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Screech Tone Noise and Mode Switching in Supersonic Swirling Jets

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An experimental study of mode switching phenomena of supersonic jets with swirl is reported. A convergent nozzle with four tangential inlets was used. The pressure ratio corresponds to a fully expanded Mach number up to 1.80. Schlieren visualization of shock structures and pressure measurements indicated effects of swirl, such as flow recirculation. Screech tone frequencies and phase information were measured for both nonswirling and strongly swirling jets. Results suggest existence of quasiperiodic shock structure in strongly swirling jets in spite of swirl-generated recirculation. However, pressure fields are quite different between swirling and nonswirling jets. Both helical and toroidal screech tones were found to exist in strongly swirling jets. Strouhal numbers of the swirling jet screech tones are compared with published theory for nonswirling jets.

I. Introduction

PREVIOUS experimental observations predicted that the screech tone noise emission from a supersonic jet can be eliminated by imparting swirling motion to the jet.[1,2] The elimination was believed to be due either to the enhanced mixing that leads to the disappearance of shock cells[2] or to the swirl-induced flow recirculation.[1] Swirl-induced flow recirculation in supersonic combustion was believed to enhance fuel–air mixing.[3] A more recent study using laser-based techniques shows that adding a moderate amount of swirl to supersonic jets increases jet entrainment by as much as 60% compared with the same in nonswirling counterparts.[4] In nonswirling compressible jets, typical two-dimensional (or azimuthal) vortex roll-up is believed to be suppressed, and mixing and entrainment are reduced compared with their incompressible counterparts. Therefore, to counter the adverse effects of compressibility on mixing, adding swirl to a supersonic jet is desirable. The enhanced entrainment and mixing in swirling supersonic jets is thought to be due to the inherent three-dimensionality associated with the axial component of turbulent vorticity in swirling jets.[4,5] A linear hydrodynamic instability analysis of compressible jets has indicated that a moderate amount of swirl increases the growth rate of a jet.[6] The increase is particularly pronounced for the helical/azimuthal instability mode.[6] Similar analyses and results have also been reported for incompressible swirling jets.[7] It appears that introducing axial vortices into a supersonic jet will help to reduce screech tone noise as a result of enhanced mixing. However, one should be cautioned that growth rates in supersonic swirling jets are still lower than those in incompressible swirling jets.[4]

In subsonic-gas-turbine-type combustors, swirl has been known to enhance fuel–air mixing and flame stabilization due to the induced internal flow recirculation (see, for examples, Refs. 8–11). Supersonic swirling jet mixing has recently been experimentally studied, where the enhanced mixing and flow recirculation was attributed to vortex breakdown,[12] similar to that in incompressible swirling jets.[13,14] However, for a long time flow recirculation had not been definitely confirmed in spite of the observed enhanced mixing that represents the significance of the effects of swirl. In a recent experimental study on swirling jet screech tones, such flow recirculation was visualized for a sufficient degree of swirl.[15] Screech tones of supersonic swirling jets were found to exist for a fully expanded Mach number M_j up to, and likely beyond, 1.80 in spite of the flow recirculation. This suggests swirl alone may not eliminate screech tones.

Screech tones are known to enhance mixing and the spread rate of nonswirling supersonic jets. The screech tone noise phenomenon is a feedback process where the instability wave generated at the nozzle exit interacts with the quasiperiodic shock cell structure to generate noise. The noise propagates upstream to the nozzle exit, where it further excites instability waves. Intense noise generation is known to occur at the jet boundary in the region of the fourth and the fifth shock cells. Such noise has distinct narrow-band frequencies, as can be seen in the porwer spectrum. Supersonic jets created by circular, elliptic, rectangular, and square nozzles all have screech tones (see, for example, Refs. 16–20). For a review of detail screech tone noise characteristics of circular jets, the reader is referred to a recent paper by Tam.[16] Jets with various nozzle shapes share the same general screech noise features as those of circular jets.

The screech-induced mixing enhancement in nonswirling jets is most significant for M_j in the range of approximately 1.12–1.50, depending on the nozzle geometry. It is known that screech tones switch modes between the axisymmetric toroidal and helical modes over similar ranges of M_j. A single helical mode is also called a spinning mode, whereas the flapping mode results from two simultaneous helical instability modes having the same frequency but opposite senses. The transition from the axisymmetric toroidal mode (azimuthal vortex) to the helical mode represents an increase in three-dimensionality, which is desirable for mixing enhancement in supersonic compressible jets. It is known that the toroidal and helical modes do not exist simultaneously, although they may switch from one to the other over this range of M_j (1.12–1.50). As M_j is increased, the helical mode becomes dominant and eventually the toroidal mode ceases to exist.[16]

Compared with their nonswirling counterparts, in supersonic swirling jets the enhanced mixing can therefore result from both flow recirculation and helical screech tones. It is therefore of interest to investigate the screech tone and mode switching characteristics of supersonic swirling jets. Questions that one can ask include the following: 1) How does swirl change the shock structure that may in turn change screech tone characteristics such as frequency and Strouhal number? 2) How can swirl reduce the screech tone amplitude if it cannot eliminate it altogether? 3) How does flow recirculation affect screech tone characteristics and mode switching? To the authors' knowledge, this study is the first to establish experimentally the effects of swirl in supersonic jets on pressure field, shock structure, and onset of flow recirculation. After the evidence of the effects of swirl is demonstrated, screech tone characteristics and mode switching in swirling supersonic jets are reported and compared with nonswirling jet results. Strouhal numbers (Sr) of screech tones of the swirling jets studied are compared with a

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theory developed for nonswirling jets (see Ref. 16 for a review). This may help to shed light on how the theory can be used and/or extended for swirling jets.

