

Spectral Peaks due to ‘Guided Jet Waves’ in Plug Nozzle Flows

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An experimental study was conducted to investigate the characteristics of ‘guided jet wave’ resonance tones occurring in nozzles with a center plug. The pressure fluctuation spectral peaks in the vicinity of the jet due to the resonance (referred as ‘GW peaks’) occur at 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 GW peaks. The relationship between the exit gap width and the GW peak frequencies is established based on near-field microphone measurements in experiments with varying plugs having different lengths, conical angles, and gap widths.

I. Introduction

‘Guided jet waves’, previously referred to as ‘trapped waves’, are a recent discovery [1, 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 GW peaks, for a variety of nozzles, have been studied in Ref. [3]. Correlation equations for the frequencies of the 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 GW 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 GW phenomenon. An interested reader may refer to past analytical aspects as well as current experimental and numerical research results in Refs. [4-8]. In connection with experiments with plug nozzles reported in [9], similar GW-like spectral peaks were noticed in the vicinity of the nozzle. However, the nondimensional frequencies (Strouhal numbers based on nozzle diameter) of those spectral peaks were an order of magnitude larger than that observed with single (no-plug) nozzles. An initial exploration with plug nozzles showed that the exit gap width between the nozzle exit and the plug crown diameter was the characteristic length scale associated with these higher frequency spectral peaks [10]. The present study further explores the details of the spectral behavior with plug nozzles to understand their characteristics relative to those of simple round nozzles.

II. Experimental Arrangement and Procedure

The experiments were conducted in an open jet facility at NASA Glenn Research Center (GRC). A photo of the facility is shown in Fig. 1(a). The same experimental setup is used to collect noise data, schlieren images as well as thrust data. In this paper mainly unsteady pressure data from a moveable microphone mounted on a traversing mechanism, marked in Fig. 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 (Fig. 1a). The flow from the floating plenum passes through two 30-

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mesh screens and then exhausts through the nozzle. The internal diameter of the floating plenum is 5” while the equivalent diameter of the exit of the plug nozzle is about 1.28”; 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., [8, 9]. As stated already, the focus of the current study is simply the near field pressure fluctuations as measured by the microphone.

A cross-sectional view of the plug nozzle assembly, with relevant dimensions, is shown in Fig. 1(b). In the present experiment, the nozzle remains fixed. It is convergent with 2” exit diameter (D) having a lip thickness of 0.050”. 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”. A threaded rod fixed to the cylindrical part 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 (Fig. 1b). Figure 1(c) shows a close-up view of the nozzle with the plug removed. This configuration is denoted ‘D2NP’ ($D=2$ ” nozzle, no plug). Even though it has the internal struts etc., the GW peaks exhibit the same characteristics as with a clean round nozzle [10]. The nozzle with a 16° conic plug, denoted as ‘P16’, is shown in Fig. 1(d). Data from D2NP will be compared with data for the P16 case to demonstrate the higher frequency peaks observed in plug nozzles relative to simple round nozzles. The microphone on the traversing mechanism placed at the reference location can be seen in both Figs. 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 Fig. 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%, leaving a base on the downstream end with a diameter of 0.582”. It is denoted as ‘P10T’. These plugs all have a nominal crown diameter of 1.54”. Another 16° conical plug with a larger crown diameter of 1.77”, denoted P16L, is shown in Fig. 1(f).

Note that the annular gap width between the plug and the nozzle depends on the axial location of the crown (Fig. 1b). The average gap width (h) for most of the data in this paper is about 0.23”, yielding an equivalent diameter of about 1.28”. However, the larger crown diameter of P16L yields a gap width of about 0.115” (equivalent diameter of 0.668”). All plugs, after installation, had slight non-concentricity relative to the nozzle exit; the gap width variation in the azimuthal direction was less than 5%. Such variations are thought to have minimal effect on the results presented in the following.

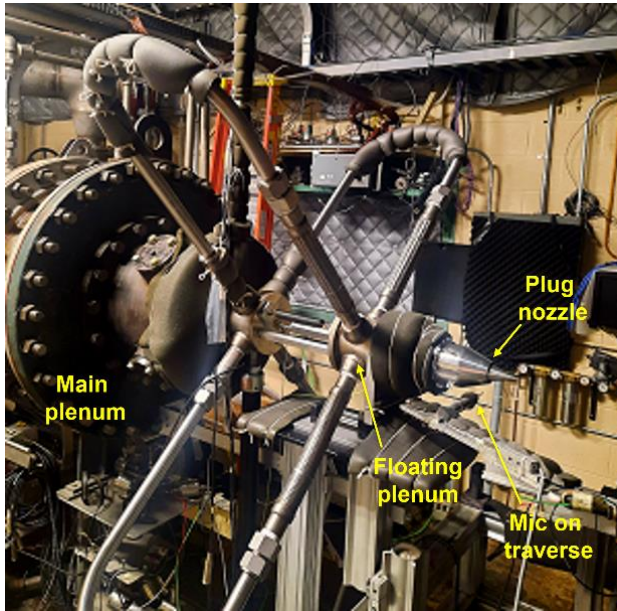
In addition, data is acquired with an 8:1 aspect ratio nozzle with a plate flush with the long edge in an effort to create a quasi-two-dimensional flow that is bounded by a wall on one edge, like ‘unwrapping’ the plug nozzle geometry. The GW behavior for this flow is compared with that of the 8:1 rectangular nozzle without the plate and the P10, P16, and P22 plug nozzles. A description of the setup is discussed with the data in Section III.

