Hole Tone Generated from Almost Choked to Highly Choked Jets

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The hole tone generated from the interaction of high-speed jets with a round hole was experimentally investigated in order to clarify its generation mechanism. Measurements of far-field pressure waves as well as schlieren flow visualization were carried out. The frequency characteristics of the present hole tone are similar to those of hole tones radiated from a low-speed jet. Flow visualization confirms that this hole tone is generated by essentially the same feedback mechanism as that of the impinging tone radiated from high-speed jets. When a ring vortex interacts with the plate with a hole, an acoustic pulse is emitted with a strong directional peak in the upstream direction. The acoustic pulse propagates outside the jet and forces the generation of a new eddy on reaching the nozzle lip. The new eddy grows as it propagates downstream to interact with the circumference of the hole.

I. Introduction

IN general, various kinds of self-sustained flow tones are generated when a jet interacts with a solid surface and the conditions for the occurrence and maintenance of the tone are satisfied. Chanaud and Powell[1] showed that the hole and ring tones radiated from a low-speed circular jet are generated by the same mechanism as that of the edge tones radiated when a thin low-speed jet from a rectangular orifice is impinged on a wedge. In that same paper, Chanaud and Powell indicated that the hole tone is also radiated from the high subsonic jet, but they did not show the data on the frequency characteristics.

Most of the investigations for self-sustained flow tones including hole tones have been carried out using low-speed jets. Recently, self-sustained flow tones radiated from a high-speed jet have been studied in relation to the investigation of V/STOL aircrafts. Wagner,[2] Ho and Nossier,[3] and Krothapalli[4] performed the experimental investigations of the impinging tone radiated when a high subsonic or choked underexpanded jet impinges on a flat plate placed normal to the jet axis. An impinging tone radiated when the high subsonic and choked underexpanded jets are impinged on a slender circular cylinder placed normal to a jet axis was investigated experimentally by Umeda, Maeda, and Ishii.[5,6]

Ho and Nossier[3] suggested a generation mechanism of the impinging tone radiated from the high subsonic jet based on the feedback model of the screech tone generation proposed by Powell.[7] Ho and Nossier[3] explained the feedback mechanism for the impinging tone as follows. Upon interaction with the plate, the downstream traveling coherent structures of the jet boundary generate strong acoustic waves. These acoustic waves propagate upstream through the ambient medium and, upon reaching the nozzle lip, excite the flow instability waves of the shear layer. These coherent structures grow as they propagate downstream. The downstream traveling vortical structures and upstream-propagating acoustic waves form a feedback loop. Wagner[2] proposed a different model in which the standing sound waves created inside the jet play a significant role in the generation of the same impinging tones.

In this paper, a hole tone radiated from high subsonic and choked underexpanded jets is described. The study of the generation mechanism of the hole tone was made using microphone pressure measurements of the sound field and flow visualization techniques. By flow visualization, it will be made clear that this hole tone is generated by the essentially same feedback mechanism as that of the impinging tone proposed by the present authors.[6] Furthermore, the conditions for the radiation of strong hole tones, the radiation of axisymmetric and asymmetric waves, and the amplitude modulation of hole tones will be discussed.

II. Experimental Apparatus

In the previous investigations[5,6] as well as in this one, the experimental apparatus and methods were almost the same. An important improvement in the present experiment was the use of a schlieren video.

A sketch of the nozzle and plate generating the hole tone and associated flowfield along with a near-sound field (as observed in the schlieren photograph) is shown in Fig. 1. A high-speed jet of air was exhausted from a circular converging nozzle with an internal diameter $d = 1.00$ cm. The pressure ratio R ($=P_0/P$, where P_0 is the stagnation pressure and P the ambient pressure) of the jet was regulated by a control valve. A rigid plate (9.4 cm × 9.7 cm) with a circular hole was mounted on the traverse mechanism. The circular hole is placed concentrically with the jet and the diameter D of the hole is 2.20 d (2.20 cm). The jet passes through this hole. The nozzle-to-plate distance h was varied by a pulse motor. The system consisting of the nozzle and the rigid plate with a hole is called the hole-tone system. In Fig. 1, the cellular structure, ring vortex, upstream-propagating sound wave, and downstream-propagating sound wave are denoted by F, V, UW, and DW, respectively.

All the experimental works were performed within a simplified anechoic chamber. The sound pressure was measured by using a 0.32-cm-diam Bruel and Kjaer-type 4135 condenser microphone, which has a flat response out to about 100 kHz. The microphone was located at a fixed position in the backward arc about 50 deg from the jet axis, at a radius of 1.35 m from the nozzle exit and 1.50 m above the floor. The experiments for the acoustic observations were carried out as follows: 1) The pressure ratio R of the jet is fixed, and the nozzle-to-plate distance h is changed. 2) The nozzle-to-plate distance h is fixed and the pressure ratio R of the jet is changed.

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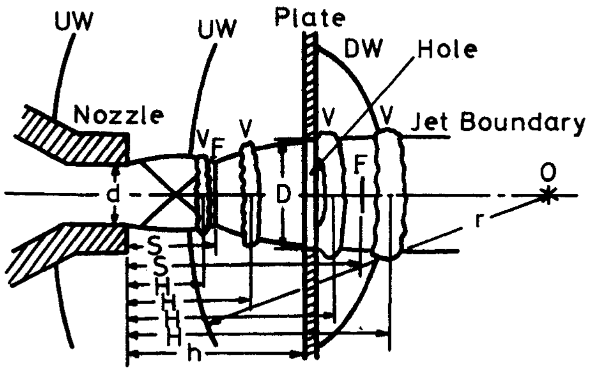

Fig. 1 Cross-sectional view of the hole-tone system.

