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A method of characterising performance of audio loudspeakers for linear alternator applications in low-cost thermoacoustic electricity generators

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ABSTRACT

This paper investigates the feasibility of using commercially available loudspeakers as low-cost linear alternators for thermoacoustic applications, to convert acoustic power to electricity. The design of a purpose built experimental apparatus, in which a high intensity acoustic wave is induced by using a high power woofer, is described. The rig is used to excite loudspeakers (referred here as "alternators") under test, while a pair of microphones and a laser displacement sensor are used to enable acoustic power measurements. The paper presents a case study in which characteristics of acoustic-to-electric energy conversion of a candidate loudspeaker (alternator) – selected from the viewpoint of general performance, as well as parameters such as: high force factor, low electrical resistance and low mechanical loss – are measured. The measurements of acoustic power absorbed by the alternator and the electric power extracted from it by the load resistor, which allow estimating acoustic-to-electric efficiencies, are presented. The alternator has been tested at different operating frequencies, cone displacements and load resistance values. The measurement results are discussed and compared in detail with the calculations based on the linear acoustics model.

1. Introduction

Thermoacoustic heat engines directly convert heat input into acoustic power, by utilising the thermoacoustic effect: a spontaneous generation of sound waves in a compressible fluid due to a temperature gradient imposed along the solid material in contact with the fluid. Thermoacoustic engines are thought to be particularly attractive because their only moving component is the gas undergoing acoustic motion [1,2]. The absence of mechanical moving parts provides a potential for high reliability and low cost. The working fluid in thermoacoustic engines is usually a noble/inert gas, making this technology environmentally friendly. Furthermore, the required operating temperature difference could be relatively small. For example, de Blok's [3] travelling-wave thermoacoustic engine starts the acoustic oscillation at a temperature difference of only 65 K. Therefore the technology shows a lot of potential for utilising industrial waste heat or renewable solar power.

The thermoacoustic engine's acoustic power derived from the heat input can be utilized in different ways for different applications. However, generally it can be used for two main purposes: one is to use the obtained acoustic power to drive coolers or heat pumps [4], which can be either thermoacoustic or pulsed-tube type. The other is to directly convert the acoustic power to electricity through the electro-dynamic transduction mechanism. Usually, flexure-bearing-supported linear alternators are an excellent solution due to their high reliability and efficiency [5]. However, high costs of commercially available linear alternators limit the advantages of the thermoacoustic heat engines for low-cost electricity generators.

Usually, ordinary audio loudspeakers are excluded as prospective candidates for linear alternators due to their relatively low power transduction efficiency, a fragile paper cone, and a limited stroke, especially when the researchers aim at obtaining generators with a high power, high efficiency and high pressure difference. However, it is possible to consider niche applications where the main driver is cost of the device, not the power transduction (or even the overall) efficiency. This is particularly true for the above mentioned waste heat and solar energy utilisation applications, where a low grade thermal energy is abundant and could be considered a limitless source [6]. Then the actual efficiency figures may become a secondary issue, as long as the electric power could be extracted at very low cost per kW h_e. Similar reasoning may be true for designing cheap electricity generators for the third world countries, as exemplified by SCORE Project [7], which is the immediate background of current work.

SCORE Project aims at designing a cheap thermoacoustic electricity generator for rural areas of developing countries, where heat typically obtained from biomass burning for cooking applications can be used for generating small amounts of electricity to improve

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the quality of life of rural people. The electricity generated (and stored in a battery) would be used for domestic lighting, charging of mobile phones or powering radios. Given that the target cost of a 100–150 W system is below 100 US dollars, one has to consider cheap linear alternators. These are likely to be commercially available audio loudspeakers, or purpose designed units based on the components of audio loudspeakers.

For the research in this paper, as a first step, a measurement methodology and an experimental set-up were developed to enable characterisation of the performance of candidate loudspeakers as linear alternators. Secondly, a commercially available 6.5-in. diameter audio loudspeaker was selected and tested. In this case study, the alternator's acoustic-to-electric power transduction efficiency is measured at various operating frequencies, cone displacements and load resistances. The experimental results are compared with the calculated ones using an analytical linear model of an alternator based on the measured Thiele/Small parameters.

2. Theoretical analysis

Fig. 1 shows schematically a simple linear model [8] describing the loudspeaker as a linear alternator. Referring to Fig. 1a, the acoustic wave exerts an oscillatory pressure on the diaphragm, which has an effective area S. The total mass of the diaphragm and the coil is M_m. The alternator has a mechanical stiffness, K_m, and a mechanical resistance, R_m. The coil has an inductance, L_e, and a resistance, R_e. The force factor is Bl. A load resistor R_L is connected to the terminals of the coil to extract the electrical power converted from the acoustic power by the alternator. Fig. 1b shows the equivalent impedance circuit of the physical model shown in Fig. 1a. The acoustic circuit is connected to mechanical circuit through a transformer and the mechanical circuit is connected to the electric circuit through a gyrator. The pressure difference (pressure drop) between the front and the back of the diaphragm is Δp, the volumetric velocity due to the diaphragm displacement is U_1. The force exerted on the diaphragm due to the pressure drop is F, and velocity of the diaphragm is u_1. The voltage on the load resistor is V_L, and the current is I_1.

