Discrete Tones Generated by an Impinging Underexpanded Rectangular Jet

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Experimental measurements were made of the frequencies of discrete tones generated by a choked underexpanded jet of air issuing from a rectangular nozzle of moderate aspect ratio and impinging on a flat plate placed normal to the jet axis. Schlieren pictures of the flowfield along with near-sound-field and surface pressure measurements were obtained at different pressure ratios. The near-sound-field spectrum shows two dominant tones, corresponding to the screech tone and the impinging tone (i.e., tone due to the impingement of the jet on a rigid surface). At the pressure ratio for which the impinging tone is strongest, a large-amplitude transverse undulation of the jet is observed. The variation of the impinging tone frequency with the plate height shows a staging behavior similar to that observed in other discrete tone-generating flows.

Introduction

THE noise generated by the impingement of a supersonic jet on a flat solid surface is of practical importance in a number of engineering applications, of which the takeoff of a V/STOL aircraft is an example. With recent emphasis on thrust vectoring for the reduction in landing and takeoff distances or for high Mach number combat maneuvering, much attention has been focused on jet flows exiting from rectangular nozzles. The configuration of interest here is a rectangular nozzle of moderate aspect ratio placed vertically above a flat solid surface as shown in Fig. 1. The noise generated by the interaction of the jet with the solid surface consists of both discrete and broadband components, but the present study focuses on the discrete components alone. The mechanism for their generation by an impinging jet is generally complicated, especially for underexpanded jets where the shock cell structure complicates the phenomenon further. The experiments described in this paper have been conducted as a first attempt to understand how the discrete noise components are generated.

The phenomenon of discrete sound radiation from an impinging subsonic axisymmetric jet has been studied recently by Ho and Nossier.[1,2] In view of the mechanisms suggested by Powell[3] and Tam and Block[4] for self-sustained oscillations, they identified a feedback mechanism that is described as follows. Upon interacting with the plate, the downstream traveling coherent structures of the jet generate strong pressure fluctuations near the impingement region that lead to acoustic waves in the near sound field. These acoustic waves propagate upstream through the ambient medium and, upon reaching the nozzle exit, excite the flow instability waves (or periodic structures) of the shear layer. These coherent structures grow as they propagate downstream. The downstream traveling vortical structures and the upstream propagating acoustic waves form the feedback loop. A similar phenomenon was also observed by Neuwerth[5] in his study of an impinging subsonic axisymmetric jet. Several other investigators studied the noise generated by an impinging axisymmetric jet, e.g., Marsh,[6] Preisser and Block,[7] and Wagner.[8] The unsteady pressure fluctuations generated by the impingement of an underexpanded axisymmetric jet on the rigid surface were studied by Back and Sarohia.[9] The flowfield of an impinging supersonic axisymmetric jet was studied by Gummer and Hunt.[10,11] Most of the work to date has dealt mainly with flows exiting from axisymmetric nozzles.

Although the structure of a rectangular jet exhibits many features similar to that of an axisymmetric jet, important differences between the two flows do exist. Some of these differences tend to make experimental study easier. For example, the nearly two-dimensional structure of the disturbances (or vortices) and their associated sound fields near the nozzle exit are easily identified in flow visualization pictures because of the long optical path length present. It is thus experimentally attractive to study the flow and sound fields of a jet exiting from a rectangular nozzle.

The principal parameters or variables governing the flow of an impinging underexpanded rectangular jet are the pressure ratio R (stagnation pressure/ambient pressure), Mach number M, Reynolds number Re, the state of the flow at the exit plane of the nozzle, the aspect ratio of the nozzle, and the position h/W and orientation of the plate with respect to the nozzle exit. In the present investigation, the pressure ratio R was varied at 2-5.8. This interval corresponds to a Mach number range (based on fully expanded isentropic flow) of 1.05-1.8. The Reynolds number employed here is based on the width W (small dimension) of the nozzle and given by $Re = MaW/\nu$, where a and ν are the speed of sound and kinematic viscosity of the ambient medium, respectively. This Reynolds number was varied from 7.2×10^4 to 1.10×10^5 in the experiment. A rectangular nozzle of aspect ratio 16.7 was used. The total pressure profile at the nozzle exit was found to be flat. The plate was oriented normally to the jet axis and at various distances h/W between 10 and 30 from the nozzle exit.

