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Abstract

An experimental study is conducted investigating the characteristics of ‘trapped wave’ (TW) resonance tones occurring with nozzles having a center plug. The pressure fluctuation spectral peaks due to these ‘guided’ or ‘trapped’ waves when the nozzle contains a center plug occur at nondimensional frequencies that are an order of magnitude larger than those noted with simple round nozzles. It appears that the exit gap width of the plug nozzle is the characteristic length-scale that dictates the corresponding TW frequencies. The results of this study further our understanding of this phenomenon as it relates to other complex nozzle geometries.

Introduction

‘Trapped waves’, now commonly referred to as ‘guided jet waves’, are a recent discovery (Refs. 1 and 2). The phenomenon involves upstream and downstream propagating waves within the potential core of the jet. These waves can interact and resonate at frequencies and wavenumbers determined by the flow conditions. A clear manifestation occurs in the near field pressure fluctuations. The p' -spectrum, measured near the nozzle and just outside the jet, is marked by a series of peaks. The characteristics of these trapped wave (TW) spectral peaks, for a variety of nozzles, have been studied in Reference 3. Correlation equations for the frequencies of the spectral peaks as a function of jet Mach number were provided that well represented data from round nozzles of various diameters regardless of exit boundary layer state and thickness. It should be noted that the TW spectral peaks disappear in the downstream and sideline directions in the far acoustic field where jet noise measurements are traditionally done. This is why the phenomenon went unnoticed in decades of noise experiments with jets.

There are several ongoing studies on the TW phenomenon. An interested reader may look up (Refs. 4 to 8) for past analytical aspects as well as current experimental and numerical research results. In connection with experiments with plug nozzles reported in Reference 9, a similar TW-like series of spectral peaks were noticed in the vicinity of the nozzle. However, the nondimensional frequencies (Strouhal numbers) of those spectral peaks were an order of magnitude larger than that observed with single (no-plug) nozzles. In the present study, we explore the detailed characteristics of the spectral behavior with plug nozzles. The objective is to gather experimental data related to the TW phenomenon with various plug nozzles and document the observations. Attempts are made to understand their characteristics relative to those of simple round nozzles.

Experimental Arrangement and Procedure

The experiments are conducted in an open jet facility at NASA Glenn Research Center (GRC). A photo of the facility is shown in Figure 1(a). The same experimental setup is used to collect noise data, schlieren images as well as thrust data. In this report mainly unsteady pressure data from a moveable microphone mounted on a traversing mechanism, marked in Figure 1(a), are discussed.

The flow from the main plenum chamber is routed through four U-shaped tubes to a ‘floating plenum’, mounted on linear bearings, allowing axial thrust measurements (Figure 1(a)). The flow from the floating plenum passes through two 30-mesh screens and then exhausts through the nozzle. The internal diameter of the floating plenum is 5 in. while the equivalent diameter of the exit of the plug nozzle is about 1.28 in.; thus, the flow goes through a contraction ratio of over 15. This together with the two screens yields a uniform flow at the exit. The plug nozzle is attached to the end of the floating plenum. Further details of the experimental setup can be found in past publications, e.g., (Refs. 8 and 9).

A cross-sectional view of the plug nozzle assembly, with relevant dimensions, is shown in Figure 1(b). In the present experiment, the nozzle remains fixed. It is convergent with 2 in. exit diameter (D) having a lip thickness of 0.050 in. The center plug is held with X-shaped struts. The strut leading edges have serrations to suppress possible resonances induced by vortex shedding. The upstream cylindrical part of the plug has a diameter of 0.75 in. A threaded rod fixed to the cylindrical centerbody is used to attach the plug end pieces, providing various plug geometries. Also, spacers placed at the junction between the end piece and the cylindrical part allow for variation of the axial location (Δx) of the plug crown relative to the nozzle lip (Figure 1(b)). Figure 1(c) shows a close-up view of the nozzle with the plug removed. This configuration is denoted ‘D2NP’ ($D = 2$ in. nozzle, no plug). Even though it has the internal struts etc., the TW spectra exhibit the same characteristics as with a clean round nozzle, to be discussed further shortly. Data from D2NP will be compared with data for the plug cases. The nozzle with a plug is shown in Figure 1(d). The microphone on the traversing mechanism placed at the reference location can be seen in both Figure 1(c) and (d).

Three conical plugs with apex half angles of 10° , 16° , and 22° (denoted as ‘P10’, ‘P16’, and ‘P22’) are shown in Figure 1(e). Also shown is a truncated plug that has otherwise the same geometry as the P10 case. The length of the conic section is truncated by 35 percent, leaving a base on the downstream end with a diameter of 0.582 in. It is denoted as ‘P10T’. All plugs have a nominal crown diameter of 1.54 in. P10T is truncated but otherwise the same as P10.

Note that the annular gap width between the plug and the nozzle depends on the axial location of the crown (Figure 1(b)). The average gap width for the majority of the data in this report is about 0.23 in., yielding an equivalent diameter of about 1.28 in. All plugs, after installation, also had slight nonconcentricity relative to the nozzle exit; the gap width variation in the azimuthal direction was less than 5 percent. Such variations are thought to have minimal effect on the TW results presented in the following.

