Twin-Jet Screech Suppression

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A facility test was performed on twin-jet configurations to determine the effectiveness of several concepts in suppressing the supersonic screech tones. Supersonic jet Mach numbers up to 1.75 were tested. The screech suppression concepts were tabs, lateral spacing, axial spacing, and secondary air jets. Acoustic and optical data were obtained. It was found that the twin-jet configuration can result in screech tone amplitudes as much as 20 dB higher than a single jet. Screech tone amplitudes up to 162 dB were measured. Small tabs located at the exit plane were shown to be very effective suppressors if they were large enough or if multiple tabs were installed. Lateral spacing can result in significant tone suppression, however, at certain spacings little suppression was achieved. Axial spacing resulted in essentially no suppression. The secondary air jet was shown to be a very effective suppressor of screech tones from a single jet but was not tested on the twin jet configuration.

Introduction

WHEN a nozzle is operated at a nozzle pressure ratio (NPR) other than the NPR that results in the design Mach number of the nozzle (i.e., where $P_e = P_a$), shocks will occur in the exhaust plume. The strength of the shocks is a function of how far off the design condition the nozzle is operated. The presence of these shocks results in additional noise. The shock-associated noise is clearly divided into two sources, a narrowband tone referred to as jet screech, and a broadband component referred to as broadband shock cell noise. The jet screech noise source is a result of the large-scale coherent structure in the jet shear layer interacting with the shocks cells generating fluctuating pressures that propagate upstream. As they travel upstream, they couple with the shear layer causing amplification of the coherent structure in the shear layer and resulting in a feedback process. When the phase relationship between the downstream traveling coherent structure in the shear layer and the upstream traveling pressure waves is matched, high amplitude screech tones can be generated. This feedback process was identified by Powell[1] as early as 1953. An explanation of the feedback process is given by Seiner,[2] and a very detailed treatment of the evolution of instabilities in axisymmetric jets is presented by Cohen and Wygnanski.[3,4] Also, a good explanation of the coupling between sound and instability waves in a shear layer is presented by Ahuja;[5] the author concludes that coupling takes place along the shear layer and not just at the jet exit.

When two jets are closely spaced, the level of the screech tone can be greatly amplified due to a coupling process between the two plumes. The noise from single jets has been extensively studied, but the noise and coupling process between two closely spaced jets has been studied only recently by a few researchers. References 6–11 represent most of the work that has been directed toward the twin-jet screech problem. It was shown by Seiner et al.[6] that the twin-jet coupling process can increase the screech tone amplitude by 6 dB (a factor of 4). Full-scale ground run-up data[7] from an F-15 aircraft also show a narrowband tone near the predicted screech frequency. Wind-tunnel data for a 6% B-1A model[9] show some narrowband tones, but not as well defined as the ground run-up data. Wind-tunnel data for the 8.3% F-15 model[8] also shows some narrowband energy but at low levels. It is well established[12] that the conditions of the flow at the exit plane can significantly affect the feedback process. The velocity profile and turbulence level can both affect the screech phenomenon. One can see the problem of trying to scale screech data from test stands, wind tunnels, and flight. Both velocity profile and turbulence level of the flow at the exit plane are different for each case.

The amount of research directed toward reducing twin-jet screech amplitudes is even more limited. However, the work for screech suppression of single jets can be applicable to twin jets because if one jet is suppressed, the two jets are decoupled, and the screech amplitude is reduced.[6] Numerous methods exist to suppress the screech tones. Some are practical and could be considered for retrofitting existing aircraft. The list of methods includes porous plugs,[13] inverted velocity profile coanular jets,[14] radial flow impingement,[15] lip projection and nozzle wrapping,[16] nozzle asymmetry,[17] and notches and tabs.[18] The effect on screech tones of lateral spacing of two jets was studied by Wlezien.[11] The effect of minor geometric alteration to one of two nozzles was considered by Seiner.[6] All of the methods investigated affected the screech tone amplitudes, and some of the methods completely eliminated the tone.

The objective of this experimental study was to investigate the effectiveness of four concepts in suppressing the screech tones in supersonic nozzles. The concepts were tabs, lateral spacing, axial spacing, and secondary air jets. Jet Mach numbers from 1.1 to 1.7 were investigated. Flow visualization was used to help verify jet coupling.

Description of Experimental Apparatus

The experiments were performed using nozzles from a McDonnell Douglas 4.7% scale model of the F-15 aircraft. Data from axisymmetric nozzles with a design Mach number of 1.41 are included in this paper. The nozzles were attached to a 45.7-cm-diam settling chamber containing honeycomb flow straightners. Flexible hose approximately 45 cm long was installed between the settling chamber and the nozzles. The hose permitted variable spacing between the nozzles and resulted in much higher screech amplitudes for the axisymmetric nozzles. An explanation of the higher levels will be discussed later.

Optical data were obtained using a phase averaged schlieren system. The signal from the center microphone was amplified, bandpass filtered at the screech frequency, divided, and used to drive a pulse generator. The signal from the generator was

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used to trigger the strobe. The dividing was necessary because the strobe had an upper limit of 2500 Hz, but the screech frequency could be in excess of 8000 Hz. The pulse duration of the strobe was approximately 3 μs. Both photographic and video records were obtained.

Description of Instrumentaton and Test Procedures

The screech environment of the jets was measured with three one-quarter-in. Gulton microphones. They were located in the exit plane of the nozzles, as shown in Fig. 1. When the nozzles were spread apart to study jet spacing effects, the two outside microphones moved with the nozzles so as to maintain a constant distance between the microphone and nozzle. The center microphone remained fixed resulting in a larger distance between it and the nozzles as they were spread apart. The signals from the microphones were routed to a real-time analyzer to monitor the levels during the test and were also recorded on analog tape for later reduction.

Results

The suppression of twin nozzle supersonic screech was experimentally studied. Twin F-15 4.7% axisymmetric nozzle geometries with a design Mach number of 1.41 were investigated. Four separate screech suppression concepts were tested. These consisted of lateral spacing, longitudinal spacing, tabs, and secondary jets. Acoustic data were obtained for fully expanded jet Mach numbers in excess of 1.7. Optical results that were helpful in distinguishing the various modes and the presence of plume coupling were also obtained. A brief discussion of the acoustic environment of the nozzles is given first. The environments of single and twin nozzles are compared. Then the results of the evaluation of the suppression concepts are presented.