Apparatus, Instrumentation, and Procedures

A high-pressure blowdown-type air supply system was used to provide the airflow to a cylindrical settling chamber having dimensions of 1.75 m long and 0.6 m in diameter. The temperature in the settling chamber was maintained constant, usually at room temperature, to an accuracy of about 0.5°C over the duration of each test. Before reaching the nozzle, the air was passed through an adapter, containing six screens set 5 cm apart, to minimize disturbances at the nozzle exit. The ratio of areas between the adapter and the nozzle exit was about 40. The dimensions of the rectangular exit of the nozzle

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used was 50 mm long (L) by 3 mm wide (W). The nozzle exit was preceded by a 40 mm long smooth rectangular channel (50×3 mm). The nozzle used in the investigation was a single central lobe of a multilobed nozzle employed in a related investigation. A flat plexiglass square ($20 \times 20 \times 1.25$ cm) plate was used to provide a large rigid surface for the impinging jet. The plate and its supporting mechanism was designed to minimize the structural vibrations during the jet operation. The experiment was conducted in an ordinary laboratory room and all of the acoustic measurements are confined to the near sound field.

A self-synchronizing schlieren system employing a phase-locked technique was used for flow visualization. The optics employed was a conventional schlieren setup, which was a single-pass design with the optical axis folded twice by using two spherical mirrors (diameters of 25 and 32 cm, focal lengths of 306 and 200 cm, respectively). The light source employed was a stroboscopic flash unit having flash durations adjustable at 1.3-7.0 μs at five discrete settings. The flash unit could be triggered by an external synchronizing signal to produce phase-locked images or by internal pulses with a frequency selected by the operator to act as a continuous source. For more details of this system, refer to Hsia.[12]

The schlieren image of the flowfield was displayed on a ground glass screen for visual observation or on a film to obtain a photographic record. Schlieren photographs were taken using Polaroid type 57 instant film (ASA 3000).

The surface pressure fluctuations were measured by a 1.1 cm diameter Kistler model 606L pressure transducer, which has a flat response out to about 100 kHz. The near-sound-field measurements were made using a standard B&K 0.32 cm ($\frac{1}{8}$ in.) diameter condenser microphone, which also has a flat response out to about 100 kHz. The signal from each of the sensors was passed through a B&K type 2113 amplifier. The signal from the amplifier was displayed on an oscilloscope and then sent to a Nicolet type 660B narrow-band spectrum analyzer for spectral analysis.

A Cartesian coordinate system (x, y, z), defined in Fig. 1, was employed with its origin located on the centerline of the jet at the nozzle exit. The controlling parameter for the jet was the stagnation pressure p_0, which varied at 30-85 psia and was maintained within an accuracy of ± 0.2 psia. The separation distance between the plate and the nozzle exit h was varied discretely at 3-9 cm. The Kistler probe is mounted flush with the surface in the central x, y plane, 1.6 cm away from the centerline of the jet (see Fig. 4c below). The near-field microphone is placed normal to the jet axis and 70 mm away from the centerline. Experiments were conducted for a number of combinations of R and h; however, only a limited selection of data is presented here. The width W of the nozzle is used as a length scale for normalization.

Results and Discussion

Flow Visualization

Typical schlieren pictures of the flow at a fixed plate location $h/W = 21$ and for four different pressure ratios are shown in Fig. 2. The knife edge was oriented parallel to the jet axis in these photographs. The schlieren system was purposely adjusted to enhance the view of the wave structure in the outer region, rather than to show the interior details of the jet flow. Consequently, features such as shock cell structure are not seen clearly in these photographs.

For pressure ratios $R > 1.9$, the flow beyond the nozzle exit is supersonic and results in the formation of a series of shock cells, as shown in Fig. 2. The observations for the four cases shown in the figure are the appearance of a very strong organized cylindrical wave pattern, a beam of acoustic waves, and an organized vortical structure. The organized cylindrical wave pattern originates alternately from the two sides of the jet (cf, Figs. 2a and 2c). The center of the arcs formed by the sound waves on each side can be located and identified as the source for each wave system. The source is located approximately at the end of the third shock cell. The picture suggests that a principal wavelength exists and that the wavelength is the same for all directions of propagation of the wave. This wave pattern is quite similar to that observed for a free underexpanded rectangular jet, which generally is identified with screech tone generation.[13,14] The mechanism for its generation is discussed by Powell[15] and Krothapalli et al.[14]