The primary diagnostic used is data from the 1/8-inch Brüel & Kjær (B&K 4138) microphone mounted on a traversing mechanism (Fig. 1a). The data acquisition is done using National Instruments A/D card and LabVIEW™ software. Sound pressure level spectral analysis is done typically over 0-90 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 an independent variable. It is given by,

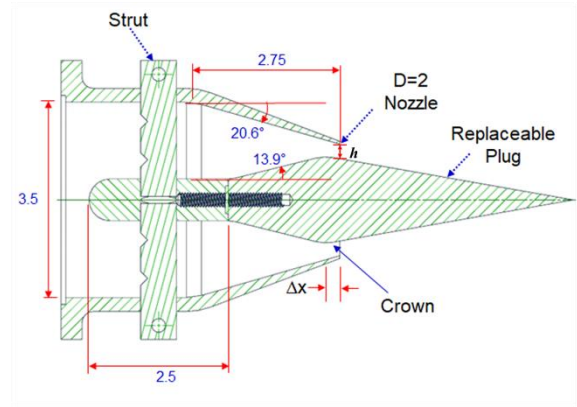
$$M_J = \sqrt{\frac{2}{\gamma-1} \left(\left(\frac{p_0}{p_a} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right)} \quad (1)$$

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 Figs. 2 and 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 in 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.



(a)



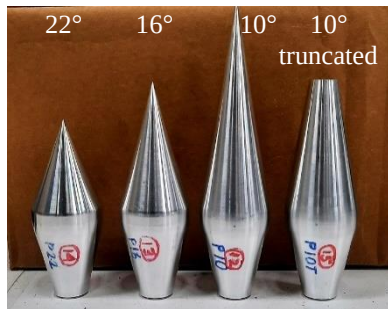
(b)



(c)



(d)



(e)



(f)

Figure 1. Experimental setup. (a) Jet facility, (b) schematic of plug nozzle, (c) nozzle without plug (D2NP), (d) nozzle with 16° conic plug, (e, f) plugs studied (P22, P16, P10, P10T, P16L)

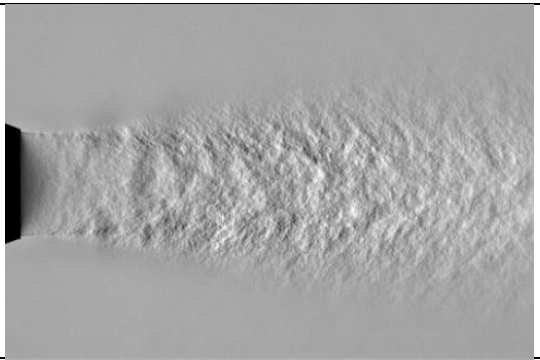
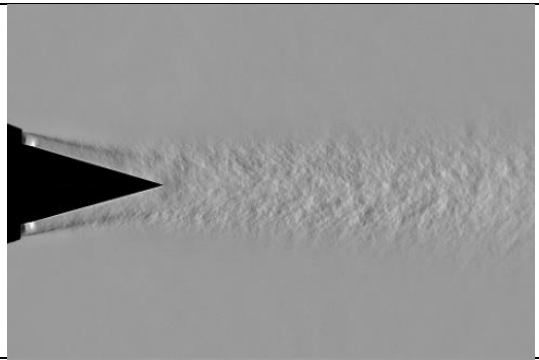
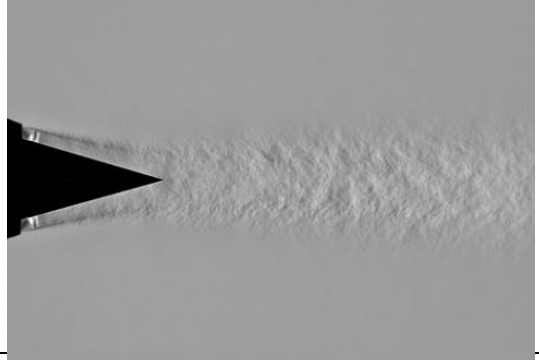
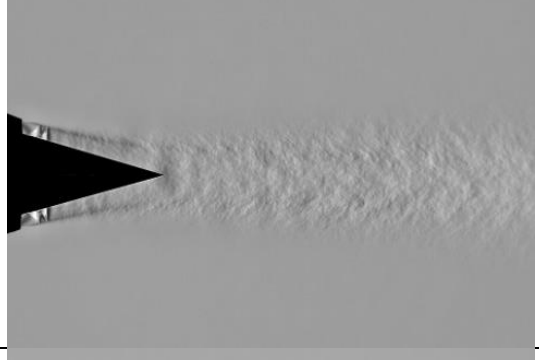
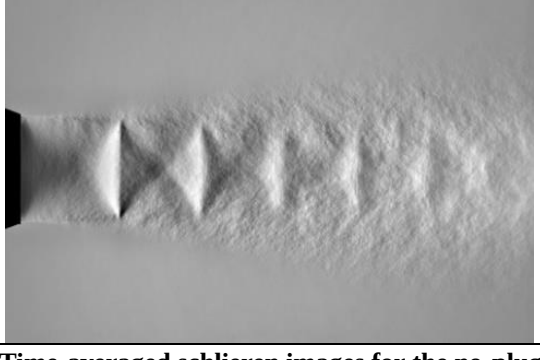
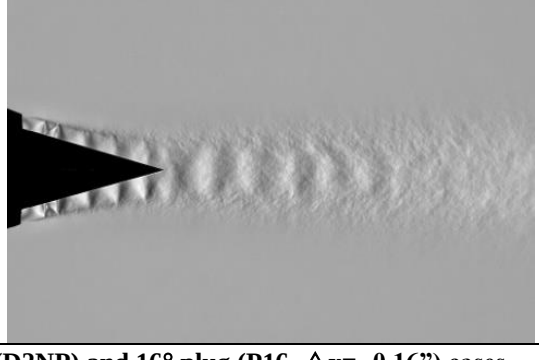
M_J	D2NP	P16
0.90		
1.00		
1.10		
1.20		

