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A STUDY OF SCREECH TONE NOISE OF SUPERSONIC SWIRLING JETS

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1. INTRODUCTION

Eliminating noise from supersonic jet plumes is important to the success of high speed transport. There exist predictions and experimental observations that swirling motion may lead to elimination of noise emission from supersonic jets [1, 2]. However, the observation was qualitative [1] and the prediction was based on a linear, inviscid and nearly isentropic theory [2]. The possible elimination of screech tones from swirling supersonic jets was attributed to either the occurrence of jet flow recirculation due to swirl [1, 3] or the elimination of the shock cell structure which is necessary for screech tones [2].

Swirl has been known to shorten the flame length, an indication of enhanced mixing [4, 5], and improve flame stabilization in subsonic combustors [6, 7]. These are also desirable characteristics in the supersonic combustion in high speed transport. It was believed that enhanced mixing due to swirl was responsible for eliminating shock cells in supersonic jets [2]. Swirl can then be a mechanism to achieve multiple purposes in the applications of supersonic flow and high speed transport.

However, experimental data of shock structures and screech tone noise of swirling supersonic jets have been limited. An experimental effort was therefore made to reveal the screech tone characteristics of underexpanded swirling jets. These characteristics are compared with their counterparts in non-swirling supersonic jets.

Key results from previous studies on non-swirling circular jets are described. For the details, a recent article [8] can be consulted. There are three major components of the noise of a supersonic jet which, in increasing order of frequency, are turbulent mixing noise, screech tones and broadband shock noise. Turbulent mixing noise is known to exist in both subsonic and supersonic flows. The broadband shock noise arises as a result of interaction of turbulent eddies with shock waves. The screech tones are special cases of the broadband noise; namely, the results of the interaction between large scale turbulence structure or the instability waves originating at the nozzle lip with the quasi-periodical shock cell structure. The interaction occurs at the edge of the jet in the region of the fourth and fifth shock cells. The screech tone noise propagates outside the jet and upstream toward the nozzle lip, and further excites the instability waves there, thus completing an acoustic feedback loop. Their sound pressure levels (SPL) are significantly higher than the other two components when measured from the upstream direction. The quasi-periodical shock cell structures are critical for the screech to occur in narrow bands, as experimentally observed. Two modes of screech tones (axisymmetric/toroidal and helical/flapping) are known to exist, although not occurring simultaneously. Helical modes become increasingly more dominant at high pressure ratios. This phenomenon is

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known as mode switching. Around the transition $\mathrm{M_j}$ for mode switching, SPL reaches its maximum and the jet fluid mixing appeared to be most significantly enhanced [9]. These screech tone characteristics are similar in non-circular jets [10–12].

2. EXPERIMENT

The convergent nozzle used for the experiment is as shown in Figure 1, with all the appropriate dimensions ($A_t(=\pi D_t^2/4)$, R_o, and r_o). The four tangentaial inlets to the nozzle introduce swirling motion to the air that exits the nozzle into the surrounding atmosphere. The air was supplied from a larger reservoir (at a nominal 298 K) with a manifold connected to the tangential and axial inlets of the nozzle. A geometrical swirl number (S_g) is defined as $S_g = (\pi r_o R_o/A_t)\{m_\theta/(m_\theta + m_a)\}$, where m_a and m_θ are the mass flow rates through the axial and tangential inlets to the nozzle, and were estimated based on the velocities measured upstream of these inlets using Pitot-static tubes. 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. The pressure gage inserted near the back wall of the nozzle (as shown in Figure 1) was used to measure the reservoir pressure, P_r, so designated because it virtually does not vary throughout the radial region at that axial location. For each pressure ratio, P_r was maintained the same while S_g was varied. The values of the fully expanded Mach number (M_j) for corresponding non-swirling jets were calculated using inviscid one-dimensional isentropic flow theory; they ranged up to 1·81. No simple calculations of M_j could be done for swirling jets since they are intrinsically two- or three-dimensional. For the pressure ratio equal to 5·76 ($M_j = 1{\cdot}81$) the total mass flow rates ($m_\theta + m_a$) for $S_g = 0$, 0·36 and 0·68 were determined to be 0·138, 0·136 and 0·124 kg/s, respectively, assuming that the turbulent flow in the inlets was uniform. Based on isentropic relationships, the mass flow was calculated to be 0·130 kg/s for non-swirling jets at this pressure ratio. Similar percentile reductions due to swirl were observed for other pressure ratios, representing thrust loss in propulsion applications.

