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Research Paper

Acoustic matching of a traveling-wave thermoacoustic electric generator

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HIGHLIGHTS

- Approach for acoustic matching of thermoacoustic electric generator is presented.
- Two coupling locations are investigated and compared.
- Coupling location has great effects on impedance match.
- Maximum electric power of 750.4 W and efficiency of 0.163 are achieved.
- Acoustically well matched condition is achieved when it's coupled at the resonator.

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ABSTRACT

Acoustic impedance matching is critical to the overall performances of a traveling-wave thermoacoustic electric generator. This paper presents an effective approach for matching the acoustic impedances of the thermoacoustic engine and the linear alternators for maximizing the output electric power and thermal-to-electric efficiency. The acoustic impedance characteristics of the engine and the linear alternators are analyzed separately, and the methods for modulating the acoustic impedances are investigated numerically. Specially, two different coupling locations including one at the resonator and the other one at the loop of the thermoacoustic engine are compared. It is found that the imaginary part of the load acoustic impedance should be near zero for a good output performance of the engine at either coupling location. The real part of the optimal acoustic impedance for the coupling location at the resonator is smaller than that for the one at the loop. The acoustic impedance of the linear alternator can be simply and effectively adjusted to the expected range by tuning the operating frequency, load resistance and the electric capacitance. Both the experiments and numerical simulations show that a better matched condition can be achieved when they are coupled at the location at the resonator. Maximum output electric power of 750.4 W and the highest thermal-to-electric efficiency of 0.163 have been achieved. When they are coupled at the loop, the maximum electric power and the thermal-to-electric efficiency become 506.4 W and 0.146 due to the lower quality of the acoustic matching. The acoustic matching approach presented in the paper would be helpful for guiding the designs of thermoacoustic/alternator and compressor/cryocooler systems.

1. Introduction

Traveling-wave thermoacoustic electric generator is capable of converting thermal energy into electric power with high reliability and efficiency with very simple structures. It is typically composed of a traveling-wave thermoacoustic engine [1–7] or several traveling-wave thermoacoustic conversion units [8,9] that consist of a hot heat exchanger, a regenerator and a cold heat exchanger, and several linear alternators. The externally added thermal energy is first converted into acoustic energy by the thermoacoustic engine, and then into electric power by the linear alternators.

In recent ten years, many research groups have been devoted into the developments of the thermoacoustic electric generation system, and great progress has been made. The earliest thermoacoustic electric generator was built by Backhaus et al. [10] in 2004, which achieved an electric power of tens of watts. The long resonator in a traditional traveling-wave thermoacoustic engine is firstly completely replaced by the linear alternators in the system. Sunpower, Inc. later developed a similar traveling-wave

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thermoacoustic electric generator with an output power of about 50 W [11]. Wang et al. experimentally optimized the shapes of the phase adjusting components at the coupling port of a small traveling-wave thermoacoustic electric generator and achieved about 73 W electric power [12]. Luo et al. [9,13–15] have conducted a series of research work on traveling-wave thermoacoustic electric generators. They proposed a double-acting thermoacoustic electric generator removing the long gas resonator, which is composed of three sets of thermoacoustic conversion units and three linear alternators arranged in a loop [15]. The designed 3 kW-scale system achieved the maximum electric power of 1.57 kW with an efficiency of 16.8%. Later, a three-stage resonant thermoacoustic electric generator capable of generating about 5 kW electric power was developed [9]. Sun et al. [16–18] were also engaged into the developments of traveling-wave thermoacoustic electric generators recently. The effects of the mechanical and electric resonances on the performances of a traveling-wave thermoacoustic electric generator with a resonator were investigated [16]. An electric power of 345.3 W and a thermal-to-electric efficiency of 12.33% were achieved. After further optimizations, the system was able to achieve 473.6 W electric power and 14.5% thermal-to-electric efficiency [17]. More improvements were recently achieved by optimizing the impedance matching of the electric generation system [18]. Several other research groups adopted low-cost loudspeakers as the electric convertors in traveling-wave thermoacoustic electric generators [19–22]. The achieved electric powers ranged from several watts to about 200 W and the thermal-to-electric efficiencies were typically less than 5%.

In a traveling-wave thermoacoustic engine, the linear alternators act as the acoustic load to the thermoacoustic engine. The acoustic impedance of the linear alternators has great effects on the performances of the engine. Besides, the required acoustic impedance for coupling the thermoacoustic engine also affects the acoustic-to-electric conversion of the linear alternators. Therefore, the match of the acoustic impedances between the thermoacoustic engine and the linear alternator is critical to the overall performance. In some cases, the system is even not able to work if they don't match.