In the flow visualization, the spark of a Xenon flash lamp with a duration time of about 1 μs was used as the light source of the schlieren technique and proved fast enough to stop the motion. Further, a schlieren video was taken by a CCD TV camera, with a videotape recorder and the Xenon flash lamp. In this case, the flash lamp was fired every 1/60 s. This schlieren video was reproduced by the slow motion or the stop-motion mode to observe the behavior of the feedback resonance and the various phenomena associated with hole-tone radiation. The controlling parameter for the jet was the stagnation pressure P_0, which varied at 1.2–6.0 kg/cm^2. The nozzle-to-plate distance h was varied at 0.0–5.5 cm so as to control the impinging effect of the jet column on the plate.

III. Experimental Results

A. Acoustic Observations

Typical spectra of sound emitted from the hole-tone system are compared in Fig. 2 with those emitted from the corresponding free jet. The abscissa is the frequency f and the ordinate is the sound pressure level p in decibels. The reference level is 2×10^{-4} dyne/cm^2. In these figures, HT_n and ST_n denote the hole and screech tones, respectively, and the subscripts n denote the fundamental frequency $n = 1$ and its harmonics $n \geq 2$. No dominant discrete tones are emitted from the subsonic free jet (Fig. 2a), and the hole tone is radiated from both subsonic and supersonic jets with the hole-tone system (Figs. 2b and 2d). It is interesting to note that the dominant screech tones of the supersonic free jet were suppressed, and their frequency is slightly varied because of the presence of the hole-tone resonance. One can observe in Fig. 2d that the discrete frequency component HS, which has a frequency nearly equal to the frequency difference between the hole and screech tones, appears. If the frequency of HS is denoted by Δf, the amplitude modulation modes $HT_1 \pm \Delta f$ and $HT_2 \pm \Delta f$ can be seen in this figure. In Fig. 3, the resonance frequencies f_M of the discrete tones are plotted against the nozzle-to-plate distance h/d for $R = 1.77$ and 3.90. The data surrounded by a dotted line and denoted by ST are associated with screech tones. The frequency of the screech tone slightly changed depending on the location of the plate. In Fig. 4, the resonance frequencies f_M are plotted against the pressure ratio R for $h/d = 3.00$ and 4.00. In these figures, open circles represent the frequencies f_M of the discrete tones whose sound pressure levels exceed those of a broad frequency band by 10 dB or more.

When the hole diameter was changed from 1.80 to 2.40 cm, any appreciable difference in the frequency characteristics of the hole tone was not observed. Only the minimum nozzle-to-plate distance h/d for the generation of the hole tone was increased with the diameter D. Then, the experimental data presented in this paper are only for the hole diameter $D = 2.20$ cm.

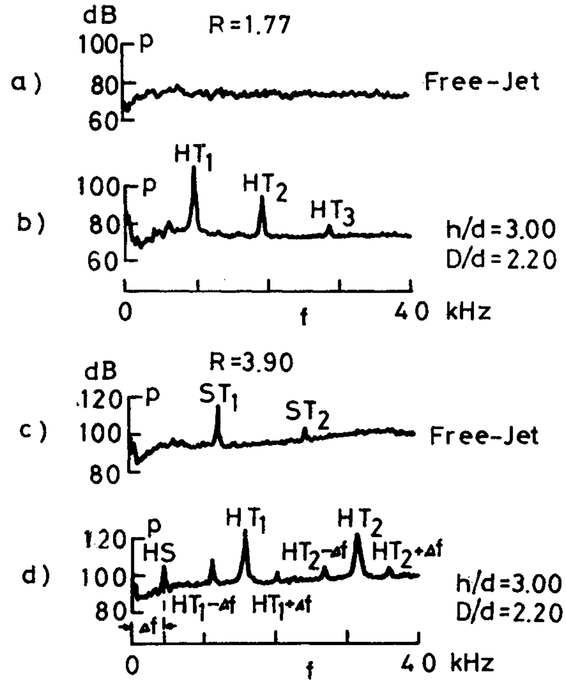

Fig. 2 Spectra of sound emitted from high-speed jets.

From the experimental results shown in Figs. 3 and 4, it is found that the present hole tone (for $D/d = 2.20$ and $d = 1.00$ cm) has the following characteristics.

1) This hole tone is generated when the nozzle-to-plate distance h/d is larger than 2.0 and a jet is operated at $1.5 < R < 5.0$.

2) When the pressure ratio R of a jet is fixed, the resonance frequency decreases gradually as the nozzle-to-plate distance is increased. For a jet of pressure ratio $R = 1.77$, the resonance frequency shows a stage character, but such a character is not observed for $R = 3.90$.

3) As the pressure ratio R increases for a fixed nozzle-to-plate distance h/d, the resonance frequency rises slightly. Three curves of the frequency characteristics are almost parallel to each other, and the frequency differences of these curves are equal in the respective figures. This phenomenon reflects the spectra as shown in Fig. 2d.

Now compare the frequency characteristics of the present hole tone with those of the other types of self-sustained flow tones. The frequency characteristics of the hole tone radiated from low-speed jets are very similar to those of the edge tones radiated from low-speed jets.[1,8] The frequency characteristics of the present hole tone are roughly similar to those of the hole tone radiated from a low-speed jet. The impinging tone radiated when a high subsonic jet impinges on the flat plate placed normal to the jet axis[2,3] also shows frequency characteristics similar to those of the present hole tone. But in the case of some other impinging tones, which are radiated when a supersonic jet impinges on the plate placed normal to the jet axis[4] and when high subsonic and choked underexpanded jets impinge on the slender cylinder placed normal to the jet axis,[5,6] the resonance frequency decreases stepwise when the pressure ratio is increased for a fixed position of the plate or cylinder. The frequency characteristics of these impinging tones are different from those of the present hole tone.

