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ACOUSTICAL LETTER

Frequency range of acoustic horn enclosing gas with various sound speeds

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1. Introduction

Acoustic horns are one of the popular acoustic devices that have been used for a long time in various situations, including outdoor public-address systems [1,2]. Acoustic horns of various shapes have long been known, including not only the most standard exponential horn but also the hyperbolic horn with better output near the cutoff frequency. Acoustic horns are generally applied to loudspeakers; however recently, applications of multiple acoustic horns as an acoustic lens to directional microphones have been proposed [3].

The most important problem of the acoustic horn is that the cutoff frequency is determined by the shape of spread. For example, for an acoustic horn whose cross-sectional area S extends along the x-axis,

$$S = S_0 \exp(mx), \tag{1}$$

the coefficient m is represented by

$$m = \frac{4\pi f_c}{c} \tag{2}$$

with cutoff frequency f_c.

Sound with frequencies lower than f_c cannot pass through the acoustic horn, where S_0 is the throat cross section and c is the sound speed. For this reason, a smaller m is required to output a low-frequency sound from the acoustic horn, which increases the size of the acoustic horn.

Ouchi and Yamasaki proposed an acoustic horn with a ring-shaped aperture, in which the length of the acoustic horn is decreased while maintaining the acoustic properties [4]. The acoustic horn with the ring-shaped aperture is considered to be effective for wall-mounted installations, because the thickness of long horns can be reduced. However, the path length has not been decreased, so instead of the overall length of the horn being reduced, the diameter of the aperture is larger than that of the original horn.

This paper proposes a method of changing the cutoff frequency without changing the size of the acoustic horn by sealing the mouth and throat of the horn with a thin film that has little acoustic effect and replacing the air inside the horn with bass with various sound speeds. Thus, this paper will show that replacing the gas inside the acoustic horn with helium, which has a higher sound speed than in air, decrease the frequency bandwidth, and replacing it with carbon dioxide or butane gas, which have a lower sound speed, increases the frequency bandwidth.

2. Gas–enclosing acoustic horn

2.1. Exponential horn and sound driver unit for experiment

In this experiment, an exponential horn with a throat diameter of 30 mm, f_c of 500 Hz, and an angle of 45° between the wall surface and the centerline of the horn at the aperture (Fig. 1(a)) was designed and produced using a 3D printer. A polyethylene film of 15 µm thickness was attached to the throat and mouth of the horn (Fig. 1(b)) in order to enclose the gas. Gas sealing was performed by water displacement, as shown in Figs. 1(c) and 1(d). Water was injected through a hole near the throat of the horn, and the gas was then pumped through a thin hose. P-250 UNI-PEX (frequency range 125–7,000 Hz) was used as the sound driver unit.

2.2. Enclosed gas in acoustic horn and the sound speed

Four types of gas, named helium (He), carbon dioxide (CO_2), butane (C_4H_{10}), and air, were tested in this experiment. The sound speed, in the gas is expressed as

$$c = \sqrt{\kappa RT/(M \times 10^{-3})}, \tag{3}$$

under cautious conditions of specific heat ratio κ, absolute temperature T, and molecular mass M, where the gas constant $R = 8.31$ J/(K·mol). Table 1 summarizes the parameters of each gas, the atmospheric temperature at the time of observation, and the sound speed inside the horn estimated using these values.

3. Frequency characteristics of gas–enclosing acoustic horn

3.1. Measured frequency characteristics

Figure 2 shows the amplitude–frequency characteristics obtained from the impulse response reproduced from a gas–enclosing acoustic horn. For the impulse response measurements, the microphone was placed 0.5 m in front of the mouth of the acoustic horn and the swept sine signal was used. The measurements were taken in an anechoic room. From these results, it can be confirmed that the lower the sound speed in the enclosed gas, the wider the range of reproducible low frequencies.

