Control of High-Speed Impinging-Jet Resonance

Mark Sheplak* and Eric F. Spina†
Syracuse University, Syracuse, New York 13244

The intense pressure fluctuations generated by high-speed impinging jets dramatically increase in amplitude and exhibit peaks at discrete frequencies under certain flow conditions. It is generally accepted that a feedback loop consisting of downstream-convecting organized motions and upstream-propagating acoustic disturbances is responsible for the maintenance of this flow resonance. This paper describes an effort to control impinging-jet resonance through the addition of an annular stream. Fluctuating wall-pressure and near-field acoustic measurements were made in a high-speed (M_j = 0.8–1.6) impinging cold jet issuing from coaxial round converging nozzles. Coherent motions critical to the maintenance of the feedback loop were examined via real-time conditional acquisition of schlieren images. The results of the fluid dynamic control were dramatic. The discrete impingement tone was eliminated and the broadband noise was decreased by an order of magnitude when the Mach number of the annular jet was properly selected. It is hypothesized that the addition of the annular stream alters the character of the downstream-convecting instabilities, thereby interrupting the fluid-dynamic feedback.

Nomenclature

M_j = fully-expanded jet-exit Mach number
x = downstream distance with origin at nozzle exit
ϕ = phase angle of signal

Subscripts

i = inner-jet conditions
o = outer-jet conditions
res = resonant flow parameter
n = shear-layer instability parameter

I. Introduction

THE control of high-speed jet flows with dominant discrete tones is of importance to the aircraft industry. Improperly expanded jets (resulting in screech) and high-speed impinging jets are two flows that exhibit dominant tones. These resonant jet flows belong to a broader class of free shear layer flows that exhibit self-sustaining oscillations (for excellent reviews see Rockwell and Naudascher[1] and Rockwell[2]). The common feature of these phenomena is the large fraction of unsteady flow energy that is concentrated at a single frequency. These high-amplitude tones are undesirable: sonic fatigue from jet screech can shorten the life of an aircraft, and impinging-jet resonance may hamper near-ground operation of future vertical or short takeoff and landing (VSTOL) aircraft. It is known that a fluid-dynamic feedback loop is responsible for these self-sustaining tones, and that coherent structures created in the mixing layer and instability waves excited at the nozzle lip play an important role in driving the feedback mechanism. In this paper, a technique for controlling impinging-jet resonance through the addition of an annular stream is presented and a hypothesis for its success is proposed. The control method is novel in that it uses fluid dynamic means to attenuate the feedback loop, whereas previous researchers have used solid surfaces to interrupt physically the feedback loop (e.g., Poldervaart et al.[3] and Glass[4]).

Because coherent motions play a critical role in jet-resonance feedback loops, it is necessary first to define their relation to jet instabilities. Organized structures in a jet are a consequence of the spatial evolution of high-frequency instability waves excited in the thin shear layer near the nozzle lip. The high-frequency instability waves created at the nozzle lip spatially evolve into large-scale coherent (vortical) motions that continue to grow until nonlinear saturation takes place. These waves are created when a time-varying source external to the jet column (an acoustic source in the case of impinging-jet resonance, for example) transfers energy to the thin shear layer at the nozzle lip. The energy transfer occurs when the acoustic waves force the separation point at the nozzle lip to oscillate, thus providing an initial perturbation to the flow. Upon creation, these disturbances grow exponentially until nonlinear effects roll-up the shear layer into what is typically termed a coherent structure.

When an impinging jet is operated at a high Mach number (M_j > 0.7) and when the nozzle-to-plate separation is on the order of the potential core or less (x/d < 7.5), the pressure fluctuations on the wall and in the near and farfield increase in amplitude and become periodic. Wagner[5] was the first to note these self-sustaining oscillations in a high-Mach-number subsonic jet. He found dramatic differences between signals from a turbulent freejet and a resonant impinging jet. In a high-speed freejet, the pressure fluctuations are aperiodic, and have a broad energy spectrum due to the high-Reynolds-number nature of the turbulent flow. When the jet impinges upon a flat surface in a resonant state, the pressure signals become nearly single-frequency fluctuations, and the energy spectrum is dominated by a sharp, narrow peak at the resonant frequency.

Wagner discovered that an increase in nozzle/plate separation (at constant M_j) initially leads to a monotonic decrease in the discrete tone frequency, followed by an abrupt rise and another steady decrease. This staging process indicates that a feedback loop is present. The connection between frequency stages and a feedback loop becomes clear when it is considered that resonance requires an integer number of disturbance wavelengths to exist in the loop. As the nozzle-to-wall separation distance is increased, the wavelength of the instability waves increases to preserve the phase lock, thus decreasing the resonant frequency. This process continues until the growth rate of the instability waves comprising the downstream leg of the feedback loop is too small to sustain the resonance, thus signifying a minimum value of resonant frequency for that stage. A further increase in nozzle-to-wall separation distance necessitates the addition of another complete period to the wave train, resulting in an abrupt increase in resonant frequency.