Unsuppressed Environment

The unsuppressed acoustic environments of a single jet and twin jets were measured before the suppression tests. The effect of several test configurations on the amplitude of the screech tones was also investigated first. The configuration resulting in the highest screech tones was selected to evaluate the suppression concepts.

Single vs Twin Environment

The spectra from the single and twin jet configuration are shown in Fig. 2. The screech tones for both configurations are readily obvious at just under 4 kHz. They differ slightly in frequency because the twin-jet configuration results in an increase in the shock-cell spacing causing a lower screech tone frequency. The amplitude of the screech tone for the twin-jet configuration is 20 dB higher than the single jet. For two identical sources, the increase should be 3 dB. However, due

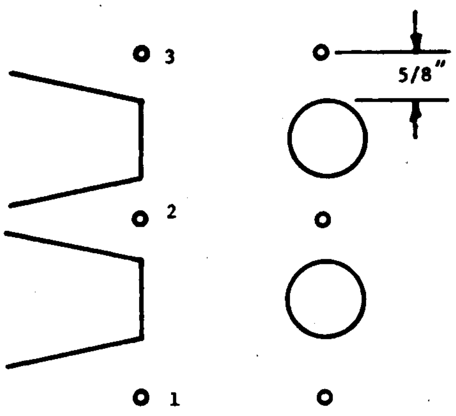


Fig. 1 Microphone orientation.

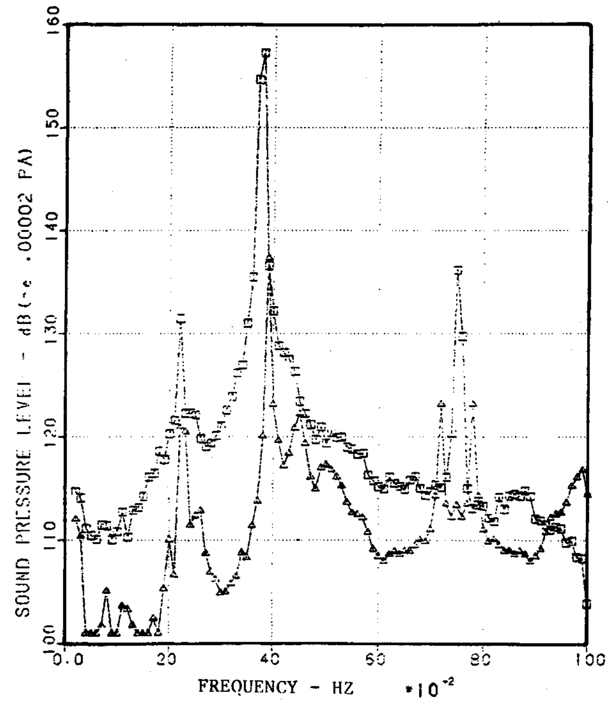


Fig. 2 Spectra from single ( ) and twin ( ) jets for $M_j = 1.56$, $s/d = 2.25$.

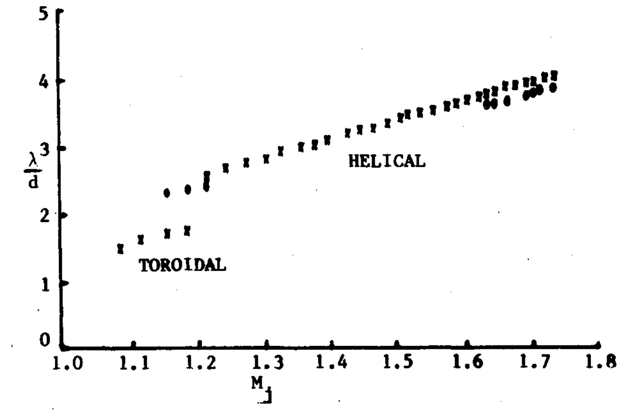


Fig. 3 Mach number dependence of screech tone wavelength, $s/d = 2.25$.

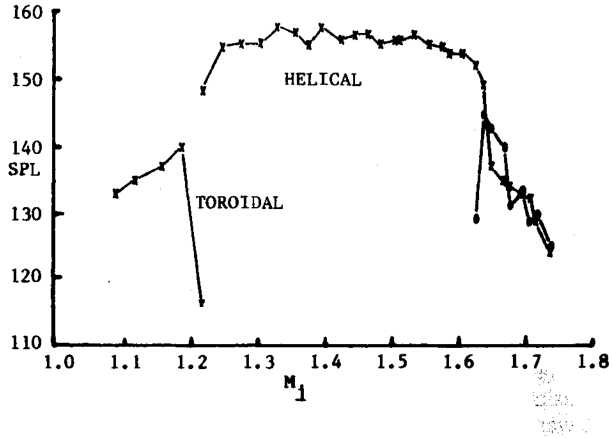


Fig. 4 Mach number dependence of screech tone amplitudes, $s/d = 2.25$.

to the coupling between the jet plumes, the jet screech tone generation mechanism is enhanced, and higher levels result. The amplitude enhancement process is believed[6] to be an effective coupling of the helical B-type, large-scale, coherent, plume resonance mode of each jet resulting in much larger growth rates. The very high acoustic levels in the internozzle region can result in structural response and fatigue. Means to suppress the amplitude of the screech tones are needed in order to minimize the structural fatigue problem.

Jet Mach Number Effect

Because the frequency of the screech tone is dependent on the shock-cell spacing, the screech tone frequency decreases, or the wavelength increases as the jet Mach number increases and the shock-cell spacing increases. The Mach number dependence of the normalized screech tones is shown in Figs. 3 and 4 for the twin-jet configuration. Figure 3 shows how the wavelengths of the screech tones increase with jet Mach number, and Fig. 4 shows the amplitude dependence. Both toroidal and helical modes are shown. It becomes very evident that the helical mode is the mode resulting in jet coupling. Essentially the same Mach number dependence was observed in Ref. 6.