3.2. Theoretical value of cutoff frequency

The acoustic horn used in this experiment was designed to have the f_c of 500 Hz in air with c of 340 m/s. Therefore, the coefficient m that determines the horn shape is 18.48 from

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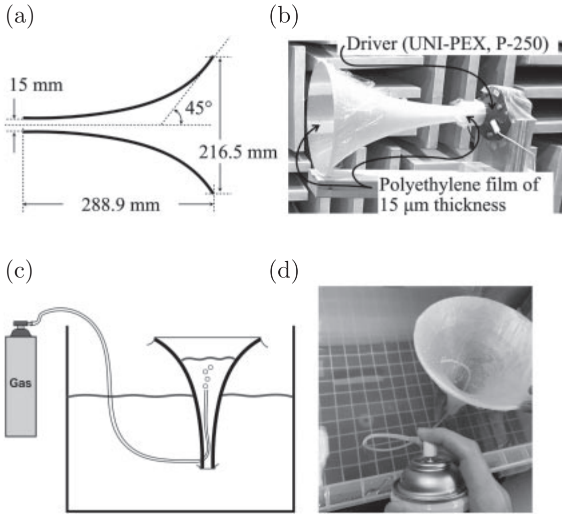

Fig. 1 Acoustic horn used in experiment and gas displacement of horn. (a) Size of acoustic horn, (b) acoustic horn with polyethylene films over mouth and throat, (c) procedure of enclosing gas by water displacement, and (d) view of water displacement.

Table 1 Gas parameters and sound speed in gas.

	He	Air	CO_2	C_4H_{10}
Heat capacity ratio κ	1.660	1.403	1.302	1.106
Molecular mass M	4.003	28.97	44.01	58.12
Temperature during measurement t [°C]	13.3	13.3	13.3	8.4
Temperature during measurement T [K]	286	286	286	282
Sound speed c [m/s]	994	340	265	211

Table 2 Cutoff frequency of gas–enclosing acoustic horn.

	He	Air	CO_2	C_4H_{10}
Cutoff frequency [Hz]	1.46×10^3	499	390	310

Eq. (2). Without changing m, the theoretical value of the cutoff frequency in Table 2 can be obtained by substituting the sound speed of each gas used in the experiment into Eq. (2).

The vertical dashed lines across each spectrum in Fig. 2 show the theoretical cutoff frequency for each type of gas. The change in the range of the reproduced spectrum with the cutoff frequency due to the enclosed gas can be confirmed.

Figure 3 shows the average of the amplitude–frequency response of 52 s of a speech sample played from the acoustic horn, analyzed every 125 ms. The speech sample was a studio-recorded reading from an English textbook by a native speaker. This result also confirms the change in the range of the reproduced voice spectrum. The so-called a "duck voice" is caused by inhaling helium into the vocal, which tract causes the sound speed in the vocal tract to increase and the frequency of the formants formed to increase. The spectra in Fig. 3 also show no frequency shift of the spectral peaks.

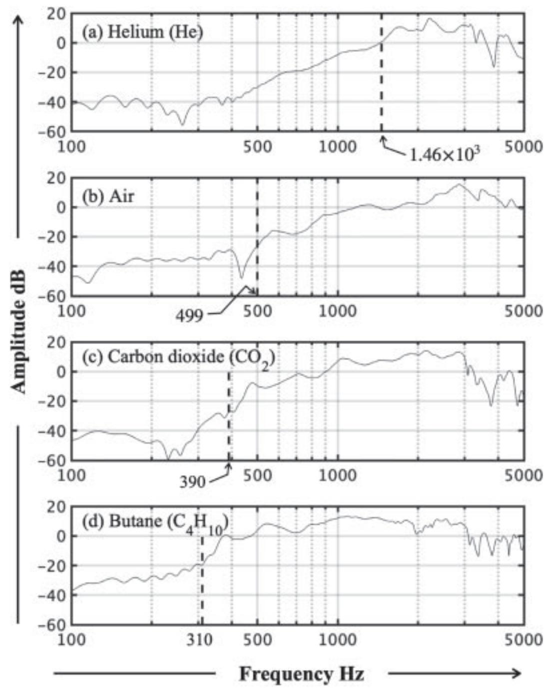

Fig. 2 Amplitude–frequency characteristics of gas–enclosing acoustic horn.

