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EXPERIMENTAL STUDY OF ACOUSTIC CHARACTERISTICS OF EXPANSION CHAMBER WITH MEAN FLOWS

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For the measurement of transmission loss of the silencers which have mean flow, the noise levels of signals depicted by microphone usually prohibit accurate measurements of the transmission loss. To overcome this difficulty, static pressure compensation technique has been developed to increase the dynamic range of the microphones, resulting accurate measurement of transmission loss in the presence of high noise level. Series of experiments to investigate the acoustic characteristics of expansion chamber with mean flow has been performed using the pressure compensated microphones. Results demonstrate: (1) frequency shift due to the presence of mean flow, (2) effect of length, diameter, offset length and twisting angles to the transmission loss of expansion chamber with and without mean flow(up to 50m/sec), (3) relation between the proposed parameter 'aspect ratio' and number of peaks of transmission loss in low frequency region.

Key Words: Transmission Loss, Silencer, Noise, Mean Flow

1. INTRODUCTION

Transmission loss of silencer has been used as a good measure of the performance of silencer. Since the transmission loss is not affected by the termination impedance or source impedance, it is easier to work theoretically compared with the insertion loss(Baxa, 1982). But the measurement of transmission loss of silencer requires careful instrumentations compared with the measurement of the insertion loss (Baxa, 1982). Especially when a silencer has mean flow, the noise generated by the turbulence of flow degrades the signal to noise ratio(S/N ratio) of the measurement system. The acoustic signal depicted by the microphone for a given dynamic range is sometimes imbedded in the noise. This might be the reason why most experimental data of transmission loss which has mean flow effect are very limited in the literature.(Munjal and Prasad, 1986, Erikson, 1979, Ih and Lee, 1985)

Singh and Katra(1978) used an impulse technique to measure the characteristics of muffler. The major drawbacks to this technique are limited dynamic range, the difficulty in triggering and limited applicability for the non-linear phenomena. Lung and Doige(1983) applied a time averaging transient method to measure the acoustic properties of piping systems and mufflers with mean flow. They were successful to increase the signal to noise ratio but did not take accoung for the time delay between microphones, resulting errors in transmission loss measurements.

Seybert and Ross(1977) used white noise for sound source and utilized two microphones which were wall mounted to measured the sound pressures of inlet and outlet tubes of silencer. They showed that auto-and cross-spectra of two microphone signals can be used to charecterize the reflection coefficient and transmission loss. But the experiments only handle the silencer without mean flow.

For the silencer experiments, the difficulties are that the generated turbulence by flows degrades the S/N ratio. Due to the sudden change of cross sectional area, the generated turbulence inside the silencer is exceedingly strong compared with that of inlet pipe. This noise generated by the turbulence generally dominates the measured signal. When white noise is used for a sound source, the speaker has to emit enough sound power to overide the noise signal and also the microphones must have wide dynamic range. Rational method to increase S/N ratio must be developed to have good data of transmission loss of expansion chamber. This was one of the motives of present experiments.

For a reactive type silencer, it is well known that the physical parameters which affect the transmission loss of a silencer are length and diameter of silencer, mean flow velocity, temperature gradient along silencer, twisting angle and offset distance between inlet and outlet pipes. But there is only limited experimental results which show these effects systematically. This was the other motives of this study.

In this paper, random excitation technique as well as sine sweep technique to measure the transmission loss are introduced. The advantages and disadvantages of those techniques are compared through the experiments with and without mean flow. Major concern on the comparision is the performance with respect to increase of signal to noise ratio. Transmission loss is calculated by using the transfer function between the signals of two microphones. Instrumentation technique to increase the dynamic range of microphone is also introduced. Static pressure compensation technique for the microphones which increases the dynamic range is explained in detail.

Numerous experimental results for the case of various

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length to diameter ratioes of silencers, 3 different offsets distances, 3 different twisting angles and 3 different mean flows are demonstrated. Over 200 tests have been performed in this experimental study.

2. INSTRUMENTATION

2.1 Background and Turbulent Noise

Anechoic chamber might be ideal for minimum background noise, but the experiment has been tried in conventional laboratory whose area is about 100㎡. The background noise levels measured at the inlet and outlet ports were quite low enough to peroform the experiment. It was below 80dB relative to 20μ Pa and the power spectra of noise show no particular peaks.

To supply flow to the silencer, two methods were investigated. one through a pipe connected obliquely (about 30° with the direction of sound propagation) and the other through a straight pipe. But there were no considerable differences. Though the flow was supplied through a noise attenuator (explained in 2-2), the sudden change of cross sectional area across the silencer induced flow noise with considerable level. It was recognized that the noise level at outlet port was 8dB, 13dB, and 19dB higher than that at the inlet port of silencer for the flow velocity, 20m/s, 35m/s and 50m/s respectively. But the coherence between the noise of inlet and outlet port was substantically small. Hence, only the noise level affects the signals depicted by the microphones independently. Averaged flow noise level at the inlet port of silencer were 90dB, 93dB and 98dB for the flow velocity 20m/s, 35m/s and 50m/s respectively.