A condenser microphone (Bruel & Kjaer type 4133) was used for the measurement of *SPL*. The microphone was placed 7·5 cm from a centerline location $x/D = 3$. Measurements were carried out for eight inlet angles (χ, as customarily defined in reference [8]), from 30° to 135°. The acoustic signals were analyzed and recorded using an HP 3582A spectrum analyzer (dynamic range: 0–25 kHz). The power spectra are averages of 16 samples, each of which contain 256 data points. The accuracy of the acoustical measurements can be seen in Table 1, in which typical Strouhal numbers of the screech tones

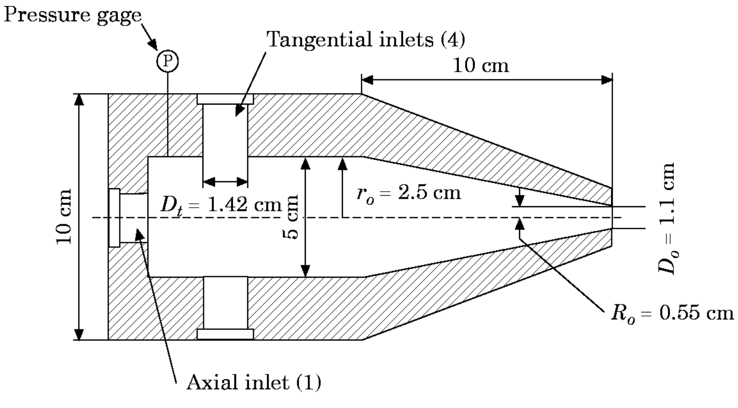

Figure 1. A schematic of the underexpanded swirling nozzle.

Table 1

Strouhal numbers for maximum screech sound pressure level of underexpanded circular jets

	Pressure ratio, P_r/P_a	Nozzle diameter (cm)	Strouhal number, $St_{max\ SLP}$	Source of data
Non-swirling	3·67	2·54	0·24	Powell*
	4·0	1·27	0·275	Sherman*
	3·01	1.90	0·29	[12]
	2·97	1·10	0·28	Present results
Swirling	3·14	1·10	0·375	Present results

*As quoted in Krothapolli *et al.* [10].

compare favorably with previously published results. The resolution of these acoustic measurements was 100 Hz. A standard Schlieren system [13] and direct photography were used to visualize the shock cell structure and flow recirculation.

3. RESULTS AND DISCUSSION

Video records of schlieren photographs were reviewed and their results are described. For simplicity, only typical schlieren results are presented in Figure 2. For $S_g = 0$ and 0·36, the shock cell structures were essentially the same (Figures 2(a) and 2(b)); the latter can then be called weakly swirling jets. It is recalled that by increasing S_g from 0 to 0·36