The primary diagnostic used is data from the 1/8-in. Brüel & Kjær (B&K 4138) microphone mounted on a traversing mechanism (Figure 1(a)). The data acquisition is done using National Instruments A/D card and LabVIEW™ software. Sound pressure level spectral analysis is done typically over 0 to 90 kHz with a bandwidth of 45 Hz, using a data rate of 180 kHz and a 90 kHz low-pass filter. Jet Mach number M_J is used as independent variable. It is given by,

$$M_J = \sqrt{\frac{2}{\gamma - 1} \left(\left(\frac{p_0}{p_a} \right)^{\frac{(\gamma - 1)}{\gamma}} - 1 \right)} \quad (1)$$

where p_0 and p_a are plenum and ambient pressures, respectively, and γ is the ratio of specific heats for air. All data are for unheated flow, that is, the total temperature is the same everywhere as in the ambient. Also, all data are for ‘static’ conditions without the presence of an external flow.

Schlieren images are shown in Figure 2 and Figure 3. Even though the unsteady pressure field due to the trapped wave resonances are not deciphered these images are included here to illustrate the basic characteristics of the flows under consideration. Figure 2 shows time-averaged images for the D2NP and P16 cases at four values of M_J . These time-averaged pictures capture the shock structures that can be seen at the supersonic conditions. Note that as the flow negotiates the plug crown, shocks occur even at subsonic jet Mach numbers (P16 case on right column). Figure 3 shows instantaneous schlieren images for the four plug cases at $M_J = 0.95$. These images will be referenced in the discussions of the noise results in the next section.

Results

Flow, noise as well as thrust of various plug nozzles were studied in Reference 9. In connection with that study a cursory observation was made on the pressure fluctuations in the near-nozzle regions that exhibited TW-like spectral peaks. Figure 4 shows a set of data obtained during that study. The data were obtained with a 1/4-in. B&K microphone, placed at the nozzle exit plane 0.5 in. away from the lip, over a bandwidth of 0 to 40 kHz. The blue curve in Figure 4(a) is for the nozzle with plug removed (D2NP). Even though the struts etc. were inside, the flow behaved the same as with a clean nozzle and the spectra showed the series of peaks due to the TW phenomenon. The Strouhal number of the fundamental (marked '0') was the same as observed with clean nozzles. The higher frequency peaks (marked '1', '2', '3') bore the same fractional ($5/3$, $7/3$, $9/3$) harmonic relationship relative to the fundamental as reported in Reference 3. The red curve in Figure 4(a) was obtained with the P16 plug installed. It can be seen that the spectral peaks get altered although some of the lower frequency peaks remain. Notably, certain peaks appear at high frequencies (around 20 and 35 kHz). The data were obtained with the protection grid (PG) installed on the 1/4-in. microphone. A PG has been known to generate high frequency noise. The data in Figure 4(b) exhibit slight increase in energy at high frequencies, however, the spectral peaks remain unchanged otherwise. This rules out the possibility that the observed high frequency peaks were PG-generated. The frequency contents of the spectra are essentially the same with and without the PG.

The near-nozzle pressure fluctuations with the plug nozzle are investigated in the current experiment. To expand the frequency range in the measurements, a 1/8-in. microphone is used, and the data are obtained over the range of 0 to 90 kHz. The microphone location in the near-field was also changed (relative to that in Figure 4) based on trials in order to capture the TW spectral peaks prominently. Repeat results corresponding to the data of Figure 4(a) are shown in Figure 5(a). Some differences are noted (the facility went through changes with the installation of the thrust apparatus since the experiments of Reference 9) but basically the same behavior is noted. Importantly, the high-frequency peaks are captured clearly over a larger bandwidth. The series of high frequency peaks occur with a fundamental (f_0) at about 20 kHz. It will be shown later that the higher harmonics, e.g., f_1 marked in Figure 5(a) also bear a similar fractional relationship as with the lower frequency TW peaks with the clean nozzle. Figure 5(b) shows another set of data at $M_J = 1.00$ exhibiting a similar trend. We note here that the pressure fluctuations due to the TW resonances are not strong enough to be captured by schlieren techniques (Figure 2 and Figure 3). This is true even in instantaneous schlieren images. They are, however, strong enough to be clearly captured using the microphone.

Figure 6 shows that the high-frequency TW peaks disappear at large radial locations (r) for a given axial location (x), and at streamwise distances away from the nozzle exit at a given r . These data are for the P16 plug at $M_J = 0.95$. A similar trend was shown for the lower frequency TW peaks with simple nozzles in Reference 3. Here, at $r = 1.5$ the high-frequency TW peaks disappear for $x > 0.8$ in. They also disappear for $r > 3.6$ in. when measured at $x = -0.6$ in. It should be noted that the TW peaks for simple

nozzles have been shown to persist in the upstream direction at shallow angles relative to the nozzle axis (forward arc). There, the TW peaks are detected even in the far-acoustic field at 75D away from the nozzle (Ref. 10). It is reasonable to expect that the high-frequency TW peaks with the plug nozzle will also persist in the forward arc, but this remains unconfirmed at this time.

Figure 7 shows spectral data where the plug crown location is varied with respect to the nozzle exit (Δx). In Figure 7(a) for the P16 case, the TW peaks are prominent when the plug crown is located near the nozzle exit ($\Delta x = -0.03$ in.). As the plug is drawn in, the amplitudes decrease, and the peaks practically disappear when $\Delta x = -0.29$ in. Thus, with the current plug nozzle geometry it appears that the ‘throat’ location needs to be near the nozzle exit to generate the high-frequency TW peaks. Interestingly, the frequency of a given peak decreases as the plug crown is positioned further inside the nozzle. Note that because of the convergence of the nozzle, with decreasing Δx the annular throat width (h) between the plug crown and the nozzle’s inner wall increases rapidly. The data in Figure 7(a) thus provides a clue that the width h might be the length-scale governing the behavior of the high-frequency TW peaks; this is examined further in the following. Figure 7(b) shows corresponding data, with variation of Δx , for the P10 case where the trends are similar but not as pronounced as with the P16 case.

