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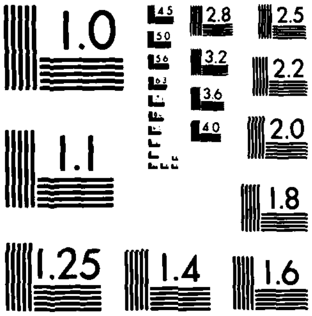

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BASIC STUDIES OF MULTIPLE FREE AND CONFINED JETS

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An experimental investigation ~~has been~~ was carried out to study the mixing characteristics of a moderate aspect ratio rectangular free and confined jet; and free and confined multiple jet. The main parameters ~~in this investigation~~ were the primary jet pressure ratio (stagnation pressure/ambient pressure) and the ejector mixing duct to width ratio. The pressure ratio varied from 1.5 to 5; the mixing duct to width ratio varied from 8 to 24, which is equivalent to the cross sectional area ratio range from 11 to 34. It is found that an underexpanded jet inside a duct generates intense discrete tones (screech tones) similar to a free underexpanded jet. For a given pressure ratio, the variation of the dominant tone with duct widths shows staging behavior, and the frequency varies continuously with duct width in each stage. Similarly, for a given duct width, the variation of the dominant discrete frequency with pressure ratio shows staging behavior. It is found that enhanced mixing and improved performance of the ejector was related to the strouhal number of the ejector screech tone. For all the duct widths

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→tested, it is found that when the screech tone strouhal number lies within the range 0.1 0.15, the primary jet spreading is increased and the ejector flow is better mixed at the exit. By incorporating a phase-locked technique with schlieren flow visualization, standing waves excited by the screech tones inside the ejector mixing duct were photographed. In case of a multiple jet ejector, acoustic interaction is not a significant feature of the flow, and screech tones, so distinctly heard in single jets are not evident. The mixing properties of the flow inside the duct depend on the area ratio, with better mixing found in a compact ejector. The location of the throat relative to the nozzle exit plane has a large effect on the ability of the ejector to entrain the ambient fluid and also deliver better performance. A multiple jet ejector was shown to be distinctly superior to an equivalent single jet ejector from a performance point of view, especially at low area ratios and highly underexpanded exit conditions.

Contents

Introduction

A research program consisting of basic experimental studies of the fluid mechanics of single and multiple rectangular jet configurations with and without confining surfaces was initiated in July 1979 under the contract no. F49620-79-0189. This final report is being written to describe the work carried out during the entire period (July 1979 - June 1984) of the contract.

The present study has the following main objectives to the general problem of the mixing processes in a single and multiple rectangular jets.

1. Investigate experimentally the flow structure of a single rectangular free jet for the following cases.
    a) Subsonic rectangular jet ($0.3 \leq M \leq 1.0$)
    b) Underexpanded rectangular jet at pressure ratios ranging from 2 to 6.
2. Investigate the flow structure of a single rectangular jet in a confined configuration such as that in an ejector.
3. Study the structure of multiple free and confined jets.

As originally envisaged that in all these studies attention was directed to the basic understanding of the mixing processes. During these investigations when important flow features not initially visualized were found, effort was devoted, in consultation with APOSR, to study those features. Such, for instance, is the phenomenon of "screech" tones which influences the structure of both free and confined jets considerably. It is of interest to mention that two new flow visualization techniques were developed, during the course of this contract, to study the organized vortical motions in jet and like shear flows.

In the following, the status of the research effort is given, along with some of the most important conclusions arrived from this study. The details of various investigations are given in a number of JIAA reports and papers, which are included here as appendices.

Status of the Research Effort

In the following, major conclusions on the various facets of the Research Program are given.

A systematic investigation has been carried out on the structure of a jet issuing from a moderate aspect ratio (AR=16.7) rectangular nozzle at flow speeds ranging from low subsonic to supersonic. The main features of the flow are given below.

a) Single rectangular free jet.

In the case of a subsonic rectangular jet, the general characteristics of the flow field do not change significantly with exit Mach number. Similar to the case of an incompressible rectangular jet, the mean flow field of the jet is characterized by the presence of three distinct regions as defined by the decay of the centerline mean velocity. These three regions are: a potential core region, a two-dimensional type region, and an axisymmetric type region (see figure 1). The onset of the second region where the shear layers separated by the short dimension of the nozzle meet appears to be independent of the jet exit Mach number. However, the location where the shear layers separated by the long dimension of the nozzle meet seems to occur farther downstream with increasing Mach number.