A second wave system, a beam of acoustic waves, is seen emanating from the region of the impingement. Examples of such sound emission or radiation are shown in Figs. 2c and 2d. The acoustic beam appears to be very directed. The waves are emanating at an angle of about 135 deg to the direction of the jet stream. This wave system has a much shorter wavelength, which corresponds to a frequency much too high as compared to the screech tone. Assuming that the propagation velocity normal to the wave fronts is equal to the ambient speed of sound, an estimate of the frequency can be made—it is found to be about 70 kHz. Similar wave systems were also observed by Karamcheti[16] in his investigation of sound radiation from surface cut-outs in high-speed flows. However, the present wave system is considerably weaker than in that study. From dimensional considerations, it seems possible that this wave system may be generated by the turbulent eddies in the

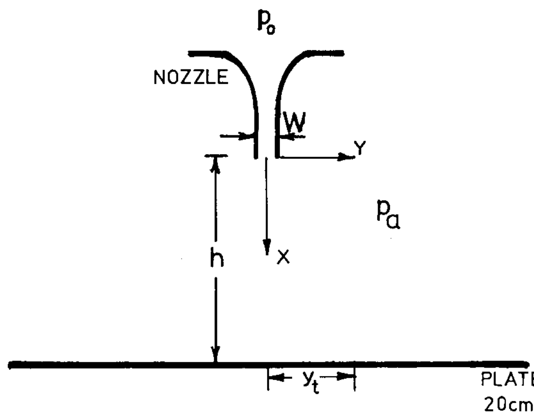
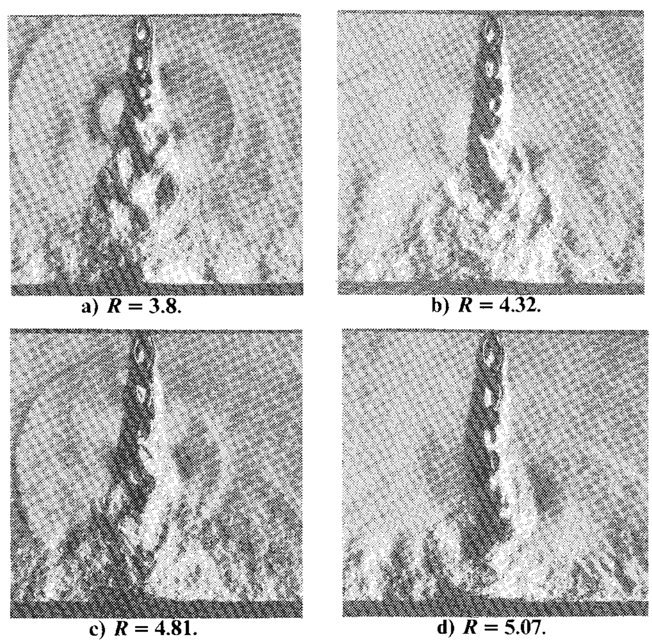


Fig. 1 Schematic of the configuration. $R = p_0/P_a = 2 \sim 6$; $h/W = 10 \sim 30$; $AR = 16.7$; $W = 3$ mm.



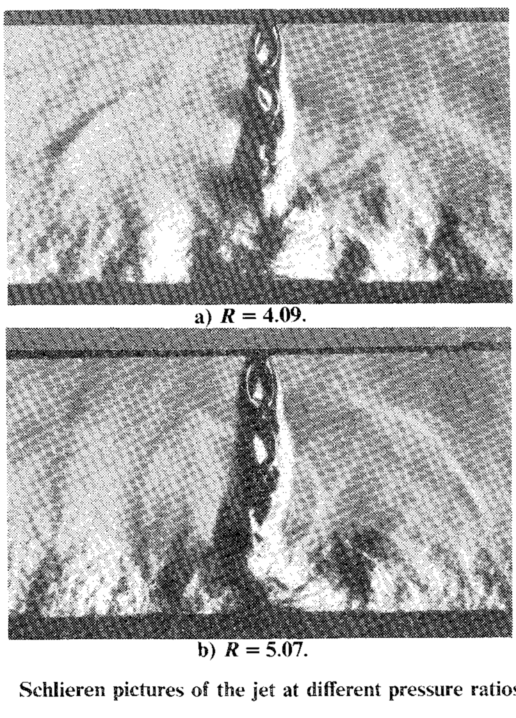
a) $R = 3.8$. b) $R = 4.32$. c) $R = 4.81$. d) $R = 5.07$.