Figure 8, Figure 9, and Figure 10 show spectral data as a function of M_J , for the P22, P16 and P10 cases, respectively. The spectra are vertically offset for clarity. In each figure, the ordinate pertains to the trace at the bottom and others are shifted successively by 5 dB. Generally, the high-frequency TW peaks become visible around $M_J = 0.8$ and persist through low supersonic conditions. At yet higher values of M_J , these peaks tend to become ambiguous. The Strouhal numbers corresponding to the spectral peaks are discussed shortly. Here, data for the P10 and the P10T cases are compared in Figure 11. The high-frequency TW peaks are basically the same for the two plug cases. This observation rules out the possibility that the overall plug length impacts the frequencies of the observed peaks.

The Strouhal numbers corresponding to the fundamental and the first harmonic of the high-frequency TW peaks (marked f_0 and f_1 in Figure 5(a)) are shown in Figure 12 for the three sets of data with P10, P16, and P22 plugs. In Figure 12(a), Strouhal numbers based on the nozzle diameter (2 in.) are plotted. The plug nozzle outer diameter D is the length scale used here since that is the diameter of the ‘duct’ created by the jet shear layer in the potential core region. Also shown are the correlations for simple round nozzle data from (Refs. 3 and 8). The Strouhal numbers for the high-frequency peaks are about an order of magnitude larger than the correlations. The same data are plotted in Figure 12(b) when the Strouhal number is based on the annular gap width of the plug nozzle at the exit ($h = 0.23$ in.). The same correlations from Figure 12(a) are replotted substituting fD/U_J with fh/U_J , i.e.,

$$\frac{fh}{U_J} = \frac{\left(\frac{1}{M_J^2} - 1\right)}{13} + \frac{\left(\frac{1}{M_J} - 1\right)}{2} + \frac{(M_J - 1)}{20} + 0.35 \quad (2)$$

Somewhat surprisingly the data fall close to the correlation curves. The annular flow with the plug nozzle is different from simple jets and is bounded by the presence of a wall (the plug) on the inner side. Intuitively, the stability characteristics of the annular flow would be expected to be different. Nonetheless, the gap width seems to be the characteristic length-scale driving the high-frequency TW phenomenon with the plug nozzles. Further experimentation, possibly with a large aspect-ratio rectangular nozzle bounded by a wall on one edge, as well as analytical studies will be needed to fully explain the observed high-frequency TW behavior. The effects of plug porosity, surface finish, and crown diameter will also be investigated.

Conclusions

When a central plug is added to a round nozzle, the trapped wave spectral peaks in the near-nozzle pressure fluctuations are altered somewhat but tend to persist. However, an additional series of spectral peaks occur at an order of magnitude higher frequencies. It is as if two sets of resonant peaks occur with the plug nozzles. The high-frequency peaks behave similarly as the lower frequency TW peaks seen with the no-plug case. The peaks disappear at sufficiently larger radial locations for a given x , and at sufficient downstream distances from the nozzle exit at a given r . It appears that the exit gap width of the plug nozzle is the characteristic length-scale that dictates the high-frequency TW frequencies.

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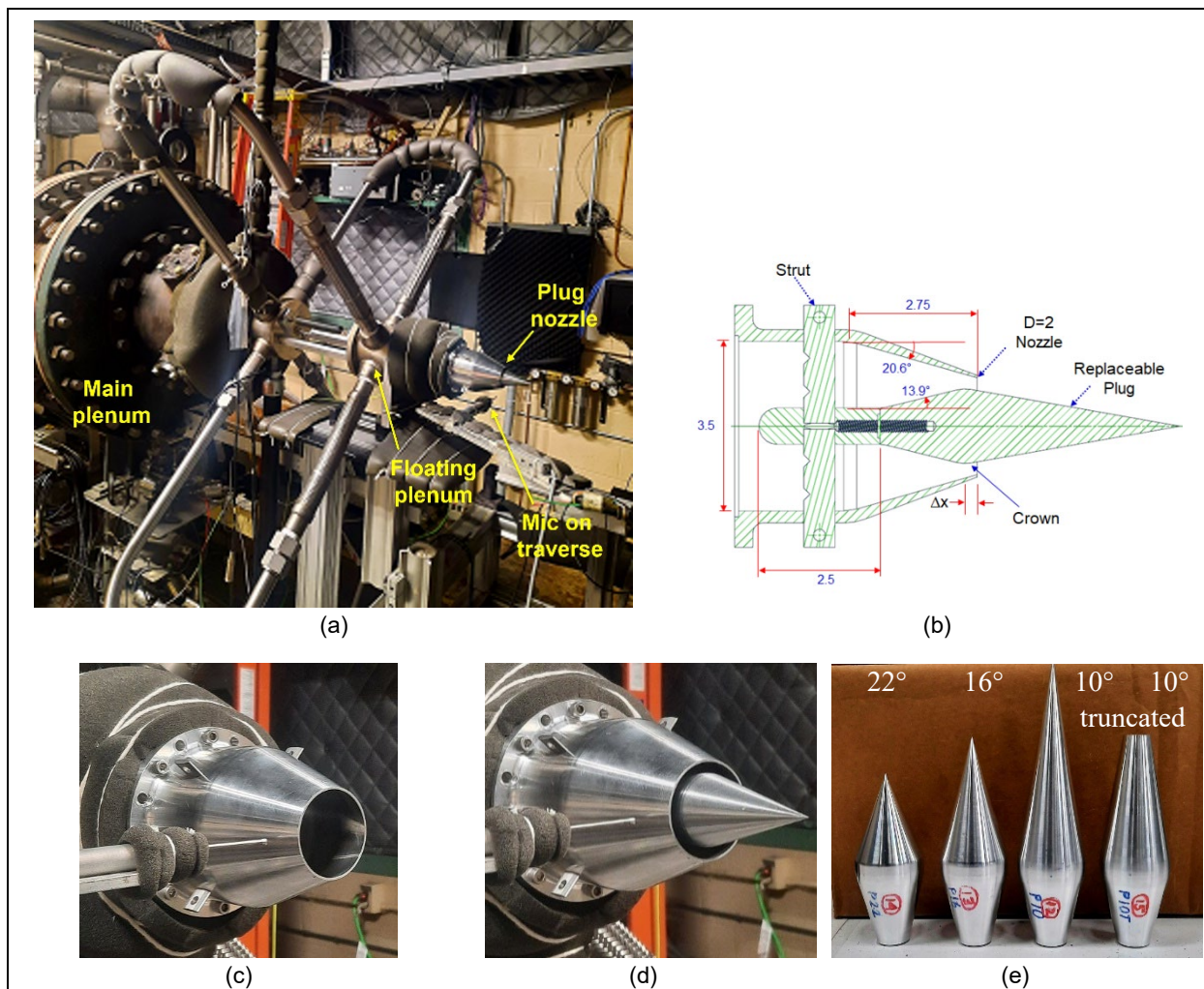


