Proc. Schl. Eng. Tokai Univ., Ser. E
31 (2006) 33-37

Resonance Tone Generated by Jet Passing through Axisymmetric Cavity with Orifice

by

Takuya KOMORI[*1], Shuntaro MURAKAMI[*2], and Toshio IIJIMA[*3]

(Received on March 31, 2006 & accepted on June 3, 2006)

Abstract

Experiments on the resonance tone induced by a jet passing through an axisymmetric cylindrical cavity with an orifice exit were carried out. Results have been obtained from measurements of sound pressure level in the tail tube and around the inflowing jet. It is shown that the jet-excited tone is mainly generated at the first and second Strouhal frequencies, which are classified according to cavity depth independently of expansion ratio. Furthermore, it is verified by the visualization of the pressure distribution around the jet that a generated-tone component can be rocked by a resonance component in a cylindrical acoustic field.

Keywords: Axisymmetric cavity, Inflowing jet, Tone generation, Strouhal frequency, Cylindrical resonance

1. Introduction

In piping systems, the flow passing through a cavity will generate the secondary noise which contains both random and periodic components. The latter, showing sharp peaks in sound pressure spectra, can be made of the tones excited by the separated shear layer impinging on the edge of a cavity end. When tone components are not masked with the noise components produced at the source, they may become an object for control.

On the problem of such periodic tone generations in a covered cavity or an expansion chamber, some studies were carried out. Davies explained the longitudinal oscillation originated by vortices running in a basic slot model concerning silencer configurations and conjectured the acoustic resonance frequency mode [1)]. Kellar and Escudier investigated the longitudinal and transverse waves due to the jet entered in a few types of cavity inserted between a nozzle and a diffuser that were modeled for regulating valves [2)]. Nomoto and Culick showed the geometric and flow conditions on which pure acoustic tones occurred in cavity models made of two baffles in a rectangular duct [3)]. Such conditions were also examined by Moriyama et al. using cylindrical expansion chambers [4)]. Additionally in connection with such a cavity tone, frequency of peak components in pressure spectra, velocity fluctuations in jet and behaviors of vortical flow were investigated by authors [5), 6)].

The results and considerations described in these papers may be of value for reference to distinguish between noise components traveling in a piping, however, the contribution of cavity configurations to tone characteristics and the relationship between tone components caused by different resonance types are not exactly clarified. Further information is required to know the periodic and predominant property of such resonance tone generations by the inflowing jet.

In this paper, with a view to provide more useful data, Strouhal frequency obtained from the jet-generated tone components is arranged with the cavity depth and its expansion ratio. From the results, the jet-excited tone generations are discussed. Next the effect of the cylindrical resonance on such components is verified by the visualization of the acoustic field around an inflowing jet.

2. Experimental apparatus and method

A schematic diagram of experimental apparatus is sketched in Fig.1. The air flow produced by the compressor whose noise was sufficiently reduced by a pre-silencer, led through the inlet pipe, was entered as a jet into the tested cavity. After traveling in the outlet

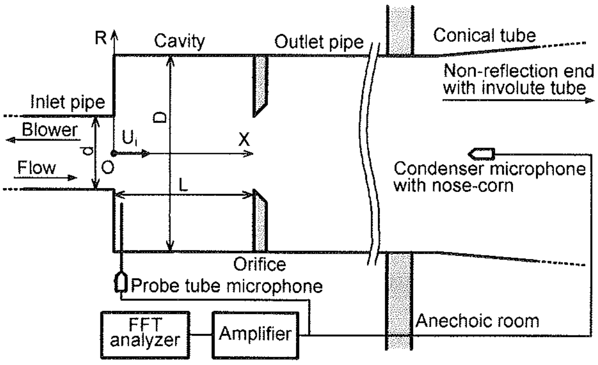

Fig.1 Schematic diagram of experimental apparatus

[*1] Research Student, Department of Prime Mover Engineering.

[*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.

pipe, conical tube and non-reflection involute tube lined with the glass wool, it was finally emitted into the anechoic room.

