APPLICATION OF A FLIP-FLOP NOZZLE ON PLUME MIXING ENHANCEMENT

Stefan Schreck and Mark Michaelian
Department of Aerospace Engineering
University of Southern California
Los Angeles, California

and

Chih-Ming Ho
Department of Mechanical, Aerospace, and Nuclear Engineering
University of California at Los Angeles
Los Angeles, California

5,3-07

OUTLINE

Motivation

Problem Statement

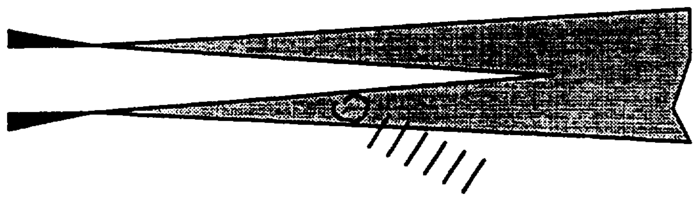
Approach
- **Rectangular Jet**
- **Jet De-stabilization**
- **Acoustic Self-Excitation**

Integration of the Design: Flip-Flop Nozzle

Evaluation
- **Jet Spreading**
- **Far-Field Noise**

Summary

MOTIVATION



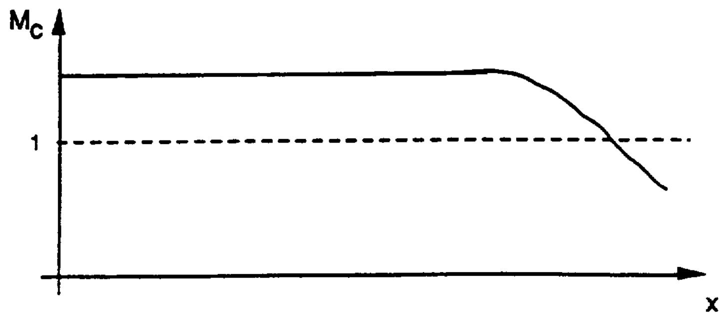
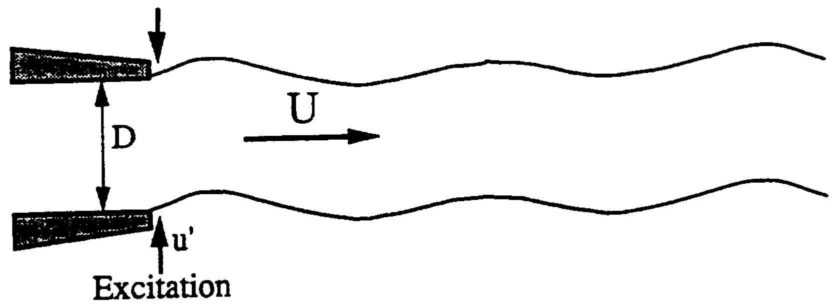


Figure 1: Eddy Mach Wave Radiation

Mach wave radiation is a major source of noise in high speed jets. It is created by turbulent eddies which travel at supersonic speed within the shear layer of the jet (Figure 1). Downstream of the potential core, the convection speed of the eddies decays and noise production is reduced. Once the convection speeds drops below the speed of sound, eddy Mach wave radiation ceases. Mach wave radiation may be reduced by shortening the core length of the jet. This requires a faster growth of the shear layer, i. e. enhanced mixing in the jet. We investigated the possiblity of mixing enhancement by the excitation of the instability waves in a supersonic rectangular jet.