Figure 1.—Experimental setup. (a) Jet facility, (b) schematic of plug nozzle, (c) nozzle without plug, (d) nozzle with 16° plug, (e) plugs studied (P22, P16, P10, P10T).

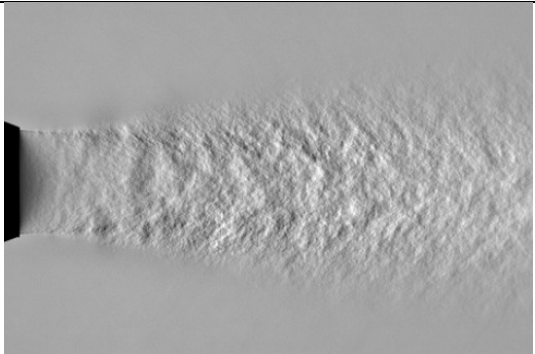
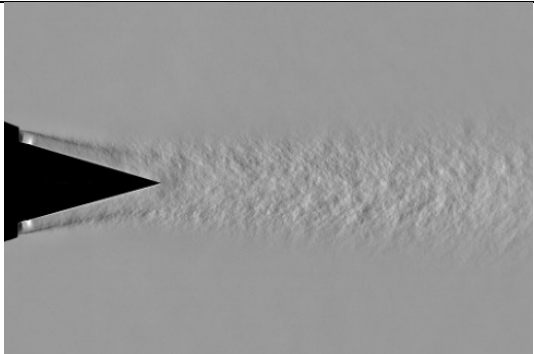
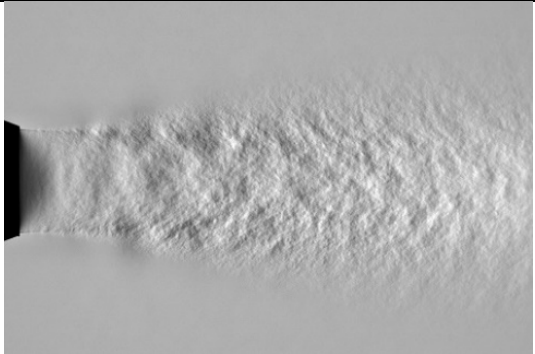
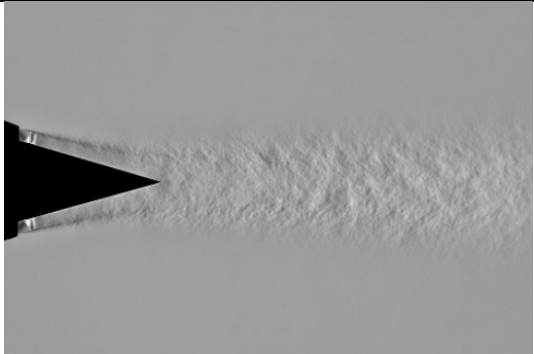
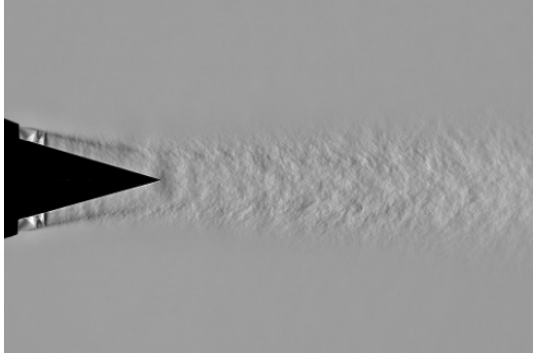
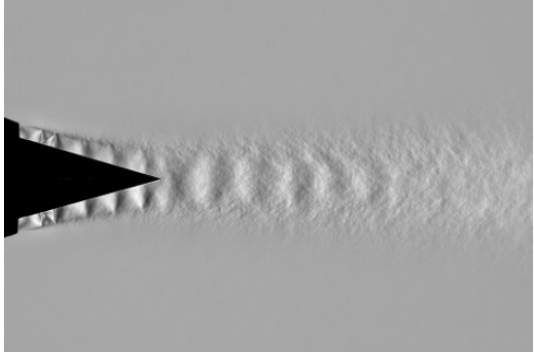
M_J	D2NP	P16
0.90		
1.00		
1.10		
1.20		