2.2 Blower and Blower Noise Attenuator

Selected blower was E.G.& G. Cyclonair whose max. flow rate is 14.16㎥/min and max. discharge pressure is about 34,500Pa. Noise generated by the blower depends on the flow velocity and frequency band of interest. Max. noise level generated by the blower was 115dB when flow velocity was 50m/s. To reduce this noise level and noise related with blade and cooling fan a dissipative noise atenuator was designed and attached to the blower. Resulting noise reduction was about 10dB for max. noise level when the flow velocity was 50m/s. More than 8dB of noise reduction up to 3kHz was obtained for the other flow speeds.

2.3 Anechoic Terminator

The definition of transmission loss (*TL*) is (Baxa, 1982)

$$TL = 20 \log \mid Pi/Pt \mid \quad (1)$$

where Pt is transmitted sound pressure and Pi is incident sound pressure to a silencer. Hence, it is obvious that the presence of reflected sound on Pt will cause biased measure of transmission loss. To reduced the reflected sound wave due to impedance mismatch at the end of outlet pipe of a silencer, an anechoic terminator of an exponential horn type was designed and manufactured. Length and opening diameter of the horn was 82cm and 42cm respectively. Steel wool, was sparcely filled in the anechoic terminator to cut out the noise from outside of test section. The absorption coefficient of the anechoic termination exceeds 91% in the frequency range from 400Hz to 1.6kHz and 96% above 2.5kHz.

Though this seems not perfect to be called "anechoic", the reflected wave may cause minor effect on *TL* estimation. For example 20% of reflection coefficient causes bias error of 1.5dB maximum in *TL* estimation. Reflected wave might be present at the inlet port of expansion chamber, but source impedence does not affect the transmission loss as indicated in the definition of transmission loss(1). Furthurmore, the source impedance can be assumed to be ρc such as reflective wave is not allowed, as discussed by Ross and Crocker (1983). Therefore the pressures measured at inlet and outlet ports are almost identical to *Pi* and *Pt* respectively in the experiment.

2.4 Sound Source

Since transmission loss is a measure of the ratio of incident sound power to transmitted one, the flatness of power spectral density of sound is not essentially required. The selected sound source was a horn driver with power amplifier of B & K Type 2706. When single tone was supplied to the horn driver, max. power which does not introduce the clipping of the power amplifier was 165dB and min. was 140dB. Those are well enough to override the turbulent noise level. In case of white noise excitation, the worst *S/N* ratio is 11dB which is not sufficient enough to get good result. Therefore, sine sweep method might be better than random excitation technique since it can produce more sound power per frequency for a given amplifier and the horn driver.

2.5 Microphone and Signal Conditioner

Instead of using a measuring micophone we used commercial microphones designed for conventional cassette tape recorder since it can be modified easily. The diameter of the microphone was about 3mm which is far less than the diameter to disregard the directivity (Kinsler et. al, 1980). These microphones was wall mounted to the inlet and outlet pipes of the silencer directly without any probe. In this way turbulence noise as well as the disturbance on the acoustic field can be minimized.

Throughout the proper calibration procedures they were proved to be good enough as measuring microphones. Calibration procedures consist of the measurement of frequency response between two microphones and comparative calibration by sine seep test with the standard microphone in the anechoic chamber of Korea Standard Research Institute. Sensitivity of the microphones are about−65dB ref. $1V/\mu$bar at 1kHz.

During the experiment without mean flow, the output signal from the signal conditioner was not saturated since the excited sound level to sustain enough *S/N* ratio is far below than those inducing the saturation voltage of signal conditioner. With mean flows, the presence of static pressure introduces dc offset to the microphone diaphragm. Furthermore, the turbulent noise generated by the mean flow as well as by the discontinuity of the geometry of the silencer tremendously reduce the *S/N* ratio. To simply increase the *S/N* ratio, one might try max. sound power. But this introduces the saturation of signal to the microphone output. This can be treated by reducing the sensitivity of microphones and by increasing dynamic range. For these purposes, static pressure was compensated by introducing a small tunnel to the back of the diaphram of the microphoen like the Eustachian tube of human ear (Fig. 1). By doing this, the sensitivity was reduced to-82dB ref. $1V/\mu$bar at 1kHz. The supply voltage to the signal conditioner was increased by 8 volt from 6 volt to increase the dynamic range.

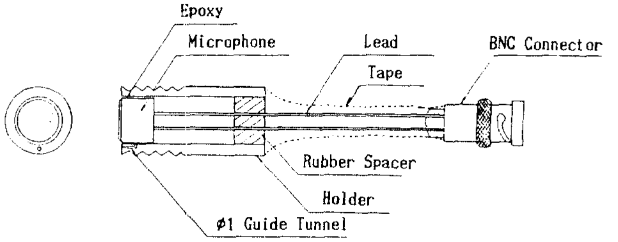


Fig. 1 Microphone adaptor and a small tunnel for static pressure compensation

3. EXPERIMENTAL SET-UP AND PROCEDURE

3.1 Experimental Design

Physical parmeters to be considered can be categorized as geometrical parameters and convective parameters. Geometrical parameters are length, diameter, offset length and twisting angle of expansion chamber (Fig. 2). Convective parameters are temperature gradient and mean flow which affect the convection term of wave equation.

Table 1 summarizes the variations of length, diameter, offset length and twisting angles. Variation of speed of mean flow has been selected to be 20m/s, 35m/s, and 50m/s. Effect of temperature gradient on the transmission loss is known to be important (Munjal and Prasad, 1986), but it is very hard to have meaningful temperature gradient in steady state. In this experimental study, systematic control of temperature gradient was left for future study.

