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RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCES



SCHOOL OF ENGINEERING AND APPLIED SCIENCE

University of Virginia

Charlottesville, Virginia 22901

A Final Report

UNSTEADY LOADS DUE TO PROPULSIVE LIFT CONFIGURATIONS PART A: INVESTIGATION OF SCALING LAWS

Grant No. NGR 47-005-219-03

Submitted to:

National Aeronautics and Space Administration Scientific and Technical Information Facility P. O. Box 8757 Baltimore/Washington International Airport Maryland 21240

Submitted by:

Jeffrey B. Morton John K. Haviland

Report No. UVA/528095/MAE78/115 March 1978



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ABSTRACT

This report is one of four parts covering investigations into the unsteady loads due to propulsive lift configurations. It specifically covers an investigation of scaling laws, and describes pressure measurements made to determine details of the large scale jet structure and to verify scaling laws by direct comparison. The basis of comparison was a test facility at NASA Langley in which a JT-15D exhausted over a boilerplate airfoil surface to reproduce upper surface blowing conditions. A quarter-scale model was built of this facility, using cold jets. A comparison between full-scale and model pressure-coefficient spectra, presented as functions of Strouhal numbers, showed fair agreement, however, a shift of spectral peaks was noted. This was not believed to be due to Mach number or Reynolds number effects, but did appear to be traceable to discrepancies in jet temperatures. A correction for jet temperature was then tried, similar to one used for far-field noise prediction, this was found to correct the spectral peak discrepancy. However, due to a lack of data on hot jets, it was impossible to demonstrate that the shift in spectral peaks was, in fact, due to temperature effects, and was not due to some other imperfection in modelling.

INTRODUCTION

Interest in the nature of the scaling laws governing jet impingement has recently been quickened by the development of two concepts for STOL (Short Take-Off and Landing Aircraft) in which the main propulsion jet engines are used during landing or take-off to augment the wing lift. In one arrangement, referred to as the blown flap, the engines are mounted below the wings, and impinge on large flaps when these are extended below the wing. In the other, referred to as upper surface blowing, the engine nozzles exhaust over the upper wing surface and follow the upper surfaces of the flaps when they are extended to large angles. In both cases, the result is the downward movement of a large volume of air, consisting not only of the jet exhaust, but also of entrained air. The large fluctuating pressure loads present in a jet exhaust result in severe pounding of the extended flaps, and would lead to excessive weights of the flaps themselves and of the supporting hinges if the unsteady pressures could not be predicted accurately for design purposes.

The principal aim of the current research has been to investigate the scaling laws associated with the unsteady pressures encountered in jet impingement, so that adequate model tests could be designed. In order to achieve this goal, a two-pronged approach was pursued in which, on the one hand, the fluctuating pressures behind jets used for upper-surface-blowing would be studied, and, on the other, the large scale jet structure would be studied in the presence of an external or "coflowing" flow, using laser anemometers.

This part of the final report, Part A, covers the fluctuating pressure studies, while Part B covers the laser studies. Parts C and D are essentially two theses which cover aspects of the pressure investigation in more detail.

Part A starts with a discussion of early studies using a small circular jet, which was used to develop techniques for the measurement of fluctuating pressures in jets. It follows with a discussion of the development of a quarter-scale model of an upper-surface blowing configuration, and concludes with a discussion of the scaling laws, as they can be verified to date.

It is concluded that the low speed cold jet can play a role in a test program designed to determine jet impingement effects. Further, it is pointed out that such a model jet could play a valuable role in the investigation of far-field noise.

Investigations will not be concluded with this report. The list of publications and presentations flowing from this study, as presented in Appendix A, will later be augmented by a doctoral dissertation on the effects of inserting a core nozzle into the model, and by a master's thesis presenting the results of a fuselage interference study.

SUMMARY OF STUDIES PERFORMED ON UNSTEADY PRESSURES
BEHIND A SMALL COLD JET

Early in the program, it was realized that little progress could be made on the development of scaling laws for jet impingement without a firm understanding of the flow characteristics of the jet itself. The traditional viewpoint was represented by the classical model shown in Figure 1a, in which a smooth emerging potential core interacts with entrained air in a region intersecting cones referred to as the sheared annulus. The growth rate of this region is so rapid that the complete potential core has been absorbed in about five diameters from the jet exit, and this fact, alone, is sufficient to eliminate turbulent mixing as the mechanism for the transport of turbulence. The region behind the potential core is known as the adjustment zone, and this finally merges into the fully developed zone of classical turbulence.

The sheared annulus together with the highly active part of the adjustment zone immediately following it have long been recognized as the source of acoustical noise, and its characteristics have been studied for this reason. A number of investigators, such as Powell (1), Bradshaw, Ferris and Johnson (2), and Mollo-christiansen (3) had suggested that this region was structured, and, in the years immediately preceding the present study, Crow and Champagne (4), and Lau, Fisher, and Fuchs (5) had performed careful measurements to determine the nature of this structure. It was suggested that the structure is as shown in Figure 2b, which is now generally accepted, but at the time that this study was initiated, the question was somewhat open, so that its resolution seemed to be of prime importance.

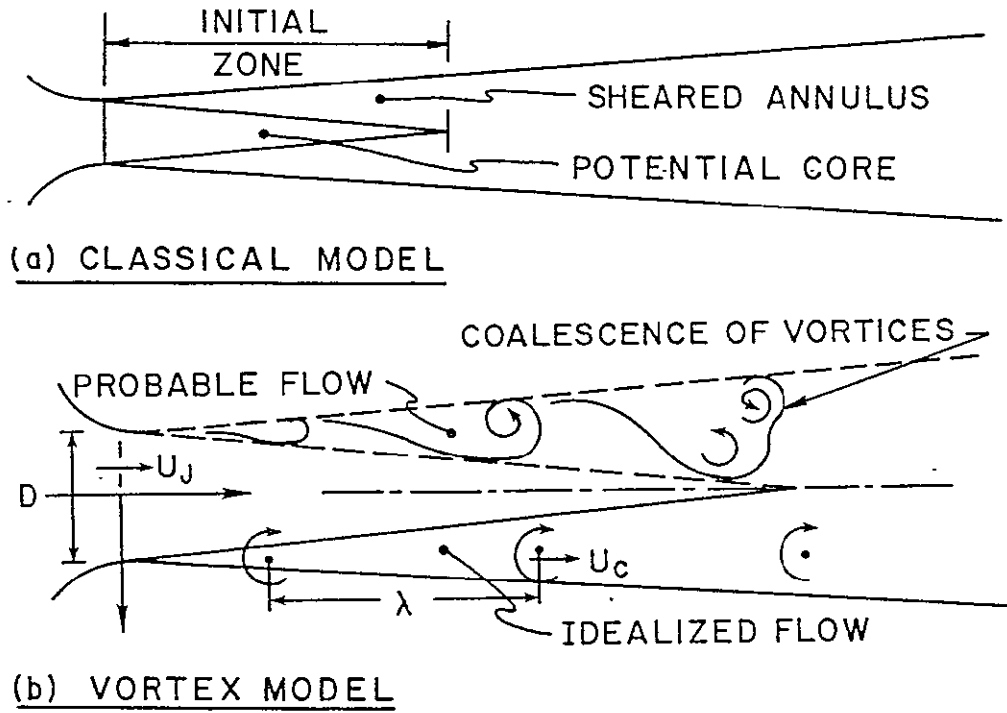


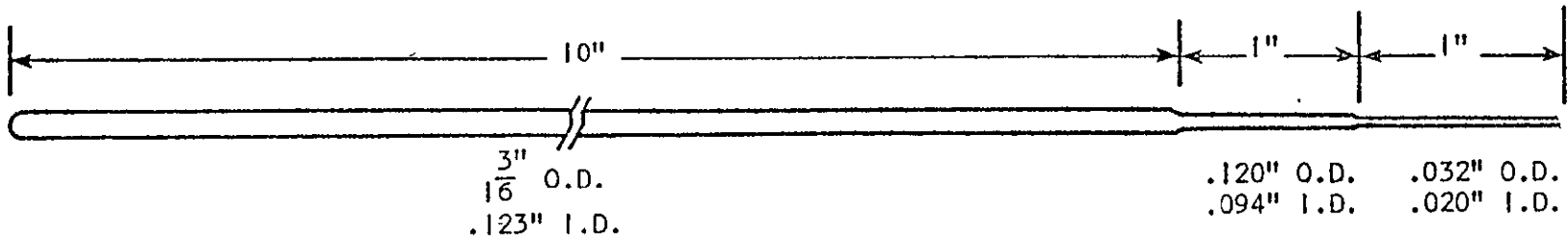
Figure 1. Current models of the structured turbulence in circular jets. (U_c is the convection velocity of the vortices.)

Accordingly, initial studies were performed on unsteady pressure measurements behind a small cold jet. The jet was identical to those used in an undergraduate laboratory, in which students were provided with miniature pitot-static tubes attached to stethoscopes, and were instructed to listen to the turbulence at different points in the jet flow. It was 3.17 cm in diameter, and was supplied by air from a small centrifugal blower, capable of providing jet flows up to 36 m/s. The contraction ratio in the jet was 22 to 1. At first the stethoscope was merely replaced by a length of plastic tubing filled at the far end by a B&K 1/8 inch microphone.

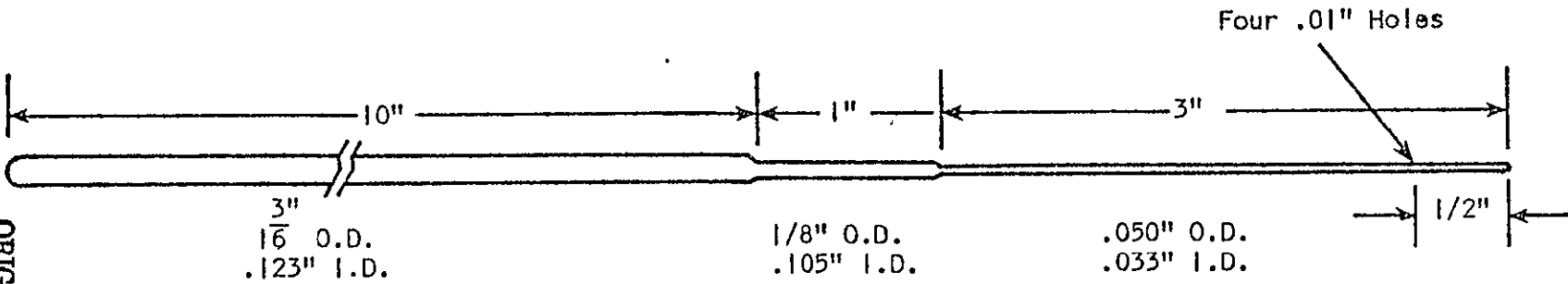
The following paragraphs describe the various experiments which were performed, and the development of the instrumentation. This work is described in detail in a thesis by Schroeder (7) and in a paper by Schroeder and Haviland (6).

Static and Pitot Tubes: The static and pitot probes shown in Figure 2 were developed early in the program. Later, the holes in the static probe were enlarged from .01" (.25 mm) to .02" (.5 mm). Levels measured with the pitot probes were generally about ten decibels higher than those measured with the static probe. However, since fluctuating pitot (i.e. total head pressures) could not be related to any physical variables of interest, the pitot probe was soon relegated to the measurement of mean total flow rates, while fluctuating static pressures continued to be measured with the static probes.

Mean Dynamic Pressures Profiles: Figure 3 shows mean dynamic pressure



Total Pressure Probe.



Static Pressure Probe

Figure 2. Pressure Probes

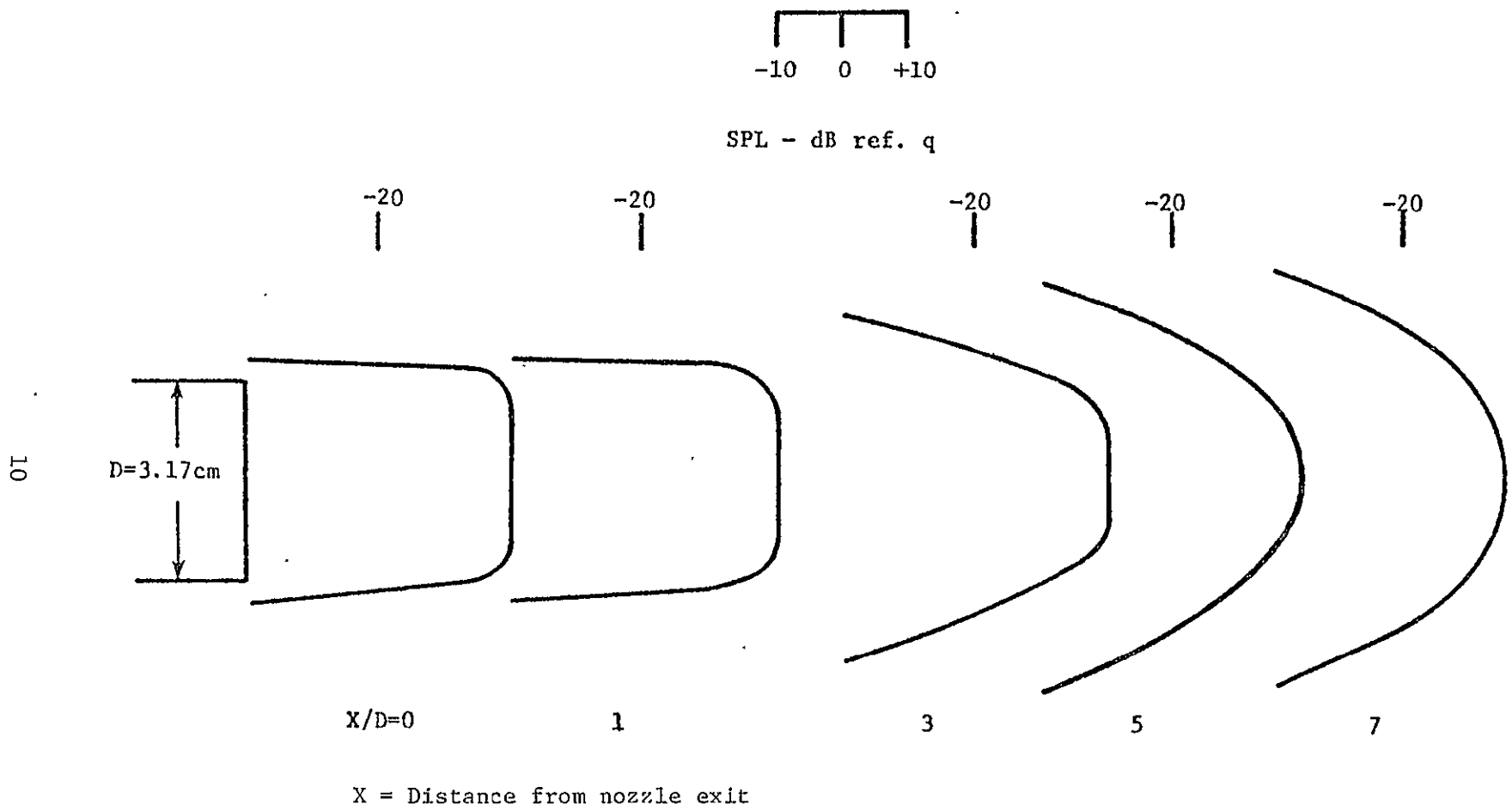


Figure 3. Free Jet Mean Dynamic Pressure Profiles

profiles at 1,3,5 and 7 diameters downstream from the jet exit, as measured with a pitot probe attached to a manometer. Results are expressed in decibels referenced to jet dynamic pressure, so that the flat profiles at the exit reach exactly 0 decibels.

