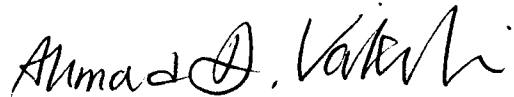


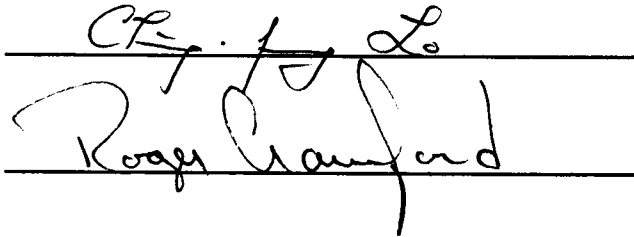
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**MEASUREMENT OF THE SHEAR LAYER OVER A CAVITY
WITH AND WITHOUT UPSTREAM MASS INJECTION**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Edward Paul Lambert

August 1993

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ABSTRACT

Measurements were carried out in the shear layer over a cavity with a free stream Mach number of 0.5 and upstream mass injection. Mass injection rates of 0.05, 0.10 and 0.15 lb/sec were used. Local pressure measurements were made at the cavity leading and trailing edges using calibrated five hole cone probes. In addition, dynamic measurements were taken of the acoustic oscillations inside the cavity.

The shear layer for the tunnel nominal operating condition was found to be relatively thick (approximately one inch) and thus no significant instabilities (Kelvin - Helmholtz) formed once the cavity was installed. Consequently the magnitudes of the cavity acoustic oscillations observed were very small. Measurements from the cone probes also indicated a variation in local static pressure in the shear layer when upstream mass injection is employed. Finally, it was observed that the cavity edge vortices were modified by the mass injection, but due to the absence of oscillations at nominal flow conditions, the details of this interaction could not be evaluated in detail.

TABLE OF CONTENTS

I	INTRODUCTION	1
II	TECHNICAL REVIEW	5
	Five Hole Cone Probes	5
	Probe Description	5
	Probe Calibration	7
	Cavity Flow	13
	Cavity Resonance Suppression Techniques .	17
	Shear Layer Modification Using Mass Injection	21
III	EXPERIMENTAL METHODS AND PROCEDURES	23
	Facilities, Installations and Instrumentation	23
	Experimental Procedures	30
	Probe Calibration	30
	Cavity Flow Evaluation	31
IV	EXPERIMENTAL RESULTS AND ANALYSIS	33
	Calibration	33
	Cavity Flow Evaluation	37
	Nominal Tunnel Flow Conditions	37
	Mass Injection Effects	41
V	CONCLUSIONS AND RECOMMENDATIONS	54
	LIST OF REFERENCES	57
	APPENDIX	61
	VITA	63

LIST OF FIGURES

Fig		Page
2.1	Five hole cone probe port numbering nomenclature .	7
2.2	Typical plots of DP13 and DP24 vs ϕ	9
2.3	Comparison of corrected misalignment angles	11
2.4	Classification of cavity flows	15
2.5	Injection patterns used by Cooper	20
3.1	Probe calibration stand	24
3.2	UTSI blow down wind tunnel schematic	25
3.3	Cavity and mass injection layout	26
3.4	Cone probe dimensions	28
3.5	Cone probe supports	29
3.6	Probe tip traverse locations	30
4.1	Comparison of PAVG vs α_t and PAV vs α_t . Probe #1, M =0.50	34
4.2	DPSQP vs α_t	36
4.3	Probe and dynamic transducer time response	37
4.4	Boundary layer profile for nominal flow conditions	38
4.5	Flow visualization of cavity flow with no mass injection	39
4.6	Cavity acoustic frequencies - no mass injection . .	40
4.7	Shear layer profile and spanwise velocity vector map	42
4.8	Cavity oscillation frequency plots	47
4.9	Sensed static pressure traverse profile	49

NOMENCLATURE

A, B, C	Probe Mach number calibration coefficients
A1, A2, A3	Probe total angle of attack calibration coefficients
C _i	Constant number i
D	Cavity depth
DP ₁₃	Differential pressure sensed by the probe between ports 1 and 3, P ₁ - P ₃
DP ₂₄	Differential pressure sensed by the probe between ports 2 and 4, P ₂ - P ₄
DPSQP	Flow angularity parameter, $=\text{SQRT}(\text{DP}_{13}^2 + \text{DP}_{24}^2) / (2 * P_5)$
L	Cavity length
L/D	Cavity length to depth ratio
mdot	Mass injection flow rate (lb/sec)
M	Local Mach number
M _e	Shear layer edge Mach number (= 0.99M _∞)
M _∞	Free stream Mach number
P _i	Pressure sensed by probe at port i, i=1-4
P ₅	Pressure sensed by probe at port 5, probe total pressure
PAV	Average of the sensed static pressures $= (P_1 + P_2 + P_3 + P_4) / 4$
PAVG	Average static pressure sensed by the probe normalized by the probe total pressure, $= (P_1 + P_2 + P_3 + P_4) / (4 * P_5)$
Re	Free stream Reynold's number
S	Strouhal number
α	Probe pitch angle
α _t	Total angle of attack defined as the

	angle between the probe roll axis and the velocity vector
α_d	Probe pitch misalignment angle defined as the pitch angle deviation from the zeroed position
ϕ	Probe roll angle
ϕ_d	Probe roll misalignment angle defined as the roll angle deviation from the zeroed position at $\phi = 0$
ϕ_t	Probe total roll angle
Φ	Probe yaw angle
Φ_d	Probe yaw misalignment angle defined as the deviation in yaw angle from the zeroed position at $\Phi = 0$