With the designed experimental parameters and instrumentation, following experimental procedure has been adapted :

(1) Straight pipe test with and without mean flow
(2) Expansion chamber test without mean flow
(3) Expansion chamber test with mean flow

Table 1 Experimental parameters

Item	Unit	Variable
Length (L)	mm	150, 300, 450
Diameters (D)	mm	150, 300
Offset distance	mm	50, 100
Twisting angle	degree	0, 120, 180
Mean flow speed	m/s	20, 35, 50

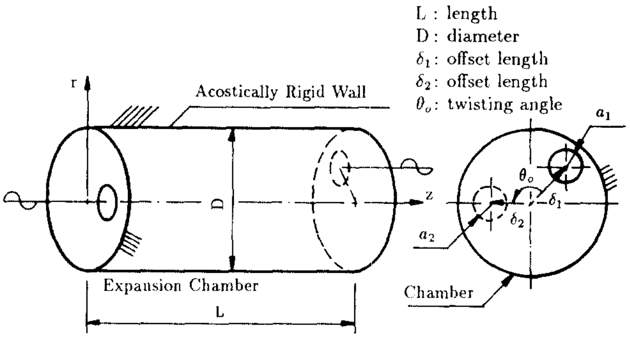


Fig. 2 Geometry of simple expansion chamber and coordinate system

Three different measurement methods ; impulse method, white noise excitation method and sine sweep method, have been tested for each experimental procedures. Main considerations of each methods are to have enough signal to noise ratio, noise rejection capability and the compensation of time delay between the signals of two microphones. Each methods are applied to estimate the transmission loss in frequency domain. Fig. 3 shows the schematic diagram of the experimental set-up. For an easy accomodation of mean flow, the blower system was designed and instrumented as independent unit.

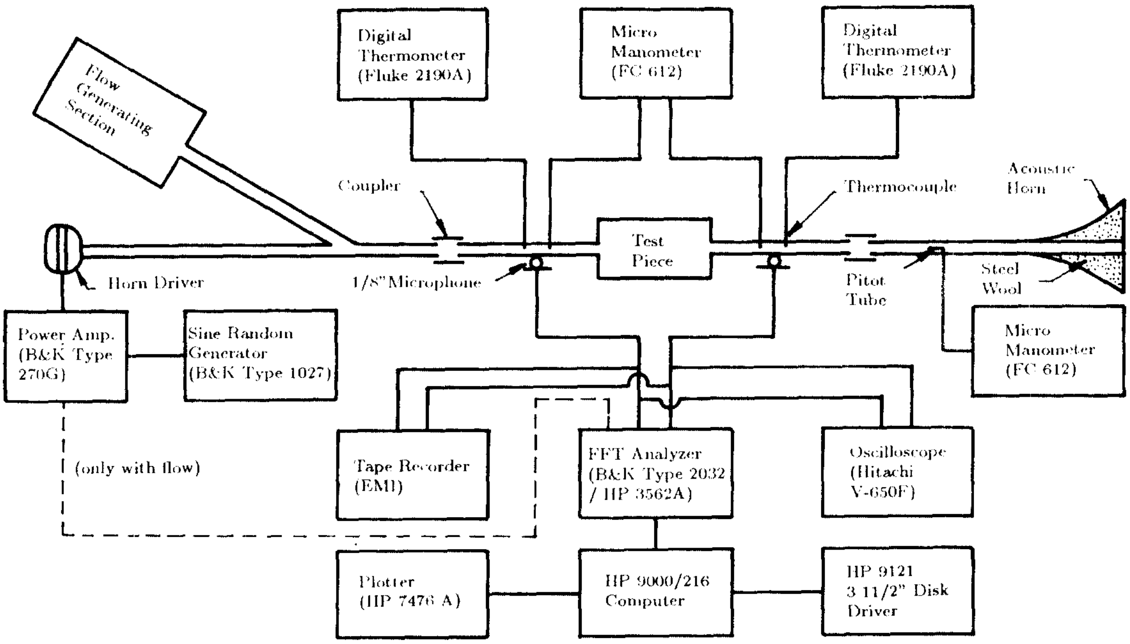


Fig. 3 Schematic diagram of measurement setup (For the experiments without mean flow, sine random generator was used as the white noise source. Signal source of sine sweep method was the generator output of HP3562A analyzer which has dual channel synchronous filters with the same center frequency as the generator signal)

3.2 *TL* in Frequency Domain via Transfer Function

If we define $G_1(f)$ and $G_2(f)$ as the power spectral densities of the acoustic signals at inlet and outlet ports of expansion chamber, *TL* can be expressed in frequency domain as

$$TL(f)=10\log|(G_1(f)/G_2(f))|. \qquad (2)$$

So the argument of log function is exactly same as the inverse of the magnitude of transfer function, *TL* can be redefined by

$$TL(f)=-20\log|H(f)| \qquad (3)$$

where $H(f)$ is the transfer function with respect to the inlet sound pressure. Singh and Katra (1978) already used the cross and auto-spectra of acoustic signals in *TL* evaluation, but they didn't unilize the transfer function to estimate the transmission loss.

