Comparison of Eigen frequency and Sound Pressure Level between Straight and Bent Ducts

Katsuhiko Kashihara, Kunihiko Ishihara

Abstract— **Ducts are widely used in various industrial fields. Ducts, which are used in many places, can be connected to sources of noise. In locations where quietness is required, ducts need to be designed to suppress noises. To reduce noises, it is necessary to suppress resonance. To avoid resonance, it is essential to know the natural acoustic frequencies of the duct. In this paper, we will clarify the changes in frequency caused by multiple bends in the duct. Furthermore, we will study and clarify the changes in the sound pressure level when sound-absorbing material is inserted into a bent duct.**

***Index Terms*—Resonant frequency, Acoustic mode, Straight duct, Bent duct**

I. INTRODUCTION

Powerful suction trucks used for tasks such as cleaning side ditches (hereafter referred to as suction trucks) are increasingly being used at night in urban areas to avoid traffic congestion caused by increasing traffic volumes. To use suction trucks at night, quietness is required, making noise reduction a challenge.

The noise source of a suction truck is the roots blower, and the connected piping system bends multiple times as shown in Figure1, reaching the final exhaust outlet. The pulsation frequency of the roots blower is proportional to the engine rotating speed and operates within a certain range of speeds. At this time, resonant noise can be heard from the piping system, which can be a significant problem. To avoid resonance, it is necessary to know the natural acoustic frequencies of the piping system. Knowing the changes in resonant frequencies due to the number of bends is important to avoid resonance.

Many studies referred to the characteristics of ducts have been made in the past [1]-[6].

Previous studies include research on the acoustic characteristics of bends by Ishihara [1]. However, the frequency characteristics when there are more than three bends have not been clarified. Therefore, this study conducted experiments and analyses to clarify the effects of having 1 to 5 bends on the resonant frequencies within the frequency range where plane waves are valid.

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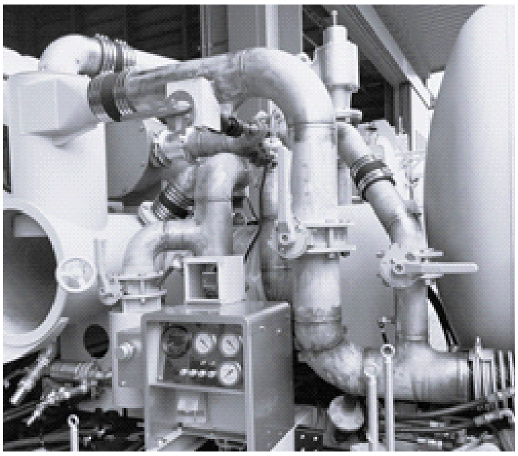

Figure 1 Piping system of a high-pressure suction truck

II. METHODS

Square-section acrylic pipes were assumed to be ducts, and two types were made: a straight duct (hereinafter referred to as "straight duct") and one with a 90-degree bend (hereinafter referred to as "bent duct"). Acrylic pipes of two different square cross-sections were made: ducts measuring 0.05m on each side and ducts measuring 0.075m on each side. The length of the 0.05m square straight duct was 0.3m, and the length of the 0.05m square bent duct was also made the same as the straight duct, at 0.3m, measured at the center of the cross-section. The length of the 0.075m square straight duct was 0.45m, and similarly, the length of the 0.075m square bent duct was made the same as the straight duct, at 0.45m, measured at the center of the cross-section. As an example, a duct measuring 0.075m on each side is shown in Figure 2.