Figure 2.—Time-averaged schlieren images for the no-plug (D2NP) and 16° plug (P16, $\Delta x = -0.16$ in.) cases, at four jet Mach numbers (M_J).

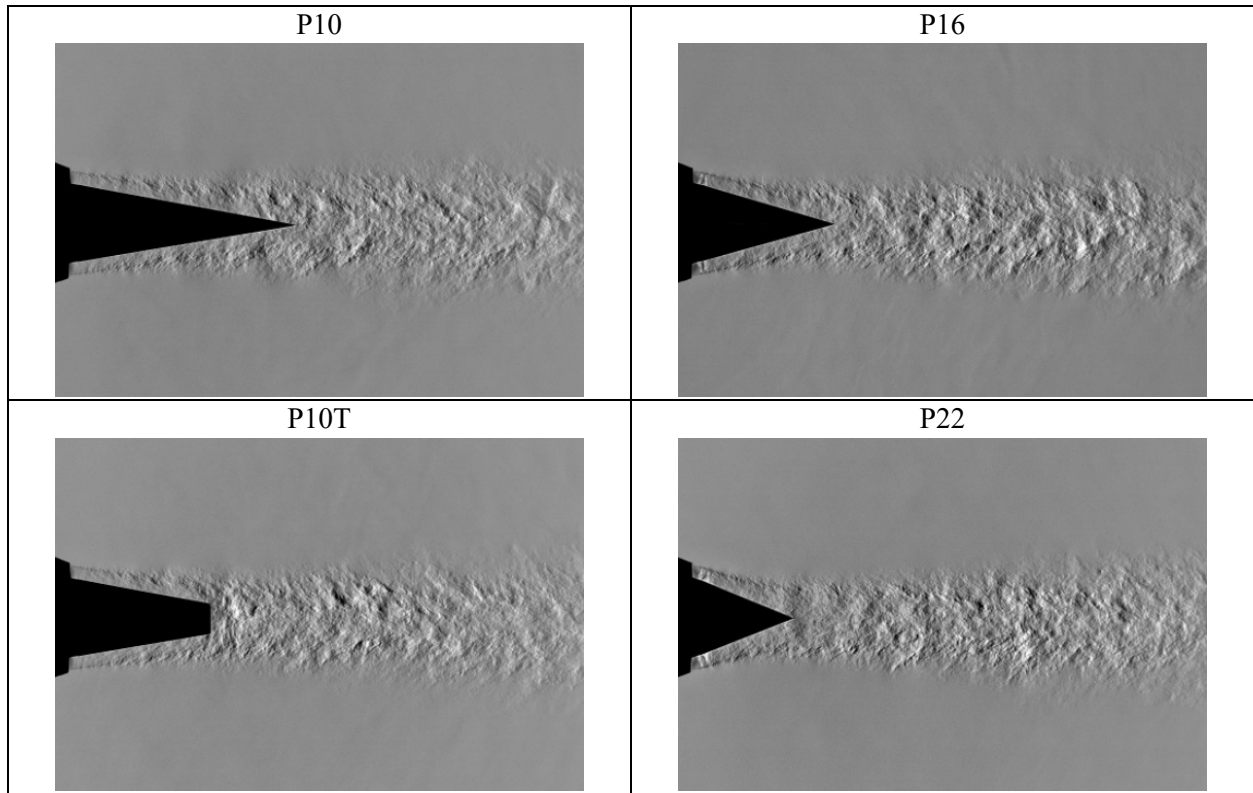


Figure 3.—Instantaneous schlieren images for the four plug cases at $M_J = 0.95$. $\Delta x = -0.13$ in. for P10 and P10T cases, and $\Delta x = -0.16$ in. for P16 and P22 cases.