There are two slightly differing theories that explain the mechanics of the resonant feedback loop. The first theory was developed from an extensive experimental study of high-Mach-number subsonic round jets by Ho and Nosseir.[6] One leg of the feedback loop in their proposed model is the downstream convection of large-scale coherent structures. Impingement of the ring-like coherent structures on the surface creates acoustic waves that act as

Presented as Paper 93-0733 at the AIAA 31st Aerospace Sciences Meeting, Reno, NV, Jan. 11–14, 1993; received Jan. 27, 1993; revision received Feb. 3, 1994; accepted for publication Feb. 4, 1994.

*Graduate Research Fellow, Center for Hypersonics. Student Member AIAA.

†Associate Professor, Center for Hypersonics. Member AIAA.

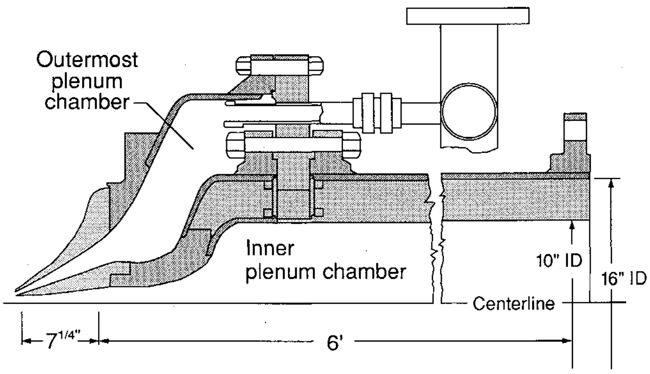

Fig. 1 Cross-sectional view of coaxial nozzle rig (Dosanjh et al.[13]).

the second leg of the feedback loop as they propagate upstream outside the jet column. The acoustic waves interact with the high-frequency instabilities present in the shear layer at the nozzle lip, completing the feedback loop. Ho and Nosseir hypothesized that the loop is actually closed through the production of large-scale vortical structures in a merging process termed collective interaction (Ho and Huang[7]). Ho and Nosseir appealed to this concept of subharmonic merging because the shear flow changes its characteristic frequency from the initial instability frequency to the order-of-magnitude lower resonant frequency over a very short distance downstream of the nozzle exit (about 1.5 nozzle diameters). They argue that a pairing process could not possibly achieve such a large increase in wavelength in such a short distance. One shortcoming of this part of their model, as with all ring-vortex models, is that it is not able to account for higher order (nonaxisymmetric) modes present in supersonic impinging-jet resonance. It should also be noted that the frequency and phase velocity of the downstream-convecting structures agree well with those predicted by linear theory (see Michalke,[8] for example). This indicates that these structures may just be the result of high-growth-rate instability waves that become nonlinear and saturate a short distance downstream from the nozzle exit.

Tam and Ahuja[9] proposed a slightly different mechanism for the feedback loop, with the upstream-traveling leg based on Tam and Hu's freejet instability analysis.[10] Instability waves again comprise the downstream-traveling leg of the feedback loop. However, Tam and Ahuja hypothesize that the impingement process excites the upstream-propagating intrinsic instability waves of the flow first visualized by Oertel.[11] These waves are the neutral modes predicted by linear stability analysis of the mean flow. The waves travel at slightly less than the speed of sound and are confined within the jet column for subsonic jets, whereas for supersonic jets they propagate upstream in the near field as acoustic disturbances. On reaching the nozzle exit, the sound waves provide a high-amplitude perturbation to the thin shear layer. This initial disturbance creates instability waves at the nozzle exit that amplify as they convect downstream, completing the loop through a direct phase lock. According to linear stability theory,[8] high-amplitude perturbations are needed to force the low-growth-rate, low-frequency instability waves into becoming the most-energetic mode—such disturbances clearly exist in such a resonant flow. Although Tam and Ahuja's model is based on a hydrodynamic stability analysis of the jet column, it is consistent with the data of Ho and Nosseir. Most importantly, the model correctly predicts the resonant mode of the jet as a function of Mach number, and it also shows that resonance is not supported below $M_j = 0.6$, which is consistent with experimental data (Wagner,[5] Ho and Nosseir,[6] and Neuwerth[12]). Finally, it offers a way to predict the average impingement tone frequency based on the fact that the Strouhal numbers of the intrinsic instability waves and the impingement tones must match.

II. Experiment

Near-field microphone and wall-pressure measurements were coupled with conditional schlieren visualization in the investigation of an axisymmetric coaxial jet impinging normally on a flat surface. The acoustic and wall-pressure measurements yielded quantitative information on the resonance, while phase-locked/stepped schlieren provided insight into coherent motion evolution and the jet-column instability mode.

The experimental study was performed in Syracuse University's High-Speed Jet Laboratory; a detailed description of this facility can be found in Dosanjh et al.[13] Briefly, two circular air jets at ambient stagnation temperature emanate from coaxial converging nozzles fed by independently controlled stagnation chambers and exhaust into the atmosphere (see Fig. 1). The inner nozzle has a 1.00-in. exit diameter and the outer nozzle has a 1.47-in. exit diameter, with the exit areas being equal. Both the inner and outer nozzle lips have a thickness of 0.031 in. The impingement surface was a 1.00-in. thick, square flat plate constructed of steel and measuring 15 inner-jet diameters square.