From the measurements in the central X,Y plane of the jet, the following conclusions can be drawn. The mean velocity profiles are geometrically similar with the shape of the profile

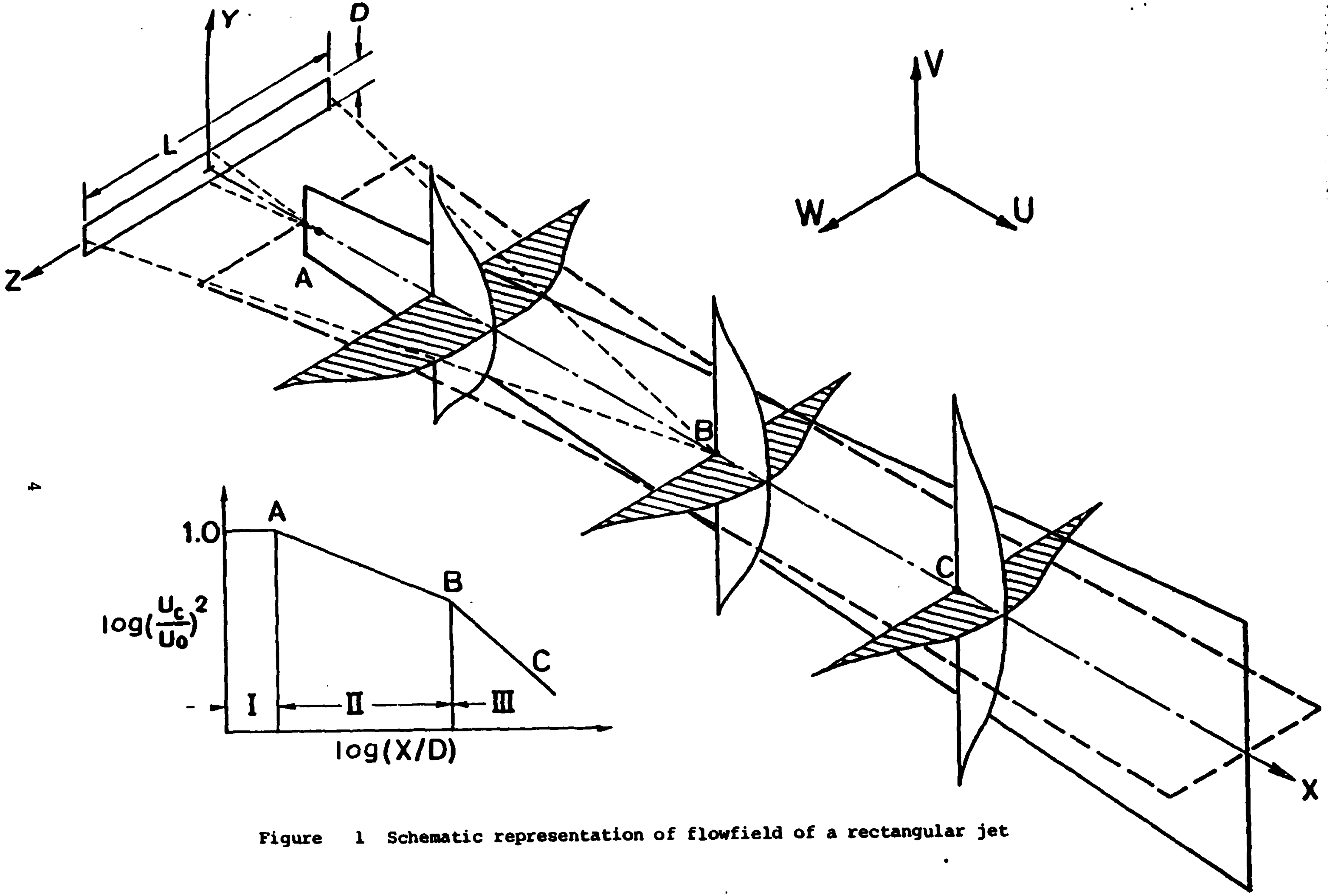

Figure 1 Schematic representation of flowfield of a rectangular jet

almost identical to that of an incompressible two-dimensional jet. The half-velocity width of the jet varies linearly with downstream distance, with its slope and virtual origin nearly independent of the exit Mach number. The r.m.s. profiles show self-similarity only in the two-dimensional type region with their shape being independent of the Mach number. In the axisymmetric type region, no geometrical similarity was observed in those profiles.

In the central X,Z plane, the saddle shape mean velocity profile observed in the two-dimensional type region of an incompressible jet becomes less pronounced as the exit Mach number increases. This observation along with the results in the X,Y plane suggests that the jet behaves more nearly like a two-dimensional jet at higher Mach numbers for downstream locations less than 100D.

From these results, it appears that for a given nozzle geometry the overall properties of a subsonic compressible rectangular jet are quite similar to that of an incompressible jet. It may be suggested that the turbulence structure of a compressible rectangular jet can be inferred from the measurements of an incompressible rectangular jet.*

For more details of the work, see Appendix (JIAA TR-43).

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* Krothapalli, A., Baganoff, D., and Karamcheti, K., "On the Mixing of a Rectangular Jet", Journal of Fluid Mechanics, Vol. 107, 1981, pp. 201-220.

b) single underexpanded rectangular jet.

While investigating the mean and turbulent velocity fields of an underexpanded rectangular jet of moderate aspect ratio, we encountered two major factors influencing the overall flow field of the jet. One is to be expected and is the effect of the density ratio between the jet and the ambient air. The second factor, typical of underexpanded jets, is the generation of "screech" tones and their influence on the structure of the jet. Although discrete tones or "screech" tones are found in the near sound field of the jet for all pressure ratios above the critical pressure ratio (i.e. R=1.9), they are most intense and have greatest effect on the overall flow field only in the range of pressure ratios from 3 to 4. The maximum screech sound radiation occurs in this experiment at a pressure ratio of 3.8. When the jet is operating outside this range of pressure ratios, the influence of screech tones is less important, as compared to the effects of varying density, on the mean and turbulence velocity fields of the jet.

