Variation in sound attenuation performance due to changing duct length and installation of sound absorbing materials

Yuka Yamashita, Kunihiko Ishihara

Abstract— **Ducts are widely used in buildings, and various types of air conditioning ducts and exhaust ducts are also used in the medical field. It has been reported that these ducts generate noise, which affects the quality of sleep and causes various physiological disorders and loss of performance when awake or at work. In this study, we evaluated the sound attenuation performance (reduction degree of resonance peak value) by extending ducts, installing sound-absorbing materials, and changing the shape of ducts as countermeasures. As a result, the attenuation performance due to the extension of the duct decreases linearly with length, and the degree of decrease is independent of the cross-sectional shape. Furthermore, as the amount of sound-absorbing material increases, the sound pressure level decreases logarithmically. As the resonance mode order increases, the peak value becomes smaller, and if the quantity doubles, the peak value decreases by about 3dB, consistent with the so-called room acoustics theory.**

***Index Terms*— Duct, Noise, Sound absorbing material, Sound attenuation performance, Acoustic natural frequency.**

I. INTRODUCTION

In buildings, ducts are widely used, and in medical settings, various types of ducts, such as those for air conditioning, are also employed. Since noise is generated from these ducts, countermeasures are necessary to address this issue. Specifically, noise levels in medical environments are ideally maintained below 50 dB during the day and below 40 dB at night [1]. It has been reported that noise during sleep and recovery can affect the quality of sleep, and noise during wakefulness and work can cause various physiological impairments and decrease performance [2]. Therefore, achieving an acoustic environment where you can concentrate on your treatment requires research from various perspectives.

In the duct noise, many studies focus on the propagation characteristics of sound waves within ducts. There is research on ducts with uniform cross-sections where the walls are rigid [3], [4], have finite impedance, meaning the duct walls are not completely rigid [5], and on ducts through which fluid flows [6]. Additionally, Ishihara has conducted studies on boiler duct systems, which are entire systems combining boiler piping and ducts [7]～[10], and on ducts with different diameters [11]. However, there are still gaps in understanding ① the relationship between duct length, cross-sectional shape and the magnitude of resonance sound, and ② the resonance sound reduction effect caused by the installation of sound-absorbing materials. Exhaust ducts have open ends to release combustion gases, while air conditioning ducts are used for ventilation within buildings, so their ends are closed with air inlets and outlets on the sides. This results in a nearly enclosed space inside the duct, differing from the acoustic characteristics of open-ended ducts.

Therefore, this study focuses on ducts with closed ends and aims to resolve the questions ① and ②. Generally, a duct with a given length L and closed-end boundary conditions has a resonance frequency of $f_{on}=nc/2L$ (where f_{on} is the resonance frequency, n is the mode order, and c is the speed of sound). Since one cause of noise is resonance due to the reflection and interference of sound within the duct, the study investigates gradually increasing the duct length to reduce resonance and determining the length at which the peak sound value becomes negligible. Additionally, the study examines whether the installation of sound-absorbing materials inside the duct can achieve noise reduction without extending the duct length.

II. METHODS

This study aims to investigate how the sound pressure level inside a duct change with its length and the amount of sound-absorbing material. For this purpose, experiments were conducted using a circular PVC duct (hereafter referred to as the "circular duct") and an acrylic rectangular duct (hereafter referred to as the "rectangular duct"), both with closed ends as boundary conditions. Since the primary concern in actual medical settings is the noise level caused by resonance, measures were taken to reduce it.

An acoustic device, the “Technics SU-V500” by Matsushita Electric Industrial Co., Ltd., was connected to a speaker, and white noise was generated using the software “WAVE Gene Ver 1.50.” Noise measurement and FFT analysis were performed using the “Sound Level Meter NL-42” by Rion Co., Ltd. The sound-absorbing material used in the measurements was "Calm flex F-2 (standard type) with a thickness of 5 mm." A simplified measurement diagram is shown in Figure 1.