Fluctuating Pressure Profiles: Figure 4 shows fluctuating pressure profiles at 1,2,3,4,5,6, and 7 diameters downstream, as measured with a static probe through a B&K 1/8 inch microphone and a B&K Model 2113 Spectrometer, set to record overall RMS pressure, and expressed in decibels referenced to jet dynamic pressure. Thus they are the fluctuating pressure coefficients expressed in decibel form. Both the fluctuating pressure and mean dynamic pressure profiles were found to be in substantial agreement with values given in the literature. It was realized, of course, that there was an unknown loss in RMS pressure in the tubing, however, if the tubing was made short, to avoid the loss, the 1/8 inch microphone was found to be susceptible to direct pickup of vibrations, so that a compromise had to be reached. Eventually, the microphones were replaced by less susceptible 1/2 inch ones, so that shorter tubing could be used, and a calibrator was developed to determine the effects of the tubing.

Fluctuating Pressure Spectra: Figure 5 shows a typical set of fluctuating pressure spectra at a section two diameters downstream from the jet exit. Spectra are given on the centerline, and .25, .5, .75, and 1 diameter from the centerline. Results are expressed in decibels referenced to jet dynamic pressure, and the frequency scale is expressed in terms of the Strouhal number (frequency x jet

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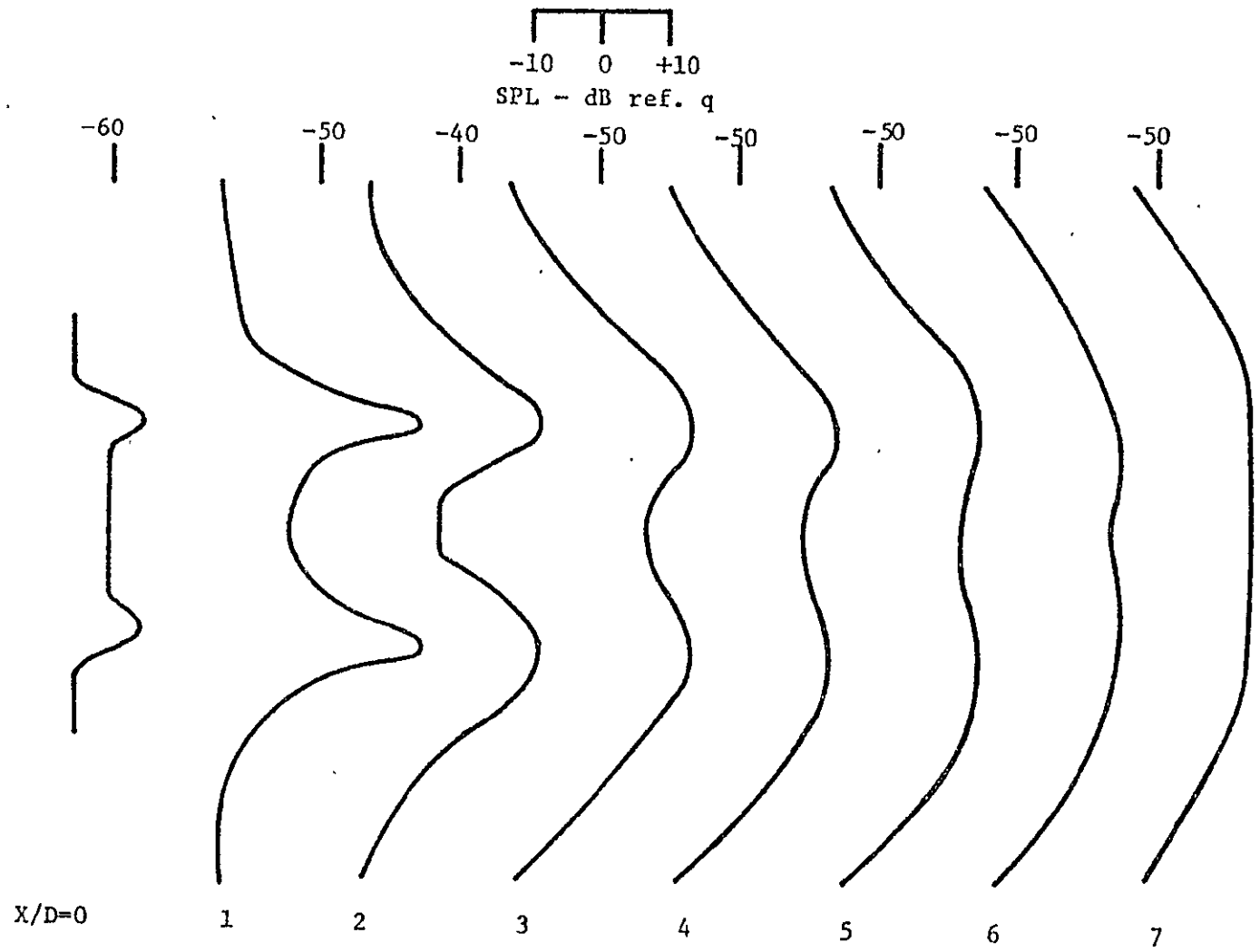
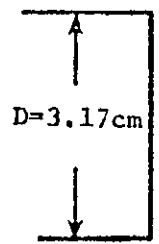


Figure 4. Free Jet "Static" Fluctuating Pressure Level Profiles

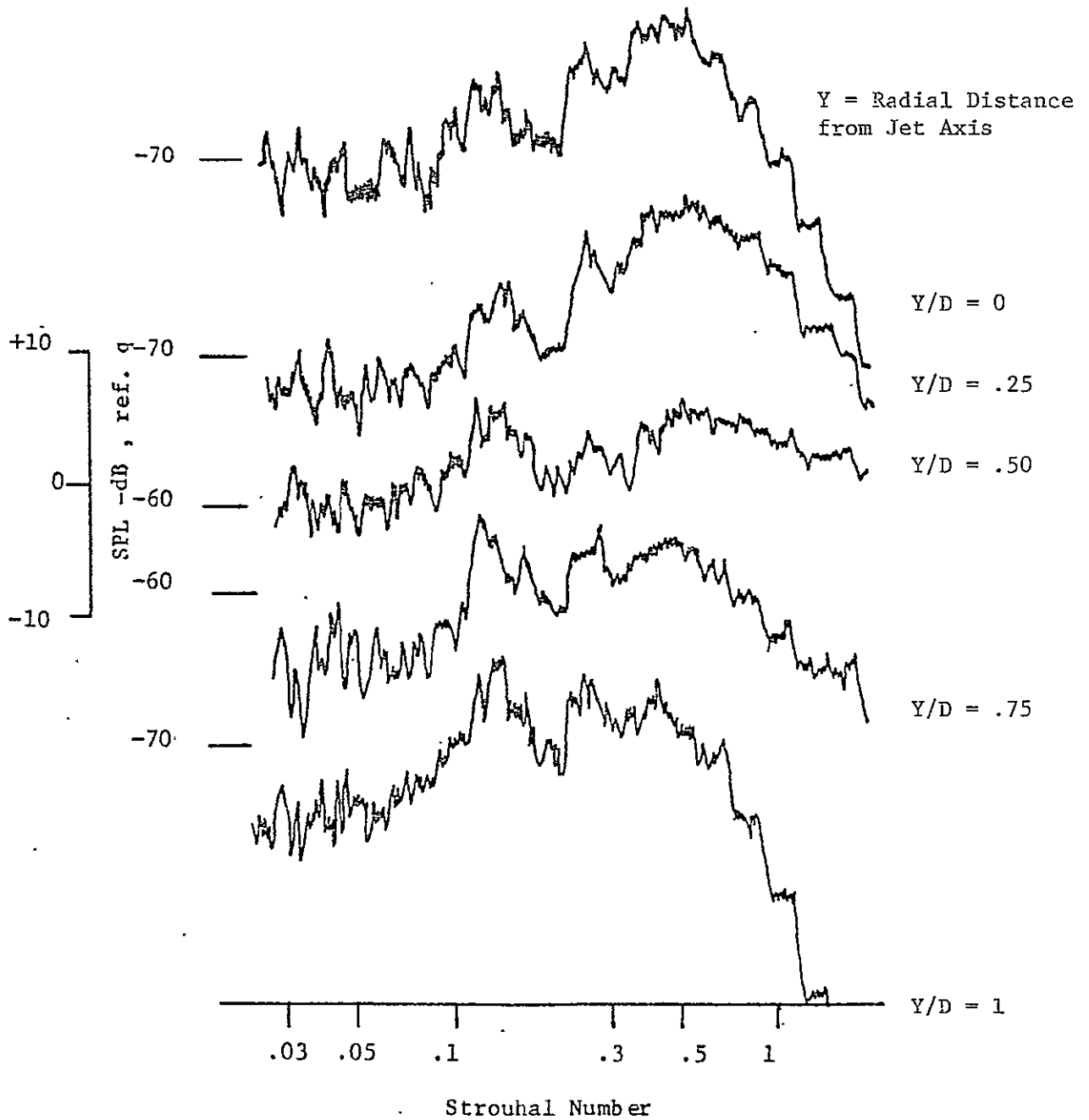


Figure 5. Free Jet 1/3 Octave Spectra: Two Diameters from Nozzle Exit.

jet diameter/jet velocity). Many such spectra were obtained, they tend to peak at Strouhal numbers between 0.3 and 0.5 over the first five jet diameters from the jet exit, and provide indirect confirmation of the vortex model of jet structure. According to this, the vortices are randomly spaced, but favour a spacing corresponding to the above noted range of Strouhal numbers. A tendency to fill in the lower frequency ranges, which leads to a breakdown of the peaks at about five diameters, can be attributed to a tendency of the vortices to coalesce. This phenomenon was investigated directly by Laufer, Kaplan, and Chu (8). Again, the results of the spectral measurements appeared to conform to what was already in the literature. The same instrumentation difficulty was present as before, in that there were unknown frequency dependent losses in the tubing.

Development of Cross-Correlation Techniques: Further progress in the investigation of the jet structure was impossible without instrumentation capable of cross-correlating flow characteristics at different points. A Federal Scientific (now Nicolet) Model US 202-B Ubiquitous Correlator was used for this purpose. It was provided with a board capable of transferring data at a 110 Baud rate to a standard TTY terminal, so that this data could either be stored on tape for later analysis, or could be transmitted directly to a computer via a data link. Data input was provided by a pair of static probes through 1/8 inch microphones. Provided that the rubber tubing connecting the two was carefully matched, attenuation in the tubing was no problem. Typical correlation coefficients between points on

the jet centerline and points at various radial distances are shown in Figure 6. These are in substantial agreement with measurements made by Fuchs (9), in a demonstration of the vortex model of jets. The peak correlations occur at zero time separation when the two points lie in a plane normal to the jet, indicating an axisymmetric structure, while the size of the correlation coefficient when the second probe is as far as two radii from the centerline indicates a large scale structure. Both of these observations are consistent with the theory that the structure consists of vortices. Further, the dip in the correlation coefficient when the second probe is behind the jet lip suggests that the vortices are equal in diameter to the jet, but that they are somewhat irregular. Theoretical studies, such as those by Batchelor and Gill (10) have suggested that the vortices may be unstable, and that they may form lobed shapes. This is further confirmed by experimental and theoretical work by Widnall and Sullivan (11) on vortex rings.

Development of Cross-Spectral Techniques: By using the correlator to obtain correlations for transmission to a computer at the University of Virginia's computer center, and by taking fast Fourier transforms, auto- and cross-spectra were obtained from the CROSSPECT Fortran program. These were further processed to obtain phase and magnitude relationships between pairs of probes, as well as their coherences. A model for the system represented by CROSSPECT is shown in Figure 7. An external signal I is operated on by two transfer functions TE_1 and TE_2 , representing external aero-

