Supersonic Jet Screech Tone Cancellation

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A new method of supersonic jet screech tone reduction is presented. The method utilizes a sound reflecting surface positioned upstream of the nozzle exit a distance of one-quarter wavelength of the fundamental screech tone. The reflector establishes a standing wave pattern of acoustic waves with a node at the nozzle exit plane. The pressure minimum at the exit halts the screech tone feedback mechanism. Experimental results indicate that the method eliminates supersonic jet screech as effectively as the currently accepted technique using an intrusive tab, but without distortion of the jet flow. The change in shock cell spacing, which occurs with an intrusive tab, does not occur when screech is cancelled with the new technique. The broadband shock-associated noise is also influenced much less when the jet screech tones are eliminated by the new method.

Introduction

NOISE components from an imperfectly expanded supersonic jet include jet mixing noise, shock-associated broadband noise, and often the entire spectrum is dominated by a third component of high-amplitude tones referred to as jet screech. The screech tones generally occur in cold flow model jets although Hay and Rose[1] have measured screech tones from full-scale jet engines at cruise conditions. Hay and Rose noted damage to nearby surfaces due to acoustic fatigue caused by these tones. Efforts to understand and eliminate jet screech have persisted because of the desirable effects of screech reduction and to allow a more accurate study of broadband shock-associated noise which is dominated in model studies by the screech tone and its harmonics.

Jet screech tones were first studied in model supersonic jets by Powell.[2,3] Powell proposed that jet screech was caused by an initial flow disturbance which issues from the nozzle exit and propagates downstream where it interacts with the shock cell system to generate noise. The resulting noise was assumed to radiate upstream outside the supersonic flow to produce another disturbance as it intersects the nozzle lip. In this manner a resonant loop is established resulting in the screech tone and associated harmonics.

Davies and Oldfield[4] performed a careful study of the shock cell system in circular jets and noted different screech "modes" associated with changes in screech frequency and pressure ratio. Poldervaart et al.[5] produced photographic evidence of the feedback loop mechanism proposed by Powell. Their results show oscillations of the shock cells at the screech frequency and acoustic feedback outside the shock system to the nozzle exit. When the screech tone impinges on the nozzle exit, it apparently causes a vortex to develop and convect downstream. The vortex interaction with the shock cells perpetuates the screech.

The screech tones have a very unsteady amplitude. Harper-Bourne and Fisher,[6] in an effort to make the screech tones more steady, placed a reflecting surface at the nozzle exit plane. This improved the stationary quality of the tones but increased the amplitude. When the surface was covered with acoustically absorbent foam, the amplitude of the screech was reduced, but remained higher than tones from the jet without the reflecting surface.

The first effective method of screech reduction, using a small tab installed at the nozzle exit plane to intrude into the flow, is described by Tanna et al.[7] It was assumed that symmetry of the nozzle exit was important in establishing the screech feedback loop so the effectiveness of the tab was attributed to the resulting distortion of the nozzle exit symmetry. The intrusive tab eliminated screech but also reduced the shock cell spacing by about 10% as reported by Norum and Seiner[8] and Seiner and Yu.[9] In addition to eliminating the screech tones, the intrusive tab altered the shock-associated broadband noise. Screech removal with the tab thus did not allow an accurate analysis of the resulting broadband noise and introduced a possibly unknown relationship between the screech tones and the broadband shock-associated noise.

Kozlowski and Packman[10] reported a screech reduction method using tabs at the nozzle lip which did not intrude into the flow. They contend that the screech tones can be eliminated by simulating full-scale nozzle lip irregularities through the use of nozzle lip modifications or nonintrusive tabs. This method aroused interest since screech reduction was obtained by a means which did not disturb the flow. Their results, however, were obtained with one-third octave band analysis which does not show discrete tones that may be present in narrowband data.