The acquisition of quantitative point measurements was accomplished via a VAXstation 3500 and a computer-automated measurement and control (CAMAC) data acquisition platform. Two analog-to-digital (A/D) modules were used in this experiment: a high-speed 12-bit LeCroy 6810 A/D for the fluctuating wall-pressure and acoustic-pressure measurements, and a lower speed 14-bit Kinetic Systems 3514 A/D for the stagnation-pressure measurements. Flush-mounted PCB piezoelectric pressure transducers (1/16 in. diameter) with a frequency response of approximately 100 kHz were used to measure instantaneous wall-pressure fluctuations. Four transducers were located every 1/4 inch along a ray with its origin at the nozzle centerline, with the signal from the centerline transducer used for triggering flow visualization. Instantaneous measurements of near-field acoustic pressure were made using a 1/8 in. diameter Bruel and Kjaer type 4138 condenser microphone with a frequency response of approximately 120 kHz. The microphone was fixed 0.4 in. downstream of the nozzle exit and 2.3 in. radially outward from the centerline of the jet. The microphone signal was amplified using a Bruel and Kjaer type 2619 pre-amplifier. Prior to digitization, the analog signals were band-pass filtered with a four-pole Butterworth filter. The high pass was set to 200 Hz to diminish low-frequency facility noise, whereas the low pass was set at 200 kHz, which is less than one-half the sampling rate to reduce aliasing. The signals were digitized at 500 kHz in continuous lengths of 512 ksamples, converted to engineering units based on calibrations, and written to disk for processing.

A method for visualizing the jet structure based on detection of specified flow characteristics helped to provide a physical understanding of the resonance control. Phase-locked/stepped video

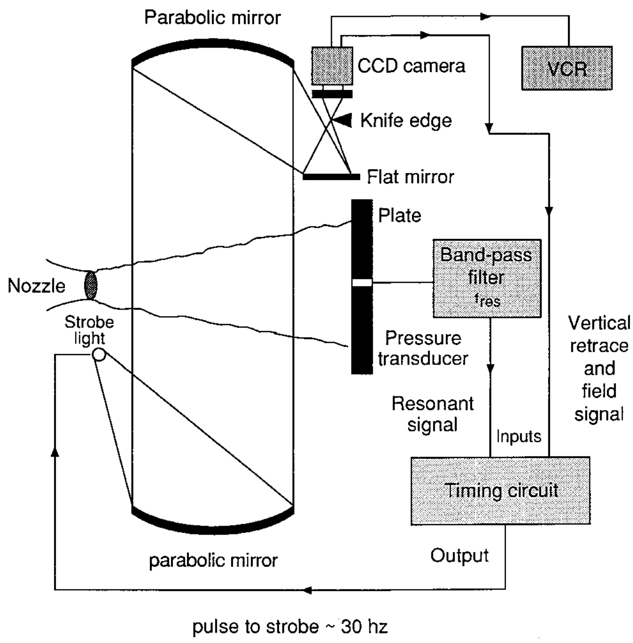

Fig. 2 Optical setup for the phase-locking/stepping schlieren experiment.

schlieren, an improvement on an existing flow visualization concept (see, for example, Whiffen and Ahuja,[14] Wlezien,[15] or Norum[16]), shed light on the structures that play an integral role in the feedback loop. Whereas most previous systems used photographic media for an image plane, video is used in the present setup. The video standard allows real-time digital control of the image acquisition based on selected characteristics of the resonant signal. The optical setup consisted of a typical Z-shaped schlieren with a Xenon 10 ns pulse arc lamp as the light source and a black-and-white change-coupled device (CCD) video camera (512 × 512 resolution) as the image plane (Fig. 2). The light source was triggered by a digital circuit that fires if: 1) the CCD camera is ready to accept an image (i.e., during the vertical retrace before the odd video field), and 2) a user-specified phase angle is detected in the filtered resonant pressure signal (see Sheplak[17] for details). This technique synchronizes the video camera with the resonance and allows the flow to be frozen at a constant angle in a cycle even though the resonant frequency is two orders of magnitude higher than the video standard. The circuit also allows the user to trigger the circuit in specified phase increments from the zero-cross reference, thus phase stepping the image acquisition. Another advantage of video is the ease of digitization and image processing. All images in this paper were refined with histogram equalization and enhanced with edge-detection filtering.

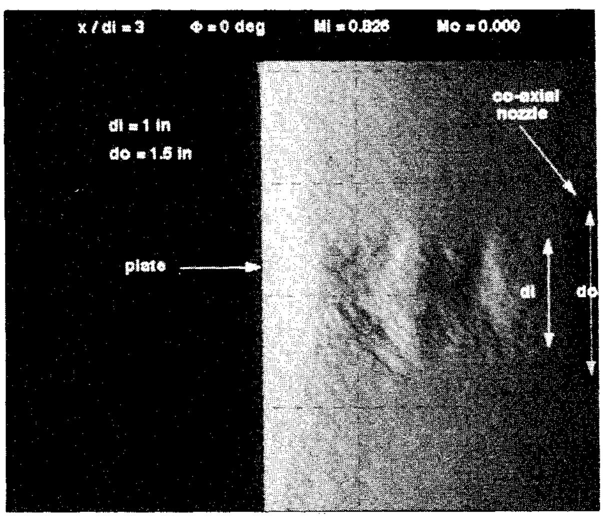

Fig. 3 Single subsonic impinging jet with $M_i = 0.83$ and $x/d_i = 3$; the jet is resonating in an axisymmetric mode; M_i and M_o represent the inner- and outer-jet Mach numbers.