One may question the screech tone amplitude at the design Mach number where there should be no shocks in the plume. The data in Fig. 4 show no reduction in amplitude near the design Mach number of 1.41. Two explanations for this are offered. The first is that the shocks may become very weak at the design conditions but yet remain just strong enough to provide the feedback path for screech to occur. The second, a more plausible case, is that the two nozzles may have slightly different design Mach numbers due to fabrication tolerances. This results in at least one of the two nozzles being off of its design Mach number for all flow Mach numbers. If one nozzle establishes screech, it will couple with the other one resulting in high amplitudes. The insensitivity of the screech amplitude to the nozzle design Mach number was observed and discussed in Ref. 11.

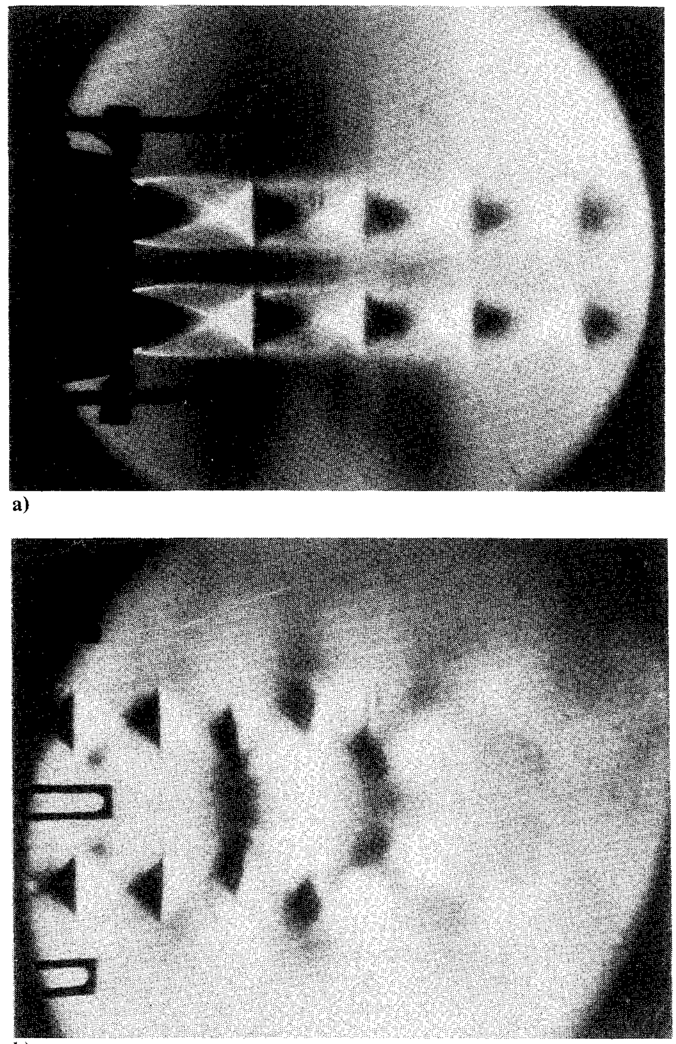
Optical Results

The phase-averaged schlieren system described earlier was used to view the jet plume coupling. Figure 5 shows typical results for uncoupled and coupled twin-jet plumes. Figure 5a shows two jet plumes with no shock cell distortion, whereas Fig. 5b reveals significant shock cell distortion. The shock cells are seen to be displaced in phase, as would be expected, since the large-scale, coherent structure has been shown to be in phase in the outside region of the two plumes. The dark area in the inner region is the intense acoustic wave. The wave propagates forward impinging on the structure of the nozzle and possibly resulting in structural failure. The alternating light and dark areas about either plume also verify that the large-scale, coherent, instability mode is helical, as was shown with coherence and phase measurements.

Screech Amplitude Enhancement

The jet shear layer is known to receive energy from outside sources.[5] To avoid the possible effects of reflected energy from surfaces ahead of the exit plane of the nozzles, all surfaces were covered with acoustically absorbent material. Measurements with and without the material on the exterior surfaces of the nozzles revealed that it had no effect on the amplitude of the screech tones. Because of this, all measurements were made with no material on the nozzles. However, the end of the plenum and the floor were covered with 2-in. thick foam for the entire test.

The largest effect on the screech amplitudes was achieved by increasing the thickness of the jet shear layer at the exit plane. This was accomplished by adding 18-in. flexible hoses between the plenum and the nozzles. The flexible hoses permitted variable spacing between the nozzles, but more importantly



a)

b)

Fig. 5 Phase-averaged schlieren showing result of plume coupling: a) no coupling; b) coupling.

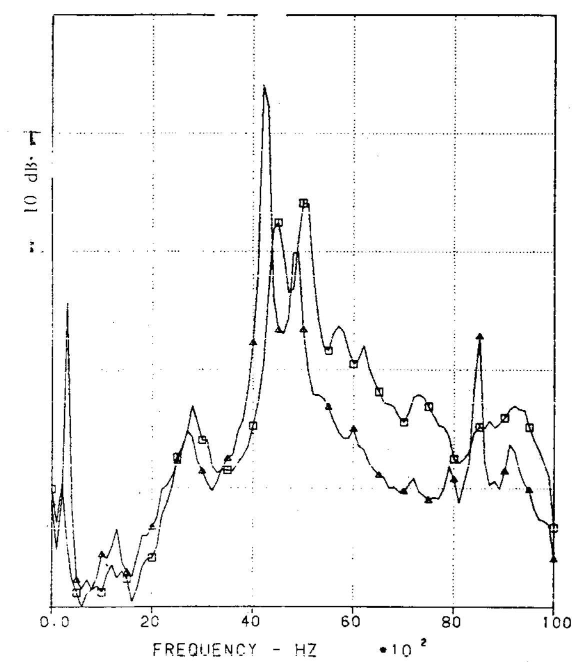


Fig. 6 Spectra from single nozzle with extension hose—and without extension hose—NPR = 3.42.

the hoses resulted in a thicker boundary layer at the nozzle exit. It is established[19] that the boundary-layer characteristics at the jet exit can greatly affect the sensitivity of a jet. Figure 6 illustrates the effect of the extension hose. Spectra from a single nozzle with and without the extension hose are shown. The extension hose significantly amplifies (12 dB) the screech mode near 4.5 kHz while suppressing the screech mode near 5.0 kHz (4 dB). There is also a small reduction in the screech frequencies. In general, at least one of the screech modes was amplified with the addition of the extension hose.

