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Acoustical Characteristics of Single-Resonator-Type Silencers

by

Ming Lokitsangtong [*1], Shuntaro Murakami [*2] and Toshio Iijima [*3]

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Abstract

Experiments on the transmission loss of single-resonator-type silencers have been carried out. The results indicate that the resonator characteristics depend on classical acoustic impedance as long as the flow speed is extremely low, and resonator performance falls as resonance frequency increases with flow speed. The relationships among the parameters contributing to such resonant functions are presented with comments on the design of resonators.

Keywords: Resonator, Transmission loss, Flow, Resonance frequency, Resonance performance

1. Introduction

The Helmholtz resonator is widely used as a silencer to reduce a noise component predominating sharply in a spectrum. A point of acoustical design for a resonator is to decide chamber volume and connector length for obtaining the maximum noise-reduction effect at the given predominant frequency. On this occasion, the Davis's equations derived from supposing non-flow ducts [1)] have still been used to estimate a resonance effect in the range of comparatively low flow-speed, however, values of connector effective-length concerned with the resonance frequency are exactly unknown. For ducts with flow, some equations containing Mach number terms have been given [2), 3)], however, those are not verified enough by experiments, even though the short data on the multiple effects of resonators were shown in the author's former investigation [4)]. Therefore degrees of influences of flow on the resonator functions are also unknown in detail since there is little information about the flow-speed limit within which the classical impedance theory may be applied to such a resonant device set so as to be at right-angle against the flow direction.

In order to present the more reasonable way for controlling narrow-range frequency noise in ventilation systems, experiments have been made of the transmission loss of single-resonator type silencers. In this paper, open-end corrections for connector effective-length and variations of resonator characteristics by flow are investigated in connection with relationships among configuration parameters and Mach number of incompressible mean flow.

2. Experimental Technique

2.1 Experimental apparatus and method

The experimental apparatus is shown schematically in Fig.1. A signal of pure tone was produced by the oscillator connected with the amplifier and conducted to the system by means of the source composed of driver units. After passing over the tested resonator, it continued down throughout the tail duct to the termination which consisted of the glass wool surrounded by the involute tube. The tone propagating the duct was detected by the condenser microphone with the probe tube traversed axially along the test section and its sound pressure level was measured by the FFT analyzer. An air flow from the blower whose noise was sufficiently reduced by the pre-muffler, progressing together with the tone from the source, was emitted into the anechoic room. The mean flow velocity U was correspondingly measured with a Venturi meter.

The experimental transmission loss at each frequency was obtained from the difference between the respective largest values at the same phase in the inlet and tail ducts. In this case, the component induced by the reflected wave in the inlet duct was corrected referring to the chart [1)]. The upper limit of the resonance frequency

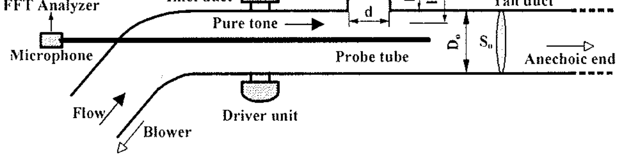
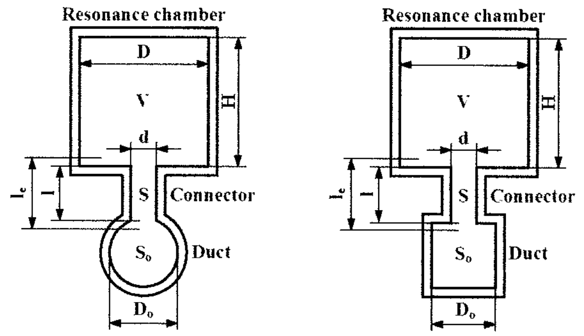


Fig.1 Schematic diagram of experimental apparatus

*1 Assistant Professor, Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand.
*2 Senior Researcher, Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand.
*3 Professor, Department of Prime Mover Engineering.

was 800Hz.