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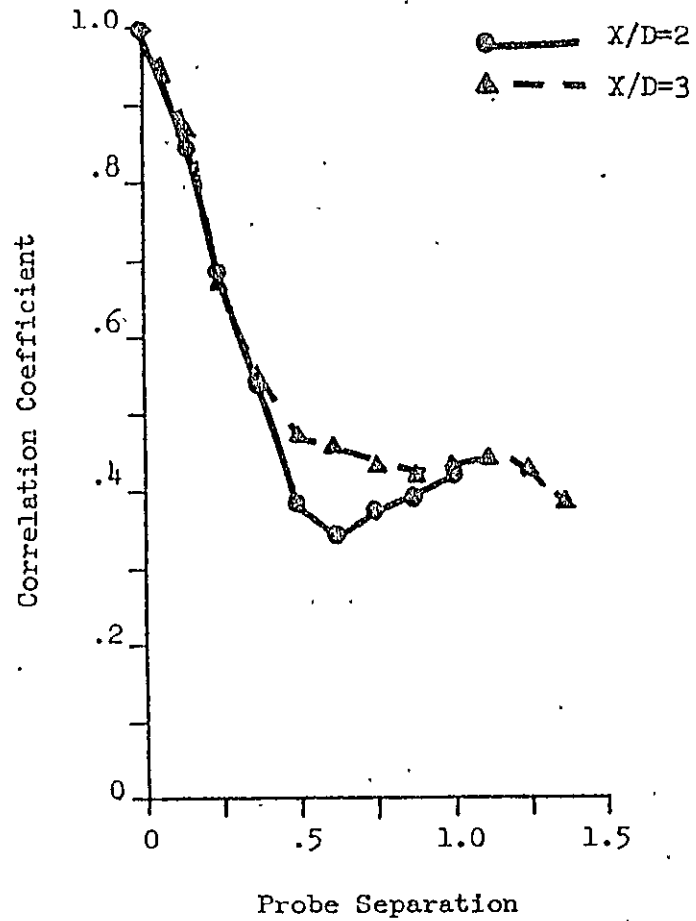
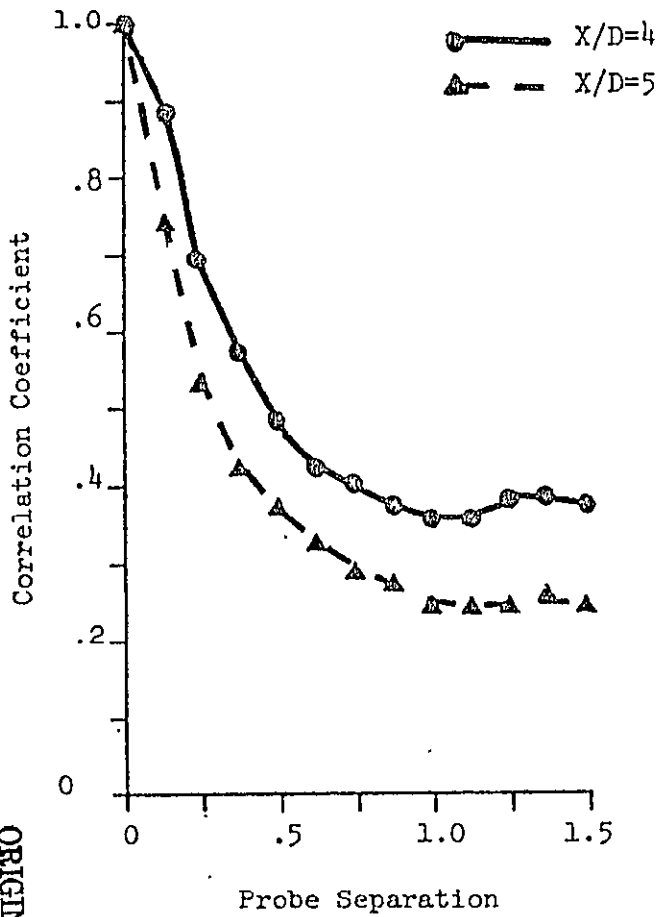


Figure 6. Free Jet Correlation Coefficients: X/D=2-5

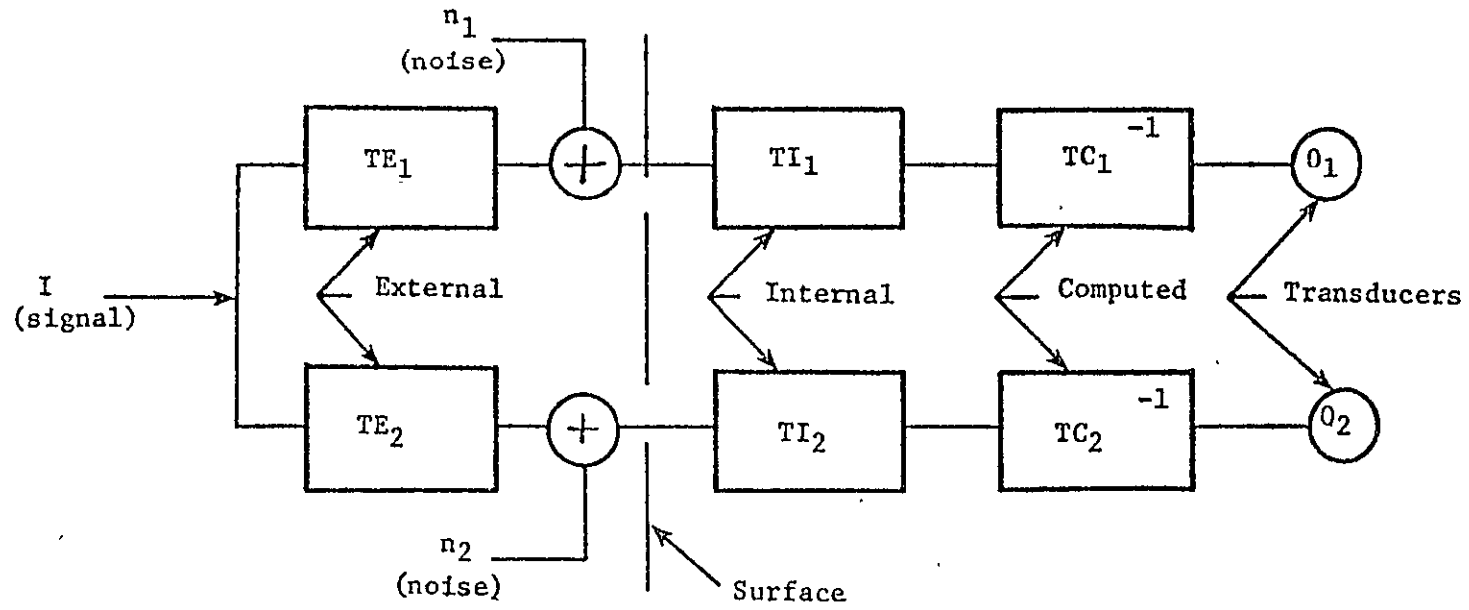


Figure 7. CROSSPECT Model

dynamic effects to provide coherent pressure fluctuation signals at the two probes. At the same time, the two probes see uncorrelated signals, n_1 and n_2 , which are considered to be noise. The probe transfer functions TI_1 and TI_2 are considered to be mainly due to attenuation in the tubing, while the transfer functions TC_1 and TC_2 are stored in the computer, and are used to make analytical corrections in the data. Finally, the two outputs O_1 and O_2 are obtained in digital form, and are expressed as spectra, relative amplitudes, relative phases, and coherence. Ideally, the internal transfer function TI should first be found, and then stored in the computer as TC so that instrumentation responses can be corrected for tubing losses. This was eventually done, but, in the meanwhile, only the relational quantities were determined using carefully matched probes. For example, when two probes were separated radially, as in Figure 8, coherence was found to be good over the peak Strouhal number range, and a close phase relationship was maintained, which was again taken to confirm the vortex model. When the probes were separated axially, as in Figure 9, the steady slope of the relative phase vs. Strouhal number indicated convection velocities of about 60% of jet velocity.

Jet Impingement Studies: A small plate was instrumented to measure fluctuating surface pressures, by drilling .04" holes and connecting these by plastic tubing to the 1/8" microphones. The plate, together with a detail of the surface instrumentation, is shown in Figure 10. Typical 1/3 octave spectra for impingement at two jet diameters on a plate inclined at 30° to the axis are shown in Figure 11, the coordinates

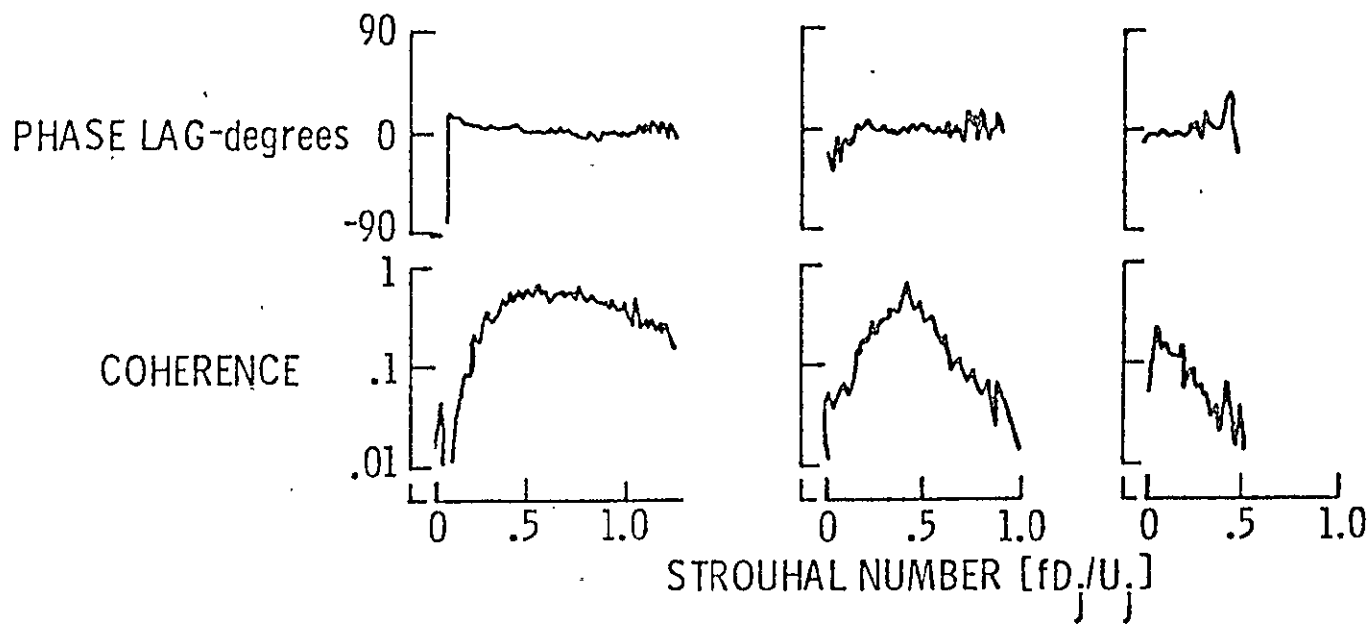
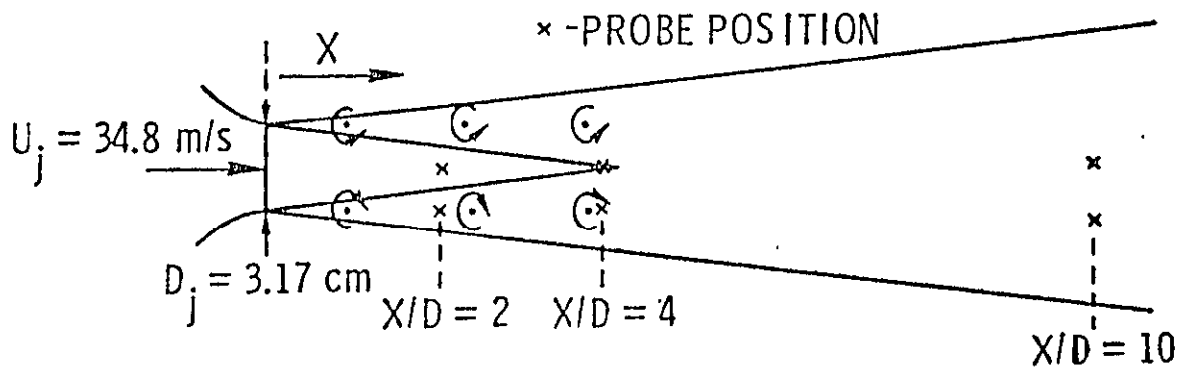


Figure 8. Coherence and phase lag behind free jet for radial separations.

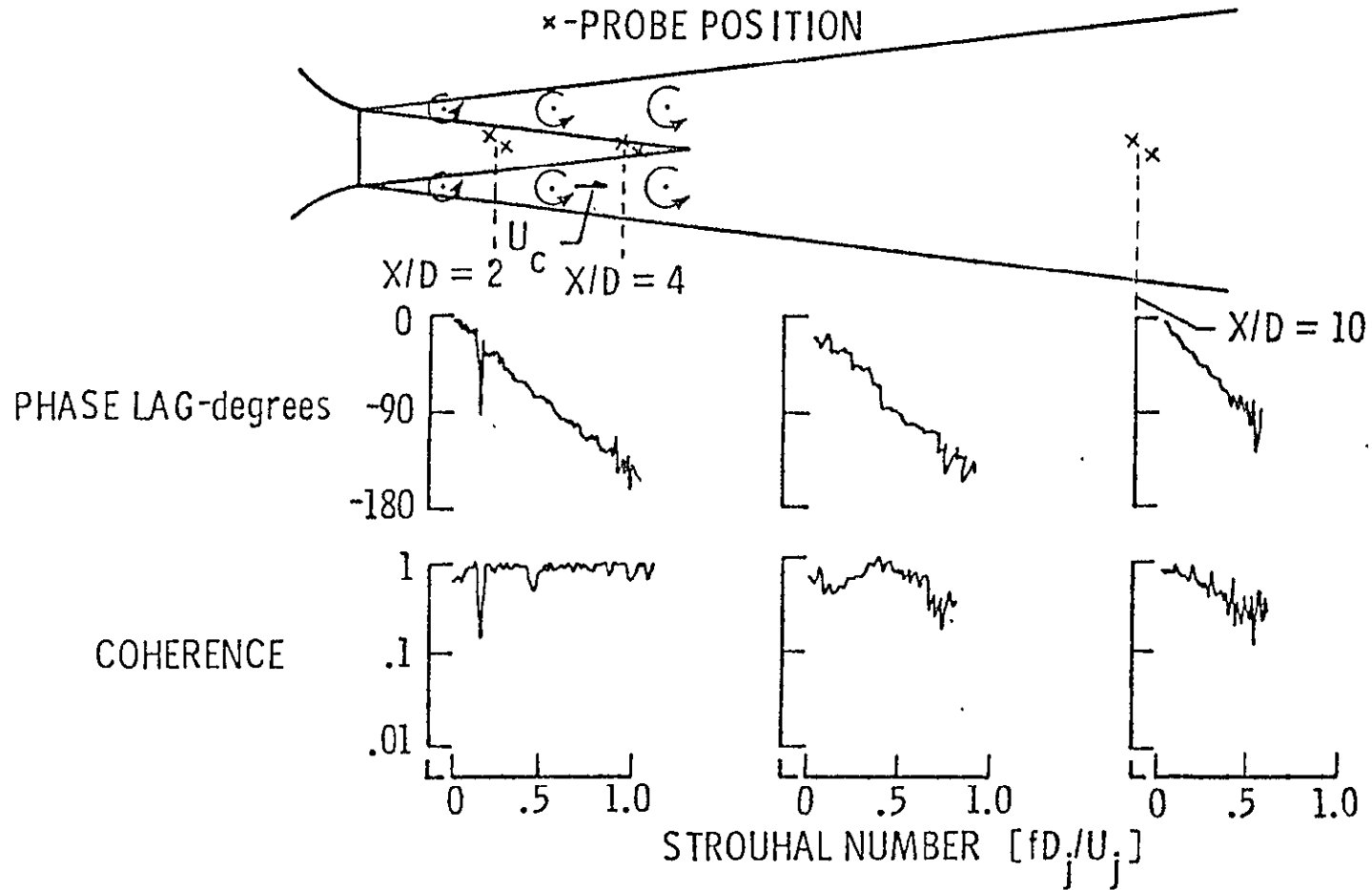


Figure 9. Coherence and phase lag behind free jet for axial separations.