PROBLEM STATEMENT



Forcing Frequency:	$f = 0\,(U/D)$
Forcing Amplitude:	$u' = 0\,(0.01\text{-}0.1\,U)$
Power Requirement:	$P \sim u'^2 f \sim U^3$

Figure 2: Excitation of the Instability Waves in Jets

Acoustic or mechanical excitation of the instabiliy waves has been shown to increase the growth rate of the shear layers in low speed jets. The application of this technique to supersonic jets, however, has been hampered by the demanding requirements on the excitation system. If the preferred mode of the jet is to be excited (Figure 2), the forcing frequency scales with the jet velocity U and is typically of the order of 0.2-0.4 U/D, where D denotes the jet diameter. The forcing amplitude u' is of the order of 0.01-0.1U. Thus, the power requirement increases with the third power of the jet velocity. Loud speakers and piezo cristal actuators, which have been used to force the shear layer instabilties in low speed jets, cannot meet the power requirement for large amplitude excitation of the instability waves in supersonic jets.

APPROACH

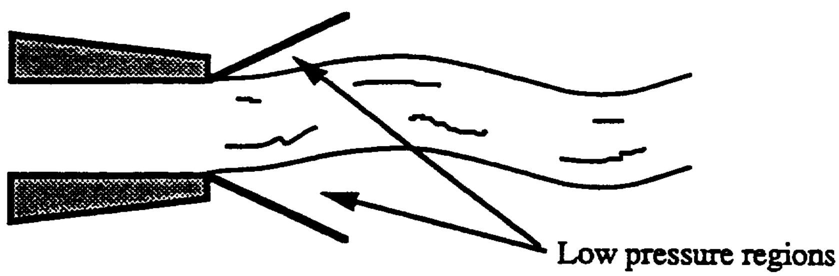


Figure 3A: Flapping Mode of Rectangular Jets

Asymmetric nozzle designs have been considered for the control of jet noise in supersonic jets. Ho and Gutmark (1984) reported an increase in the growth rate of the shear layer in elliptical jets by vortex self induction. Seiner et al. (1992) found that the increased mixing in a small aspect ratio elliptical jet reduces noise radiated at supersonic speeds.

Part I: Flapping Mode of Rectangular Jets -- Besides vortex self induction, small aspect ratio rectangular jets also feature an asymmetric flapping mode similar to that in two-dimensional jets (Figure 3A). This flapping mode may be excited to enhance mixing in supersonic jets. To reduce the force necessary to deflect a rectangular jet, we applied the Coanda effect to de-stabilize the jet. Acoustic self-excitation was then used to flip-flop the jet at a high frequency.

Part II : Destabilizing a Rectangular Jet -- The Coanda effect was used to increase the deflection of the jet from the centerline when excitation is applied. Coanda discovered that a jet attaches to a wall that is placed adjacent to the jet column. The attachment is caused by a low pressure region created between the jet and the wall, which pulls the jet towards the wall. If walls are placed symmetrically on both sides of a two-dimensional jet, the jet might become bi-stable, i. e. it may attach to either

APPROACH (con't)

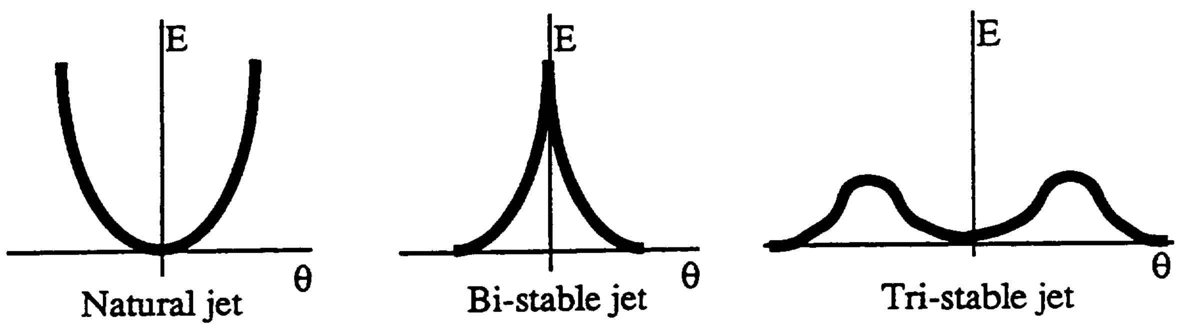


Figure 3B: Stability of the Jet Column

side (Figure 3A). Depending on the configuration, a naturally stable, a bi-stable, or a tri-stable jet may be achieved (Figure 3B). Proper choice of the size and location of the walls creates a destabilzed jet that does not attach to either wall but is less stable in the central position. Such a jet can be deflected from the centerline with less force than the natural jet.