Swift [23] pointed out that the best position for placing an acoustoelectric transducer in a standing-wave resonator depends on the acoustic impedance of the transducer itself. High-impedance transducer should be placed at a point of high acoustic impedances, and a low-impedance transducer is best located at a point of low acoustic impedances. This is one of the earliest statements about the impedance match in a thermoacoustic system. Several researchers [24–28] used the equivalent circuit method to obtain the equivalent acoustic impedances of the acoustoelectric transducers, and then coupled it with standing-wave thermoacoustic systems. The effects of the frequency on the efficiencies of the transducers were extensively studied. However, the effects of the acoustic impedance on the performance of the thermoacoustic system and whether the systems were acoustically well matched have not been studied by the above work. Dai et al. [29] studied the impedance match for Stirling type cryocoolers. The study mainly focused on the requirements of the acoustic impedance for maximizing the efficiency and output acoustic power of the linear compressors, while the characteristics of the cryocooler part were not considered. Hatori et al. [30] reported an experimental method to determine the acoustic impedances of a traveling-wave thermoacoustic loop and its acoustic load by using an acoustic driver. Sun et al. [5] studied the output characteristics of a traveling-wave thermoacoustic engine, and showed that the output position have great effects on the output performances. It was demonstrated that the double output method helped to improve the output performances. Zhang et al. [31] studied the output characteristics of a traveling-wave thermoacoustic engine numerically and experimentally. RC-type and RL-type acoustic loads driven by the engine were studied and compared. It was shown that the acoustic impedance is critical and unique for a good output performance. The work is helpful for designing an appropriate acoustic load to couple with the engine. In the studies about the small thermoacoustic electric generator, Backhaus et al. [10] pointed out that the moving mass of the linear alternators should be in a resonance state under the combined actions of the forces from the gas spring, the flexure bearing and the electromagnetism effect. The details about the designs and impedance match were not presented. In the work about the kW-class thermoacoustic electric generator of Ref. [14], the system was not operated at its optimal acoustic impedance when pure helium is used as the working gas due to the mismatch of the working frequency. Argon–helium mixed gas was used to decrease the frequency so as to have a better impedance match. In all, there are few detailed and comprehensive studies about the impedance match between the thermoacoustic engine and the alternators in thermoacoustic electric generation systems. Particularly, the effects of the coupling positions of the linear alternators on the performance of the thermoacoustic electric generation systems have never been studied. How to match the system effectively by modulating the acoustic impedances of the engine and the linear alternators to achieve the best performance still remains a question.

In this paper, the acoustic impedance match in a traveling-wave thermoacoustic electric generator is studied numerically and experimentally. The general procedure to match the thermoacoustic engine and the linear alternators to reach an acoustically well matched working condition is presented. The acoustic impedance characteristics of the thermoacoustic engine and the linear alternators are then calculated and analyzed individually. Two different locations for coupling the linear alternators are investigated and compared. Several effective measures are used to match the acoustic impedances. Experiments are finally conducted to verify the numerical analysis and demonstrate the acoustically well matched working conditions.

2. Procedure of acoustic impedance match

Acoustic impedance denotes the ratio of pressure to volume flow rate in acoustic systems, such as thermoacoustic engines, and pulse tube refrigerators. Acoustic impedance Z_a is defined by,

$$Z_a = \mathrm{Re}[Z_a] + j \cdot \mathrm{Im}[Z_a] = \frac{p_1}{U_1} = \frac{|p_1|}{|U_1|}\cos\theta_{p-U} + j \cdot \frac{|p_1|}{|U_1|}\sin\theta_{p-U} \quad (1)$$

where p_1 and U_1 denote the complex pressure amplitude and volume flow rate amplitude, respectively; θ_{p-U} is the phase difference between the pressure and volume flow rate.

A traveling-wave thermoacoustic electric generator is generally composed of a traveling-wave thermoacoustic engine and several linear alternators. When the acoustic impedance is matched in a thermoacoustic electric generator, it means that the thermoacoustic engine and the linear alternators can both work at or near their optimal working conditions simultaneously when they are connected. The coupled system is able to achieve the maximum electric power output and the highest thermal-to-electric efficiency at its full potential. In order to achieve the matching condition stated above, three aspects of matching should be considered. Firstly, the frequencies of the engine and the alternators should be matched so that the coupled system is harmonically operated. Secondly, the required acoustic impedances to reach the optimal performances of the engine and the alternators should be matched. In other words, they can be both operated at the optimal states simultaneously at a certain acoustic impedance and frequency. Thirdly, the output acoustic power of the engine and the acoustic power that can be extracted by the alternators should be matched.