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Design issues and performance analysis of a two-stage standing wave thermoacoustic electricity generator

A. Piccolo

Department of Engineering, University of Messina, Contrada di Dio, 98166 S. Agata (Messina), Italy

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ABSTRACT

This paper is concerned with the study of low-cost low-power thermoacoustic electricity generators. Based on a target electrical output power of 100 W, a two-stage standing wave prototype integrating a commercial loudspeaker in side branch arrangement is conceived. Each stage consists of a square-pore stack sandwiched between hot and ambient heat exchangers. The working gas is air at atmospheric pressure oscillating at the operation frequency of 194.5 Hz. Design issues and optimization procedures are discussed in detail. The prototype efficiency in converting heat to electrical power is simulated by the specialized design tool DeltaEC based on the linear theory of thermoacoustics. Computations reveal that at the heating temperature of 527 °C the target electrical output power is extracted by the loudspeaker with an acoustic-to-electric efficiency of around 70% and that the overall thermal-to-electrical conversion efficiency of the engine is 5.7%. This result suggests that in applications involving the use of loudspeakers as linear alternators and air at near atmospheric pressure as working fluid, electricity generators of the standing wave type could perform, comparably to their travelling-wave counterparts. This is likely due to a simpler design of the alternator-engine coupling and a simpler and more compact configuration.

Introduction

Thermoacoustic (TA) engines has the immediate potential to be a reliable, efficient, clean, and low-cost technology. This extraordinary potential derives from their ability to directly convert heat into acoustic power without involving any moving mechanical component. In these engines, in fact, the phasing of the transformations which build up the underlying thermodynamic cycle is naturally accomplished by an acoustic wave rather than by pistons, valves and displacers. This sound wave is spontaneously excited inside a solid porous medium when a sufficiently high temperature gradient is imposed on it [1,2]. This characteristics account for the engineering simplicity of these devices and for the associated high technical reliability and low cost. Additional favorable features derive from being environmental friendly, since they use noble gases (or simply air) as working fluids and from allowing the exploitation of waste heat and renewable energy sources, since they are potentially configurable to operate with low temperature differentials [3].

The first TA engine implementations date back to the 1980 s (Los Alamos National Laboratory) and refer to the so-called standing-wave typology [4]. In these devices the working fluid undergoes an intrinsically irreversible Brayton-like cycle that limits their thermal-to-acoustic conversion efficiencies (η_{ha}) typically below 20%. At the end of the 1990 s, research switched to the development of TA engines of the travelling-wave typology. In these devices the working fluid undergoes a reversible Stirling-like cycle that enables higher conversion efficiencies, as proved by the demonstrators developed by Backhaus and Swift [5] and Tijani and Spoelstra [6] characterized by $\eta_{ha} = 30$ and 32% respectively.

A great body of research in TA technology is being recently addressed to the development of TA electricity generators (TAEG). A TAEG is essentially a TA engine coupled to an electroacoustic transducer (linear alternator, loudspeaker, piezoelectric crystal, bidirectional gas turbine, etc.) to convert a fraction of the useful acoustic power (generated from heat) into output electrical energy. Flexure bearing supported linear alternators (LA) characterized by low friction losses appear to date to be the most promising candidates for transduction in TAEGs. These devices are capable of achieving transduction efficiencies up to 90%. The first example of this new class of electricity generators integrating LAs in TA engines is the device implemented in 2004 by Backhaus et al. [7] which consists of a compact travelling wave TAEG working without a resonance tube. This prototype is able to produce up to 57 W of electrical power with 17.8% thermal-to-electric efficiency (η_{he}).

However, when designing low-cost TAEGs the use of LAs is precluded by their high cost so a different electro-acoustic transducer

E-mail address: apiccolo@unime.it

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has to be considered. This problem has been recently investigated by different researchers who found that standard electrodynamic loudspeakers operated in reverse mode can be conveniently used as LAs, but in low power applications (a few hundred of Watts). This is due to the fact that a loudspeaker, generally designed for high fidelity applications, is characterized by a weak and fragile cone, a short stroke, a low power handling and a low acoustic-to-electric transduction efficiency (η_{ae}). Anyway, when the particular application requires low power levels, low-cost for generated kW_e, and not very high transduction efficiencies (~50%) the use of loudspeakers could be authorized.

The development of TAEGs integrating conventional loudspeakers was firstly undertaken by Hartley [8] and Morrison [9] who considered vibrating air columns in standing-wave mode without stacks. More recently, Kitadani et al. [10] developed both standing- and travelling-wave TAEGs prototypes using loudspeakers as LAs and obtained a maximum electrical output power of 1.1 W with $\eta_{he} \approx 0.3\%$. Yu et al. [11], implemented a travelling-wave TAEG of the looped-tube type with a commercially available loudspeaker placed within the loop and obtained an overall η_{he} efficiency of the order of 1% with around 4–5 W output power. The performance of the device was subsequently improved [12] by optimizing the impedance matching of the alternator and an output power of 11.6 W with $\eta_{he} \approx 1.5$–2% was achieved. Analogous performance levels were obtained by Chen et al. [13] who developed two travelling wave TAGEs based on the same looped-tube configuration and powered by waste heat from cooking stoves. These engines are able to generate power outputs of the order of 20 W with $\eta_{he} \approx 3\%$. Conversion efficiencies η_{he} slightly greater than 1% with about 1 W electrical output power were obtained by Olivier et al. [14] by a torus-shaped TAGE coupled to a loudspeaker placed at the end of the resonator. The performance was observed to improve by about 25% when an active control mechanism was added to the device. The coaxial two-stage travelling-wave TAEG developed by the de Blok [15] and working with air at 2 bar static pressure is able to generate about 25 W electrical power with $\eta_{he} \approx 2\%$ for temperatures of the hot heat exchanger near 350 °C. Recently, Kang et al. [16] developed a two-stage travelling-wave TAEG working with helium pressurized at 18 bar. The couple of installed loudspeakers extract 204 W of electrical power with $\eta_{he} \approx 3.4\%$.