Fig. 2 Schlieren pictures of the jet at different pressure ratios, $h/W = 21$.

impingement region. In light of the poor performance of the standard microphones in this range of frequencies and the fact that the tone is not in audible range, the study of the paper has been restricted to the frequency range below 20 kHz. On reviewing all of the pictures taken in this study, an organized vortical structure appears to be identifiable in the shear layers on either side of the jet, which grows in intensity as the jet approaches the plate. At a pressure ratio of 5.07 (Fig. 2d), a large-amplitude lateral oscillation of the jet was observed. It will be shown later that this impingement oscillation corresponds to strong peaks in the spectra of the near-field microphone and the surface pressure transducer signals at both the impinging tone frequency itself and its harmonics.

To study the dependence of the flowfield on the parameter h, schlieren pictures were taken at several combinations of R and h/W. Two typical photographs of the flow taken at $h/W = 14$ for two different pressure ratios are shown in Fig. 3. The interesting observation here is the appearance of large-scale vortical motions in the wall jet region of the flow. This feature is clearly seen in Fig. 4 to be discussed below.

For the range of h studied and at a pressure ratio of 5.07, a strong peak in the spectrum of the near-field microphone signal was found. This is identified with the frequency corresponding to the jet resonance. The typical period of the signal corresponds to about 150 μs. In order to identify the nature of the flow evolution, schlieren pictures were taken within a cycle of operation of the resonance or impinging tone period. Figure 4 shows such a sequence of pictures taken in the plane containing the small dimension of the nozzle. The time interval between two successive pictures is 25 μs. The knife edge is oriented parallel to the jet axis. The signal from the surface mounted pressure transducer, positioned as shown in Figs. 4c and 4d, was used to trigger the light source. It seems evident from these pictures that the physical phenomenon is indicated by the transverse undulation of the jet. As additional evidence, it may be verified that the characteristic wave length of the phenomenon corresponds roughly to 5 cm, which scales with the distance h (6.3 cm) of the plate with respect to the nozzle exit rather than the width of the jet or the thickness of the boundary layer or the wall jet. The density variation induced by this phenomenon may not be strong enough to be visible in the schlieren photograph, in particular, on account of the small size of the photograph itself.



a) $R = 4.09$.

b) $R = 5.07$.

Fig. 3 Schlieren pictures of the jet at different pressure ratios, $h/W = 14$.

Frequency Measurements

Typical frequency spectra of the near-field microphone signal for a jet operating at conditions close to those for Fig. 2 are shown in Fig. 5. The abscissa is frequency f and the ordinate is the amplitude in decibels. The spectra show not only the dominant discrete frequencies and its harmonics, but also other frequencies. From all of the spectra studied, it became apparent that two principal discrete frequencies exist. The first one corresponds to the screech tone and is denoted in the figure by the letter S. Associated with the screech tone is an organized cylindrical wave pattern that originates alternatively from two sides of the jet as shown in Fig. 2. The second tone, having a lower frequency as compared to the screech tone, is called an impinging tone and denoted in the figure by the letter I. No such distinct peaks, corresponding to the impinging tone, are found in the spectra of a free jet (see Fig. 6 for $R = 4.81$). Instead, a broadband subharmonic of the screech tone is observed in this range. When the amplitude of the impinging tone is dominant in the spectrum, the corresponding schlieren picture of the flow shows a transverse undulation of the jet column. For instance, a jet operating at a pressure ratio of 5.07 (see Fig. 2) shows such phenomenon. Figure 7 presents a corresponding sequence of the spectra of the surface pressure signal. The jet operating conditions in this figure correspond to those for Fig. 2. The position of the pressure transducer to generate the signal is shown in Fig. 4c. On comparing the corresponding spectra from Figs. 5 and 7, it is found that the frequencies of the dominant peaks coincide, suggesting further the presence of both screech and impinging tones.