Norum[11] recently studied possible nonintrusive screech suppression techniques using a turbulent jet issuing from a small tube with various exit alterations such as slots and bevels, and various reflector plates similar to Harper-Bourne and Fisher. Norum's results provide good documentation of screech behavior under a variety of conditions.

The experimental study described here suggests an alternative method of screech reduction. Preliminary work on the new method is described by Denham.[12] Acoustic measurements along with selected schlieren photographs compare this new method with existing techniques.

Experimental Apparatus

Unheated air, supplied by compressors, passed through three large (7.6 m long, 1.5 m diameter) tanks and then through a pressure control system to the jet. The pressure could be set from a control room and automatically maintained within ±1034 Pa (±0.15 psia). This allowed a maximum error of 0.6% in the pressure set point for a fully expanded jet Mach number of 1.4. After the pressure control valves, the flow was diffused through a 4 deg included angle diffuser to a settling chamber. The pressure control system was far upstream from the diffuser so valve noise in the

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settling chamber was insignificant. A Keil probe and thermocouples were installed in the settling chamber to obtain necessary aerodynamic data. From the settling chamber the flows passed through two contractions to a 2-cm-diam conical nozzle. The nozzle was convergent with a sharp edge lip.

Far-field acoustic data were obtained in an anechoic chamber with a free-field cavity of 5.8×5.5×3.6 m high. The low-frequency cutoff for the chamber was 120 Hz. Above this frequency, the wedge/fiberglass combination had a combined absorption coefficient of 0.99. The free-field sound was measured with a ¼ in. Bruel & Kjaer free-field condenser microphone mounted on a traversing stand. The measurements were obtained with normal incidence at locations parallel to the jet axis. The sideline distance was 183 cm as shown in Fig. 1. The acoustic near field was found to be well contained in a region within 40 cm of the jet axis thus measurements at 183 cm are indeed in the far field. The flow was directed toward the open chamber doors and a large 60 deg foam wedge was constructed and positioned in the doorway to keep the chamber anechoic. Entrainment air was provided through several acoustically treated air-conditioning ducts.

Acoustic data were also obtained in a reverberation room with an empty volume of 525 m³. These data were obtained with averaging over space and time using a ⅛ in. Bruel & Kjaer pressure microphone on a slowly rotating boom with a diameter of 183 cm. The rotating boom was necessary because tones due to jet screech occur in the spectrum. Noise in a reverberation room, particularly tones in a rectangularly shaped room, may produce a lattice of standing waves. Several metal and concrete objects were placed near the walls of the reverberation room to help diffuse the sound field. The rotating boom continuously moved through any remaining standing wave lattice sampling points in space during the averaging process. The boom rotated at 1 rpm and the averaging process continued for approximately 5.5 min. Five hundred summations were averaged for each point of the 800 point spectrum. The boom was started at the same position for each measurement. The path of the boom was free from air flow. The reverberation room, jet, and rotating boom are schematically shown in Fig. 2.

Because of the complexities associated with the jet noise signal, which contained both high-frequency tones and broadband noise, it was felt that attempts to calibrate the signal to a true power level would not be accurate. Accurate acoustic decay rates could not easily be determined for this type of noise. Acoustic data obtained in the reverberation room are therefore uncalibrated and should only be compared to other reverberation room results. These data, however, provide good insight regarding the overall noise signal. All acoustic signals were processed with a Nicolet 660B Dual Channel Noise Signal Processor.

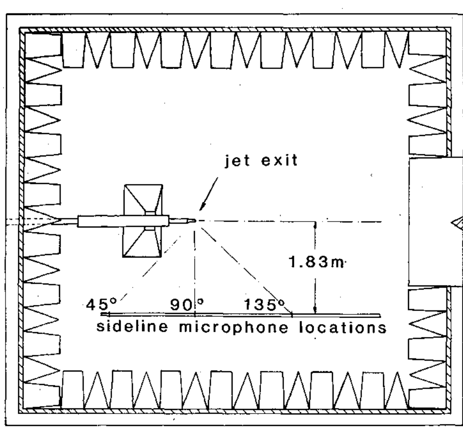

Fig. 1 Anechoic chamber, jet and microphone configuration.