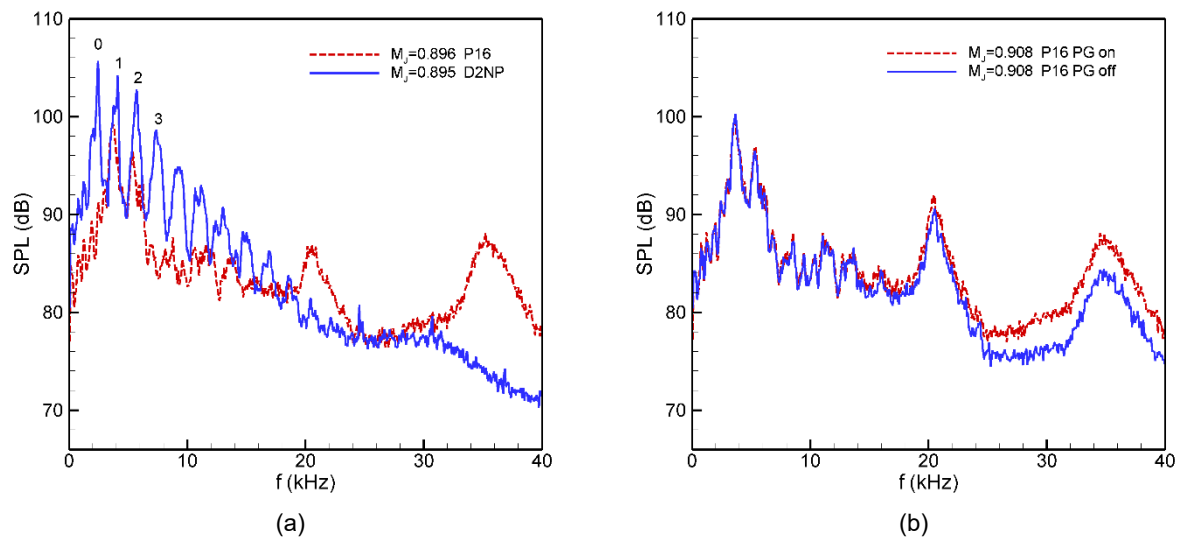


Figure 4.—Earlier observations with 1/4 in. microphone. (a) p' -spectra at $x = 0$, $r = 1.5$; blue curve: no plug (D2NP), red curve: plug P16 case with $\Delta x = -0.16$ in. (b) Plug P16 case, with (red curve) and without (blue curve) microphone protection grid.

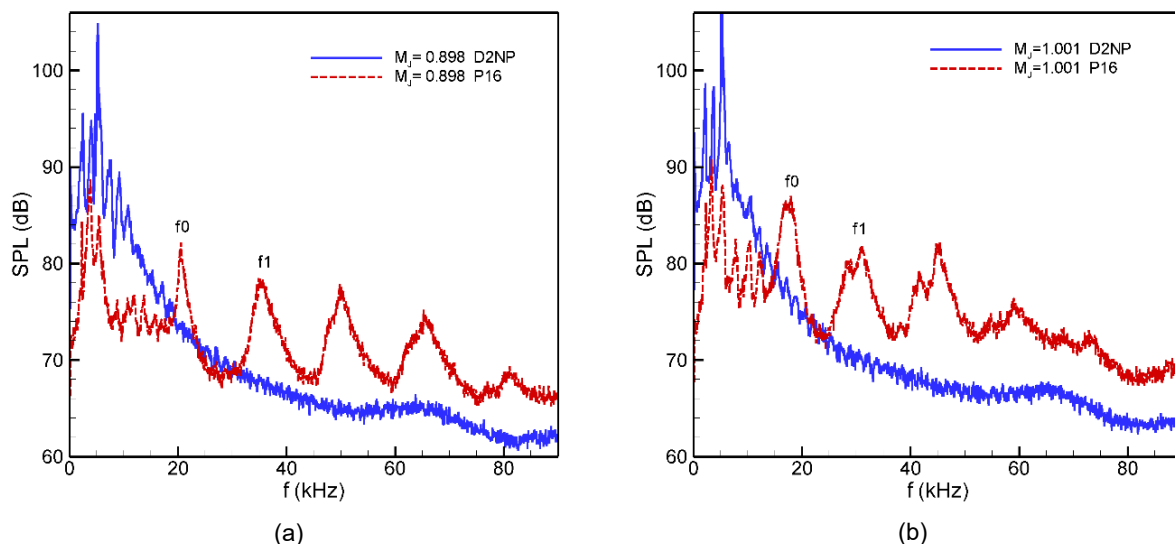


Figure 5.—D2NP versus P16 case data over 0 to 90 kHz at two jet Mach numbers; microphone at $x = -0.60$ in. and $r = 1.50$ in.; $\Delta x = -0.16$ in. for P16. (a) $M_j = 0.90$, (b) $M_j = 1.00$.

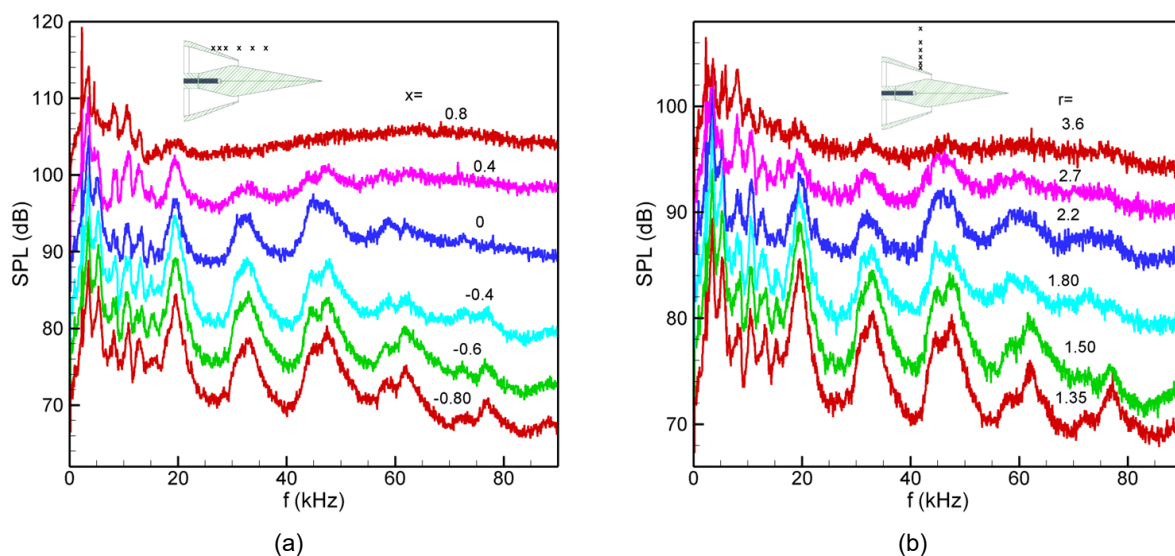


Figure 6.—P16 ($\Delta x = -0.16$ in.) case data at various locations near nozzle; $M_j = 0.95$. (a) Varying microphone x -locations with $r = 1.5$, (b) varying microphone r -locations with $x = -0.60$ in.