The main dimensionless parameters of importance are the Strouhal numbers, which are defined here as

$$St_h = f_I h / U_e; \quad St_W = f_S W / U_e$$

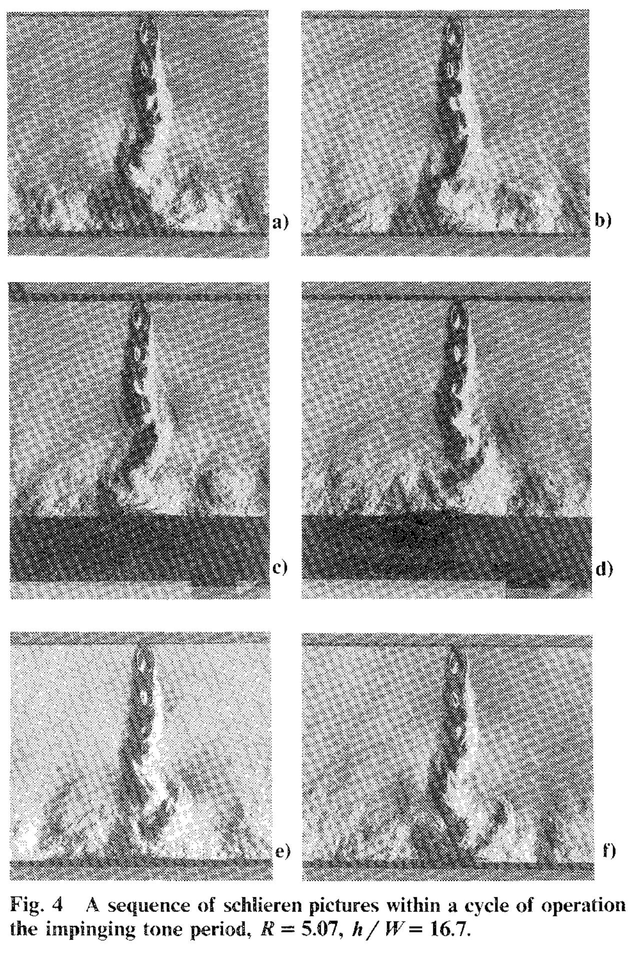


Fig. 4 A sequence of schlieren pictures within a cycle of operation of the impinging tone period, $R = 5.07$, $h/W = 16.7$.

where f_I and f_S are impinging and screech tone frequencies, respectively, h the separation distance between the plate and the nozzle exit, W the nozzle width, and U_e the calculated mean velocity at the nozzle exit, assuming ideally expanded isentropic flow. Figure 8 shows the variation of the Strouhal number corresponding to the screech tone with pressure ratio for both free and impinging ($h/W = 21$, 14) jets. It is observed that the value of St_W decreased monotonically with increasing pressure ratio. The data of the impinging jet agrees well with that of a free jet. On examining all the data present, it was found that the frequency of the screech tone was not affected significantly by the presence of the plate.

In addition to screech tones, the near-field spectrum shows several other discrete frequencies. The Strouhal numbers St_h corresponding to these are plotted against the pressure ratio in Fig. 9. Usually, only frequencies associated with the maximum amplitude are presented in plots such as Fig. 9, and the dark symbols in the figure represent the Strouhal numbers of these frequencies. Unlike the continuous variation of the screech tone frequency with pressure ratio, the variation of the amplitude-dominant frequency (or impinging tone) with pressure ratio show staging behavior. The other frequencies present during the stage operation are weak in amplitude as compared to the stage frequencies and they belong to one of the other stages that will arise at different plate heights h.

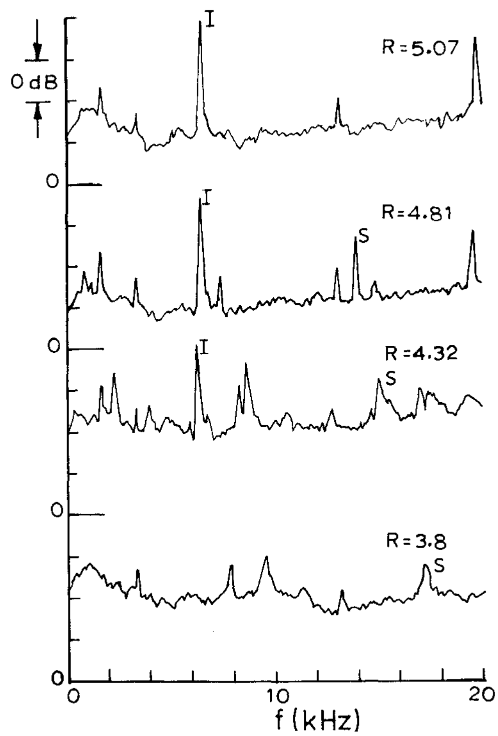


Fig. 5 Spectra of the near-field microphone signal, $h/W = 21$.