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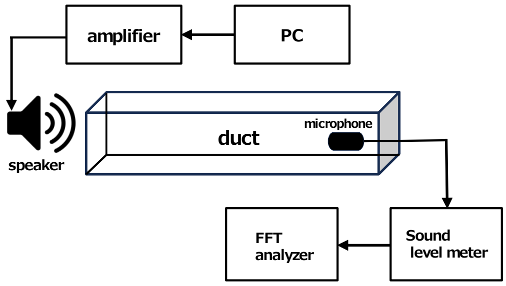

Figure 1 Experimental setup

The following experiments were conducted:

1) Using a PVC duct with a diameter of 70 mm and a wall thickness of 2 mm (circular cross-section) and an acrylic duct with a cross-section of 75 mm × 75 mm and a wall thickness of 5 mm (rectangular cross-section), the lengths were varied to 0.45 m, 0.9 m, 1.35 m, 1.8 m, and 2.25 m. Sound pressure level measurements were performed to investigate the relationship between the cross-sectional shape, duct length, and sound pressure level.

2) Using the 0.9 m ducts from experiment 1, the sound-absorbing material inside was progressively reduced from one end, changing the lengths to 0.9 m, 0.45 m, 0.225 m, 0.1125 m, and 0.0 m. Sound pressure level measurements were performed to investigate the relationship between the amount of sound-absorbing material and the sound pressure level. A simplified measurement diagram is shown in Figure 2.

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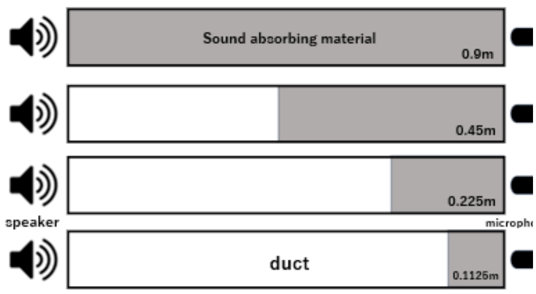

Figure 2 Experimental diagram when sound absorbing material is installed

III. RESULTS AND DISCUSSION

A. Reproducibility

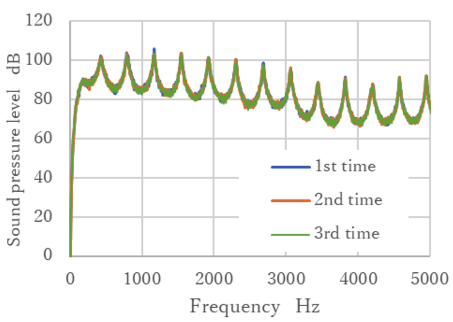

Figure 3 Confirmation of reproducibility

FFT analysis of the measurement results from experiments 1) and 2) was performed at 2.5 Hz intervals up to 5000 Hz. To demonstrate reproducibility, each measurement was conducted three times, and the averaged results were used as the data. Figure 3 shows the results of three experiments for a specific case plotted on the same graph.

From figure 3, the three measurements completely overlapped, confirming reproducibility.

B. Sound Pressure Level as a Function of Duct Length and Cross-sectional Shape Variation

Sound pressure level measurements were performed by varying the lengths of the PVC duct (hereafter referred to as the "circular duct") and the acrylic duct (hereafter referred to as the "rectangular duct").

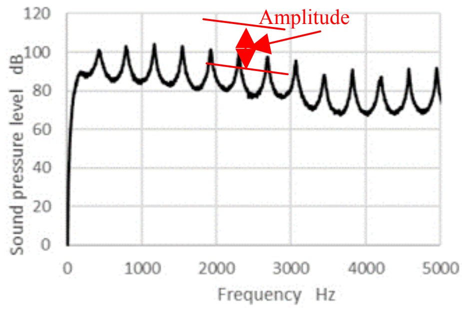

Figure 4 SPL of circular duct with 0.9m without sound absorber.