II. Experiment

The nozzle used for the experiment is shown in Fig. 1 with all of the appropriate dimensions. The jet fluid is air, supplied from a large reservoir (at a nominal 298 K) with a manifold connected to the four tangential and one axial inlets of the nozzle. The ambient fluid is also air. By controlling the amount of air to these inlets, various degrees of swirl can be achieved. Following a definition used for incompressible swirling jets,[21] a geometrical swirl number S_g is defined as $S_g = (\pi r_0 R_0 / A_t)[m_\theta/(m_\theta + m_a)]$, where m_a and m_θ are the mass flow rates through the axial and tangential inlets to the nozzle, respectively. The values of $A_t(\pi D_t^2/4)$, R_0, and r_0 are shown in Fig. 1, whereas those of m_a and m_θ were measured using a pitot-static tube inserted in the axial and tangential inlets upstream of the nozzle. Note that there is no unique definition for swirl number. However, none of the existing definitions are ideal as these definitions represent only the integral effects and not detailed jet exit velocity profiles that should also be considered.[4,7] In Table 1 the theoretical mass flow rate of the choked nozzle flow was calculated and listed for comparison. It was found that the total mass flow rate of nonswirling jets determined by the pitot-static probe and the theoretical value are within 5%. The mass flow rates of the inlets and their sums, i.e., the total mass flow rate, are listed in Table 1. Note that the total mass flow rate decreases with an increase in the degree of swirl at a given pressure ratio for all pressure ratios. This trend of decreasing mass flow rate with increasing degree of swirl is in at least qualitative agreement with previous theoretical prediction for swirling nozzle flows.[22–24] This trend is also one of several manifestations of the effects of swirl, possibly due to the extra stagnation pressure loss arising from the additional tangential shear stress between the flow and the nozzle wall. The three swirl numbers studied are 0, 0.36, and 0.68, with 0.68 representing the maximum degree of swirl achievable with the nozzle. In this study, jets with $S_g = 0.68$ possess flow recirculation and are referred to as strongly swirling jets. It is clear that the mass flow rates of $S_g = 0$ and 0.36 jets are within 2% at any given pressure ratio, whereas the mass flow rate of the $S_g = 0.68$ jets is at least 10% less. The pressure gauge inserted near the back wall of the nozzle (as shown in Fig. 1) was used to measure the reservoir pressure P_r, so designated because it does not vary throughout the radial region at that axial location. The values of M_j for corresponding nonswirling jets, calculated using inviscid, one-dimensional, isentropic flow theory, ranged from 1.05 to 1.80. No simple calculations of M_j could be done for swirling jets because they are intrinsically three dimensional.

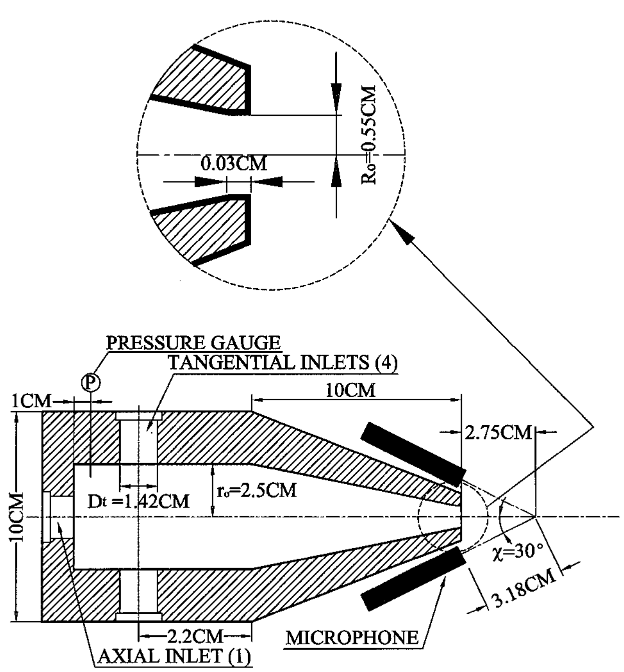


Fig. 1 Schematic of swirling nozzle.

Table 1 Experimental conditions: mass flow rates at tangential and axial inlets

Pressure ratio, P_r/P_a	M_j	S_g	Tangential flow rate, kg/s	Axial flow rate, kg/s	Total flow rate, kg/s
2.36	1.18	0	0	0.0537[a]	0.0537[a]
		0	0	0.0566	0.0566
		0.36	0.0315	0.0240	0.0555
		0.68	0.0497	0	0.0497
3.04	1.37	0	0	0.0692[a]	0.0692[a]
		0	0	0.0727	0.0727
		0.36	0.0404	0.0314	0.0718
		0.68	0.0640	0	0.0640
3.72	1.51	0	0	0.0847[a]	0.0847[a]
		0	0	0.0892	0.0892
		0.36	0.0480	0.0397	0.0877
		0.68	0.0782	0	0.0782
4.40	1.62	0	0	0.1001[a]	0.1001[a]
		0	0	0.1054	0.1054
		0.36	0.0564	0.0471	0.1035
		0.68	0.0923	0	0.0923
5.08	1.72	0	0	0.1156[a]	0.1156[a]
		0	0	0.1220	0.1220
		0.36	0.0643	0.0552	0.1195
		0.68	0.1006	0	0.1006
5.76	1.80	0	0	0.1311[a]	0.1311[a]
		0	0	0.1382	0.1382
		0.36	0.0723	0.0637	0.1360
		0.68	0.1208	0	0.1208

[a]Calculated assuming one-dimensional isentropic nozzle flow through the choked nozzle.