From the Schlieren photographs studied, the following observations are made. For the condition of maximum screech sound radiation, a very strong organized cylindrical wave pattern is observed, which originates alternately from each side of the jet. The souce for this wave system is located approximately at the end of the third shock cell and serves as an acoustic excitation for the entire jet flow field. Associated with the presence of the wave system is an increased spreading rate of the jet in the plane containing the small dimension of the nozzle. When the frequency of the acoustic excitation lies within the instability band for a plane incompressible jet, it serves to introduce large scale coherent structures in the turbulent flow. Such structures are observed here in both planes of the jet. However, in the x,y plane they appear just downstream of the acoustic source, i.e. at x/D = 10, while in the x,z plane they are observed at downstream locations of x/D greater than about 60. The existence of these large scale structures at different downstream locations in the two planes was also confirmed by oscillograph records of hot-wire signals and their respective frequency spectra. The Strouhal number for these organized motions was found to be equal to 0.12, which is close to the most unstable frequency for the antisymmetric modes of the planar incompressible jet. The frequencies in the two planes thus scale with the aspect ratio of the nozzle. These observations are supported by the theoretical work of Crighton 1973*, who studied the stability of a jet with an elliptic cross-section. He found that in the case of spatially growing disturbances, modes representing sideways oscillation parallel to the major axis, or long dimension of the nozzle, have a small growth rate, while

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*Crighton, D.G., "Instability of an Elliptic Jet", Journal of Fluid Mechanics, Vol. 59, 1973, pp. 655-672.

those representing a flapping motion parallel to the minor axis, or small dimension of the nozzle, have a large growth rate.

The mean and rms intensity profiles, for x/D greater than 80, in both the central x,y and x,z planes, exhibit separate geometrical similarity in their respective planes, thus suggesting that complete axisymmetry (i.e. identical profiles in both planes) of the jet may not be achieved within a reasonable distance downstream. This is in contrast to one's intuitive notion that a rectangular jet should reach a complete axisymmetric state in a relatively short distance downstream of the nozzle exit.

In the absence of acoustic excitation with increasing pressure ratio (increase in reservoir pressure), a decrease in the spreading angle of the jet was observed. Similar observations have also been made in studies of other supersonic shear layers and is associated with the increasing density of the jet.

Using phase-locked Schlieren pictures to study the flow, an acoustic wave generation process is suggested. The main features of the process are: the vortical fluid in the shear layer adjacent to the shock cell, under some conditions, enters into the cell and interacts with the normal shock wave at the end of the cell. The interaction of the vortical fluid with the shock wave then produces an acoustic wave. The downstream location for the birth of this acoustic wave depend on the local thickness of the shear layer, and its frequency seems to depend upon the instability characteristics of the shear layer. When the Strouhal number of the acoustic wave matches closely with that of the most highly amplified instability wave of the shear layer, a strong organized cylindrical wave structure is generated. The experiment with the roughened walls showed that, when the shear layer is thickened, it moves the interaction region upstream but it does not alter the frequency of the wave system. Therefore, the onset must be tied closely with the conditions in the shear layer, namely its thickness. In order to place the above qualitative description of the mechanism on a proper footing, detailed experimental investigations need to be carried out to measure the instantaneous flow field both in the shear layer and in the adjacent shock cell.

For more details see Appendix (JIAA TR-47 and AIAA paper no. 83-0727).

c) confined underexpanded rectangular jet.

The experimental studies that have been carried out thus far have contributed to a general understanding of the ejector flow. However, little is understood about the nature of the mixing phenomenon of a confined underexpanded rectangular jet, which is essential to the development of the augmentor wing ejector. Several key questions to be answered are:

- Is the behavior of an underexpanded rectangular jet inside the ejector different from that in free space?

- What is the role of the screech tone in the ejector performance and flow mixing?
- How does the screech tone interact with the jet flow?

In the present study acoustic and flow measurements were made to investigate the characteristics of an underexpanded rectangular jet in a rectangular duct. The investigation is exploratory in nature. The emphasis is on the effects of aeroacoustic interactions between the screech tone and the confined jet on the mixing and performance of the ejector.

In the present investigation, a convergent rectangular nozzle of fixed geometry was used for all the experiments. Top-hat pitot pressure profiles were obtained at the nozzle exit. The mixing duct cross-sectional area was constant along the duct and a fixed duct length was used (see figure 2). The area of the duct cross-section could be varied by adjusting the width of the duct. No diffuser was employed in this study. Experiments were made at various jet pressure ratios up to a value of 4.4. For the highest pressure ratio tested, the Reynolds number based on the nozzle width and the exit velocity, assuming isentropically expanded flow, was about 1.7×10^5.