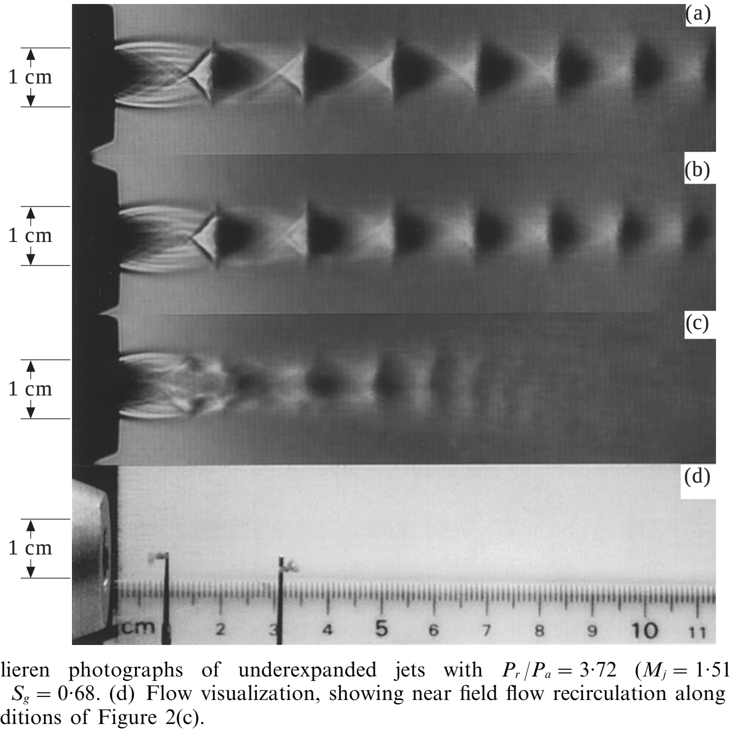

Figure 2. Schlieren photographs of underexpanded jets with $P_r/P_a = 3·72$ ($M_j = 1·51$): (a) $S_g = 0$; (b) $S_g = 0·36$; (c) $S_g = 0·68$. (d) Flow visualization, showing near field flow recirculation along the jet centerline with the conditions of Figure 2(c).

the mass flow rate was reduced by only 2%. A semi-periodical shock cell structure, as necessary for screech tones, can clearly be seen for all 12 combinations of the two values of S_g and six of M_j(or P_r/P_a). The number of shock cells for both swirl numbers was observed to exceed seven. For $P_r/P_a \geqslant 4{\cdot}40$ ($M_j \geqslant 1{\cdot}62$), normal shocks (or shock disks) appeared in the first shock cell for $S_g = 0$ and 0·36 jets.

For $S_g = 0{\cdot}68$, the shock cell structure appeared to be more complex for $P_r/P_a \geqslant 3{\cdot}72$ ($M_j \geqslant 1{\cdot}51$), as can be seen in Figure 2(c). More than seven shock cells were observed for the pressure ratios investigated, similar to weakly and non-swirling jets. The first two shock cells are not conical; nor can shock disks be seen. Their centerline regions appear to be connected, and this is believed to be due to the recirculation of the jet flow. The flow recirculation in this region was visualized by inserting small "flags" into the flow. The result of direct photography can be seen in Figure 2(d). The flag was swept forward near the flow centerline within the first shock cell, indicating flow reversal, while downstream flag indicated the bulk flow direction.

The flow recirculation within the first shock cell was observed in $S_g = 0{\cdot}68$ jets for $P_r/P_a \geqslant 3{\cdot}72$ ($M_j \geqslant 1.51$). Although not shown, the recirculation zone size increased slightly with P_r/P_a. The reversed flow region for $P_r/P_a = 5{\cdot}76$, by traversing the flag, is approximately ellipsoidal in shape (5 mm × 3 mm). The shock structure downstream of the recirculation zone recovered the quasi-periodicity, as in non-swirling jets. The flow was increasingly unsteady with increasing pressure ratio, with shock waves moving around their mean positions. The shock spacing at these locations for swirling jets is smaller than that of the non-swirling jets (Figures 2(a)–2(c)). The reduction in shock spacing with $S_g = 0{\cdot}68$ ranged from 20% for $M_j = 1{\cdot}18$ to 35% for $M_j = 1{\cdot}81$. This is a possible indication of enhanced mixing by swirl (or, by the swirl-generated flow recirculation, as is known in subsonic flows [4, 5]). These observations are in contrast to a linear theory that predicted the elimination of shock cell structures and, therefore, screech tone noise [2]. For the same range of pressure ratios, no flow recirculation was observed for $S_g = 0$ and 0·36.

For reasons given above, only the *SPL*s of jets with $S_g = 0$ and 0·68 are presented in Figures 3 and 4. The discrete spectral peaks in these figures are the screech tones. At lower frequency is turbulent mixing noise and at higher frequency is shock related broadband noise. The spectral contents for the six values of P_r/P_a are not significantly different, except that the peak magnitude decreases relative to that of the broadband as P_r/P_a is increased. Some peaks are harmonics of each other ($f_s \approx 10{\cdot}5$ kHz and 21·0 kHz in Figures 3(b)). As well known in non-swirling jets, harmonics do not necessarily occur. Examples of non-harmonic screech tone peaks can be seen in Figures 3(d) and 4(a); these are different modes (toroidal and helical/flapping) of screech tones.