A standard schlieren system, as described in Ref. 25, was used to reveal shock structure. The static pressure profiles were determined using a static pressure probe made of a stainless-steel rod 1.59 mm in diameter and supported by a motor-driven traversing mechanism. The probe tip is conical with a half-angle of 6.5 deg. The pressure port was located 23 mm from the tip and was connected to a pressure transducer. A desktop computer with data acquisition interface was used for data collection. Schlieren visualization revealed no visible shock waves around the tip of the pressure probe, and the static pressure measurements are believed to be accurate. The accuracy was further confirmed by comparing previously published nonswirling jet results with a similar pressure ratio (see a later discussion in Sec. III.A).

Two condenser microphones (Bruel and Kjaer Type 4133) were used for the sound pressure level (SPL) and phase angle measurements. The microphones were diametrically positioned across the jet centerline, as shown in Fig. 1. They were aimed in the downstream direction at a centerline location 2.5 exit diameters (2.75 cm) downstream of the nozzle exit, forming an angle 30 deg (i.e., the inlet angle is 30 deg) with the jet centerline. The distance between the centerline point and the microphones was 7.5 cm. The acoustic signals and power spectra at various inlet angles were reported elsewhere.[15] The results confirmed the upstream propagating nature of screech tones of swirling jets, similar to that of nonswirling jets.

The acoustic signals were analyzed and recorded using a Hewlett Packard 3852A spectrum analyzer (dynamic range: 0–25 kHz). The analyzer yields both spectral contents and phase angles ϕ between signals detected by the two microphones. A toroidal mode should give $\phi \approx 0$ deg, whereas a helical mode should ideally give $\phi = 180$ deg. A computer-assisted data acquisition system with an analog-to-digital converter coupled with a fast Fourier transform algorithm[26] was also used to obtain the power spectra over 0–40 kHz. The spectral contents using both methods yielded the same screech tone frequencies over the 0–25 kHz-range for the same given experimental conditions. The peak identification was therefore considered accurate. Because of the limits of the spectrum analyzer, however, only phase angles of screech tones having frequencies in the 0–25-kHz range were measured.

The day-to-day and run-to-run repeatability was observed within ±5% for quantitative data such as pressure and noise quantities.

Noise was measured in decibels, and the repeatability of the screech tone sound pressure level was ±1 dB.

III. Results and Discussion

The SPL at various inlet angles were reported elsewhere.[15] The results reveal that the screech tones of both weakly ($S_g = 0.36$) and strongly swirling jets propagate in the upstream direction, a well-known characteristic of nonswirling jets. However, the flowfields and shock and pressure structures of $S_g = 0.36$ jets were found to be essentially the same as those for nonswirling jets. Therefore, the following discussion will concentrate on the results and comparison of the $S_g = 0$ and 0.68 jets.

A. Effects of Swirl on Shock Structure, Pressure Fields, and Flow Recirculation

The results of this subsection help to quantify the effects of swirl in supersonic jets. The shock structure using schlieren photography for jets with $S_g = 0$ and 0.68 are shown in Figs. 2 and 3, respectively. Representative cases of $P_r/P_a = 2.36$, 3.72, 4.40, and 5.76 (i.e., $M_j = 1.18$, 1.51, 1.62, and 1.80, respectively) are presented. The

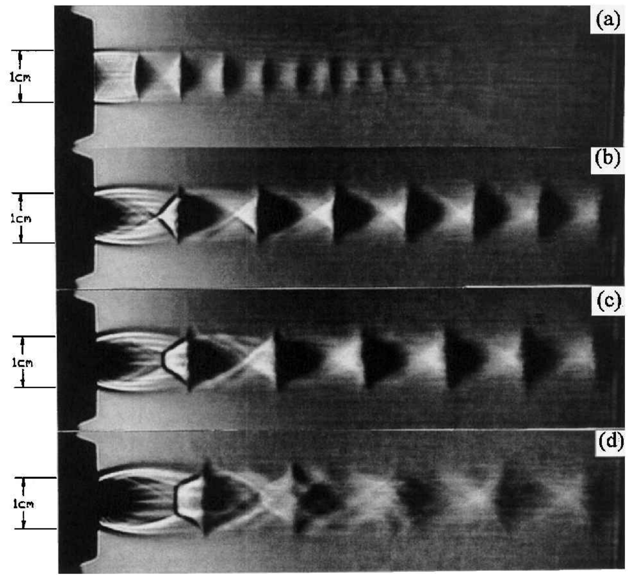


Fig. 2 Schlieren photograph of nonswirling jets: a) P_r/P_a = 2.36 (M_j = 1.18), b) P_r/P_a = 3.72 (M_j = 1.51), c) P_r/P_a = 4.40 (M_j = 1.62), and d) P_r/P_a = 5.76 (M_j = 1.80).

