Study on Acoustic Characteristics of Lined Duct

Comparison between Experiment and BEM Analysis Using Impedance of Absorbent Measured by Impedance Tube

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***Abstract*- Lined ducts are widely used to reduce the noise generated from various equipments such as large wind tunnels and exhaust pipes of engines. Especially, noise reduction is required in offices and hospitals accompanying with the spread of air conditioning equipment. The noise reduction of non-lined ducts is usually predicted by using the FEM and the BEM techniques. However, there were a few cases that the analytic value was compared with the actual measurement of the lined duct which the noise absorbing material was used. In this research, the analytic value of BEM was compared with the actual measurement value for the attenuation quantity within a lined duct. Then, a noticeable gap was caused between both results in specific frequency. Thus, the cause was probed with a viewpoint of the specific acoustic impedance ratio used for BEM. As a result, it was found that the prediction of sound attenuation of the duct agrees with the experimental result by applying the impedance measured by the impedance tube with φ100 diameter to the BEM analysis.**

Keywords- Sound and Acoustics; Noise Control; Boundary Element Method; Environmental Engineering

I. INTRODUCTION

Lined ducts are widely used to reduce noise generated from ducts such as large wind tunnel ducts and exhaust ducts. Especially, noise reduction is required in offices, hospitals and in railway vehicles with air conditioners becoming widely used. The acoustic characteristics of lined ducts have mainly been studied experimentally. Shiokawa and Itamoto [1] studied the acoustic characteristics of a grass fiber duct, and Itamoto et.al [2] and Saito et.al [3] studied the flow and acoustic characteristics of lined ducts. These data are often used in data reports [4]. On the other hand, the commercial software due to FEM (Closed space) and BEM (Closed space and Open space) are often used to obtain the acoustic field analytically and they are used in many other fields such as automobiles, airplanes, ships and home appliances. Concerning the applicability of software, it is possible to know easily the applicability by carrying out the analyses of the resonant frequency and the frequency response in the cases without absorbents. However impedance is needed on the boundary in the case of using absorbents and it is difficult to evaluate the noise reduction analytically. The number of studies comparing experiments and analyses is low. In analyses, there are two ways. Namely, one is conducted with impedance given on the boundary. The other is when the absorbent is modeled using effective density ρ_e and the effective sound speed c_e . There are reports that the latter gives a more precise result but the former is more widely used [5-6]. In this study, analytical results are compared with experimental results of the noise reduction of lined ducts to confirm the analytical precision due to methods that impedance is given to the boundary with commercial software widely used for analysing acoustic fields. Then, it was confirmed that both results differed in specific frequencies. The cause is considered to be the impedance given to the BEM analysis. We then examined these presumptions. As a result, it was found that the precise analytical result could be obtained by using the impedance measured by the impedance tube with a large diameter.

II. EXPERIMENT

A. Experimental Setup

The experimental setup is shown in Fig.1. In the present experiment, four kinds of cross section ducts are used. They are (1) $W270\times H400$ (2) $W320\times H450$ (3) W370×$H500$ and (4) $W470\times H600$. The absorbent is rock wool with a thickness of 50 mm and a density of 80kg/mm^3. The surface is covered with punching metal with an aperture ratio of 22.7% (many holes with 2.5φ are arranged staggeringly). The surface impedance and normal incidence absorbing factor are measured by the acoustic tubes which are its characteristics as shown in Fig.2. Symbol (L) in Fig.2 shows results measured by acoustic tubes with φ100mm (Large tube) and a frequency range of 50～1600Hz. On the other hand, symbol (S) in Fig.2 shows a result measured by acoustic tubes with φ29mm (Small tube) and a frequency range of 500～6400 Hz. Thus, there are two values in the frequency region 500Hz～1600Hz. The measurement system used here is “PULSE Analyzer based on ISO 10534-2 and ASTM E1050”. These are made by Brüel & Kjær Division, Spectris Co.