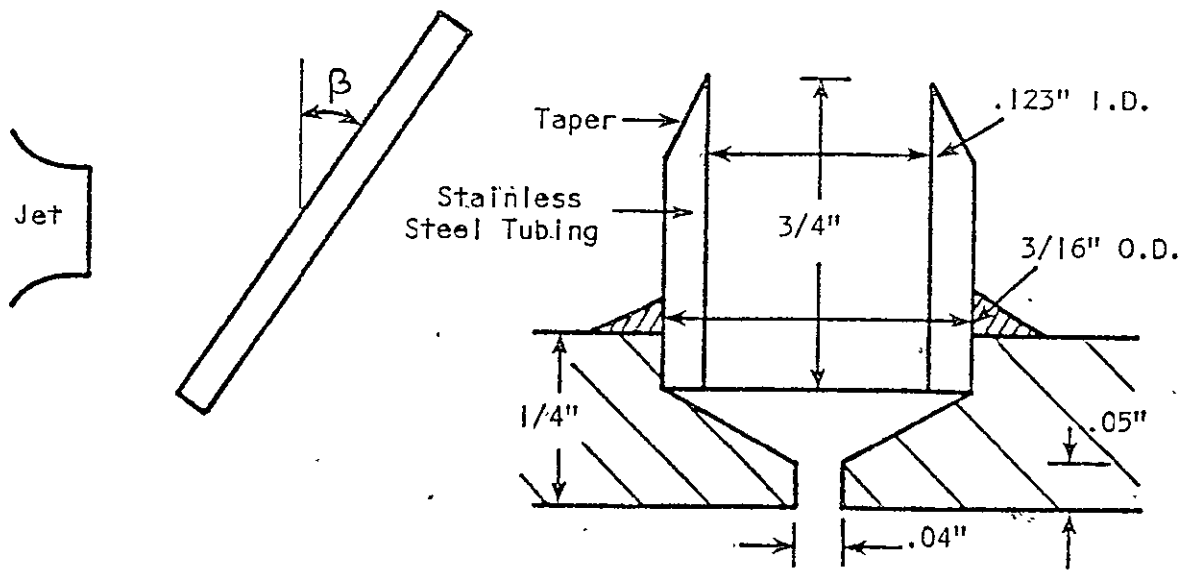
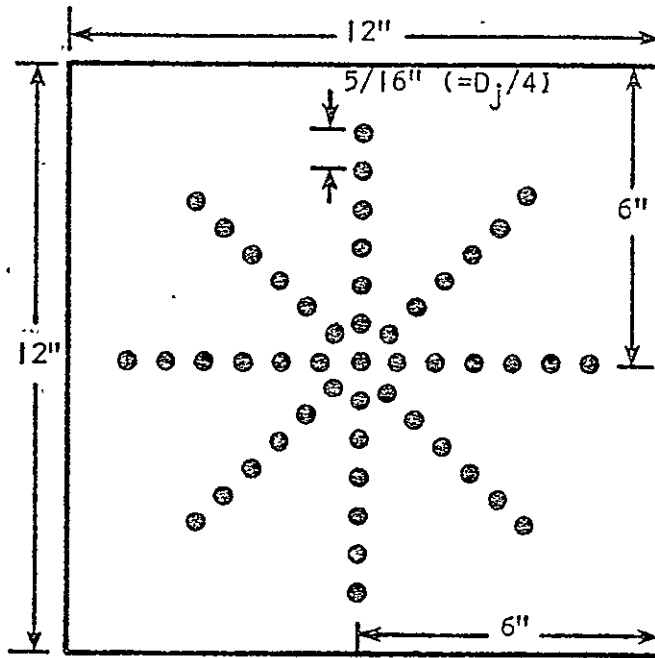


Figure 10. Flat plate for impingement studies.

η is distance along plate in axial direction

ζ is lateral distance

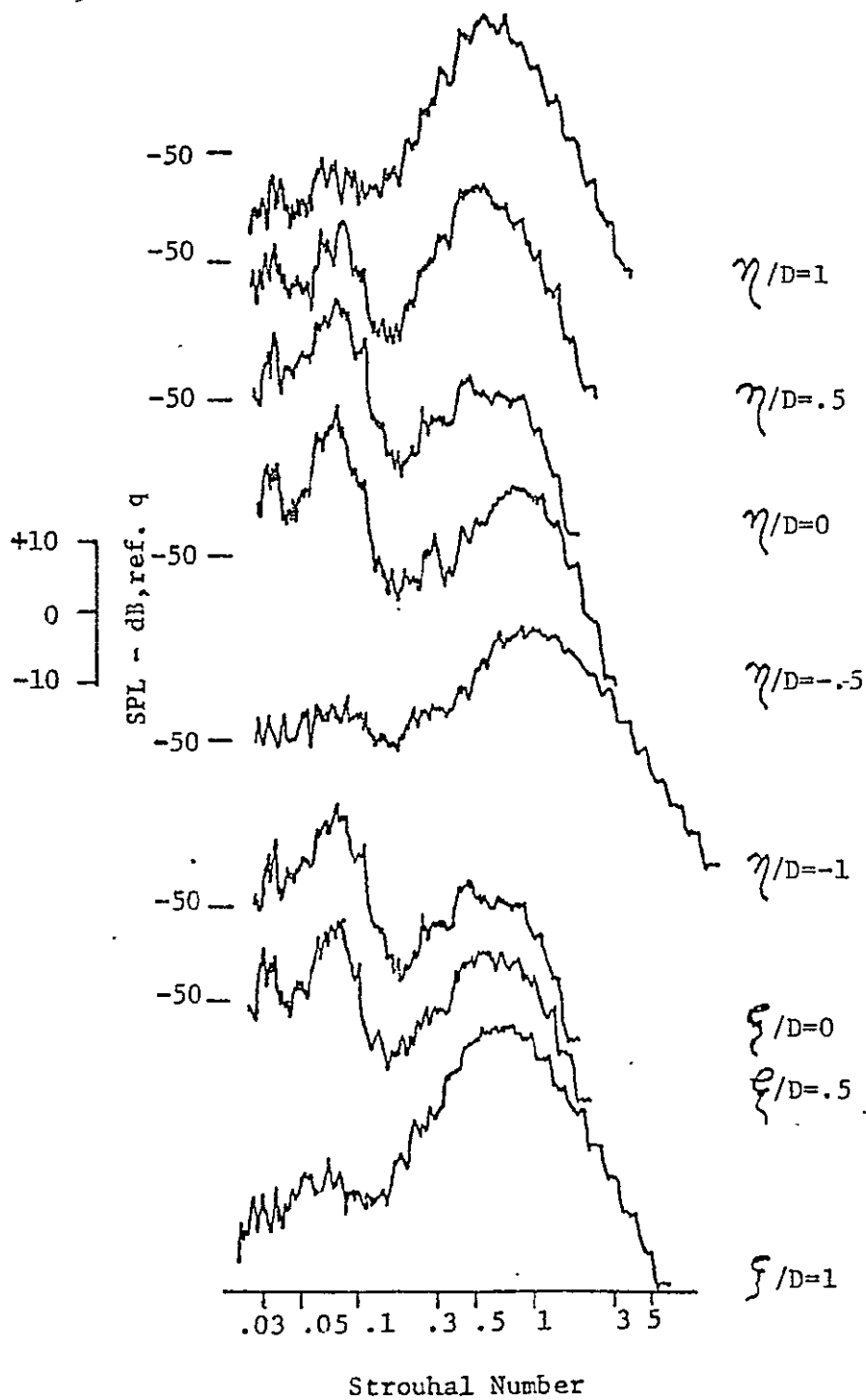


Figure 11. Jet Impingement 1/3 Octave Spectra:
 $X/D=2$, $\beta=30$. *

ζ and η are measured on the plates, ζ being normal to the centerline, and η being positive in the direction of the jet axis. It will be noted that the spectra peak at the same Strouhal numbers as in the free flow (Figure 5) but that the peaks are even more pronounced. This indicates that the vortices in the jet sweep over the plate, and that the fluctuating pressures on the plate are mainly due to the presence of these vortices. Using the correlator together with the CROSSPECT program, the relative phase angles and coherences shown in Figure 12 were obtained. These indicate convection from the jet centerline out for normal impingement, and in the direction of flow for impingement at other angles.

Development of Calibration Techniques: Overall calibration was obtained in all cases by applying a B&K piston phone directly to the 1/8 inch microphones, and then passing the resulting signal through the same process as the measured data. However, several attempts were made to correct for the frequency sensitivity of the instrumentation, particularly that due to the tubing. First of all, attempts were made to develop analytical expressions for the transfer functions of the system. Although these were partially successful, satisfactory methods of predicting attenuation in the tubing were never found. Another technique used was to compare the signal from the probes with a signal obtained in some other manner. For example, static pressure probes were calibrated by placing them close to a jet alongside a plain microphone. This was only partially successful, mainly because the calibration was performed in a relatively weak

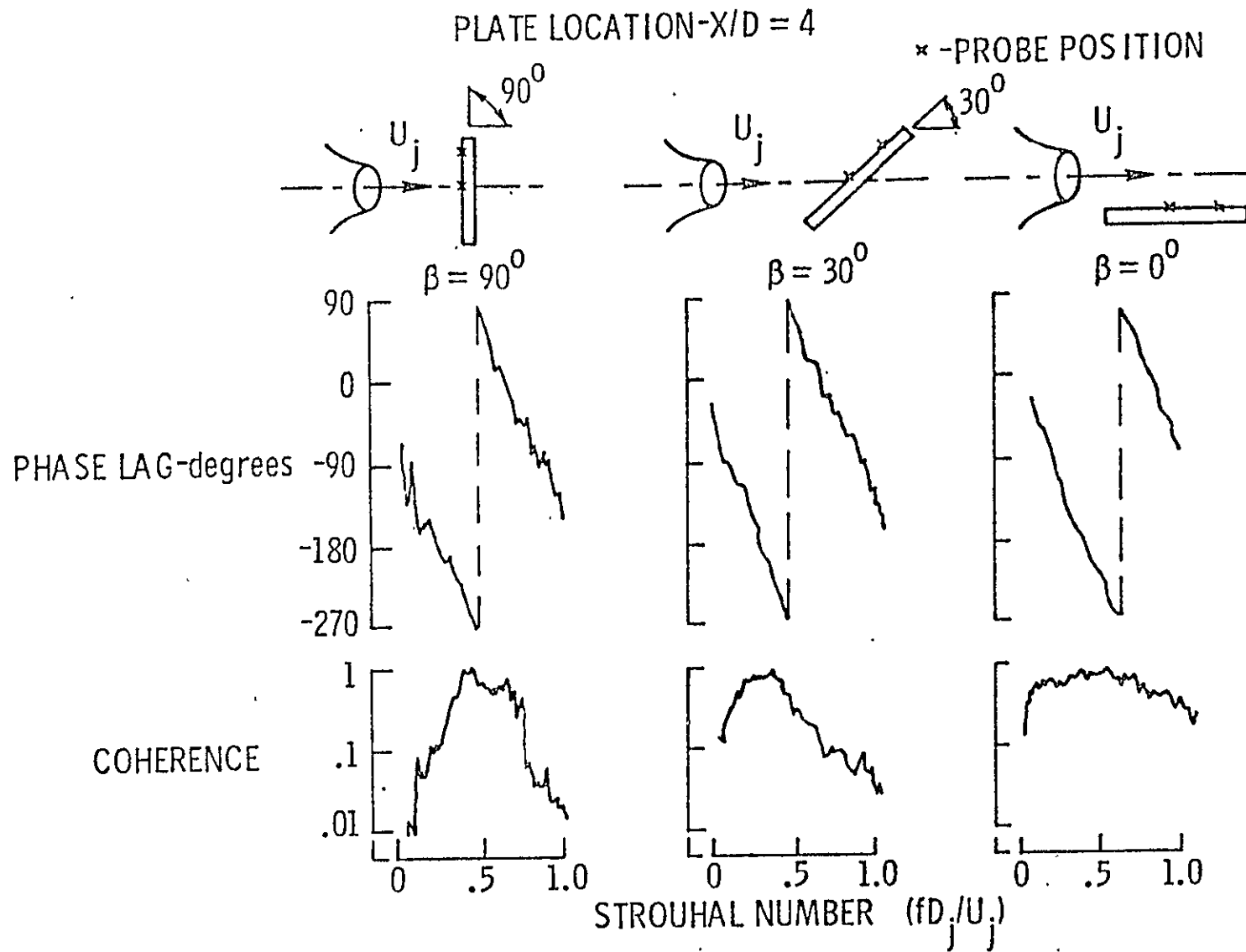


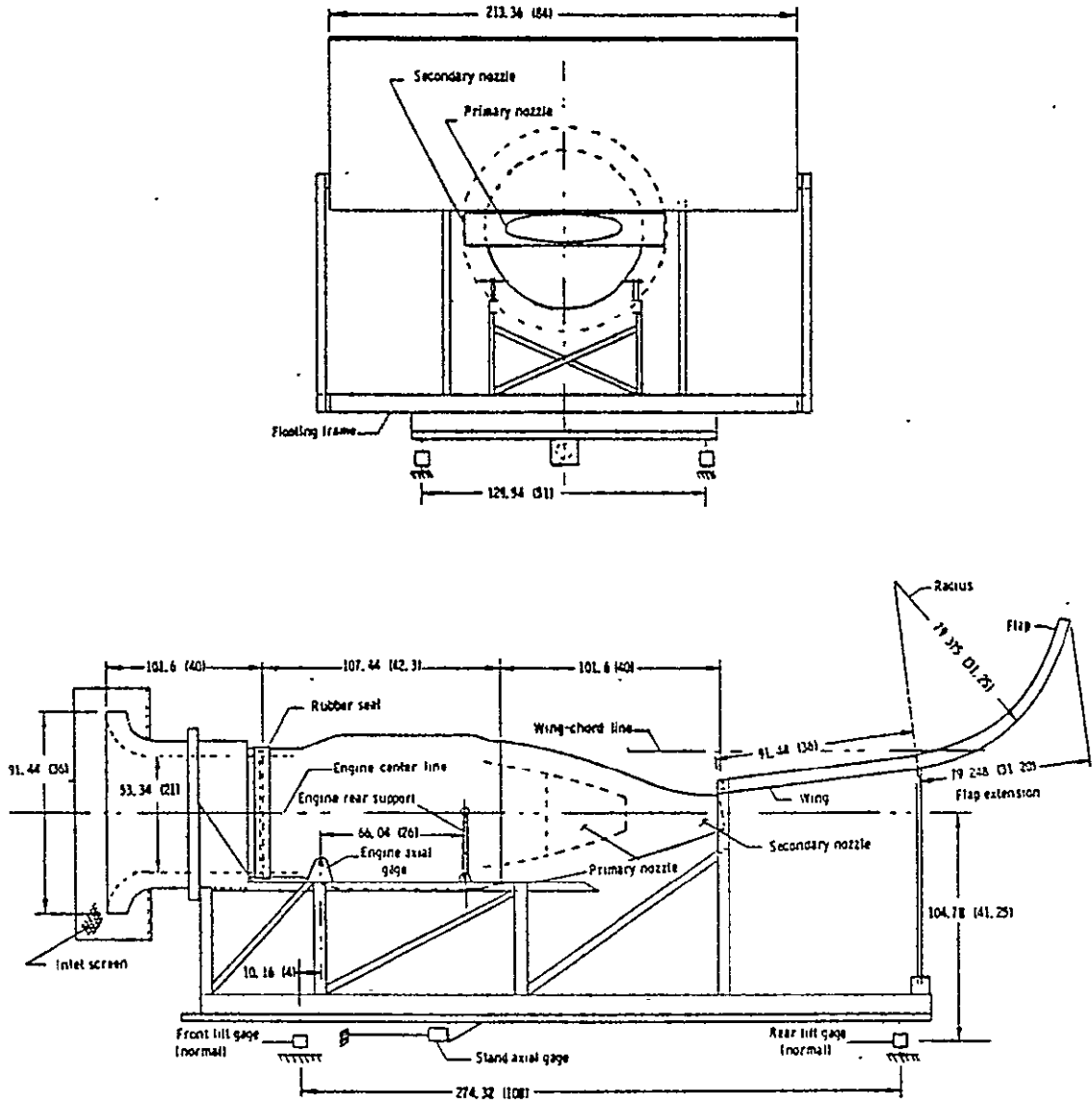
Figure 12. Coherence and phase lag on flat plate.