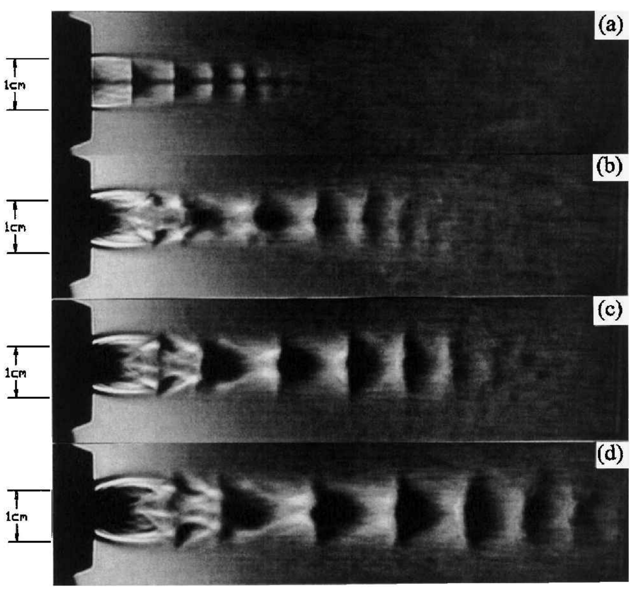


Fig. 3 Schlieren photograph of S_g = 0.68 jets: a) P_r/P_a = 2.36 (M_j = 1.18), b) P_r/P_a = 3.72 (M_j = 1.51), c) P_r/P_a = 4.40 (M_j = 1.62), and d) P_r/P_a = 5.76 (M_j = 1.80).

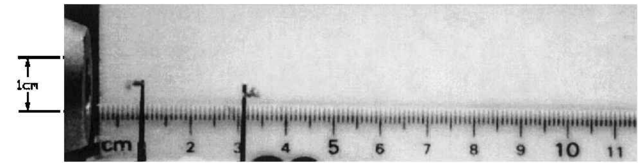
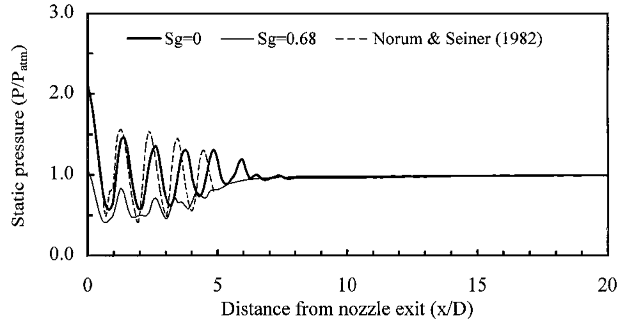
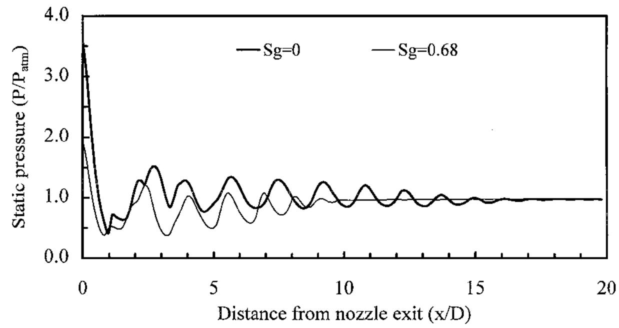


Fig. 4 Direct photograph of flow recirculation of S_g = 0.68 jets with P_r/P_a = 4.40 (M_j = 1.62). Flow recirculation was observed within S_g = 0.68 jets for $P_r/P_a \geq$ 3.28, and no flow recirculation was observed for S_g = 0 and 0.36 jets over the pressure range of this study.



a) P_r/P_a = 3.04 (M_j = 1.37)



b) P_r/P_a = 3.72 (M_j = 1.51)

Fig. 5 Centerline pressure structure of nonswirling and swirling jets.

$S_g = 0.68$ jets possess a shock structure quite different from that of their nonswirling counterparts, especially in the region of the first and second shock waves (Figs. 2 and 3). For $S_g = 0.68$, the first and the second shock cells appear to be connected for $P_r/P_a \geq 3.72$; that is, the clear diamond-shaped cell structure does not exist in this region as in the $S_g = 0$ jets. The effect of swirl also appears to alter the shock structure of jets at high values of P_r/P_a. For example, the shock disk of Fig. 2d ($S_g = 0$) seems to have disappeared when a strong degree of swirl is added (Fig. 3d) for the same pressure ratio of 5.76. This is caused by the swirl-induced recirculation zone in that region for $S_g = 0.68$, as discussed later.

The existence of flow recirculation can be considered as the most convincing evidence of the effects of swirl. Visualization of the flow reversal was obtained by inserting tassels into this region. Typical results are shown in Fig. 4 (similar results were reported in Ref. 15), where the upstream tassel (located at $x \approx 1$ cm) pointed against the bulk flow, whereas the downstream tassel (at $x \approx 3$ cm) pointed in the direction of the bulk flow. The flow recirculation was not observed for $S_g = 0$ and 0.36 for the pressure range studied.

It is interesting to note that the quasiperiodic shock cells can be seen downstream of the recirculation zone in $S_g = 0.68$ jets (Fig. 3). The shock cell spacings of $S_g = 0.68$ jets are smaller than those of the $S_g = 0$ jets. For example, the $S_g = 0.68$ jet with $P_r/P_a = 5.76$ (Fig. 3d) had one more cell than the $S_g = 0$ jets (Fig. 2d) for the same field of view (six vs five). The reduction of the shock spacing by swirl suggests enhanced mixing, which is then expected to change the screech tone frequency and Strouhal number. During the experiment, it was noticed that $S_g = 0.68$ jets were more unsteady than $S_g = 0$ jets, as revealed by video records (not shown).

