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On the performance of piezoelectric harvesters loaded by finite width impulses

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A B S T R A C T

The response of cantilevered piezoelectric harvesters loaded by finite width impulses of base acceleration is studied analytically in the frequency domain in order to identify the parameters that influence the generated voltage. Experimental tests are then performed on harvesters loaded by hammer impacts. The latter are used to confirm analytical results and to validate a linear finite element (FE) model of a unimorph harvester. The FE model is, in turn, used to extend analytical results to more general harvesters (tapered, inverse tapered, triangular) and to more general impulses (heel strike in human gait). From analytical and numerical results design criteria for improving harvester performance are obtained.

1. Introduction

In recent years piezoelectric harvesters have proved to be able to transform kinetic energy of vibrations into electrical energy that can be used to feed sensors and other small electronic devices. Many applications have been proposed in the fields of automotive engineering [1], monitoring of structures and machines [2], bioengineering [3], sport apparel and equipment [4], and efficient commercial piezoelectric harvesters are now available.

Multi-physics mathematical simulations and experimental results [5,6] show that a piezoelectric harvester generates the maximum electric power in resonance condition, when the natural frequency of the harvester is tuned to the frequency of ambient vibrations; performance strongly decreases when the harvester does not operate in resonance. If ambient vibrations are dominated by an harmonic component at constant frequency, the harvester can be tuned accordingly prior to its installation on the vibrating structure [5]. However, harmonic vibrations with variable frequency, usually found in vehicles running at different speeds [1,7] or in household appliances driven by electric motors equipped with inverters, require a continuous tuning of the harvester or a wide band harvester [8] able to effectively convert kinetic energy into electrical energy in the whole frequency band between the maximum and minimum frequencies of operation [5].

Harmonic vibrations are important, but they represent only a particular class of ambient vibrations. Given the need for harvesters to collect periodic, impulsive or random vibrations, it is necessary to adopt specific technical solutions to tune them or widen their operation band [9].

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This research focuses on the problem of harvester tuning in the presence of impulsive vibrations, which may be found in nature [10,11], or during machine operation [12]. Moreover some recent studies on the problem of energy harvesting from low frequency vibrations (1–30 Hz) proposed a frequency up-conversion that is based on devices capable of generating series of impacts from low frequency motions [13]. Thus the interest in impulsive excitation is increasing. The problem of collecting kinetic energy from impulsive vibrations by means of harvesters has been addressed in the literature for a decade. In [14] a cantilever piezoelectric harvester was optimized to collect energy from impulses whose duration was very short compared to the natural period of the harvester. The analysis was carried out by means of a lumped element network model. Optimized values of load resistance and thickness ratio (between the piezoelectric material and the structural material) were found. Short duration impulses were also considered by Wei et al. in [15]. In [16] the energy harvesting performance of a piezoelectric stack under shock events was investigated. In this case the duration of the impulses was very long compared to the natural period of the harvester. A lumped element model of the harvester was developed and numerical results in the time domain showed a good agreement with experimental results. The impulse duration can be comparable with the natural period of the harvester in many energy harvesting applications such as intelligent tires [12,17] and energy harvesting from human motion [18,19]. In [17] an impulsive method for testing piezoelectric harvesters for tires was developed. Preliminary results showed the effect of impulse duration on the harvester's performance. The impact harvester investigated in [20] was studied in the time domain and finite duration impacts were described through a Hertzian contact law. In [21] the response of a piezoelectric harvester to finite width impulses modeled as Gaussian functions was investigated. The effect of various parameters on the harvester's performance was studied. Numerical results showed large variations in the performance when the impulse duration changed from values shorter than the natural period of the harvester to values longer than the natural period of the harvester.

This paper aims at studying the effects of the shape and duration of a finite width impulse on the performance of a cantilever harvester, using analytical, experimental and numerical methods. A one degree of freedom (DOF) model of a cantilever harvester excited by ideal impulses is considered and a frequency domain approach similar to the one used to study the shock response of structures [22] is adopted. Analytical results show that it possible is to exploit the relation between impulse duration and harvester natural period to ultimately maximize the harvester's performance.

Experimental tests corroborate the analytical model, show that the maximum excitation condition holds for cantilevered unimorph and bimorph harvesters loaded with impacts generated by a hammer for modal testing.

A 3D multi-physics finite element (FE) model of a rectangular unimorph harvester is then developed in COMSOL. Both frequency and time domain responses to impacts are validated by means of experimental tests. The validated FE model is used to develop various models of cantilever harvesters having the same layers and piezoelectric properties but different geometries (tapered, inverse tapered, triangular).

Numerical results obtained by means of these models show that a harvester of assigned geometry, stiffness and mass can be excited in the best way by an impulse of base acceleration only if the impulse has a certain shape and duration. If the characteristics of the impulse are assigned, some different solutions (geometry, added mass) can be found to design a harvester that can be excited in the best way.

Finally the response of various harvesters to a more complex impulse of practical interest is simulated: the acceleration impulse caused by heel strike in human gait. Numerical results show that a maximum excitation condition can be found for this impulse as well.

2. Harvester response to a finite width impulse

A piezoelectric harvester converts mechanical energy into electrical energy. The harvester is typically connected to an electric circuit for power extraction. In the framework of this research open circuit voltage $v_{oc}(t)$ is used as a reference parameter since it is an important variable for the design of the electric circuit [23].

In Fig. 1 the equivalent electric circuit for the harvester in open circuit condition is represented in the frequency domain: ω is the angular frequency, $I(\omega)$ is the current generated by the piezoelectric layer, C_{pu} is the internal capacitance of the piezoelectric layer.

In the frequency domain, the open circuit voltage is related to the mechanical excitation through this equation:

$$V_{oc}(\omega) = FRF(\omega)F_r(\omega) \tag{1}$$

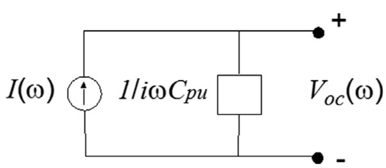

Fig. 1. Equivalent circuit of the harvester.