These measured *SPL*s (Figures 3 and 4) for the eight χ's were purposely shifted to avoid overlapping. For both $S_g = 0$ and 0·68 jets, the magnitudes of the *SPL*s of the fundamental screech tones are in general significantly larger than the broadband noise for $\chi < 90^\circ$. The screech tone *SPL* decreased with increasing χ. This implies the upstream propagating nature of swirling jets (Figure 4), as observed for the present (Figure 3) and many previously studied non-swirling jets [8]. For both $S_g = 0$ and 0·68, the *SPL* of fundamental screech tones are lower than the broadband in the downstream direction ($\chi > 90^\circ$).

The above observations reveal similar screech tone emission characteristics between the swirling and non-swirling jets, although there exists flow recirculation within the near field of the swirling jets. To confirm whether swirl reduces the screech tone noise, the maximum *SPL* for both $S_g = 0$ and 0·68 jets were measured with incrementally increased pressure ratio (or M_j). The results are as shown in Figure 5. It is noted that by

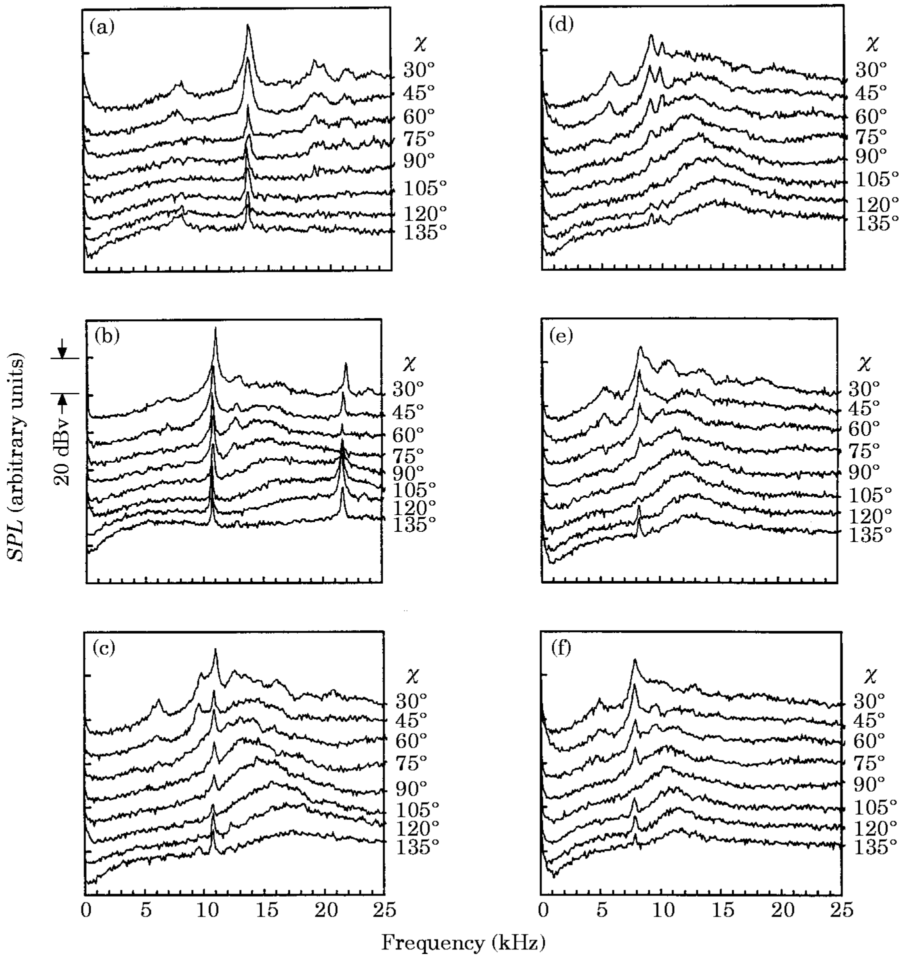

Figure 3. The sound pressure levels of non-swirling jets ($S_g = 0$) as functions of jet inlet angles (χ): (a) $P_r/P_a = 2{\cdot}36$ ($M_j = 1{\cdot}18$; (b) $P_r/P_a = 3{\cdot}04$ ($M_j = 1{\cdot}37$); (c) $P_r/P_a = 3{\cdot}72$ ($M_j = 1{\cdot}51$); (d) $P_r/P_a = 4{\cdot}40$ ($M_j = 1{\cdot}62$); (e) $P_r/P_a = 5{\cdot}08$ ($M_j = 1{\cdot}72$); (f) $P_r/P_a = 5{\cdot}76$ ($M_j = 1{\cdot}80$).