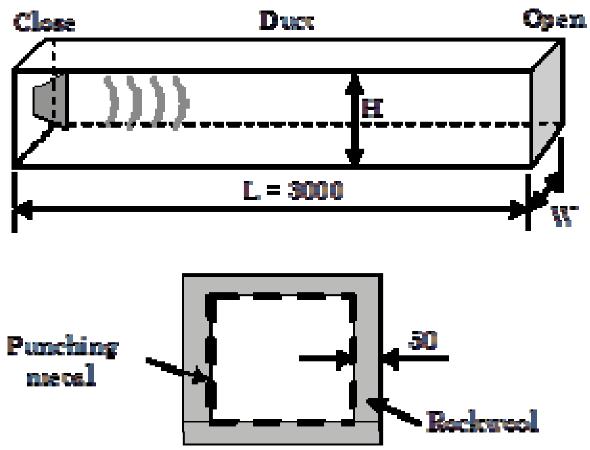

Fig. 1 Test apparatus

B. Experimental Method

The speaker (Sony SRS-88) is set near the closed end of the duct with pink noise output from the signal generator. The noise is radiated after amplifying and exciting the acoustic field of the duct. The measurement of the sound is carried out by varying the position every 200mm in the axial direction. The microphone is fixed at the center of the cross section of the duct. The obtained data are processed by a FFT analyzer using the one third octave value.

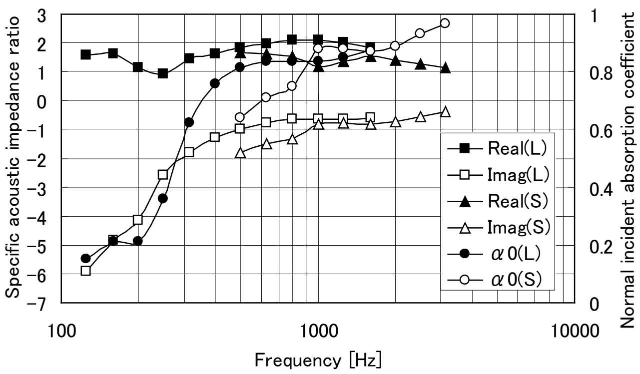

Fig. 2 Normalized acoustic impedance

III. EXPERIMENT

A. Distance Attenuation in Acoustic Field of Duct

Experiments were conducted by using four ducts of (1) W270×H400 (Internal dimension W 170×H 300) (2) W 320×H 450 (Same W 220×H 350 (3) W 370×H 500 (Same W 270×H 400) and (4) W 470×H 600 (Same W 370×H 500). Fig.3 and Fig.4 show distance attenuation in acoustic field of ducts with cross sections of as the parameters of the frequencies as examples. Getting off the low frequencies of 125Hz and 250Hz, the sound pressure level decays almost linearly with an increase in distance. This follows Sabine's expression [7].

$$ATT = 1.05\alpha^{1.4}\frac{P}{S}L \tag{1}$$

where *ATT* is attenuation [dB], *α* is the average absorbing factor of absorbent (Rock wool with 50mm thickness and 80kg/m^3 density), *P* is the internal dimension length [m], *S* is the internal dimensional cross sectional area [m2] and L is the distance [m] where the definition of the average absorbing factor is given as follows.

$$\alpha = \frac{\sum_i \alpha_i S_i}{\sum_i S_i} \tag{2}$$

However the average absorbing factor becomes the same as that of the absorbent because the absorbent is patched in all of the inner walls of the duct.