The cavity was composed of a cylindrical pipe having suddenly-expanded entrance and orifice exit, being symmetric around the axis. The inlet-pipe diameter *d* was the same as the orifice diameter, i.e. 21mm, 30mm and 48mm. The cavity length *L* was varied from 21mm to 192mm as L/d=1.0~4.0 and the cavity diameter *D* was 48mm, 80mm and 105mm. From these dimensions, the range of the geometric parameters related to the cavity configuration are determined as follows; the expansion ratio D/d=1.6~5.0, and the cavity depth L/D=0.2~2.5, respectively.

The sound pressure spectra containing the periodic tone components radiated from these models were measured at every frequency band of 6.5 Hz with the nose-cone type condenser microphone which were set in the conical tube and connected to FFT analyzer. At the same time, the distributions of the tone pressure level measured likewise around an inflowing jet were drawn as contour maps. In this case, the distance between measured positions, decided according to a cavity dimension, was 3mm to 12mm in the longitudinal direction and 2mm to 9mm in the radial direction, and the data in the middle points of respective positions were interpolated by computations. The central velocity of jet at the open end of the inlet pipe, measured with a Pitot tube, was varied in the range of 30m/s~80m/s.

3. Results

3.1 Frequency characteristics of resonance tone generated by jet

In Fig.2 (a) and (b), the spectra of sound pressure level measured in the conical tube are shown with two kinds of the fixed conditions on cavity dimension and jet velocity. Since there should be little resonance effect in the tail pipe where the standing wave is enough weakened, the marked peaks observed on each spectrum are able to be all regarded as the first, second, third and fourth components of the tone generated by jet excitement. Their frequencies are denoted in order of f_1, f_2, f_3 and f_4, and it is difficult to distinguish a component higher than the fourth order from small peaks of random noise. When the jet is comparatively fast and so short as to progress nearly straight, the generated components become further sharp. On the other hand, when the jet is relatively slow and long, they are not so much remarkable. In these peak characteristics, the first and second components show larger levels than the others, and either of them predominates according to the change of cavity diameter, but the inlet-pipe diameter hardly contribute to such predominance.

As shown in Fig.3 (a), (b) and (c), each of peak frequencies altogether represented by f_p varies in direct proportion to central velocity of jet U_i irrespective of cavity diameter and inlet-pipe diameter. In this case the gradient of the variations becomes larger as the cavity length is decreased. The fact indicates that the short cavity in which a jet passes at higher speed not only sharpen peak components of the generated tone, but also raise their frequencies.

In Fig.4, Strouhal number obtained from the relationship among the quantities mentioned above is arranged with the parameter on cavity configuration *L/D* by which the cavity depth can be expressed. Strouhal number appears to be unchangeable against the cavity depth except for especially-deep cases and unaffected by the expansion ratio *D/d* increasing roughly similar interval with mounting of periodic component-order number *m* (=1,2, etc.). Accordingly the horizontal solid lines are drawn in the manner that Strouhal number increases by 0.5 from its initial value as the order number rises numerically one by one. Experimental values for the first order are, on the whole, gathered along these lines, even though they lower in the region of higher order components for deep cavities. On the above occasion, the values on the predominant components are divided into classes depending on the cavity depth, as marked by gray.