In Fig. 5, the overall sound pressure levels are plotted against the nozzle-to-plate distance h/d for the pressure ratios $R = 1.77$, 2.25, and 3.90, respectively. For comparison purposes, those for corresponding free jets are shown by dotted lines. From this figure, it can be seen that the overall sound pressure levels are nearly equal to those of the free jets in the range of about $h/d < 2.0$. On the contrary, they change

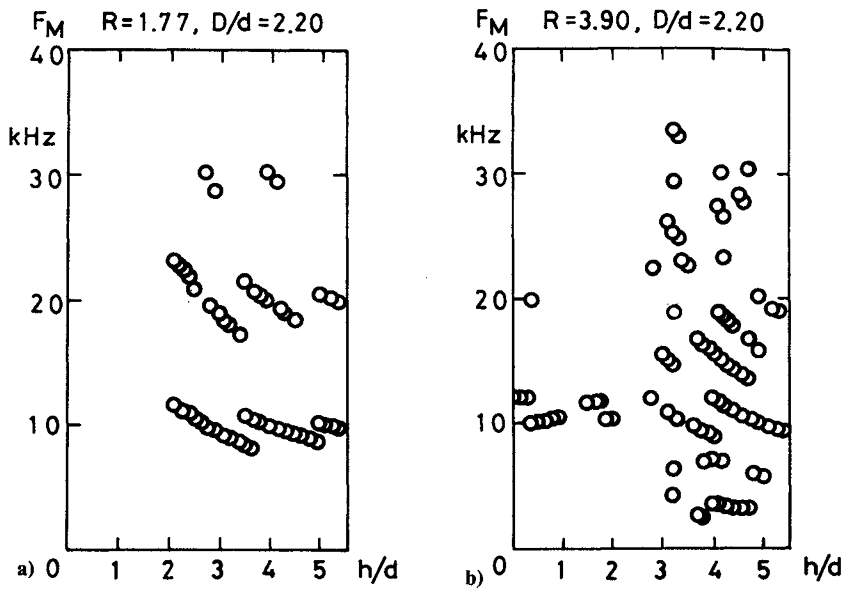

Fig. 3 Resonance frequency vs nozzle-to-plate distance for fixed pressure ratio: a) $R = 1.77$, b) $R = 3.90$.

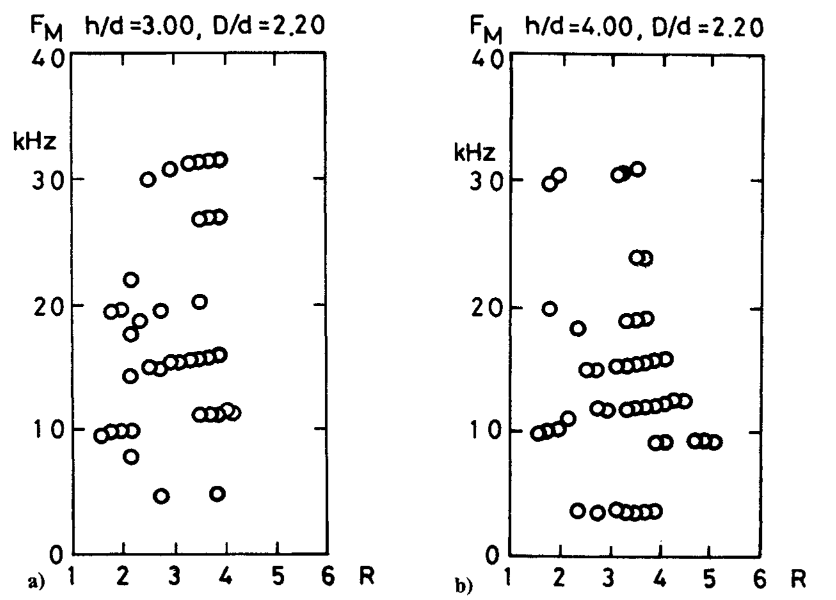

Fig. 4 Resonance frequency vs pressure ratio for fixed nozzle-to-plate distance: a) $h/d = 3.00$, b) $h/d = 4.00$.

markedly in the range $h/d > 2.0$ due to the generation of the hole tone. This shows that the jet passes through the hole without interaction with the circumference of the hole because the hole diameter is large compared with the jet diameter for $h/d < 2.0$.

B. Flow Visualizations

A schlieren photograph of the supersonic free jet for $R = 3.90$ is shown in Fig. 6a. In this photo, one can observe several cellular structures inside the jet, the helical vortex surrounding the jet, and the helical wave front of the screech tone outside the jet. Figure 6b shows a jet for $R = 3.90$ and $h/d = 3.00$. In this picture, a quite different facet of the flowfield from that of Fig. 6a can be seen. Namely, jet instabilities couple with the resonance of this hole-tone system to produce very powerful axisymmetric pressure waves (hole tone). On the left side of the plate, two predominant upstream-propagating sound waves outside the jet, a cellular structure, and a ring vortex can be seen. On the right side of the plate, three ring vortices and somewhat weaker downstream-propagating sound waves can be seen. In this case, the jet does not impinge on the plate, but it passes through the hole. Figure 6c shows a jet for $R = 3.90$ and $h/d = 5.00$, where an appreciable part of the jet boundary impinges on the plate (outer edge of the round hole). Compared with the jet in Fig. 6b, the asymmetric mode of jet structures is clearly very enhanced. It has to be stressed that the pressure waves in the jet (Fig. 6b) are much stronger than those in the jet (Fig. 6c). This suggests that the direct interaction of the jet with the solid plate does not always result in an emission of strong acoustic waves. It must be pointed out that the interaction between the large vortical structure and circumference of the hole is more effective in the generation of the tone than the interaction of the whole jet with the plate.