pressure field. Another method for surface probes was to compare them with microphones embedded in the surface. The main problem here was that the embedded microphone picked up signals due to vibration, but some good results were obtained. A pair of Kulite pressure probes was obtained and tried out. Due to the very weak pressure fluctuations experienced, their output could be only barely detected, and that only after precautions had been taken to screen out interference from local radio stations. It was realized that a calibration chamber was needed for the pressure probes, and some consideration was given to acquiring a B&K Type 4991 Calibrator for this purpose. Finally, a homemade calibration chamber was developed, as is described later in this report.

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SUMMARY OF STUDIES PERFORMED ON ONE QUARTER SCALE MODEL

Once experience had been gained with instrumentation for fluctuating pressure measurements in jets, and some conformation of the vortex model of jet structure had been obtained, plans were made to study scaling effects by building a scale model of a known configuration. The system finally chosen was the so-called "Beach Model" at NASA Langley (Refs. 12,13). This consisted of a JT15D-1 engine blowing over a small curved surface, representative of an upside-down wing with a deflected flap. The full-scale facility is shown in Figure 13, while the one-quarter scale model is shown in Figure 14. Initially, tests were run without a core nozzle, representative of a case of perfect mixing, however final tests (results unavailable to date) were run with the core nozzle in place. Air was initially supplied to the plenum chamber by two blowers identical to that used for the small jet, these gave a flow velocity of 32 m/s (23.4 m/s with one blower) in the 23.4 cm by 4.2 cm rectangular nozzle. Later, a larger blower was substituted, giving a flow velocity of 45 m/s, the other two blowers being available for providing bypass air when the core nozzle was inserted. Large mufflers were added to both air supplies, constructed from cardboard drums, to filter out pressure fluctuations caused by the blowers. The philosophy used in the design of the model was that it should be one which could be installed and operated in a normal laboratory. This essentially ruled out the use of engines, or the use of hot air supplies to represent combusted fuel. It was assumed



Dimensions in Centimeters (Inches)

Figure 13. NASA "Beach" Facility

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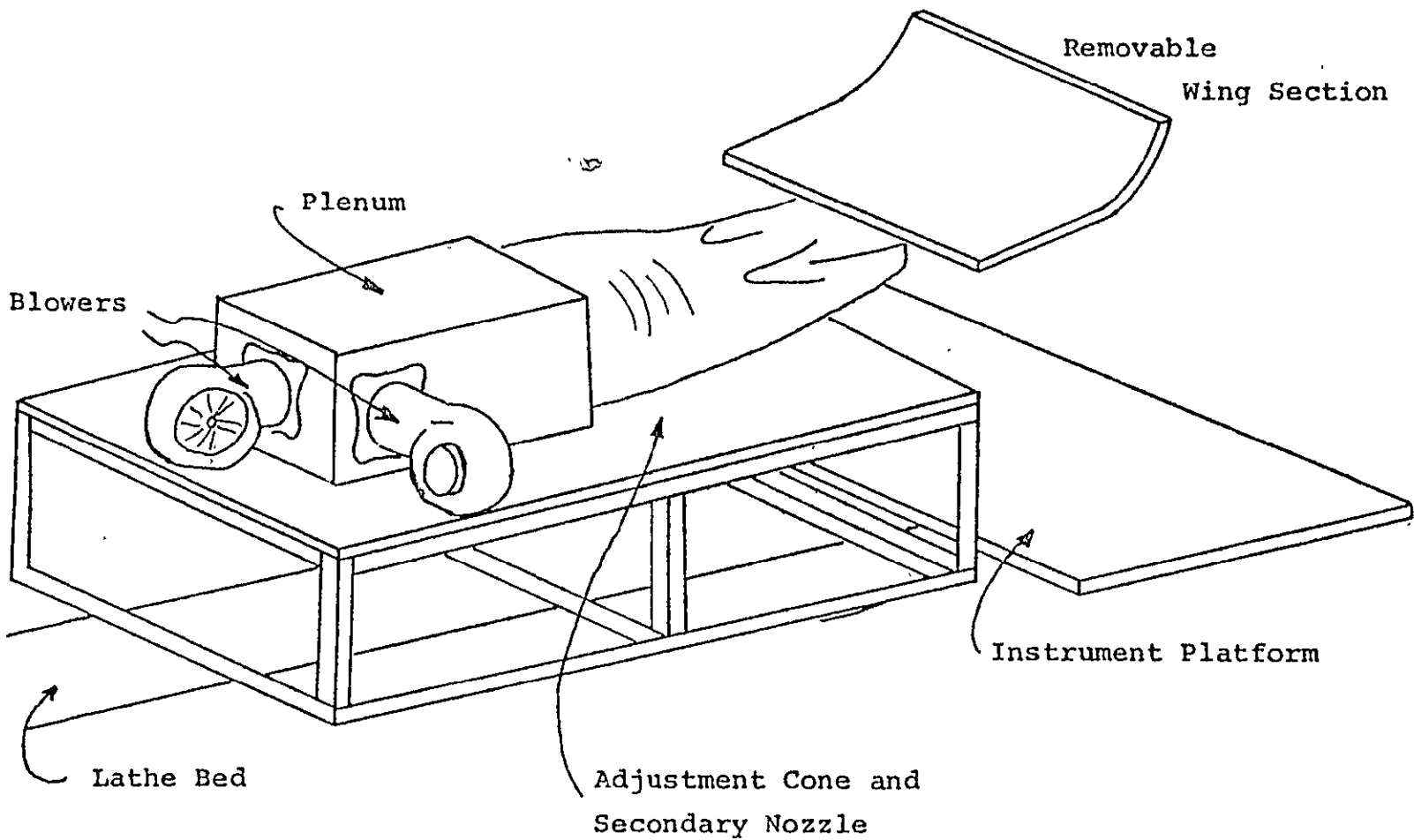


Figure 14. The Initial Quarter-Scale Facility.

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from the start that Reynolds number and Mach number effects would be minimal, however, difficulties were experienced in the scaling of the core and bypass nozzles for cold air. In the full-scale jet the core flow is of course hot, and therefore has a lower density than the bypass flow. This leads to two irreconcilable concepts of scaling, dynamical scaling, in which the core flow in the model has reduced velocity to maintain the correct dynamic pressure, and kinetic scaling, in which the correct velocities are maintained, so that the Strouhal numbers are, in turn, correct. Some compromises can be made, such as changing nozzle diameters to maintain correct Strouhal numbers, but none are entirely satisfactory. Eventually, the model was built to scale, but the core nozzle was omitted initially. Some of the important test variables are given in Table 1 below. Values given for the model are the maximum possible.

Table 1 Test Variables for One Quarter Scale Model

<u>Variable</u>	<u>Full Scale Max/Min</u>	<u>Model</u>
Equivalent Diameter, m	0.357	0.0934
Jet Velocity, m/s	277.4/96.6	45.0
Jet Dynamic Pressure, N/m ²	22300/3280	1190
Jet Mach Number	0.559/0.214	0.13
Jet Temperature, °K	611/506	300
Reynolds Number Based on Jet Diameter (10 ⁶)	3.7/1.6	0.4

Tests carried out to date are described in the following paragraphs. Analysis of the results of the tests with core nozzle in

place are presently being evaluated, and have not been reported here. Also, some tests are now in progress with a representative fuselage. Most of the results given here were also reported in a thesis by Herling (14), and in the proceedings of two conferences by Haviland and Herling (15,16).

Development of Calibrator: A calibrator for surface and static pressure probes shown in Figure 15 was developed early in the quarter-scale model program. This consisted of the driver from a folder horn speaker with a small enclosure into which a probe can be inserted for comparison with a standard half inch microphone. By exciting the driver with pink noise, and using the CROSSPECT program, the transfer function for the probe can be determined, and used later as TI (see Figure 7) in analysis of data obtained through the probes.

Surveys of Quarter-Scale Model Jet: Flow surveys were made of the quarter-scale model jet, both with the airfoil installed, and with it removed to provide a free rectangular jet. Both mean velocities and RMS static pressures were obtained, the former using the pitot probes, and the latter the static probes. Typical RMS static pressure profiles are shown in Figure 16 for the case where the airfoil was installed. These surveys were followed by measurements of one-third octave spectra at a number of points in the jet. A composite plot of these spectra, both with and without the airfoil, is shown in Figure 17.

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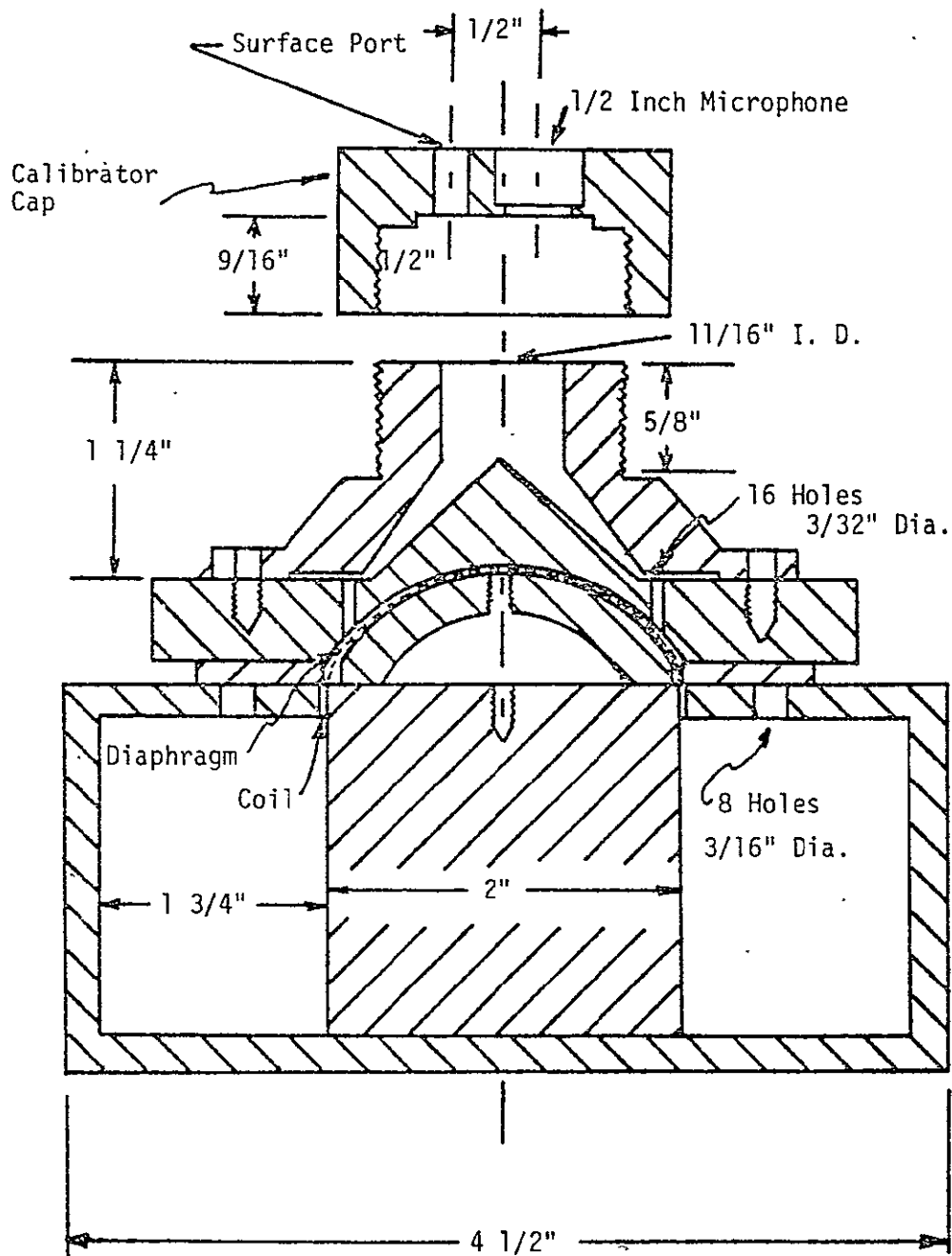


Figure 15. Cutaway view of Calibrator and Cap.