CHAPTER I

INTRODUCTION

Modern aerodynamics tends to focus on the optimization of drag reduction in vehicle design using a myriad of tools such as complex flow visualization methods and computational fluid dynamics analysis. Thus virtually all transport vehicles emerge as sleek bodied engineering marvels which operate very efficiently at design point conditions. Opening an automobile sunroof while travelling at 60 MPH or opening an aircraft's landing gear doors on final approach demonstrate that even the most optimum aerodynamic designs are subject to significant efficiency losses and sometimes violent unsteady flow conditions at some point during normal operations due to free stream - cavity flow interaction mechanisms.

This interaction phenomena has been studied extensively dating back to the late nineteenth century. Covert [1] outlines the early historical perspective of cavity flow research and Stallings and Wilcox [2] present a continuation focussing on more recent efforts in this field. Modern research has been driven by attempts to reduce attack aircraft radar signatures by eliminating external stores carriage. Thus weapons normally carried on external pylons are now being carried in closed weapons bays which when opened for stores delivery tend to exhibit classical shear layer - cavity interaction phenomena. This mechanism has demonstrated the potential to cause

significant store separation problems, and in worst case scenarios, cause damage to the weapons and surrounding structure. The limited stores carriage capabilities of modern attack aircraft and the cost of modern weapons have resulted in renewed interest in research to reduce the effects of the interaction mechanism.

The mechanism can be described as a self excited feedback mechanism where the shear layer interacts with the trailing wall of the cavity setting up acoustic waves which travel forward within the cavity. As these waves reach the forward wall, they interact with the shear layer at the forward wall this in turn modifies the shear layer over the cavity and thus the interaction at the trailing wall. The cavity has a natural acoustic frequency resulting from it's geometry (length to depth ratio L/D) and the free stream flow conditions and if the acoustic oscillations within the cavity approach this frequency, resonance will occur with potentially violent results. Research has therefore focussed on modifying the interaction of the shear layer and the trailing wall.

Early attempts to reduce this interaction used passive methods such as ramps, spoilers and vortex generators in front of the cavity to thicken the shear layer over the cavity. These methods generally worked well and reduced the interaction and thus the acoustic oscillations for a given free stream condition. At other flow conditions removed from the 'design' free stream condition, these methods were not effective and in some cases even aggravated the interaction.

Lessons learned in passive flow control methods were then applied to active control devices such as variable geometry spoilers and fences etc. where the device geometry was driven by free stream flow conditions. These devices had limited success in reducing the acoustic oscillations within the cavity.

Recent research has focussed on active flow control using mass injection upstream of the cavity. Vakili and Gauthier [3] conducted experiments using this technique and demonstrated that the amplitude of acoustic oscillations within a cavity could be reduced from 1.5 psi to 0.075 psi. Cooper [4] studied the effect of various mass injection patterns in an attempt to optimize cavity oscillation suppression using this technique. Their results indicate that control of shear layer induced cavity acoustic oscillations using upstream mass injection is an effective and efficient active control method which warrants further study.

Gauthier and Cooper both had difficulty explaining the data they measured over the injection plate and the cavity using total pressure traverses. Characterizing the flow field due to injection demanded more detailed knowledge of the flow parameters, particularly the local static pressure and velocity vector. Therefore the current study was undertaken to provide an opportunity to better explain the significant aeroacoustic suppression observed.

The object of the current experimental work is to employ five hole cone probes to measure shear layer flow characteristics over a cavity in free stream flow of Mach 0.5

with and without mass injection. This will help explain previous experimental results found using total pressure probe measurements.

Measurement with five hole cone probes is rather complicated and requires a careful and thorough calibration. Details of this process are described in chapter 2.

CHAPTER II

TECHNICAL REVIEW

Five Hole Cone Probes

Combination pressure probes have been used for many years to measure flow pressures, velocities and directions. Whenever practicable, their use is preferred primarily due to their relative simplicity, low cost, contamination tolerance, and robustness.

Advances in probe design and manufacturing techniques coupled with automated data acquisition systems have made it possible to employ small pressure probes in unsteady flow where hot wire anemometers have historically been dominant. This represents a significant advancement in flow measurements, particularly in harsh high speed unsteady flow environments.

The conical five hole combination probe was one of the earliest probes developed for complete velocity measurements in three dimensional flows [5], and substantial reference literature has been published on the design and calibration of these probes.