introducing swirling motion to the jets, no consistent trend of noise reduction can be achieved. It was believed that if swirl causes the jet flow to recirculate, the noise level would be reduced [1]. From the direct photograph of Figure 2(d), the jet flow appeared to recirculate in the region between the first and second shock cells for $S_g = 0{\cdot}68$. It was argued by others that shock cells and, therefore, screech tones could be eliminated by swirl [2]. The swirl-induced flow recirculation under the present conditions does not eliminate shock cells; the quasi-periodical shock structure appeared downstream of the recirculation zone. In light of the finding that screech tones of non-swirling jets are generated around the fourth and the fifth shock cells, swirl does not affect the noise generation. Whether the swirling motion persists beyond the recirculation zone and how it affects the characteristics of the screech tones would require knowledge of the velocity fields. It is not presently known whether extending the ranges of pressure ratio and/or degree of swirl will eliminate shocks downstream of the recirculation and, therefore, the screech tones. The degree of swirl can by increased by reducing the number and/or the diameter (D_t) of the tangential inlets for a given reservoir pressure.

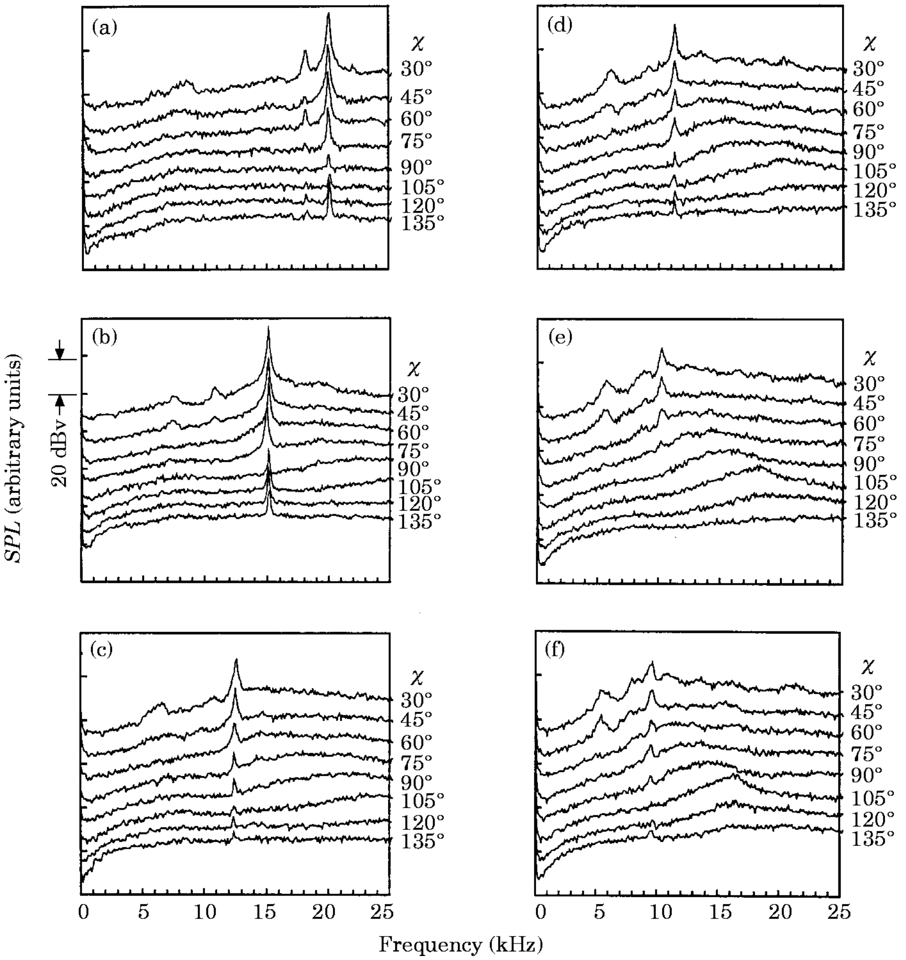

Figure 4. The sound pressure levels of swirling jets ($S_g = 0{\cdot}68$) as functions of jet inlet angles (χ): (a) $P_r/P_a = 2{\cdot}36$ ($M_j = 1{\cdot}18$); (b) $P_r/P_a = 3{\cdot}04$ ($M_j = 1{\cdot}37$); (c) $P_r/P_a = 3{\cdot}72$ ($M_j = 1{\cdot}51$); (d) $P_r/P_a = 4{\cdot}40$ ($M_j = 1{\cdot}62$); (e) $P_r/P_a = 5{\cdot}08$ ($M_j = 1{\cdot}72$); (f) $P_r/P_a = 5{\cdot}76$ ($M_j = 1{\cdot}80$). Note that M_j is calculated assuming one-dimensional isentropic non-swirling jets.

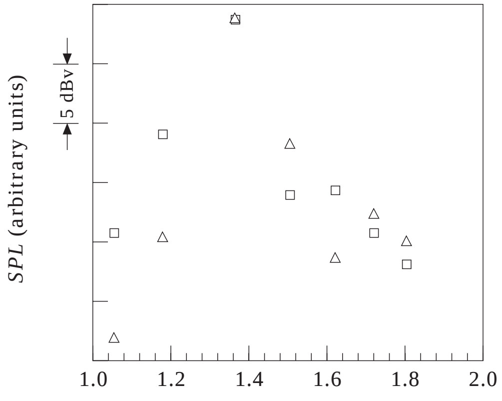

Figure 5. The sound pressure levels of non-swirling jets ($S_g = 0$; triangles) and strongly swirling jets ($S_g = 0{\cdot}68$; squares) as functions of the fully expanded jet Mach number (M_j). Note that for swirling jets M_j is calculated assuming the one-dimensional isentropic non-swirling jets.