The resonator models shown in Fig.2 were produced with cylindrical pipes, attached to the circular duct (diameter: D_o=48mm) and the square duct (side length: D_o=51mm), respectively. Each dimension of resonators was decided in the following ranges of configuration parameters; D_o/d=1.06 ~ 2.55, l/d=0.42 ~ 2.0, D/d=1.5 ~ 5.25 and H/D=0.19 ~ 2.5, where d is diameter of connector, l: length of connector, D: diameter of resonance chamber, H: height of resonance chamber, V: volume of resonance chamber, S: cross-sectional area of connector and S_o: cross-sectional area of duct.



(a) Resonator set in circular duct **(b) Resonator set in square duct**

Fig.2 Resonator models

2.2 Equations for experimental analysis

A transmission loss equation for the single resonator has been derived from the transfer matrices for the multiple resonators [4], expressed by

$$TL = 10\log\left|1+\frac{(1-M)^2\left\{(1+M)^2+4\left(M+\frac{R}{Z_0}\right)\right\}}{4\left\{\left(2M+\frac{R}{Z_0}\right)^2+\left(\frac{R}{Z_0}+\frac{X}{Z_0}\right)^2\right\}}\right| \quad (1)$$

where R is connector resistance, X is chamber reactance, Z_0 is characteristic impedance of duct and M is Mach number of mean flow passing over resonator. The dimensionless impedance is divided into the resistance ratio R/Z_0 and the reactance ratio X/Z_0, which are written as follows from the classical impedance theory [1, 5].

$$\frac{R}{Z_0}=\frac{K}{c}\left(\frac{l_e}{d}\right)\left(\frac{D_0}{d}\right)^2\sqrt{\frac{\mu f}{\rho_0}} \quad (2)$$

$$K = 4\sqrt{\pi} \text{ (Circular duct) or } \frac{16}{\sqrt{\pi}} \text{ (Square duct)}$$

$$\frac{X}{Z_0}=S_0\left(\frac{f}{f_{ro}}-\frac{f_{ro}}{f}\right)\sqrt{\frac{l_e}{VS}} \quad (3)$$

where c is sound speed, μ is viscosity coefficient of air, ρ_0 is mean density of air, f is frequency, f_{ro} is resonance frequency when U=0 and further l_e is connector effective-length corrected by the additional value Δl, that equals air mass portion projected by its oscillation from both open ends into the duct and chamber.

The relation between resonance frequency and connector effective length is given by

$$f_{ro}=\frac{c}{2\pi}\sqrt{\frac{S}{Vl_e}} \quad (4)$$

In calculating transmission loss, the respective values at room temperature are used for the physical quantities, and a peak frequency in each experimental datum is regarded as the resonance frequency, so that the effective length could be obtained from Eq. (4). The geometric parameter $\sqrt{VS/l_e}/S_0$ and the resistance ratio are calculated using such an effective length given experimentally.

Dividing Eq. (4) by connector diameter, one gets

$$\frac{l_e}{d}=\frac{l}{d}+\beta=\frac{1}{16\pi\left(\frac{1}{\lambda_{ro}}\sqrt{\frac{V}{d}}\right)^2} \quad (5)$$

where β is the coefficient for open-end corrections, i.e. the ratio of corrected-portion length to diameter of connector ($\Delta l/d$) and λ_{ro} is resonance wavelength, i.e. the ratio of sound speed to resonance frequency, c/f_{ro}. The parametric experimental analysis is carried out using this relation.

