Study on thermoacoustic resonance pipe driven by loudspeaker using two-microphone method

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Generally, the characteristic frequencies of a resonance pipe is the determinant of the working frequency of a thermoacoustic system, however, in a thermoacoustic refrigerator driven by a loudspeaker the match between the loudspeaker and resonance pipe is also significant. The two-microphone method is introduced in this paper to measure the working frequency of such a thermoacoustic system, moreover, it is demonstrated that the lowest match frequency of the loudspeaker and resonance pipe changes little with the length variation of the pipe.

INTRODUCTION

Research efforts have been made to develop thermoacoustic refrigerators for more than twenty years and the performance of the refrigerators has been improved greatly. However, the efficiency of a thermoacoustic refrigerator is still lower than traditional refrigerators, which becomes a major disadvantage of thermoacoustic refrigerators. Therefore, many researchers focus their study on the optimized working frequency of the thermoacoustic system [1,2,3].

In this paper a system is set up to measure the acoustic properties in the thermoacoustic resonance pipe using the two-microphone method, which is similar to the technique presented by Seybert, et al [4]. Then the distributions of the sound pressure, particle velocity and acoustic impedance in the pipe are calculated utilizing the decomposition theory [4]. On the other hand, the acoustic impedance of the loudspeaker is measured using the clio software. Therefore the match frequency between the loudspeaker and resonance pipe can be found, which is just the optimized working frequency of the system. It is shown that the most efficient working frequency of a thermoacoustic refrigerator driven by a loudspeaker is not the resonance frequency of the pipe itself. The optimized working frequency mainly depends on the impedance of the loudspeaker when the lowest antiresonance frequency of the pipe is much higher than the mechanical resonance frequency of the loudspeaker. The lowest match frequency, which is considered to be the best working frequency of the system, changes little with the length variation of the pipe. Besides, the stack position for high efficiency and power of refrigeration can be achieved by analyzing the distributions of the sound pressure and particle velocity in the resonance pipe.

EXPERIMENT METHOD AND SYSTEM

The measurement system of the two-microphone method, which has been used to measure the acoustic impedance distribution in the pipe, is shown in Figure 1. A loudspeaker located at one termination of the pipe is driven by a broadband stationary random signal and two microphones separated by a distance of 3.5cm with each other are mounted in the wall of the resonance pipe to measure the sound pressure of two positions in the pipe. The amplified output signal of both microphones are collected by the sound card and transmitted into a computer. By power spectrum analysis and decomposition theory, the sound pressure, particle velocity and acoustic impedance distributions in the pipe and their variations with the frequency are calculated and consequently the optimized working frequency and appropriate position to set the stack are obtained.

In our experiments, two pipes with the same inner radius of 2.4cm and different lengths of 16.2cm and 32.4cm are used to inspect the influence of the pipe length to the match frequencies. A frequency range of 50Hz-4kHz is covered, in which both microphones have good frequency responses and consistency, meanwhile, the low-frequency parameters of the loudspeaker are valid and the characteristic wave number problem [4] of the two-microphone method, which can cause serious error in the measurement, is avoided. According to the coordinates in Figure 1, the termination of the resonance pipe, which is a rigid iron plate, is indicated as $x = 0$, and the pipe is towards the left, i.e., the negative direction.

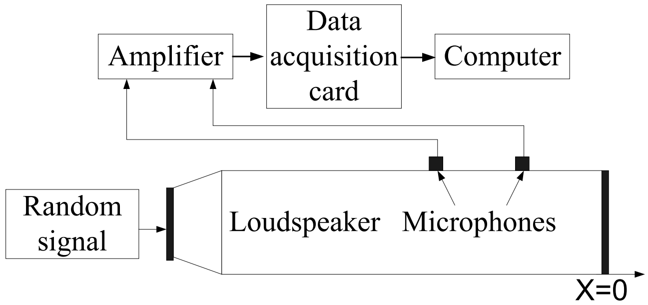

Figure 1 Experiment system

On the other hand, the low-frequency parameters of the loudspeaker are measured with the clio software, and it is obtained that the equivalent quality and mechanical compliance of the loudspeaker vibration system are 5.13×10^{-4} kg and 5.97×10^{-4} m/N, respectively, and its mechanical resonance frequency is 288Hz. Therefore, the low-frequency impedance curve of the loudspeaker can be obtained.