Since the primary objective of the effort was to study the effectiveness of screech-tone suppression techniques, the higher the amplitude of the screech tone, the better the evaluation of the suppression technique. Thus, the extension hoses were used for the entire test.

Screech Tone Suppression

Tabs

Methods to suppress choked jet noise were investigated in the early fifties by Powell.[1,18] He clearly showed that altering (thickening) the shear layer at the jet exit would reduce the generated noise. He used notches and radial vanes to thicken the shear layer. In the midseventies,[20] rectangular tabs were investigated as a means to disturb the jet at the exit plane. Recently[6] tabs have been applied to the twin-jet screech problem. It has been demonstrated that a tab on one jet can decouple the jets and thus reduce the screech amplitude. However, there was a lack of information on the size or number of tabs necessary to obtain the desired suppression.

A series of three tab sizes and multiple tabs (up to 3) were investigated in the current study. A sketch of the tabs is shown in Fig. 7 along with a typical installation on the nozzle. The tabs were attached to the outside of the nozzle with only the tapered portion of the tab in the flow, resulting in less than one-half of 1% of the nozzle exit area per tab for the largest tab. Actual penetration of the tabs into the flow is equal to one-half of their width. The effectiveness of each of the tabs was evaluated on a single nozzle. The rationale for this was that if a suppression concept could effectively suppress the screech of one nozzle, it could effectively decouple two jet plumes in close proximity. This has been established in Ref. 6. The single nozzle tab suppression is given in Fig. 8 for jet Mach numbers of 1.22 and 1.47. Suppression levels are shown for all three tab sizes and for 1, 2, or 3 tabs installed. Suppression is based on the amount of reduction in the peak mode without regard to which mode it is. Tab 1, the smallest tab, was not as effective as the two larger tabs, and in many cases Tab 3 was more effective than Tab. 2. These suppression levels were obtained with no flexible hoses between the plenum and nozzle. It has already been shown that the hoses increase the screech-tone amplitudes, and thus the tabs result in more suppression when the screech tones are of higher amplitude. Based on these results, Tab 3 was selected for testing on the twin-jet configuration.

Figure 9 illustrates the effectiveness of Tab 3 in suppressing the screech-tone amplitudes. The suppression shown is for the

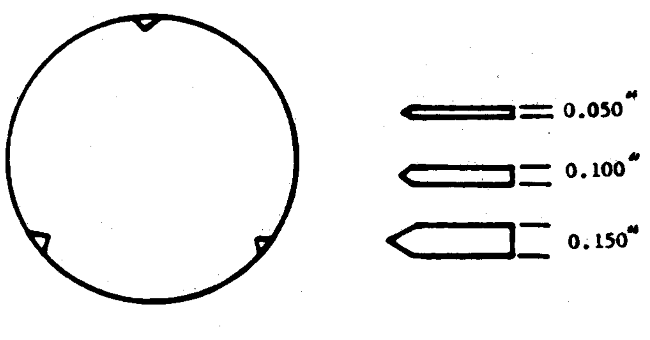


Fig. 7 Sketch of tabs and typical installation on nozzle.

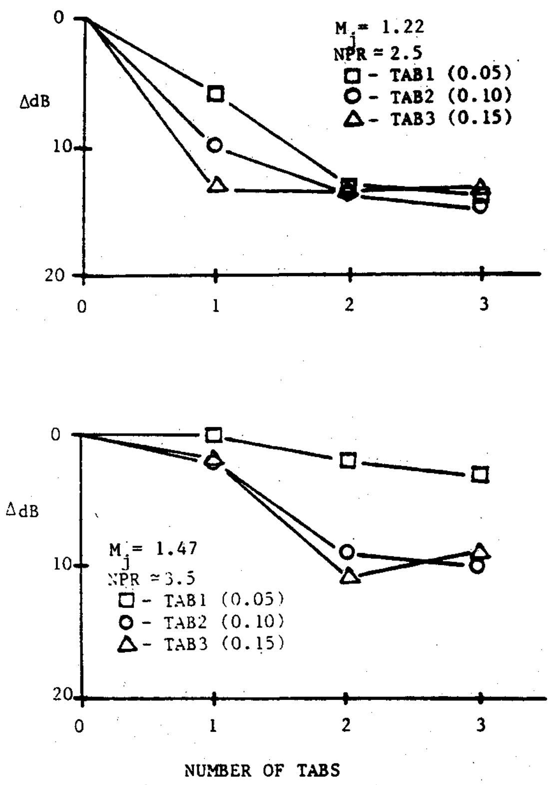


Fig. 8 Screech suppression for single nozzle tab configurations.

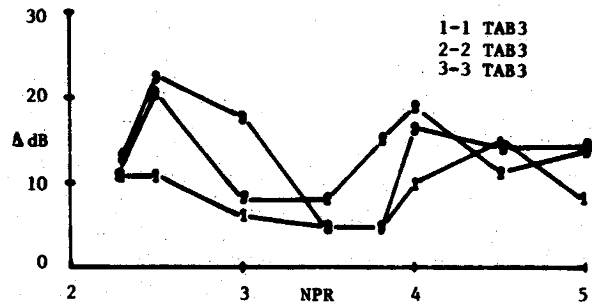
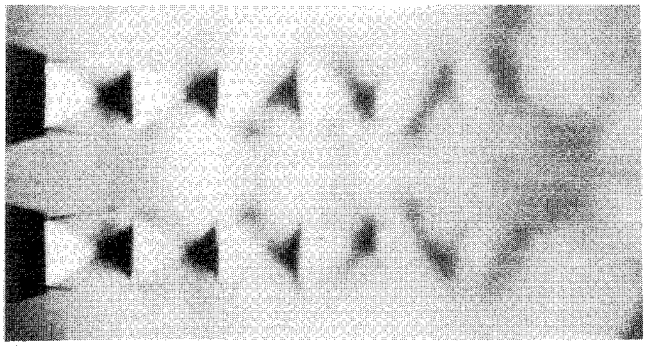


Fig. 9 Screech tone suppression with Tab 3 for twin-jet configuration, $s/d = 2.25$.