3. Results

3.1 Transmission loss characteristics of resonators

Fig.3(a), (b) shows transmission loss characteristics of ordinary type resonators attached to the circular and square ducts respectively. The lines calculated by Eq. (1) ~ Eq. (4) lower with increasing of flow velocity. The measured points also lower in like manner of these lines as an overall trend. Namely the mean flow

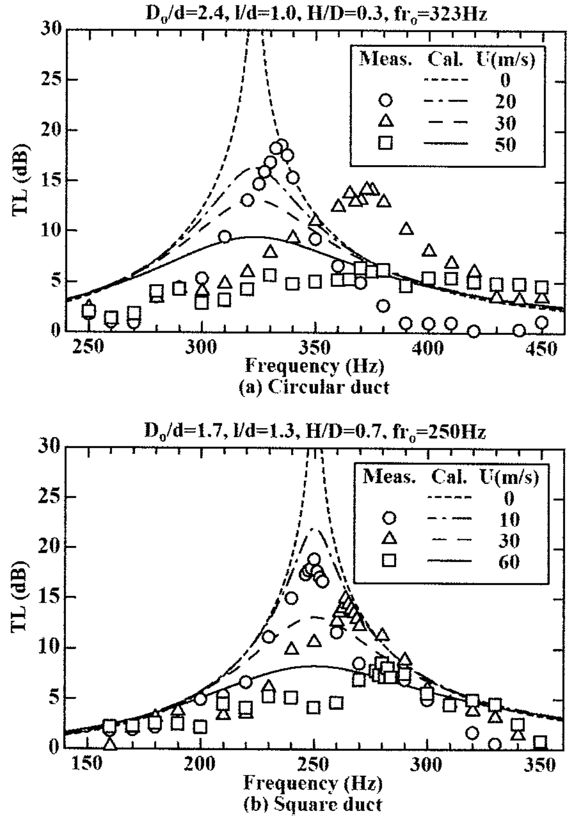


Fig.3 Transmission loss of ordinary type resonator

changes resonator characteristics from a sharp-ridge shape to a gentle-hill one. But in this case, the resonance frequency shifts to the higher region as flow velocity is increased exceeding a certain value. This means that the use of Eqs. (3), (4) and (5), which contains the resonance frequency terms, is limited to the especially low-speed flow.

Fig.4 shows transmission loss characteristics of the resonator attached to the small-sized cavity (L=120mm, W=D_0=51mm, h=10mm) set in the square duct. The measured values, keeping the resonance frequency unchanged, distribute with similar characteristics to the calculated results, though cavity effects are a little observed. This suggests that the change of resonance frequency occurs when an air mass oscillating in the connector is projected into the duct and touches the separated flow passing over the connector entrance.