The main features of the flow and acoustics of an underexpanded rectangular jet ejector are examined experimentally. Of special concern is the role of screech tone on the performance of the ejector. In addition, certain phenomena of the acoustically excited jet in a duct are observed for the first time using a phase-locked schlieren flow

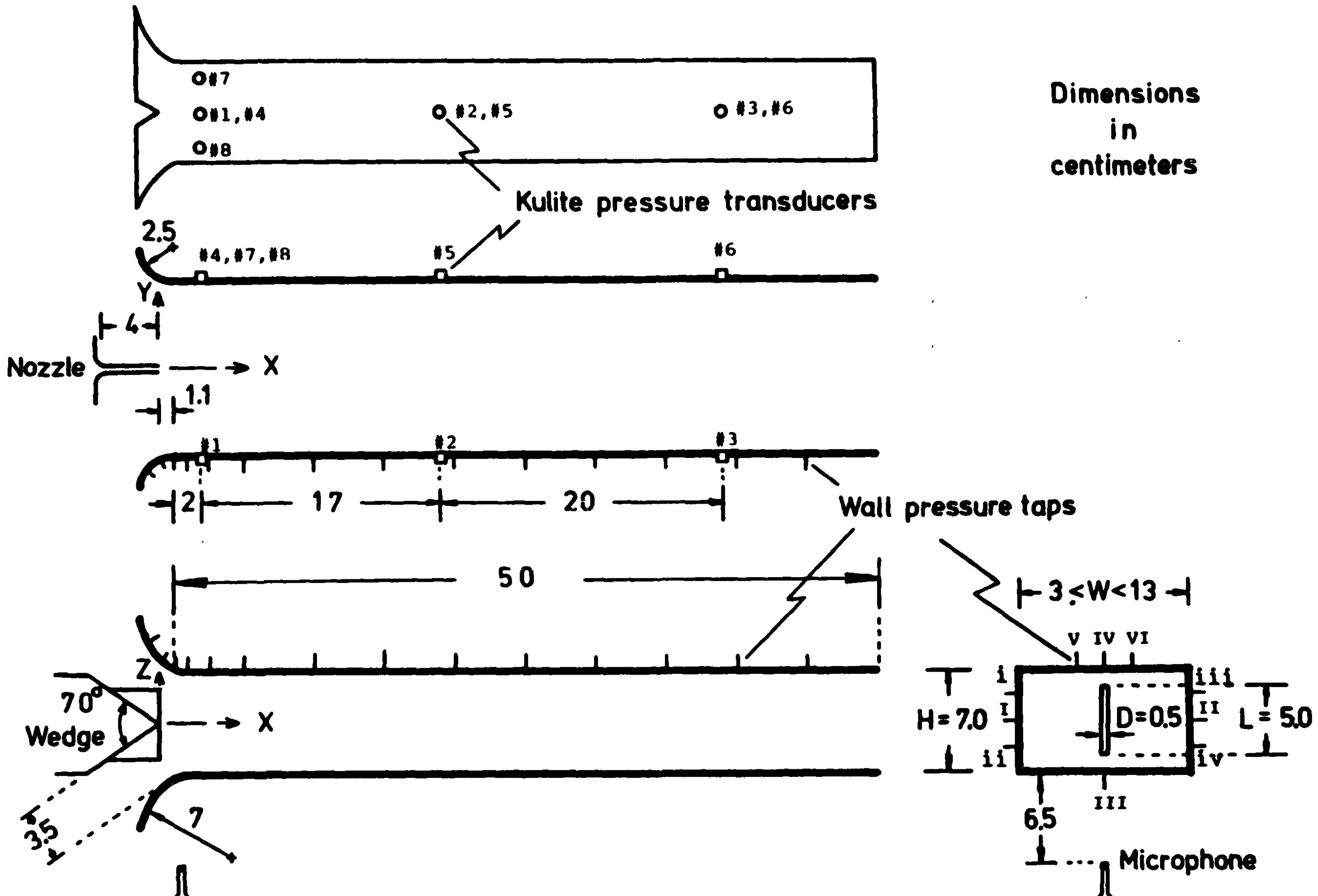


Figure 2 Schematic of the ejector model and probe locations

visualization technique. Main observations and implications are summarized in the following.

From the acoustic measurements, it is found that the underexpanded jet inside a duct generates intense discrete tones (screech tones) similar to a free underexpanded jet. However, the screech tones of the confined jet are different from those of the free jet in a way that the frequency of the dominant tone generated by the confined jet depends not only on the jet pressure ratio but also on the duct width. For a given pressure ratio, the variation of the dominant tone with duct width shows staging behavior, and the frequency varies continuously with duct width in each stage. This is a typical characteristic of feedback mechanism tone generation. Such a feedback loop may be modeled as a triangle with the three vertices being the sound source, the nozzle lip, and the reflection point on the wall.

For a given duct width, the variation of the dominant discrete frequency with pressure ratio also shows staging behavior. In each of these stages, the frequency is nearly constant and matches with one of the transverse duct modes. Standing waves corresponding to these duct modes are observed in phase-locked schlieren photographs; this verifies the existence of the duct modes excited.