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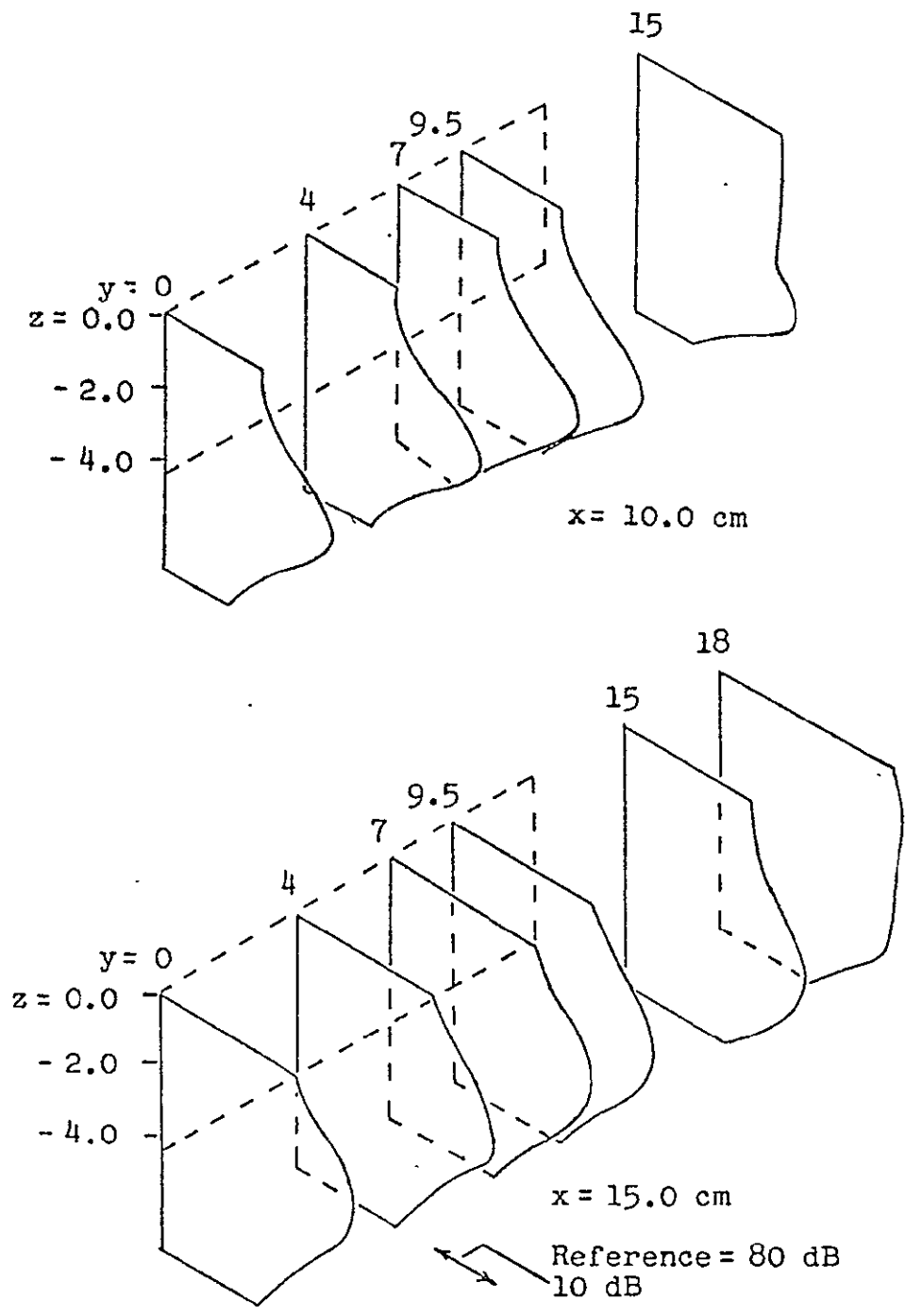


Figure 16. Rms Static Pressure Profiles - Airfoil Installed

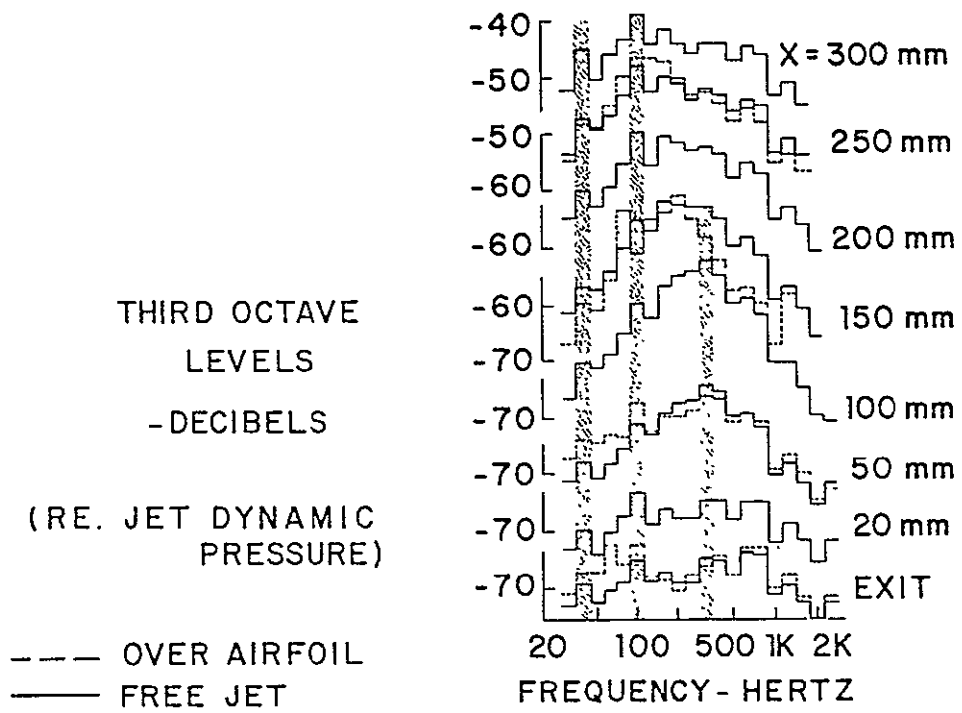


Figure 17. Growth of 1/3-octave pressure levels in quarter-scale model rectangular jet, both free and blowing over airfoil.

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Cross-Correlations in Quarter-Scale Model Jet: Cross-Correlations were obtained for several pairs of points in the rectangular jet, both with and without the airfoil. Typical values relating points lying in a normal plane to a common point are shown in Figure 17. As in the case of the circular jet, significant correlations were obtained at a distance, and these were enhanced by the presence of the airfoil. These results were taken as indicating a vortex structure, the vortices probably being of the order of the jet depth (minimum dimension) in size, and forming horseshoe vortices touching the airfoil when the airfoil is present.

Phase and Coherence in Quarter-Scale Model Jet: Phase and coherence were determined for several pairs of points in the rectangular jet, both with and without the airfoil. Measurements for pairs lying in a plane normal to the jet were made to obtain confirmation of the presence of a large-scale vortex structure, several such measurements are shown in Figure 19. When the pairs lay in the axis of the jet, they were used to determine convection velocities in the jet.

Excitation of Quarter-Scale Jet: The rectangular jet, with wing in place, was excited at various frequencies by a speaker attached to the plenum chamber, and the response of the jet was measured at several axis positions. The results of this investigation, are shown in Figure 20. Levels measured at station zero, the exit, were arbitrarily assigned the level of zero decibels, so that levels measured at other stations could be directly compared with these. Thus, for example, at 100 mm from the exit there is an amplification

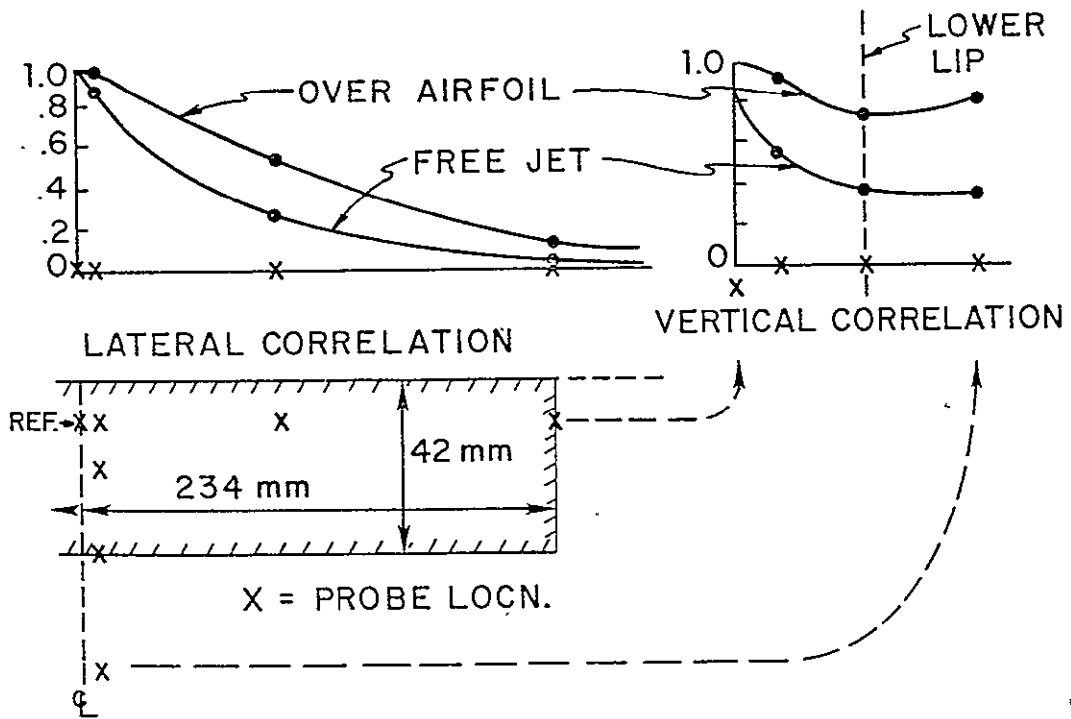


Figure 18. Pressure correlation coefficients 170 mm from exit plane of quarter-scale model rectangular jet, both free and blowing over airfoil.

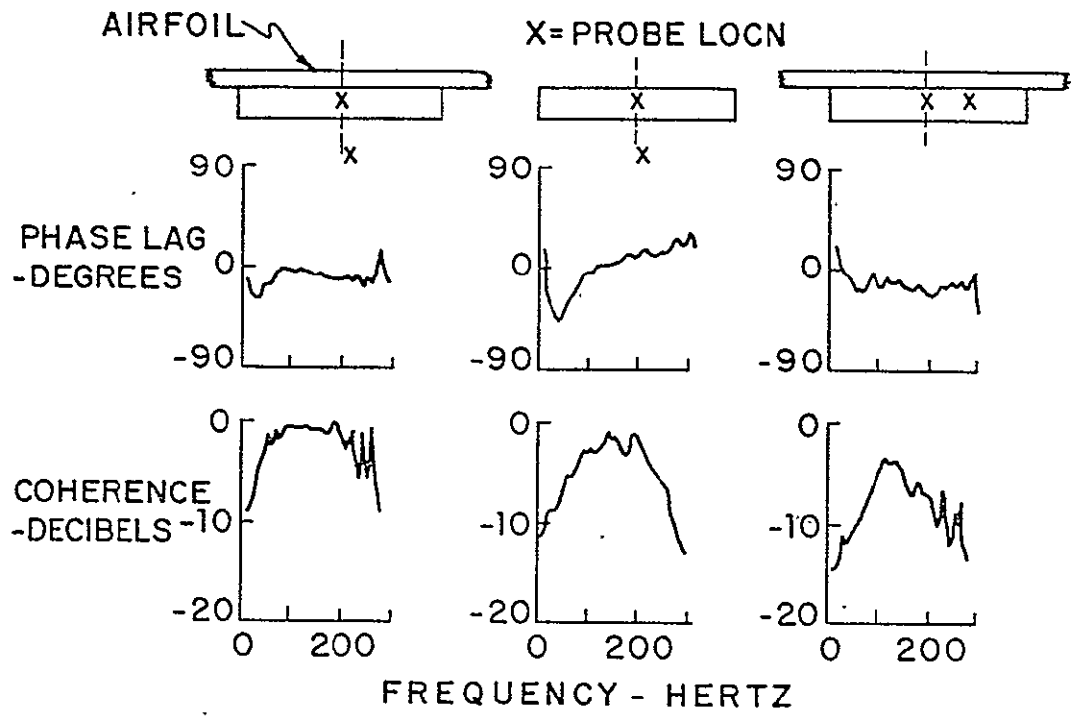


Figure 19. Phase and coherence plots 220 mm from exit plane of quarter-scale model rectangular jet, both free and blowing over airfoil.

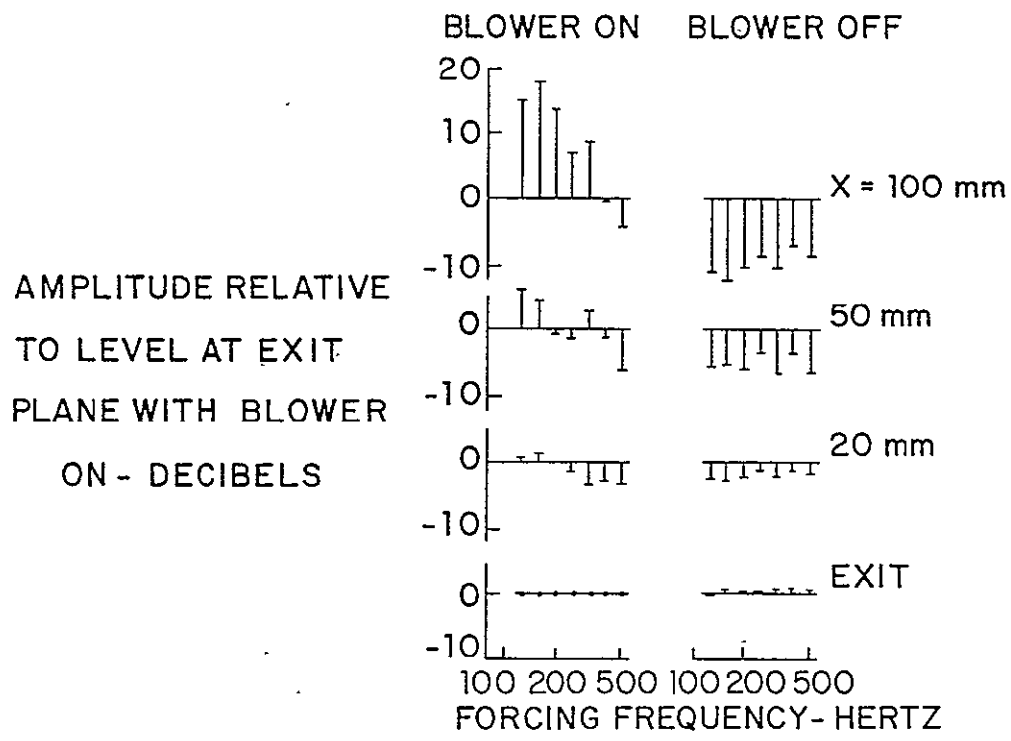


Figure 20. Effect of forcing separate 1/3 octave band center frequencies in rectangular jet blowing over airfoil, compared with acoustical levels without airflow. Quarter-scale model.

of about 18 decibels when the plenum is excited at 160 Hertz (Figure 19, left hand plots). This result is qualitatively similar to that obtained by Crow and Champagne (4) in a circular jet, and is further confirmation of the presence of a large-scale vortex structure in the jet. In order to eliminate the possibility that some of the disturbance could have been transmitted acoustically, the experiment was repeated, at identical excitation levels, with the blowers turned off, so that there was no jet (Figure 19, right hand plots). The levels measured at the jet exit were almost identical with those measured with the jet running, indicating almost no internal acoustical coupling with the jet up to the jet exit. In the free jet region, however, the acoustical levels with the jet off drop with distance from the exit, while the levels with the jet running increase. Thus, at the 100 mm station, where there had been an 18 decibel amplification at 160 Hertz when the jet was running, the purely acoustical contribution with the jet off was -9 decibels, a difference of 27 decibels thus being attributable to excitation of the vortices in the jet.