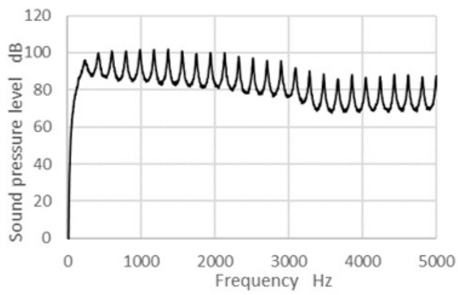

Figure 5 SPL of circular duct with 0.45m without sound absorber.

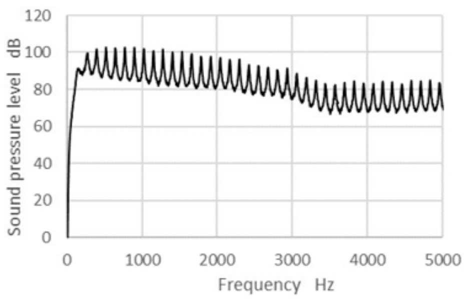

Figure 6 SPL of circular duct with 1.35m without sound absorber.

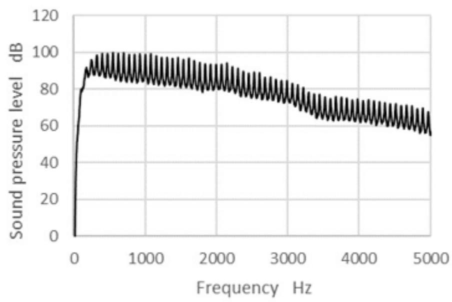

Figure 8 SPL of circular duct with 2.25m without sound absorber.

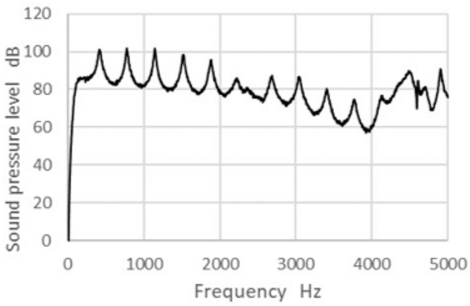

Figure 9 SPL of circular duct with 0.45m without sound absorber.

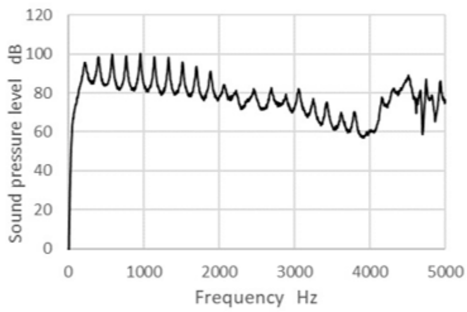

Figure 10 SPL of circular duct with 0.9m without sound absorber.

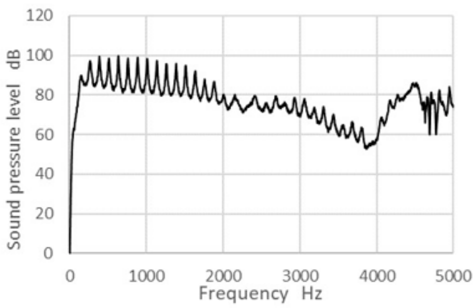

Figure 11 SPL of circular duct with 1.35m without

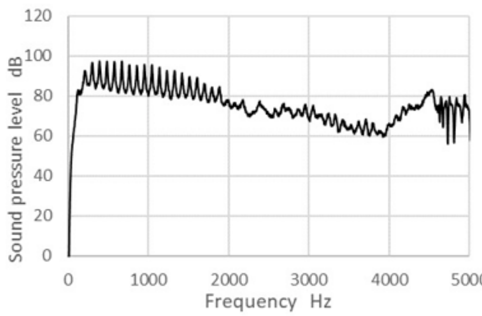

Figure 12 SPL of circular duct with 1.8m without sound absorber.

