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Theoretical modeling and experimental realization of dynamically magnified thermoacoustic-piezoelectric energy harvesters

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ABSTRACT

Conventional thermoacoustic-piezoelectric (*TAP*) harvesters convert thermal energy, such as solar or waste heat energy, directly into electrical energy without the need for any moving components. The input thermal energy generates a steep temperature gradient along a porous medium. At a critical threshold of the temperature gradient, self-sustained acoustic waves are developed inside an acoustic resonator. The associated pressure fluctuations impinge on a piezoelectric diaphragm, placed at the end of the resonator. In this study, the *TAP* harvester is coupled with an auxiliary elastic structure in the form of a simple spring–mass system to amplify the strain experienced by the piezoelectric element. The auxiliary structure is referred to as a dynamic magnifier and has been shown in different areas to significantly amplify the deflection of vibrating structures. A comprehensive model of the dynamically magnified thermoacoustic-piezoelectric (*DMTAP*) harvester has been developed that includes equations of motions of the system's mechanical components, the harvested voltage, the mechanical impedance of the coupled structure at the resonator end and the equations necessary to compute the self-excited frequencies of oscillations inside the acoustic resonator. Theoretical results confirmed that significant amplification of the harvested power is feasible if the magnifier's parameters are properly chosen. The performance characteristics of experimental prototypes of a thermoacoustic-piezoelectric resonator with and without the magnifier are examined. The obtained experimental findings are validated against the theoretical results. Dynamic magnifiers serve as a novel approach to enhance the effectiveness of thermoacoustic energy harvested from waste heat by increasing the efficiency of their harvesting components.

1. Introduction

Thermoacoustics is an emergent technology that involves interaction of sound fields with solid surfaces to develop heat engines or refrigerators [1]. In a typical thermoacoustic engine, acoustically excited gas parcels can experience a piston-free thermodynamic cycle. In the presence of a temperature gradient that exceeds a specific threshold, an acoustic wave is

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sustained while the gas parcels are kept in intimate thermal contact with the adjacent solid boundaries. In a standing wave thermoacoustic engine, the solid surface is referred to as the stack. The stack is placed between two heat exchangers that act as a heat source and a sink, and the three components are placed inside an acoustic cavity called the resonator. The pressure and velocity fluctuations in the stack are such that heat is given to the oscillating gas particles at high pressures while it is removed at lower pressures so as to satisfy Rayleigh's criterion [1].

Considerable attention has been devoted to the development of such a class of engines in recent years [2–4]. This attention can be attributed to the fact that such devices are compact and possess few, if any, moving parts. Thermoacoustic engines are environmentally benign and can be driven by any source of heat, waste heat [5] or concentrated solar power [6,7]. The induced acoustic wave carries energy that can be usefully converted into electric power by means of a linear alternator or piezoelectric membranes, thus creating a viable alternative class of energy harvesters.

The integration of thermoacoustic systems with piezoelectric elements has recently been investigated. Keolian and Bastyr [8] placed emphasis on the development of large scale engines with a proposed system that involved heavy moving masses communicating with arrays of piezoelectric alternators. Symko et al. [9,10] presented primarily experimental work focusing on small scale devices for thermal management of microelectronics. Wekin [11] and Matveev et al. [12] introduced a simplified mathematical model to explain the operation of a standing wave thermoacoustic engine coupled with a piezoelectric transducer, referred to as the thermoacoustic-piezoelectric (*TAP*) energy harvester. In a *TAP* harvester, a piezoelectric transducer is placed at the end of the resonator to harness power from the incoming acoustic waves, generated in the stack, and convert it into electricity. The model enables the prediction of the device's operating frequency and onset temperature difference as a function of the characteristics of the piezoelectric element. Smoker et al. [13] and Zhao et al. [14–16] presented a detailed performance analysis of an experimental prototype of a *TAP* energy harvester.

Optimization of the stack parameters such as the material, porosity, spacing and/or the resonator geometry have been shown to magnify the amount of acoustic energy generated in the stack, thus ultimately improving the thermoacoustic device's overall efficiency. However, very few attempts have been devoted towards the improvement of a harvester component. Nouh et al. [17,18] have presented a radically different approach whereby a conventional *TAP* harvester is coupled with an elastic structure in the form of a simple spring–mass system to amplify the strain experienced by the piezoelectric element. The proposed system is referred to as a dynamic magnifier and has been shown in different areas to significantly amplify the deflection of vibrating structures [19–21]. Dynamically magnified thermoacoustic-piezoelectric systems (*DMTAP*) can be advantageous when the appropriate properties of the magnifier are chosen. The *DMTAP* can be designed to achieve a higher efficiency than a conventional *TAP* of the same size, a higher voltage output and/or a lower temperature gradient across the stack ends. In previous attempts to discuss thermoacoustic harvesters with coupled dynamic magnifiers, the analysis was always limited to theoretical predictions extracted from a mathematical model of the coupled system. The present work attempts to show the potential and feasibility of *DMTAP* energy harvesters experimentally as the means of improving the output power from thermoacoustic-piezoelectric harvesters. Experimentally developed prototypes of this class of energy harvesters are tested and validated against mathematical predictions. The current work also confirms that self-sustained thermoacoustically induced oscillations inside the harvester's resonator are not jeopardized by the introduction of the elastic coupling, provided proper selection of the magnifier's parameters is done.

The paper is organized in 4 sections. Following the brief introduction outlined in Section 1, a quick mathematical overview of the equations governing thermoacoustic-piezoelectric harvesters with and without dynamic magnifiers is presented in Section 2. In Section 3, the experimental performance of the *DMTAP* in comparison with a conventional *TAP* harvester is discussed. The conclusions are summarized in Section 4.

2. Mathematical problem and governing equations

2.1. Pressure and velocity

The behavior of thermoacoustic devices is generally described by a one-dimensional linear mathematical model. Such a simplified model is usually attributed to the fact that the device dimensions in the direction of the working gas displacement are greater enough than those normal to it to ignore possible nonlinear effects. It is, however, worth noting here that more complex models of thermoacoustic devices that take into account nonlinearities arising from the response of such systems to cross-sectional area variations, stack position, gas properties and other design variables have been introduced in the literature [22–24]. For simplicity, the mathematical overview given here will be restricted to the simplified linear behavior.

For sinusoidal one-dimensional acoustic wave propagation in a resonator in the x-direction, the spatial components of pressure $P(x)$ and velocity $u(x)$ at any point x along the resonator are coupled by a set of two differential equations:

$$\frac{d^2P(x)}{dx^2}+k^2P(x)=0 \tag{1}$$

$$u(x)=\frac{i}{\rho\omega}\frac{dP(x)}{dx} \tag{2}$$