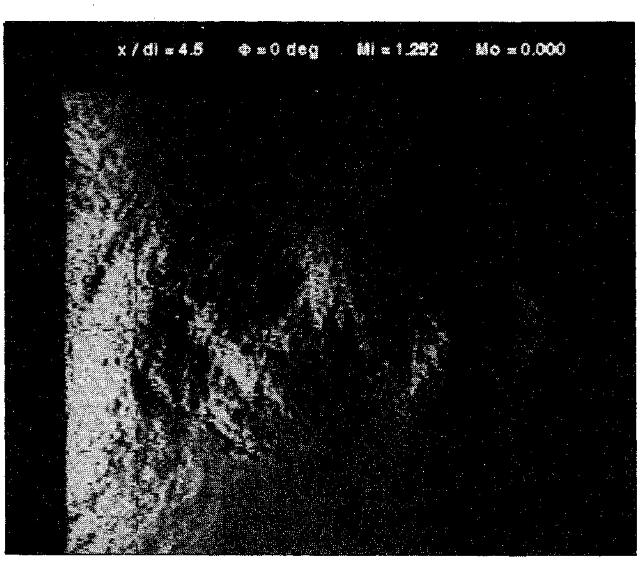

Fig. 4 Single supersonic impinging jet ($M_j = 1.25$, $x/d_i = 4.5$) resonating in a higher order mode.

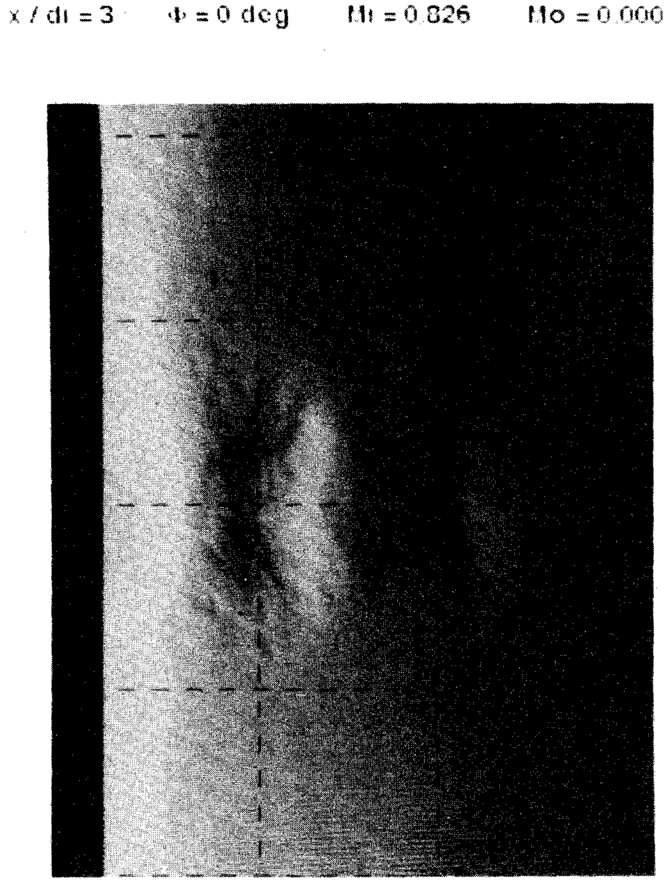

Fig. 5a Ensemble average of a subsonic ($M_j = 0.83$, $x/d_i = 3$) single impinging jet resonating in an axisymmetric instability mode; no phase lag.

III. Single Impinging Jet Results

A preliminary investigation of a single impinging jet was performed to test the experimental techniques and to develop a baseline for comparison with the controlled coaxial jet configurations. The experimental setup consisted of an under-expanded jet issuing from a convergent nozzle (fully expanded $M_j = 0.8$–1.6) impinging on a flat plate at nozzle-to-plate separation distances of $x/d_i = 3$, 4.5, and 5.

Fluctuating wall-pressure measurements revealed resonance characteristics that exhibit good agreement with previous results. Phase-locked video schlieren froze the coherent motions in the feedback loop at a given phase angle in the resonant cycle. The images yielded information on the jet-column instability mode and the spatial distribution of the organized structures. Phase-stepped video schlieren furnished insight into the evolution of the coherent motions, and further confirmed the dominant role that these structures play in the downstream-convecting leg of the feedback loop. The resonance modes revealed by the schlieren visualizations were in accordance with those predicted by Tam and Ahuja's model.[9] Specifically, impinging supersonic jets supported both axisymmetric and higher order modes (helical and flapping), whereas subsonic jets only supported axisymmetric modes. This differs from high-speed subsonic freejets, which are susceptible to higher order modes as well as to axisymmetric instabilities (Tam and Hu[10]).