B1 mode, which was maximum at most jet Mach numbers. One tab generally resulted in the least suppression. Three tabs clearly result in the most suppression at the lower Mach number, whereas two tabs appear to do somewhat better than three tabs at the midrange Mach numbers. At the higher Mach numbers, the results are mixed. It is interesting to note that all three configurations (1, 2, or 3 tabs) exhibit a significant decrease in suppression in the mid-Mach number range. It implies that the large-scale coherent structure is less susceptible to distortion at those Mach numbers. Even increasing the number of tabs does not increase the effectiveness. It can be concluded that more than one tab is necessary to achieve maximum suppression. Suppression of the screech-tone amplitudes by 15 dB can be achieved at most jet Mach numbers. However, at some Mach numbers, the suppression may only be 5 dB.

Phase-averaged schlieren results for the various tab configurations are shown in Fig. 10. The nozzles are spaced at 2.25 D (jet diameters) and operating at a NPR of 3. Figure 10a clearly illustrates jet coupling when no tabs are installed by the inphase distortion of the shock cells. Figure 10b shows the effect of one Tab 3. The two jet plumes are completely decoupled. Figures 10c and 10d show the effect of two and three tabs,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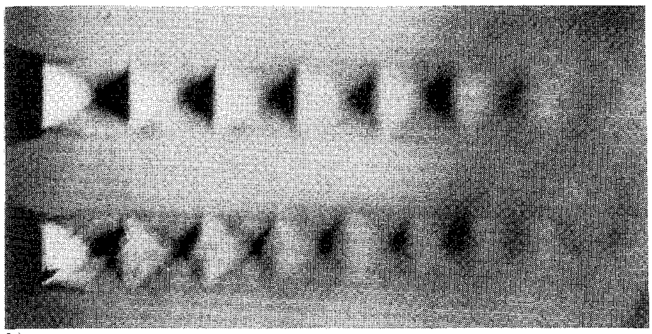
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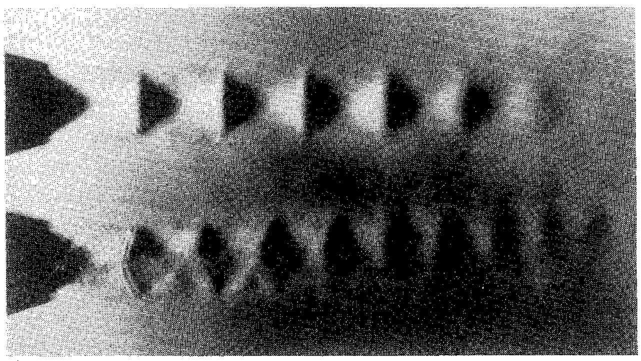
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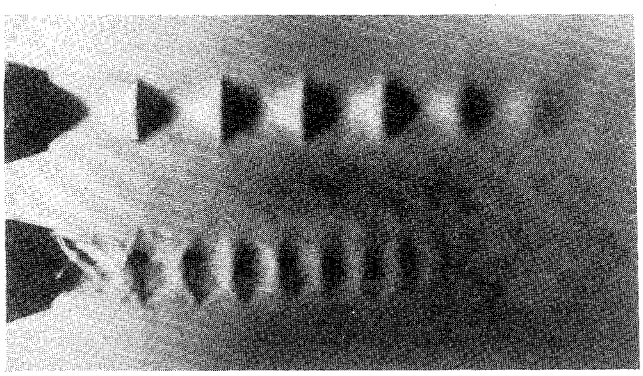
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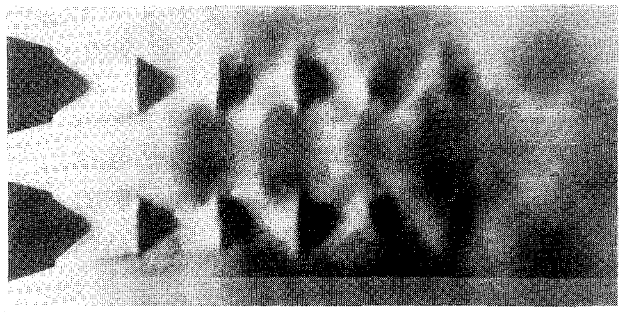
Fig. 10 Phase-averaged schlieren of a) no Tab 3, b) 1 Tab 3; c) 2 Tab 3; d) 3 Tab 3; for NPR of 3.0 and spacing of 2.25D.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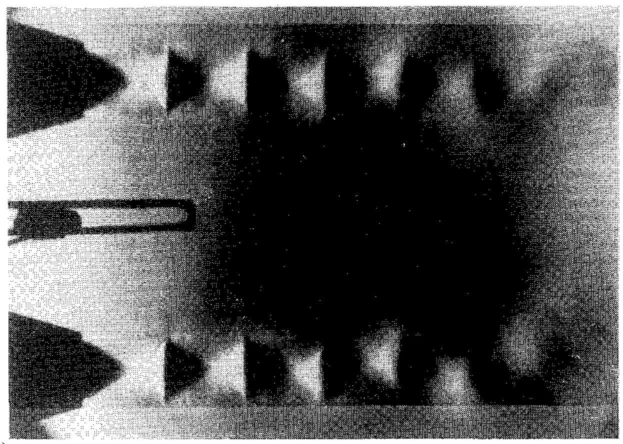
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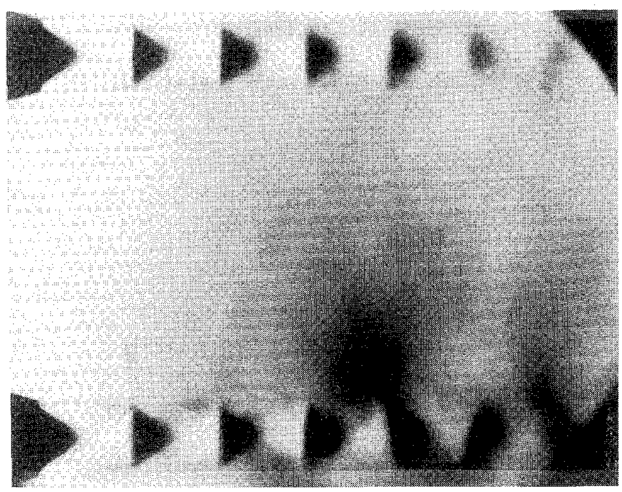
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Fig. 11 Phase-averaged schlieren showing nozzle spacing effect: a) $s/d = 2.25$; b) $s/d = 4.5$; c) $s/d = 6$; NPR = 3.0.

respectively. It is clear that one tab can be sufficient to decouple the jet plumes, but increased screech suppression is obtained by adding additional tabs, which further break down the shock cells.

