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Technical Notes

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Elimination of Screech Tone Noise in Supersonic Swirling Jets

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Introduction

SCREECH tone noise occurs in supersonic jets as a result of the interaction of the instability wave emanating from the jet exit and the quasiperiodic shock cell structure (see, for example, the review paper of Ref. 1). Specifically, screech noise has its origin residing in the region of the fourth and fifth shock cells. Most of the existing literature deals with screech tone characteristics of nonswirling jets with various jet nozzle exit geometries. The potential of being able to control and even eliminate such noise may yield environmental benefits and increased airworthiness.[2]

The periodic shock structure and screech tone noise and mode characteristics of supersonic swirling jets have recently been documented.[3,4] The effects of swirl or swirl-generated flow recirculation on screech tone noise were also speculated on by other authors.[5,6] Some of the documented screech tone characteristics[3,4] are similar to those of nonswirling jets, primarily because the quasiperiodic shock cells exist beyond the fifth shock cell, just as in nonswirling jets.[1] The elimination of shock cells downstream of the fourth shock cell appears to be necessary for screech tone elimination. Highly underexpanded nonswirling jets may not have screech tones, primarily because the strong shock disk leads to the disappearance and/or weakening of the downstream shock waves.[7] Using various nozzle exit geometries may not be effective in eliminating screech tone noise.[8] Because swirl is known to cause flow recirculation and enhance mixing in both subsonic and supersonic circular jets,[9–12] it may help to eliminate shock cells that are necessary for screech tone generation. It is of interest to investigate whether the screech tone can be eliminated by increasing the strength of swirl beyond those reported in Refs. 3 and 4.

Experiment

The nozzle used for the experiment, exactly the same as that in Ref. 3, is shown in Fig. 1. The jet fluid is air (at a nominal 298 K in the reservoir) with a manifold connected to the tangential and axial inlets to the nozzle. The ambient fluid is also air. To increase the strength of swirl, two diametrically opposite tangential inlets were used in this study (four were used in Ref. 3). 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 (=0 in the present study) and m_θ are the mass flow rates through the axial and tangential inlets to the nozzle, respectively, as described in Ref. 3. The values of the total area of tangential inlets A_t is equal to $\pi D_t^2/4$ multiplied by the number of tangential inlets used. Values of R_0 and r_0 are shown in Fig. 1. With these conditions, S_g (now $= \pi r_0 R_0 / A_t$) was increased to 1.36 from 0.68 when four tangential inlets were used.[3] A more frequently defined swirl number would require measurements of density and both axial and tangential velocity components at the nozzle exit.[9,13] We caution that the definition of most swirl numbers represents only the integral effects of the measured parameters.

The mass flow rates for $S_g = 1.36$, in kg/s, are 0.0497, 0.0617, 0.0759, 0.0866, 0.0996, and 0.1144 for reservoir pressure ratio $P_r/P_a = 2.36$, 3.04, 3.72, 4.40, 5.08, and 5.76, respectively. These mass flow rates are about 8% lower than those for $S_g = 0.68$ with same pressure ratios, consistent with results of increasing swirl previously reported.[3,14–16] The values of M_j for corresponding nonswirling jets with the same reservoir pressures ranged from 1.18 to 1.80. They were calculated using inviscid, one-dimensional, isentropic flow theory, as no simple calculations of M_j could be done for swirling jets because they are intrinsically three dimensional.

All details for acoustic measurements and the schlieren system can be found in Ref. 3. The day-to-day and run-to-run repeatabilities were observed within ±5% for quantitative data such as pressure and noise levels. The screech tone sound pressure level (SPL) repeatability was ±1 dB (Ref. 3).

Results and Discussion

The results of SPL for $S_g = 1.36$ and $P_r/P_a = 2.36$ ($M_j = 1.18$) and 3.72 jets ($M_j = 1.51$) jets are presented in Fig. 2. For brevity, spectra for higher pressure ratios are not shown. However, they resemble those shown in Fig. 2. At all values of χ studied, no distinct peaks (i.e., screech tones and their harmonics) at discrete frequencies f can be seen. These results appear to collaborate with the observation that no shock cells exist downstream of the third or the fourth cell (as can be seen in Fig. 3). As shown in Fig. 2, turbulence and the broadband noise are indistinguishable. For the same pressure ratios but $S_g = 0.68$, not only screech tones but also as many as seven or more quasiperiodic shock cells were observed.[3,4] Increasing S_g from 0.68 to 1.36 appears to help to eliminate the screech