Schlieren photographs were obtained using an Aerolab dual mirror system. A continuous mercury arc lamp source was projected directly on the focal plane of a sheet film camera. The knife edge was vertical. Photographs compared in this work are from the same setup, developed in the same tank, and exposed and printed with identical times and conditions.

Results and Discussion

Screech reductions obtained with intrusive and nonintrusive tabs were compared to screech reduction by a third cancellation method. The cancellation technique was developed in this study. Most data were obtained at values of the shock parameter β equal to 0.98 which corresponds to a fully expanded jet Mach number of $M_j = 1.4$ as determined by

$$M_j^2 - 1 = \beta^2 = 5(P_t/P_a)^{2/7} - 6 \tag{1}$$

where P_t is the jet stagnation pressure and P_a is the ambient pressure.

The first screech reduction technique examined was that suggested by Kozlowski and Packman.[10] Several nonintrusive tab blanks were manufactured in two sizes. The large blanks were $0.4d$ wide by $0.15d$ thick, and the small blanks were $0.15d$ wide by $0.15d$ thick where d is the nozzle diameter. The blanks could be modified as desired and secured to the outside of the nozzle at any of 15 equally spaced circumferential locations. In this manner a wide variety of nozzle lip

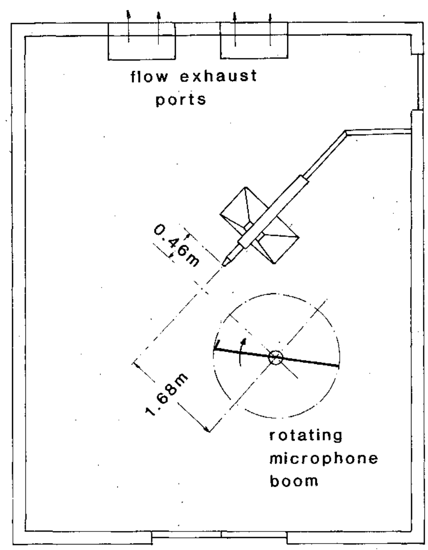

Fig. 2 Reverberation room, jet and microphone configuration.

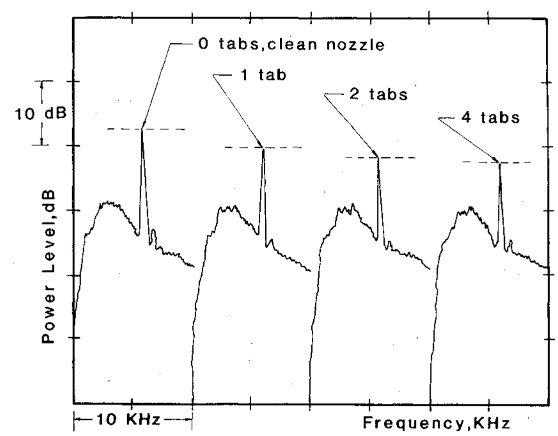

Fig. 3 Nonintrusive tab screech tone reduction as measured in reverberation room.

modifications were studied with narrowband analysis which provided more detailed spectra than the one-third octave band analysis of Kozlowski and Packman.

The basic results obtained with the nonintrusive tabs are summarized in the composite narrowband spectra of Fig. 3. The results obtained in the reverberation room are similar to results from the anechoic chamber. Tone reductions of up to 5 dB are achieved with the addition of several tabs, but in no case was the screech tone eliminated. It was concluded that nonintrusive tabs were not practical for screech elimination although screech reduction was possible without intrusions into the basic flow.