There are three ways to estimate the transfer function that is

$$|H(f)|^2=[G_{yy}(f)+G^{y}_{nn}(f)]/[G_{xx}(f)+G^{x}_{nn}(f)] \qquad (4)$$
$$H(f)=G_{xy}(f)/[G_{xx}(f)+G^{x}_{nn}(f)] \qquad (5)$$
$$H(f)=[G_{yy}(f)+G^{y}_{nn}(f)]/G_{yx}(f) \qquad (6)$$

Where $G_{xx}(f)$ and $G_{yy}(f)$ are autospectra of input and output sound pressures, $G^{x}_{nn}(f)$ and $G^{y}_{nn}(f)$ are autospectra of noise components of input and output signals and $G_{xy}(f)$ and $G_{yx}(f)$ are the cross-spectra between input and output sound pressure respectively.

Estimation of the transfer function using equation (5) and (6) is better in the sense of bias error since those have noise rejection characteristics while equation (4) does not. The estimated transfer funcitions, consequently the transmission loss, using equation (4), (5) and (6) were found to be indential in the case of experiments without mean flow. These are expected results since there is no significant noise except inherent noise coming electronic components of the measurement system. But in the case of experiments with mean flow, special care must be taken into account as Mitchell (1982) pointed out; low coherence at resonance due to noise results poor estimation of transfer function. Contamination of noise to the measured signals at inlet and outlet port was minimized by the sine sweep method as discussed in 3.5.

3.3 Impulse Test

Ideal impulse is a time domain representation of white noise. Theoretically there is no difference betwen impulse and ideal white noise. But practically it is not easy to generate useful impulse sound due to the limitation of mechanical structure of speaker. Impulse test was used only to measure the time delay between the two microphones mounted on the wall. The measured time delay has been used to compensate the signals between two microphones.

3.4 White Noise Test

White noise was extensively used for the sound source to measure the transmission loss of silencers. It was understood that the white noise excitation technique is better than the sine sweep technique in the sense that the former requires less processing time for each experiments. For the experiment without mean flow, the noise level is much smaller than that of the experiment with mean flow as discussed before. The white noise excitation method was used for the experiment without mean flow.

3.5 Sine Sweep Test

White noise test failed to measure the transmission loss of the test silencer when the mean flow was present. This can be explained as follows; (1) the trubulent noise level generated by the mean flow was significantly high compared with the excited sound pressure level, which introduced low S/N ratio, (2) for the selected speaker power, the generated sound pressure was not strong enough in the selected frequency band of 6.4kHz, since the designed sound power must be shared along the frequency band.

To overcome these difficulties, sine sweep test was selected since the speaker is only responsible to generate single tone at each sweep. Consequently, the sound power generated by the horn driver can be concentrated over an extremly narrow band frequency and S/N ratio could be increased dramatically (more than 20dB.)

The transfer function estimation was based on equation (5). Because the noise level of outlet section of the silence is much higher than that of inlet section whereas the signal level is higher in general.

4. RESULTS AND DISCUSSIONS

4.1 Length Effect to *TL*

Figure 4 shows the effect of length to the transmission loss. The experimental results essentially show that plane wave theory (Baxa, 1982) well predicted the transmission loss at low frequency range. This implies that the length ratio essentially transforms the frequency scale inversely in the plane wave region. Since the dips in *TL* curves are mainly due to the "open tube" like behavior of the silencer, the interval between adjacent dips decreases in inversely proportional way as the length of chamber increases.

4.2 Diameter Effect to *TL*

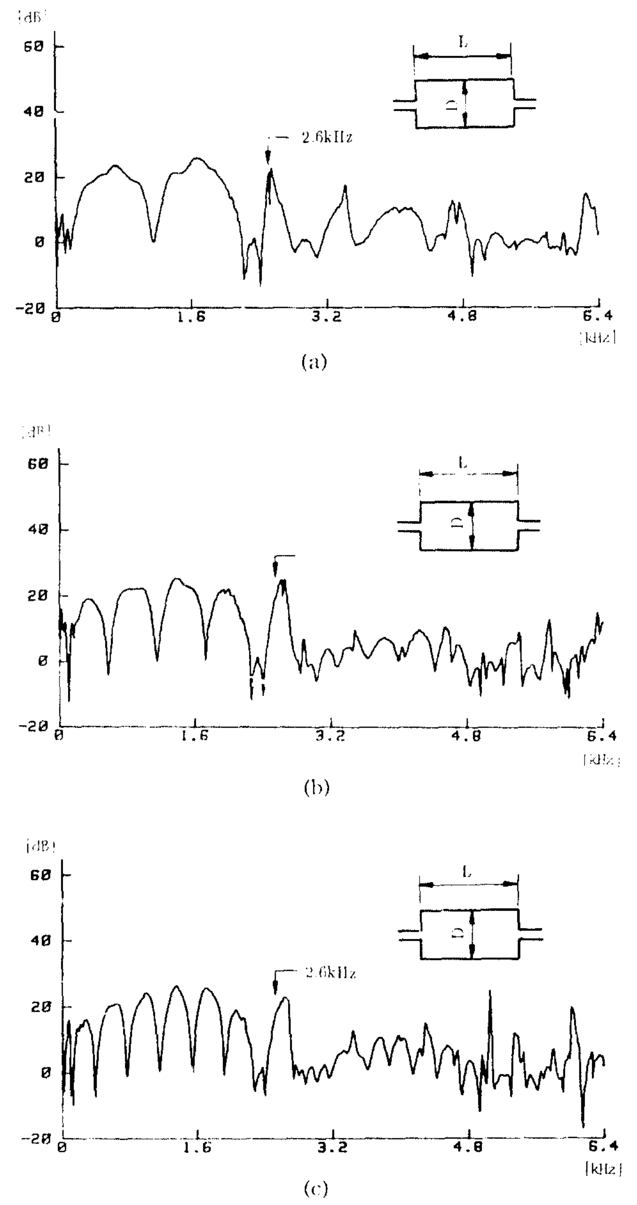
Diameter of a silencer dictates the occurence of the lowest cutoff frequency. Two different diameters (150mm and 300mm) of reactive silencers were tested. Fig. 4(b) and Fig. 5 show the results. For 300mm diameter, the cutoff frequency occurs at 1.3kHz. For 150mm diameter it is at 2.6kHz. These cutoff frequencies are resulted from satisfying (0.1) modes where (m,n) mode denotes m th circumferential mode with n the radial mode. In general, it is not easy to confirm the cutoff frequencies from the transmission loss curves. But the corresponding phase diagram of the transfer function between the two signals of the microphones (Fig. 6 and Fig. 7) clearly shows the location of cutoff frequencies. From these observations, we can conclude that the phase diagram reveals the occurence of cutoff frequency better than the amplitude of transmission loss.