EXPERIMENT RESULTS AND ANALYSIS

Match frequencies

In Figure 2 and Figure 3 the dotted lines show the variation of the minus value of the acoustic reactance of the pipe at the pipe mouth where the loudspeaker is equipped and the solid lines show the variation of the equivalent acoustic reactance of the loudspeaker. Therefore, the crossing points of both curves are just the match frequencies since the total input acoustic reactance is zero. It can also be seen that all the match frequencies except the lowest one are near the antiresonance frequencies of the pipe, where the acoustic reactance curve is incontinuous. Meanwhile, the reactance curve of the pipe below the first antiresonance frequency nearly coincides with the transverse axis and the mechanical resonance frequency of the loudspeaker is lower than the first antiresonance frequency of the pipe. Therefore, the lowest match frequency is near the mechanical resonance frequency of the loudspeaker itself and changes little with the length variation of the pipe. In addition, the frequency spectra of the sound pressure level at the termination of the pipes are also measured by the similar system, but which is with one microphone equipped at the termination of the pipe, the results are shown in Figure 5 and Figure 6.

Comparing Figure 2 with Figure 4 and Figure 3 with Figure 5, it can be seen that the sound pressure resonance peaks can be obtained at the match frequencies, moreover, the sound pressure resonance peak at the lowest match frequency is the highest, which is in agreement with the theory presented by Kinsler, et al [5], i.e., the resonance frequency most closed to the mechanical resonance frequency of the loudspeaker can produce stronger resonance. Since the working frequency between 200Hz and 600Hz is typical in a thermoacoustic refrigerator [3], a low-frequency loudspeaker is recommended in a thermoacoustic system. Meanwhile, a shorter resonance pipe is proposed because higher sound pressure can be obtained in it when the output power of the sound source is invariable, which also makes the first antiresonance frequency of the pipe much higher than the mechanical resonance frequency of the loudspeaker. Therefore, the lowest match frequency of the loudspeaker and the resonance pipe, which changes little with the length variation of the pipe, is the best for the working frequency.

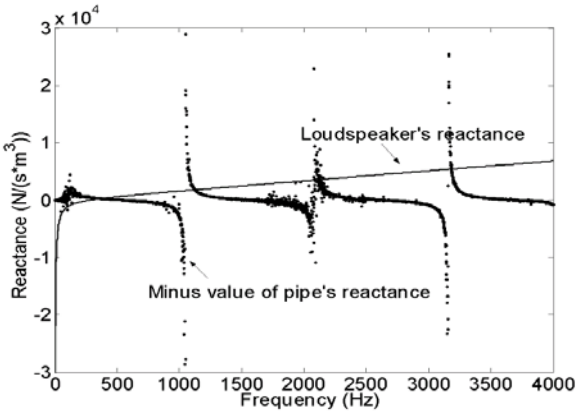

Figure 2 Reactance of the pipe with the length of 16.2cm

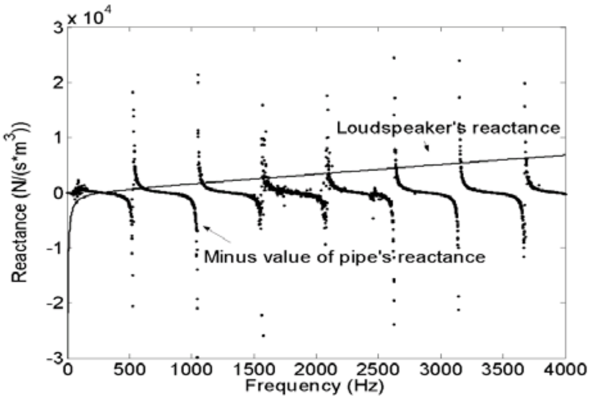

Figure 3 Reactance of the pipe with the length of 32.4cm

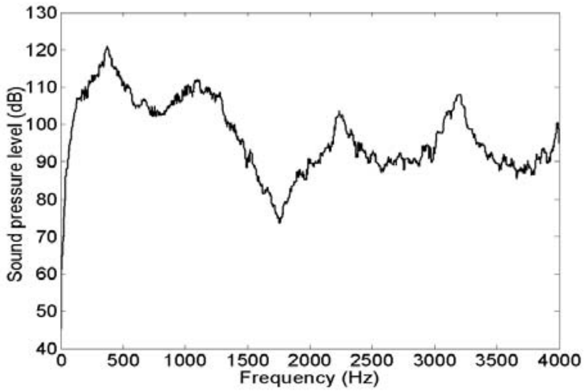

Figure 4 Sound pressure in the pipe with the length 16.2cm

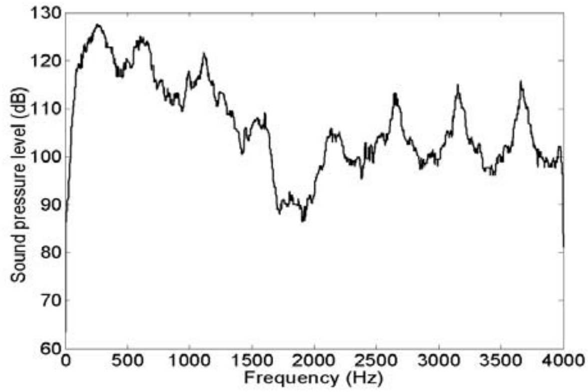

Figure 5 Sound pressure in the pipe with the length 32.4cm

<u>Position of stack</u>

According to the simplest single plate model [1] of the thermoacoustic system, the total heat flux Q along the plate and the efficiency of the refrigerator COP can be expressed as:

$$Q = -\Pi \delta_\kappa T_m \beta p_1^s u_1^s (\Gamma - 1)/4 \tag{1}$$

$$COP = \rho_m c_p u_1^s / \Delta x \beta \varpi p_1^s \tag{2}$$

where T_m, ρ_m, c_p are the mean temperature, density and specific heat of the fluid in the pipe, Γ is the ratio of actual temperature gradient ∇T_m to the critical temperature gradient defined as $\nabla T_{crit} = T_m \beta \varpi p_1^s / \rho_m c_p u_1^s$, β is the ordinary thermal expansion coefficient, δ_κ is the thermal penetration depth, Π is the perimeter of the plate, Δx is the length of the plate, p_1^s and u_1^s are amplitude of the sound pressure and particle velocity in the pipe, respectively. ϖ is the angular frequency. It can be seen from these equations that under a certain condition COP is proportional to u_1^s / p_1^s, i.e., the reciprocal of the acoustic impedance's module and Q is proportional to $p_1^s u_1^s$. Therefore, the distributions of the sound pressure and particle velocity in the pipe can be used to determine a proper position to set the stack. The distributions are obtained from the experiment data utilizing the decomposition theory [4], as is shown in Figure 6 and Figure 7. Figure 6 shows the distribution of u_1^s / p_1^s with both frequency and position in the pipe of length 16.2cm and the distribution of $p_1^s u_1^s$ in the pipe is shown in Figure 7.

Since the working frequency should be the lowest match frequency, only the frequency range around this match frequency is covered in Figure 6 and Figure 7. From the figures, it can be seen that if the stack is set at the position far from the pipe's termination, higher COP can be achieved. In fact, at the sound pressure nodes the highest COP can be achieved since it is proportional to the reciprocal of the module of acoustic impedance. But it is not proper to set the stack at the sound pressure nodes for Q is nearly zero here. Consequently, the proper position for the stack should be a little away from sound pressure nodes, which is recommended be chosen according to the practical refrigerating power required.

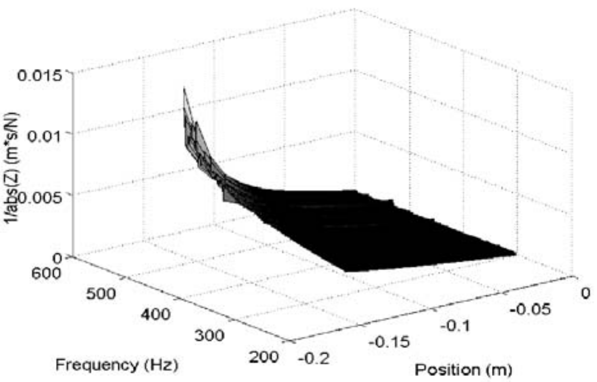

Figure 6 Distribution of $1/|Z|$

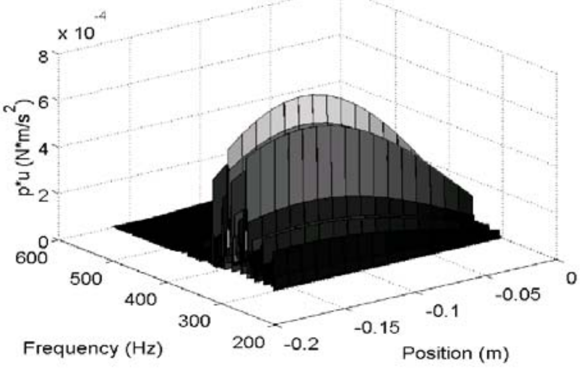

Figure 7 Distribution of $p_1^s u_1^s$

CONCLUSION

The two-microphone method is used to measure the match frequency of a thermoacoustic system and the sound pressure and particle velocity distributions in the pipe. The results demonstrate that the two-microphone method is appropriate to study the characteristics of a thermoacoustic pipe. By this method the optimized working frequency and the proper position of the stack of a thermoacoustic system can be obtained easily. Besides, the study of a quarter-wavelength resonance pipe system terminated by a sphere cavity has been set up and the experiments utilizing the same method on the new system are in progress.

ACKNOWLEDGEMENT

This work is supported by National Natural Sciences Foundation of China (No.50206008).

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