Spacing

The spacing between two jets is known to affect the acoustic environment in the internozzle region.[11] Since the spacing affects the internozzle acoustic levels, it was considered as a technique to suppress the levels. In the current study, center-to-center spacings of 2.25–7.0 jet diam were tested to quantify the effect of nozzle spacing on the screech tone amplitudes in

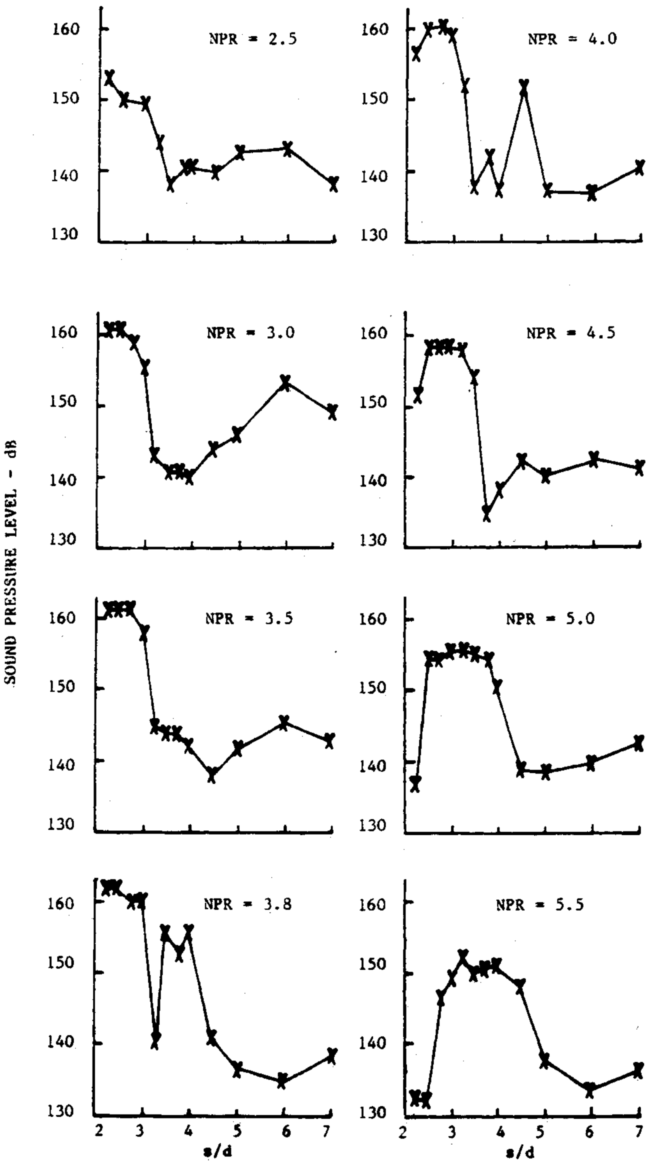
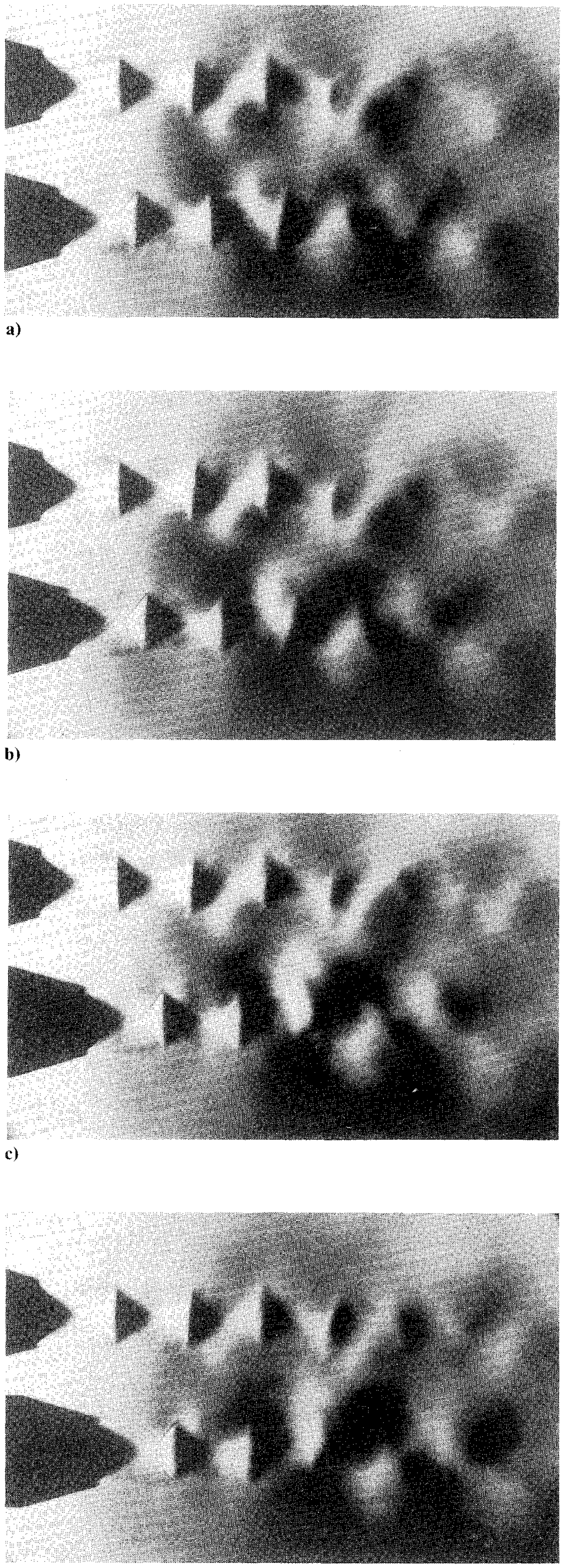


Fig. 12 Effect of nozzle spacing on screech tone amplitude.

the internozzle region. Acoustic measurements and flow visualization were used to characterize the screech environment.