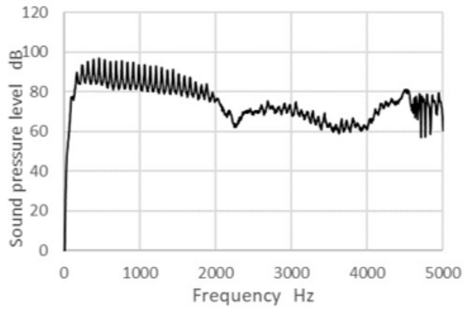

Figure 13 SPL of circular duct with 2.25m without sound absorber.

In figures 4 to 13, the differences between the peak values and the trough values (hereafter referred to as amplitude as shown in Figure 4) were determined in three frequency ranges: low frequency (0 to 2000Hz), mid frequency (2000 to 4000Hz), and high frequency (4000Hz and above). These values were summarized with the overall amplitude (O.A. value). The O.A. value is the sum of the sound intensity (energy) at each frequency across all frequencies. Expressed as a formula,

$$L_p = 10log\left(\sum_{i=1}^{N} 10^{\frac{L_{pi}}{10}}\right)$$

(1)

(expressed as Lp: O.A. sound pressure level, Lpi: sound pressure level at each frequency.)

From figures 4 to 13, it was observed that as the frequency increased, resonance frequencies became less prominent in the rectangular duct, and the sound pressure levels fluctuated at frequencies different from the resonance frequencies.

Here, from the results of Figures 4 to 13, when the sound pressure level amplitude decrease due to changes in duct length is plotted with duct length on the horizontal axis and amplitude on the vertical axis, Figure 14 is obtained.

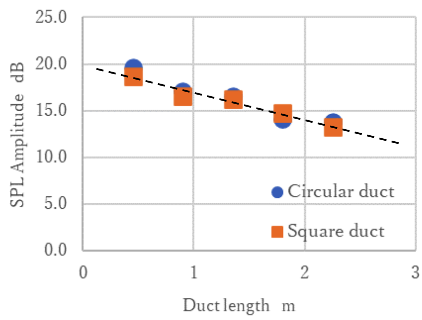

Figure 14 Relation between duct length and SPL amplitude.

From figure 14, it was observed that there was no significant difference in the change in amplitude with respect to duct length between the circular and rectangular cross-sections. These two lines can be approximated by straight dashed lines as shown in Figure 14. The amplitude decrease can be approximated as y=−3.26x+20.65 for the circular duct and y=−2.79x+19.66 for the rectangular duct, where x is the duct length and y is the amplitude. Therefore, the amplitude becomes zero at 6.33 m for the circular duct and 7.04 m for the rectangular duct, indicating that resonance will no longer occur. This represents the distance from the sound source at which no peaks are formed. However, this is not a universal value and depends on the sound absorption capacity inside the duct.

Next, in Experiment 1) where significant distortion was observed in the frequencies, the measurement range was extended up to 10,000 Hz and measurements were taken again. The results for the circular duct are shown in Figure 15, and the results for the rectangular duct are shown in Figure 16.

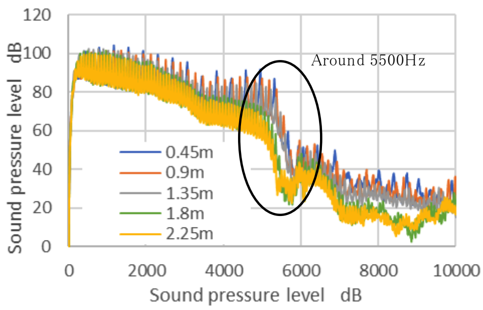

Figure 15 Relation between amount of absorbing material and SPL for circular duct.