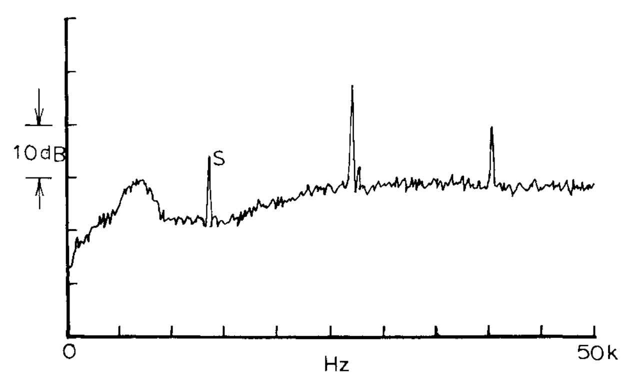


Fig. 6 Spectrum of the near-field microphone signal for a free jet, $R = 4.81$.

Figure 10 shows the variation of the Strouhal number with exit velocity for different plate heights. As before, the dark symbols represent amplitude-dominant frequencies. Within the limits of error for the experiment, it is observed that the data lie on well-defined bands. For clarity, solid lines are drawn through the data points. On examining all of the data on self-sustained oscillations, it was found that the discrete frequencies generated by flow past a cavity fall into bands, similar to those in Fig. 10, in the Strouhal number vs Mach number plot (for example, see Tam and Block[4]). To explain the mechanism of the discrete sound generation for flow over rectangular cavities, Tam and Block developed a mathematical model based on the coupling between shear layer instabilities and acoustic feedback. Good agreement was found between discrete tone frequencies predicted by the model and experimental measurements over a wide range of Mach numbers. Although the acoustic wave generation process described by Tam and Block may not be valid here, the nature of the feedback mechanism seems applicable to the present problem. On the basis of this and other observations, the following feedback mechanism is suggested. As evidenced by flow visualization, the shear layer contains large-scale vortical structures. These structures, upon interacting with the plate (or impinging surface), produce intense acoustic disturbances. These acoustic disturbances propagate upstream through the ambient medium. When reaching the nozzle exit they excite the flow instability waves of the shear layer, which grow as they propagate downstream. This instability usually generates large-scale vortical structure in the shear layer. In this way, the acoustic disturbances and the shear layer instability form a feedback loop. Although the above explanation for the feedback mechanism seems reasonable, several questions remain to be answered. For example, how are the acoustic disturbances generated by the interaction of the shear layers with the plate? When once they are generated, how do they excite the instability waves in the shear layer near the nozzle exit?

While studying the dependence of pressure ratio on discrete tones, it was found that at $R = 5.08$, the microphone and surface pressure signals have a form of the sine wave. The spectra then are dominated by peaks at the fundamental and its harmonics (see Figs. 5 and 7). For reasons to be explained

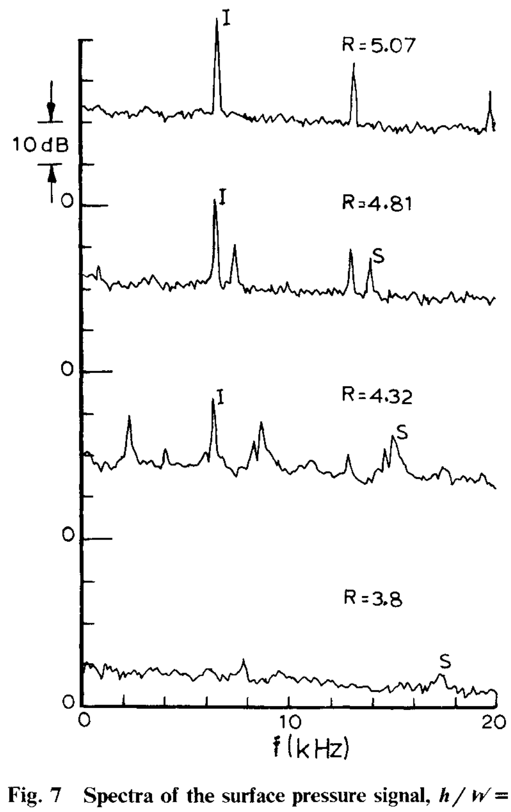


Fig. 7 Spectra of the surface pressure signal, $h/W = 21$.