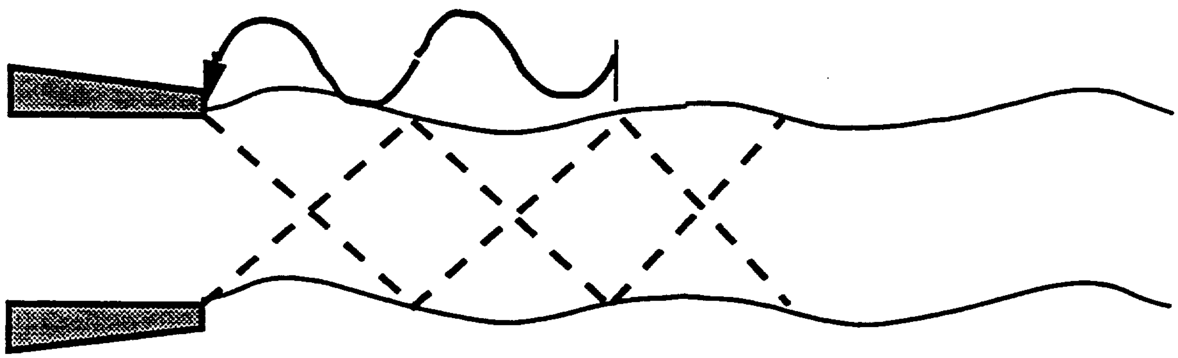
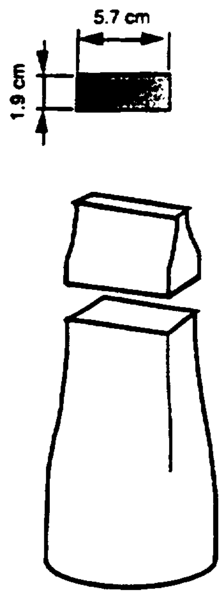


Figure 4: Acoustic Self-Excitation

Part III: Acoustic Self Excitation -- Shock cell structures exist in non-ideally expanded jets. They are confined within the potential core of the jet and interact with the shear layer as shown in Figure 4. This process emits acoustic sound waves that travel outside of the jet upstream to the nozzle lip. When the acoustic waves and the downstream traveling instability waves form a closed loop, the instability waves are excited by their own acoustic radiation and a discrete screech tone is audible. We used the acoustic power of the upstream travelling waves to excite the flapping mode of the jet.