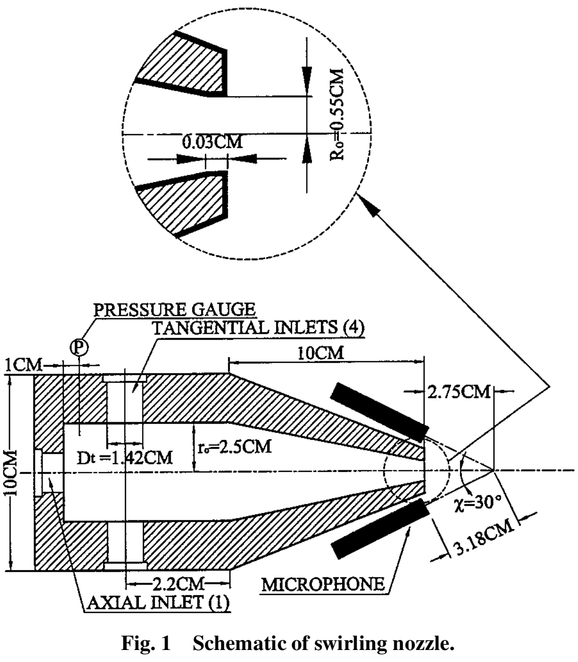

Fig. 1 Schematic of swirling nozzle.

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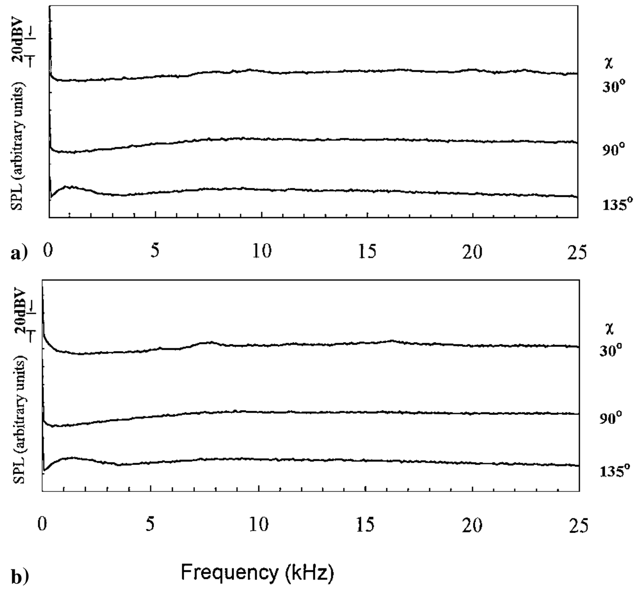

Fig. 2 Spectra of supersonic jet noise with $S_g = 1.36$ measured at three inlet angles: a) $P_r/P_a = 2.36$ ($M_j = 1.18$) and b) $P_r/P_a = 3.72$ ($M_j = 1.51$).

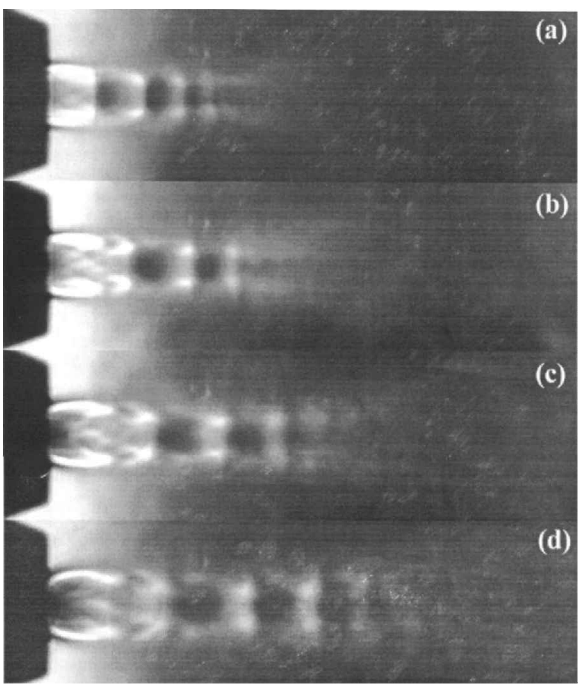

Fig. 3 Schlieren photograph of $S_g = 1.36$ jets: a) $P_r/P_a = 2.36$ (M_j = 1.18), b) $P_r/P_a = 3.04$ ($M_j = 1.37$), c) $P_r/P_a = 3.72$ ($M_j = 1.51$), and d) $P_r/P_a = 4.40$ ($M_j = 1.62$).

tones for similar pressure ratios. A question arises as to how the shock cell structure and flow recirculation, which are both relevant in screech tone emission, may be affected by this increase in the degree of swirl.

