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Spectral Peaks due to 'Trapped Waves' in Jets from Plug Nozzles

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Abstract

An experimental study is underway 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. Experiments are planned to further examine the relationship between the exit gap width and the TW frequencies which will be presented in the final paper.

Introduction

'Trapped waves', now commonly referred to as 'guided jet 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 trapped wave (TW) spectral peaks, for a variety of nozzles, have been studied in [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 [4-8] for past analytical aspects as well as current experimental and numerical research results. In connection with experiments with plug nozzles reported in [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. An initial exploration of TW 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]. In the present study, we will further explore the detailed characteristics of the spectral behavior with plug 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 Fig. 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 Fig. 1(a), are discussed. Additional details on the experimental setup are given in [10].

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

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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 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 (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 TW spectra exhibit the same characteristics as with a clean round nozzle. 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). Additional conical plugs with apex half angles of 10° and 22°, as well as a truncated 10° plug were evaluated in [10] and demonstrated similar behavior as the P16 case. 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 for most of the data in this report is about 0.23”, yielding an equivalent diameter of about 1.28”.

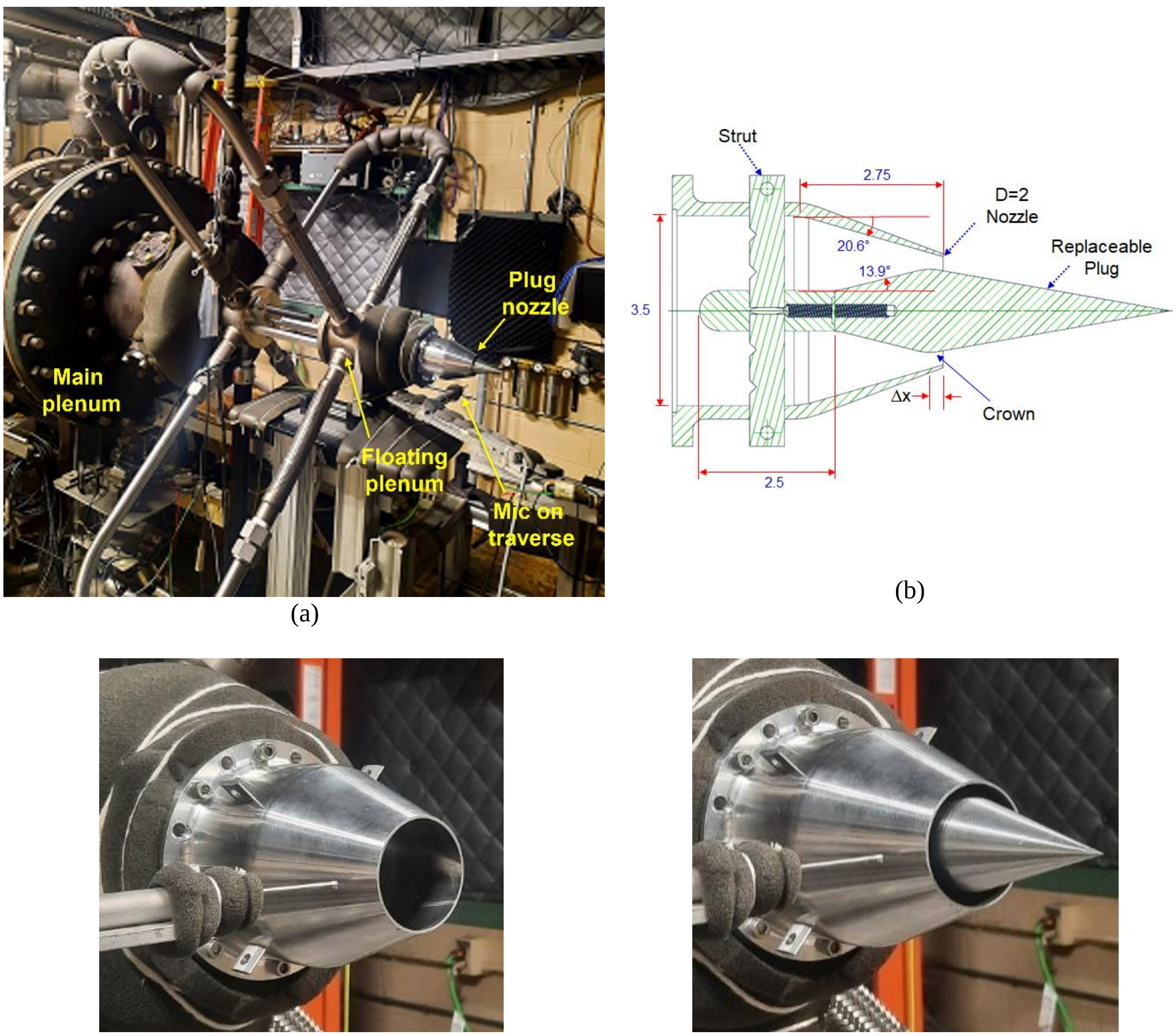


Figure 1. Experimental setup. (a) Jet facility, (b) schematic of plug nozzle, (c) nozzle without plug (D2NP), (d) nozzle with 16° plug.