INTEGRATION OF THE DESIGN - A Flip-Flop Nozzle



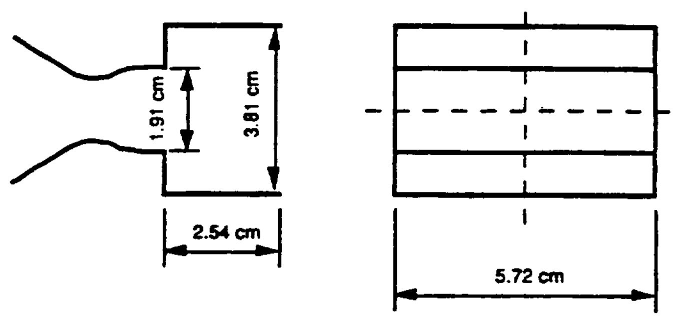


Figure 5B: Collar of the Flip-Flop Nozzle

Figure 5A: The Rectangular Nozzle

The ideas of using the flapping mode of a rectangular jet, destabilizing the jet column, and the self-excitation of the flapping mode by screech were integrated into a flip-flop nozzle. Figure 5A shows the orginal rectangular nozzle. An initially axisymmetric contraction reduces the cross-sectional area of the settling chamber from d = 15.3cm to a square opening of 5.7cm x 5.7cm. The rectangular nozzles feature a two-dimensional contraction from 5.7cm x 5.7cm to 1.9cm x 5.7cm. Two nozzles designed for ideal expansion at M = 1.45 and M = 1.90 respectively were manufactored. The aspect ratios of both nozzles are 3:1. Figure 5B shows the flip-flop nozzle. A collar is mounted onto the nozzle creating a sudden expansion in the minor axis plane of the jet. This design fulfills two functions: similar to the side walls in Figure 3A, it destabilizies the jet by low pressure regions located in the two pockets inside the collar; it also acts as a resonator amplifying selctive acoustic waves created by the shock cell structures in the jet.

EVALUATION OF THE FLIP-FLOP NOZZLE

Figure 6: Shadowgraph Image of the Ideally Expanded Rectangular Jet at M=1.45

Figure 7: Shadowgraph Image of the Rectangular Jet Designed for Ideal Expansion at M=1.9 run at M=1.45

To evaluate the performance of the flip-flop nozzle, the flip-flop jet was compared with an ideally expanded jet at M = 1.45. Since the flip-flop jet has to be run overexpanded to make use of acoustic self-excitation, a rectangular nozzle designed for ideal expansion at M = 1.9 was used. Shadowgraph images of the jets were recorded with a video camera. Digitized images from the recordings are presented here.

The Rectangular Jet

Figure 6 shows minor axis planes of the ideally expanded rectangular jet at M = 1.45. The jet spreads slowly and the potential core extends beyond the viewing area of the shadowgraph system. Figure 7 shows the rectangular jet designed for ideal expansion at M = 1.9 run at M = 1.45. Although this jet is overexpanded and screech is present, the spread rate is similar to that of the ideally expanded jet at M = 1.45.

THE TRI-STABLE JET

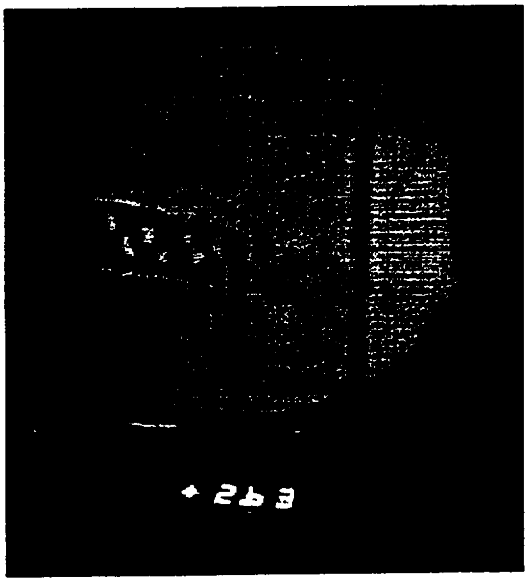


Figure 8A: Shadowgraph Image of the Tri-Stable Jet Attached to the Left Wall.

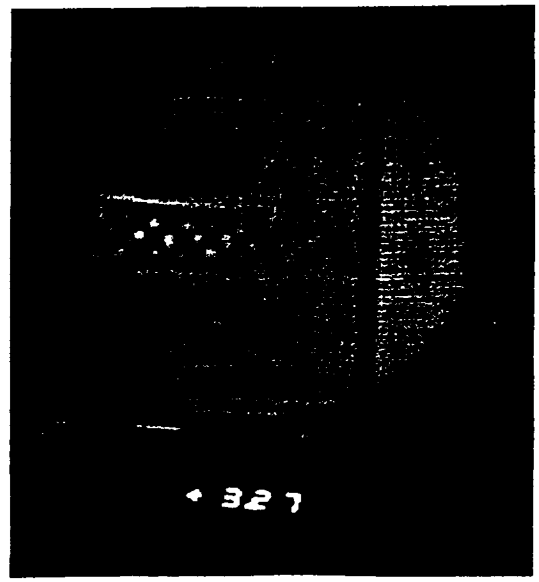


Figure 8B: Shadowgraph Image of the Tri-Stable Jet in the Center Position.