Effects of swirl can also be found in centerline pressure profiles, as presented in Fig. 5. Representative cases of $P_r/P_a = 3.04$ and

3.72 are shown. A nonswirling jet result for $P_r/P_a = 3.06$ (Ref. 27) was also plotted in Fig. 5a for comparison. For nonswirling jets, the pressure peaks (immediately downstream of shocks) and troughs (immediately upstream of the shocks) are seen to alternate around the atmospheric value ($P/P_a = 1$), typical of underexpanded jets without swirl. However, the static pressure peaks and troughs of swirling jets do not exceed $P/P_a = 1$ until downstream of the fifth or sixth shock cell, depending on the pressure ratio (Figs. 5a and 5b). Therefore, the $S_g = 0.68$ jets are qualitatively very different from the $S_g = 0$ jets; the centerline regions of $S_g = 0.68$ jets are able to undergo at least five expansion-compression series under subatmospheric conditions.

The open symbols of Fig. 6 represent pressure profiles measured downstream of shock cells and others, upstream of shock cells. The results of Fig. 6a are the radial static pressure profiles for $P_r/P_a = 3.72$ and $S_g = 0$. The static pressure alternates around $P/P_a = 1$ as x/D is increased until the shock region ends. For $S_g = 0.68$, the static pressure profiles (Fig. 6b) resemble those of a vortex both upstream and downstream of shock waves. That is, the pressures both upstream and downstream of the shock waves have a minimum near the centerline. The lowest pressure around the centerline is $P/P_a \approx 0.3$ for $S_g = 0.68$ and 0.5 for $S_g = 0$, further suggesting the effect of swirl. These observations are consistent with centerline pressure results (Figs. 5a and 5b). It can therefore be concluded that the effects of swirl in $S_g = 0.68$ jets with $P_r/P_a \geq 3.72$ continue to exist toward the end of or beyond the shock cell train. This region covers the fourth and the fifth shock cells where intense sound scattering, i.e., screech tones, is known to occur as a result of shock/instability wave interaction.

B. Existence of Screech Tones in Strongly Swirling Jets

The SPLs of $S_g = 0$ and 0.68 jets are shown in Fig. 7 measured at an inlet angle χ of 30 deg. This angle was chosen because of the upstream propagating nature of the screech tone. The screech tones correspond to the peaks with discrete frequencies in Fig. 7. More detailed results such as directionality of propagation and SPL dependence on values of χ can be found in Ref. 15. It can be concluded from that study and the results of Fig. 7 that the screech

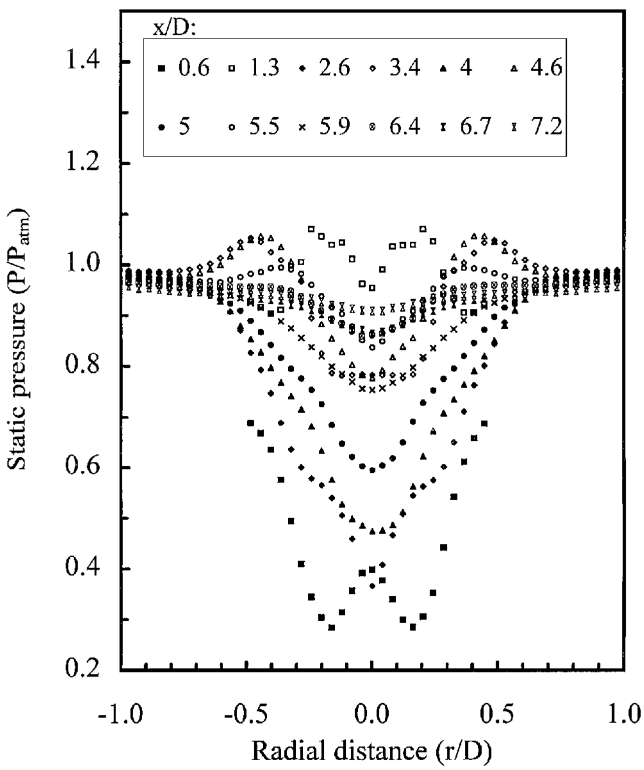


Fig. 6a Radial pressure profile of a nonswirling jet ($S_g = 0$) at various axial locations (x/D): $P_r/P_a = 3.72$ ($M_j = 1.51$). Solid symbols designate data upstream of shock waves, and open symbols designate downstream data.

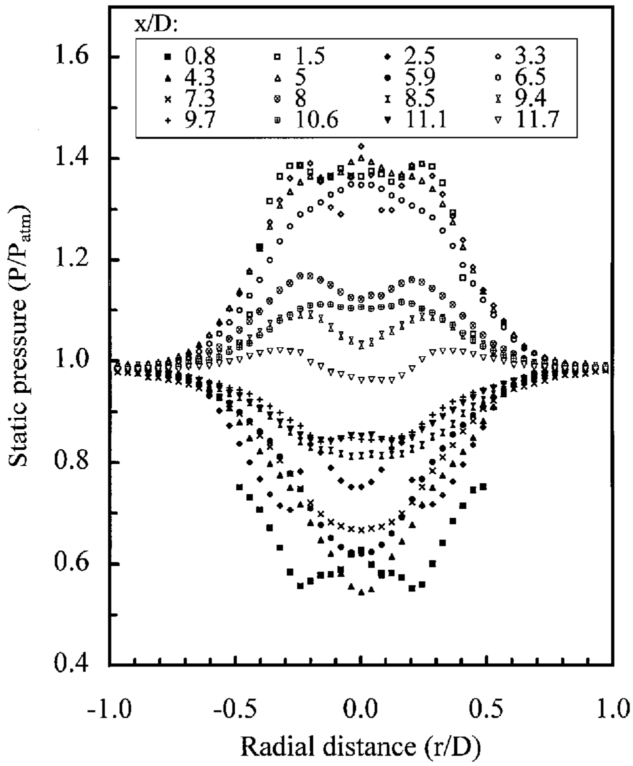
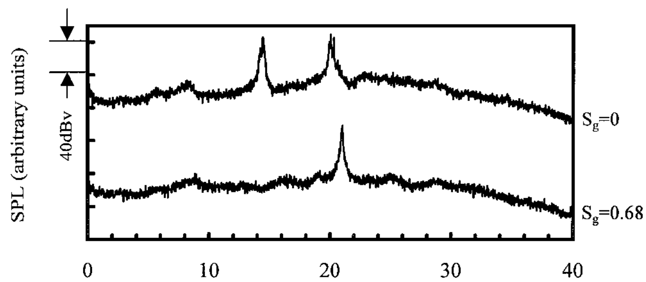
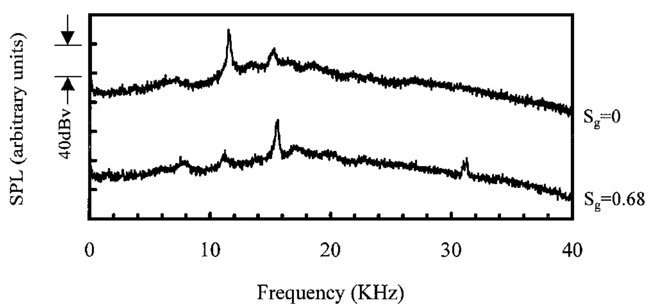