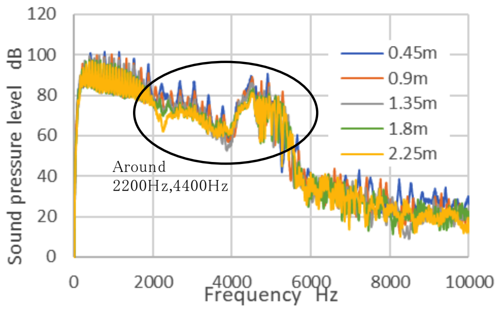

Figure 16 Relation between amount of absorbing material and SPL for square duct.

From figures 15 and 16, the cause of the waveform distortion can be attributed to what is known as the cut-off frequency. Since the duct is long in the longitudinal direction (x-direction), the longitudinal mode is primarily generated as the resonance frequency. Meanwhile, there are resonance modes in the cross-sectional directions perpendicular to the longitudinal direction (y and z directions), and these resonance frequencies are higher. Generally, these appear as composite modes, so when the frequency reaches the point where the cross-sectional mode resonance appears, the previously clear longitudinal modes are disrupted.

The formulas to calculate the cut-off frequency are given by Equations (1) and (2) below [12]. Equation (1) is used for circular ducts, and Equation (2) is used for rectangular ducts.

$$f_c = \frac{1.2197 \times C}{2a} \qquad (2)$$

$$f_c = \frac{C}{2b} \qquad (3)$$

(a: radius, b: side length, c: speed of sound, f_c: cut-off frequency)

By substituting the values into Eqs. (2) and (3), the cut-off frequency was obtained to be 5925 Hz for the PVC duct (circular duct) and 2267 Hz for the acrylic duct (rectangular duct). From this, it can be concluded that the frequencies of the waveform distortions in the results approximately match the cut-off frequencies, suggesting that the composite modes exceeding the cut-off frequency are the cause of the distortions. The distortions result in fluctuations in the sound pressure levels, thereby affecting the measured values.

C. Sound Pressure Level Due to Changes in the Amount of Sound-Absorbing Material in the Duct

As mentioned in Chapter *B*, sound pressure levels were measured and FFT analysis was performed after attaching sound-absorbing materials of different lengths to a 0.9 m circular duct. The results are shown in Figures 17 to 20 for the circular duct and Figures 21 to 24 for the rectangular duct. In both cases, the amplitude decreases as the frequency increases. This is because the sound absorption coefficient of the material is larger at higher frequencies.

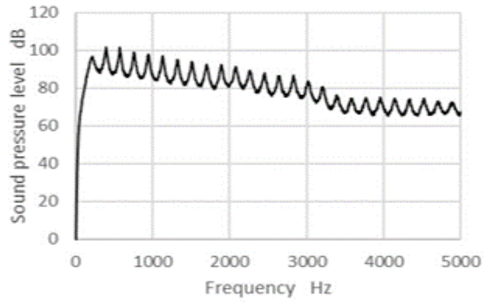

Figure 17 SPL of circular duct Sound absorbing material 0.1125m.

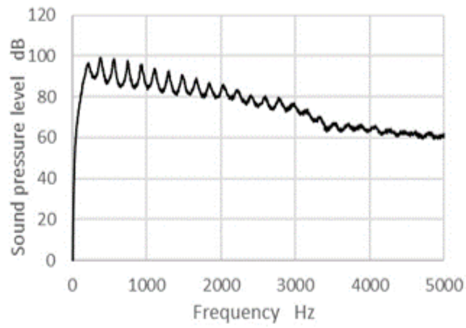

Figure 18 SPL of circular duct Sound absorbing material 0.225m.

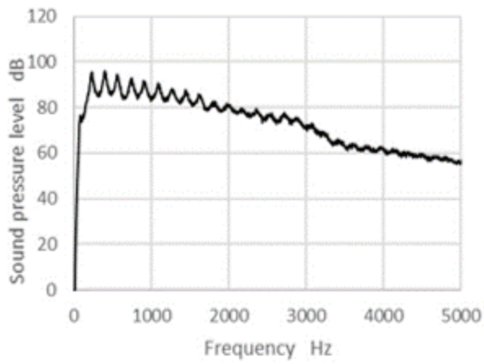

Figure 19 SPL of circular duct Sound absorbing material 0.45m.