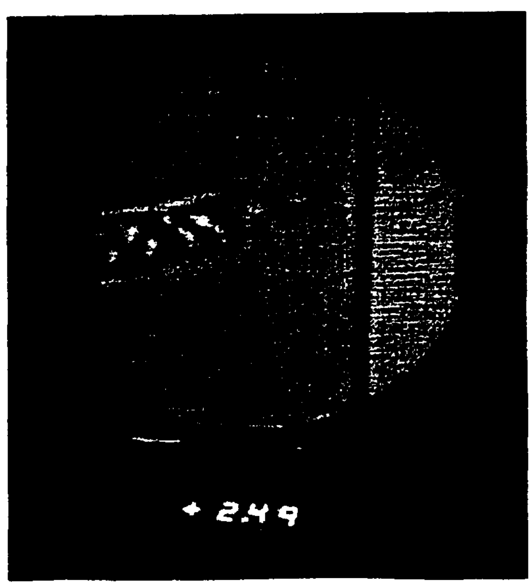


Figure 8C: Shadowgraph Image of the Tri-Stable Jet Attached to the Right Wall.

Figures 8A, 8B, and 8C illustrate the effect of walls on the stablity of a rectangular jet. 5cm long walls were mounted on both sides of the rectangular jet at an angle of 20 degrees. For visual access, plexiglass plates were placed along the narrower sides of the expansion section. In the configuration shown, the jet column is stable in three positions: attached to either wall and in the center. The jet was moved from one position to the other by injecting air normal to the jet at the lip of the nozzle.

THE FLIP-FLOP NOZZLE

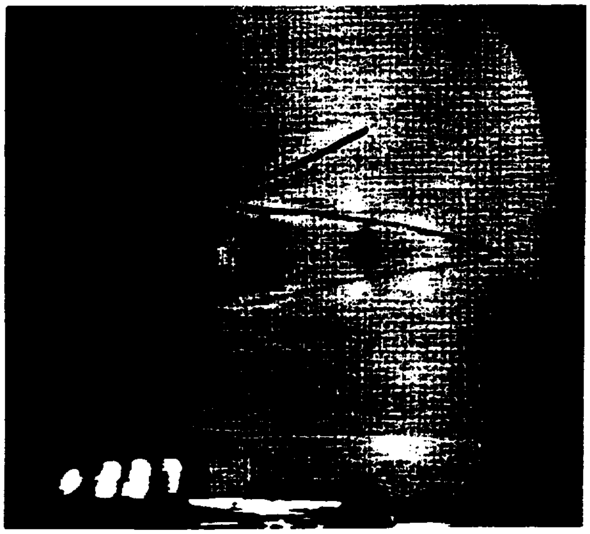


Figure 9A: Shadowgraph Image of the Flip-Flop Nozzle Showing the Large Spreading of the Jet