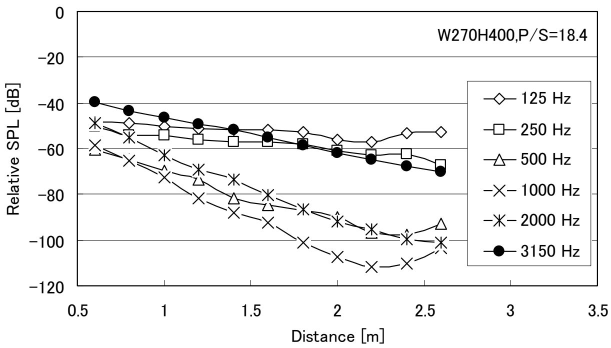

Fig. 3 Noise reduction with distance P/S=18.4

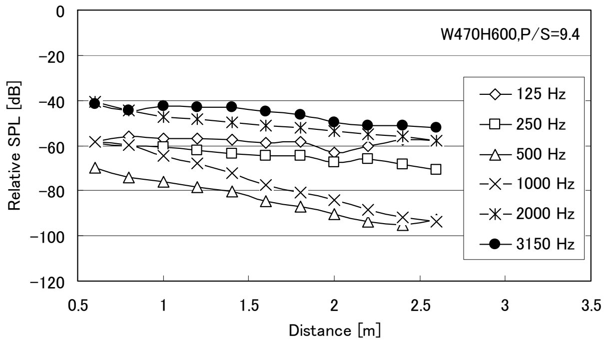

Fig. 4 Noise reduction with distance P/S=9.4

B. Attenuation per Unit Length of Lined Duct

Fig.5 shows the attenuation per unit length obtained every one third octave from the gradient as shown in Fig.3～Fig.4. It could be clarified that the maximum attenuation was proportional to *P/S* as shown by Eq.(1). Because the maximum values of the four kinds of cross section of ducts are 35dB, 30dB, 25dB, 20dB in small order and the same value could be obtained by dividing these values by *P/S*. However the frequency characteristics of attenuation are very different from Sabine's expression and the range of application [8] is under *c*/2*D* (*D*: length of short side). Additionally, it can be seen from Fig.5 that the frequency where the attenuation per unit length becomes maximum is near 1000 Hz and it shifts to a lower frequency side with a large dimension. Moreover it can be seen that the size dependency is small in the lower frequency range and large in the high frequency range. The tendency coincides with the Itamoto et al's result.

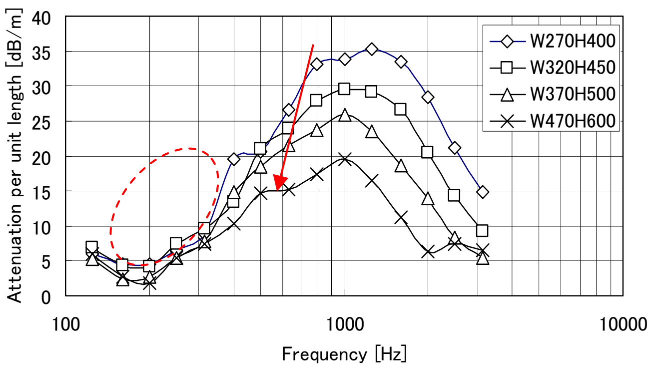

Fig. 5 Attenuation per unit length

IV. ANALYTICAL RESULTS AND CONSIDERATION

A. Analytical Model

Fig.6 shows an analytical model. The analysis was carried out by the commercial software using BEM. The boundary conditions are that one end is open and the other end is closed. Impedance values shown in Fig.2 are used on four side walls as the impedance boundary. The open end has no mesh and is the method to solve the inner and the outer parts of the duct simultaneously. Thus the open end correction is considered by this method. Values of impedance are shown in Table 1. The divided length is 30mm and the effective frequency range becomes 0Hz~1889Hz. The unit velocity 1 m/s is given at the position shown in Fig.6 as the noise source.

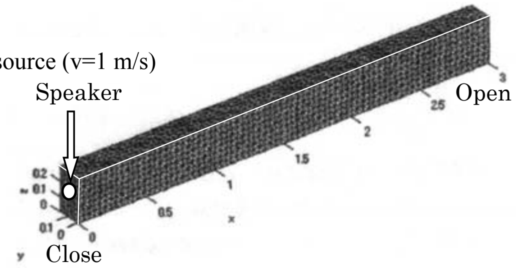

Fig. 6 Analytical model by BEM

TABLE I VALUES OF SPECIFIC ACOUSTIC IMPEDANCE RAITIO

1/3 Oct frequency	φ100 tube (L)			φ29 tube (S)		
	Re(Z)	Im(Z)	α	Re(Z)	Im(Z)	α
125	1.560	-5.920	0.150			
160	1.621	-4.838	0.214			
200	1.159	-4.126	0.214			
250	0.927	-2.578	0.358			
315	1.420	-1.800	0.625			
400	1.605	-1.299	0.758			
500	1.823	-0.988	0.815	1.678	-1.824	0.639
630	1.981	-0.764	0.837	1.612	-1.511	0.708
800	2.096	-0.657	0.837	1.537	-1.333	0.748
1000	2.108	-0.647	0.827	1.200	-0.794	0.877
1250	2.025	-0.640	0.847	1.352	-0.785	0.880
1600	1.835	-0.595	0.875	1.541	-0.802	0.868
2000				1.413	-0.731	0.889
2500				1.284	-0.558	0.929
3150				1.155	-0.381	0.965

B. Comparison between Analytical Results and Experimental Ones and Considerations

The acoustic fields of the four kinds of cross sectional ducts such as (1) *W* 270×*H* 400 (*P/S* =18.4) (2) *W* 320×*H* 450 (*P/S* =14.8), (3) *W* 370×*H* 500 (*P/S* =12.4) and (4) *W*470×*H* 600 (*P/S* =9.4) were analysed at every one third octave. As a representative for the results of distance attenuations of 250Hz, 1000Hz and 2000Hz about (1) *W* 270×*H* 400 (*P/S* =18.4) and (4) *W* 470×*H* 600 (*P/S* =9.4) are shown in Fig.7～Fig.8.