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

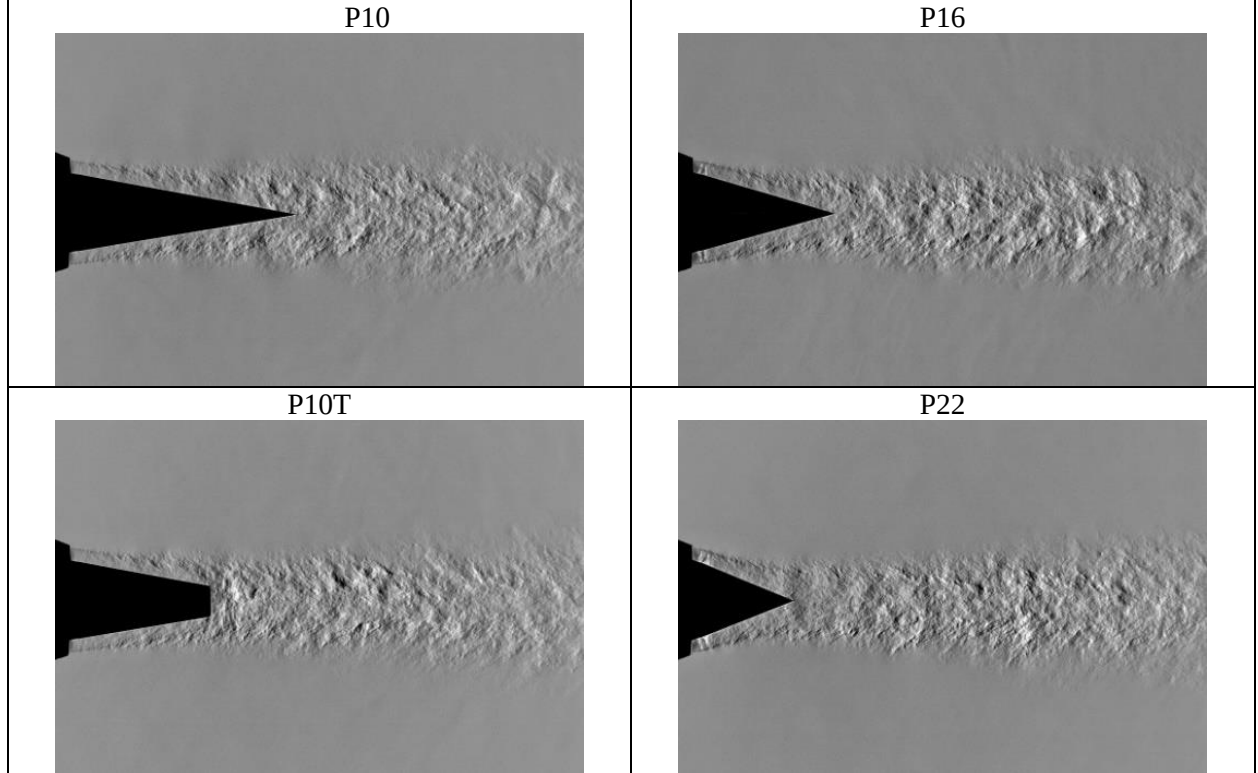


Figure 3. Instantaneous schlieren images for the four plug cases at $M_J=0.95$. $\Delta x = -0.13''$ for P10 and P10T cases, and $\Delta x = -0.16''$ for P16 and P22 cases.

III. Results and Discussion

Flow, noise, as well as thrust of various plug nozzles were studied in Ref. [9]. In connection with that study a cursory observation was made on the pressure fluctuations in the near-nozzle regions that exhibited GW-like spectral peaks. Figure 4 shows a set of data obtained during that study. The data were obtained with a $\frac{1}{4}$ -inch Brüel & Kjær microphone, placed at the nozzle exit plane $0.5''$ away from the lip, over a bandwidth of 0-40 kHz. The blue curve in Fig. 4 is for the nozzle with the 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 GW 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 Ref. [3]. The red curve in Fig. 4 was obtained with the P16 plug installed. The spectral peaks got altered although some of the lower frequency peaks remained, which apparently still scaled on the basic round nozzle diameter. Notably, however, certain additional peaks appeared at high frequencies (around 20 and 35 kHz).

The near-nozzle pressure fluctuations with the plug nozzle relative to a simple round nozzle are investigated further in the current experiment. To expand the frequency range in the measurements, a $1/8$ -inch microphone was used, and the data were obtained over the range of 0-90 kHz. The microphone location in the near-field was also moved upstream (relative to that in Fig. 4) to capture the GW spectral peaks prominently. Repeat results of the data of Fig. 4 are shown in Fig. 5(a). Differences are noted, possibly related to changes in the facility with the installation of the thrust apparatus since the experiments of [9]. For reasons unknown, the 2nd harmonic is larger than in the previous study [3]. However, the same basic behavior is still present where the fundamental and the higher frequency peaks for the simple round nozzle occur at the same Strouhal numbers and exhibit the same fractional ($5/3$, $7/3$, $9/3$) relationship. Figure 5(b) shows another set of data at $M_J = 1.00$ where this trend is perhaps clearer for the D2NP case with '0'=2.16kHz, '1'=3.64kHz, and '2'=5.22kHz. Importantly, the high-frequency peaks for the P16 case are captured clearly over the larger bandwidth. The series of high frequency peaks occur with a

fundamental (f_0) at about 20kHz and first harmonic (f_1) at about 35kHz. It will be shown later that the higher harmonics, e.g., f_1 marked in Fig. 5 also bear a similar fractional relationship as with the lower frequency GW peaks with the simple round nozzle.

Figure 6 shows that the high-frequency GW 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 $M_J = 0.95$; (the multiple spectral traces in this and later figures are staggered successively by 5dB for clarity). A similar trend was shown previously for the GW peaks with simple nozzles [3]. Here, at $r = 1.5$ the high-frequency GW peaks disappear for $x > 0.8''$. They also disappear for $r > 3.6''$ when measured at $x = -0.6''$. The lower frequency GW peaks for the P16 plug also exhibit this diminishing trend; however, the distances covered are not large enough for them to disappear completely [3]. It should be noted that the GW 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 GW peaks are detected even in the far-acoustic field at 75D away from the nozzle [11]. It is reasonable to expect that the high-frequency GW 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 Fig. 7(a) for the P16 case, the GW peaks are prominent when the plug crown is located near the nozzle exit ($\Delta x = -0.03''$). As the plug is drawn in, the amplitudes decrease, and the peaks practically disappear when $\Delta x = -0.29''$. Thus, with the current plug nozzle geometry the ‘throat’ location needs to be near the nozzle exit to generate the high-frequency GW 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. The data in Fig. 7(a) thus provides a clue that the gap width h might be the length-scale governing the behavior of the high-frequency GW peaks; this is discussed 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.