Fig. 6b Radial pressure profile of a nonswirling jet ($S_g = 0.68$) at various axial locations (x/D): $P_r/P_a = 3.72$ ($M_j = 1.51$). Solid symbols designate data upstream of shock waves, and open symbols designate downstream data.



a) P_r/P_a = 2.36



b) P_r/P_a = 3.04

Fig. 7 Spectra of supersonic jet noise with S_g = 0 and 0.68.

tone noise exists for $S_g = 0.68$. It is also noted that for $S_g = 0.68$ nonharmonic peaks also exist, similar to those in nonswirling jets. Nonharmonic peaks are known to be screech tones due to different modes of instability that interact with the shock cell structure. Although a strong degree of swirl can cause flow to recirculate (as seen in Fig. 4) and alter the pressure structure within the jet boundary (see Fig. 6), the swirling jet screech tone noise possesses similar characteristics as nonswirling jets. The screech tone SPLs (in arbitrary units) as functions of M_j for $S_g = 0$ and 0.68 are shown and compared in Fig. 8. Note that the increments of M_j of Fig. 8 are smaller than those listed in Table 1. For the $S_g = 0.68$ jet, SPL is the highest at around $M_j = 1.3$, with the corresponding $Sr \approx 0.375$. At $M_j = 1.3$ the screech tone is that of a helical mode, as will be shown in the following section. It appears that swirl does not help to eliminate screech in the pressure range of this study, in contrast to previous beliefs.[1] The quasiperiodic shock cell structure, whether the jet is swirling or not, seems to be the determining factor in screech tone noise. For comparison, the helical instability waves are most strongly excited in an incompressible swirling jet by an excitation frequency with $Sr = 0.75$–1.5 (Ref. 7).

C. Mode Switching

The nondimensional parameter characterizing the frequency is the commonly used Strouhal number Sr that is based on the screech tone frequency and the fully expanded jet velocity and diameter.[16]

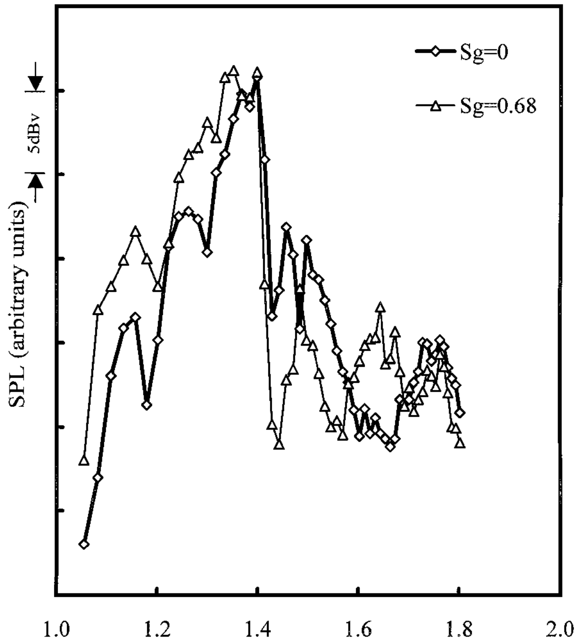


Fig. 8 Maximum SPL of jets with S_g = 0 and 0.68 as a function of fully expanded Mach number (M_j). Strouhal numbers for maximum SPL of S_g = 0 and 0.68 jets are 0.28 and 0.375, respectively.

Note that the theoretically derived Strouhal number is for the most amplified helical mode[28]; however, there is no distinction between the spinning and the flapping modes. In the following, measured results of Strouhal numbers for swirling jets are compared with the theoretical prediction and also with some previously published data for nonswirling jets.[29] Various modes will be identified and compared for both swirling and nonswirling jets.