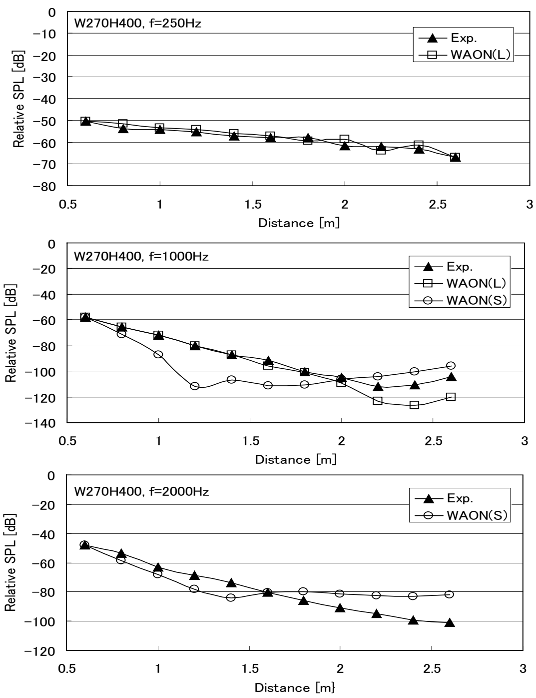

Fig. 7 Noise reduction with distance (P/S=18.4)

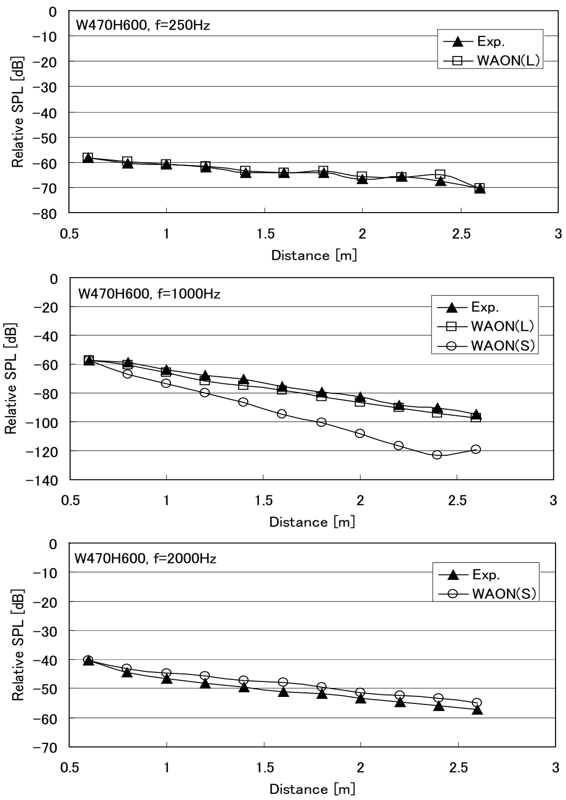

Fig. 8 Noise reduction with distance (P/S=9.4)

The analytical result is compared with the value measured at the center of cross section in the experiment. In these figures, the analytical value is in very good agreement with the experimental one at 250Hz. Also, the analytical result at 2000Hz is not agreement with the experimental one. However it can be said that the analytical result agrees with the experimental one by taking into account the effective frequency range of up to 1889Hz. On the other hand, two values of impedance exist at 1000 Hz and analytical values calculated by using these impedance values are shown at 1000Hz. The analytical value using the impedance obtained by the large impedance tube (WAON (L)) is in good agreement with the experimental value. On the contrary, that using the impedance obtained by the small impedance tube (WAON(S)) is larger than the experimental value.

This is due to the impedance value given to the BEM analysis. Then the impedance measured by the small impedance tube was examined in detail.