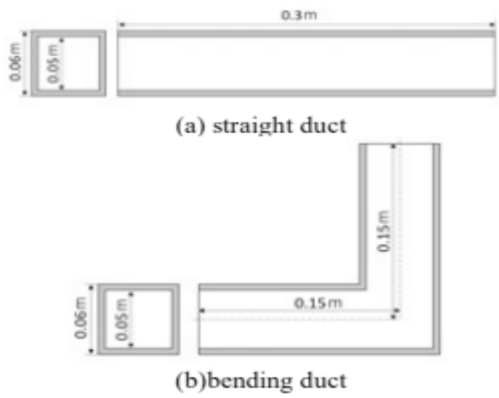

Figure 2 Bending and straight ducts with 0.05m square

A white noise signal was generated by a computer and transmitted through a Technics SU-V500 audio amplifier (manufactured by Matsushita Electric Industrial Co., Ltd.) to a speaker unit P650K (cone diameter 0.065m, produced by FOSTEX company) to create white noise. The speaker was installed on one side of the experimental duct, and a standard sound level meter NL-42 (manufactured by Rion Co., Ltd.) was placed at the other end for noise measurement. Thus, the boundary conditions of the duct were "closed-open". For FFT analysis, a dedicated program NX-42FT (manufactured by Rion Co., Ltd.) was used.

Measurements were carried out by gradually increasing the number of ducts from one to five, conducting measurements for 0.05mm square ducts from 0.3m to 1.5m, and for 0.075mm square ducts from 0.45m to 2.25m. After each measurement, sound-absorbing material with a thickness of 0.005m was applied inside each duct, and the measurements were repeated using the same procedure. Figure 3 shows an assembly of five bent ducts connected together. Here, the number of bent ducts is meant the number of bends.

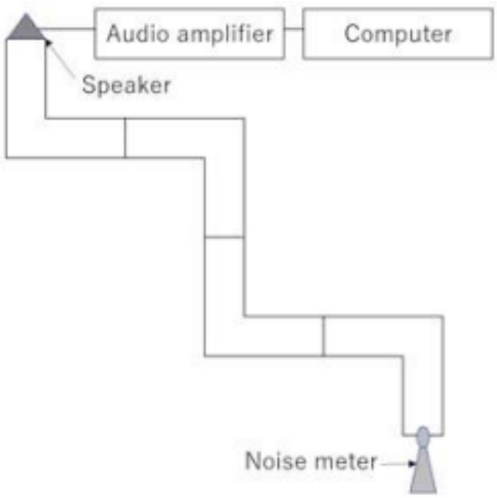

Figure 3 Connected four bending ducts

For the analysis, FFT analysis was used to perform narrowband frequency analysis at 2.5Hz intervals up to 2,000Hz.

III. Results and Discussion

A. Reproducibility

Measurements were conducted three times for each of the following: straight ducts and bent ducts with dimensions of 0.05m and 0.075m, with connection conditions ranging from one to five pieces. Subsequently, measurements were similarly conducted after applying sound-absorbing material inside. As an example, the results of the FFT analysis for three connected straight ducts of 0.05m are shown in Figure 4. The graphs from the three measurements overlap, confirming their reproducibility. Although not shown here, reproducibility has been confirmed for all other measurement results as well.

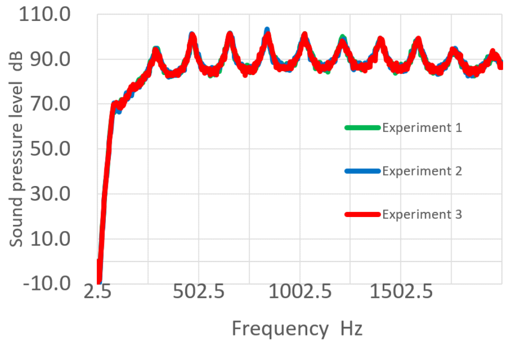

Figure 4 FFT result for three straight ducts with 0.05m square

B. Resonant Frequencies without Sound-absorbing Material

Next, the resonant frequencies of straight and bent ducts with a dimension of 0.05m were determined from FFT analysis, and the second, third, and fourth modes are illustrated in Figure 5. For two straight ducts, and two, three, four, and five bent ducts, the peak of the first mode was not formed, making it impossible to read from the graph.

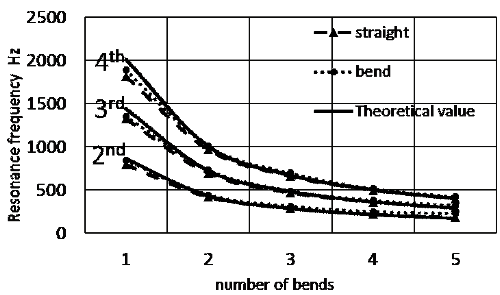

Figure 5 Resonant frequencies of ducts with 0.05m square in case of without absorbent.