The standard technique for screech tone elimination, intrusive tabs, suggested by Harper-Bourne and Fisher[6] and Tanna et al.,[7] is quite successful at eliminating the screech tone and harmonics from the spectrum. The disadvantage of the technique is the severe distortion to the flow caused by the small tab intruding into the flow at the nozzle exit plane. Results from this method will be compared to those of a new screech reduction technique in the following sections.

Screech Cancellation

A new method for screech elimination has been devised which assumes that the screech mechanism is the feedback process proposed by Powell[2] and that the acoustic waves propagating back to the nozzle exit are nearly plane waves at the nozzle. Under these conditions it is possible to position a reflective surface near the nozzle which establishes a local standing wave pattern from the incident and reflected screech tone. The governing equation for the resulting pressure field is available in elementary acoustic texts such as Kinsler and Frey[13] and is given as

$$P = [(A+B)^2\cos^2(2\pi x/\lambda) + (A-B)^2\sin^2(2\pi x/\lambda)]^{1/2}\cos(\omega t+\phi) \quad (2)$$

where A and B are the amplitudes of the incident and reflected wave, respectively, and λ is the wavelength. x is the distance from the reflective surface and $A \approx B$ for a hard reflector. Equation (2) shows that at distances from the reflecting surface equal to one-quarter of the screech wavelength, three quarters of the wavelength and so on, a minimum pressure occurs. If a reflecting surface is positioned at the proper distance upstream of the exit, a node will occur at the nozzle exit plane. The node will serve to cancel the screech at the nozzle exit and interrupt the feedback mechanism. The concept is sketched in Fig. 4.

Poldervaart et al.,[5] Harper-Bourne and Fisher,[6] and Norum[11] used reflectors at the nozzle exit plane and noted an increase in the screech level. This occurred because the amplitude of the screech at the exit plane was increased by the reflecting surface. For a reflection coefficient of 1.0 the amplitude is doubled.

For measurements with screech tones, a foam disk 10 cm in diameter with a reflection coefficient of 0.59 was placed at the nozzle exit plane. This significantly improved screech amplitude stationarity but also introduced some small changes in the acoustic signal. Narrowband spectra measured at various sideline angles in the anechoic chamber indicate that the reflector disk at the exit plane increases both tones and the surrounding broadband noise in the upstream quadrant while causing decreases in the downstream quadrant. Results from the reverberation room indicate that the net effect is a small increase in screech amplitude (approximately 1 dB) similar to that observed by Harper-Bourne and Fisher.[6] Data also indicate an unexplained increase in screech frequency of about 13% with the foam disk. This increase in frequency is similar to that observed by Norum.[11] Despite the changes produced by the disk, the disk was used at the exit plane to improve stationarity of the screech tones. With the foam disk and increased averaging, screech tone amplitudes were repeatable within 0.6 dB.

In theory the reflector surface for screech cancellation shown in Fig. 4 should be an acoustically hard material with a reflection coefficient of 1.0. In practice, screech cancellation was achieved with such a reflector, but the positioning of the disk needed to be very exact and often proved quite difficult. Screech cancellation with a hard surface reflector was obtained only in the anechoic chamber. It was not obtained in the reverberation room, presumably because of the diffuse acoustic field there. If a porous reflector material is used, such as foam, the reflection coefficient is less than 1.0 and the reflected wave is not 180 deg out of phase with the incident wave. Nonetheless, screech cancellation could still be achieved in both the anechoic chamber and the reverberation room. Figure 5 compares acoustic spectra obtained in the reverberation room for cases with screech, screech removed with an intrusive tab, and screech cancelled with a foam disk located at approximately one-quarter of the screech tone wavelength from the nozzle exit. The effectiveness of the screech cancellation by the foam reflector disk is equal to that of the intrusive tab. The broadband noise in the reverberation room is relatively unaltered when the cancellation method is used. The intrusive tab, however, significantly alters the broadband noise in addition to eliminating the screech tone. The intrusive tab had dimensions based upon nozzle diameter similar to those suggested by Tanna et al.[7]