Fig.9 shows impedance ratios obtained by both large and small impedance tubes. In general, the impedance ratio draws a grease curve line. However the dip and the hip can be seen in the real and the imaginary impedance ratio in 200Hz～300Hz (L) and 900Hz～1100Hz (S), respectively. In this regard, it can be seen that the wave is steep and irregularly high in the small tube compared to the large tube being smooth and small.

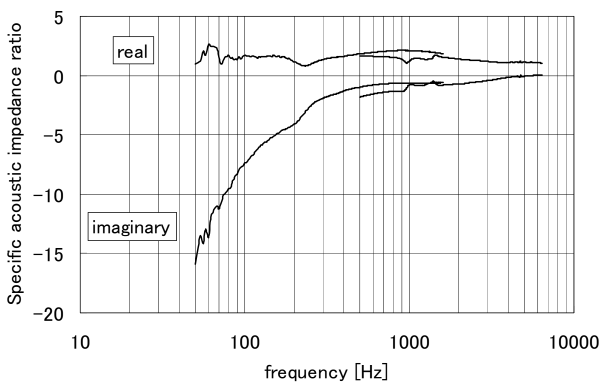

Fig. 9 Specific acoustic impedance ratio

It can be seen that both data lose touch with each other at around 1000 Hz. It can be considered that the cause is the punching metal covering the surface of rock wool or the resonance of the rock wool itself. The latter was reported by Iwase et al. [9, 10]

which a significant dip was yielded due to the resonance of the absorbent by a bound when the propagation coefficient was measured by the impedance tube. Then the difference of impedance due to the existence or non-existence of punching metal covered on the surface of rock wool is compared. These results are shown in Fig.10 (Large tube) and Fig.11 (Small) in order to judge the effect of the punching metal.

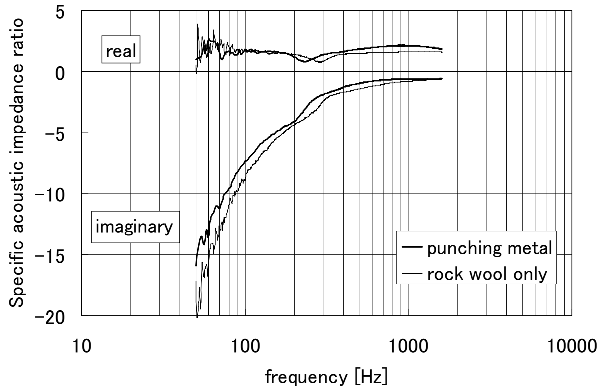

Fig. 10 Specific acoustic impedanc*e ratio (φ100)*

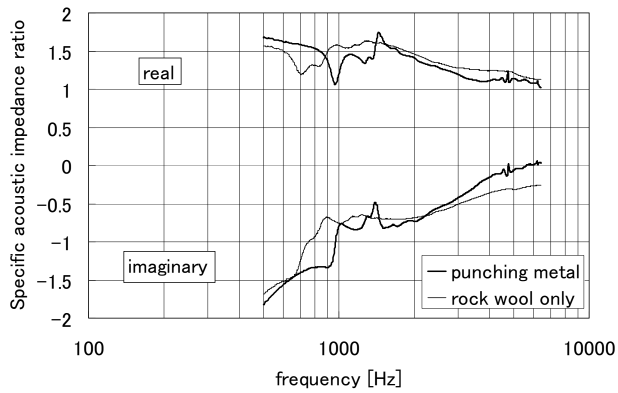

Fig. 11 Specific acoustic impedance ratio (φ29)

The “punching metal” and “rock wool only” indicated in these figures are the cases of covering the surface of rock wool by the punching metal and of bareness, respectively. By removing the punching metal, the frequencies at which the dip and the hip yield are shifted and the sharpness of the wave is loosen up, though they remain in the both tubes. Thus this is not the cause of the effect of punching metal but due to the resonance of the test piece. However another cause can be considered. Namely in this study, the punching metal is set on the rock wool when the impedance ratio is measured. The boundary condition at that moment is different from the setting condition of the lined duct. If the punching metal is put on the rock wool without fixing circumference when the impedance ratio is measured by using the small impedance tube, the punching metal is easy to vibrate.