Probe Description

The five hole conical pressure probe has one pressure port in the nose of the cone and four symmetrically spaced holes around the cone displaced at a specified distance from the nose

as illustrated in Fig 2.1. The port in the nose of the cone senses total pressure while pressures and pressure differentials between symmetrically opposing ports is correlated to flow speed and direction about the cone through calibration.

Two modes of operation are employed with conical pressure probes, namely the Nulling and Non Nulling modes. The former uses mechanical linkage to align the probe such that pressure sensed in the symmetrically spaced ports is equal, and flow direction is then deduced from the physical displacement of the probe. Although very accurate, this method is relatively slow and measurement at a point requires complex carriages be incorporated to prevent displacement of the nose as the probe is rotated.

In the Non Nulling mode, the probe remains stationary in the flow and the direction is found by a correlation between sensed port pressures and calibration data. This mode can be less accurate, but is much faster in operation.

There are theoretical approaches which can be used to deduce the pressure distribution on the surface of axisymmetric bodies in a flowfield [6], but probe manufacturing defects (tolerances) and the non ideal behavior of fluid flows reduce the accuracy of these predictions significantly. It is therefore necessary to carry out detailed calibration of each probe before use. It is good experimental practice to calibrate any measuring device under conditions closely approximating the conditions in which measurements are to take place, but this is critical with cone probes due to the nonlinear Mach and Reynold's number

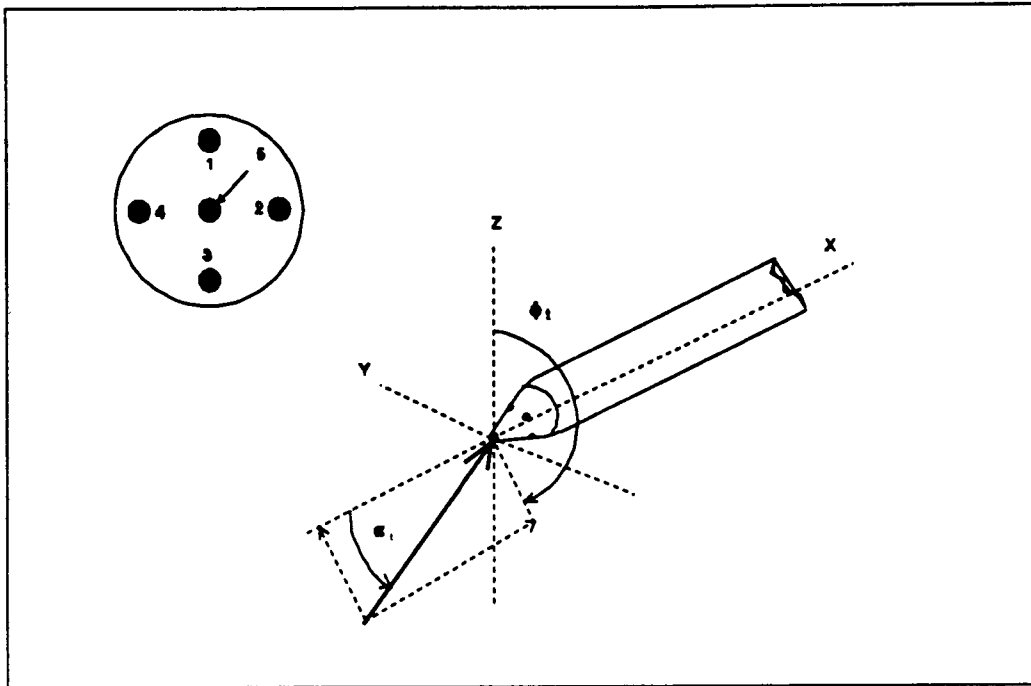


Fig 2.1 Five hole cone probe port numbering nomenclature

dependence of the probes.

Probe Calibration

The calibration of a five hole cone probe consists of placing the probe in a known flowfield and correlating sensed pressures to known flow characteristics through calibration constants. Once these constants have been determined they can be used to correlate sensed probe pressures to flow Mach no. and angle of attack in unknown flows. Numerous methods of correlating this data have been well documented in literature ranging from simple look-up tables to complex curve fitting routines or various combinations of the two. A recent method proposed by Hatcher [7] is based on two pressure non dimensional parameters which characterize the probes sensitivity to local

Mach number and total angle of attack, namely:

$$PAVG = \frac{P_1 + P_2 + P_3 + P_4}{4 \times P_5}$$

$$DPSQP = \frac{\sqrt{DP_{13}^2 + DP_{24}^2}}{2 \times P_5}$$

where

$$DP_{13} = P_1 - P_3$$

$$DP_{24} = P_2 - P_4$$

PAVG is simply the average of the static pressures sensed in the circumferential ports normalized by the total pressure. This parameter can thus be related to local mach number through the Rayleigh pitot relation. DPSQP is the square root of the sum of the differential pressure squares normalized with the total probe pressure. This parameter in conjunction with the local Mach no. can be related to probe angle of attack (α). DP_{13} and DP_{24} can be related directly to probe roll angle (Φ).