From the ejector duct wall pressure measurements, it is found that the ejector performance is improved within a certain range of jet pressure ratios, which matches with one particular screech tone stage. In this range, the ejector flow at exit was found to be almost fully mixed in the plane containing the short dimension of the nozzle. The flow velocity in the plane containing the long dimension of the nozzle is not uniform and shows similar behavior for all the pressure ratios above the critical pressure ratio.

The criterion for the enhanced mixing and improved performance to occur is found to be related to the Strouhal number of the ejector screech tone. For all the duct widths tested, it is found that when the screech tone Strouhal number lies within the range 0.10-0.15, the primary jet spreading is increased and the ejector flow is better mixed at exit. This Strouhal number range is also the most unstable Strouhal number of the free underexpanded rectangular jet. For more details see Appendix (JIAA TR - 53).

d) underexpanded multiple jet ejector.

The above mentioned study is on an ejector using a single jet. In real life application - as in an augmentor wing for V/STOL aircraft - it is common to use an array of nozzles. These multiple jets are, generally, believed to have superior mixing characteristics. Hence, a multiple jet ejector is expected to deliver a better performance. In addition, the multiple jet flow is quieter than a single jet - even under supersonic conditions - making a multiple jet ejector an attractive alternative to a long slot jet ejector. The available data on a multiple jet ejector over the operating range encountered in the present day application is scant, at best. The present study is aimed at providing this vital information.

In order to be able to compare the performance of a multiple jet ejector, it is necessary to obtain results on an 'equivalent' single jet. This is because of the fact that the entrainment characteristics in the near-field would be vastly different for the two cases. A complete definition of the equivalent jet is not possible because such a jet should be able to generate all the effects of the multiple jet. This means that the pressure field set up by the merging jets, the appropriate length scale for this flow, the effect of spacing, etc. should all be reproduced by this equivalent jet. With these limitations in mind, the equivalent single jet is defined as a jet having the same total area and aspect ratio as that of the multiple nozzle tested. Identical tests were carried out on this jet under identical conditions to establish the reference.

In the experiment, the nozzle pressure was varied over a range starting from 1 psig to 38 psig. The area ratio was varied from 14:1 to 33:1. The shroud length was kept fixed. The nozzle-throat distance was varied from 1.1cm to 5.2cm. The number and spacing between the jets were also varied.

Detailed velocity traverses were taken at the ejector exit plane for 4 specific pressure ratios. The wall static pressure distributions were obtained over the entire range of nozzle pressures. Schlieren flow visualization pictures of the jet were taken with and without the ejector.

Two nozzle assemblies were used in the experiment. The multilobe nozzle was the same as that used by Krothapalli et al. (1979). This is shown in figure 3. It consists of 5 rectangular slots each 0.3cm wide and 5cm long placed on a wedge of 70° included angle. The lobes are placed 2.4cm (8 slotwidths) apart. It is possible to block any of these lobes to get a different arrangement of the multiple jet flow. Most of the experiments were performed by blocking the outer most slots, on either side of the central slot, thus resulting in 3 jets spaced 2.4cm apart. Since it was felt worthwhile to study the effect of the number of jets and spacing, some tests were done on the 5 jet configuration also. To obtain the operating pressure ratios, however, it was necessary to reduce the exit area of these slots. This was accomplished by attaching a shim of aluminum onto one of the inner walls of the slot for all the slots. The combined thickness of the insert was 1 mm. The shims were of the same height as the slots. The settling chamber end of these were chamfered so as to guide the flow properly into the slot. The resulting slot dimension was 0.2cm x 5cm, with the slots now placed 2.5cm (12.5 slot widths) apart. The total flow area was only about 10% greater than that of the three jets. Thus, fair comparison of the performance under identical operating conditions was possible.

Data on the equivalent single jet was obtained using the nozzle shown figure 4. As stated earlier, the exit dimensions of this nozzle were arrived at by stipulating that the aspect ratio