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 independent variable. It is given by,

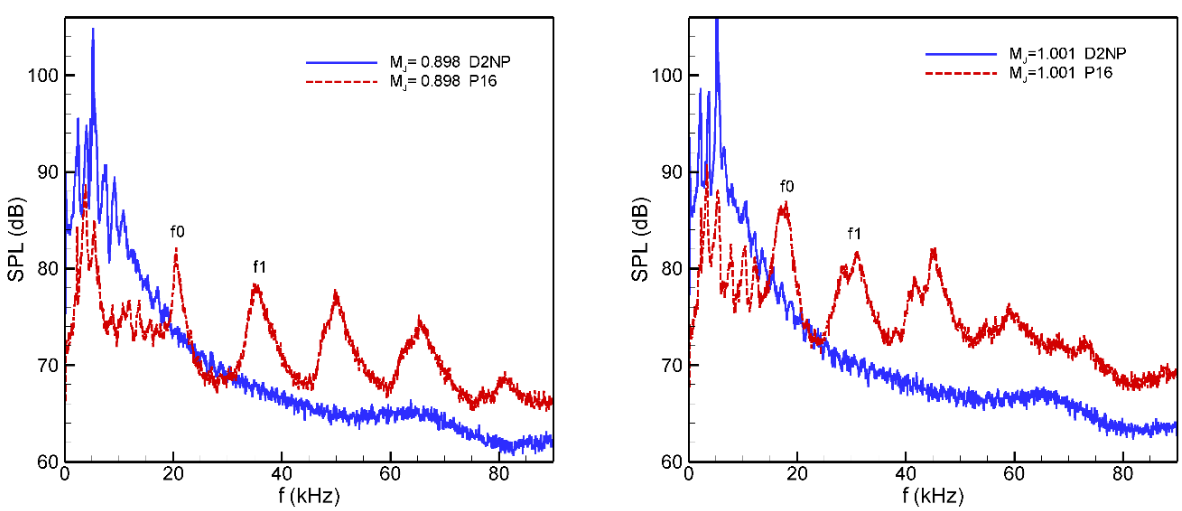
$$M_J = \sqrt{\frac{2}{\gamma-1}\left(\left(\frac{p_0}{p_a}\right)^{\frac{(\gamma-1)}{\gamma}} - 1\right)} \tag{1}$$

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.

Results

The near-nozzle pressure fluctuations with the plug nozzle relative to a simple round nozzle are investigated in the current experiment. A 1/8-inch microphone is used, and the data are obtained over the range of 0-90 kHz. Figure 2 shows data comparing the sound pressure level spectra for the D2NP and P16 configurations at two different Mach numbers (M_J=0.9 and M_J=1.00). In the D2NP cases (blue curves), the Strouhal number of the fundamental and the higher frequency peaks exhibit the same fractional (5/3, 7/3, 9/3) harmonic relationship relative to the fundamental as reported in [3]. The red curves in Fig. 2 were 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 with a fundamental (f0) at about 20kHz. It will be shown later that the higher harmonics, e.g., f1 marked in Fig. 2(a) also bear a similar fractional relationship as with the lower frequency TW peaks with the clean nozzle.

Figure 3 shows spectral data where the plug crown location is varied with respect to the nozzle exit (△x) for the P16 case. The TW peaks are prominent when the plug crown is located near the nozzle exit (△x = -0.03"). As the plug is drawn in, the amplitudes decrease, and the peaks practically disappear when △x = -0.29". 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 △x the annular throat width (*h*) between the plug crown and the nozzle's inner wall increases rapidly. The data in Fig. 3 thus provides a clue that the width *h* might be the length-scale governing the behavior of the high-frequency TW peaks.



(a) (b)

Figure 2. D2NP vs. P16 case at two jet Mach numbers; microphone at x= -0.60" and r=1.50"; △x = -0.16" for P16. (a) M_J = 0.90, (b) M_J = 1.00.

Figure 4 shows spectral data as a function of M_J for the P16 case. The spectra are vertically offset for clarity. In the figure, the ordinate pertains to the trace at the bottom and others are shifted successively by 5dB. 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 fundamental and the first harmonic of the high-frequency TW peaks (marked f0 and f1 in Fig. 2a) are shown in Fig. 5 for three sets of data with P10, P16 and P22 plugs [10]. In Fig. 5(a), Strouhal numbers based on the nozzle diameter (2”) 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 [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. 5(b) when 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. 5(a) are replotted substituting fD/U_J with fh/U_J, i.e.,

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

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 experiments are planned to explain the observed high-frequency TW behavior; these results will be presented in the final paper. The experiments will include studies with plugs of different crown diameters to allow variation of the exit gap width, h, as well as studies with large aspect-ratio rectangular nozzles bounded by a wall on one edge, like ‘unwrapping’ the plug nozzle geometry. Limited numerical studies may also be presented to help explain the observed unsteady behavior. The effects of plug porosity and surface finish may also be investigated.