During the experiment, the flowfields of these $S_g = 1.36$ jets appeared to be more unsteady than those of $S_g = 0.68$ jets, resulting in a fuzzier appearance of the shock cell structure shown in Fig. 3. Only three or four shock cells exist for these $S_g = 1.36$ jets, fewer than those observed in $S_g = 0.68$ jets. The first and the second shock cells are joined by a certain flow structure, without the distinct diamond-shape shock cells in that region. The flow structure is believed to be the flow recirculation zone, as previously demonstrated for $S_g \geq 0.68$ (Refs. 3 and 4). An attempt was made to visualize flow recirculation using a tassel. The recirculation zone was found to be located at $0.75 < x/D < 1.5$ for $P_r/P_a = 3.72$. The reader should be cautioned that the tassel may prompt the flow recirculation. Similar results were found for higher pressure ratios. However, for $P_r/P_a \leq 2.36$ (e.g., Fig. 3a) no recirculation was indicated,

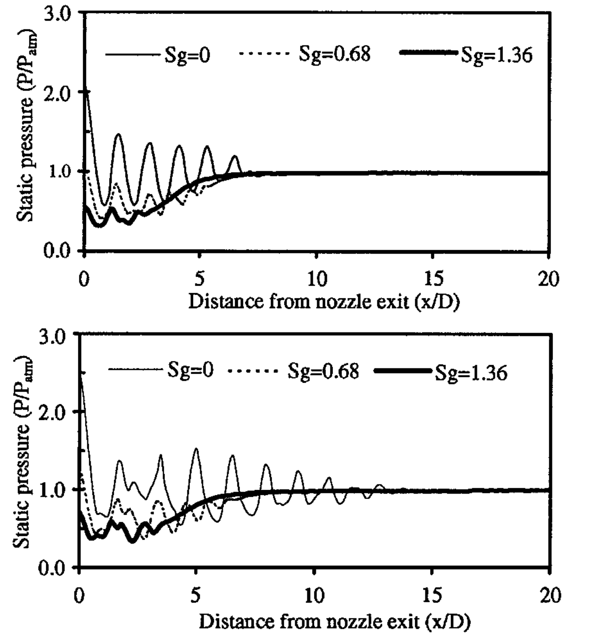

Fig. 4 Centerline pressure structure of nonswirling and swirling jets: $P_r/P_a = 3.72$ ($M_j = 1.51$).

but the screech tone noise was eliminated (Fig. 2a). Comparing the results of Figs. 2 and 3, the conclusion can be made that effects of swirl other than flow recirculation help to eliminate the shock cells downstream of the third or the fourth cell that are necessary for screech tone noise generation.[1]

The effect of swirl on the elimination of shock cells can also be seen from the measured centerline static pressure P/P_a shown in Fig. 4 [$S_g = 1.36$ and $P_r/P_a = 3.72$ jets ($M_j = 1.51$)]. Also presented for comparison are results of published nonswirling and $S_g = 0.68$ jets for the same pressure ratios.[3] Great care was taken for the dimensions of the static probe and port location to ensure minimum flow disturbance. In fact, the probe currently used reproduced results of some previous investigation of supersonic jet noise in the near field.[3] The shock-expansion sequence can be seen to occur in a pressure environment lower than the surrounding pressure. Such shock phenomena (transition from a local minimum to a local maximum or pressure) under subambient pressure conditions can be attributed to the tornadolike effects of swirl.[3] This tornadolike structure exists well downstream of the recirculation zone, i.e., from $x/D > 1.5$ to $x/D = 6.0$, indicating the effects of swirl in the region downstream of the recirculation zone. In Fig. 4 the number of shock cells can be counted to be three, consistent with those of the schlieren visualization in Fig. 3. Although not shown, results of centerline pressure for both larger and smaller pressure ratios resemble those of Fig. 4.

Conclusion

Imparting a sufficient degree of swirl in underexpanded jets issuing from a convergent nozzle can eliminate the quasiperiodic shock cells downstream of the third shock cell, which is also downstream of the flow recirculation zone. Because the existence of the fourth and the fifth shock cells is responsible for the screech tone noise generation, imparting swirl to a supersonic jet can eliminate screech tone noise, as the acoustic measurements of this study demonstrated. Flow recirculation alone does not eliminate the quasiperiodic shock cell structure downstream of the third shock cell. Swirl helps to eliminate the quasiperiodic shock cell structure that is essential for screech tone noise generation.