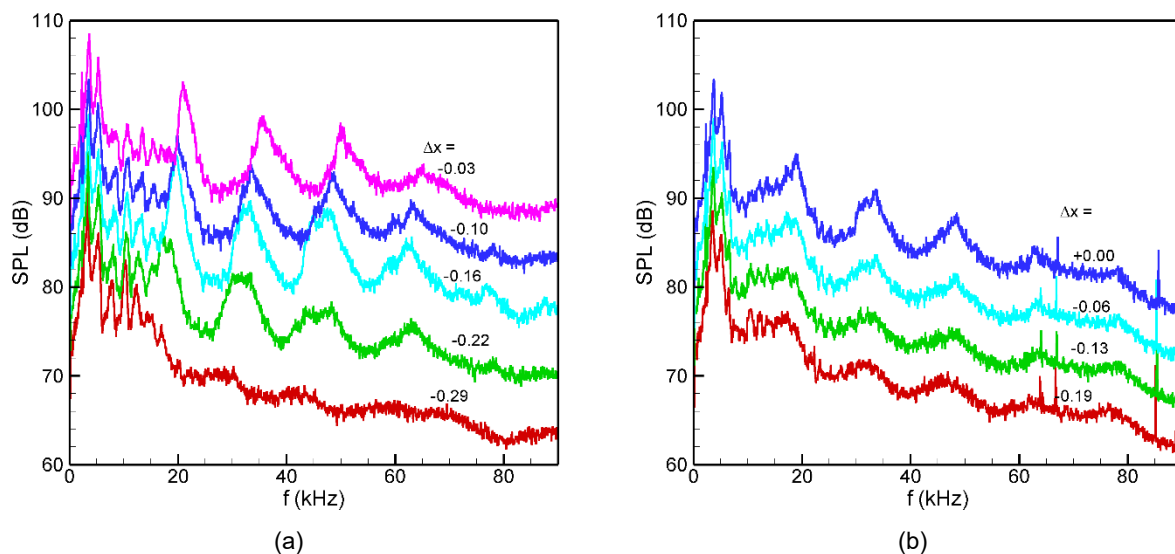


Figure 7.—Data with variation of plug crown location (Δx); $M_J = 0.95$. (a) P16 case. (b) P10 case.

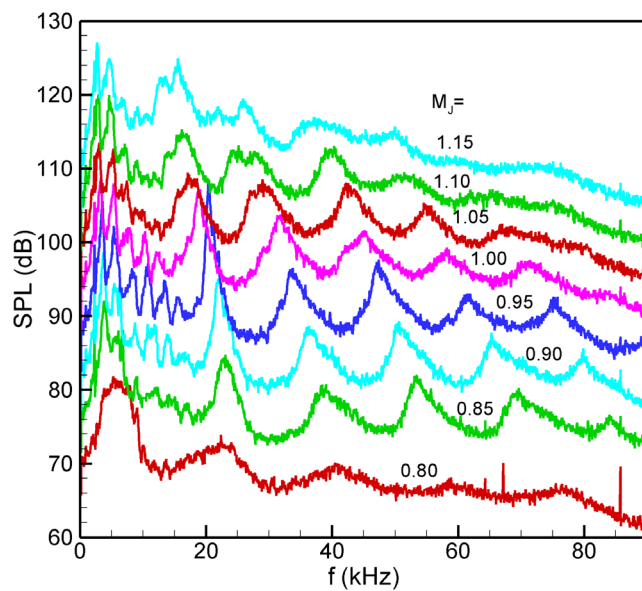


Figure 8.—Data for P22 case with varying M_J ; crown location $\Delta x = -0.16$.

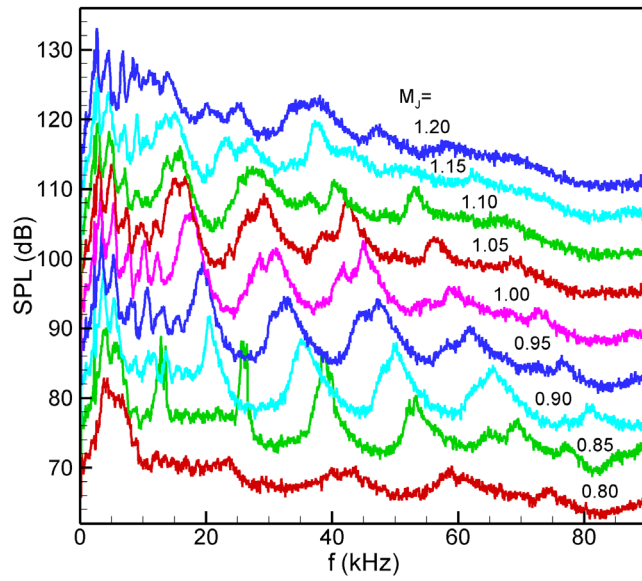


Figure 9.—Data for P16 case with varying M_j ; crown location $\Delta x = -0.16$.