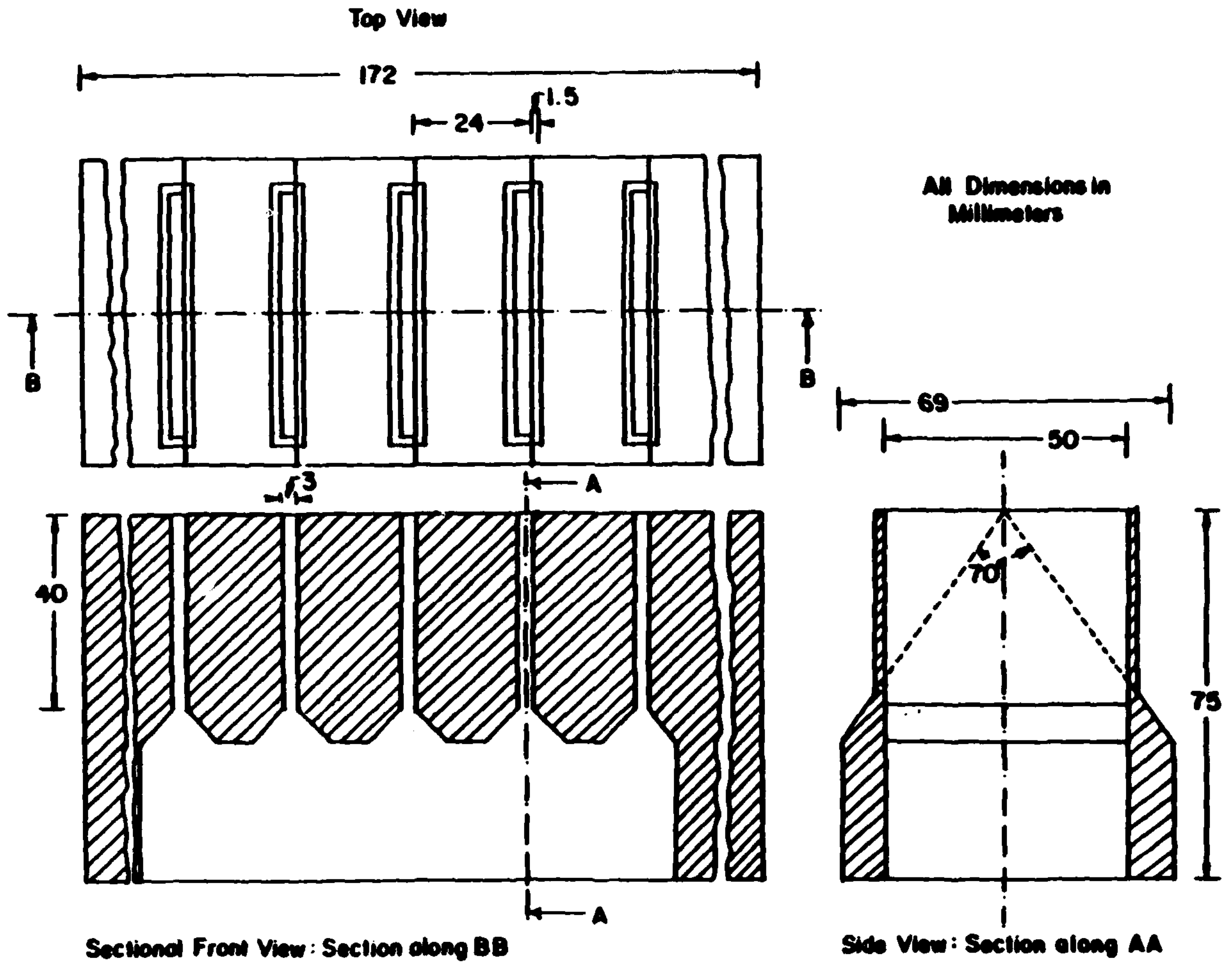
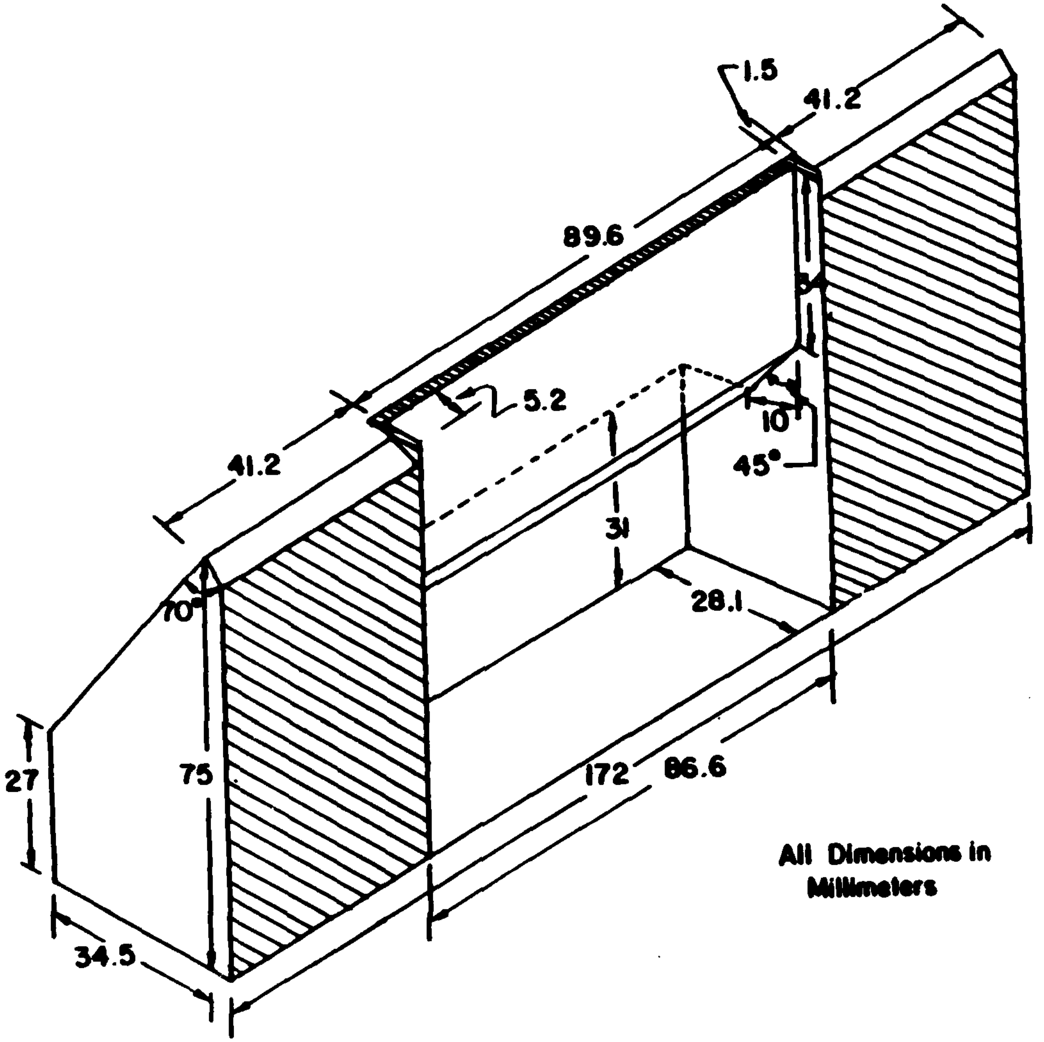