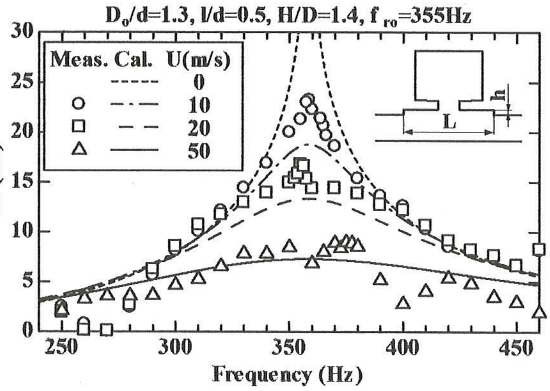


Fig.4 Transmission loss of cavity type resonator

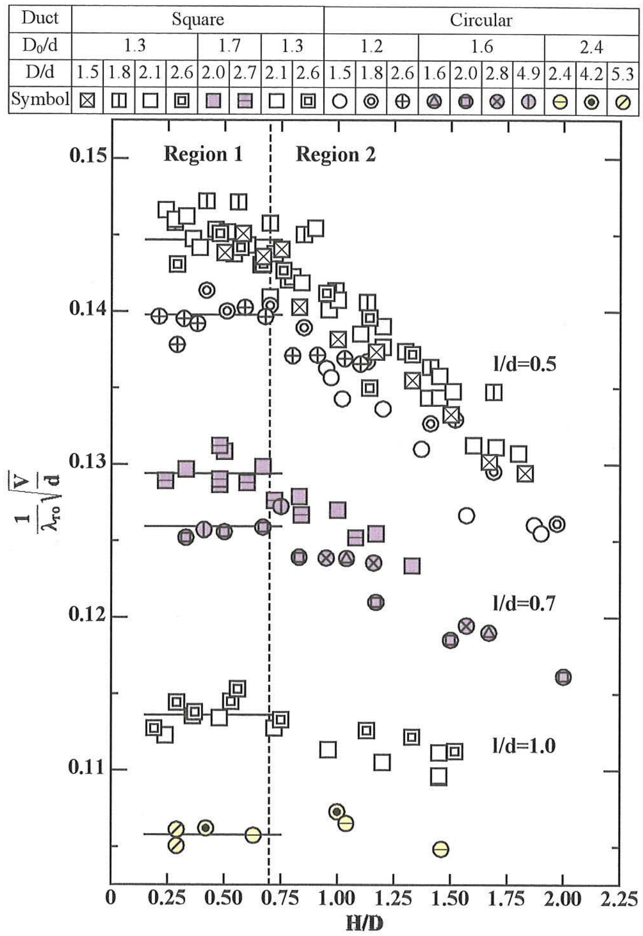
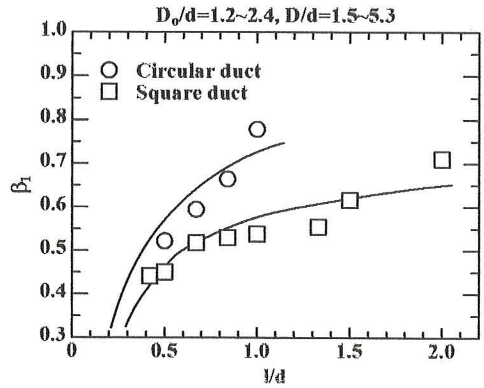


Fig.5 Parameters related to open-end corrections for connectors

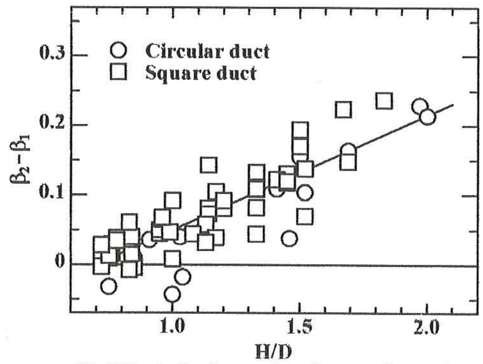
3.2 Open-end corrections for resonators

In order to obtain the connector effective-length in the low velocity range, where the resonance-frequency change by flow is regarded as an enough narrow width, the parametric experimental analysis has been carried out using Eq. (5). The result is shown in Fig.5. The parameter denoted on the vertical axis, that is, the dimensionless expression of resonance wavelength has been given experimentally by f_{ro} ($=c/\lambda_{ro}$) corresponding to frequency of the peak transmission loss without flow. When the connector configuration parameter l/d is fixed, this parameter becomes constant with a fairly good accuracy up to the chamber configuration parameter H/D of about 0.7 (Region 1) and then decreases with comparatively slight discrepancies (Region 2), and moreover it is viewed as a quantity independent of the parameters on both open-end configurations of connector, D_0/d and D/d.

As seen Eq. (5), open-end correction coefficient increases with decreasing of $\sqrt{V/d}/\lambda_{ro}$ which is smaller as l/d is larger. Consequently the average values of β_1, which have been obtained from the data for Region 1 in Fig.5, can be arranged as a function of the only connector configuration as shown in Fig.6 (a). Each point means the minimum value at every l/d because the coefficient β_2 in the Region 2 becomes larger than β_1. The difference between respective data for both ducts may take place for the reason that the shortest value is adopted as a real length of the connector in the



(a) Effect of connector configuration



(b) Effect of volume chamber configuration

Fig.6 Open-end correction coefficient

circular duct because it cannot be specified for the complicated structure of the connector-set place (see Fig.2 (a)). In Fig.6 (b), the coefficient β_2 for Region 2 is shown by the subtraction with β_1 as values to be added to the basic data arranged in Fig.6 (a). The β_2 value is changed with the variation of H/D irrespective of the duct kinds. Eventually the two charts give the end-correction coefficient from 0.45 to 0.90 as a whole according to the connector and resonance-chamber configurations for the usual use.