Theoretically, when a five hole cone probe is aligned with the free stream flow, DP_{13} and DP_{24} should equal zero. Experimentally this rarely occurs due to probe manufacturing anomalies and the inability to perfectly align the probe with the free stream. A typical raw data curve of DP_{13} and DP_{24} vs Φ at a constant α is shown in Fig 2.2 where probe misalignment angles are evident. In the absence of misalignment angles, at $\Phi = 0^\circ$ DP_{24} would equal zero while at $\Phi = \pm 90^\circ$ DP_{13} would equal zero (approximately).

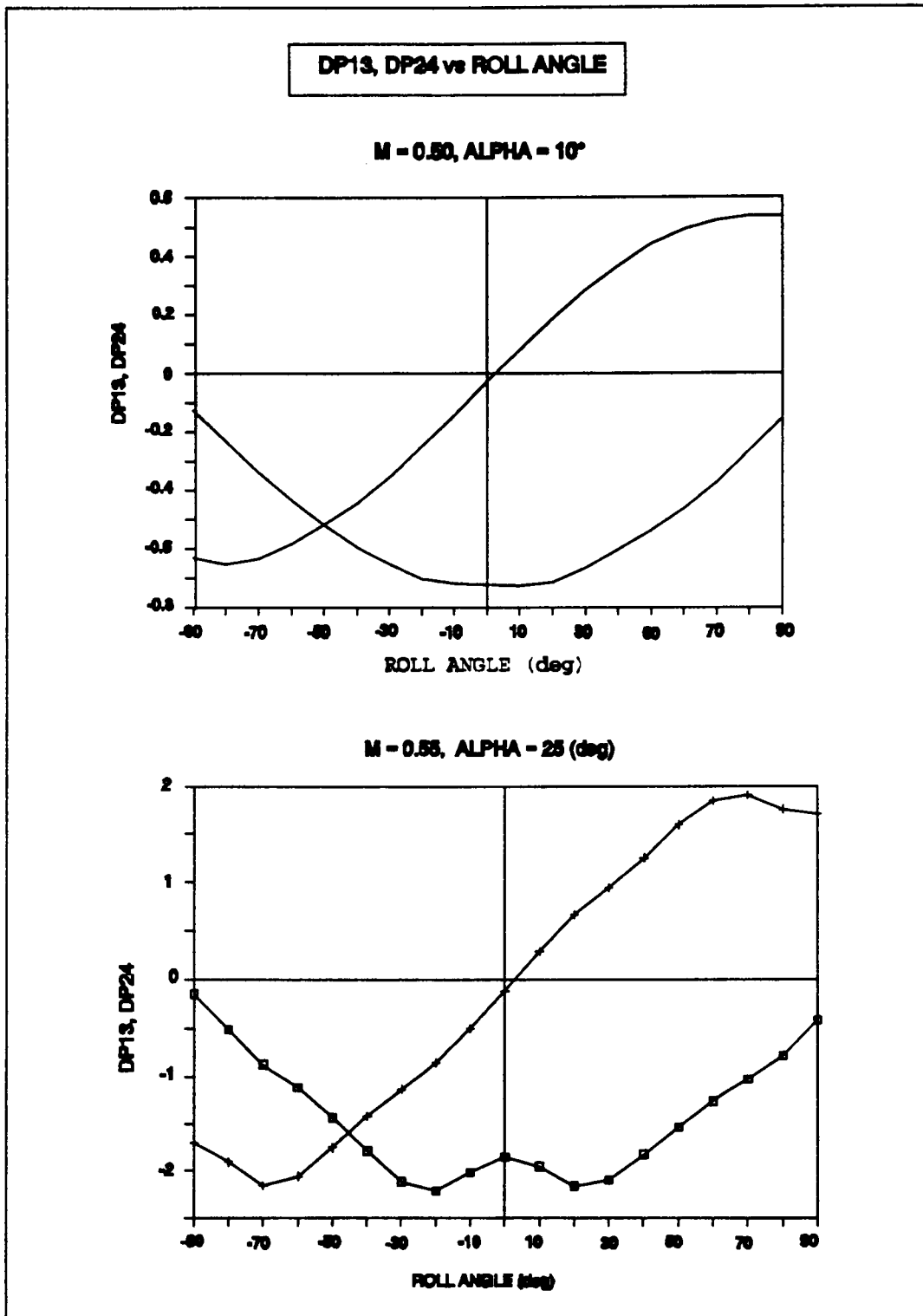


Fig 2.2 Typical plots of DP13 and DP24 vs ϕ

Manufacturing anomalies are accounted for in the probe calibration process, but probe misalignment angles in the calibration setup yields biased results during flow measurement. These misalignment angles α_d , Φ_d , and ϕ_d must be accurately determined and probe calibration data corrected prior to any curve fitting etc. Hatcher suggested that for zero probe misalignment, a plot of DPSQP vs probe local total angle of attack (α_t) would consist of two coincident straight lines passing through the origin. An interactive computer program he developed predicts the probe misalignment angles based on minimizing the disagreement between the two straight lines and asserting a zero intercept. The program permits user input for the misalignment angles once the initial prediction has been made. Changing α_d varies the agreement between the curves and changing ϕ_d shifts the intercept point.