Figure 3 Details of the multiple jet assembly.



All Dimensions in Millimeters

Figure 4 Details of the equivalent single jet.

and the total flow area are the same for this jet as the multiple jet. The dimensions of such a slot are 0.52cm x 8.66cm. This nozzle has the same included angle (70°) as the multilobe array. However, its longer dimension is along the wedge so that the same settling chamber and ejector shroud could be used for the test.

The contraction leading up to the nozzle is two-dimensional in both the models. Sufficient care was exercised during model fabrication to ensure smooth flow passages.

The experiment itself consisted of taking velocity profiles and pressure distributions for various conditions. Velocities were measured for stagnation pressures of 7.7, 15, 25, and 35 psig (corresponding to pressure ratios of 1.52, 2.02, 2.7 and 3.38) for the multiple jet and equivalent single jet at the exit plane. Two area ratios, 20:1 and 26:1, were considered for both the jets.

The wall static pressure distribution was obtained for stagnation pressures ranging from 1 psig to 38 psig and for nozzle-throat distances of 1.1cm, 2.6cm and 5.2cm. The exercise was repeated for both the jets at area ratios of 26:1 and 33:1.

Axial total pressure distributions were measured for P = 7.7, 15, 25 and 35 psig starting from the jet exit (except for P = 35 psig, for which the measurements were started slightly downstream) and for area ratios of 20:1, 26:1, and 33:1.

In addition, single flash schlieren pictures were taken for the free multiple jets and the confined jets (ejector) for an area ratios of 14:1 and 20:1, at various pressure ratios.

Also, throat static pressure was obtained manually for a multiple jet ejector with 5 primary jets and with an area ratio of 20:1.

The major conclusions drawn from this study are given below.

- Acoustic interaction is not a significant feature of the multiple jet flow and ejector-screech tones, so distinctly heard in single jets are not evident in the multiple jets. The flow mixing that occurs should then be mainly due to the interaction of the jets. The mixing properties of the flow inside the duct depend on the area ratio, with better mixing found in a compact ejector.

- The location of the throat relative to the nozzle exit plane has a large effect on the ability of the ejector to entrain the ambient fluid and also deliver a better performance. The performance deteriorates monotonically as the throat moves farther, in the range of distances tested, in contrast to the behavior of a two-dimensional incompressible ejector.

- The wall static pressure distribution shows self-similarity in a multiple jet ejector, when normalized by the throat pressure, for the closest nozzle-throat spacing. At longer distances, a slight break down in self similarity can be seen.

- A multiple jet ejector is distinctly superior to a single jet ejector from a performance point of view, especially at low area ratios and highly underexpanded exit conditions.

- Increasing the number of jets may not result in a better ejector for jet spacing of up to $\simeq$ 15 jet widths.
- In a multiple jet system, the velocity profiles at the duct exit are fairly uniform and thus the flow quality in it is better. However, in a single jet ejector, the velocity variations could be as much as 100% and this is highly undesirable.
- The gross variation in velocity at the exit from the shroud of a single jet ejector establishes the need to perform detailed measurements in several planes during bench tests before the results can be extended to flight conditions.

Written Publications in Journals

1. Hsia, Y., Krothapalli, A., Baganoff, D., and Karamcheti, K., "Effects of Mach Number on the Development of a Subsonic Rectangular Jet", AIAA Journal, Vol. 21, No. 2, 1983.

2. Krothapalli, A., Karamcheti, K., Hsia, Y., and Baganoff, D., "Edge Tones in High Speed Flows and Their Application to Multiple Jet Mixing", AIAA Journal, Vol. 21, No. 7, 1983.

3. Hsia, Y., Baganoff, D., Krothapalli, A., and Karamcheti, K., "An Enhanced Flow Visualization Technique for Planar Shear Layers", AIAA Journal, Vol. 22, No. 3, 1984.

4. Krothapalli, A., Hsia, Y., Baganoff, D., and Karamcheti, K., "The Role of Screech Tones on Mixing of an Underexpanded Rectangular Jet", submitted to Journal of Sound and Vibration.

