy sources such as solar, geothermal, hydro-energy, ambient vibration energy entice the burgeoning interest of scientists and engineers [1]. One important kind of energy harvesting is the use of piezoelectric materials to directly transform ambient mechanical vibration to the electrical energy. A capture of such mechanical vibrations can be implemented from bridges, buildings, railways, surface of highways as well as from human mobility. Most significant precondition to such energy harvesting systems is an efficiency of energy transformation and its conservation [2]. Numerous methods to provide the satisfactory quality indicators of PZT based energy harvesters are discussed in monographs and survey papers [3–5]. Many difficulties at the

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PZT vibration energy harvesters design are because the output impedance of piezoelectric energy source and input impedance of electric sink should be matched at the frequency spectrum of mechanical vibrations. For the lightweight host vibrating structure, energy harvesting significantly increases a structural damping [3,4,6,7]. To enhance the efficiency of energy transformation, a multitude of various remedies for the load electric circuits are offered. These remedies involve low-pass filters with rectifier, semi-active circuits that switch the rectified current when the maximum force is attained across the load bearing element of the device, and also the bidirectional switch-mode converters to manage the output voltage [3,4].

Among many types of piezoelectric transducer, the power piezoelectric stacks are best suited to transform the ambient mechanical vibration to the electric energy due to their ability to perceive high force excitations [4,6,8]. Some works [8] construct and then use the analytical models of high power harvesters based on PZT stacks, but due to complexity of their analysis, the lumped models of PZT stacks [6] that are usually derived from preliminary experiments or FE investigation can be coupled and solved conjointly with an equation of electric circuit in a frequency domain. For our study that is oriented to the transform of mechanical vibrations generated by moving transporters, it is important to note that even first resonance frequency of the stiff PZT stack is considerably higher of the frequency of mechanical excitations [4].

At the formulation of PZT stack's optimization problem we assume a design space, which includes a total number of piezoelectric layers, their plane shape, dimension, and thickness at constrained mass, volume, height, and material. This approach is similar to used in Ref. [9]. The operating conditions of power PZT stacks harvester present some further constraints (see Fig. 1). The value of PZT stack's cross-section depends on the mechanical forces and on the strength of piezoelectric ceramics that has a substantial reduction at the combined action of mechanical loading and electric field [10]. Another requirement to the harvester is due to the random character of mechanical excitation, when PZT stack is unable to be a steady source of electric energy, hence the electric power generated cannot be used immediately. Consequently, purely resistive, capacitive or inductive electric load for the stack don't allow to store the harvested energy, but the use of electric battery as a sink of generated electric energy is very promising technical solution. Complexity of use of the battery is that its impedance varies during charge and discharge, thereby worsening the conditions for impedances matching. However, a hysteretic phenomena [11–14] that accompanies the charge/discharge of the batteries, and complicates their functioning analysis. Such phenomena are principally substantial for Lead-Acid, NiSD battery, and notably lower in the Li-Ion batteries [11,12]. That is why we are investigating this type of battery.

In our paper we accept the given vibration excitation spectrum, which is the inherent of the highway substrate, and from the utmost achievable mechanic loads. For the given excitation conditions we examine the FE models of PZT stacks with varied total numbers of layer, which area and strength of the piezoelectric ceramics can withstand cyclic mechanical load without the formation of fatigue damage. For these FE models we examine the frequency response functions (FRF) of output voltage at the various load resistances. Then all acquired data, whose validity was confirmed by the experimental studies [15,16], are used to tune the simplified lumped model of PZT stack. The harvesting circuit was modeled using the block-library of Simscape MATLAB, which includes Sim-Mechanics and SimElectronics toolboxes. Assuming parameters of random mechanical excitation, the battery's characteristics that depend on a voltage and current consumable by illuminant, the constrained dimensions of PZT stack, we investigate an effect of the number and thickness of piezoelectric layers and electric circuit parameters on the efficiency of harvester.

Methodology

Modeling of multilayered PZT stack harvester at low frequency excitation

For the available samples of PZT stacks that have been studied experimentally in Ref. [15], their FE models were formulated in Comsol Multiphysics soft package and were subjected to the transient analysis. FE models consist of 16 and 32 layers, each of 1 mm thickness, coated by Ag electrode layers with 0.05 mm thickness (see Fig. 2). The governing equations for piezoelectric layers were assumed in the strain-charge form

$$\begin{aligned} S &= s^E T + d\mathbf{E} \\ \mathbf{D} &= dT + \varepsilon^T \mathbf{E}, \end{aligned} \tag{1}$$

where S is the strain tensor, T is the stress tensor, $\mathbf{E}$ and $\mathbf{D}$ are the electric field and electric displacement vectors respectively, s^E is the compliance matrix, d is the matrix of

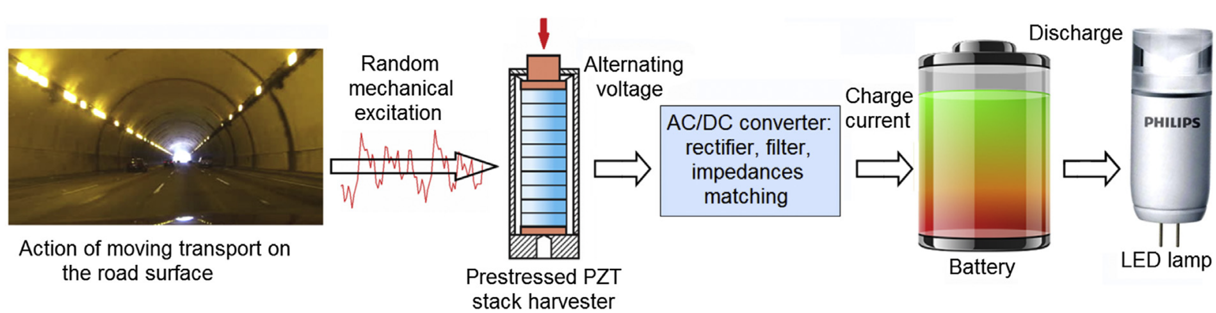

Fig. 1 – Scheme of transforming the random mechanical energy to the electric current and charging to a battery.