Now, we will use the flow visualization technique to investigate the generation mechanism of the hole tone. Since this phenomenon is very periodic and the reproducibility is very good, we can use the location of the upstream-propagating wave front outside the jet as a reference time in order to investigate the feedback loop of the present hole tone. A series of pictures was taken of the jet at a fixed pressure ratio and nozzle-to-plate distance. These pictures, having their own built-in clock in the position of the sound waves, then could be arranged in chronological order. Figure 7 shows a series of such pictures during one cycle of the hole-tone generation for $R = 3.90$, $D/d = 2.20$, $h/d = 3.00$, and $d = 1.00$ cm. The

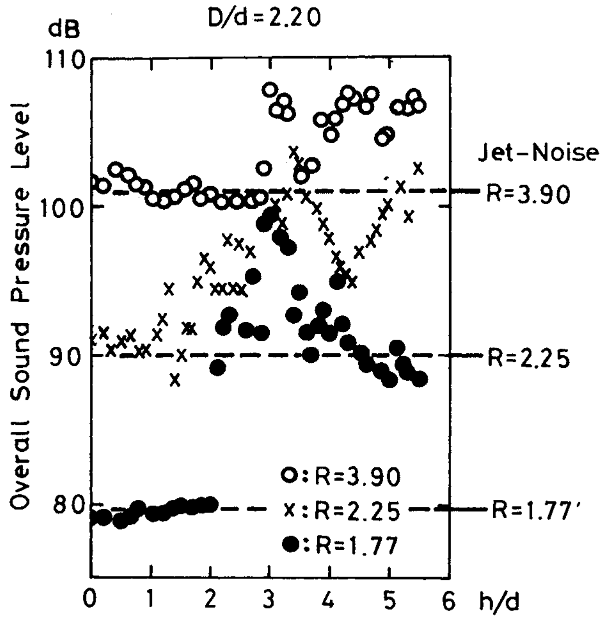

Fig. 5 Overall sound pressure level vs nozzle-to-plate distance.

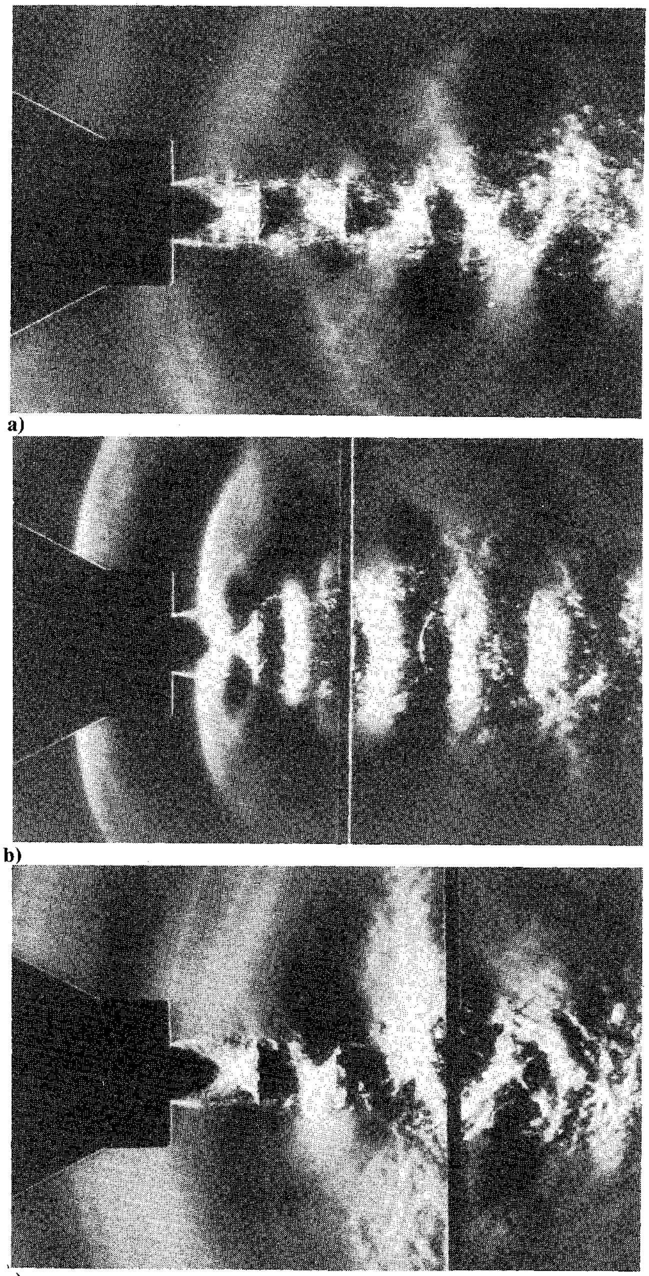
a)
b)
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Fig. 6 Hole tones and jet instabilities for $R = 3.90$.

pictures are those at the peaks of the oscillations, since they are the most interesting. The time intervals between the pictures can be judged by the progress of the sound waves. It is observed from Fig. 7 that the hole tone is generated in the following manner. When a ring vortex interacts with the plate with a hole, an acoustic pulse is emitted with a strong directional peak in the upstream direction. The acoustic pulse propagates outside the jet and forces the generation of a new eddy on reaching the nozzle lip. The new eddy is convected downstream and grown up to interact with the hole. The same process repeats itself.

In a similar manner, we can demonstrate one cycle of the feedback resonance for a high subsonic jet ($R = 1.77$ and $h/d = 2.55$) by a series of schlieren photographs as shown in Fig. 8. Although the sound wave is not visible in these photographs because the intensity of the sound wave is not strong enough to be taken by the photograph, we can arrange a series of pictures in this case in chronological order according to those for impinging tones radiated from a high subsonic jet represented in Ref. 6. In the high subsonic case, one can see from Fig. 8 that two large collective coherent structures (ring vortices) merge together into one large coherent structure during one cycle of the feedback loop. This situation is the same as that for the impinging tone radiation from the subsonic jet reported in Ref. 6.

We will now investigate the present feedback loop more quantitatively. For a supersonic jet ($R = 3.90$ and $h/d = 3.00$), the locations of the vortex rings and the trailing edge of the cellular structures (H and S) were measured from a number of pictures. The results are shown in Fig. 9 as a function of the distance r from an apparent source of the sound wave O to the upstream-propagating wave front UW. The notations are explained in Fig. 1 for a supersonic jet. In Fig. 9, a hatch shows the position of the plate with a hole and the r axis shows that of the nozzle exit. The ring vortices are convected along the parallel sets of points shown in Fig. 9a. In Fig. 9b, the distances S from the nozzle exit to the trailing edge of the cellular structure are shown against the distance r for the same jet of Fig. 9a. The first trailing edge of the cellular structure does not appreciably change its shape and location. The second one oscillates along the jet axis around some averaging position ($S/d = 3.15$). The third and fourth trailing edges follow the motion of the second one. All the schlieren photographs on which r, H, and S were measured were taken at random. In spite of such a situation, the measured data are almost on the solid lines. This shows that the present resonance phenomenon is suprisingly periodic.