The resonant frequencies of both straight and bent ducts with a dimension of 0.075m were also determined from FFT analysis, illustrating the first, second, third, and fourth modes in Figure 6.

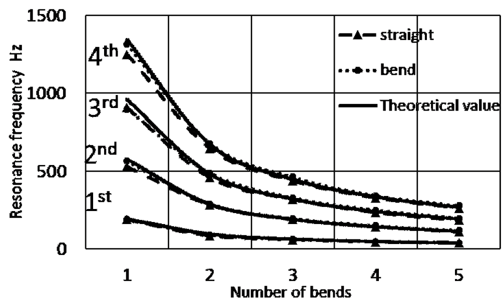

Figure 6 Resonant frequencies of ducts with 0.075 square in case of without absorbent.

From the figures, it was found that the resonant frequencies, regardless of being straight or bent ducts, agree with the theoretical formula (1).

$$fn=(2n-1)\times c/(4L) \qquad (1)$$

Here, fn is the resonant frequency (Hz), n is the mode order, c is the speed of sound (m/s), and L is the length of the duct (m). Therefore, it is concluded that if the central length of the bent duct is the same as that of the straight duct, the resonant frequencies will match.

C. Resonant Frequencies with Sound-absorbing Material

Experiments were conducted in a similar manner for both straight and bent ducts with a cross-section of 0.05m, by applying a 0.005m thick layer of sound-absorbing material inside the ducts. A comparison of the resonant frequencies was made through FFT analysis. Since a 0.005m thick layer of sound-absorbing material covers the entire inside, the internal dimensions become equivalent to a 0.04m square duct. The resonant frequencies for straight and bent ducts, illustrating the first, second, third, and fourth modes, are shown in Figure 7. For one straight duct and one to five bent ducts, the peak of the first mode was not formed, and also, for four and five bent ducts, it was impossible to read from the graph.

With the presence of sound-absorbing material, the resonant frequencies deviated from the theoretical values compared to when no sound-absorbing material was present.

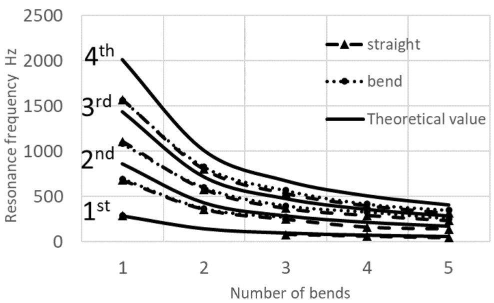

Figure 7 Resonant frequencies of duct with 0.04 square in case of with absorbent.

Subsequently, experiments were similarly conducted for both straight and bent ducts with a cross-section of 0.075m, by applying a 0.005m thick layer of sound-absorbing material inside the ducts, and a comparison of the resonant frequencies was made through FFT analysis. As a 0.005m thick layer of sound-absorbing material covers the entire inside, the internal dimensions become equivalent to a 0.065m square duct. The resonant frequencies for straight and bent ducts, illustrating the first, second, third, and fourth modes, are shown in Figure 8.

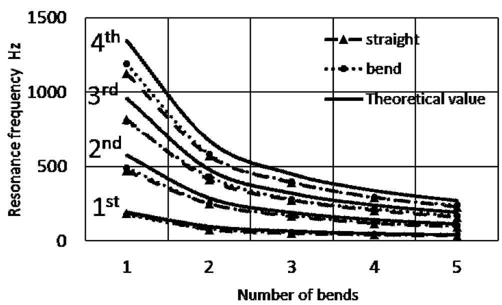

Figure 8 Resonant frequencies of duct with 0.065m square in case of with absorbent.

From the above results, it was found that the presence of sound-absorbing material results in resonant frequencies that are lower than the theoretical values.