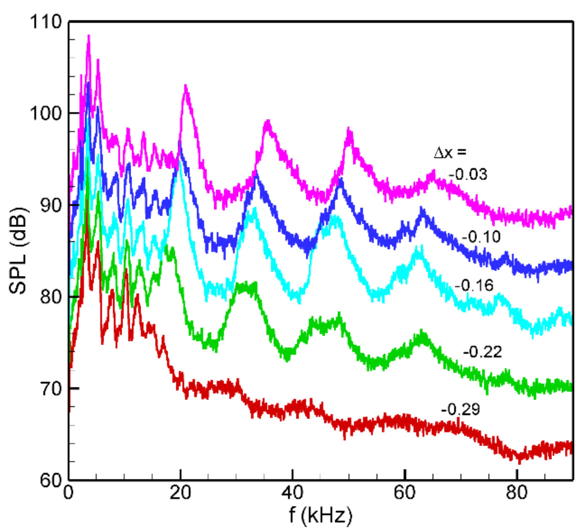


Figure 3. Data with variation of P16 plug crown location (△x); M_J = 0.95.

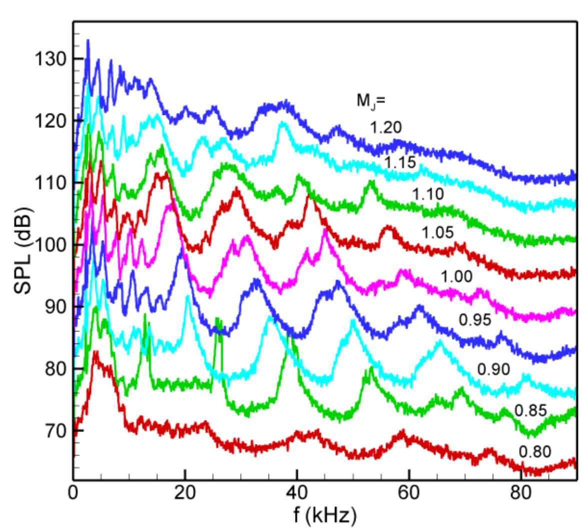
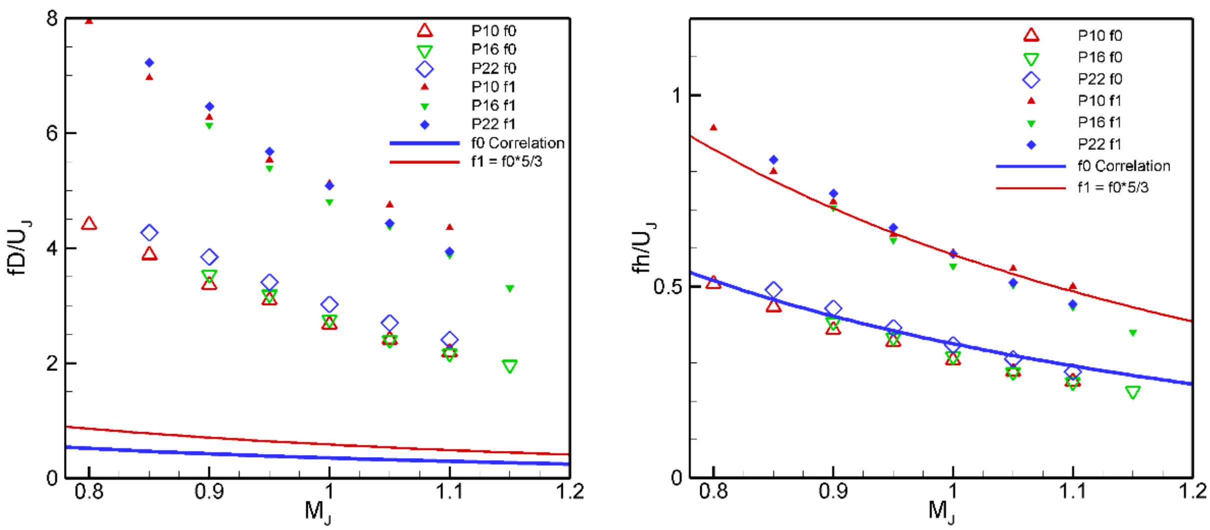


Figure 4. Data for P16 case with varying M_J; crown location △x = -0.16.



(a) (b)

Figure 5. Nondimensional frequencies. (a) Strouhal number (St_D) based on nozzle diameter (D=2”) for the first two high-frequency peaks, compared to correlations for TW spectral peaks of round nozzles [3], (b) Same data expressed as Strouhal number (St_h) based on gap width (*h*=0.23”); the two lines represent same correlation equations as in (a) when St_D is replaced by St_h.

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. It appears that the exit gap width of the plug nozzle is the characteristic length-scale that dictates the high-frequency TW frequencies. Experiments are planned to further characterize and understand this phenomenon and will be reported in the final manuscript.

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