In these diagrams the region where phase varies linearly with frequency is where the plane wave controls the acoustic characterisitcs. The beginning of non-linear phase variation stands for the lowest cutoff frequency.

This method enables easy determination of cutoff frequency even when the effect of higher order modes are so weak that the *TL* curves are almost same as those without higher order mode effect (see Fig. 4(a) and Fig. 8(a)).

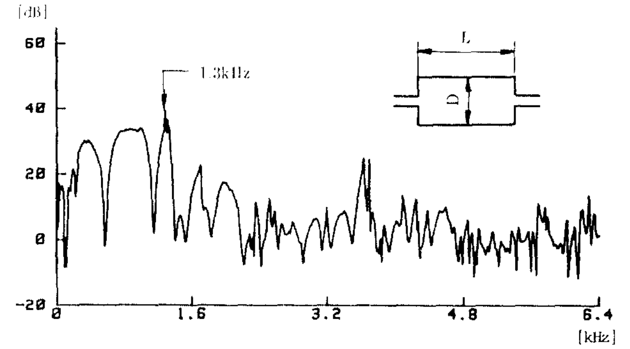
4.3 Area Ratio

The effect of area ratio on the *TL* of silencer can be easily recognized by comparing Fig. 4(b) and Fig. 5. For a plane wave reigon, the *TL* of silencer can be expressed in terms of



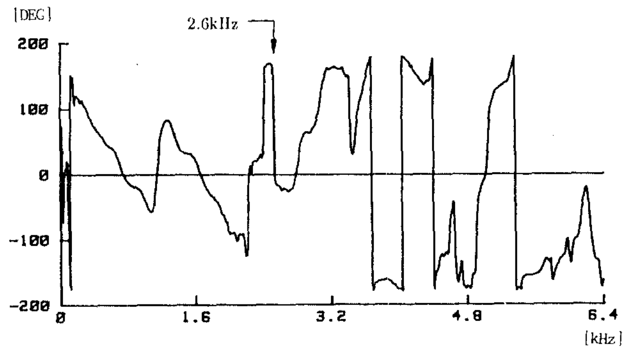
(a) $D=150$mm, $L=150$mm, center to center
(b) $D=150$mm, $L=300$mm, center to center
(c) $D=150$mm, $L=450$mm, center to center

Fig. 4 *TL* of circular simple expansion chamber with the same diameter but different lengths (Effect of lengths on the *TL* of circular simple expansion chamber with the same diameter)



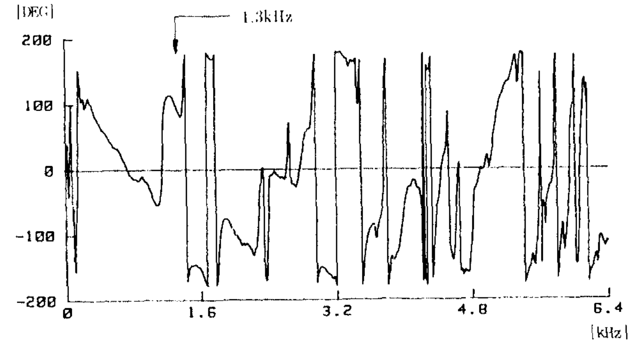
$D=300$mm, $L=300$mm, center to center

Fig. 5 *TL* of circular simple expansion chamber which shows the effect of diameter on the cutoff frequency of higher order modes as compared with Fig. 4(b)



$D=150$mm, $L=150$mm, center to center

Fig. 6 Phase diagram of transfer function corresponding to the *TL* curve shown in Fig. 4(a)



D=300mm, L=150mm, center to ceter

Fig. 7 Phase diagram of transfer function comparing with Fig.6 the cutoff frequency is shifted to 1.3kHz as the diameter increases twice.

area ratio(m) as (Baxa, 1982)

$$TL=10\log[1+(m-1/m)^2\sin^2 kL]. \tag{7}$$

For the same length, there is 12dB difference in *TL* between the silencer whose diameter is 150mm and 300mm, it can be also verified from the experimental results.