3.3 Effect of flow on resonance frequency

As shown in Fig.7 (a), when l/d is fixed, the ratio of resonance frequency with flow to that without flow f_r/f_{ro} increases with Mach number of mean flow, finally converging in a constant value. Such a frequency change by flow begins and stops at higher Mach numbers, respectively, as the basic frequency fro becomes higher in order of 170Hz, 232Hz, 348Hz. Fig.7 (b) indicates that the moves of resonance frequency to the higher region is marked as the connector configuration becomes flat for shortening in its axial direction, that is, l/d becomes larger such as 0.5, 1.0, 1.5.

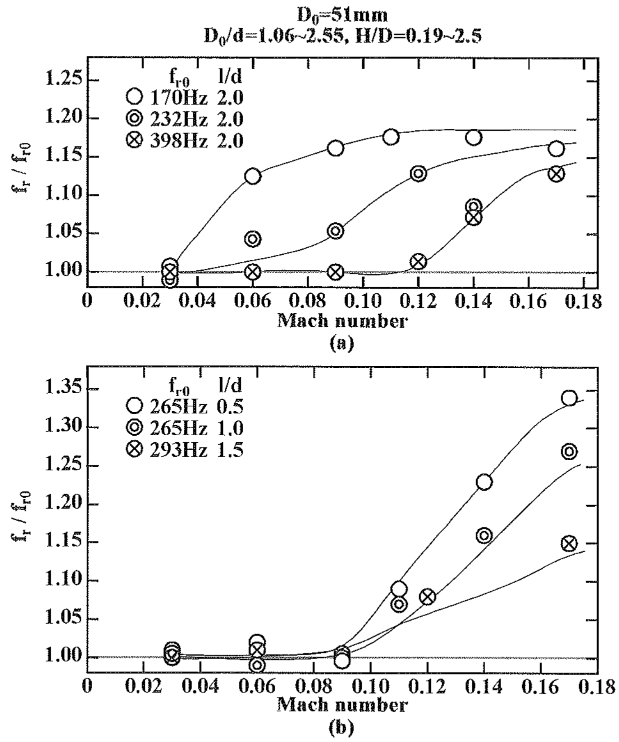


Fig.7 Variation of resonance frequency by flow

As seen in Fig.8, the f_r/f_{ro} value for the low resonance frequency (200Hz) can shows roughly 1.05 at M=0.05 ~ 0.08. On this condition, shifting of resonance frequency gives the fall of transmission loss by a few decibels. This fact could be regarded as a start of the change of resonator frequency characteristics by flow that should not be ignored. In case of the high resonance frequency (800Hz), such a change hardly occurs up to Mach number of 0.1 at least. Fig.9 shows the extent of frequency-shifting at higher Mach number. The ratio f_r/f_{ro} changes by around 0.2 within the limits of l/d from 0.5 to 2.0.