Evaluation of Scaling Effects on Surface Pressures: The principal objective of the overall study was to investigate scaling effects in jet impingement, and it had been for this reason that the quarter-scale model had been built. By the time that extensive measurements started in support of the scaling effects investigation, the method of calibration had been put into effect, so that probe transfer functions could be stored for use in the CROSSPECT program. At

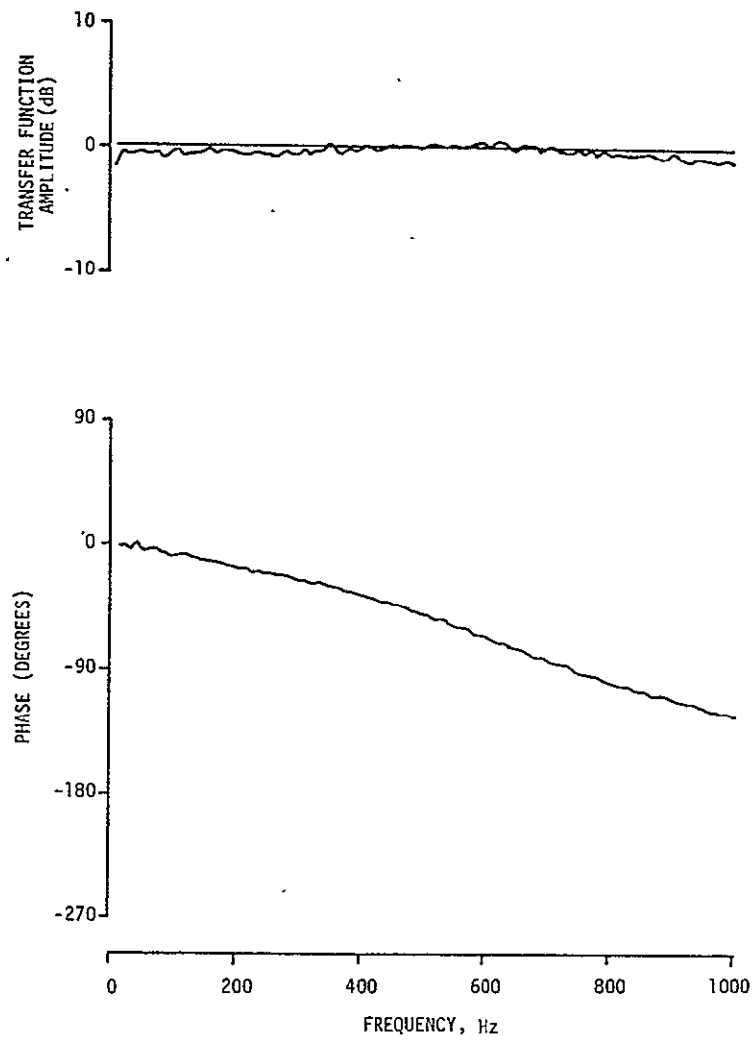


Figure 21. Typical Transfer Function for Surface Pressure Probe

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the same time, the availability of probe transfer functions led to considerable probe development. In the first case, a decision was made to change from 1/8 inch to 1/2 inch microphones, this eliminated much of the vibration interference, and made it possible to mount the microphones and preamplifiers very close to the surface probes, thus eliminating the lengths of tubing which were responsible for attenuation of the pressure signals. At the same time, the use of steel wool in the probes as pressure dampers led to elimination of the overshoot in the pressure response, so that the flat response of Figure 21 could be obtained.

Initial studies covered the case of a single rectangular jet without the core nozzle in place. This represented a hypothetical situation in which there would be perfect mixing within the longer outer nozzle. The results of these studies were presented at the AIAA/NASA Ames Conference in June 1977. Because of their overall importance to this investigation, these results are discussed elsewhere in this report. Following this, a core nozzle was installed, and further measurements were made which have not yet been evaluated. These will be presented as part of a doctoral dissertation by W. W. Herling. Finally, the measurements have been made with a fairing alongside the airfoil, representative of a fuselage. These have also not yet been evaluated, they will be presented as part of a Master's thesis by T. Baker.

INVESTIGATION OF SCALING EFFECTS IN JET IMPINGEMENT

The quarter-scale model was used in an investigation of scaling effects in jet impingement. The procedure used was to measure unsteady pressure at points on the airfoil surface, and then, by applying the scaling law under investigation, to attempt to predict what the full-scale pressure spectrum would have been. This spectrum was then compared with the one obtained at NASA Langley on the full-scale model.

Consideration of Possible Scaling Parameters: Consideration of possible scaling parameters for the fluctuating pressures in near-field jet impingement led to the following for a single jet

$$\text{Strouhal Number } S_t = fD_{eq}/U_j$$

$$\text{Pressure Coefficient } c_p = p/q_j$$

$$\text{Jet Temperature Ratio } = T_j/T_a$$

$$\text{Jet Mach Number } M_j = U_j/c_j$$

$$\text{Reynolds Number } R = \rho_j U_j D_{eq} / \mu_j$$

where the subscripts j and a refer to jet and ambient conditions, respectively, f is the frequency, D_{eq} is an equivalent jet diameter which is undefined at this point, U_j is the jet velocity, p is any pressure, q_j is the total head of the jet, c the speed of sound, ρ the density, and μ the viscosity.

The addition of coaxial jets would further complicate this list, as would the consideration of engine noise.

Evaluation of a Two-Parameter Rule: The first assumption to be tested was that three parameters could be ignored, the Temperature Ratio, the Jet Mach Number, and the Reynolds number. On this basis, only the Strouhal Number and the Pressure Coefficient would be of importance, and so, if all data were to be reduced to a plot of the spectral level, in coefficient form, vs. the Strouhal number, then model and full-scale results should agree. When such plots were made, it was found that the peak pressure coefficients were not in agreement, those for the model being consistently higher than those for the full scale article.

Evaluation of a Temperature Corrected Two-Parameter Rule: An examination of the farfield noise spectra, as summarized by Stone (17) shows that the noise spectra have their highest peak at a corrected angle of 30° to the aft axis, and that the Strouhal number of the peak in this case is in the same range as the Strouhal number of the peak of the near-field pressure spectrum. Thus there would seem to be some close connection between the large scale jet structure, responsible for near-field pressures, and the mechanism which produces jet noise. In the procedure described by Stone, a corrected angle θ' is derived from the true angle θ and a Mach number correction.

This corrected angle, together with the temperature ratio T_j/T_a is used to determine the modified Strouhal number S_t^* , where

$$S_t^* = S_t (T_j/T_a)^{0.4(1+\cos\theta')}$$

The modified Strouhal number S_t^* is then entered into the collapsed spectral plots to obtain the noise spectrum for a given angle θ to the axis.

It is of particular interest to note that, for the maximum temperature condition of 611.1^oF, the factor by which S_t is multiplied in the above equation is 1.039 when θ' is 15^o (i.e., 30^o to the aft axis, where the noise spectrum peaks) and 1.701 when θ' is 30^o. However, the peak Strouhal numbers in the quarter-scale model test and the full-scale test were also in the ratio of 1.7:1, which suggests that the near-field pressure spectra could also be collapsed if the above equation were applied for an angle θ' of 30^o. Unfortunately, there is insufficient data over a wide enough range of temperature variations to prove that this correction is valid, and not a mere coincidence. Also, there is no way that this kind of information can be obtained with cold jets.

Nevertheless, the quarter-model test spectra were evaluated by using a temperature corrected two-parameter rule, which essentially requires the pressure coefficient to be a function of the modified Strouhal number. The procedure used was to predict the spectra for the maximum test condition of Table 1, i.e., with the 611.1^oF jet temperature, using the following equations for determining predicted full-scale data from model data based on Stones correction with θ' equal to 30^o

$$S_{tPFS}^* = (f D_{eq} / U_j)_M (T_j / T_a)_{FS}^{0.75}$$

$$LPSD_{pFS} = LPSD_M + 20 \log_{10}(q_{jFS} / q_{jM}) - 10 \log_{10}(U_{jFS} / U_{jM}) \\ + 10 \log_{10}(D_{eqFS} / D_{eqM}) + 10 \log_{10}(T_j / T_a)_{FS}^{0.75}$$

In the above equations, LPSD stands for the power spectral density level in decibels, which is to be plotted against the modified Strouhal number S_t^* . Most of the terms appearing in the above equation for LPSD are required for the normalization of the power spectral density as presented against a dimensionless frequency. Subscripts FS and M refer to measured values under full-scale and model conditions, respectively, while subscript PFS refers to predicted full-scale conditions using model data.

Plots of the predicted power spectral densities obtained in this manner are shown together with the full-scale power spectral densities in Figure 22. They are presented in the form of power spectral density ($LPSD_{PFS}$ & $LPSD_{FS}$) plotted against modified Strouhal number (S_{tPFS}^* or S_{tFS}^*). They indicate reasonably good agreement, especially for measurements that are furthest from the nozzle. Agreement is poor only for point P3 which is very close to the nozzle, possibly because the details of the model were not sufficiently accurate. For example, in another study of the effect of sealing the gap between the airfoil and the nozzle, quite large effects were found on the pressure spectra at point P3, as is indicated by Figure 23.

Verification of Temperature Correction for Strouhal Number: The 1.7 times temperature correction was found to be effective in predicting the full-scale spectral peaks from the model data, as is shown in Figure 22. However, there is no assurance that this is not, in fact, a coincidence. The temperature correction could be verified

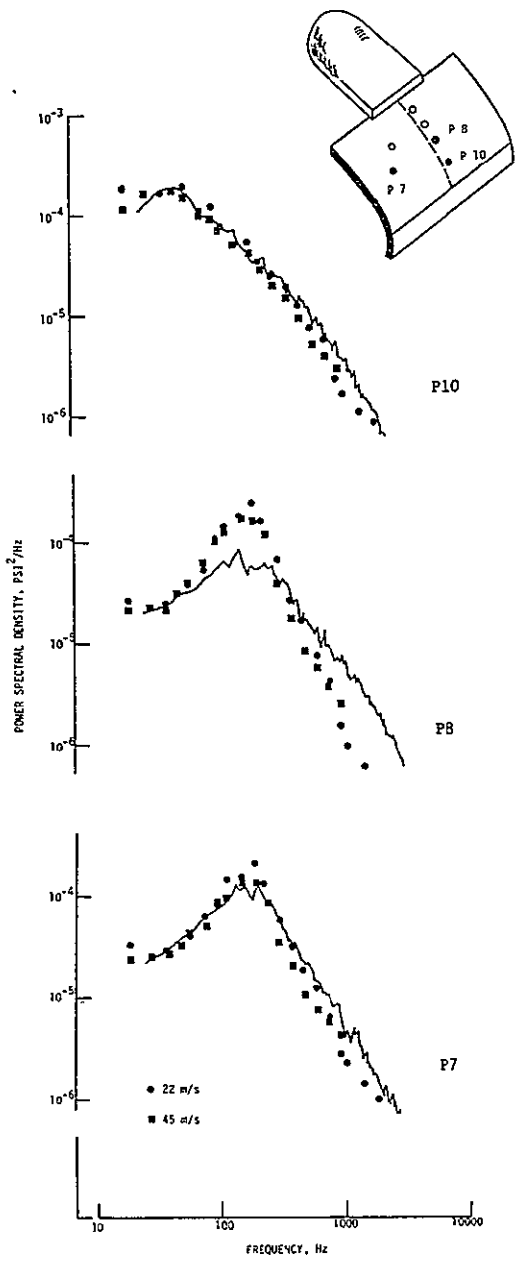


Figure 22a. Comparative Spectra Scaled to Full-Size, Solid Line Represents Full-Size Data.