The SPL of non-swirling jets reaches a maximum for $P_r/P_a \approx 3{\cdot}0$ ($M_j \approx 1{\cdot}35$) and decreases with increasing pressure ratio, although it may increase with M_j over smaller ranges of pressure ratios (Figure 5). However, the general trend is consistent with previous findings regarding SPL and the jet spread/mixing rate [10, 12]. The SPL of swirling jets follows a similar trend. Extending pressure ratio for swirling jets beyond the range studied is expected to further reduce the SPL. However, this reduction may not be due so much to swirl but for the same reasons as for non-swirling. Again, this is because the shock structure of the screech tone noise generating region in swirling jets is not qualitatively different from that in non-swirling jets.

The pressure ratio and the screech tone Strouhal number ($f_s D_j/U_j$) for which maximum SPL, denoted by $St_{max\,SLP}$, is produced are of interest [10] because they are related to the conditions for the most enhanced mixing. Values of St of present swirling and non-swirling jets are compared with jets with various nozzle geometries in Table 1. It is noted that D_j and U_j are the fully expanded jet diameter and velocity, respectively, calculated according to Tam [8], assuming that all jets are non-swirling. The $St_{max\,SLP}$ of the present non-swirling jets agrees well with previous results, as can be seen in Table 1. The agreement is excellent with that of a more recent study [12]. It is noted from Table 1 that $St_{max\,SLP}$ for swirling occurs at a slightly higher pressure ratio. It is also interesting to note that $St_{max\,SLP}$ for the swirling jets is about one-third larger than that of their non-swirling counterparts. This is believed to be due to the shortened shock cell, as seen in Figure 2.

4. SUMMARY

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

Screech tone noise was observed in supersonic swirling jets. Their characteristics, such as the directionality, are similar to those of nonswirling jets. Swirl by itself did not eliminate the quasi-periodic shock structure which is necessary for screech tones in non-swirling jets. A strong degree of swirl generated a recirculation zone between the first and second shock cells. However, it did not eliminate the shock cells; nor did it affect their quasi-periodic nature. The sound pressure level of the swirling jets as a function of pressure ratio is nearly qualitatively similar to that of non-swirling jets. It may be concluded that, whether or not the jet is swirling, screech tones exist because of the quasi-periodic shock structure and the inherent instability waves propagating downstream of the nozzle at the jet boundary. Furthermore, opposite to previous beliefs, no consistent trend was found regarding noise reduction with increasing swirl or flow recirculation.

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