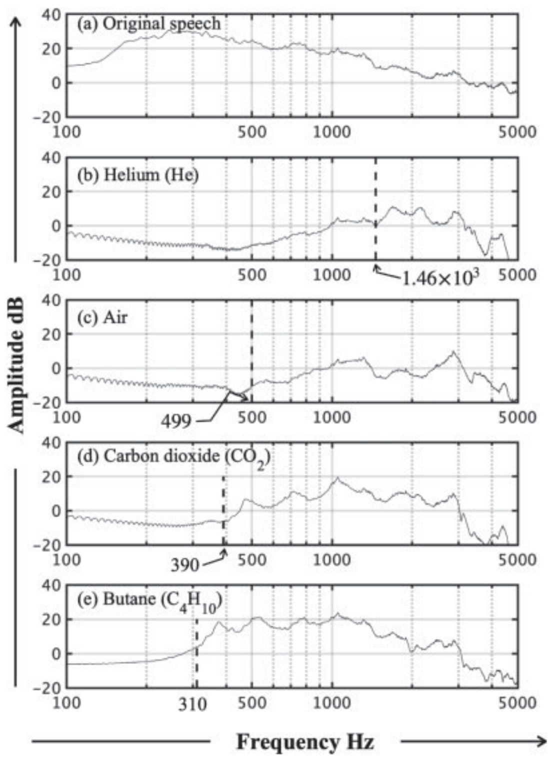

Fig. 3 Moving average of speech spectra reproduced by a gas–enclosing acoustic horn.

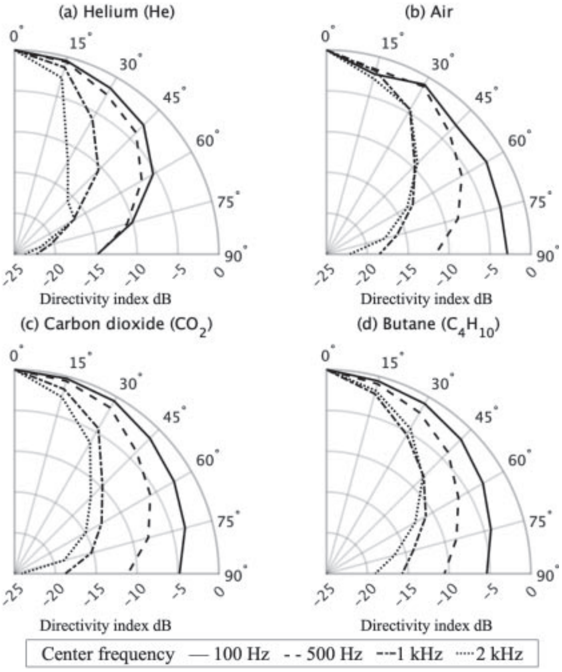

Fig. 4 Directivity for each octave band.

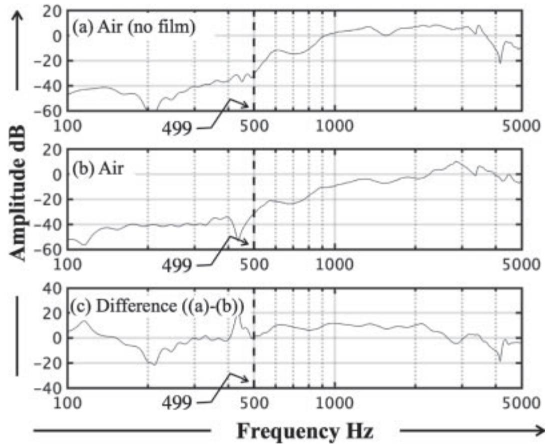

Fig. 5 Effect of thin film used for enclosing gas.

4. Directivity for each frequency band

Figure 4 shows the measured directivity of the gas–enclosing acoustic horn for each octave frequency band. The directivity were obtained from the impulse responses measured every 15 degrees around the center of the mouth of the acoustic horn. There is no significant difference in the directivity with differences in the enclosed gases.

5. Effect of thin film used for enclosing gas

Figure 5 shows the effect of the thin film used in the mouth of the acoustic horn when the gas was enclosed. Figure 5(a) shows the amplitude–frequency characteristics without the film on the mouth, and Fig. 5(b) shows the amplitude–frequency characteristics with the film applied on the mouth. Figure 5(c) shows the difference between the two amplitude–frequency characteristics. Although spectral peaks and dips can be observed at some frequencies, the average attenuation is 5.2 dB for higher than the cutoff frequency.

6. Conclusion

This paper described how the cutoff frequency can be changed by enclosing a gas that was a different sound speed from that of air in an acoustic horn. The frequency response of the reproduced sound from the gas–enclosing acoustic horn was measured, and it was confirmed that the frequency range of the reproduced sound and the theoretical value of the cutoff frequency were generally consistent. These results indicate that by enclosing a gas whose sound speed is lower than that of air, it is possible to extend the frequency range of the output sound from an acoustic horn. In the experiment presented in this paper, a polyethylene film of 15 μm thickness was attached to the mouth of the acoustic horn to enclose the gas; however, there is room for investigating the gas–enclosing method.

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