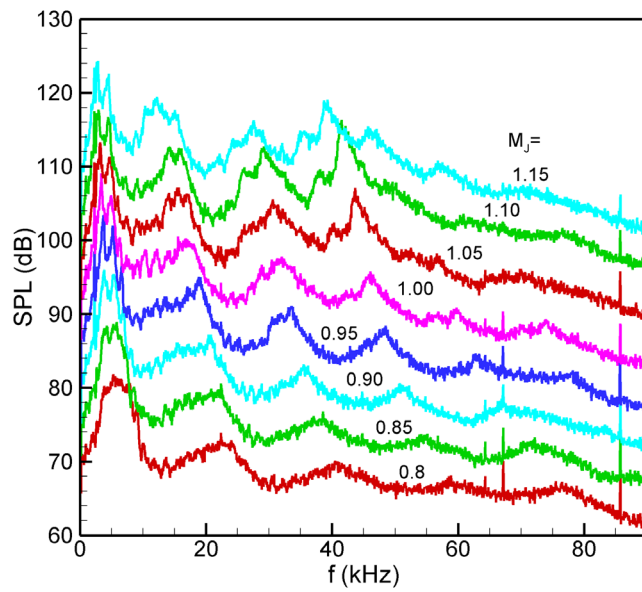


Figure 10.—Data for P10 case with varying M_j ; crown location $\Delta x = 0$.

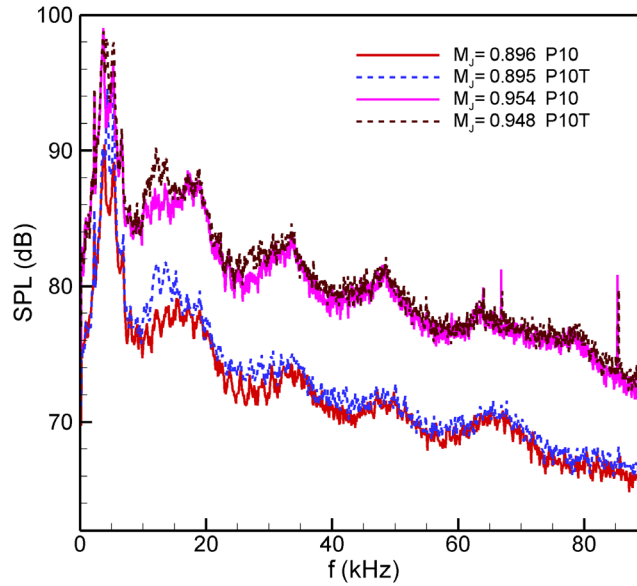


Figure 11.—Comparison of data for P10 and P10T at two values of M_J . At each M_J , the data are plotted with same ordinate scale, but the two pairs are vertically offset by 10 dB. Crown locations are $\Delta x = -0.13$ in. and $\Delta x = 0$ for the $M_J = 0.9$ and 0.95 cases, respectively.

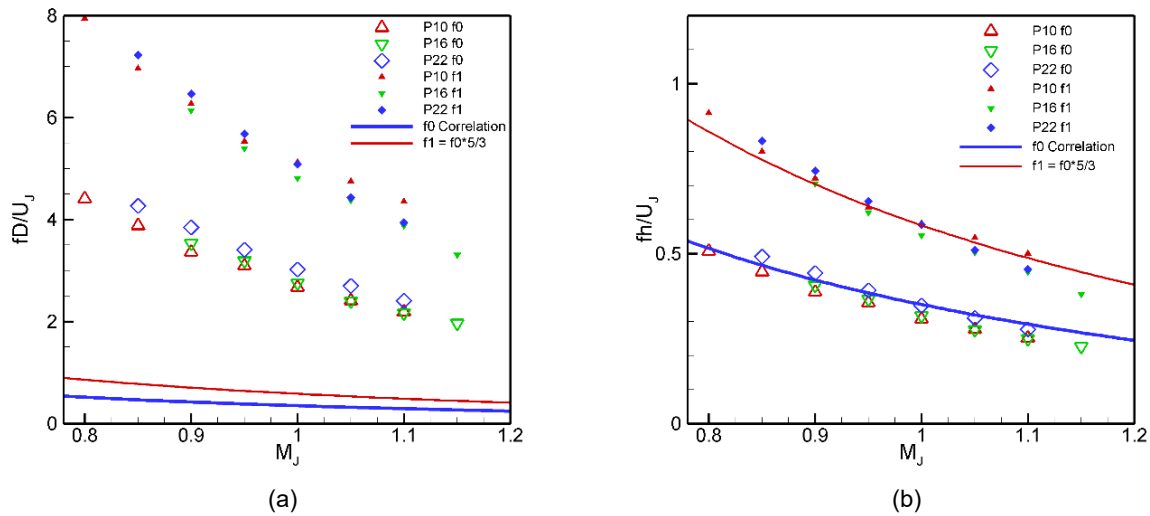


Figure 12.—Nondimensional frequencies. (a) Strouhal number (St_D) based on nozzle diameter ($D = 2$ in.) for the first two high-frequency peaks, compared to correlations for TW spectral peaks of round nozzles (Ref. 3), (b) Same data expressed as Strouhal number (St_h) based on gap width ($h = 0.23$ in.); the two lines represent same correlation equations as in (a) when St_D is replaced by St_h .

