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Modern Developments in Shear Flow Control with Swirl

S. Farokhi* and R. Taghavi†
University of Kansas, Lawrence, Kansas 66045
and
E. J. Rice‡
NASA Lewis Research Center, Cleveland, Ohio 44135

Abstract

EXCITABILITY of a turbulent swirling round jet is explored both qualitatively and quantitatively in the subsonic regime. Plane-wave acoustic excitation as the forcing mechanism caused periodic coherent vortical structures to appear in the shear layer, very close to the nozzle lip. Spectra of the hot-wire measurements along the jet axis reveal the growth of the fundamental wave and no amplification of a subharmonic. Vortex pairing as a mechanism for jet spread in the near field is hence ruled out for turbulent swirling jets. At large forcing amplitudes, a 10% reduction of the mean centerline velocity at nine nozzle diameters, and a corresponding increase in the shear-layer momentum thickness, are measured. It is remarkable to achieve this level of mixing enhancement in a rotating jet by an axisymmetric excitation, while the jet's "preferred" mode is of helical nature corresponding to Taylor-Görtler instability waves.

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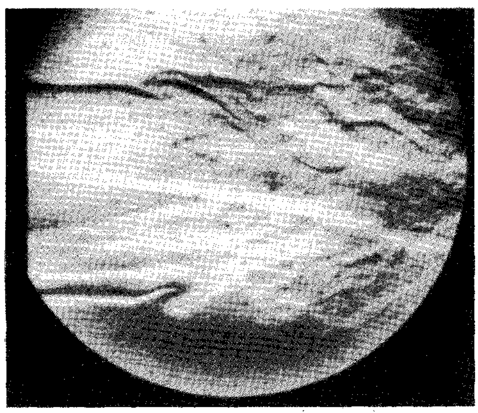
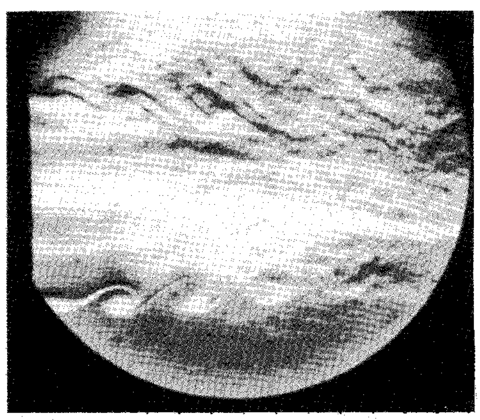
The mean evolution of a turbulent swirling jet is shown by the authors to depend strongly on the initial swirl profile.[1] This constitutes a passive technique to control a rotating shear layer through manipulation of its Rayleigh instability character. In the active control arena, however, one attempts to control mixing enhancement or suppression, in a given swirling jet, by exciting its preferred instability mode at preferred frequencies. In a recent theoretical study, Wu et al.[2] identified helical instability waves, of opposite spin to the rotating jet, as the preferred modes. The results of their linear stability analysis, however, do not identify a preferred Strouhal number ($St \equiv fD/V_0$, where f is the excitation frequency, D the nozzle diameter, and V_0 the mean axial jet velocity at the nozzle exit) where the maximum amplification rate of the most unstable wave occurs.

The response of a warm swirling jet to a single-frequency, plane-acoustic wave excitation is investigated by schlieren optics and shown in Fig. 1. The promotion of periodic, large-scale coherent structures in the near field is evidenced in this figure, which confirms the excitability of a turbulent shear layer with swirl, even by plane-wave forcing at preferred frequencies. Will the promotion of these large-scale structures lead to enhanced mixing? Is vortex pairing a dominant mechanism in shear-layer growth in the presence of rotation? How will excitation change the turbulence intensity profile along a swirling jet? These are some of the fundamental questions we attempt to answer in the present paper.

For this purpose, the excitability of a swirling jet, with a mass-flow rate of 1.2 lb/s (0.54 kg/s) is experimentally investigated. The experiments are conducted by exciting a free jet with a swirl number of $S = 0.12$ by plane acoustic waves. The swirl number is defined as the ratio of jet torque to jet thrust nondimensionalized with nozzle radius. The maximum time-mean tangential and axial velocities at the nozzle exit plane are 58.8 fps (17.9 m/s) and 275 fps (83.8 m/s), respectively. The respective Mach and Reynolds numbers of the jet based on the mass-averaged axial velocity at the nozzle exit are 0.22 and 4.6×10^5. The variation of the rms amplitude of velocity fluctuations at the fundamental excitation frequency u_f' along the jet centerline, corresponding to various excitation Strouhal numbers, identifies a preferred Strouhal number of about 0.39. The forcing amplitude of the excitation at this frequency is 6.88% of the time-mean centerline axial velocity at the nozzle exit (u_{fe}'/U_{ce}) . Figure 2 shows, on a relative scale, the



a) Unexcited



b) Excited at 125 Hz

Fig. 1 Schlieren flow visualization of a shear layer with swirl and excitation.