C. This possibility is one example. However it can be considered that the real setting condition of absorbents on the duct is different from that of the small impedance tube. Attenuation per Unit Length

In order to judge the effect of the resonance of the test piece at each frequency, the attenuation per unit length at each one third octave was obtained by using the analytical values of distance attenuation as shown in Fig.7～Fig.8 and compared with the experimental values. The results are shown in Fig.14～Fig.17. In each duct, the attenuations per unit length in low frequency range 160Hz～250Hz are omitted by judging that it was difficult to obtain the precise attenuation. This is because the mode yields as shown in Fig.12 (in the case of W270×H400) and the attenuation is small in this frequency range. In order to confirm how improvement can be obtained in the case of using an impedance ratio excluding the dip as the countermeasure of the resonance, the impedance corrected in the manner of approximate linearization was made from data which excluded the dip at 1000Hz, 1250Hz, 1600Hz. The concrete method of approximate linearization is the logarithmic approximation with Excel. A large effect of dip in the small tube as shown in Fig.13 was obtained and the attenuation was obtained by BEM analysis. These results were put down in Fig.14～Fig.17 and compared with the analytical values before correction. The “φ100” and “φ29” indicated in these figures are the results calculated by using the impedance obtained by large and small impedance tubes, respectively and “correct” is the result calculated by using the corrected impedance shown in Fig.13. First, in comparison between measured and analytical values in each cross sectional duct, the data of the large tube lose touch with those of the small tube in a large way around 1000Hz. This is the same as the case of distance attenuation. It can be seen that an analytical value using the impedance value obtained by the large tube is a good correspondence with the experimental value. Next, in comparison between before and after correction, the data after correction comes close to the measured data and large improvements can be seen at 1000Hz in cases of (1) W270×H400 and (2) W 320×H 450. However improvements cannot be seen at other frequencies (1250Hz, 1600Hz). Furthermore, improvement cannot be seen at all frequencies. The present correction using the approximate line excluding the dip of impedance is not effective and it becomes an ineffective countermeasure in (3) W 370×H 500 and (4) W 470×H 600.

From the results mentioned above, it is the effective countermeasure that the data obtained by the large impedance tube are used to improve the misfit due to the dip of impedance between the analytical and the measured data. The causes of dip are the resonance of the test piece and others. This is reasonable because the Reference [11] shows that the measured frequency range is below 2kHz in the large tube and the 1mm clearance has no effect on the measurement. On the contrary, the clearance has a large effect on the measurement in the small tube. The resonance of the test piece can be avoided by the proposed method [11-13] and it is important to measure by a method in which resonance is hard to occur.

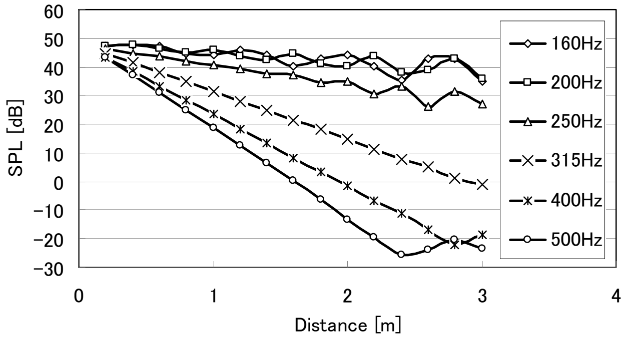

Fig. 12 Noise reduction with distance (W270H400)

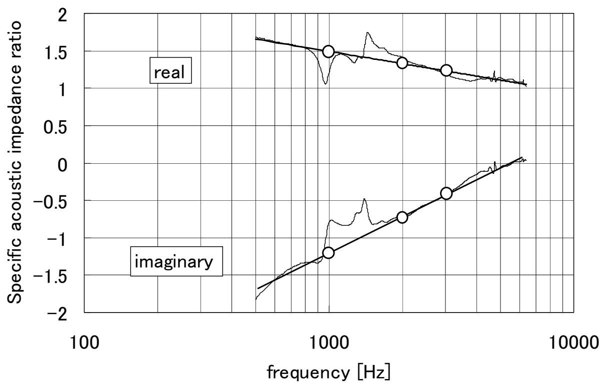

Fig. 13 Specific acoustic impedance ratio (Correct)

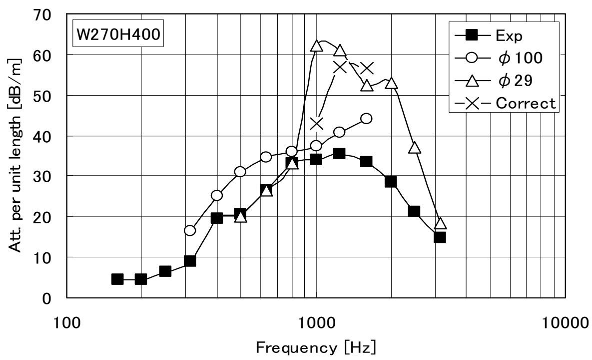

Fig. 14 Attenuation per unit length (P/S=18.4)