Such programs work well for probes at relatively low α where DP_{13} and DP_{24} vs α for well designed probes resemble cosine and sine curves. At higher angles of attack separation of the flow on the cone surface introduces non linearities and the curves are not as well behaved as shown in Fig 2.2. In these cases the plots of DPSQP vs the total angle of attack relative to the probe (α_t) curves also become non linear above a critical α_t , and manually varying α_d and Φ_d yield much better results. Fig 2.3 is a comparison of the plots of DPSQP vs α_t corrected for misalignment angles predicted by the computer program and interactively. With the misalignment angles determined, Hatcher's method continues with a coordinate transformation of

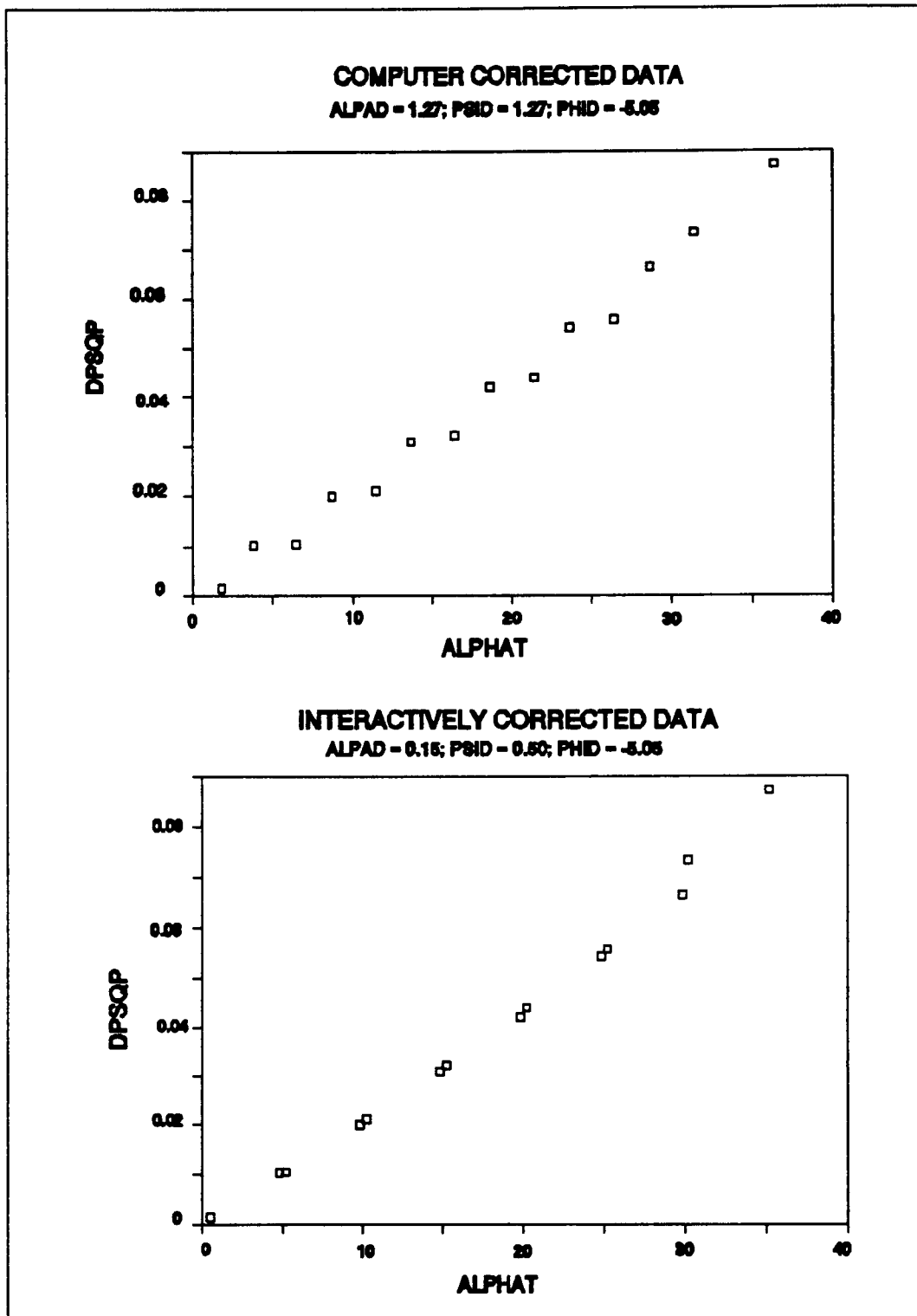


Fig 2.3 Comparison of corrected misalignment angles

the free stream velocity vector to a total angle of attack α_t and total roll angle ϕ_t . For a calibration process where the probe is set at a given α and then rolled, the transformation matrix yields the following:

$$\alpha_t = \arccos U_p$$

$$\phi_t = \arctan \left[-\frac{U_p}{W_p} \cos \psi_d + \frac{V_p}{W_p} \sin \psi_d \right]$$

where

$$U_p = U \cos \psi_d + V \sin \psi_d$$

$$V_p = -U \sin \psi_d + V \cos \psi_d$$

$$W_p = \sin \alpha_d \cos \alpha + \cos \alpha_d \sin \alpha \cos [\phi + \phi_d]$$

$$U = \cos \alpha_d \cos \alpha - \sin \alpha_d \sin \alpha \cos [\phi + \phi_d]$$

$$V = \sin \alpha \sin [\phi + \phi_d]$$

Note: these equations are only valid for the sequence of angular rotations stated above.

