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Connection of attenuation coefficients of Kirchhoff's formula with the absorption of air in a tube

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In a measurement of sound propagation in a tube, it is important to know the exact values of the attenuation coefficient. In these measurements, many researchers have used the value which has been derived from Kirchhoff's law as an attenuation coefficient.¹⁾ Small differences have been found between observed and theoretical values of Kirchhoff's law. But in a low frequency region, the values are almost equal to the ones of Kirchhoff's law, so most of researchers neglected the small differences and didn't pay deep considerations to the absorption coefficients of air.

On the other hand, though the value of absorption coefficients of air is enough small and able to be neglected in a low frequency region, the value of that is proportional to the square of frequency, thus we cannot neglect this value in a high frequency region. Especially, in the cases when we treat the sounds which have shock fronts, there are very high frequency components in the spectra, therefore the effects of absorption of air appear more clearly. But there are few reports that describe this point, and sometimes the calculations have been carried out for the propagations of sounds which have shock fronts by using Kirchhoff's law only.²⁾

In this report, the authors describe the differences when we use the total attenuation coefficients (the total values of Kirchhoff's law and absorption of air) instead of Kirchhoff's law only.

The attenuation coefficient derived from Kirchhoff's law is denoted by the expression

$$\alpha = \frac{1}{ac_0} \sqrt{\pi\nu f} \left(1 + \frac{\gamma-1}{\sqrt{\text{Pr}}} \right), \quad (1)$$

where f is the frequency, a is the tube internal radius, c_0 is the sound speed, ν is the kinetic viscosity, Pr is Prandtl number and γ is the specific heat ratio. Equation (1) shows that the value of α is proportional to the square root of the frequency.

Then the attenuation coefficient due to the absorp-

tion of air is divided into two parts; these are classical absorption β_1 and molecular absorption β_2 , these are presented in the next formulas³⁾

$$\beta_1 = \frac{2\pi^2 f^2}{\rho c_0^3} \mu \left[\frac{4}{3} + (\gamma-1) \frac{\kappa}{C_p \mu} \right] \quad (2)$$

and

$$\beta_2 = \frac{A f_m f}{f_m^2 + f^2}, \quad (3)$$

where κ is the thermal conductivity, μ is the viscosity, C_p is the specific heat at constant pressure, ρ is the density, f_m is the frequency of maximum molecular attenuation which depends on the relative humidity and A is a constant.

The total of the attenuation coefficient due to the absorption of air is given by the formula $\beta = \beta_1 + \beta_2$. It is shown that the value of β is almost proportional to the square of the frequency.

Then the effective total attenuation coefficient α_T , that acts to the sound propagating in a tube, is represented by $\alpha_T = \alpha + \beta$.

Measurements were carried out using a 5 cm i.d. and 40 m long tube, and a sinusoidal wave was transmitted into the tube. Attenuation coefficients of some frequencies were measured by the observed values at the positions 0.2 m and 30 m away from the source, and was compared with the theoretical values. It is also recognized experimentally that the waves propagate as a plane wave at the position of 0.2 m.

Figure 1 shows the relationships between frequency and attenuation coefficients. In this figure, the measured values are in approximate agreement with Kirchhoff's law, but it is found that as the frequency increases, the differences between observed and theoretical values increase further. Other researchers have described that these differences were caused by the reflections of flanges which assemble the tubes, or the irregularities of the inner surface of the tube.^{1,2)} But the authors think that the attenuation coefficients should be thought of as the total of Kirchhoff's law and absorption of air. Practically, we find more suitable agreements between the observed values and total attenuation coefficients.

Then the propagation characteristics of a sinusoidal finite-amplitude sound were observed. The harmonics were generated by the highly intensive nonlinearity and these were diminished with the increase of propagation distance.

Figure 2 shows the relationships between propagation distance and the sound pressure levels of the fundamental (3.8 kHz) or the harmonic components.

Fig. 1 Attenuation coefficients.

In this example, the region over 25 m is thought to be a linear region because the fundamental pressure level is below 120 dB. From the comparisons of the attenuation characteristics in this region, it is also clear that the slopes of the curves, which are fitted to the observed data, gradually approach the slopes calculated by the total attenuation rather than the ones calculated by Kirchhoff's law only.

From the above results, we may conclude that when we treat a sound propagating in a tube the total attenuation coefficient should be used instead of Kirchhoff's law only.

References

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Fig. 2 Relationships between sound pressure levels and propagation distance.

- · —: Calculated by the total attenuation coefficient,
- : calculated by the Kirchhoff's law,
- : fitted to the observed data.

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