Acknowledgment

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Nonlinear Eddy-Viscosity Turbulence Model and Its Application

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Introduction

THE computational fluid dynamics (CFD) method is becoming widely applicable in almost all areas following the rapid development of computer capabilities and numerical algorithms. Because directly solving the Navier–Stokes equations is still not practical for most turbulent flows, the turbulence model is an indispensable tool in CFD methods. Currently, the standard eddy-viscosity (SEV) model, or k–ε turbulence model, is most commonly used in CFD applications in almost all engineering areas. This is because the SEV model is relatively simple to use, stable in computation, and effective in providing reasonable results. However, as demands from CFD analyses increase, there is less satisfaction because the SEV model cannot provide some important physical features of complex turbulent flows, due to the inherent deficiencies of the SEV model. One of the deficiencies of the SEV model is that the model is subject to the isotropic and local equilibrium assumptions. For complex turbulent flows or for more accurate results, the Reynolds stresses (RS) turbulence model is chosen. However, the RS model requires extensive computing capabilities and is often numerically unstable. Therefore, the RS turbulence model is not an alternative turbulence model for practical use, especially in industrial applications.

Therefore, there is a considerable research effort toward the development of turbulence models that can overcome the deficiencies of the SEV model but that have the advantages of the SEV model. The fundamental studies and the development of the algebraic second-moment (ASM) turbulence models of the 1970s (Refs. 1–5) led to the success of the development of the second-order k–ε turbulence models in the following decades.[6–11] The second-order k–ε turbulence models are now playing more roles in CFD applications.

The nonequilibrium anisotropic eddy-viscosity/diffusivity (NAEV) turbulence model developed by this author[11] can deal not only with anisotropy and the nonlocal effect of turbulent flows, but also with thermal turbulence quantities and the buoyancy effect. However, it was found that the NAEV model cannot provide correct solutions in some cases, such as the fully developed asymmetric channel flow between smooth and rough walls studied in Refs. 7 and 12. The unique feature of the asymmetric channel flow is that there is a region in the channel where both the velocity gradient and the Reynolds shear stress are positive. It was also found that the reason that the NAEV model is incapable of modeling this asymmetric flow case is related to the use of Rodi's proposal[3] in developing the ASM model from the RS model. To deal with cases such as the asymmetric channel flow, a proposal for deriving a nonlinear algebraic RS equation from its differential equation was presented in Ref. 13. In the present Note, the detailed derivation proposed in Ref. 13 is provided. Also, the alternative form of the NAEV turbulence model based on the proposed nonlinear algebraic Reynolds stresses equation is given. Finally, the application of the new form of the NAEV model to the asymmetric channel flow case is presented.

Model Derivation

The RS model involves transport equations to take proper account of the transport of the Reynolds stresses $\overline{u_i u_j}$, where u_i is the fluctuating velocity component in the x_i direction. In general, the transport equations are a set of differential equations and can be expressed as follows[2]:

$$\frac{\mathrm{d}\overline{u_i u_j}}{\mathrm{d}t} = D_{ij} + P_{ij} + \Pi_{ij} - \varepsilon_{ij} \tag{1}$$

where $\mathrm{d}/\mathrm{d}t = \partial/\partial t + U_j(\partial/\partial x_j)$, U_i is the mean velocity component in the x_i direction, D_{ij} is the diffusion, P_{ij} is the production, Π_{ij} is the pressure–strain correlation, and ε_{ij} is the dissipation. Based on the model presented in Ref. 2, each term on the right-hand side of Eq. (1) can be expressed as follows:

$$D_{ij} = c_s \frac{\partial}{\partial x_k}\left(\frac{k}{\varepsilon}\overline{u_k u_l}\frac{\partial \overline{u_i u_j}}{\partial x_l}\right) \tag{2}$$

$$P_{ij} = -\overline{u_i u_k}\frac{\partial U_j}{\partial x_k} - \overline{u_j u_k}\frac{\partial U_i}{\partial x_k} \tag{3}$$

$$\Pi_{ij} = -c_1(\varepsilon/k)\left(\overline{u_i u_j} - \tfrac{2}{3}k\delta_{ij}\right) - c_2\left(P_{ij} - \tfrac{2}{3}P\delta_{ij}\right) - 2c'_\mu k S_{ij} - c_3\left(C_{ij} - \tfrac{2}{3}P\delta_{ij}\right) \tag{4}$$

$$\varepsilon_{ij} = \tfrac{2}{3}\varepsilon\delta_{ij} \tag{5}$$

In Eqs. (2–5), the summation convention applies where repeated indices appear, k and ε are the turbulence kinetic energy and its dissipation rate, δ_{ij} is the Kronecker delta,

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$$

is the mean rate-of-strain tensor,

$$C_{ij} = -\overline{u_i u_k}\frac{\partial U_k}{\partial x_j} - \overline{u_j u_k}\frac{\partial U_k}{\partial x_i} \tag{6}$$

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