A phase-locked schlieren image of a subsonic impinging jet is shown in Fig. 3. In this image, as in all others, the nozzle-to-plate separation distance has been scaled with the inner-jet diameter. The phase angle at which the image was acquired, ϕ, is measured relative to the positive-edge zero cross. The superimposed grid lines are separated by one inner-jet diameter for ease in viewing. The jet clearly contains large-scale axisymmetric instabilities or coherent structures. The structures evident in this image appear at the same position in nearly every phase-locked frame taken at

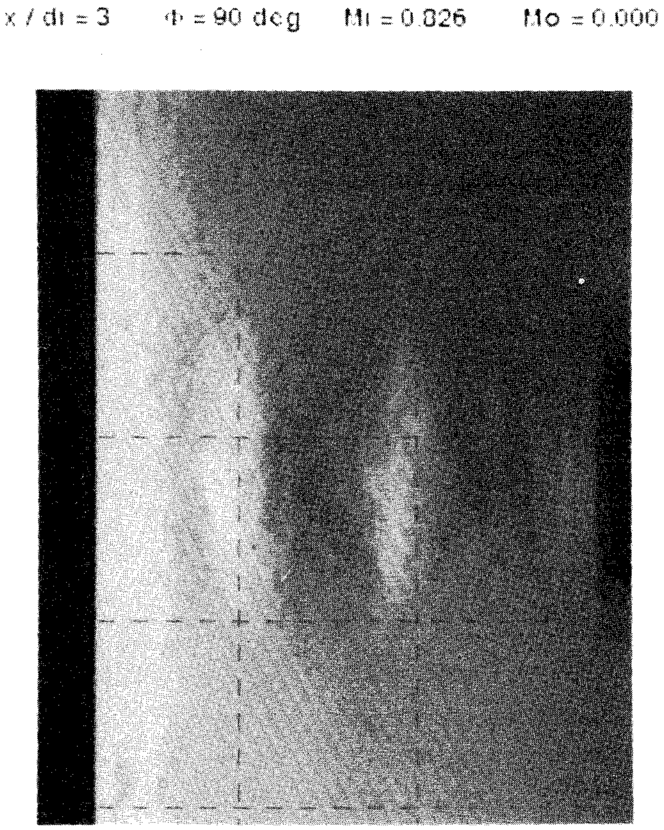

Fig. 5b Same jet flow as in Fig. 5a, but images are captured at a 90-deg phase lag from the positive zero cross.

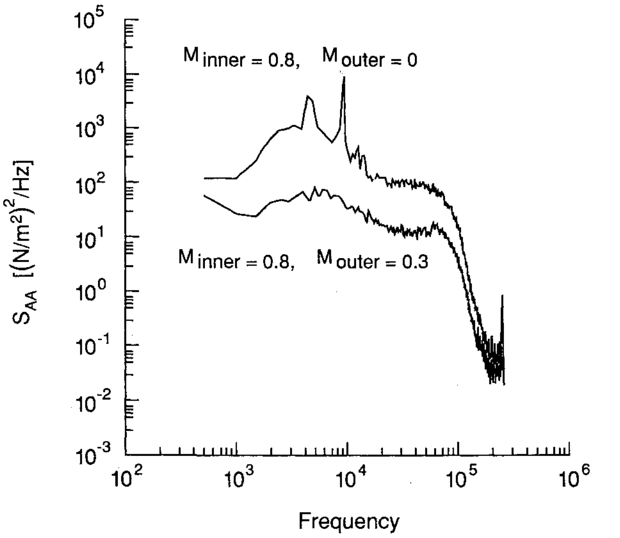

Fig. 6 Power spectral density of condenser microphone signal in the near-field of an impinging jet flow; inner-jet Mach number is 0.8, and the curves are plotted for outer-jet Mach numbers of 0 and 0.3 ($x/d_i = 3$).

these flow conditions. This frozen pattern strongly suggests that the structures play an important role in the resonance.

A supersonic impinging jet captured in a higher order resonant mode by the phase-locking technique is shown in Fig. 4. The jet column displays a corkscrew-like geometry that disrupts the shock structure a short distance downstream from the nozzle exit. In addition to the jet-column structures, acoustic waves emanate alternately from each side of the jet column—a clear indication of the existence of a higher order mode.

The results of phase stepping are shown in Figs. 5a and 5b for the case of a subsonic jet resonating in an axisymmetric mode. The downstream convection of the ring-like structures along the jet column is seen by comparing the position of the structures relative to vertical grid lines in each figure. From an examination of these images and others at phase angles of 45, 135, and 180 deg, it was determined that the axisymmetric structure can appear as close to the nozzle exit as $0.75d_i$. This rapid evolution supports Ho and Nosseir's[6] notion that a pairing process is not a likely mechanism for producing these structures in a subsonic jet. Several pairings would be needed to produce a growth rate of the magnitude seen here, requiring a much longer evolution distance than is evident. On the other hand, this could also demonstrate the rapid growth, then saturation, of an axisymmetric instability.