Results of the cancellation method are shown in more detail in Fig. 6 where spectra shown are typical far-field results obtained in the anechoic chamber. These data confirm that when screech exists, the amplitudes are highest at the upstream locations. The cancellation method is shown to effectively reduce the screech tone at all positions. Although Fig. 5 indicates that the power level at each frequency in the broadband portion of the spectrum is relatively unchanged by

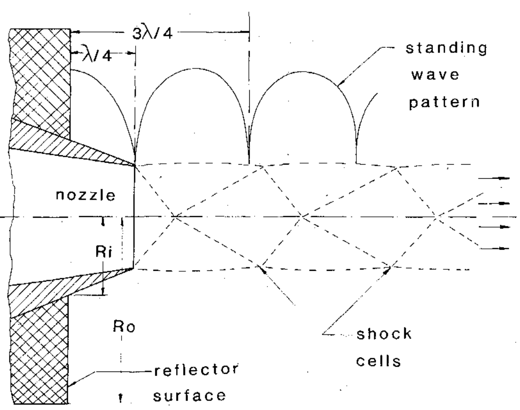

Fig. 4 Schematic diagram of nozzle exit and reflector surface showing the standing wave and flowfield.

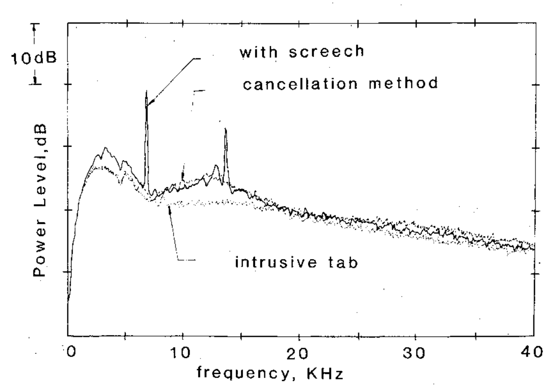

Fig. 5 Reverberation room spectra comparing two screech reduction methods.

screech cancellation, Fig. 6 indicates that the directivity of the broadband peak has shifted. When screech is removed, there is apparently more broadband energy in the upstream locations and less downstream.

It is interesting to compare the flowfields for the cases of screech removal with the intrusive tab and with the cancellation method. When screech is removed with the tab the shock cell spacing is reduced by about 10%, the shock cells are distorted and flow over the tab creates new shock waves.[8]

Figure 7 shows schlieren photographs of the jet in the vicinity of the nozzle exit. When screech is removed with an intrusive tab, Fig. 7c, the shock cell spacing is indeed reduced by about 10% and severe distortions caused by the tab are evident in the flow and shear layer. The tab dramatically changes the character of the flow. When the screech is removed by cancellation, Fig. 7a, the flow appears unaltered from the clean nozzle case with screech. This same result is also observed at downstream locations. It is clear from Fig. 7 that when screech is removed by insertion of an intrusive tab, the changes in the shock cell spacing are a result of the tab and not the screech removal process. Although the results are not shown, schlieren photographs obtained with the clean nozzle and with the foam disk at the exit plane have similar shock cell spacing.

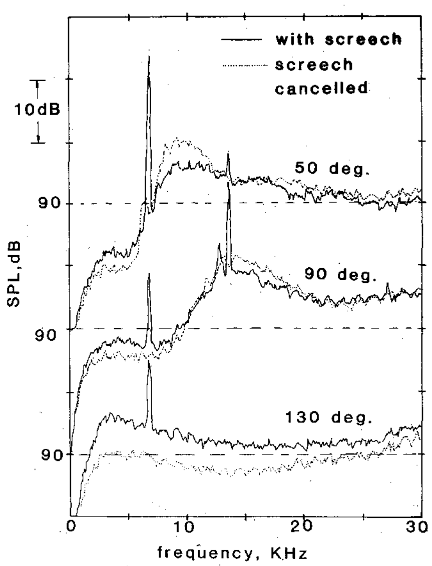

Fig. 6 Typical far-field spectra with screech tones and with screech cancelled.