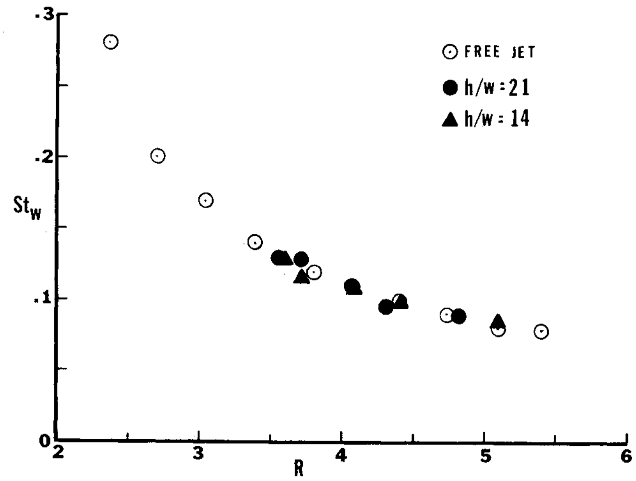


Fig. 8 Variation of the screech tone frequency with pressure ratio.

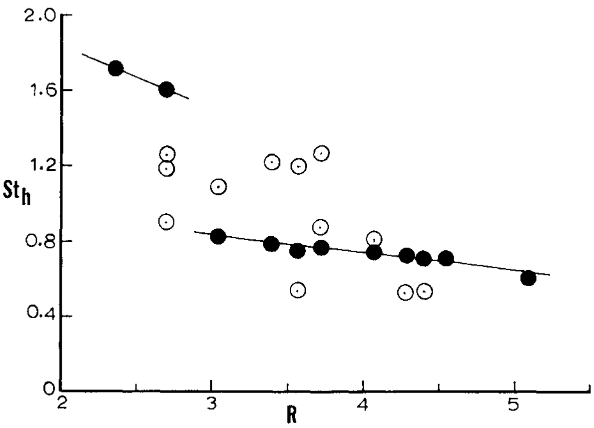


Fig. 9 Variation of the impinging tone frequency with pressure ratio, $h/W = 14$.

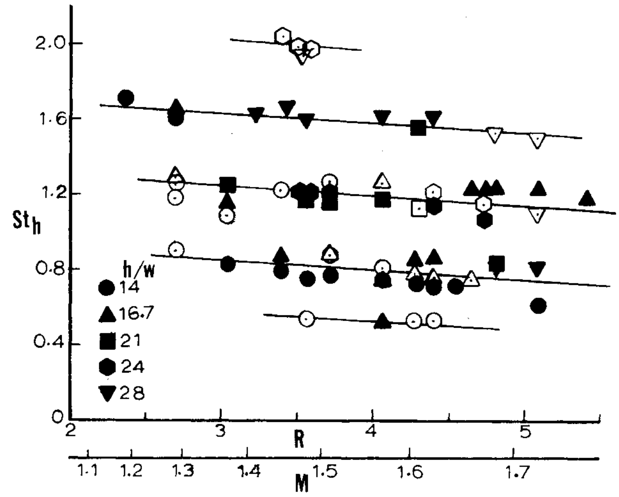


Fig. 10 Variation of the impinging tone frequency with pressure ratio for different plate heights.