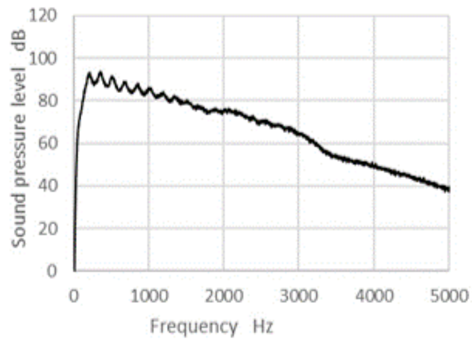

Figure 20 SPL of circular duct Sound absorbing material 0.9m.

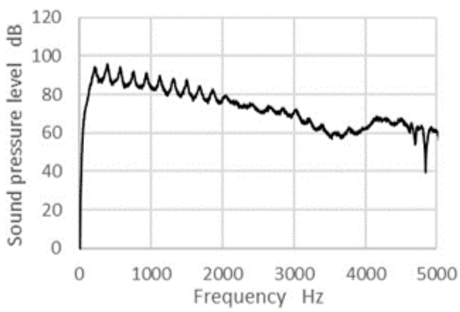

Figure 21 SPL of square duct Sound absorbing material 0.1125m.

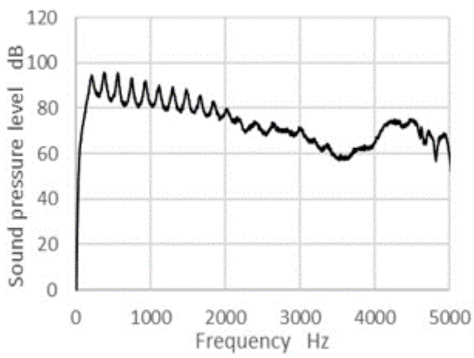

Figure 22 SPL of square duct Sound absorbing material 0.225m.

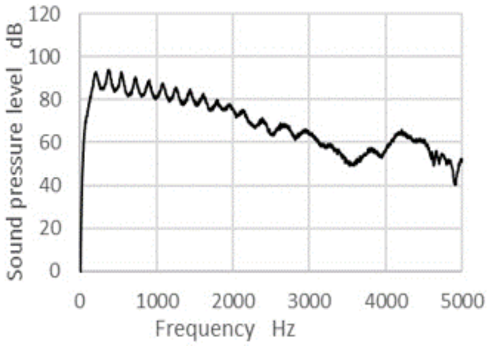

Figure 23 SPL of square duct Sound absorbing material 0.45m.

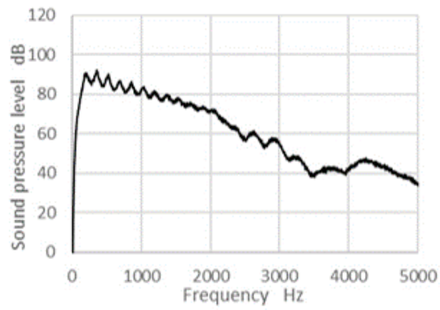

Figure 24 SPL of square duct Sound absorbing material 0.9m.

From the measurement results in Figures 16 to 24, the variation in peak sound pressure level for each mode order is shown for the circular duct in Figure 25 and for the rectangular duct in Figure 26. (Horizontal axis: logarithmic scale).

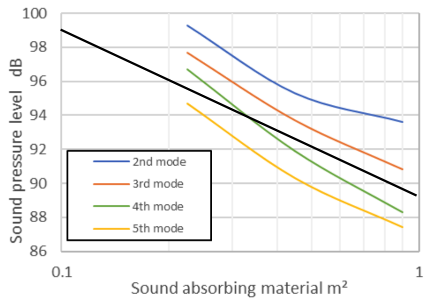

Figure 25 Peak SPL of each mode for circular duct.