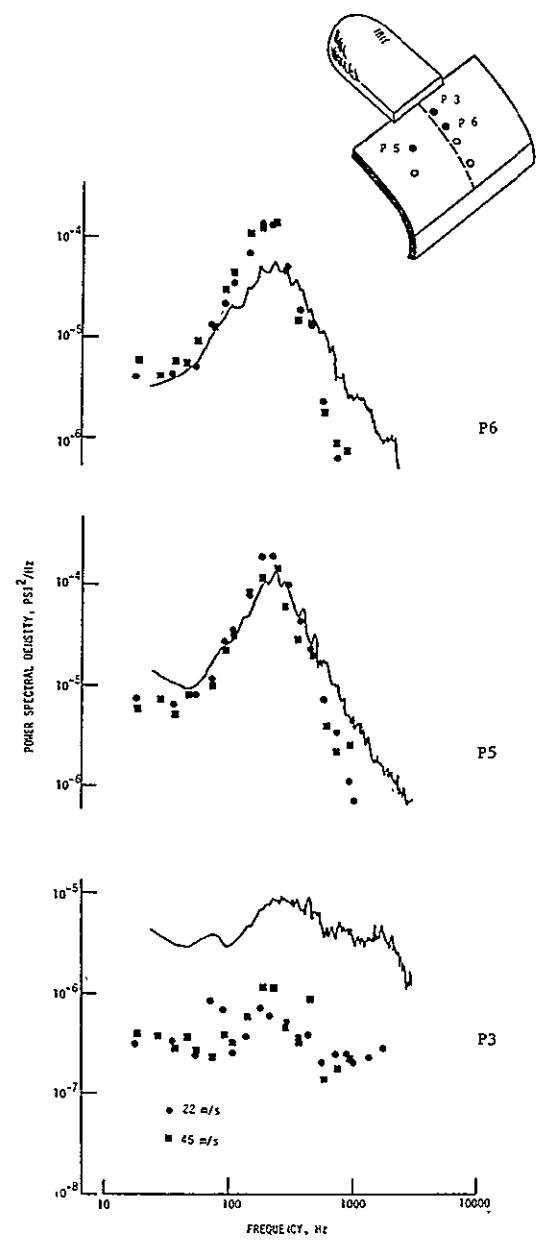


Figure 22b. Comparative Spectra Scaled to Full-Size Solid Line Represents Full-Size Data (continued)

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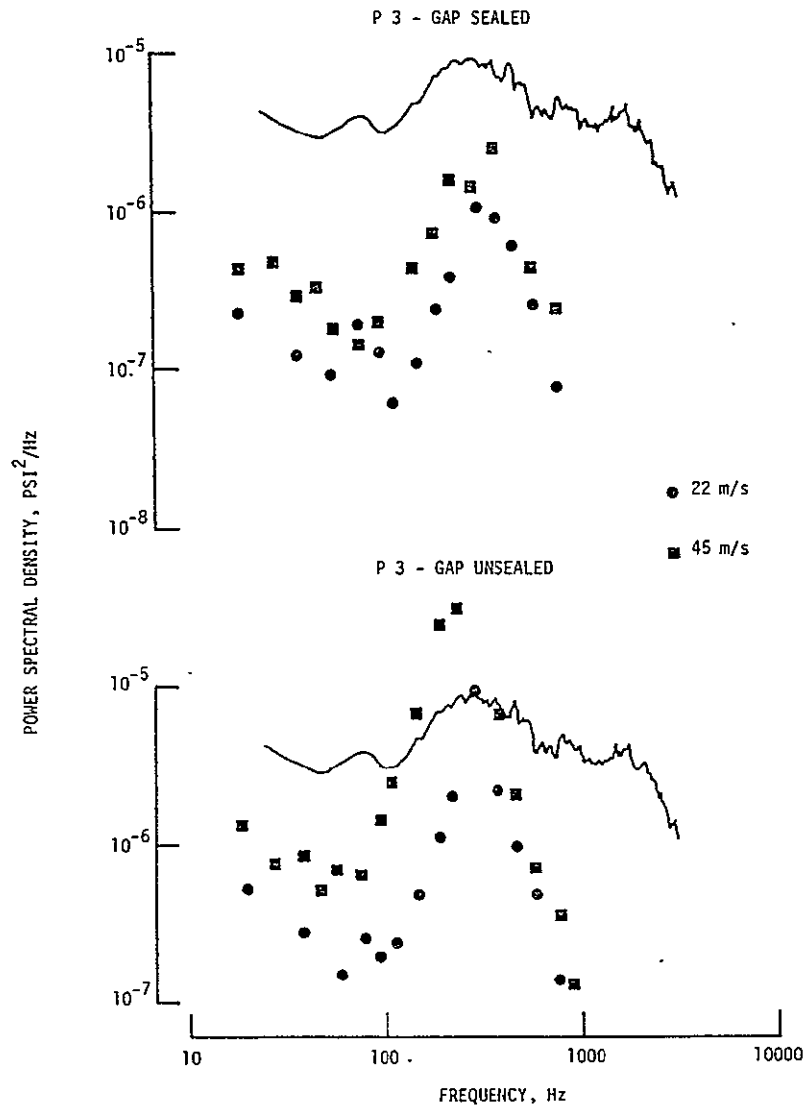


Figure 23. Effect of Sealing Wing Surface to Nozzle Gap, Solid Line Represents a Full-Size Data.

if sufficient data were available from jets at different temperatures.

An attempt was made to do this, but with the limited range of jet temperatures as listed in Table 1, the range of temperature corrections to frequencies was limited to between 1.5 and 1.7, much too small to verify the correction. The frequency spectra obtained from the NASA tests were plotted, with and without these corrections, and, although a slight tendency for the data to collapse into a single plot could be detected, results are too tenuous to present in this report.

Effect of Core Nozzle: A close look at the comparisons between model and full-scale in Figure 22 will reveal that, for points close to the nozzle, the higher frequency spectral levels measured in the full-scale test exceed those for the model, whereas lower frequency results are in better agreement. This could be attributed to the presence of the core nozzle in the full-scale test, which was not reproduced in the model. Accordingly, it was decided that the tests should be rerun with a simulated core nozzle in place. Results of these tests are presently being analyzed, and will be presented in due course by W.W. Herling as part of a doctoral dissertation.

Effect of Engine Noise: Following the test in which a speaker was placed in the plenum chamber (see Figure 20), it was believed that the internal noise generated by the engine could be responsible for part of the jet pressure spectrum. However, nothing in Figure 22 seemed to indicate that this was, in fact, an effect of any significance

at all. Thus earlier plans to model jet engine noise spectra were not followed up.

Effect of Mach Number: It has of course been assumed that the Mach number effect was negligible, however, given the range of Mach numbers covered by the model and full scale tests, it was possible to carry out a limited investigation of the effects of Mach number. The overall or RMS averaged pressure spectra are shown plotted against Mach number for six points on the airfoil in Figure 24. With the exception of point P3 near the nozzle, little or no Mach number dependency is seen in model or full-scale test data, which cover the range up to a Mach number of 0.6. One could also argue that the same test points cover a Reynolds number range up to 3.7×10^6 , and that, therefore, the test data indicate no Reynold's number dependency. Note also that the test data cover a range of jet temperatures, therefore jet temperature is seen to have little effect on the RMS pressure even though it may shift the spectral peaks.

The Effective Diameter of a Non-Circular Nozzle: The classification of data obtained in non-circular nozzles would be greatly facilitated if it could be shown that the pressure spectra in a non-circular nozzle were related to those obtained in a circular nozzle of a given diameter. One essential feature of circular nozzles appears to be that the vortices in the jet flow are of constant diameter, and that, although some coalescence of vortices takes place, the frequency of the spectral peaks varies very little within the first five jet diameters. This was not found to be the case for the

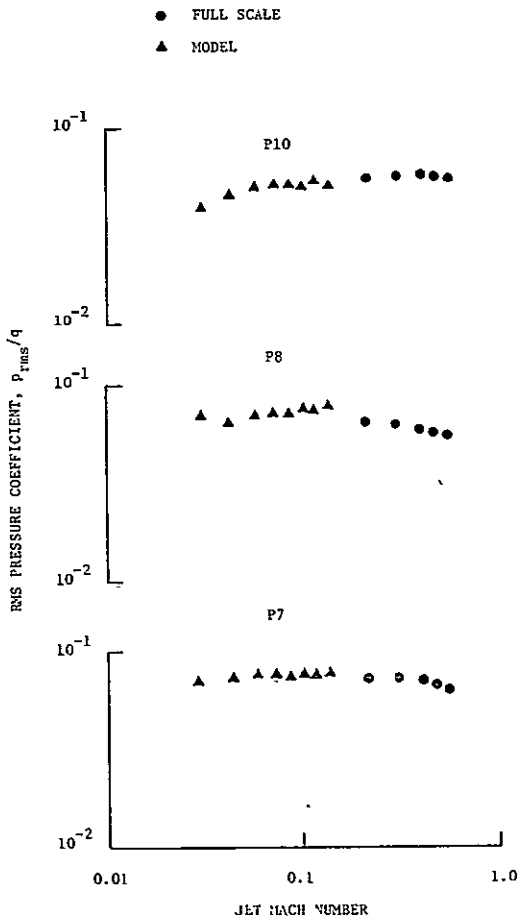


Figure 24a. Pressure Coefficients vs. Jet Mach Number

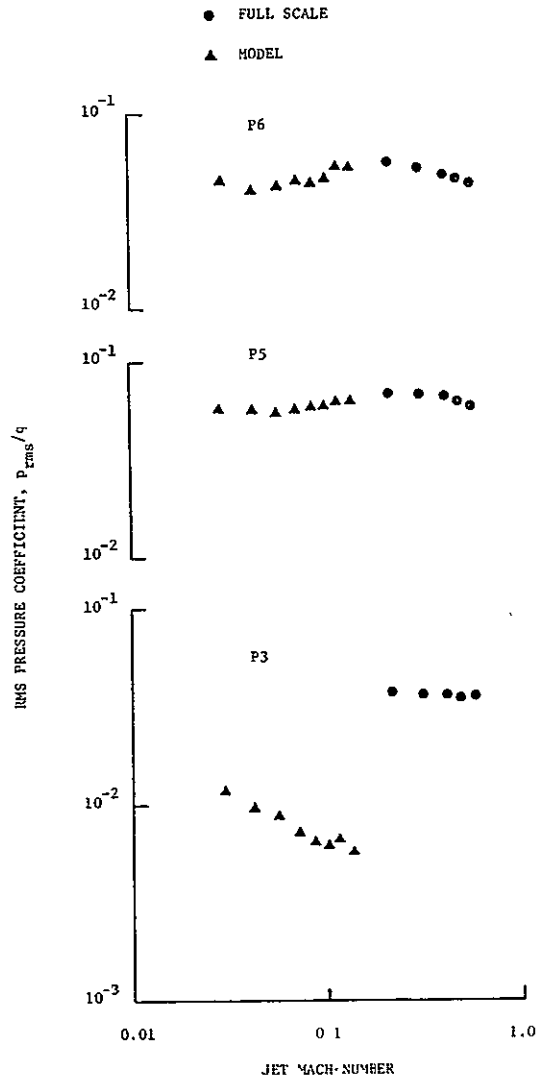


Figure 24b. Pressure Coefficients vs. Jet Mach Number (continued)

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rectangular nozzle, for example, Figure 17 shows that there is a spectral peak at 315 Hz which decays quickly, and gives way to a peak at 100 Hz, while another peak builds up at 40 Hz. One can use an inverse procedure to estimate the effective diameter based on these frequencies. First, one assumes that all spectra peak at a Strouhal number of 0.3, then one calculates the diameter which makes this so. Using this approach, the effective diameters are 29 mm, 92 mm, and 231 mm, respectively. The first and last correspond to the 42 mm by 234 mm dimensions of the rectangular nozzle, so that one could imagine that vortices are originally formed with diameters equal to the nozzle depth, that these coalesce, and finally some large vortices are left with diameters equal to the major nozzle dimension. The 92 mm diameter, however, conforms to the effective diameter D_e used by Stone (Q) where

$$D_e = D_a^{0.6} D_h^{0.4}$$

in which D_a ($\sqrt{4A/\pi}$) is the diameter based on area, and D_h ($4A/P$) is the hydraulic depth, A and P being the area and perimeter respectively. The presence of such frequencies in the pressure spectra and in the far-field noise spectra gives further evidence of a connection between the large scale jet structure and the far-field noise.

The Effect of a Fuselage: In the full-scale NASA tests, a small panel was installed to represent a fuselage intersection.

A similar panel has been attached to the model, and a comparison

has been made between model and full-scale data, this will be published in a thesis by H. Baker.

Miscellaneous Variations in Geometry: Several minor variations were made in the geometry of the full-scale article, and some of these were also reproduced in the scale model tests. These variations included (1) presence or absence of a gap between the nozzle and the airfoil, (2) presence or absence of an extension on the airfoil, (3) variations in the impingement angle between the nozzle and the airfoil, and (4) presence or absence of a deflector plate on the nozzle. The full-scale data in Figure 22 are for no nozzle gap, with an airfoil extension, and a deflector plate.

CONCLUSIONS

Scaling Laws: It is evident that the two-parameter scaling rule, in which the PSD of the fluctuating pressure coefficient is presented as a function of Strouhal number only, is only approximately true. An improved three-parameter rule, incorporating a temperature correction, appears to be promising, but could not be verified within the scope of this study.

Core Nozzle: There is some evidence that a core nozzle would be preferable. However, an investigation now in progress should shed further light on the matter.

Engine Spectra: There was no evidence that the internal engine noise has sufficient effect that it would have to be modelled.

Effective Diameter: It does not appear to be possible to relate the near-field pressure spectra in a non-circular nozzle to that in a circular nozzle of some equivalent diameter. Thus, the concept of an equivalent diameter does not appear to be valid for prediction of jet impingement pressures.

Use of Cold Jets: The low-speed cold jet appears to have a valid place in any test program intended to determine jet impingement pressures. It should be possible to predict pressures with reasonable accuracy from such a test, and it should also be possible to investigate the effects of configuration changes. The agreement noted would lend credence to the idea that the large scale jet structure is reproduced to a fair degree of accuracy in a low speed cold jet, and thus that it might have its place in far-field noise investigations.

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APPENDIX A

PUBLICATIONS PRODUCED FROM THIS STUDY

1. G. D. Catalano, "An Experimental Investigation of an Axisymmetric Jet Exhausting into a Coflowing Airstream", Master's Thesis, The University of Virginia, 1975.
2. G. D. Catalano, J. B. Morton and R. R. Humphris, "An Experimental Investigation of an Axisymmetric Jet Exhausting into Coflowing Airstream", NASA Contractor's Report, NGR 47-005-219, 1975.
3. G. D. Catalano and J. B. Morton, "An Experimental Investigation of Upper Surface Blowing in Coaxial Flow Field," Presented at Twenty-Eighth Meeting of the American Physical Society, Division of Fluid Mechanics, 24-26 November, 1975.
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7. J. K. Haviland and W. W. Herling, "Fluctuating Pressures in Jet Flows over Airfoil Surfaces", submitted to the Ninety-First Meeting of the Acoustical Society of America, 5-9 April, 1976.
8. J. C. Schroeder, "Development of Experimental Techniques for Investigation of Unsteady Pressures Behind a Cold Model Jet", Master's Thesis, The University of Virginia, May 1976.
9. W. W. Herling, "The Development of an Experimental Facility for the Investigation of Scaling Effects in Propulsive Lift Configurations," Master's Thesis, The University of Virginia, May 1976.
10. Morton, J. B., Catalano, G. D., and Humphris, R. R., "Measurements in the Mixing Region of a Turbulent Jet in a Coflowing Airstream", Presented at the Workshop on Laser Velocimetry, May 5-7, 1976, Saint-Louis, France.

11. Catalano, G. D., J. B. Morton, and Humphris, R. R., "An Experimental Investigation of a Three-Dimensional Wall Jet," Virginia Academy of Science, May 1977.
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14. Catalano, G. D., Morton, J. B., and Humphris, R. R., "Two Point Velocity Measurements in a Three-Dimensional Wall Jet," presented at the AIAA/NASA Ames V/STOL Conference, June 13-15, 1977.
15. Catalano, G. D., Morton, J. B., and Humphris, R.R., "An Experimental Investigation of the Mixing Region of a Turbulent Jet", the 1977 Engineering Foundation Mixing Conference, Franklin Pierce College, August 21-26, 1977, Ringe, New Hampshire.
16. Morton, J. B., Catalano, G. D. and Humphris, R. R., "Some Two Point Properties of a Three Dimensional Wall Jet", Accepted for Publication in AIAA Journal, March, 1978.

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