These angles (α_t and ϕ_t), DPSQP and PAVG now form the basis for look up tables or curve fitting routines to determine the probe calibration constants. Strike [8] developed a computer code which uses essentially a modified Newton - Raphson method to curve fit the data as:

$$\left[\frac{P_a}{P_t} \right]_c = A + B \times \text{DPSQP}^2 + C \times \text{DPSQP}^4$$

where

$$A = \sum_1^6 C_k [PAVG]^{k-1}$$

$$B = \sum_7^{11} C_k [PAVG]^{k-7}$$

$$C = \sum_{12}^{16} C_k [PAVG]^{k-12}$$

and

$$\alpha_t = A_1 + A_2 \left[\frac{P}{P_t} \right] + A_3 \left[\frac{P}{P_t} \right]^2 \times DPSQP$$

$$\phi_t = \arctan \left[-\frac{DP_{24}}{DP_{13}} \right]$$

For the initial guess, the constants are set equal to one and the iteration is halted when the desired convergence criteria has been met.

This method works very well, but again at higher angles of attack the data trends tend to change significantly due to non linearities imposed due to separation. Thus for higher angles of attack (ie > 30°), two curve fits could be performed to yield distinct sets of calibration constants for the different flow regimes.

Cavity Flow

An excellent review of cavity flow research is given by Gauthier [9] and Cooper [4]. A brief summary is presented below of the highlights which directly pertain to this work. For more

detail the reader is referred back to these references.

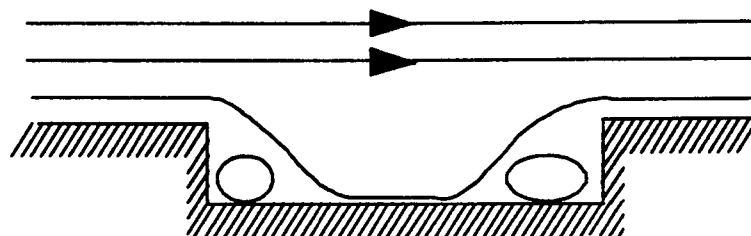
Komerath [10] described the fluid dynamics of flow over a cavity as separation of the incoming boundary layer at the cavity lip followed by the creation of a free shear layer over the cavity. Spanwise instabilities begin to develop within the shear layer which typically reattaches downstream or at the rear wall of the cavity. He further commented that most of the flows over cavities are susceptible to oscillations.

The principal parameter used to characterize cavity flow dynamics is the cavity length to depth ratio (L/D). Chen [11] used this to assign cavity flows to three categories as follows:

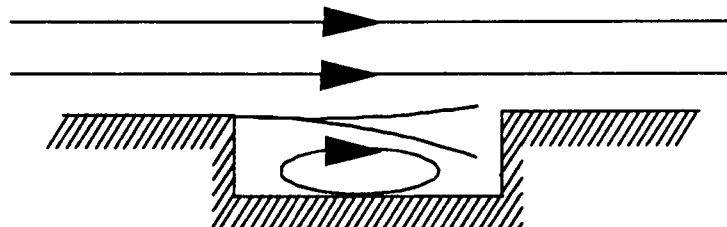
- a. Closed cavity - for large L/D ratios where the external flow attaches to the cavity floor;
- b. Open cavity - for low L/D ratios where the external flow does not attach to the cavity floor;
- c. Transition Cavity - for intermediate L/D ratios where the flow is unstable closed or open type which may tend to oscillate between the two.

Fig 2.4 illustrates typical open and closed cavity flow patterns.

The oscillatory tendency of the flow is generally governed by the cavities' longest dimension. Sarohia [12] described cavities with L/D greater than one as shallow cavities and those less than one as deep cavities. The flow over shallow cavities were strongly influenced by the shear layer longitudinal oscillatory modes while deep cavities exhibited acoustic depth modes with oscillations primarily governed by the cavity



(a) Closed (attached) cavity flow for large L/D



(b) Open (unattached) cavity flow for low L/D

Fig 2.4 **Classification of cavity flows**

geometry.