IV. Coaxial Impinging Jet Results

Once the single impinging jet configuration was investigated and the experimental techniques were validated, the coaxial configuration was examined to evaluate the prospects for resonance control. The inner-stream Mach number M_{ji} was restricted between 0.8 and 1.4, with the outer-stream Mach number M_{jo} varied between 0.3 and 1.5. Measurements were taken with the impingement plate located 3, 4.5, and 5 inner-jet diameters downstream of the nozzles.

For each inner-jet Mach number, a range of outer-jet Mach numbers was found that had a dramatic effect on the flowfield, eliminating the resonance and decreasing the associated broadband noise. The near-field acoustic spectra shown in Fig. 6 for an inner-

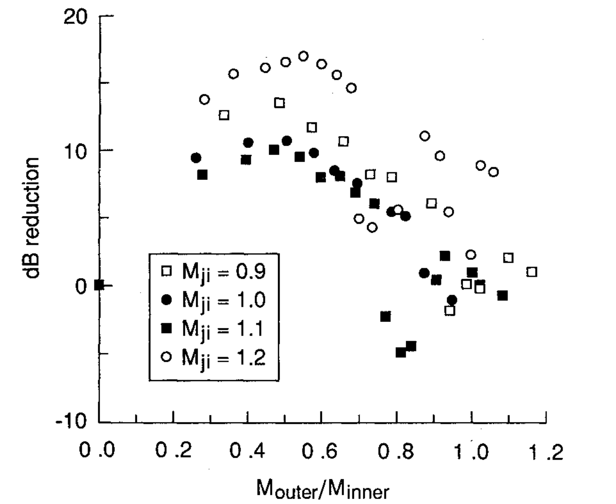

Fig. 7 Reduction of near-field microphone signal rms for several inner-jet Mach numbers as a function of outer-jet Mach number ($x/d_i = 3$).

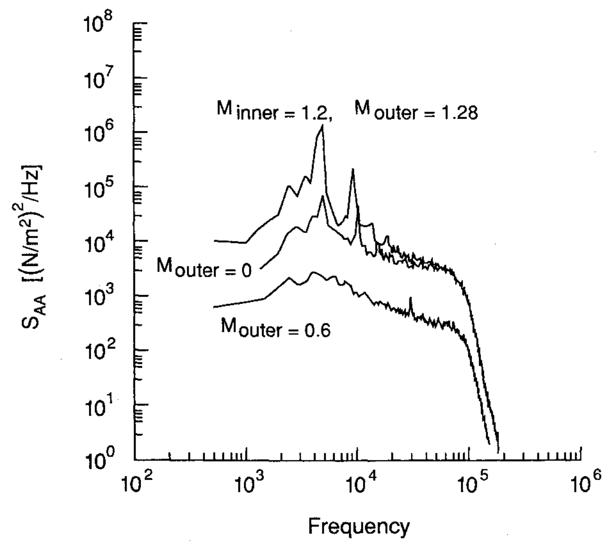

Fig. 8 Power spectral density of condenser microphone signal in the near field; inner-jet Mach number is 1.2, and the curves are plotted for outer-jet Mach numbers of 0, 0.6, and 1.28 ($x/d_i = 5$).

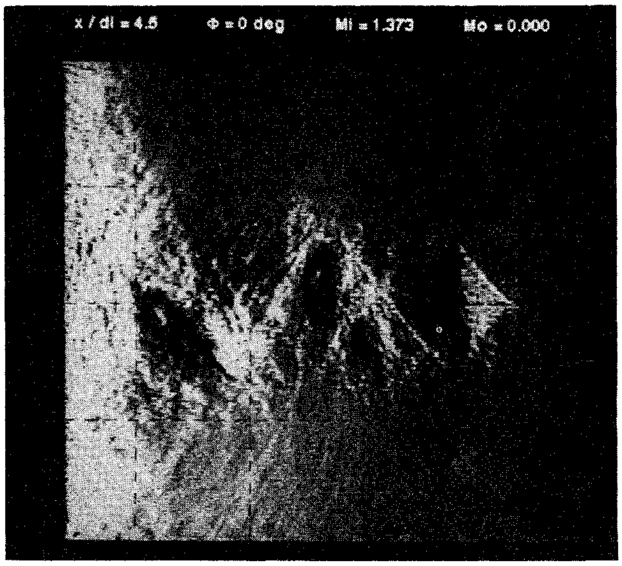

Fig. 9a Single supersonic impinging jet (M_{ji} = 1.37, x/d_i = 4.5).