A frequency equation containing Mach number has been

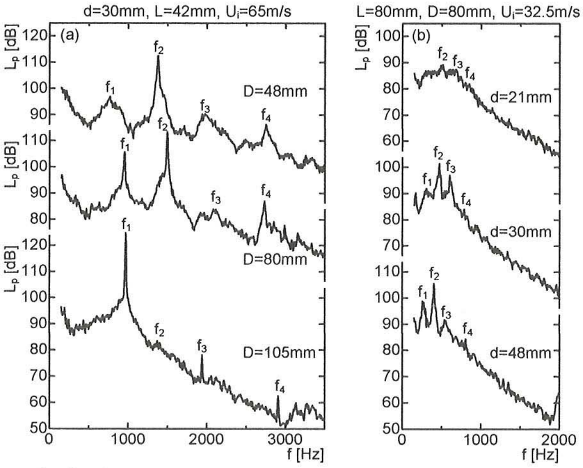

Fig.2 Sound pressure spectra measured in tail pipe

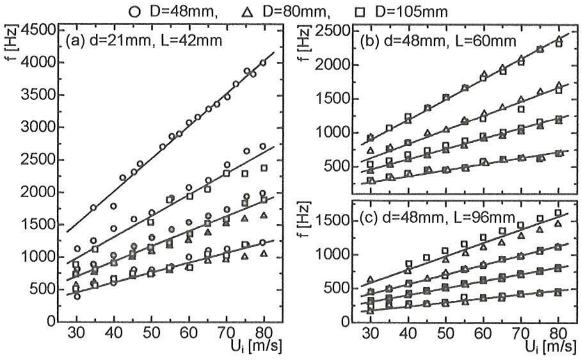

Fig.3 Frequency of the resonance tone generated by jet

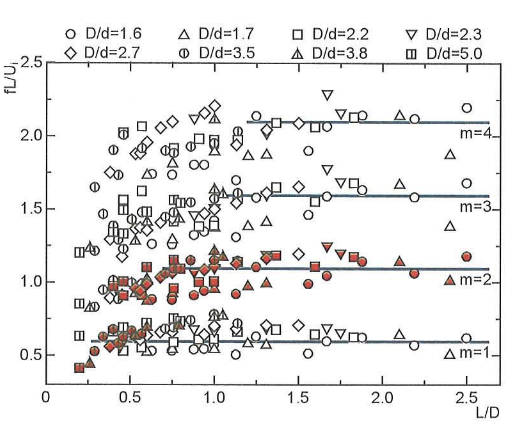

Fig.4 Strouhal number of the jet-generated tone

presented by Rossiter from investigations on pressure fluctuations excited by compressible flow over the wall-mounted cavity in the wind tunnel 7). It has been verified that this equation can also be applied to the open-cavity resonance in the range of incompressible flow speed, and the dimensionless frequency characteristics of tone components are little influenced by pretty low Mach number 8). Indeed when cavity length is fixed, tone frequency varies straight and does not curve against jet velocity within the upper limit measured (see Fig.3). For these reasons, Mach number term in Rossiter's equation could be neglected. The expression is

$$\frac{f_{\mathrm{p}}L}{U_{\mathrm{c}}} = m + \gamma \tag{1}$$

where U_c is convection velocity and γ is constant. By author's former experiments 5), the ratio U_c/U_i has been given as 0.53 which are included within the limits of numerical values, i.e. 0.52~ 0.58, described in the reference 9). If the convection velocity changed from the central velocity U_i by the above ratio is used together with the obtained data on frequency f_p and length L each value of Strouhal number represented in equation (1) will be about two times as long as that shown with the solid line in Fig.4, and may be evaluated by the constant γ. The value of this constant, having the positive sign, is about +0.2 on the average in the range of the ordinary and shallow cavity depths. Consequently such dimensionless frequencies should be somewhat larger, respectively, than the equivalent component-order numbers, i.e. 1, 2, 3 and 4.

Strouhal number on vortical flow is expressed by

$$\frac{f_{\mathrm{v}}L}{U_{\mathrm{c}}} = \frac{L}{\lambda} \tag{2}$$

where f_v is vortex frequency and λ is vortex space. From referring to the visualizations of vortex shedding in the similar-shaped models to the acoustic one, the vortex space is shorter than the cavity length. Namely the ratio L/λ is from 1.1 to 1.2 for deep cavities, being from 2.0 to 2.5 for the others 6), 10). These shows the values near acoustic Strouhal numbers at the first order and second one, which are obtained from respective predominant frequencies using the convection velocity as a representative velocity. Such an approximation between both values suggests that the feedback resonance tone originates around a jet at the frequency corresponding to the period of vortices impinging on the orifice-edged end of a cavity, radiated into the jet, travels in the piping. Thus the measured primary components of the jet-generated tone will exhibit themselves as excellent peaks, respectively, at the dimensionless frequencies divided into classes at the boundary of cavity depth L/D whose value is about 0.5.

Accordingly this type of tone generation may have two frequency modes, and the expression m in equation (1) could be explained as the mode number as far as it points out a primary component. But either of the first and second components can be primary in the transitional region close to the boundary of cavity depth, as shown by red dots in Fig.4. The fact seems to be due to the instability of the period of vortices, which should excite the acoustic oscillation, and as a result, to be induced by the shift of predominant frequencies from the typical case. This matter is considered as the reason why Strouhal number of the higher accompanying components becomes smaller as the cavity configuration especially deepens.