To obtain the phase information it was decided to increase the pressure ratio with small increments, smaller than those shown in Table 1, so that the evolution and mode switching could be clearly tracked. The phase angle between signals detected by the two microphones was recorded. When these results are overlapped with results of SPL for the same pressure ratio (or M_j) such as those in Fig. 7, the phase angle and the screech tone mode for each peak can be determined. Shown in Figs. 9 and 10 are the results of the phase angle as a function of M_j. As can be seen, the normalized wavelength increases with M_j. The appearance and disappearance of various screech tone modes can be seen as M_j is increased. The phase angles of the screech tones are labeled for selected values of M_j. Ideally the phase angle ϕ for a toroidal mode is nearly zero, whereas that of a helical mode is expected to be 180 deg. The superposition of two helical modes of equal strength and equal angular speed but opposite sense creates a stationary flapping mode ($\phi = 180$ deg). However, it is possible that the orientation of the flapping plane is a function of time.[30] This may create a situation where ϕ deviates from 180 deg for the flapping mode and accounts for the observed ϕ ranging from -70 to near -180 deg for both swirling and nonswirling jets. For convenience, the series of screech tones that started appearing at low M_j with $|\phi| > 70$ deg will be categorized as helical modes.

It is known that imperfect jet qualities, such as imperfect nozzle lips and deviation from perfect symmetry, may cause deviation from ideal values. The phase angles of toroidal modes appear to indicate reasonably good jet quality for all three swirl numbers. This can be clearly seen especially for low supersonic conditions $M_j < 1.3$, under which ϕ are within the range of ± 30 deg (Figs. 9 and 10). It is further noted that no differentiation between spinning and flapping modes could be made with the two microphones used in this study.

For nonswirling jets with $1.05 \leq M_j \leq 1.80$ (Fig. 9), there were five different screech tone modes: two toroidal and three helical. Two toroidal and two helical modes were previously reported under a similar range of M_j using a convergent-divergent nozzle (see Ref. 16; also shown in Fig. 9 for comparison). The vertical axis is the ratio of acoustical wavelength to the fully expanded jet diameter, as

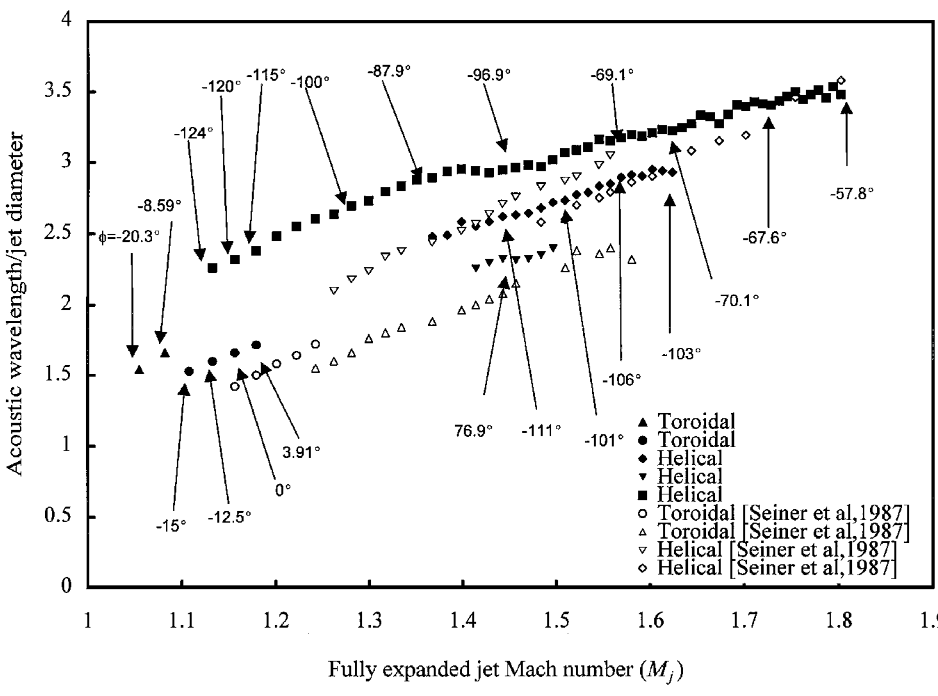


Fig. 9 Wavelength of screech tones of S_g = 0 jets as a function of fully expanded jet Mach number (M_j), showing the screech tone mode phase angle.

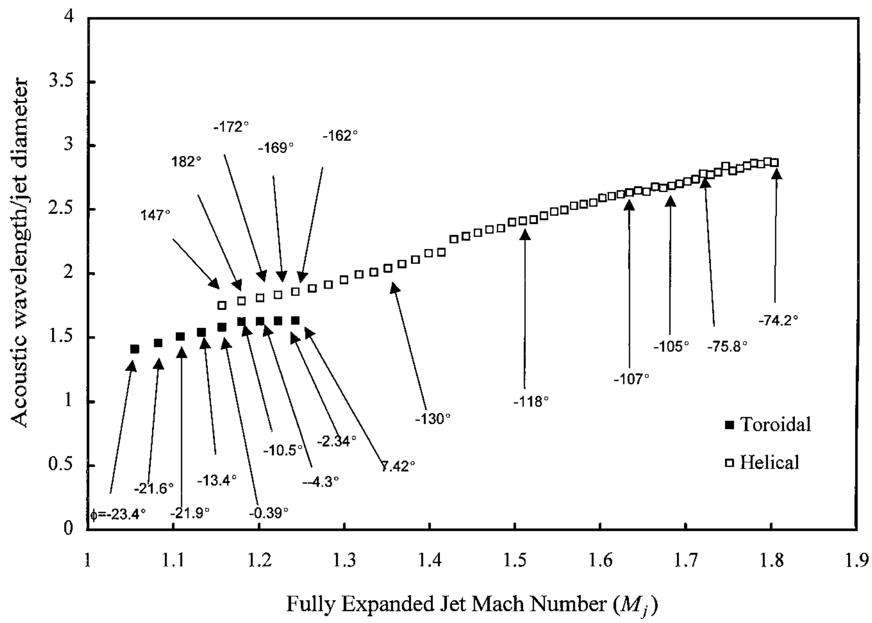


Fig. 10 Wavelength of screech tones of $S_g = 0.68$ jets as a function of fully expanded jet Mach number (M_j), showing the screech tone mode phase angle.