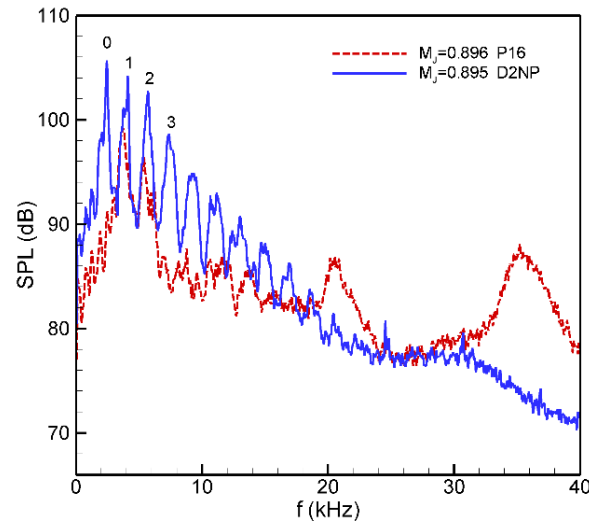


Figure 4. Earlier observations with $\frac{1}{4}$ inch microphone; p' -spectra at $x=0$, $r=1.5$; blue curve: no plug (D2NP), red curve: plug P16 case with $\Delta x = -0.16''$.

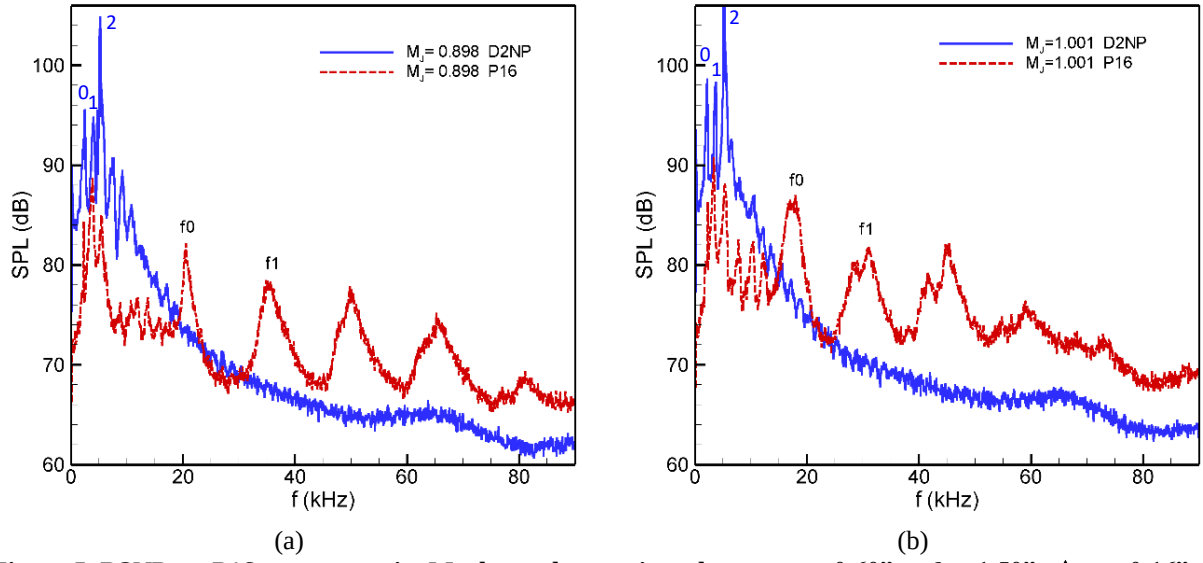


Figure 5. D2NP vs. P16 case at two jet Mach numbers; microphone at $x = -0.60''$ and $r = 1.50''$; $\Delta x = -0.16''$ for P16. (a) $M_J = 0.90$, (b) $M_J = 1.00$.

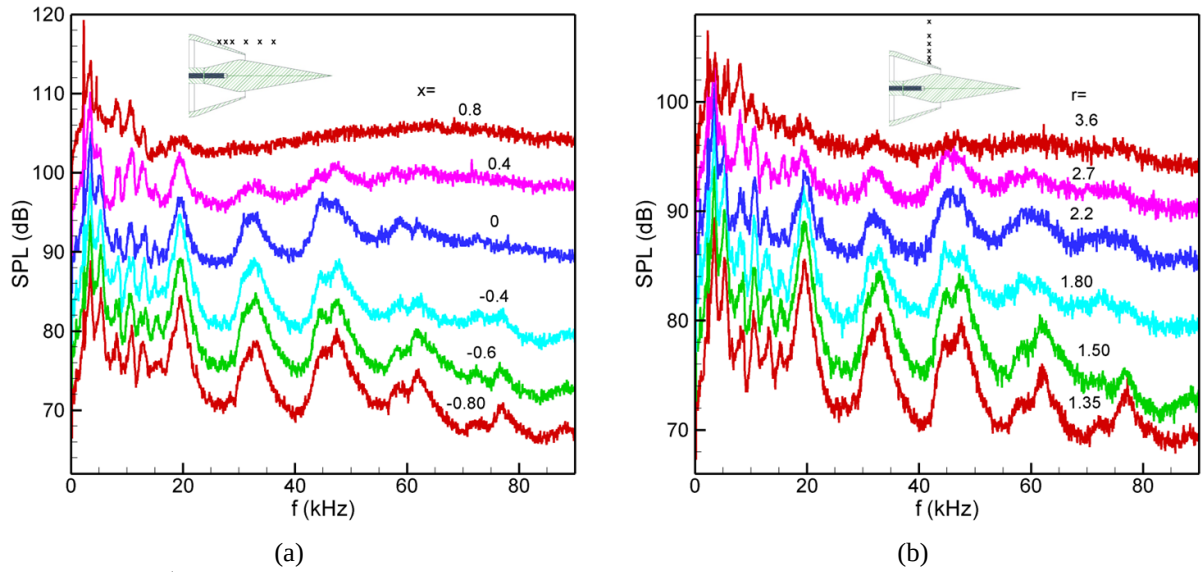


Figure 6. P16 ($\Delta x = -0.16''$) case data at various locations near nozzle; $M_J = 0.95$. (a) Varying microphone x -locations with $r = 1.5$, (b) varying microphone r -locations with $x = -0.60''$.