If the mode number is given, the dimensionless frequency characteristics on cavity oscillation will be determined by the constant γ mainly concerned with behaviors of vortex shedding. On the wall-mounted cavity opened against free stream, when m=1, Davies has described that the vortex space is typically twice as long as cavity length, so that the value of γ should be −0.5 1), and from Rossiter's experiments for incompressible flow, it takes values from −0.6 to −0.25 with changing of cavity height 7). Therefore the initial values of Strouhal number are smaller than numerically one, being different from the authors result on axisymmetrically-covered cavity, that is over one, except for case of the especially deep cavities.

The wave traveling process in a cavity may bear such difference between frequency characteristics on both cavity configurations. Fluctuating-pressures wave will take innumerable ways repeating reflections among the discontinuous faces and side wall in a covered cavity, however, in case of open cavity, considerable part of them will run into free stream. So the time for making effective pressure feedback appears to be distinguished between the covered and opened constructions. It could be understood that the vortex-issued period, which may be stabilized at the jet exit, is quickened in the former as compared with that in the latter, even though both have the same length and height.

3.2 Resonance tone formed in cylindrical acoustic field

The sound pressure spectrum for the deep cavity is shown in Fig.5 (a). The very marked sharp peak having a larger level than the first and second components of the jet-generated tone occurs at about 2000Hz. Such a peak appears to be related to the resonance in a cylindrical acoustic field whose frequency is expressed by the following equation.

$$f_{\mathrm{qrs}} = \frac{c}{2\pi}\sqrt{\left(\frac{2K_{\mathrm{qr}}}{D}\right)^2 + \left(\frac{s\pi}{L}\right)^2} \tag{3}$$

where c denotes sound speed, q, r, s, are the number of mode in the circumference, radial and axial directions, which are given by 1, 2, etc. and K_{qr} is characteristic value determined by q and r. As seen in Fig.5 (b), there is a particular case where tone-component frequency is no longer directly proportional to jet velocity. The higher component frequencies, f_3 and f_4, are unchangeable and fairly agree with the calculated frequency f_{100}, shown by a broken line,

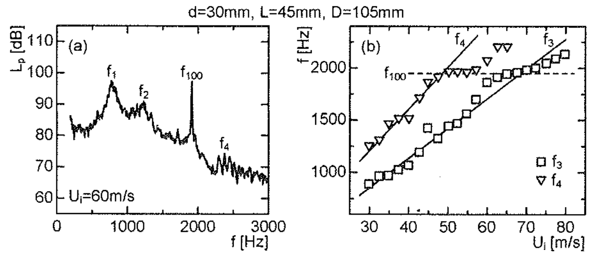

Fig.5 Frequency of the resonance tone formed in cylindrical acoustic field

roughly speaking, from 50m/s to 70m/s. This may be due to the matter that the third and fourth jet-excited tone components are rocked and amplified at f_{100} by another resonance component which is formed in the cylindrical acoustic field induced by random noise, at almost the same time, radiated into inflowing jet. Accordingly, if a periodic acoustic tone does not exist, the radiation of this sort will never occur [11].

On the f_{100}-component, a series of contour maps has been made of sound-pressure level distributions measured around an inflowing jet. On the cross sections shown in Fig.6 where f_{100} is denoted with the experimental average, pressure fluctuations change only in the circumference direction. Their distributions exhibit the phase having a minimum and a maximum at every 180 deg. independently of the axial direction denoted by X and a regular change of pressure in the radial direction is not observed. That means q=1 and r=0. On the vertical sections shown in Fig.7, the strength and weakness of pressure take place in accordance with the circumference phase with changing of its angle. On these sections, the longitudinal resonance caused by the reflection between both open ends of the cavity is not observed, so that s=0. From these visualizations, the cylindrical acoustic resonance of (1, 0, 0) mode has been verified. By the way, three minimum pressures can be seen near jet on some sections.