4.4 Aspect Ratio of Silencer

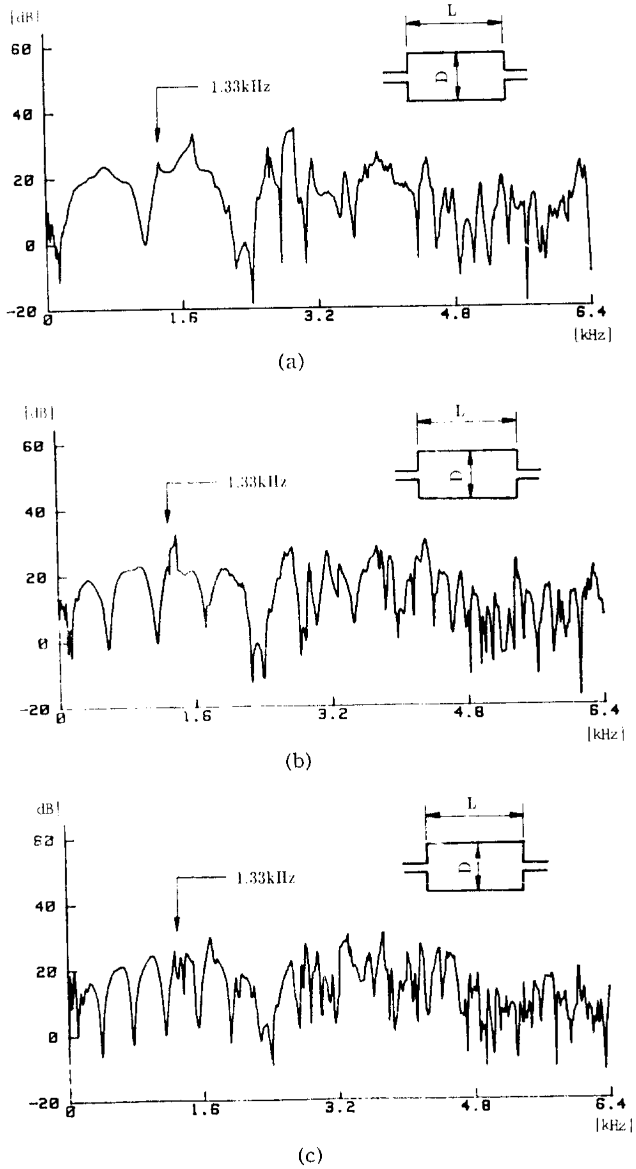
The physical meaning of aspect ratio of silencer is a new concept but it is well known parameter in wing theory and other related engineering fields.

Aspect ratio of a silencer (A_{LD}) is defined as

$$A_{LD}=L/D \tag{8}$$

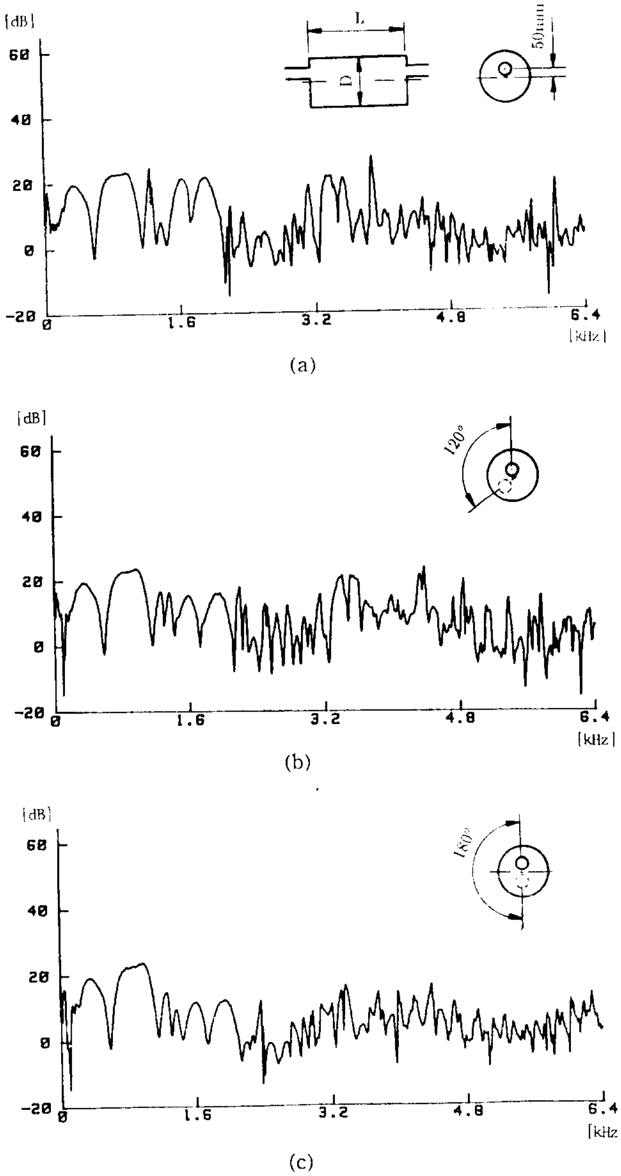
where L is the length of sillencer and D is the diameter of silencer. When A_{LD} tends to be infinity, the *TL* of silencer will be same as those of infintely long straight pipe where plane wave theory dominates over wide range of frequency. Conversely, when the aspect ratio tends to be zero, then higher order mode will dominate the entire frequency domain. Fig. 4 (a), Fig. 4(b), 4(c), and Fig. 5 are the results for the aspect ratio 1,2,3, and 1 respectively.