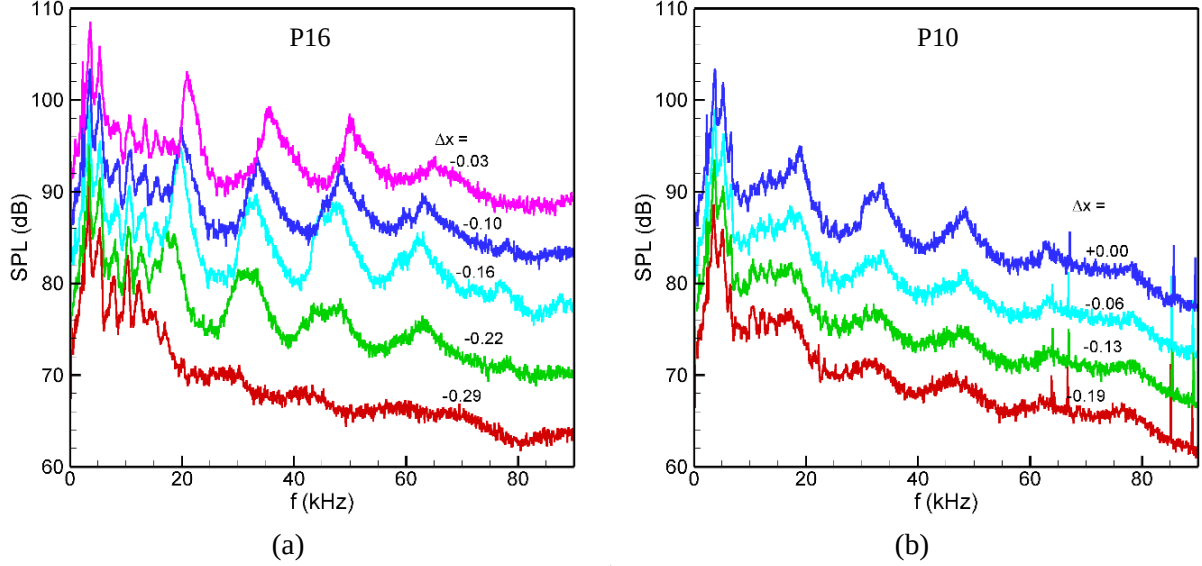


Figure 7. Data with variation of plug crown location (Δx); $M_J = 0.95$. (a) P16 case, (b) P10 case.

Figures 8, 9 and 10 show spectral data as a function of M_J , for the P22, P16 and P10 cases, respectively. As stated before, 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 5dB. Generally, the high-frequency GW 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 Fig. 11 for two different Mach numbers. The high-frequency GW 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 GW peaks (marked f_0 and f_1 in Fig. 5) are shown in Fig. 12 as a function of Mach number for three sets of data with P10, P16 and P22 plugs. In Fig.12(a), Strouhal numbers based on the nozzle diameter ($D = 2''$) are plotted. Also shown by solid lines are the correlations for simple round nozzle data from [3, 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 Fig. 12(b) where the Strouhal number is based on the annular gap width of the plug nozzle at the exit ($h = 0.23''$). The same correlations from Fig. 12(a) are replotted substituting fD/U_J with fh/U_J , i.e.,

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

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 GW peaks seen with the plug nozzles.

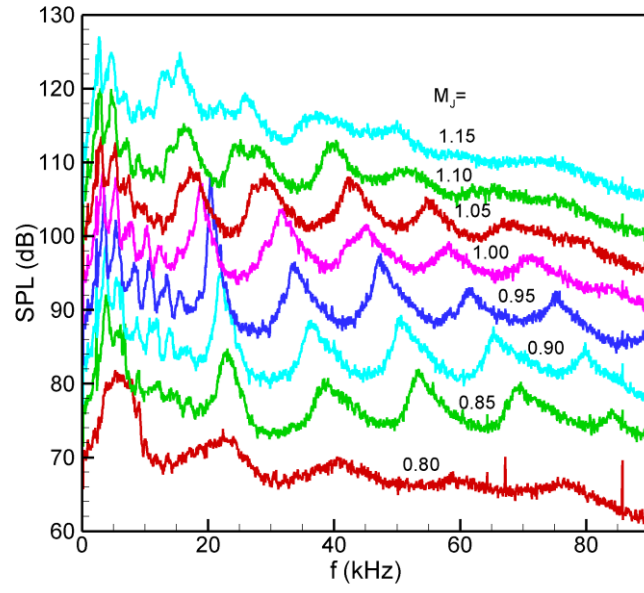


Figure 8. Data for P22 case with varying M_j ; crown location $\Delta x = -0.16$.

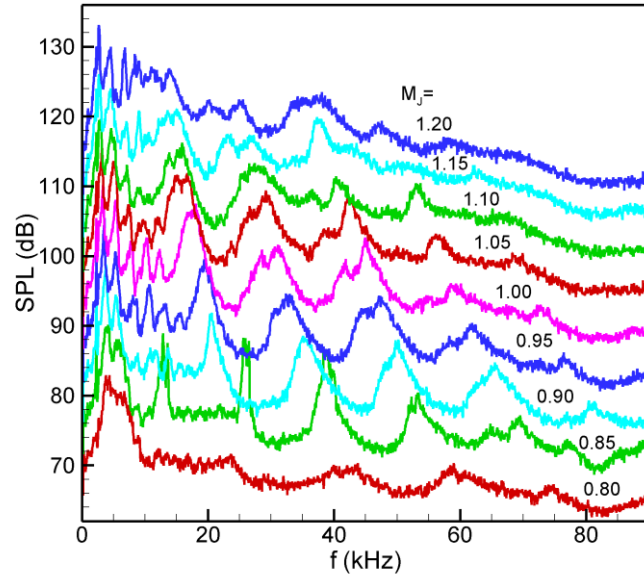


Figure 9. Data for P16 case with varying M_j ; crown location $\Delta x = -0.16$.