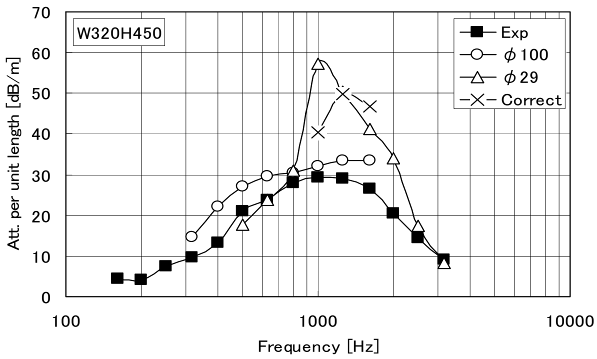

Fig. 15 Attenuation per unit length (P/S=14.8)

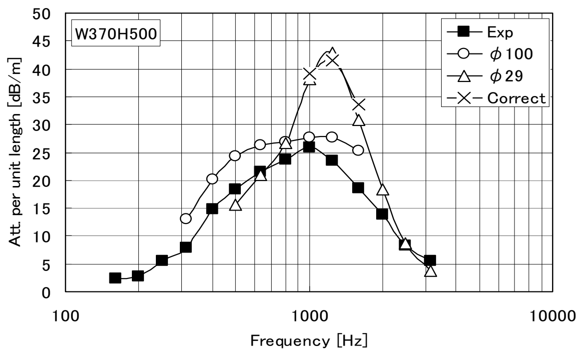

Fig. 16 Attenuation per unit length (P/S=12.4)

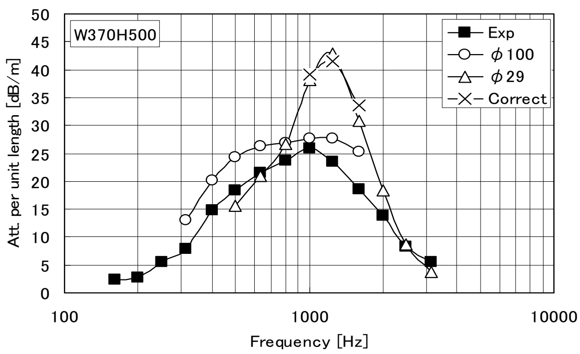

Fig. 17 Attenuation per unit length (P/S=9.4)

In this study, the dip of impedance yields due to the effect of resonance of test pieces in both large and small tubes. When both analytical and experimental data were compared to each other, mismatches were easy to notice at frequencies where the resonance of test pieces occurred in the small tube which became no problem in the large tube. This is because the rock wool in the large tube is near the physical dimension of the real absorbent applied to the duct and the resonant state is similar to that of the real thing. However the detail is not clear.

V. CONCLUSIONS

The attenuation per unit length was measured in lined ducts with different cross sections. Also, an analysis by BEM was also carried out and compared with measured values. When analysis is performed with two values of impedance which are given to a BEM analysis the frequency range of 500Hz～1600Hz exists. As can be seen in the analytical results using both data are very different when the causes and the countermeasures are examined. As a result, the following concluding remarks were obtained.

(1) It was clarified that mismatches appeared between attenuations per unit length by the BEM analysis and experiment due to the dip of impedance yielded when the impedance of absorbent is measured by the impedance tube.

It was also clarified that when the mismatch yields in the frequency range 500Hz～1600Hz where both impedance data exist, analytical value using the impedance obtained by the large impedance tube has high consistency of an experimental value.

(2) The punching metal with an open ratio of 22.7% used in this study gives little effect on the impedance ratio.

(3) It could be confirmed again that the maximum attenuation per unit length in lined ducts is proportional to the length L and perimeter/area (P/S) in the frequency range where the absorbing effect exists.

(4) The attenuation per unit length of lined ducts could be obtained by the experiment. Also, it becomes the maximum in frequency ranges 1000～2000Hz under the present experimental conditions. It was also clarified that its frequency becomes lower with an increasing open area of the duct end.

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