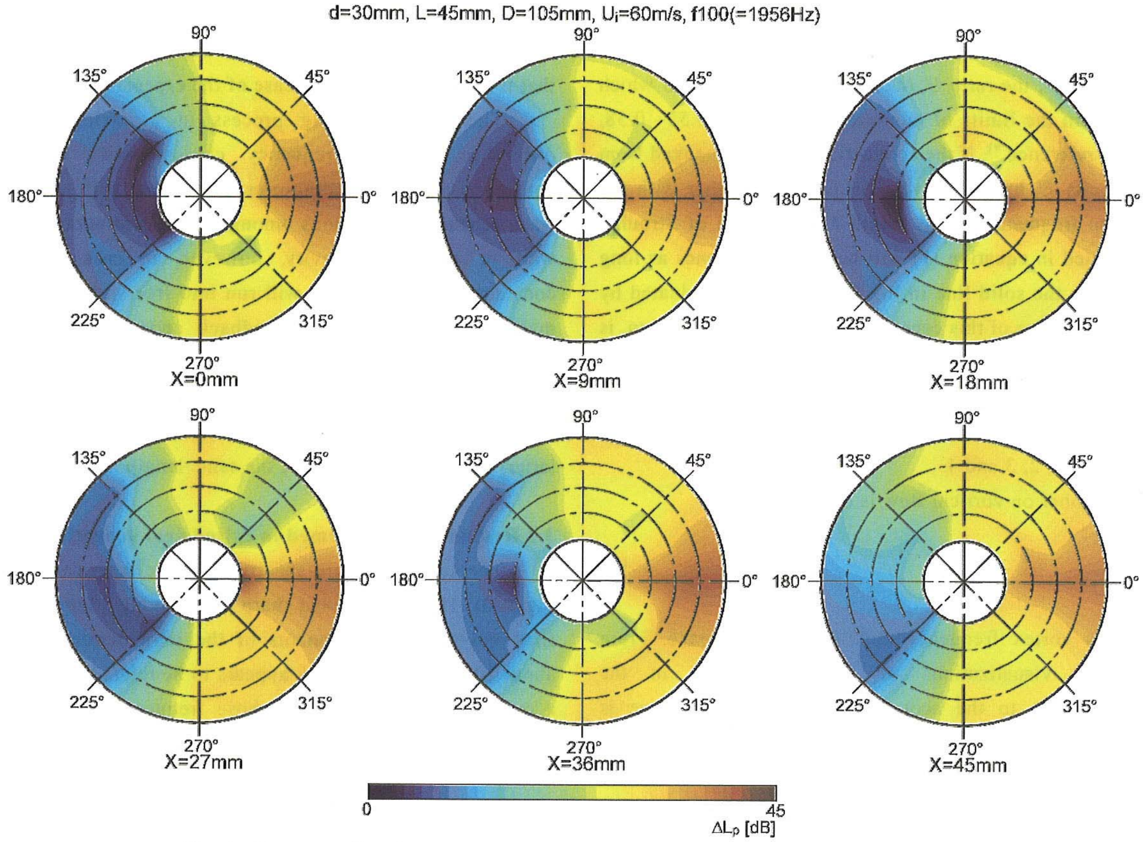

Fig.6 Pressure distribution of a tone component around jet (vertical section)

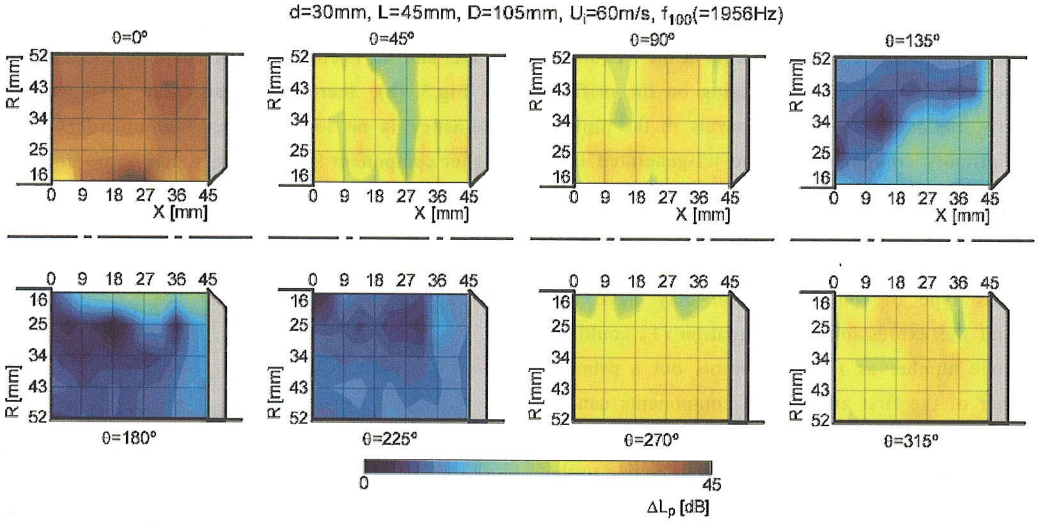

Fig.7 Pressure distribution of a tone component around jet (cross section)