Numerous attempts have been made to model the mechanics of oscillatory cavity flows, but these have been met with very limited success due to the free shear layer interactions which have proved very difficult to predict. Rossiter [13] developed a semi empirical formula based on Strouhal number for predicting the possible acoustic resonance frequencies for rectangular cavities. Heller and Bliss [14] modified Rossiter's equation for high speed flows to account for variations in sonic speeds between the internal cavity flow and the external free stream by assuming the cavity speed of sound was equal to the stagnation speed of sound. This modified Rossiter's equation which yields realistic estimates of resonant frequencies is as follows:

$$S = \frac{fL}{U_o} = \frac{(m-n)}{\left[\frac{M}{\sqrt{1 + \frac{(\gamma-1)}{2} M^2}} + \frac{1}{K_v} \right]}; m=1, 2, 3, \dots$$

where f is the frequency, L is the cavity length, m is the number of complete wavelengths of acoustic radiation (mode no), n accounts for the phase difference between vortex shedding and acoustic waves and K_v is the vortex convection speed. Rossiter's data was correlated using $n = 0.25$ and $K_v = 0.57$.

Tam and Block [15], citing various discrepancies with previously developed models of cavity oscillatory flows, vigorously analyzed the excitation of the shear layer instabilities by acoustic disturbances and developed a mathematical model which accounted for the thickness of the free shear layer and the reflection of acoustic waves at the cavity

floor. They added two parameters not previously considered in modelling the dynamics, namely the L/D ratio and the boundary layer momentum thickness to length ratio θ/L . Unfortunately their efforts met with limited success mainly because of the inability to accurately model the shear layer interaction phenomena, but they did highlight the importance of understanding these new parameters.

Results of research thus far have led to prediction of possible resonant frequencies of cavity flow oscillations, but have fell short of predicting those likely to become dominant and which modes will occur under various flow conditions. This is directly attributable to the complexity of the free shear layer encountered in cavity flows.

Cavity Resonance Suppression Techniques

As mentioned previously, many novel approaches have been taken to suppress the amplitude of acoustic oscillations within cavities. Cooper [4] presents an indepth review of these methods and their effectiveness as acoustic suppressors. The general conclusion was that passive methods such as the addition of fixed ramps, spoilers and vortex generators demonstrated successful attenuation over very limited flow regimes. These devices attempted to suppress the oscillations by either increasing the shear layer thickness over the cavity, or by simply deflecting the shear layer over the cavity such that impingement on the rear wall of the cavity was minimized. Shaw [16] obtained reduction of oscillation amplitudes of 30 dB using

optimally positioned spoilers and trailing edge ramps, but the geometry and positioning was crucial and the reduction was strongly dependent on free stream Mach no.

Attempts to modify the shear layer interaction have also been made by growing the shear layer using mass injection. Cooper [4] noted that increasing the shear layer thickness reduced the velocity gradients thus making the shear layer more stable. He cited the work of both Vakili et al [17] and Taylor [18] which demonstrated complete attenuation of acoustic oscillations in water table experiments using upstream mass injection. Vakili et al also used pulsed mass injection but found that although initially effective, a change in frequency response and phase shifts between the signals resulted in an increase in oscillation amplitudes.

Franke and Sarno [19] used mass injection through narrow slits at the cavity leading edge with the injectant first parallel to the free stream and then at a 45° angle to the free stream. They reported that when the mass injection was parallel to the free stream no effective suppression was observed, and in the case of no free stream flow, the injectant set up acoustic oscillations on it's own. When the mass was injected at 45° , amplitude suppression of 8 to 10 dB was observed.

Gauthier [9] and Schatt [20] used upstream mass injection through rectangular injection plates. Schatt evaluated two different plate hole density configurations which had the same size and number of injection holes but the effective injectant plate overall length in the streamwise direction was varied.

They also varied the blowing parameter B_c , which is defined as:

$$B_c = \frac{\rho_w V_w}{\rho_w V_w} \frac{A_{inj}}{A_{cavity}}$$

between 0.0 and 0.05. Their results indicated substantial acoustic oscillation suppression of primary peaks up to a maximum of 27 dB and almost virtual elimination of secondary frequencies which they attributed to the increase in shear layer thickness thus altering it's instability features. They noted that the best suppression was observed using the low density (ie longer) injection plate configuration.

Gauthier and Schatt's efforts illustrated that shear layer modification was a function of not only mass quantity injected but also the injection plate geometry. Cooper followed up on this fact by conducting experiments using the same apparatus as Gauthier and Schatt, but varying the injection plate geometries. Patterns evaluated are illustrated in Fig 2.5.

Cooper found that the rectangular pattern and inverted 'T' provided the greatest attenuation. He hypothesized that in addition to growing the shear layer, streamwise vortical flow patterns which are significantly modified by the injection also played a major role in the oscillatory amplitudes due to entrainment of high energy flow into the cavity. He suggested that the resulting flow patterns from the other various shapes were inherently three dimensional in nature and were in a manner which caused increased interaction between the shear layer vortices and the cavity sidewalls thus aggravating acoustic oscillations.