The above-mentioned change of resonance characteristics could be explained as follows. If the period of air oscillation in the

	D_0/d		
f_{r0}(Hz)	1.3	1.7	2.6
200	○	⦶	◎
800	△	⚠	▲

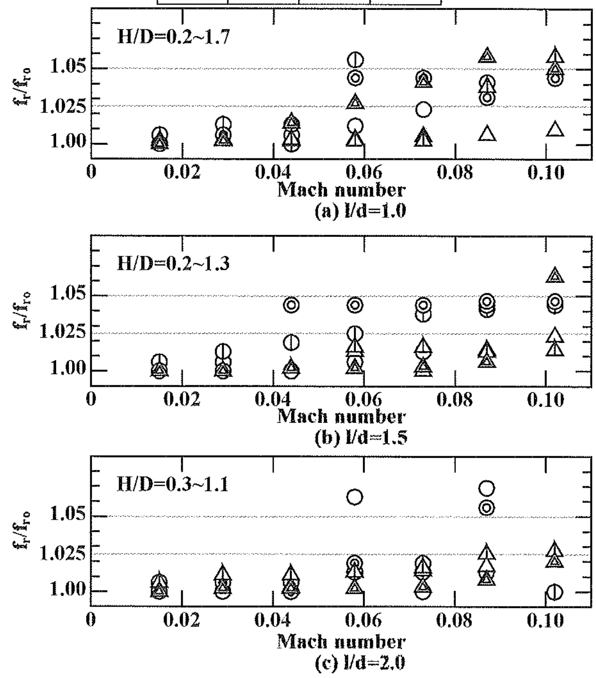


Fig.8 Variation of resonance frequency at lower flow-speed

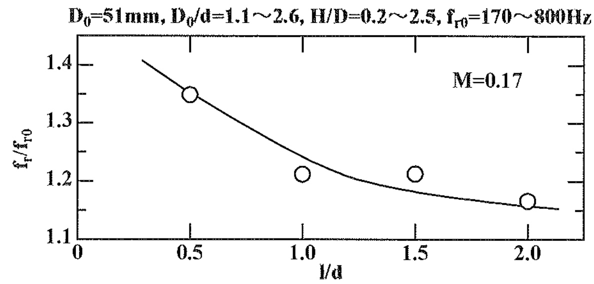


Fig.9 Variation of resonance frequency at higher flow-speed

connector is sufficiently short as compare with a time during which a flow passes over the connector, the bulk of the mass portion projected from the connector entrance will nearly equal the bulk without flow. As a cycle of the mass oscillation is delayed against a flow moving toward the rear duct, the mass projection into the duct will be reduced in its bulk to be restrained to avoid the mass shedding, finally limited to connector exit opened into the resonance chamber. The sound energy inducing the resonance effect appears to be attenuated only by its dissipation at the connector discontinuity where the flow separation occurs and after that conserved for the process mentioned above. Hence it is thought that the resonance frequency heightens corresponding to the reduction of the amplitude of mass oscillation and finally becomes unchanged once more at larger Mach number with the stabilization of mass projection at the only open-end on the chamber side.

3.4 Effect of flow on resonance transmission loss

When frequency f is f_{ro} in Eq. (3), reactance ratio X/Z_0 is zero and the resonator resonance-transmission loss $[TL]_r$ can be obtained using Eq. (1) as a function of specific resistance $[R/Z_0]_r$ given by Eq. (2) and Mach number M.

In Fig.10, the calculated results are shown by the solid and broken lines along with measured data plotted. The calculated values decrease abruptly at extremely low Mach numbers and then become smaller with the gentle slope as Mach number is increased. The measured points vary with the tendency similar to the calculated lines, and depend on D_0/d (Fig.10 (a)), slightly affected by l/d (Fig.10 (b)). In Fig.11, the subtract expression of the resonance transmission loss is given by

$$[\Delta TL]_r = [TL]_{re} - [TL]_{rc} \tag{6}$$

It is seen that except for greatly-small Mach numbers, the experimental $[TL]_{re}$ is larger than the calculated $[TL]_{rc}$ within 10 dB at maximum as the ratio D_0/d diminishes and additional value, $\Delta[TL]_r$, appears to be unchangeable in the Mach number range exceeding 0.1 on the whole.