These are considered as evidences that the third order rocked component exists, however, the detail is not clear because of short data.

If f_{qrs} is near frequencies of the jet-generated components, the change of resonance frequency like the above instance for f_{100} will rise as usual case. In large-sized cylindrical cavity, the oscillation at f_{200}, f_{010}, etc. may also occur in turn from lower side and much influence frequencies f_1, f_2, etc.

4. Conclusions

The tone generation in axially-symmetric cavity has been investigated within the upper limit of incompressible flow speed. The results are summarized as follows.

(1) The primary component of the resonance tone generated by inflowing jet with vortices generally appears at its second-order Strouhal number whose experimental value is unchangeable on the whole against cavity depth. It can also appear at the first-order Strouhal number in case of the particularly deep cavities.

(2) Such dimensionless frequency characteristics are not influenced by the expansion ratio of cavity diameter to inlet-pipe diameter.

(3) The resonance component formed in the cylindrical acoustic field can rock jet-induced components by its own frequency, so that there is the jet-speed region where resonance frequency is fixed.

References

1) P. O. A. L. Davies: FLOW-ACOUSTIC COUPLING IN DUCTS, Journal of Sound and Vibration, No. 77(2), 1981. pp.191-209.

2) J. J. KELLER, M. P. Escudier: FLOW-EXCITED RESONANCES IN COVERD CAVITY, Journal of Sound and Vibration, No. 86(2), 1983, pp.199-226.

3) H. NOMOTO., F. E. C. CULICK: AN EXPERIMENTAL INVESTIGATION OF PURE TONE GENERATION BY VORTEX SHEDDING IN A DUCT, Journal of Sound and Vibration, No. 84(2), 1982, pp.247-252.

4) H. MORIYAMA, S. MURAKAMI and S. HAGI: Studies on Noise Generated by Flow in Expansion Chamber Type Silencers (1st Report), Transactions of the Japan society of Mechanical Engineers, No. 53-495, 1987, pp.3300-3308.

5) T.KOMORI, S. MURAKAMI: NOISE GENERATION BY JET IMPINGING ON THE ORIFICE EDGE INSIDE A PIPE, Proc FLUCOME2000, No 12, 2000, pp.1-5.

6) T. KOMORI, S. MURAKAMI and Y. NAKAZONO: VISUALIZATION OF JET PASSING THROUGH AN EXPANSION CHAMBER, Proc 9th International Symposium on Flow Visualization, No.366, 2000, pp.1-8.

7) J. E. Rossiter: Wind-Tunnel Experiments on the Flow over Rectangular Cavities at Subsonic and Transonic Speeds, A.R.C. Report and Memorandum, No.3438, 1964, pp.1-32.

8) K. W. TAM, J. W. BLOCK: On the tones and pressure oscillations induced by flow over rectangular cavities, Journal of Fluid Mechanics, Vol. 89(2), 1978, pp.373-399.

9) J. A. Clark, Lam Kit: Shear Layer Transition and the Sharp-Edged Orifice, Journal of Fluids Engineering, Vol. 102, 1980, pp.219-225.

10) T. KOMORI, S. MURAKAMI: Characteristics of the Acoustic Resonance Induced by Jet Passing through Axisymmetric Cavities, Proc. Japan Society of Mechanical Engineers Fluids Engineering Conference 2001, No. G404, 2001, pp.1-4.

11) H. MORIYAMA, S. MURAKAMI, S. HAGI, Studies on Noise Generated by Flow in Expansion Chamber Type Silencers (2nd Report), Transactions of the Japan society of Mechanical Engineers, No.58-546, 1992, pp.594-601.