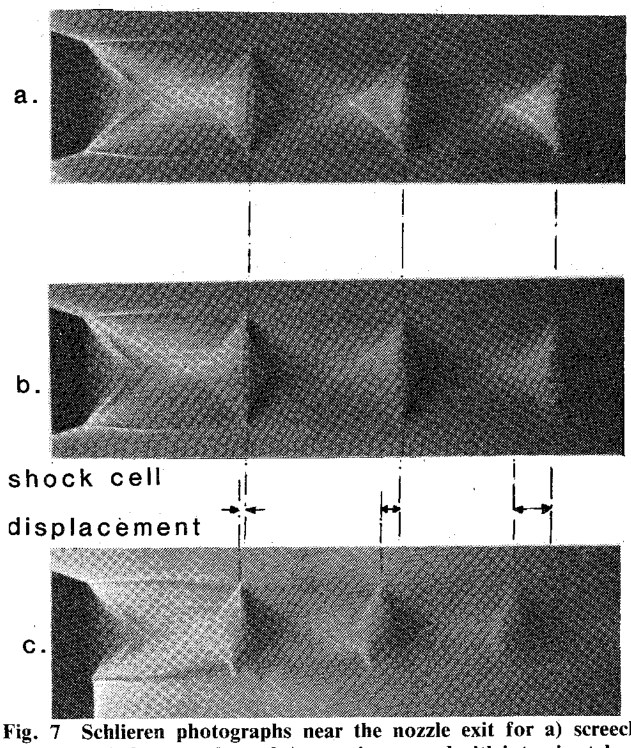

Fig. 7 Schlieren photographs near the nozzle exit for a) screech cancelled, b) clean nozzle, and c) screech removed with intrusive tab.

Verification of the Cancellation Mechanism

If the mechanism is as proposed, it should be possible to move the foam reflector further upstream and obtain cancellation of the screech tone at the second node point. This should occur at three quarters of the screech wavelength as indicated in Fig. 4. Figure 8 shows far-field measurements of the screech tone amplitude at 110 deg sideline angle as a function of foam reflector location. The reflector location, x, is measured from the nozzle exit plane to the foam surface. Clearly the screech amplitude varies in a manner which corresponds to the classic standing wave pattern sketched in Fig. 4. The screech is cancelled when a node occurs at the nozzle exit plane and interrupts the feedback process. When the reflector is positioned such that an antinode occurs at the nozzle exit, the screech feedback mechanism is enforced. Based upon the screech frequency, the first cancellation node should occur at the reflector location where $x = \lambda/4$. Figure 8 shows the first cancellation to occur at $x/\lambda = 0.23$. Since the foam surface is porous, the true reflective surface is not the physical surface of the foam disk, but rather an effective surface located a small distance inside the foam. Foam disk locations of Fig. 8 were measured from the nozzle exit plane to the physical surface of the disk. If x is extended 2.3 mm

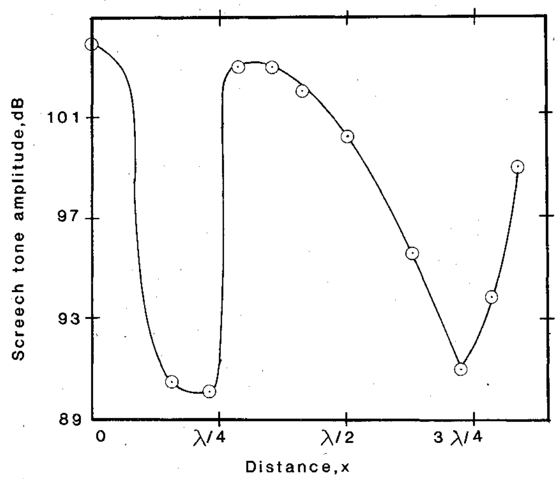

Fig. 8 Variations of screech amplitude with distance, x, from reflector to nozzle exit in terms of λ (λ = screech tone wavelength).