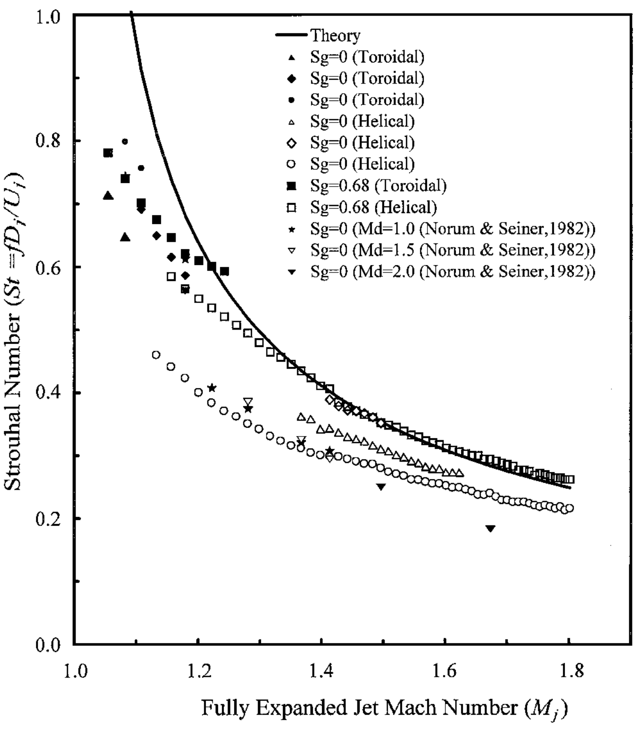


Fig. 11 Comparison of fundamental screech tone Strouhal numbers of swirling and nonswirling jets. The solid line represents the theory of Refs. 16 and 28. Seiner's data are as quoted in Ref. 16.

used in Ref. 16. Present results of nonswirling jets agree well with previous data, as can be seen in Fig. 9. For $S_g = 0$, the dominant mode switched from toroidal to helical for $M_j \approx 1.18$, consistent with previous findings ($M_j \approx 1.12$–1.18) for nonswirling circular jets.[19] The switching occurred at $M_j \approx 1.25$ for $S_g = 0.68$ (Fig. 10). A strong degree of swirl ($S_g = 0.68$ in the present study) appeared to favor only one toroidal mode and only one helical mode for M_j up to 1.80, as opposed to the five and seven modes of $S_g = 0$ and 0.36 jets, respectively. (The latter are not reported here.)

For both $S_g = 0$ and 0.68 jets, there was a helical mode that began to appear at $M_j \approx 1.15$ and might well continue beyond $M_j = 1.80$, as can be seen from Figs. 9 and 10. These helical modes had the longest wavelength, i.e., lowest frequency and Strouhal number, among all modes for both $S_g = 0$ and 0.68, and their phase angle magnitude decreased, as M_j was increased, by as much as 100 deg (cf. $S_g = 0.68$).

To test how nonswirling circular jet theory may predict the screech tone frequency/Strouhal number, the theory of Tam[16] and Tam et al.[28] was used to correlate the present swirling and nonswirling jet data. The results, along with some previously published data, are as shown in Fig. 11. Note that M_j in Fig. 11 is that of the nonswirling jet for a given pressure ratio. The present nonswirling jet data agree well with the theory and previous data of Ref. 16, with the theory slightly overpredicting the Strouhal number.

The predictions for the helical mode of $S_g = 0.68$ jets are excellent. As can be seen from Fig. 11, the theory appears to work better for swirling jets than for nonswirling jets, although it was developed for the latter. However, the reason is not currently known. The good agreement between the theory and the experimental results for swirling jets suggests that the quasiperiodic shock structure of the supersonic swirling jets studied is essential for screech tone generation, just as in nonswirling jets. The flow recirculation generated by swirl does not, at least qualitatively, alter screech tone characteristics of supersonic jets.

IV. Concluding Remarks

Under the present experimental conditions, the findings for screech tone noise of supersonic swirling jets are summarized as follows:

1) Swirl can induce flow recirculation in supersonic jets as in subsonic jets. Adding swirl to jets can cause flow recirculation in the region of the first and second shock cells and changes the pressure field structure in the near field. For the highest degree of swirl of this study, the jets were able to undergo five or six shock-expansion series under subatmospheric conditions. However, it does not appear to alter the quasiperiodic nature of the shock cells downstream of the recirculation zone, which is known to be crucial for screech tone generation in nonswirling jets. The qualitative fundamental characteristics of screech tone noise are therefore similar in swirling and nonswirling jets.

2) For the pressure range studied, swirl does not help eliminate screech tone noise. This may again be due to the quasiperiodic nature of shock cells downstream of the swirl-induced recirculation zone. A theory for predicting Strouhal number of screech tones of nonswirling jets as a function of fully expanded jet Mach number was found to be suitable for swirling jets as well. This is true if the fully expanded Mach number is calculated based on the reservoir pressure assuming no swirl.

3) For the strongest swirl, the number of modes reduces to one toroidal and one helical mode. The helical mode is the dominant one for sufficiently high pressure ratios, as in nonswirling jets. Phase angles of helical modes appeared to decrease with increasing pressure ratio and M_j for swirling as well as for nonswirling jets.

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