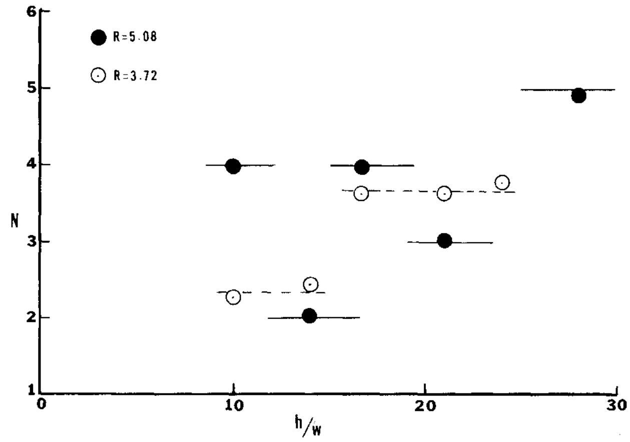


Fig. 11 Variation of the impinging tone frequency with plate height.

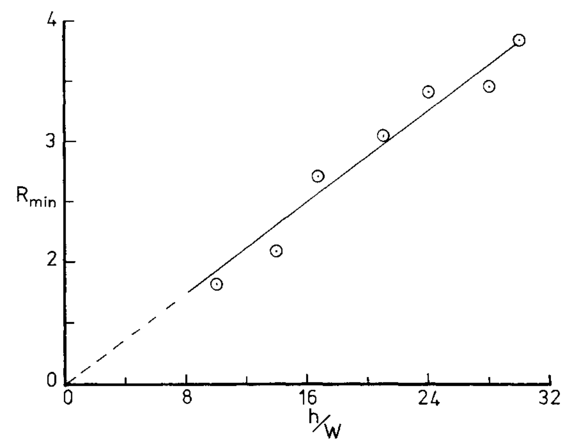


Fig. 12 Variation of the minimum pressure ratio with plate height.

below, the fundamental frequency is called a resonance frequency. Concomitant with this is a strong transverse undulation of the jet column (see Fig. 4).

It has been suggested by Ho and Nossier[1] that resonance requires an integer number of waves N to exist in the feedback loop. By their definition

$$N = fh/U_c + fh/a_0$$

where U_c and a_0 are the mean velocities of the downstream traveling large-scale structures and upstream traveling acoustic disturbances respectively ($a_0 = 340$ m/s ambient speed of sound). From Fig. 4, it was found that the large-scale vortices are traveling at a mean velocity of 0.52 U_e, where U_e is the exit mean velocity of the jet. The measured frequencies are plotted according to the above equation in Fig. 11. The solid lines in the figure represent the integer values of N. It is observed that, for $R = 5.08$, each of the frequencies coincide with one of the integer values as shown in the figure. While for $R = 3.72$, such coincidence was not observed. It was observed by Ho and Nossier[1] that, in each of the frequency stages, the number of waves N remain constant and increased by one for each succeeding stage. However, in the present case, such orderly variation is not observed. In accordance with the feedback loop suggested by Ho and Nossier, it appears that the jet at $R = 5.08$ is operating at the resonance condition.

For a given plate height, the impinging tone appears in the spectrum only beyond a certain value of the pressure ratio. This minimum pressure ratio required for a tone to be first generated is denoted as R_{min}. The variation of R_{min} with plate height h is shown in Fig. 12. The distance h is normalized with respect to the nozzle width W. As shown in the figure, R_{min} increases linearly with h. Similar observation was also made by Krothapalli et al.[17] in their investigation of high-speed edge tones.

Conclusions

The objective of this work was to study the discrete tones generated by a choked underexpanded jet of air issuing from a rectangular nozzle of moderate aspect ratio and impinging on a flat plate placed normal to the jet axis. By means of a schlieren system, two different wave systems were observed to emanate from different regions of the flow. The first one, typical of underexpanded jets, is a strong organized cylindrical wave pattern that originates alternately from each side of the jet; it describes the "screech" tone. The origin of this wave system is located approximately at the end of the third shock cell. The second wave system takes the form of a beam that emanates from the impingement region of the flow. This wave system has a much shorter wavelength as compared to the cylindrical wave pattern. At the pressure ratio for which the impinging tone is strongest, a large-amplitude transverse undulation of the jet is observed. An organized vortical structure appears to be identifiable in the shear layers on either side of the jet.

The near-field sound spectra verify that two principal discrete frequencies corresponding to the screech tone and the impinging tone do in fact exist. At the pressure ratio for which the impinging tone is strongest, the variation of the frequency with plate height shows a staging behavior, similar to that observed in edge tones and described by Karamcheti et al.[18] But at other pressure ratios no staging behavior is apparent.

Acknowledgments

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