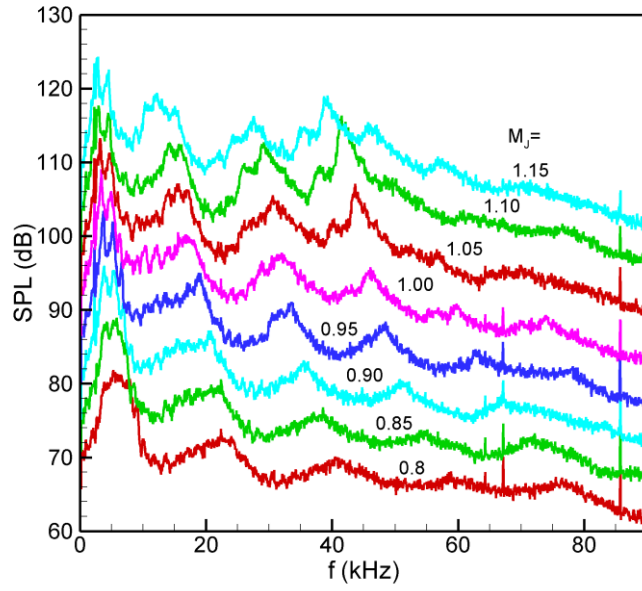


Figure 10. Data for P10 case with varying M_j ; crown location $\Delta x=0$.

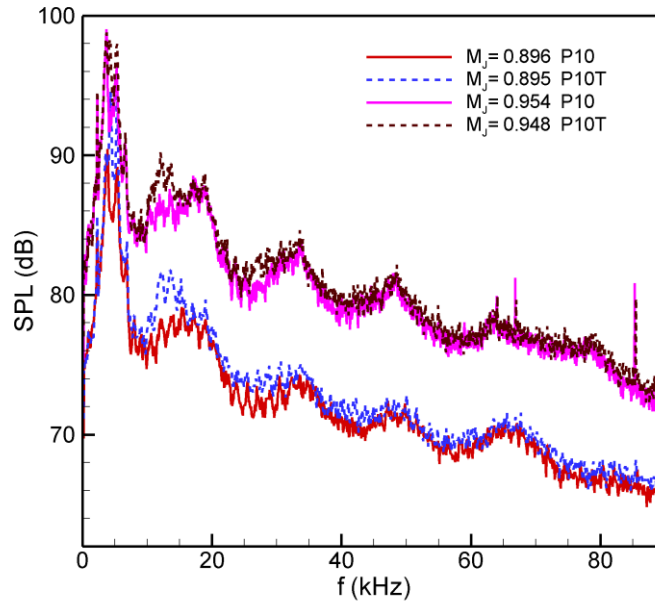


Figure 11. Comparison of data for P10 and P10T at two values of M_j . At each M_j , the data are plotted with the same ordinate scale, but the two pairs are vertically offset by 10dB. Crown locations are $\Delta x = -0.13''$ and $\Delta x=0$ for the $M_j = 0.9$ and 0.95 cases, respectively.

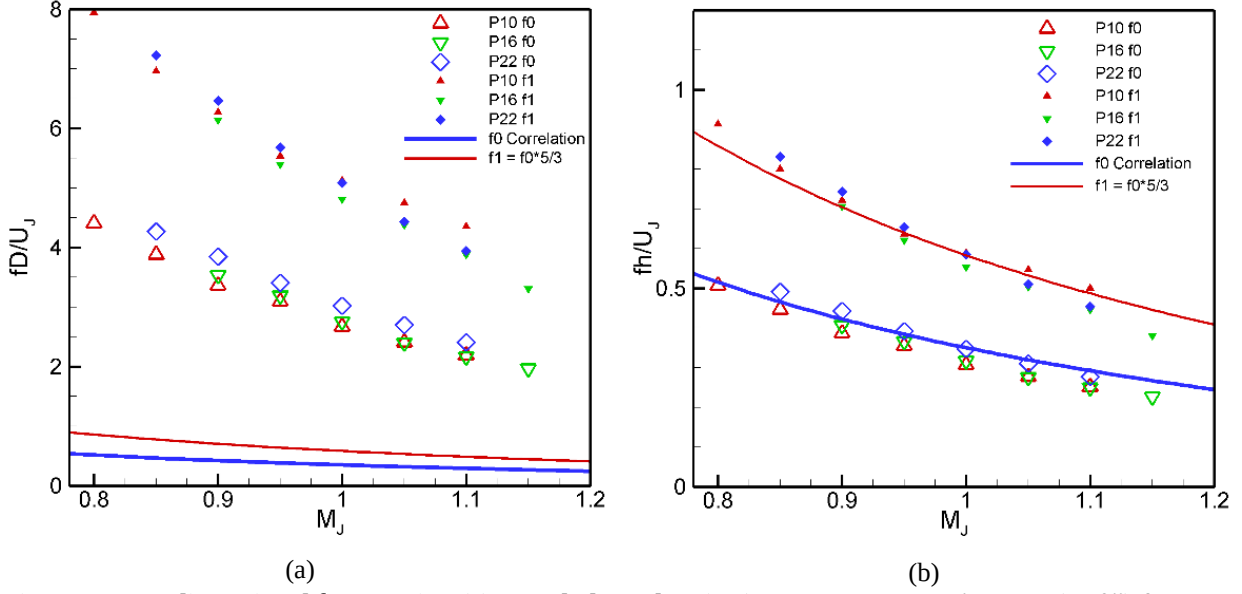


Figure 12. Nondimensional frequencies. (a) Strouhal number (St_D) based on nozzle diameter ($D=2''$) for the first two high-frequency peaks, compared to correlations for GW peaks of simple round nozzles shown by solid lines [3]. (b) Same data expressed as Strouhal number (St_H) based on gap width ($h=0.23''$);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