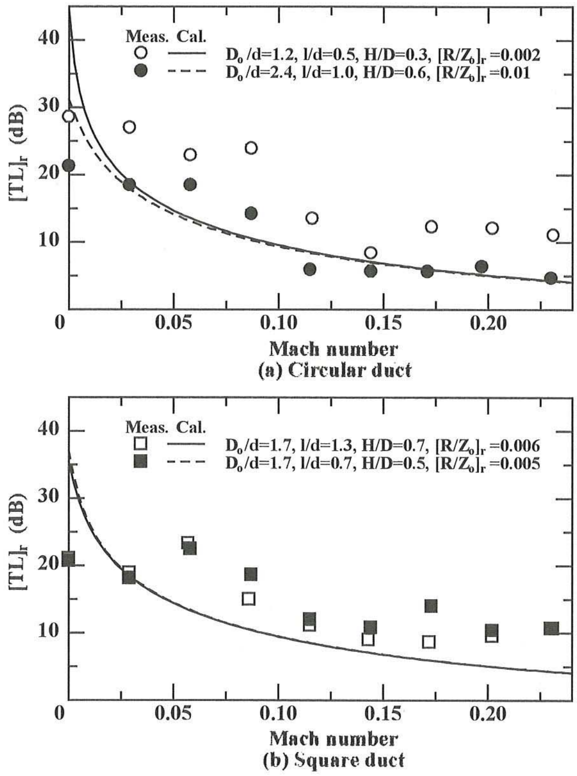


Fig.10 Resonance transmission loss of ordinary type resonators

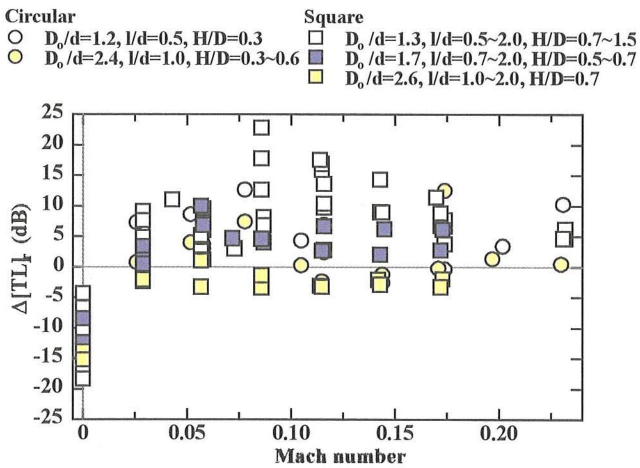


Fig.11 Different between measured and calculated transmission loss values at resonance frequency

The matrix used for deriving Eq. (1) has been obtained on the basis of the concept that it is possible to apply the classical impedance to sound wave entering the connector and dissipations of sound energy are induced by entropy fluctuations in the separated flow at the front discontinuity of resonator [3, 6]. At the resonance frequency, the impedance is given by the only resistance, and the specific resistance $[R/Z_0]_r$ may contribute a fairly large extent to the fall of transmission loss in calculations at greatly-small Mach numbers. In this parameter, the resistance itself is given assuming an ideal linear model, however, actual resonators have neither complete geometric configuration nor perfect plane wave entering the connector. This may be the reason why the experimental transmission loss considerably lowers in level than the calculated one at flow speed near zero. Such a contribution of resistance to the resonance performance remarkably diminishes with increasing of flow speed, and the calculated transmission loss level lowers depending on almost only Mach number. The approximate correspondence between measured and calculated results in this region could be explained like the following. The pressure oscillating a mass in the connector, which also vibrates an air in the volume chamber, may be weakened by the energy loss promoted by increasing of flow velocity in the shear layer, resulting in the fall of the resonance effect. In deriving the matrix, however, the term of entropy fluctuations was introduced into the continuity, energy and momentum equations as a finally-eliminated quantity. Accordingly Eq. (1) contains merely Mach number as a parameter representing degrees of energy dissipation, and has no other one, for example, concerned with the area of flow separation or the configuration of connector open-end. For this reason, the calculations may not fully correspond to the experimental results in which resonance transmission loss is affected by D_0/d. For knowing the detail of this difference, it is expected to make an analysis on the impedance when the connector entrance is observed out of a flow field.