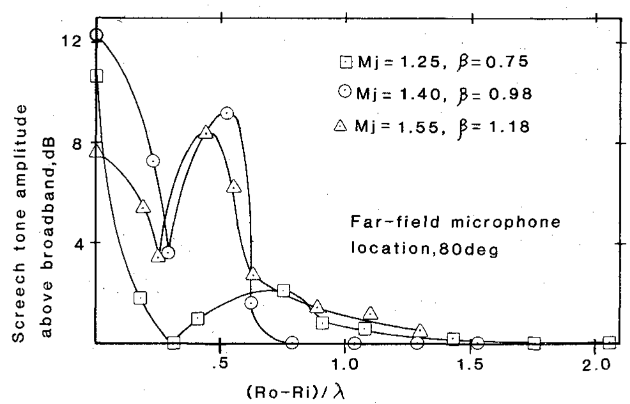

Fig. 9 Variation of screech tone amplitude with radius of reflector foam disk.

into the foam then the first screech cancellation point would occur at precisely $x/\lambda = 0.25$. The second node should occur at $x = 3\lambda/4$ and is measured at approximately $x/\lambda = 0.71$. Agreement with theory appears good.

The effects of the reflector disk diameter are shown in Fig. 9. Figure 9 was generated by setting various size foam reflectors at the optimum screech reduction position, a distance approximately $\lambda/4$ from the nozzle exit. Three different wavelengths were examined by operating at each of three jet Mach numbers (or β). The level of the screech tone above the broadband signal is zero when the disk annular dimension $R_o - R_i$ is larger than 1.5λ. Disk sizes in this range effectively cancel the screech. In the range $(R_o - R_i)/\lambda < 1.0$, the screech tone is not readily cancelled and the results are not well understood. When the reflector extends above the outside nozzle surface by about $\lambda/4$ the cancellation is increased compared to the screech reduction possible at other disk sizes where $(R_o - R_i)/\lambda < 1.0$. At these reflector sizes the disk may act less as a reflector and more as a scattering object. The nonmonotonic behavior of the screech amplitude at small disk sizes is qualitatively similar to the pressure backscatter from a small sphere.[14] The process of edge diffraction may also complicate the results for small disk sizes. As the disk size approaches zero, the screech tone resumes its usual amplitude and frequency. To effectively cancel the screech tone a reflector disk must extend from the nozzle surface to a distance greater than one wavelength of the screech tone.

Several phenomena associated with the cancellation technique are not well understood. The reflector disk increases the screech frequency by approximately 13%. This is observed if the disk is not properly positioned or if it is not of adequate size to cancel the screech tone. This frequency shift has been noted by previous investigators and has been described as a change in screech mode.

Conclusions

It is possible to effectively eliminate supersonic jet screech tones by cancelling the tone at the nozzle exit with a standing acoustic wave thus stopping the screech feedback phenomenon. Changes in shock cell spacing have been shown to be a consequence of the intrusive tab and not the actual removal of screech. With the new cancellation method, screech tones are eliminated without large-scale changes in the shock cell structure.

The relation between broadband shock-associated noise and screech tone removal is also different when the cancellation technique is employed. The broadband noise is less effected by the cancellation technique as compared to the intrusive tab. It is strongly recommended that the cancellation technique be used to eliminate jet screech tones when studying broadband shock-associated jet noise.

For practical applications a reflector surface with a reflection coefficient less than 1.0 is adequate and much easier to position. The reflector disk should extend above the nozzle surface at least a distance of one wavelength of the fundamental screech tone. When the reflector dimensions are less than one screech-tone wavelength, adequate screech cancellation is not assured, because, for reflector sizes in this range, the amount of cancellation is not monotonic as the reflector size changes.

Acknowledgment

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