Phase-averaged schlieren photographs of three jet lateral spacings (s/d = 2.25, 4.5, 6) are shown in Fig. 11. The high internozzle screech tone amplitudes can be associated with a synchrophased coupling of the two jet plumes.[6] This synchrophased coupling can be observed for each of the jet lateral spacings by noting the in-phase displacement of the shock cells of both jets. Plume coupling was observed visually for the maximum spacing tested of 7 jet diam.

The results of lateral spacing effect on the maximum screech tone amplitude are summarized in Fig. 12. Data for jet spacings from 2.25 to 7.0 diam are presented. The levels shown are for the maximum screech tone without respect to which mode it was. However, in most cases the B mode was dominant. When the B mode was not the maximum tone, the C mode was maximum. The C mode was dominant mainly at a NPR of 3.5 for the larger nozzle spacings (greater than s/d = 3.0). Switching of the dominant mode from B to C for larger spacings was observed by Wlezien[11]; however, his larger spacings were limited to s/d = 3.2. The switching from B mode to C mode did not occur for other NPR ratios, even at the larger spacings.



a)

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Fig. 13 Phased-averaged schlieren of axial shift a) 1/4-in. shift; b) 1/2-in. shift; c) 3/4-in. shift; d) 1-in. shift (s/d = 2.25).

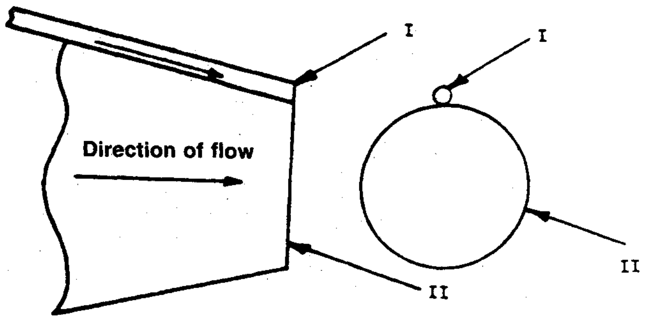

Fig. 14 Sketch of secondary jet concept.

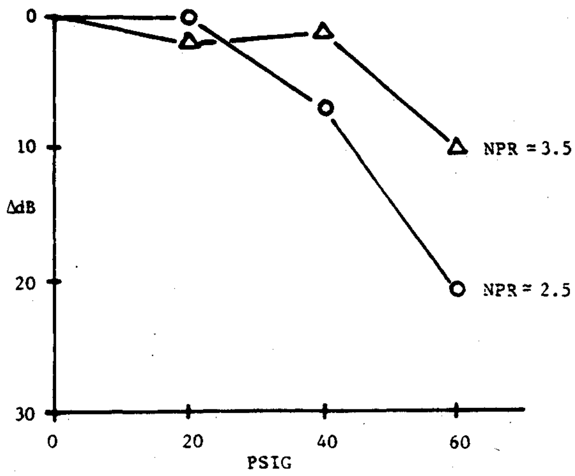

Fig. 15 Single nozzle secondary air-jet suppression.

Many observations can be made from the data in Fig. 12. The maximum screech tone amplitude reached a level of 162 dB for NPRs from 3.0 to 4.0. Above and below this range, the maximum amplitude is lower. Another observation is that the screech-tone amplitudes are a strong function of jet spacing. The amplitudes decrease dramatically at a spacing near 3 diam for the lower NPR; however, as the NPR increases, the spacing at which the dramatic decrease occurs also increases. At NPR = 3.0, the decrease occurs at $s/d = 3.2$, whereas for NPR = 5.0, it occurs at $s/d = 4.5$. One should note that the screech-tone amplitudes can increase significantly as the spacing is increased. For example, at an NPR of 4.0, the amplitude increased 13 dB by increasing the spacing from 4 jet diam to 4.5 jet diam. Also, at higher NPRs (>4.0) and close spacings ($s/d = 2.5$), the screech amplitude decreases as NPR increases. Thus, at a high NPR, the screech amplitude could be attenuated by decreasing the jet spacing.

Axial Displacement

The coupling of twin-jet plumes is a phased phenomenon. It has been shown that the large-scale, coherent structures in each jet plume are syncrophased. It was believed that if one jet was shifted axially, altering the spatial phasing of the two plumes, the syncrophasing of the large-scale coherent structure would also be altered resulting in a reduction of the screech-tone amplitude. Measurements were made at four different axial positions, 1/4-, 1/2-, 3/4-, and 1-in. displacement. Phase-averaged schlieren results are presented in Fig. 13. These can be compared to the unshifted results in Fig. 11. All of the results are for a NPR of 3.0 and lateral spacing of $s/d = 2.25$. From the photographs it appears that axial shifting of one nozzle does not decouple the plumes. In fact, at the larger shifted locations, Fig. 13, it appears that the plume coupling is enhanced. The acoustic measurements revealed only 1–2 dB variation in the screech-tone amplitude for all axial positions. Both attenuation (1 dB) and amplification (1–2 dB) were observed. Thus it can be concluded that axial shifting of one nozzle to suppress screech tones is not effective.

Secondary Air Jet

A tab protruding into the jet at the exit plane has been shown to be effective in suppressing the screech tone. It was speculated that a small high-pressure jet emanating at the exit plane of the larger jet would also be effective in disrupting the large-scale structure in the jet and hence suppress the screech tone. A sketch of the arrangement tested is shown in Fig. 14. The secondary jet consisted of a tube with a constant inside diameter of 3/16 of an inch. The concept was tested on a single jet with the results shown in Fig. 15. The pressure in the secondary jet was varied up to 60 psig. The amount of suppression increased as the pressure in the secondary jet increased. The amount of suppression is also a function of the NPR of the primary jet. For an NPR of 2.5 and 60 psig in the secondary jet, 20 dB of suppression of the screech tone was achieved, but for an NPR of 3.5, only 10 dB of suppression was realized. These results are for a single jet. Valid data for the twin-jet configuration were not obtained. However, since the secondary jet suppression concept was successful in suppressing the screech tone for a single jet, it should be equally successful for the twin-jet configuration. To be as successful as the single jet may require a secondary jet on each of the twin jets.