Especially Fig. 4(a) and Fig. 5 have same aspect ratio and have same number of peaks in plane wave region. From the aforementioned figures, one can realize the number of



(a) $D=150$mm, $L=150$mm, center to offset(50mm)
(b) $D=150$mm, $L=300$, center to offset(50mm)
(c) $D=150$mm, $L=450$mm, center to offset(50mm)

Fig. 8 Effect of outlet pipe offset on *TL*(*TL* curves are similar but modified compared with those in Fig.4 in phase wave region but above the cutoff frequency *TL*'s are generally increased)



(a) $D=150$mm, $L=300$, twisting angle$=0$, offset to offset(50mm each)
(b) $D=150$mm, $L=300$mm, twisting angle$=120$, offset to offset(50mm each)
(c) $D=150$mm, $L=300$mm, twisting angle$=180$, offset to offset(50mm each)

Fig. 9 Effect of twisting angle to *TL*

peaks in the plane wave region is approximately 2 x A_{LD}. This observation can be proved by plane wave theory. For plane wave, when the condition, $kL=q\pi(q=1,2,3\cdots)$ is met, all incident waves are transmitted through the silencer. For circular expansion chamber, the frequency when the higher modes occurs can be expressed as

$$kD/2=X_{mn} \tag{9}$$

where k is the wave number, $2\pi f/c$, and X_{mn} is n th zero of the first derivative of Bessel function of order m. For a concentric circular expansion chamber X_{01} is 3.83. Hence, denoting q as the number of dips in the plane wave region besides zero Hz(also as the number of peaks), q will satisfy the following inequality

$$q<2/\pi X_{mn}\ L/D=2/\pi X_{mn}\ A_{LD}. \tag{10}$$

For a concentric circular expansion chamber, substituting X_{mn} with X_{01} leads to

$$q<2.44\ A_{LD}. \tag{11}$$

From these discussions, we can conclude that the number of peaks of *TL* for concentric circular expansion chamber can

be predicted by the largest integer q satisfying the inequality of(11). In other words the aspect ratio and the Fresnel number kL are the only required parameters when the Helmholtz equation governing the acoustic field in a concentric expansion chamber is to be non-dimensionalized.
Consequently the *TL*'s of silencers with same aspect ratio are similar with respect to the Fresnel number. Moreover *TL*'s are same in shape and magnitude if the aspect ratio and the area ratio are same.

4.5 Effect of Offset and Twisting Angle to *TL*

Figure 8 shows the *TL* of silencers which have offset of 50mm at the end of outlet side.

The presence of offset introduces different boundary condition from those of silencers which do not have offsets. For higher order modes,(1,0) mode will occur by satisfying X_{mm} of 1.84(Baxa, 1982). Corresponding frequencies for this mode are 1.33kHz and 660Hz for the diameter 150mm and 300mm respectively. The *TL* plots show excellent agreement with this claculation. As depicted from Fig. 8,(1, 0) mode only slightly modifies the *TL*'s of not having offsets(Fig. 4) and plane wave still dominates the behavior of *TL* in low frequency region. When both inlet and outlet pipes have offsets, *TL* curves are no more similar to those without offsets(see Fig. 9(a)).

Figure 9 shows the effect of twisting angle to *TL*. The presence of twisting angle will introduce the modes in the circumferenctial direction of silencer. As a result of these modes, the behavior of *TL*, after higher order modes are occured, is quite different with those which do not have twisting angles. These figures demonstrate that the *TL* of the silencer with 120° "blocks" the transmission of $(1, n)$ mode $(n=0,1,\cdots)$ which is easier for the twisting angle of 0° or 180°.

4.6 Effects of Mean Flows on *TL*

Figure 10 illustrates the effect of mean flow on the occurence of cutoff frequency for a straigh pipe. Two microphones which have the static pressure compensation were wall mounted on the steel tube of 38mm diameter. Comparing with the cut off frequency for zero mean flow, there is considerable shift in cutoff frequency for 20m/s, 35m/s and 50m/s of mean flows which correspond to the Mach number of 0.06, 0, 1 and 0.14 respectively. Figure 11 shows the *TL* of silencer whose diameter is 150mm and length 450mm at different flow speeds. The results illustrate that the mean flow just modifies wave number as

$$k_M = k/(1-M^2)^{1/2} \tag{12}$$

where k_M is wave number when mean flow is present, k is acoustic wave number in free space and M is Mach number. Predicted cutoff frequencies by equation (12) and the measured values are agreed within 0.05%.