D. Peak Sound Pressure Levels at Resonant Frequencies without Sound-absorbing Material

For ducts with a cross-section of 0.05m without sound-absorbing material, the sound pressure levels at the resonant frequencies for the second to fourth modes, shown in relation to the number of bends, are presented in Figures 9 to 11.

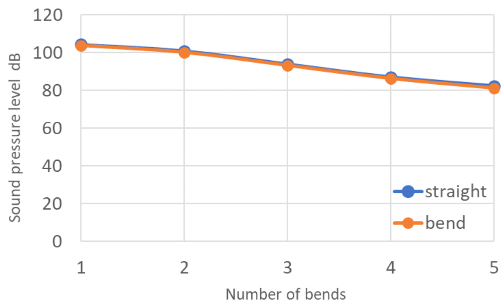

Figure 9 Peak sound pressure level of 2nd mode in case of 0.05 square and without absorbent.

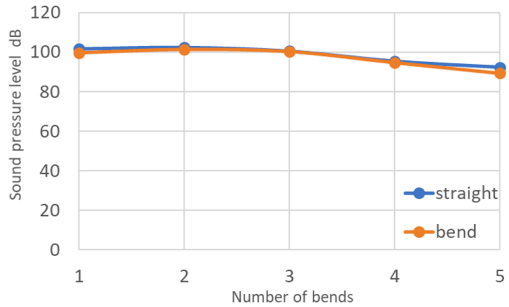

Figure 10 Peak sound pressure level of 3rd mode

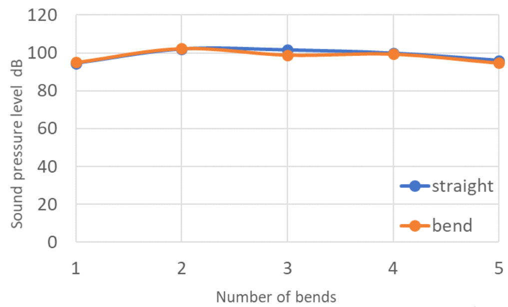

Figure 11 Peak sound pressure level of 4th mode

For the ducts with a cross-section of 0.075m without sound-absorbing material, the sound pressure levels at the resonant frequencies for the first to fourth modes are presented in Figures 12 to 15.

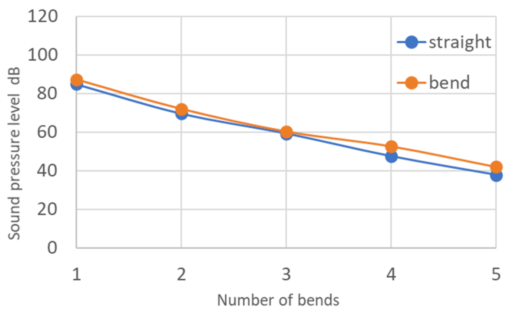

Figure 12 Peak sound pressure level of 1st mode
in case of 0.075 square and without absorbent