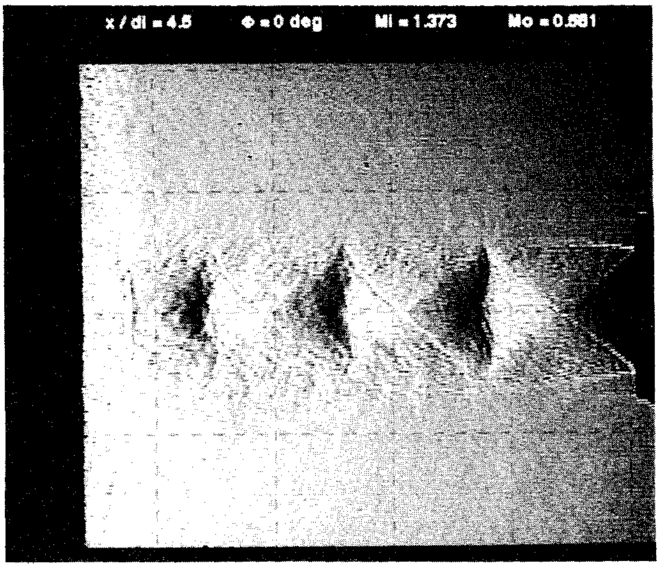

Fig. 9b Same central jet as depicted in Fig. 9a, controlled through the addition of an annular stream with M_{jo} = 0.58.

jet Mach number of 0.8 typifies the effect of adding a coaxial stream to a resonant jet flow. The top spectrum represents a single impinging jet clearly in a resonant state. The bottom curve represents the controlled case in which an annular stream has been added to the central jet. This unequivocally illustrates that this method of control can completely eliminate the resonance, while simultaneously reducing broadband noise by approximately 50%. Figure 7 illustrates the reduction in the rms near-field acoustic pressure as a function of outer-jet Mach number for various inner-jet Mach numbers. The fluid dynamic control decreased the rms of the near-field acoustic pressure by at least 10 dB for all inner-jet Mach numbers.

It is also evident from Fig. 7 that resonance control is limited to certain combinations of inner/outer Mach numbers. As the jet Mach number ratio (M_{jo}/M_{ji}) was increased from zero, an attenuation in resonant power was observed. This trend continued until optimal control was realized at $M_{jo}/M_{ji} \approx 0.5$. Increasing the outer-jet Mach number further, to nearly that of the inner jet, results in the coaxial jet behaving as a single jet with increased momentum. The intensity of the resonance and the broadband noise increases, exceeding the single-jet values in some cases. The transition from single-jet resonance to control to coaxial-jet resonance with increasing annular Mach number is better illustrated by comparing spectra from each regime. Figure 8 again shows that the resonance and broadband noise of a single jet is greatly diminished by adding an annular stream. However, the energy in the resonance and the broadband noise are increased when the jet is operated in an inverted mode ($M_{jo} > M_{ji}$). The resonant frequency exhibited no clear pattern as the annular jet Mach number was varied, sometimes remaining constant over a significant range, and sometimes increasing or decreasing slightly.

Not surprisingly, the addition of the annular stream and the resulting resonance control has a profound effect on the jet structure, as illustrated in Figs. 9a and 9b. The phase-locked schlieren technique clearly shows that the single jet is resonating in a higher order mode, with the shock structure of the improperly expanded jet disrupted by the instability of the jet column. In the controlled jet case, however, the resonant instability mode is completely suppressed. In addition to the disappearance of the instability mode, the intense acoustic waves are no longer visible, and the shock structure is preserved, complete with a stand-off shock near the plate.

V. Final Discussion and Conclusions

The primary conclusion drawn from this research is that impinging-jet resonance can be eliminated and the associated broadband noise dramatically reduced by the addition of an annular stream. However, the addition of the annular flow can also intensify the resonance if the ratio of inner-to-outer-jet Mach numbers is not chosen properly. It is hypothesized that this control technique disrupts the fluid-dynamic feedback loop that maintains the resonance. The feedback loop is comprised of several key elements: 1) receptivity of the shear layer at the nozzle lip, 2) downstream convection of large-scale coherent motions, 3) sound generation at the impingement plate, and 4) upstream propagation of acoustic waves. Thus, there may be several ways in which the annular flow is affecting these processes and thereby inhibiting the jet resonance.

As was previously discussed, the external excitation of the shear layer at the nozzle exit comes from near-field acoustic disturbances for supersonic jets, whereas the forcing waves may be contained within the jet column itself for the subsonic case. The upstream-propagating disturbances must be of high amplitude to cause significant growth of the shear layer instability waves in the resonant jet case. This is because the instability waves at these relatively low frequencies have a low growth rate, and to dominate the flow they must become the most-energetic mode.[8] It is suggested that an alteration in the nature of the downstream-convecting instabilities is at least partly responsible for the resonance control seen in this experiment. The next question is: what mechanism causes this alteration?

The ambient air/jet shear layer thickens with increasing annular flow, relative to the single jet case (see Champagne and Wygnanski,[18] for example). For a coaxial jet, the shear layer thickness is defined as the radial distance from where $U = U_{max}$ to where $U = 0$ (note that U_{max} does not necessarily correspond to the centerline velocity for coaxial jets). Although there are presently no stability calculations available for coaxial jets, it is known from single jets that the reduced mean strain rates in thicker shear layers support lower instability growth rates, lower characteristic frequencies, and higher phase velocities (Michalke[8]). In the flow studied here, any change in the frequency or growth rate of the characteristic instability could result in a departure from the highly tuned, phase-locked condition necessary to maintain the resonance. For example, reduced growth rates lead to weaker downstream-convecting waves, in turn resulting in lower amplitude waves actually reaching the impingement plate. The strength of the acoustic source at the plate is thus decreased, with two important consequences: reduction of broadband noise, and weakening of upstream-propagating acoustic waves, which in turn diminish the amplitude of the disturbance ultimately reaching the nozzle lip. This further weakens the downstream-convecting waves, thus attenuating the resonant feedback loop.