The shapes of *TL* curves(Fig. 11 and Fig. 4(c)) are much similar though the magnitude of *TL* with mean flow is sligtly increased comparing with those without mean flow.
This can be explanined in three ways;
(1) Slight difference of microphone sensitivities(Fig. 10) in plane wave region gives the level-up effect on *TL* curves,
(2) Peaks can detected more sharply with the increased

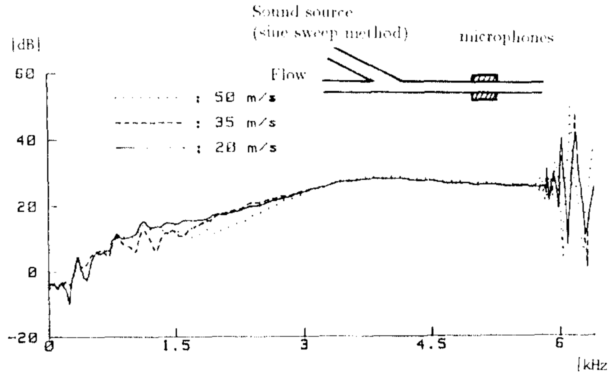
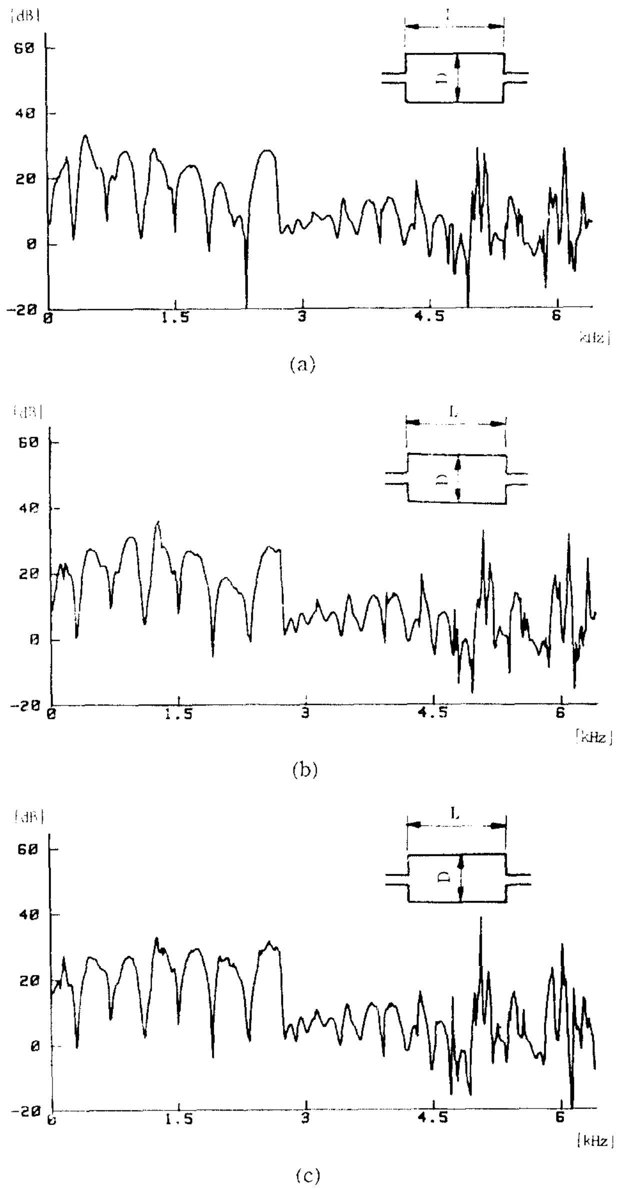


Fig. 10 Amplitude response of the signals from the two microphones which were mounted on the wall of which shows the shift of cutoff frequency due to mean flow



(a)

(b)

(c)

(a) $D=150$mm, $L=450$mm, center to center(Mean flow speed$=20$m/s)
(b) $D=150$mm, $L=450$mm, center to center(Mean flow speed$=35$m/s)
(c) $D=150$mm, $L=450$mm, center to center(Mean flow speed$=50$m/s)

Fig. 11 Effect of mean flow to *TL* of circular simple expansion chamber with concentric inlet and outlet pipes resolving capability of sine sweep method compared with the random noise method,

(3) Due to the viscosity of the flow, boundary layer is introduced along the cross section of expansion chamber, resulting refraction of sound and slight increasing *TL* of expansion chamber.

5. CONCLUSIONS

Experimental evaluation of silencer's performance requires careful instrumentations, measurement set-up and procedures. When mean flows are fed into the silencer system, the static pressure induced by the flow introduces undesirable dc offset to the signal from the micorphone. The static pressure was compensated by introducing small tunnel to the inside of microphones.

Transmission loss of a silencer was evaluated by estimating the transfer function of the acoustic signals from the microphones of inlet and outlet port. Time delays between inlet and outlet ports which cause error in transfer function estimation, was measured by inpulse test and compensated in the estimation.

TL without mean flow was evaluated by the white noise method. On the contrary, *TL* with mean flow was evaluated by the sine sweep method because of limited power capacity of sound source and high level noise induced by the flow. We found that sine sweep method is better to estimate the *TL* when excessive noise is unavoidable.

The experimental results without mean flow agree well with the existing theory. Defined parameter, aspect ratio turns out to be a good measure to predict the number of peaks in plane wave region and can be used for the design of practical silencer.

The most prominent effect of mean flow is the frequency shifts as described in Eq. (12) and might be increase in the magnitude of *TL* due to refraction of sound toward the wall.

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