3.5 Comments on resonator design

Narrow-range frequency noise propagating a duct system generally keeps the sharply-predominating component also after radiations into the outside. Therefore the equations and experimental results, which are shown in this investigation on the sound field inside the ducts, will comparatively be useful for the basic resonator design.

When the resonance frequency is higher, its change by flow has little significance for estimating measures of a resonator not only at small Mach numbers, but also at large ones since the fall of noise-reduction level is slight due to the gentle characteristics shown in Fig.3 and Fig.4. In the lower resonance-frequency range, characteristic changes by flow could be disregarded to the extent of Mach number of 0.05 at most conjecturing from the results given in Fig.8. In the above cases, Eqs. (4), (5) will be available. Namely, after deciding β_1 or/and β_2 according to the parameters l/d, H/D, in Figs.6(a), (b), one will be able to obtain le first and next, if f_{ro} is chosen so as to agree with the peak frequency of the predominant noise-component required to be controlled. Then each dimension of connector and volume chamber will finally be determined in connection with the parameters obtained. Additionally, for avoiding the sudden resonance-function drop caused by errors in estimating of frequency shifting, it gives a safety that the geometric parameter in Eq. (3) is taken into account because this parameter raises transmission loss level around f_{ro}.

When frequency changes by flow cannot be disregarded at relatively low frequency and middle Mach numbers around 0.1, i.e. 30m/s ~ 40m/s at room temperature, the resonance frequency should be estimated higher than f_{ro} by roughly 25Hz ~ 50Hz referring to the individual results shown in Figs.3 (a), (b). Naturally for more reliable estimations, the data are in short supply for the present.

To estimate the resonance performance of a single resonator, Eq. (1) when X/Z_0=0 and Fig.11 are applicable. The estimation will be possible by adding a negative or positive value of $\Delta[TL]$r to the calculated value according to the Mach number range under or over 0.02. For instance, in the case when D_o/d=1.7, the average value of $[TL]_r$ will be roughly 25dB, 15dB, or 10dB at higher Mach numbers if mean velocity is 10m/s, 30m/s or 50m/s, being heightened by several dB with more diminishing of Do/d. But these levels for noise reduction are to be short, if the still greater resonance effect is necessary. One of ways to get the full resonance performance is to expand cross section of the duct in order to decrease flow velocity. But this may cause a considerably large-sized device. Another way is to mount the number of resonators in the axial direction. A few resonators can markedly raise the resonance performance by their multiple effects [4]. If the latter of the above ways is adopted, the influence of frequency changes by flow should be considered also at higher Mach number, and one could refer to Fig.9.

4. Conclusions

Transmission loss of a single resonator set, respectively, in the circular and square ducts with incompressible flow has been investigated. The results are summarized as follows.

(1) The resonance frequency is much the same as that without flow up to the limits of relatively low Mach number. In this case, the classical impedance is useful for obtaining the parameters concerned with resonance characteristics, and the end correction for connecter length is determined by the configurations of connector and volume chamber independently of both open-end configurations of the connector.

(2) As Mach number is increased exceeding the above limits, the resonance frequency characteristic moves to higher region as converging, finally stabilized. Such a change by flow depends on the original resonance frequency without flow and connector configuration.

(3) The resonance performance greatly drops with functions of acoustic resistance at extremely low Mach number and falls by slow degrees with the loss of resonance energy entering the connector as flow speed is increased, being also related to the connector open-end configuration on the duct side.

(4) The relationships among the parameters on the above resonator configurations are arranged in Fig.6 ~ 9 and 11, which could be used for acoustic design of a resonator.

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