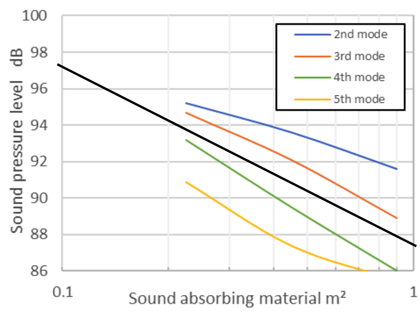

Figure 26 Peak SPL of each mode for square duct.

In Figures 25 and 26, the bold lines indicate 3 dB decrease when the amount of sound-absorbing material doubles, as demonstrated by room acoustics theory [12]. Peak values from the 2nd mode to the 5th mode are shown. It can be observed from Figures 25 and 26 that as the mode order increases and the amount of sound-absorbing material increases, the peak values decrease. This trend closely matches that of the bold lines. Among these, the values for the 3rd mode exhibit the greatest similarity.

From these results, it can be observed that as the amount of sound-absorbing material increases, the resonance peaks become less prominent. However, similar to Experiment 1), as the frequency increases, resonance frequencies become less distinct in the rectangular duct.

Here, the amplitude values at resonance frequencies with respect to the amount of sound-absorbing material are shown in Figure 27.

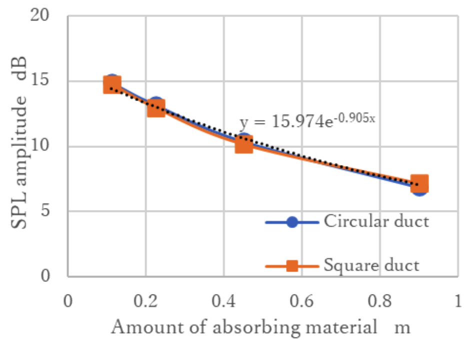

Figure 27 Change in peak value with amount of sound absorbing material

From Figure 27, little variation due to the cross-sectional shape of the circular and rectangular ducts was observed.

IV. Conclusion

To address two unresolved questions regarding the acoustic properties of ducts, namely: ① whether the magnitude of resonance varies with duct length and duct cross-sectional shape, and ② how the attenuation characteristics change with the presence of sound-absorbing material compared to when it is absent, experiments were conducted. The results led to the following conclusions.

(1) The reduction in sound pressure level with respect to length is linear regardless of whether the cross-sectional shape is circular or rectangular, with a reduction rate of approximately 3 dB/m. However, this value is not universal and varies depending on the sound absorption capacity within the duct. While the cross-sectional shape does not affect the amplitude (magnitude of resonance peaks), the frequencies at which cross-sectional modes appear differ depending on the cross-sectional shape, resulting in differences in the spectrum.

(2) In the presence of sound-absorbing material, the reduction in sound pressure level amplitude with respect to the amount of sound-absorbing material follows an exponential function, and the attenuation rate approximately matches the room acoustics theory, which states that the sound pressure level decreases by approximately 3 dB when the amount of sound-absorbing material doubles.

(3) In long ducts with low sound absorption capacity, there is a possibility of resonance occurring at modes of 50 or higher. One of the authors has been involved in addressing noise issues for many years and had doubts about whether resonance occurs in long ducts. This is because resonance is caused by the superposition of traveling waves and waves reflected at the ends (standing waves), resulting in standing waves. As the length increases, the sound pressure amplitude decreases, and the amplitudes of the reflected and traveling waves become different. Therefore, it was thought that resonance would not occur as the length increased. However, in this experiment, it was judged that resonance is possible, as evident from Figure 7, where clear peaks are observed even at the 50th mode (the 50th peak).

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