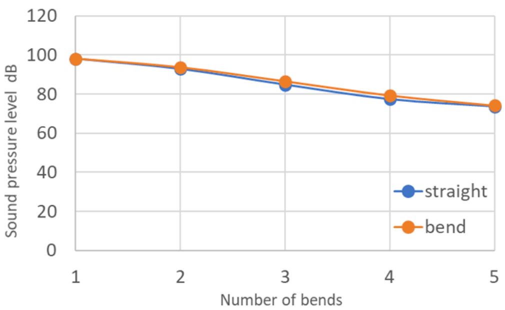

Figure 13 Peak sound pressure level of 2nd mode

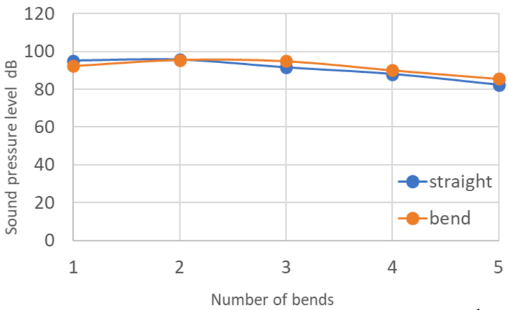

Figure 14 Peak sound pressure level of 3rd mode

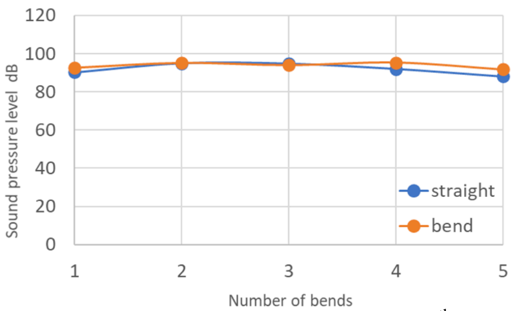

Figure 15 Peak sound pressure level of 4th mode in case of 0.075 square and without absorbent

From these figures, it was confirmed that there is no change in the peak values of the sound pressure levels regardless of the presence of bends. In general, bending ducts suppress the noise in frequency more than a certain frequency fc (fc=c/2b:345/2/0.065≈2654Hz, where c is sound speed, b is length of one side). Therefore it is thought that the difference in SPL's between straight and bending ducts arises. Contrary to expectations, there is no difference between two ducts. It is because that the target frequency is lower than fc described before. Furthermore, it was observed that the attenuation due to an increase in duct length is greater for lower modes, and there is almost no attenuation by the time it reaches the fourth mode.

E. Peak Sound Pressure Levels at Resonant Frequencies with Sound-absorbing Material

Experiments were conducted for both straight and bent ducts with a cross-section of 0.05m by applying a 0.005m thick layer of sound-absorbing material inside the ducts, and the results were graphed. The sound pressure levels at the resonant frequencies for the first to fourth modes are shown in Figures 16 to 19. With the 0.005m thick layer of sound-absorbing material covering the entire inside, the internal dimensions become equivalent to a 0.04m square duct. For Figure 16, only the graph for the straight duct is shown, as the peak values for the bent ducts could not be read.

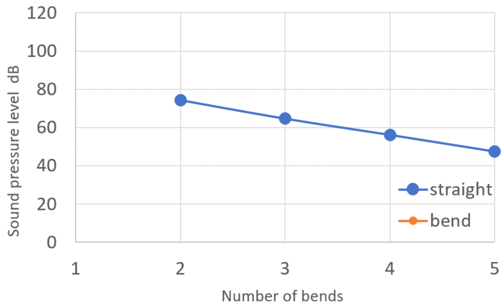

Figure 16 Peak sound pressure level of 1st mode in case of 0.04m square and with absorbent

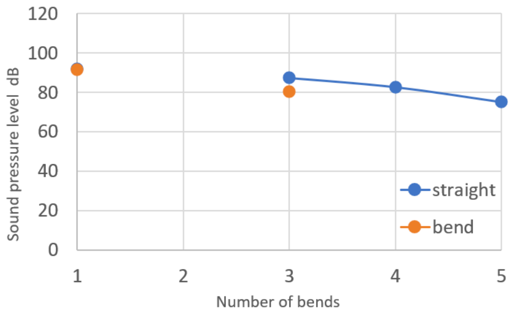

Figure 17 Peak sound pressure level of 2nd mode

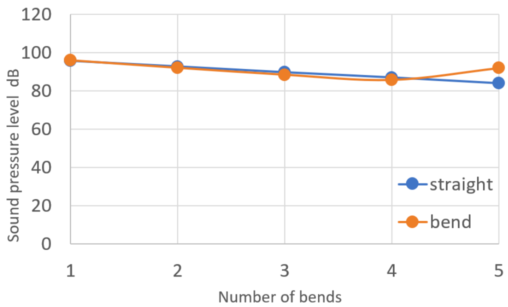

Figure 18 Peak sound pressure level of 3rd mode

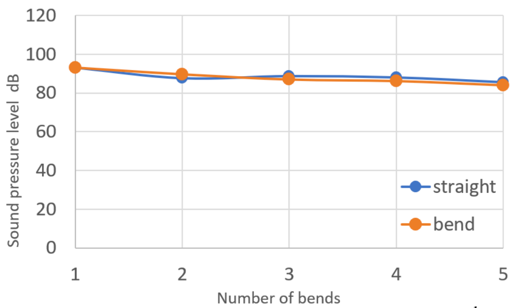

Figure 19 Peak sound pressure level of 4th mode

The presence of sound-absorbing material resulted in irregular outcomes.