5. Hsia, Y., Krothapalli, A., and Baganoff, D., "Some Observations on Mixing of an Underexpanded Rectangular Jet Ejector", to be submitted to the AIAA Journal.

6. Chandrasekhara, M.S., Krothapalli, A., and Baganoff, D., "On Mixing Characteristics of an Underexpanded Multiple Jet Ejector", to be submitted to the AIAA Journal.

7. Hsia, Y., and Krothapalli, A., "Features of Discrete Tones Generated by a Confined Underexpanded Rectangular Jet" to be submitted to the Journal of Aircraft.

8. Chandrasekhara, M.S., Krothapalli, A., and Baganoff, D., "On the Similarity of the Ejector Wall Pressure Distribution", to be submitted to AIAA Journal.

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Ph.D. Students

1) Dr. Y.C. Hsia (July 1, 1979 - Dec. 30, 1983)
   Graduated in June 1984.
   Thesis Title: An Experimental Investigation of an Underexpanded Rectangular Jet Ejector.

2) Dr. Blair G. McLachlan (Jan. 1, 1983 - June 30, 1983)
   Worked as a research assistant on the program for a period of six months. Dr. McLachlan worked on the problem of multiple jet mixing, which resulted in a AIAA paper.

3) Miss Pamela Logan (Oct. 1, 1982 - June 30, 1983)
   Worked as a research assistant on the program for a period of 9 months. Miss Logan worked on developing computer software for the acquisition and the reduction of experimental data.

Paper Presentations

1. A. Krothapalli, D. Baganoff, Y. Hsia, and K. Karamcheti, Some features of tones generated by an underexpanded rectangular jet"; AIAA Paper no. 81-0060, 19th Aerospace Sciences meeting, January 1981.

2. A. Krothapalli, Y. Hsia, D. Baganoff, and K. Karamcheti, "Some observations on mixing of free and confined underexpanded rectangular jets": Proceedings of the Ejector Workshop for Aerospace Applications; Dayton, Ohio, August 1981, AFWAL-TR-82-3059.

3. A. Krothapalli, D. Baganoff, Y. Hsia, and K. Karamcheti, "On the mixing of an underexpanded jet"; Bulletin of American Physical Society, vol. 26, no. 9, November 1981.

4. Y. Hsia, A. Krothapalli, D. Baganoff, and K. Karamcheti; "Effects of Mach numbers on a rectangular jet", Bulletin of American Physical Society, vol. 26, no. 9, November 1981.

5. A. Krothapalli, "On discrete tones generated by an impinging underexpanded rectangular jet", AIAA Paper no. 83-0729, The 8th Aeroacoustics meeting, April 1983.

6. A. Krothapalli, D. Baganoff, and Y. Hsia, "On the mechanism of screech tone generation in underexpanded jets", AIAA Paper no. 83-0727, The 8th Aeroacoustics meeting, April 1983.

7. Y. Hsia, A. Krothapalli, D. Baganoff, and K. Karamcheti, "Some observations of discrete tones generated by an underexpanded rectangular jet ejector", AIAA Paper no. 83-0728, The 8th Aeroacoustics meeting, April 1983.

8. Y. Hsia, A. Krothapalli and D. Buerman, "A visualization technique for multiple tone generating flows", Bulletin of the American Physical Society, Division of Fluid Dynamics meeting, November 1983.

9. Y. Hsia, A. Krothapalli and D. Baganoff, "Some observations on the mixing of an underexpanded rectangular jet ejector", AIAA Paper no. 84-0280, 21st Aerospace Sciences meeting, January 1984.

10. B.G. McLachlan and A. Krothapalli, "Effects of Mach number on the development of a subsonic multiple jet", AIAA Paper no. 84-1656, the AIAA 17th Fluid Dynamics, Plasma Dynamics and Lasers Conference, June 1984.

11. Y. Hsia and A. Krothapalli, "Features of discrete tones generated by a confined underexpanded rectangular jet", AIAA Paper no. 84-2256, The 9th AIAA Aeroacoustics meeting, October 1984.

Seminars by Dr. Krothapalli

Aeroacoustics Seminar, NASA Langley Research Center, May, 1980

Fluid Mechanics Seminar, California Institute of Technology, January 1981

Seminar, General Electric Company, Ohio, August 1981

Engineering Mechanics Seminar, VPI and State University, June 1982

Aeroacoustics Seminar, NASA Langley Research Center, June 1982

Noise Technology Seminar, Boeing Airplane Company, September 1982

Applied Mechanics Seminar, University of Southern California, March 1983

APPENDIX

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1. JIAA TR-43; The Structure of a Subsonic Rectangular Jet.
2. JIAA TR-47; On the Structure of a Underexpanded Rectangular Jet.
3. AIAA Paper No 83-0727; On the Mechanism of Screech Tone Generation in Underexpanded Rectangular Jets.
4. JIAA TR-53; An Experimental Investigation of an Underexpanded Rectangular Jet Ejector.
5. AIAA Paper No. 84-1656; Effects of Mach Number on the Development of a Subsonic Multiple Jet.
6. JIAA TR-55; Mixing Characteristics of an Underexpanded Multiple Jet Ejector.

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