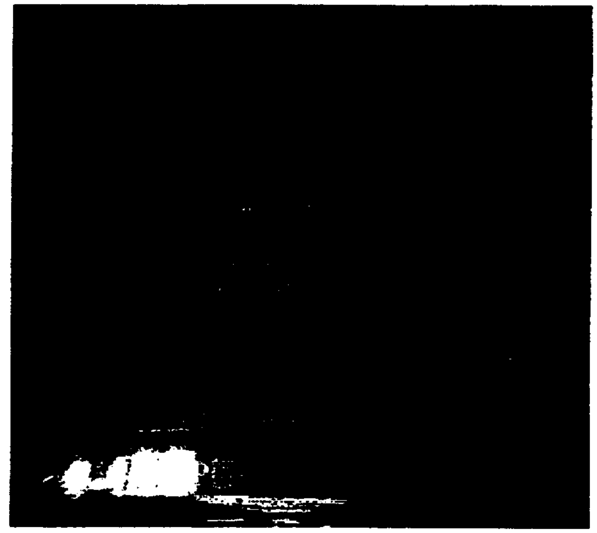


Figure 9B: Phase-Averaged Image of the Flip-Flop Nozzle Showing the Large Coherent Structures in the Jet

Figure 9C: Shadowgraph Image of the Major Axis Plane of the Flip-Flop Nozzle

Figures 9A, 9B, and 9C show images of the flip-flop jet at M = 1.45. In Figure 9A, a time averaged shadowgraph image of the minor axis plane is shown. The outline of the shear layer is highlighted with a marker to demonsrate the spreading of the jet. For Figure 9B, a strobe light was used. The light was triggered with the acoustic signals from the self-excitation of the jet. In the phase-averagd image, large coherent structures are visible in the minor axis plane of the jet. Again, a marker was used to outline the structures. These structures are created by the asymmetric distortion of the jet column. In the major axis plane (Figure 9C), coherent structures are less visible. Note the fast growth of the shear layer towards the centerline of the jet.

CHARACTERISITICS OF THE ACOUSTIC EXCITATION

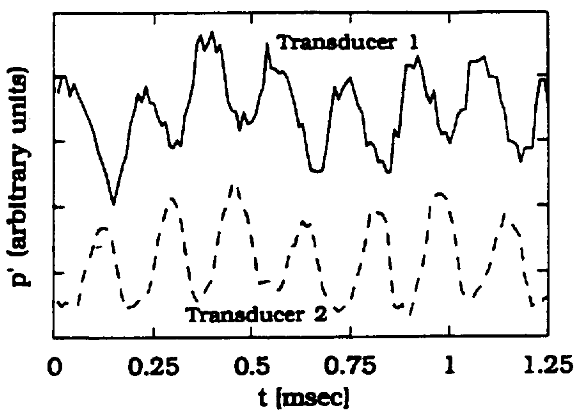


Figure 10A: Time Traces of the Excitation Signals

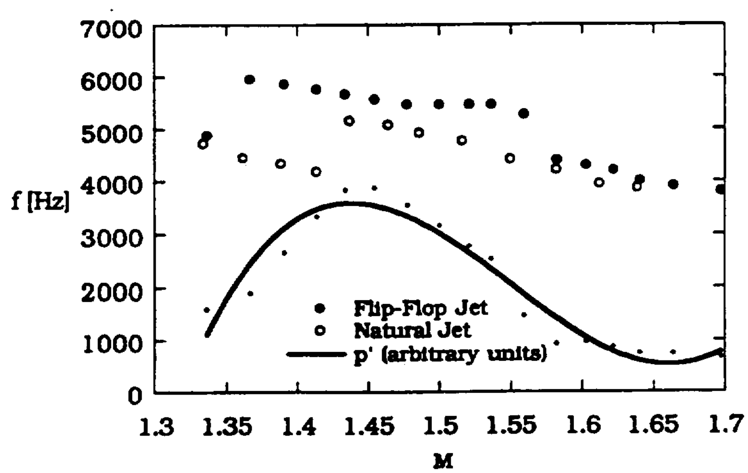
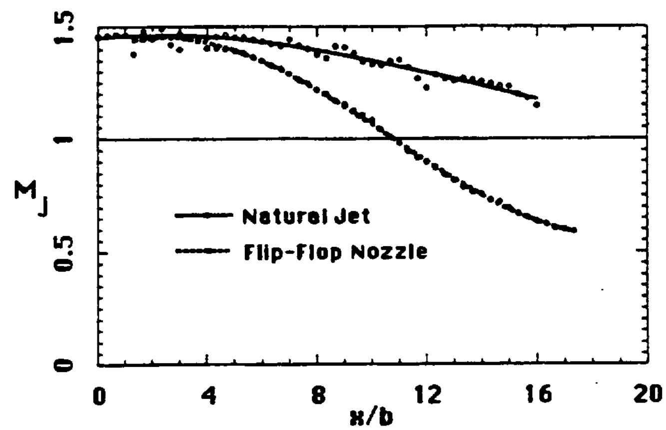