Next, experiments were similarly conducted for both straight and bent ducts with a cross-section of 0.075m by applying a 0.005m thick layer of sound-absorbing material inside the ducts, and the sound pressure levels at the resonant frequencies were graphed. Since a 0.005m thick layer of sound-absorbing material covers the entire inside, the internal dimensions become equivalent to a 0.065m square duct. The sound pressure levels at the resonant frequencies for the first to fourth modes are shown in Figures 20 to 23.

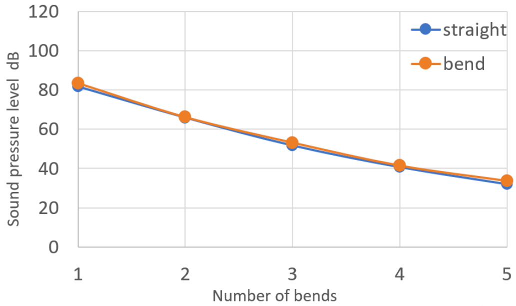

Figure 20 Peak sound pressure level of 1st mode

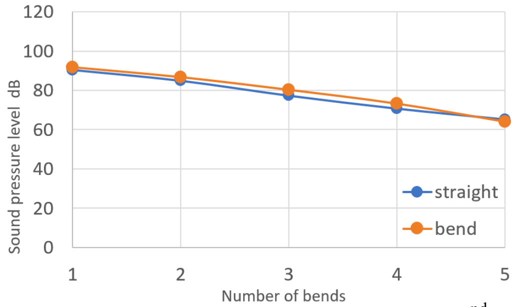

Figure 21 Peak sound pressure level of 2nd mode

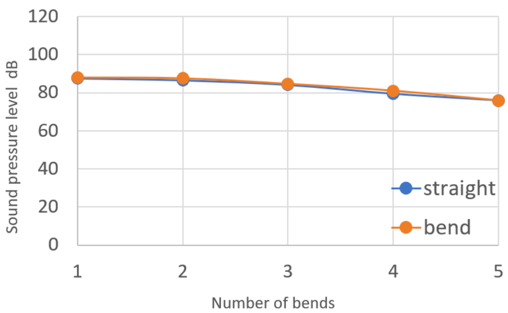

Figure 22 Peak sound pressure level of 3rd mode

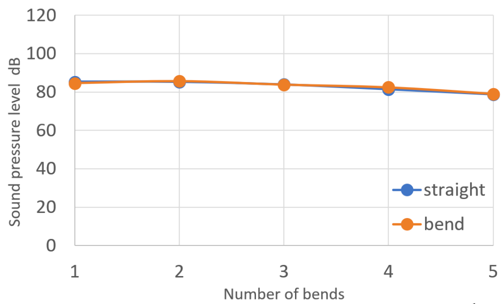

Figure 23 Peak sound pressure level of 4th mode

From these figures, it can be said that the sound pressure level decreases with increasing the number of bent and its tendency is greater than the lower order mode. And the sound pressure level of the bent duct is almost the same as that of the straight duct.

IV. CONCLUSION

Connections ranging from one to five pieces were made for straight and bent ducts with the same inner diameter and length, and changes in resonant frequency and sound pressure level at the resonant frequency were confirmed. Through experimentation and analysis, the following insights were gained:

(1) The resonant frequency fn (Hz) of the bent duct is represented by the formula $f\,n = ((2n-1)c)/(4L)$, where n is the mode order, c is the speed of sound (m/s), and L is the length of the duct (m). The presence or absence of bends had no effect on the resonant frequency.

(2) Installing sound-absorbing material in the duct could suppress resonance, and it was found that the resonant frequency becomes lower than that of without absorbing materials.

(3) Regarding the sound pressure level at the resonant frequency, the attenuation effect decreases as the mode order increases, and there was no difference between straight and bent ducts. It is because that the target frequencies are lower than fc.

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