The passage frequency f_v of a ring vortex is given by the distance between two successive vortices and the convection velocity determined from Fig. 9a. Frequencies of the hole tones can also be given by measuring the wavelength (the distance between two successive wave fronts) on the schlieren photograph and the microphone measurements. We denote the former frequency by f_{UW} and the latter one by f_M, respectively. Three hole-tone frequencies f_v, f_{UW}, and f_M for a supersonic jet ($R = 3.90$, $D/d = 2.20$, $h/d = 3.00$, and $d = 1.00$ cm) are 15.5 kHz, 15.1 kHz, and 15.2 kHz, respectively. Agreement among these frequencies is very good.

Although the frequency characteristics of the present hole tone are different in some respect from those of impinging tones investigated by the present authors,[6] we can conclude from the foregoing flow visualization that both tones are radiated essentially by the same mechanism.

IV. Discussion

Some interesting phenomena associated with the hole-tone radiation are found in the present experiment.

A. Conditions for the Radiation of Strong Hole Tone

In order to investigate the conditions of the radiation of the strong hole tone, the observations by the schlieren TV and its video were made against various nozzle-to-plate distances h/d and the pressure ratios R. The result is shown in Fig. 10a. In this figure, solid and open circles represent the radiation condition of the hole tones whose sound pressure levels exceed those of a broad frequency band by 27 dB or more and by 20–27 dB, respectively. It can be seen from this figure that very strong wave fronts (denoted by solid circles) are radiated for the pressure ratio R from about 2.8 to 4.2 for the nozzle-to-plate distance h/d from 2.0 to 4.0. Under these conditions, it is observed that the jet column does not impinge on the circumference of the circular hole with $D/d = 2.20$. This range of the pressure ratio almost corresponds to that for the occurrence of the discontinuities in the frequency of the screech tone as is shown in Fig. 10b. It is considered that the discontinuities in the frequency of the screech tone are due to Mach disk generation. In the aforementioned range of the pressure ratio, the jet instability is relatively great. Therefore, the strong coherent structures (large ring vortices) are easily generated, and the very strong sound waves are radiated by the impingement of the ring vortices on the circumference of the hole.

B. Radiation of Axisymmetric and Asymmetric Waves

In Fig. 6, schlieren photographs of the free jet and jets with the hole-tone system are shown. The pressure ratio R of the jet is 3.90. The sound wave fronts in the case of Figs. 6a and 6c are asymmetric, and the observed sound waves are screech tones. The sound wave front in the case of Fig. 6b is axisymmetric, and the observed sound waves are hole tones. Generally, the interference between the screech tone and hole tone, as well as the interference between the screech tone and the impinging tone, occurs in the case of the supersonic jet. The latter case was discussed in Ref. 6. In the case of Fig. 6c, the screech tone with an asymmetric wave front predominates over the hole tone. In the case of Fig. 6b, the situation is reversed and the axisymmetric wave front of the hole tone is predominant. The reason why the asymmetric or axisymmetric sound wave is radiated from the jet can be considered as follows. In the former case, the second and successive cellular structures can oscillate radially and asymmetric waves are radiated. However, in the latter case, since the trailing edge of the second cellular structure is close to the hole, the radial oscillation of the cellular structure is suppressed by the restriction of the circumference of the hole, and then the cellular structure can oscillate along the jet axis only. Therefore, it is considered that only axisymmetric waves are radiated strongly. Such a situation is also observed when the hole is placed at the trailing edge of the third cellular structure. This situation is similar to the sound radiation from an oscillating diaphragm in a baffle board.

C. Amplitude Modulation of Hole Tone

In the spectrum of Fig. 2d, it can be seen that HT_1 and HT_2 have double sideband frequencies at distance Δf. This fact shows that HT_1 and HT_2 are amplitude-modulated by the signal HS of the frequency Δf. The frequency of Δf is nearly equal to the frequency difference between the hole tone HT_1 in Fig. 2d and that of the screech tone ST_1 in Fig. 2c radiated from the free jet. It must be noted, however, that the frequency of the screech tone is slightly changed with the position of the plate as is shown by the frequency data surrounded by a dotted line in Fig. 3b. In this case, the jet is issued through the hole without direct interaction with the