Summary and Conclusions

A laboratory test was performed to evaluate the effectiveness of several concepts in suppressing twin-jet screech. The axisymmetric C-D nozzles used to generate the screech were 4.7% model of the F-15 aircraft simulating military power. The suppression concepts consisted of tabs, lateral spacing, longitudinal spacing, and secondary jet. Data were obtained for nozzle pressure ratios up to 5.5, resulting in fully expanded jet Mach numbers up to 1.75.

Narrowband screech tone amplitudes as high as 162 dB were measured. For most test conditions, the helical B modes were dominant. Twin-jet screech tone amplitudes can be as much as 20 dB greater than single jet amplitudes. The large-scale coherent structure in the jet plumes can be visually observed with a phased averaged schlieren system.

Small tabs placed in the flow at the exit plane of the nozzle have been shown to be very effective in suppressing the amplitudes of the screech tones. The size and number of tabs affect the amount of suppression realized. A tab may be too small, or two tabs may be required to achieve maximum suppression. Lateral spacing of the twin jets can significantly affect the screech-tone amplitudes. As the lateral spacing is increased, the screech tone amplitude drops rapidly at some spacing in the range of 3–5 jet diam depending on the NPR. However, as the lateral spacing is increased beyond this point, the screech tone amplitude increases. In some cases this increase was as large as 15 dB. Axial spacing (or shifting) of the nozzle exit planes was found to have very little effect on the screech-tone amplitudes. A small secondary jet was shown to be very effective in suppressing the screech tone of a single jet; it should be just as effective on twin jets, but this was not verified.

It is concluded that twin-jet screech tones can be effectively suppressed by the proper size and number of tabs or by a small secondary jet. Either concept can essentially eliminate the screech tone with proper optimization.

References

[1]Powell, A., "On the Mechanism of Choked Jet Noise," *Proceedings of the Physical Society of London*, Section B, Vol. 66, 1953, pp. 1039–1056.

[2]Seiner, J. M., "Advances in High Speed Jet Aeroacoustics," AIAA Paper 84-2275, Oct. 1984.

[3]Cohen, J., and Wygnanski, I., "The Evolution of Instabilities in the Axisymmetric Jet. Part 1 The Linear Growth of Disturbances Near the Nozzle," *Journal of Fluid Mechanics*, Vol. 176, Feb. 1987, pp. 191.

[4]Cohen, J., and Wygnanski, I., "The Evolution of Instabilities in the Axisymmetric Jet. Part 2 The Flow Resulting From the Interaction Between Two Waves," *Journal Fluid Mechanics*, Vol. 176, March 1987, pp. 221–235.

[5]Ahuja, K. K., "Some Unique Experiments on Receptivity," AIAA Paper 85-0533, March 1985.

[6]Seiner, J. M., Manning, J. C., and Ponton, M. K., "Dynamic Pressure Loads Associated with Twin Supersonic Plume Resonance," AIAA Paper 86-1539, Aug. 1986.

[7]Seiner, J. M., Manning, J. C., and Ponton, M. K., "Model and Full Scale Study of Twin Supersonic Plume Resonance," AIAA Paper 87-0244, Jan. 1987.

[8]Shaw, L. L., Otto, C. J., Banaszak, D. L., and Plzak, G. A., "F-15 8.33% Model Internozzle Dynamic Pressure Environment," AFWAL-TM-86-198-FIBG, May 1986.

[9]Berndt, D. E., "Dynamic Pressure Fluctuations In the Internozzle Region of a Twin Jet Nacelle," Society of Automotive Engineers, Warrendale, PA, SAE-841540, Oct. 1984.

[10]Tam, C. K. W., and Seiner, J. M., "Analysis of Twin Supersonic Plume Resonance," AIAA Paper 87-2695, Oct. 1987.

[11]Wlezien, R. W., "Nozzle Geometry Effects on Supersonic Jet Interaction," AIAA Paper 87-2694, Oct. 1987.

[12]Karamchete, K., Bauer, A. B., Shields, W. L., Stegen, G. R., and Woolley, J. P., "Some Features of an Edge-Tone Flow Field," NASA SP207, July 1969.

[13]Maestrello, L., "An Experimental Study on Porous Plug Jet Noise Suppression," AIAA Paper 79-0673, July 1979.

[14]Tanna, H. K., Tam, C. K. W., and Brown, W. H., "Shock Associated Noise Reduction From Inverted-Velocity Profile Coanular Jets," NASA CR-3454, Sept. 1981.

[15]Dosanjh, D. S., and Montegani, F. J., "Underexpanded Jet Noise Reduction Using Radial Flow Impingement," *AIAA Journal*, Vol. 7, No. 3, March 1969, pp. 458–464.

[16]Tanna, H. K., "An Experimental Study of Jet Noise Part II: Shock Associated Noise," *Journal of Sound & Vibration*, Vol. 50, No. 3, 1977, pp. 419–444.

[17]Wlezien, R. W., and Kibens, V., "The Influence of Nozzle Asymmetry on Supersonic Jets," AIAA Paper 86-0277, Jan. 1986.

[18]Powell, A., "The Reduction of Choked Jet Noise," *Proceedings of the Physical Society, London,* 4-B, Vol. 67, 1953.

[19]Chambers, F. W., and Goldschmidt, V. W., "Acoustic Interaction with a Turbulent Plane Jet: Effects on Mean Flow," *AIAA Journal*, Vol. 20, No. 6, 1982, pp. 797–804.

[20]Bradbury, L. J. S., and Khaden, A. H., "The Distortion of a Jet by Tabs," *Journal of Fluid Mechanics*, Vol. 70, pt. 4, 1975, pp. 801–813.

[21]Lepicovsky, J. et al., "Coherent Large-Scale Structures In High Reynolds Number Supersonic Jets," *AIAA Journal*, Vol. 25, No. 11, Nov. 1987 pp. 1419–1425.