Figure 10B: Frequency and Amplitude of the Excitation Signal

PCB piezo crystal pressure transducers were placed next to the nozzle lip to investigate the characteristics of the acoustic self excitation. In Figure 10A times trace of the pressure signals recorded on both sides of the flip-flop nozzle are plotted. Note the phase shift of 180 degrees between the two signals. The peak frequency of the pressure signals are presented in Figure 10B for the natural jet and the flip-flop nozzle. Outside the range of M = 1.35 to M = 1.55, the peak frequencies of the two jets are identical. They represent the natural screech components in the rectangular jets. In the range from M = 1.35 to M = 1.55, the frequency of the flip-flop nozzle locks into the resonance frequency of the collar. The amplitude of the pressure signals is also shown in Figure 10B. The amplitude increases significantly at resonance.

CENTERLINE VELOCITIES



Convective Mach Number of K.-H. Instability Waves in Cold Jets:

$M_C = (M_J+1)/2$

Figure 11: Centerline Velcocities

Measured centerline velocities of the two jets are presented in Figure 11. The downstream distance is normalized by the minor axis diameter b = 1.9cm. The length of the potential core is considerably reduced by the flip-flop nozzle. The velocity at the centerline of jet reaches Mj = 1 at about x/b = 10 for the flip-flop nozzle and an estimated x/b = 20 for the natural jet. Using the equation for the convection speed of Kelvin-Helmholtz instability waves in cold jets, Mc < 1 for Mj < 1. Consequently, Mach wave radiation ceases in the flip-flop jet at x/b = 10 versus x/b = 20 in the natural jet.