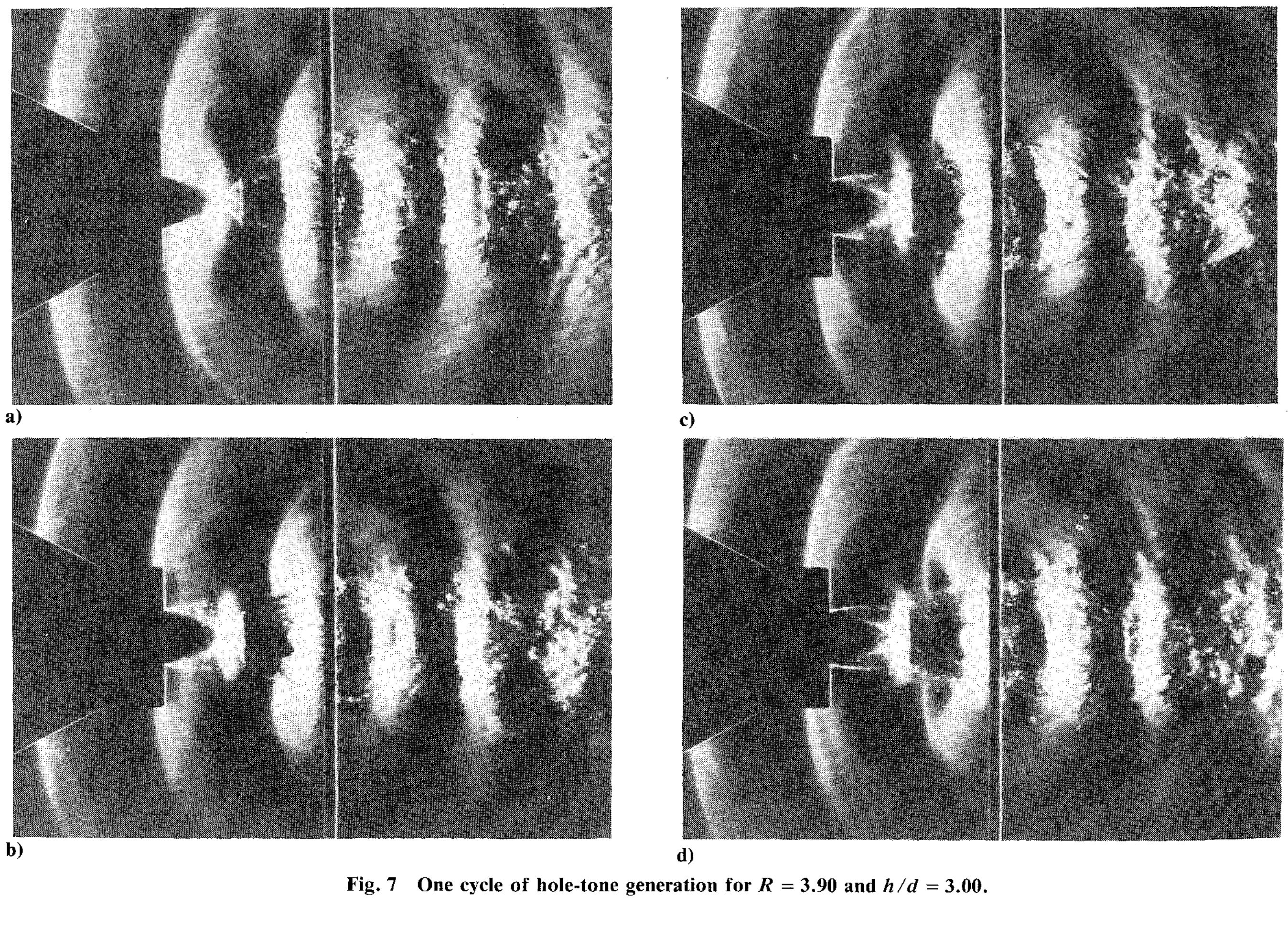


Fig. 7 One cycle of hole-tone generation for $R = 3.90$ and $h/d = 3.00$.

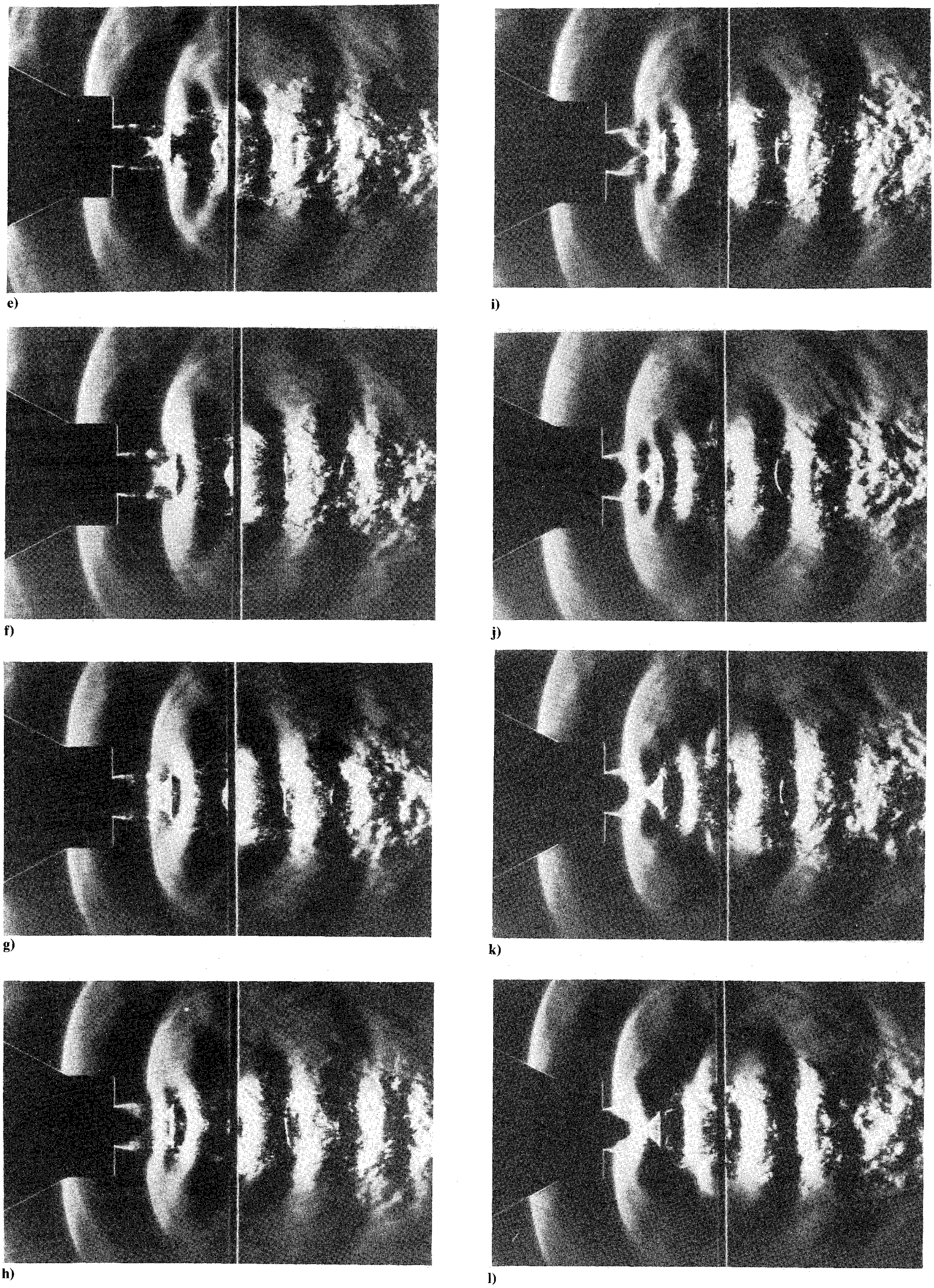
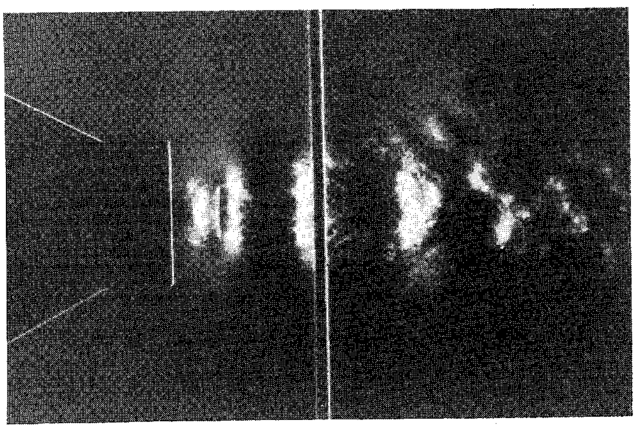