To further validate the observed behavior, noise data are acquired for the P16L plug having a larger crown diameter and smaller exit gap width ($h=0.115''$ for P16L compared to $h=0.23''$ for P16). Figures 13(a) and 13(b) show data comparing the pressure fluctuation spectra for the P16 (blue curves) and P16L (red curves) configurations at two different Mach numbers, $M_j=0.9$ and $M_j=1.00$, respectively. The data clearly show that halving the gap width roughly doubles the fundamental frequency of the GW peaks, as predicted by the above correlation (Eq. 2).

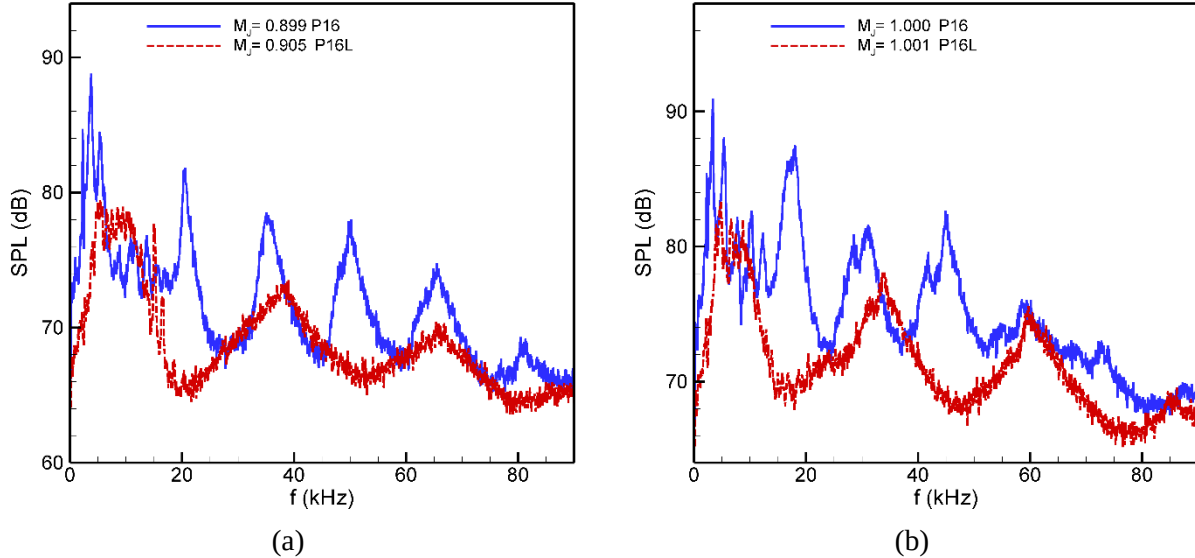


Figure 13. P16 vs. P16L cases at two jet Mach numbers; microphone at $x= -0.60''$ and $r=1.50''$; $\Delta x = -0.16''$ for both plugs. (a) $M_j = 0.90$, (b) $M_j = 1.00$.

Another experiment to further characterize this phenomenon involved the creation of a quasi-two-dimensional flow that is bounded by a wall on one edge, akin to ‘unwrapping’ of the plug nozzle geometry. The setup for the experiment is shown in Fig. 14(a) where a large 8:1 aspect-ratio rectangular nozzle (referred to as ‘R8’) is

configured with a flat plate mounted flush with the lower edge of the nozzle. The nozzle exit is 5.28" x 0.66". The plate is 3" long in the axial direction and extends ± 4 " from the jet centerline in the spanwise direction. Microphones are placed on both the long and short edges of the nozzle at $x = -0.5$ " and $r = 0.65$ " from the nozzle outer wall. Note that during data acquisition the protection grids on the microphones (Fig. 14a) were taken out; also, for this experiment $\frac{1}{4}$ " microphones were used. A comparison of sound pressure level spectra is shown in Fig. 14(b) and 14(c) for the R8 nozzle with the plate (blue curves) and without the plate (red curves) at two different Mach numbers, $M_J = 0.9$ and $M_J = 1.00$, respectively. Data for the case without the plate at both long and short edges repeated well relative to the data presented in [3]. For correspondence with the plug nozzle experiment, only data from the microphone placed near the long edge (minor axis) is considered in the following. The fundamental peak for each case, in Fig. 14 (b, c), is observed to increase in frequency with the addition of the plate. Also, spurious low frequency peaks appear that are not related to the GW phenomenon and are assumed to be due to flow over exposed surfaces or 'scrubbing noise'. Additional data (not shown for brevity) taken with plates of different streamwise length (1" and 6.6") did not significantly change the frequency of f_0 , except the scrubbing noise amplitudes were higher with the longer plate.

The Strouhal numbers based on gap width, St_h , corresponding to the fundamental of the GW peaks (marked f_0 in Fig. 14) are shown in Fig. 15 as a function of Mach number for the R8 nozzle with and without the plate. The data are compared with the f_0 data for the P10, P16 and P22 plug nozzles. The R8 data represents the Strouhal number based on the gap width $h = 0.66$ ". The dashed line represents the correlation Eq. 2. The data for the R8 case with the plate can be seen to agree with the correlation curve. Figure 15 illustrates that the Strouhal number of a jet-plate combination agrees with the plug nozzle data. The flow from the R8 nozzle plus a plate behaves very similar to an (unwrapped) plug nozzle flow.