From the above discussion it results that research on low power TAEGs integrating standard loudspeakers has mainly focused on travelling-wave engines with looped-tube configuration. However, in applications where conversion efficiency is not a major factor, as the one here discussed, configurations based on the (intrinsically less efficient) standing-wave typology might be worthy of attention. On the other hand, the drop in performance could be compensated by a simpler design and technical implementation, a more compact structure and a lower fabrication cost. This work is specifically concerned with the study/development of low-cost TAEGs of the standing-wave type using standard loudspeakers as LAs. Based on a target electric output power of 100 W, a two-stage standing-wave prototype working with air at atmospheric pressure and integrating a loudspeaker in side branch arrangement is conceived. Design issues and optimization procedures are discussed in detail and the prototype performance is simulated by standard codes based on the linear theory of thermoacoustics. Results are compared to those of analogue TAEGs integrating conventional loudspeakers found in literature.

Theoretical modelling

An electrodynamic loudspeaker can be operated both in direct mode, as a source of sound (driver), or, in reverse mode, as an electric power generator driven by sound. The optimal matching of electrodynamic drivers to thermoacoustic devices has been widely discussed by Wakeland [17]. The treatment here reported, concerning the optimization of reverse-operated electrodynamic loudspeakers, is parallel and strictly refers to the Wakeland's theory, but in the present case the load the power is delivered to is a (frequency independent) electrical resistance rather than the (frequency dependent) input acoustic impedance of a thermoacoustic device.

The essence of the acoustic-to-electric transduction mechanism can be qualitatively captured observing that the difference of the acoustic pressures acting on the opposite sides of the diaphragm forces the voice coil to move in the radial magnetic field of the permanent magnets. The alternating motion of the voice coil induces then a current in it according to the Faraday's law. This complex interaction among acousto-mecahanical and electro-magnetic physical quantities is quantitatively described by the well-known canonical equations for an antireciprocal transducer which is schematized as a two port network relating electric quantities at one port to acoustical quantities at the other. These equations are conveniently written in complex notation which allows to express any variable $a(t)$ oscillating harmonically at angular frequency ω about its mean value a_0 as

$$a(t) = a_0 + \mathrm{Re}\{Ae^{j\omega t}\} \tag{1}$$

where t is the time j the imaginary unit, Re{} signifies the real part and where the complex amplitude A accounts for both magnitude and phase of the oscillation. Neglecting hysteresis losses and considering that the electric terminals are closed on a load electric resistance R_L the canonical equations assume the form of the following two linear equations (see Ref. [18] pg. 397, Eq. (14.3.11) and (14.3.12))

$$0 = (Z_e + R_L)I - \frac{(Bl)}{A_d}U \tag{2}$$

$$(p_1 - p_2) = \frac{(Bl)}{A_d}I + \frac{Z_m}{A_d^2}U \tag{3}$$

where p_1 and p_2 are the complex amplitudes of the acoustic pressures acting on the front and back side of the diaphragm of area A_d (see Fig. 1), I is the complex amplitude of the current flowing in the voice coil, U is the complex amplitude of the volumetric velocity due to the diaphragm motion, Bl is the "force factor" (the product of the magnetic field, B, times the length of the voice coil wire, l) and where Z_e (the electrical impedance with blocked

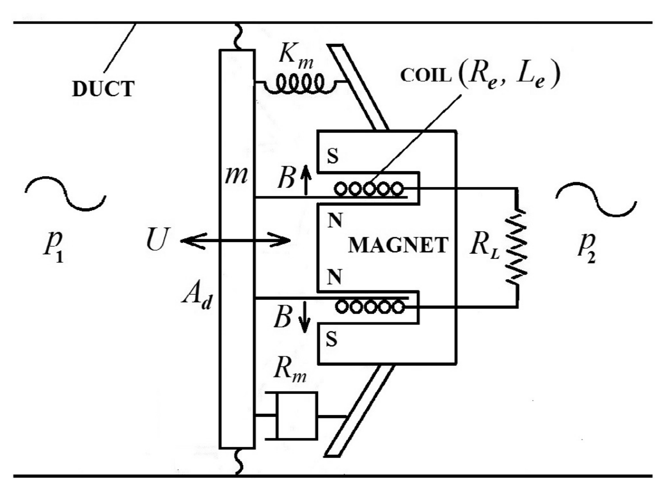

Fig. 1. Schematic illustration of the loudspeaker. The dashpot symbolizes the frictional forces (R_m) while the spring symbolizes the stiffness (K_m).

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