Fig 7 Continued; one cycle of hole-tone generation for $R = 3.90$ and $h/d = 3.00$.



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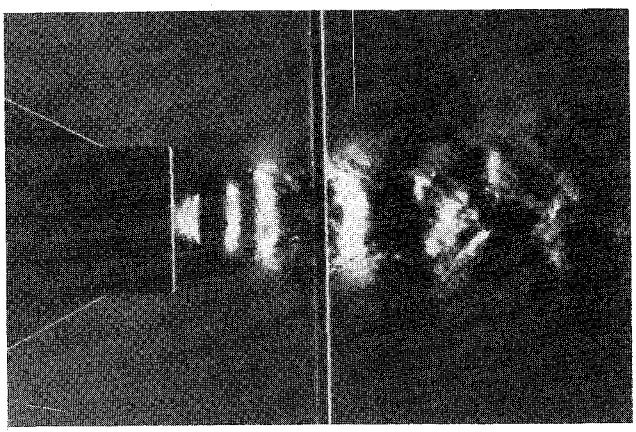

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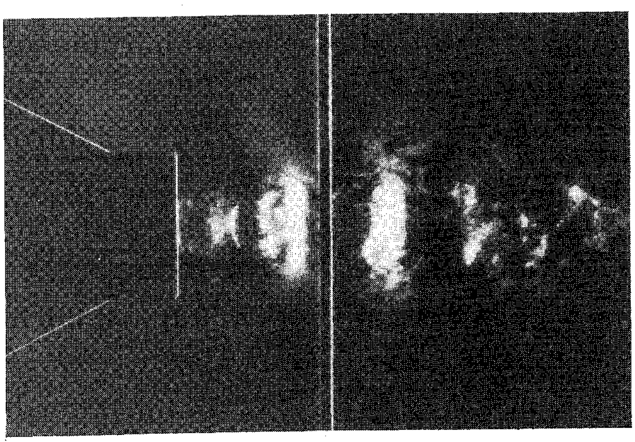

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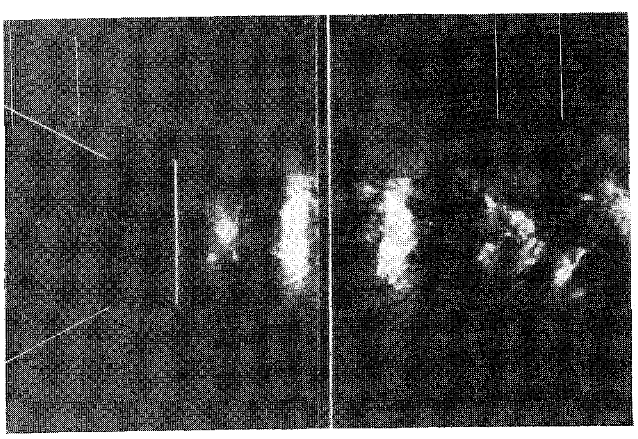

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Fig. 8 One cycle of hole-tone generation for $R = 1.77$ and $h/d = 2.55$.

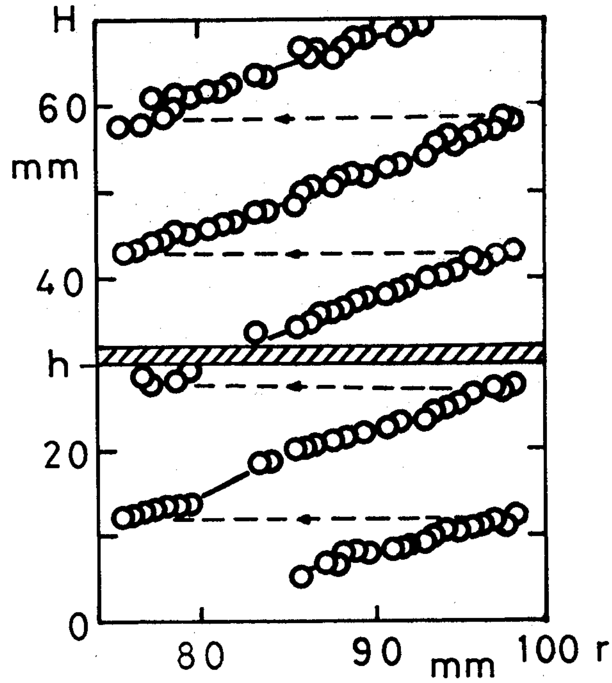

Fig. 9a Loci of ring vortices for $R = 3.90$ and $h/d = 3.00$.