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*Associate Professor of Aerospace Engineering and Director of the Flight Research Laboratory, Aerospace Engineering Department. Member AIAA.

†Assistant Professor of Aerospace Engineering, Aerospace Engineering Department. Member AIAA.

‡Senior Research Engineer, Inlets and Nozzles Flow Physics Branch, MS 5-9. Member AIAA.

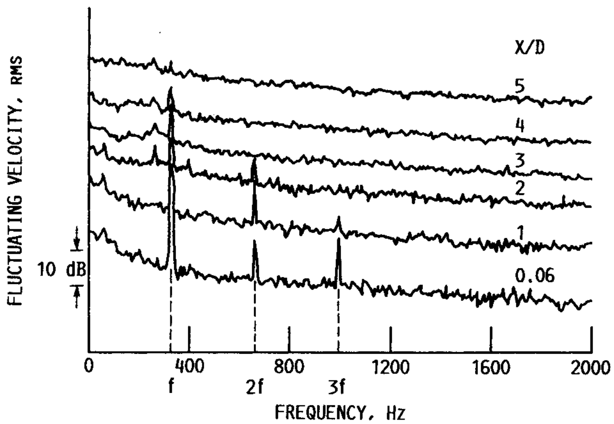

Fig. 2 Evolution of u' spectra along the jet axis; $St = 0.39$, $S = 0.12$, $M = 0.22$, bandwidth = 7.5 Hz.

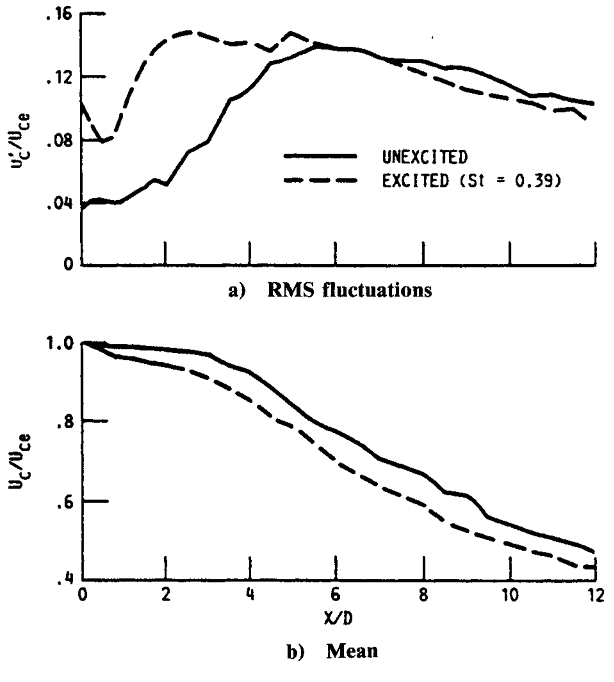

Fig. 3 Effect of excitation on the axial velocity components along the jet axis; $S = 0.12$, $M = 0.22$.

streamwise evolution of velocity spectra along the jet axis at an excitation frequency of 330 Hz ($St = 0.39$). The isolated peaks at 660 Hz (first harmonic) and 990 Hz (second harmonic) are not amplified by the flow and therefore are not further pursued in this study. Also from this figure, it is clear that no growth of the subharmonic (165 Hz) is experienced in the case of the swirling jet excited by plane waves. This observation is in contrast to nonswirling jets, in which considerable growth of the subharmonic is measured and found responsible for jet mixing via vortex pairing phenomenon. Recent work of Panda[3] also supports our findings.

Distributions of total axial turbulence intensity along the jet centerline for the unexcited and excited ($St = 0.39$) cases are compared in Fig. 3a. It is seen that, as a result of excitation, the total axial turbulence intensity at the nozzle exit is almost doubled and the location of its maximum value on the jet axis has moved upstream from $x/D = 6$ to $x/D = 2.5$. For a similar excited jet without swirl, the peak value is reached at a location much further downstream ($x/D = 9$).[4] The increase in streamwise turbulence fluctuation at the peak shows a 15% increment due to excitation. The decay of the time-mean axial velocity along the jet axis is compared for excited and unexcited cases in Fig. 3b. Clearly, as seen from this figure, excitation results in a faster decay starting immediately downstream from the nozzle exit. A 10% reduction of the mean centerline velocity is notable at nine nozzle diameters. The enhanced jet mixing due to excitation is further verified by a radial traverse at $x/D = 7$. The half-velocity radius, at seven nozzle diameters, increases by about 13.2% due to excitation. As another indicator of enhanced mixing, the excited shear-layer momentum thickness is measured at $x/D = 7.0$ and shows a 5.8% increase over the unexcited case. To complement the present investigation, excitation of Taylor-Görtler instability waves of negative and positive helicity—i.e., counter and corotating disturbances with respect to the swirling jet—will be produced, and their effect on mixing enhancement will be studied.

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