FAR-FIELD NOISE

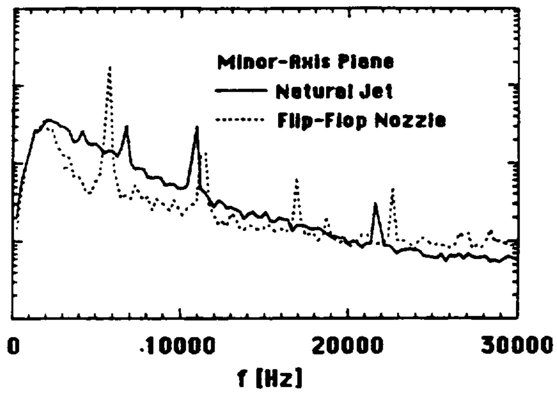


Figure 12A: Noise Spectra in the Minor Axis Planes

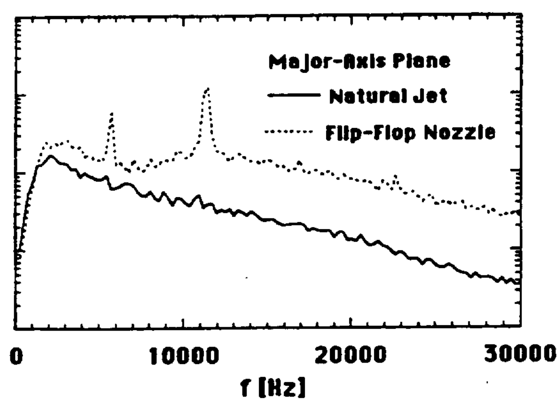


Figure 12B: Noise Spectra in the Major Axis Planes

The goal of enhanced mixing in supersonic jets is the reduction of eddy Mach wave radiation. The far-field noise of the flip-flop nozzle was measured with 1/2" B&K microphones placed in the minor and major axis planes 50 equivalent jet diameters away from the nozzle and 30 degrees off the jet axis. The locations of the microphones coincide with the main direction of the Mach wave radiation. In Figure 12A, the noise spectrum taken in the minor axis plane of the flip-flop nozzle is presented together with that of the ideally expanded natural jet at $M = 1.45$. The spectrum for the flip-flop nozzle is dominated by discrete tones associated with the excited instability waves in the jet. Broadband noise is considerably reduced. The overall SPL is about the same as that for the natural jet. Figure 12B shows the respective spectra in the major axis planes. Conversely to the minor axis plane, broad band noise is increased at the high frequency end of the spectrum. The overall SPL is increased by about 4dB.

DISCUSSION AND CONCLUSIONS

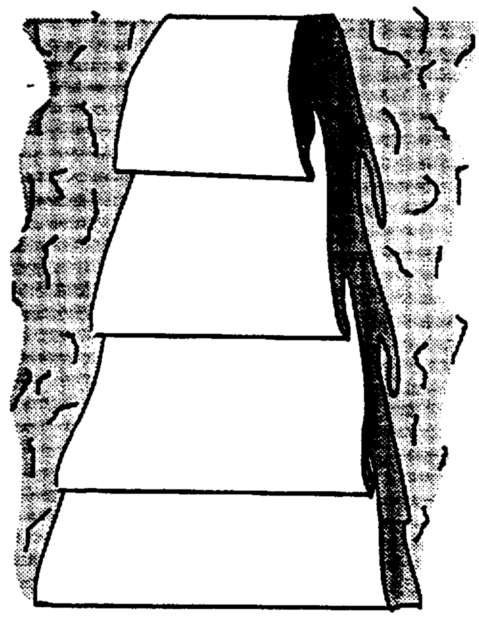


Figure 13: Breakdown of the Jet Column

We have demonstrated that mixing in supersonic jets can be enhanced by utilizing the flapping mode of small aspect ratio rectangular jets. High amplitude excitation of the flapping mode was accomplished by destabilizing the jet column and by amplification of the natural screech tones. The result is a considerable reduction in the length of the potential core of the jet and a rapid decay of the convection speed of the Kelvin Helmholtz instability waves. Acoustic measurements in the far-field of the jet indicate that noise radiation is not reduced in the current design of a flip-flop jet at $M = 1.45$. This is due to an increase in the mixing noise. Unlike in two-dimensional jets, the large scale coherent structures in the flip-flop jet do not extend infinitely along the major axis of the jet. On both ends of the rectangular jets, the coherent structures cannot maintain their two-dimensional shape and rapidly break down into small scall turbulence. This is illustrated by the sketch in Figure 13. The disintegration of the coherent structures is responsibe for the fast mixing of the jet. The increase in the high-frequency content of the noise spectra taken in the major axis plane is associated with the breakdown of the coherent structures.

The contribution of Mach wave radiation to the total acoustic power of the jet increases with the Mach number. We hope that at $M = 2.0$, the increase in mixing noise of the flip-flop nozzle will be more than offset by the reduction in Mach wave radiation. We also consider using the flip-flop nozzle in conjunction with an ejector. The rapid mixing in the flip-flop jet would increase the efficiency of ejectors in entraining ambient air. Lining on the inner walls could be used to absorb the high-frequnecy mixing noise in the major axis plane. Supported by NASA Grant NAG-1-1096 and Zumberge Research Innovation Fund, USC.

CONCLUSIONS

MIXING ENHANCEMENT

- FLAPPING MODE OF RECTANGULAR JET
- DESTABILIZATION OF THE JET COLUMN
- SELF-EXCITATION BY SCREECH
- SIMPLE, PASSIVE DEVICE