In addition to eliminating the resonance, the presence of the annular stream may cause changes in the shock-reflection condition as compared to the single underexpanded jet (Fig. 9). This change, coupled with smaller amplitude instability waves, may weaken the shock-wave/turbulence interaction and thus reduce shock-associated broadband noise.

Acknowledgments

This research was sponsored by the National Science Foundation through Grant CTS-89-10119, monitored by Stephen Traugott. The assistance of Patrick Magari in developing the phase-locking circuit and Geoff Bruce in acquiring some of the pressure data is gratefully acknowledged. The authors also thank Richard Wlezien for his many helpful comments and suggestions.

References

[1]Rockwell, D., and Naudascher, E., "Self-Sustained Oscillations of Impinging Free Shear Layers," *Annual Review of Fluid Mechanics*, Vol. 11, 1979, pp. 67–94.

[2]Rockwell, D., "Invited Lecture: Oscillations of Impinging Shear Layers," AIAA Paper 77-1286, Jan. 1977.

[3]Poldervaart, L. J., Wijnands, A. P. J., vanMoll, L. H. A. M., and van Voorthuisen, E. J., "Modes of Vibration," Audio-Visual Center, Eindhoven Technical Univ., The Netherlands, 1974; reviewed by J. E. Ffowcs Williams, *Journal of Fluid Mechanics*, Vol. 78, Pt. 4, Dec. 1976, pp. 859–862.

[4]Glass, D. R., "Effect of Acoustic Feedback on the Spread and Decay of Supersonic Jets," *AIAA Journal*, Vol. 6, No. 6, 1968, pp. 1890–1897.

[5]Wagner, F. R., "The Sound and Flow Field of an Axially Symmetric Free Jet Upon Impact on a Wall," NASA TTF-13942, Jan. 1971.

[6]Ho, C., and Nosseir, N. S., "Dynamics of an Impinging Jet. Part 1. The Feedback Phenomenon," *Journal of Fluid Mechanics*, Vol. 105, April 1981, pp. 119–142.

[7]Ho, C., and Huang, H., "Subharmonics and Vortex Merging in Mixing Layers," *Journal of Fluid Mechanics*, Vol. 119, June 1982, pp. 443–473.

[8]Michalke, A., "Survey on Jet Instability Theory," *Progress in Aerospace Sciences*, Vol. 21, 1984, pp. 159–199.

[9]Tam, C. K. W., and Ahuja, K. K., "Theoretical Model of Discrete Tone Generation by Impinging Jets," *Journal of Fluid Mechanics*, Vol. 214, May 1990, pp. 67–87.

[10]Tam, C. K. W., and Hu, F. Q., "On the Three Families of Instability Waves of High-Speed Jets," *Journal of Fluid Mechanics*, Vol. 201, April 1989, pp. 447–483.

[11]Oertel, H., "Mach Wave Radiation of Hot Supersonic Jets," *Mechanics of Sound Generation in Flows*, edited by E. A. Muller, Springer-Verlag, Berlin, 1979, pp. 275–281.

[12]Neuwerth, G., "Acoustic Feedback of a Subsonic and Hypersonic Free Jet Impinging on a Foreign Body," NASA TTF-15719, July 1974.

[13]Dosanjh, D. S., Bhutiani, P. K., and Ahuja, K. K., "Supersonic Jet Noise Suppression by Coaxial Multi-Nozzle Cold/Heated Jet Flows," Department of Transportation Final Rept., Washington, DC, March 1977.

[14]Whiffen, M. C., and Ahuja, K. K., "An Improved Schlieren System and Some New Results on Acoustically Excited Jets," *Journal of Sound and Vibration*, Vol. 86, No. 1, 1983, pp. 99–105.

[15]Wlezien, R. W., "Nozzle Geometry Effects on Supersonic Jet Interaction," *AIAA Journal*, Vol. 27, No. 10, 1989, pp. 1361–1367.

[16]Norum, T. D., "Supersonic Rectangular Jet Impingement Noise Experiments,"*AIAA Journal*, Vol. 29, No. 7, 1991, pp. 1051–1057.

[17]Sheplak, M., "Passive Control of Impinging Jet Resonance," M.S. Thesis, Mechanical, Aerospace, and Manufacturing Engineering Dept., Syracuse Univ., Syracuse, NY, Dec. 1992.

[18]Champagne, F. H., and Wygnanski, I. J., "An Experimental Investigation of Coaxial Turbulent Jets," *International Journal of Heat and Mass Transfer*, Vol. 14, Sept. 1970, pp. 1445–1464.