Assuming all parameters are linear and independent from frequency, ignoring hysteresis losses, the model in Fig. 1b can be described approximately by the following linear equations:

$$\Delta p = \frac{BlI_1}{S} + \frac{R_m + j(\omega M_m - \frac{K_m}{\omega})}{S^2} U_1, \tag{1}$$

$$\frac{BlU_1}{S} = (R_e + R_L + j\omega L_e) I_1. \tag{2}$$

The input acoustic power to the alternator $P_{a,in}$ is defined as

$$P_{a,in} = \frac{1}{2}\mathrm{Re}[p_1 \widetilde{U}_1] = \frac{1}{2}|p_1||U_1|\cos(\theta_1). \tag{3}$$

In Eq. (3), θ_1 is the phase angle between p_1 and U_1. Accordingly, the acoustic power that runs out from behind of the alternator is defined as

$$P_{a,out} = \frac{1}{2}\mathrm{Re}[p_2 \widetilde{U}_1] = \frac{1}{2}|p_2||U_1|\cos(\theta_2). \tag{4}$$

In Eq. (4), θ_2 is the phase angle between p_2 and U_1. Therefore the acoustic power absorbed by the alternator P_a is defined as

$$P_a = \frac{1}{2}\mathrm{Re}[\Delta p \widetilde{U}_1] = P_{a,in} - P_{a,out}. \tag{5}$$

In Eq. (5), Δp is defined as $\Delta p = p_1 - p_2$ in a vector sense. The extracted electric power by the load resistor (assuming it is purely resistive), P_e, is defined as

$$P_e = \frac{1}{2}R_L|I_1|^2 = \frac{1}{2}\frac{|V_L|^2}{R_L}. \tag{6}$$

In Eq. (6), $|I_1|$ is the amplitude of current I_1. Accordingly, the acoustic–electric efficiency can be defined as

$$\eta = \frac{P_e}{P_a}. \tag{7}$$

According to the analysis above, to measure the acoustic–electric transduction efficiency of the alternator, one needs to measure p_1, p_2, U_1, θ_1, θ_2 and $|V_L|$ (or $|I_1|$).

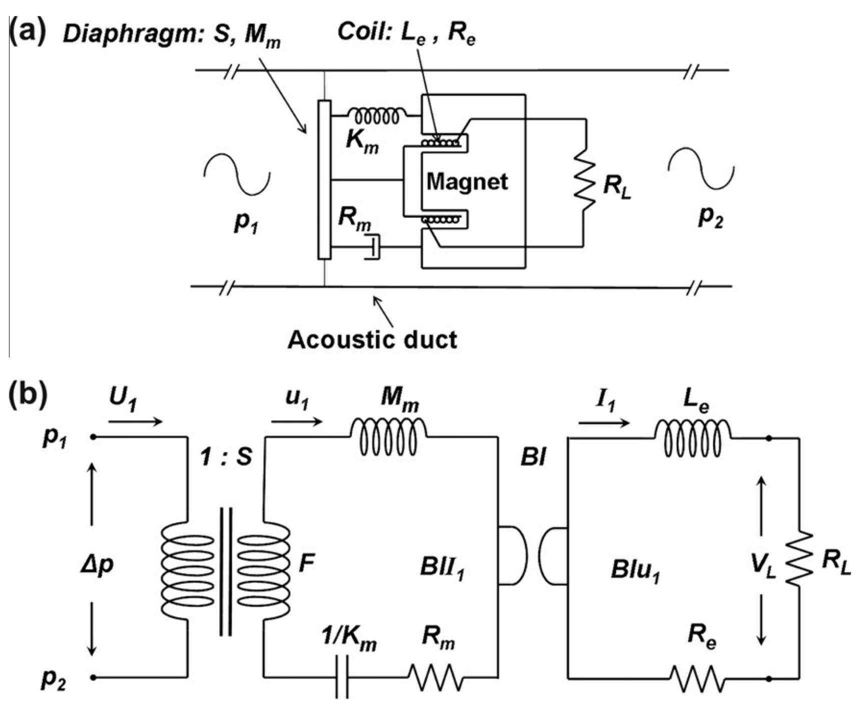

Fig. 1. Schematic of the alternator's physical model (a); the equivalent impedance circuit (b).