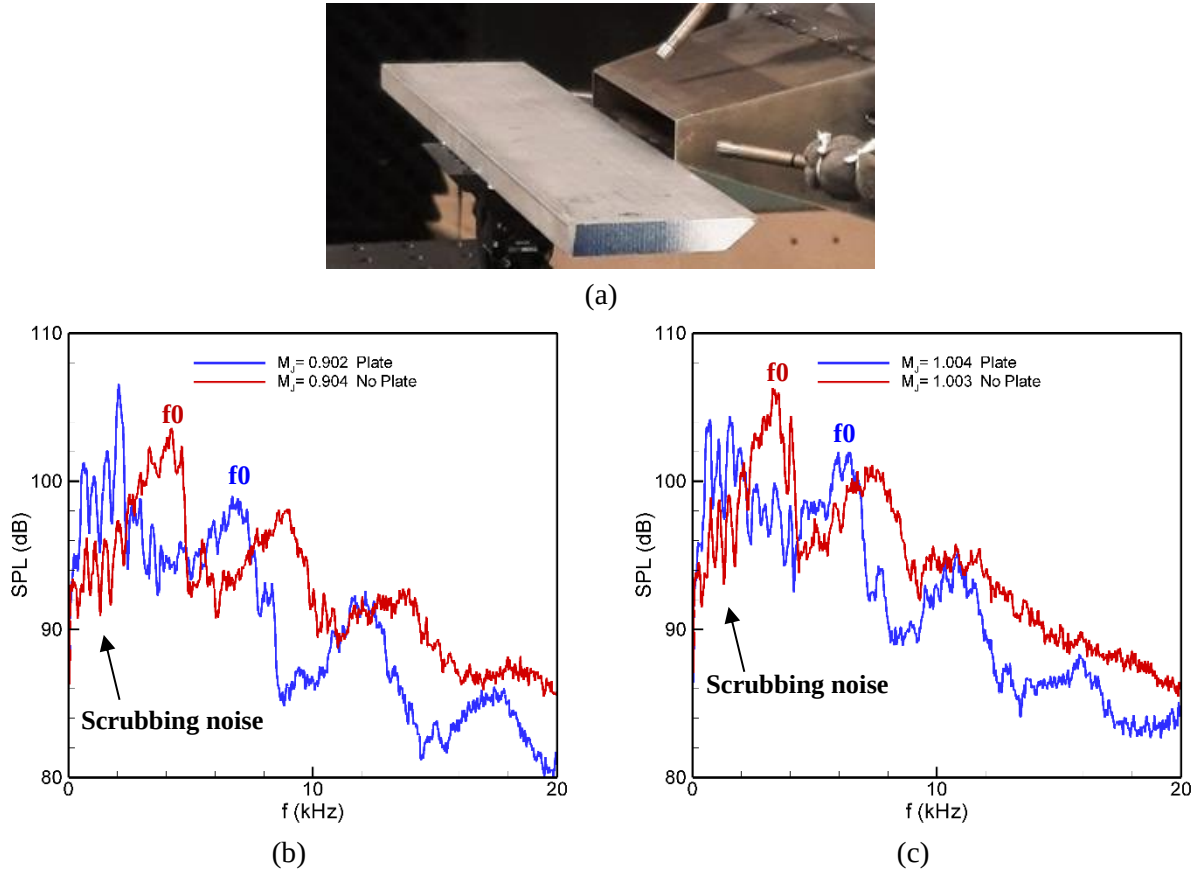


Figure 14. (a) Experimental setup to study an 8:1 rectangular nozzle with and without a flat plate flush with the lower edge of the nozzle; both microphones on long and short edges are placed about $x = -0.5$ " upstream of nozzle exit and $r = 0.65$ " from the nozzle outer wall. Data from the microphone placed near the long edge are shown for plate vs. no plate cases at two jet Mach numbers: (b) $M_J = 0.90$, (c) $M_J = 1.00$.

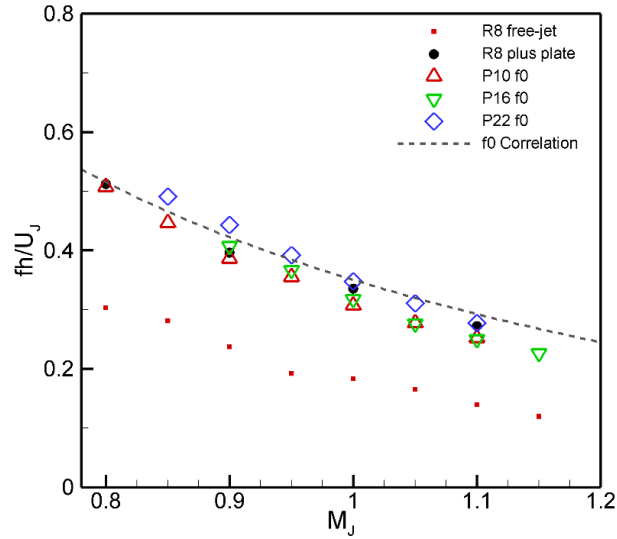


Figure 15. Nondimensional frequencies for the fundamental GW spectral peaks for the 8:1 rectangular nozzle with and without the plate and three plug nozzle cases, P10, P16, and P22, where the Strouhal number (St_h) is based on gap width ($h=0.66''$ for the R8 nozzle, $h=0.23''$ for the plug nozzles). The dashed line represents the correlation expressed in Eq. 2.

IV. Conclusions

When a central plug is added to a round nozzle, the near-nozzle pressure fluctuation spectra are altered somewhat but the GW peaks 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 GW peaks seen with the no-plug case. It is shown that the exit gap width of the plug nozzle is the characteristic length-scale that dictates the high-frequency GW peaks. Varying the gap width with a larger crown diameter plug further validated this conclusion. An experiment with a large aspect ratio rectangular nozzle and a flat plate flush with the long edge of the nozzle provided additional validation. This geometry was analogous to ‘unwrapping’ a plug nozzle into a two-dimensional geometry. Nondimensional frequencies based on the gap width in the plug cases and the narrow dimension of the exit in the rectangular nozzle with plate case fell on a single curve. The curve agreed with correlation equation developed before for round nozzles in [3], when the nozzle diameter D was substituted by the gap width h .

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