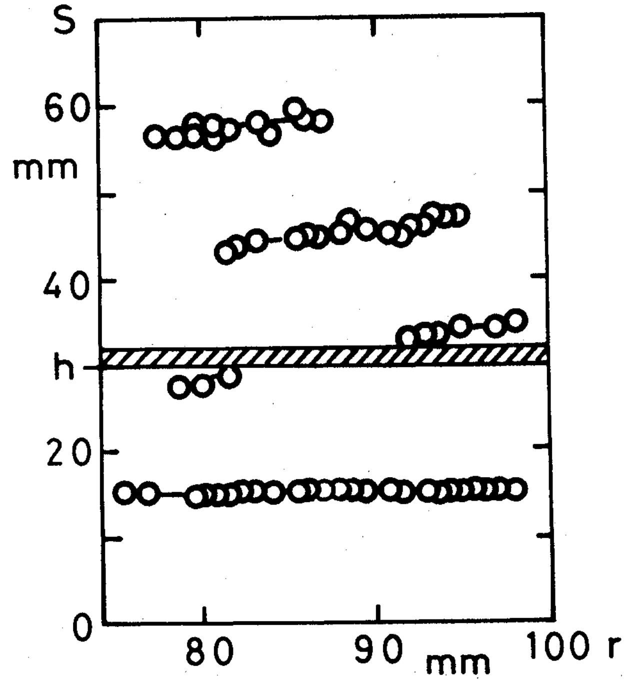

Fig. 9b Loci of the trailing edge of cellular structures for $R = 3.90$ and $h/d = 3.00$.

solid boundary of the hole. In the case of Fig. 2d, the frequency of the screech tone radiated from the jet with the plate ST' is slightly lower than that radiated from the free jet ST_1 in Fig. 2c. The frequency of Δf is equal to the frequency difference between HT_1 and the modified frequency of screech tone ST' (Fig. 2d), and it is a little larger than the frequency difference between HT_1 and ST_1. It is considered that the amplitude modulation of the hole tone occurs when the jet is excited by the sound wave having a beat frequency Δf. In this situation, the jet exhaust velocity is slightly affected by the excitation of the sound wave having a beat frequency. This brings a slight change in the amplitude of the hole tone but does not change its frequency. Because the change in the hole-tone amplitude is small, this phenomenon cannot be detected from a series of schlieren photographs as shown in Fig. 7.

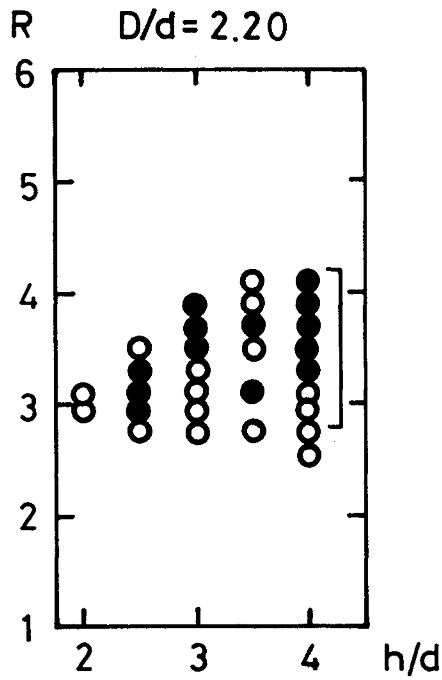

Fig. 10a Conditions for generation of strong hole tones against nozzle-to-plate distance and pressure ratio.

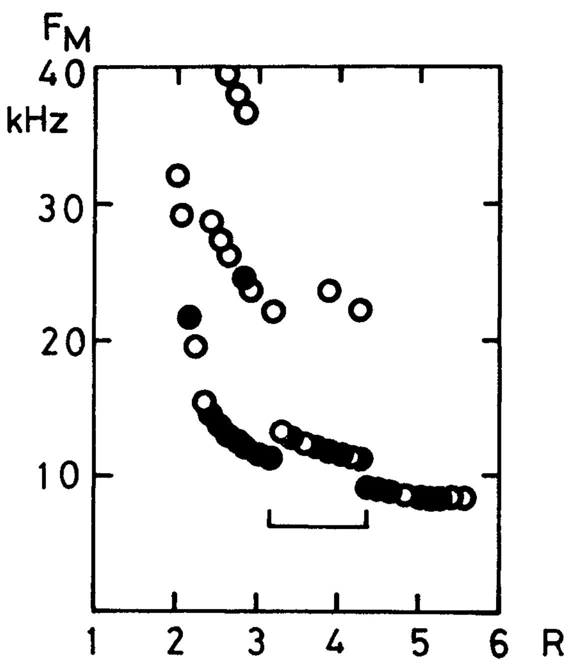

Fig. 10b Frequency characteristics of screech tone.

D. Effects of Hole Diameter on the Generation of Hole Tone

When the hole diameter D/d was changed from 1.80 to 2.40, any appreciable difference in the frequency characteristics of the hole tone was not observed.

It will, however, be interesting to investigate the effects of the hole diameter relative to the nozzle diameter D/d on the generation of the hole tone. When D/d tends to zero, it is reasonable to expect that the discrete tones that would be radiated from the jet are the impinging tones. Then, our next task is to investigate the conditions of the hole-tone radiation, the transition from the hole tone to impinging tone, and the difference between the generation mechanisms of these discrete tones by changing D/d from zero to some sufficient large value.

V. Conclusions

A hole tone radiated from high subsonic and choked underexpanded jets was investigated experimentally. Flow visualization shows that the present hole tone is generated essentially by the same mechanism as that of the impinging tone generated from high-speed jets of air issuing from a circular nozzle and impinging on a slender circular cylinder placed normal to the jet axis. Therefore, it is considered that in the generation of both tones, a significant role is played by the interaction between the coherent structures and the solid body such as the cylinder or circumference of the hole. The following interesting phenomena were also found in the present experiment.

1) A very powerful hole tone is generated in the range of the pressure ratio corresponding to that where the discontinuities in the frequency of the screech tone appear.

2) A powerful hole tone with an axisymmetric wave front is radiated when the plate is placed close to the trailing edge of the second and the third cellular structures.

3) The amplitude modulation of the hole tone occurs in association with the generation of the powerful hole tone.

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