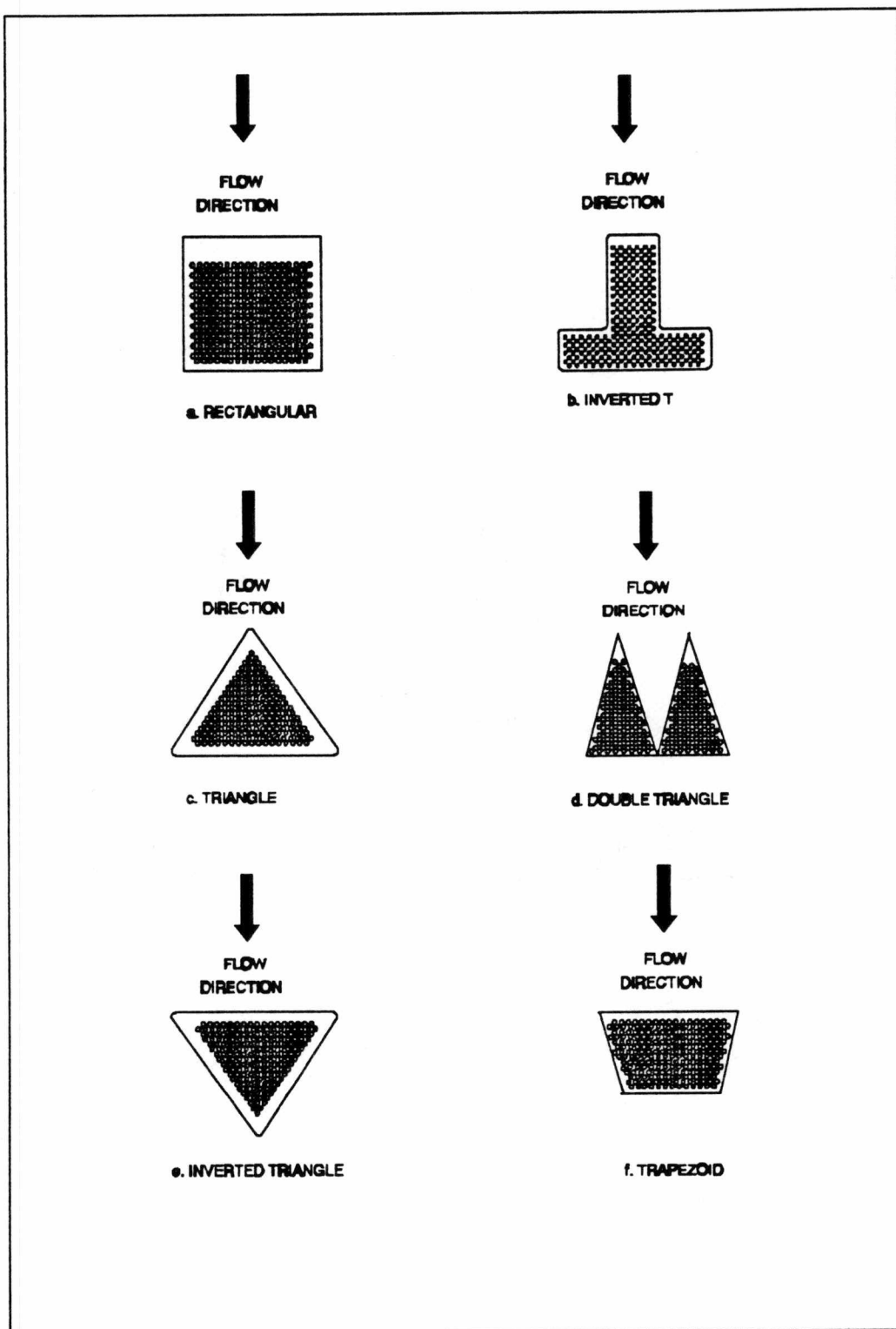


Fig 2.5 Injection patterns used by Cooper

Gauthier, Schatt and Cooper could not explain their results totally due to lack of experimental evidence, primarily the local flow parameters of velocity vectors and local static pressures. Static pressure measurements in their experiments were taken from ports in the tunnel floor and thus did not account for any variance due to mass injection. They all noted this discrepancy, but it could not be overcome using their experimental apparatus.

In summary, it appears that upstream mass injection is a viable means for active cavity acoustic oscillation suppression through a shear layer modification process. The exact physics of the interaction between the shear layer and the overall cavity must be investigated further if this method of suppression is to gain application as an active control process.

Shear Layer Modification Using Mass Injection

Boundary layer control using mass injection has been studied in past years primarily as a means to reduce skin friction and heat transfer on aerospace vehicles. As a result, a thorough literature search revealed all research in this area has produced two dimensional modelling techniques for both weak and massive mass injection.

Walace and Kemp [21], Ting [22], and Bott [23] studied the effects of massive blowing to high speed free stream flows (supersonic to hypersonic regime). The trend in results was that in the inviscid limit, the shear layer could be approximated by a separation streamline leaving the leading edge of the

injection plate at a prescribed angle. This of course is of very limited use in the present study where shear layer development is crucial for understanding the suppression phenomena resulting from the mass injection.

No 3D analytical models detailing shear layer growth resulting from mass injection were found.

CHAPTER III

EXPERIMENTAL METHODS AND PROCEDURES

Experimental work was conducted at the University of Tennessee Space Institute's Gas Dynamics Laboratory. It consisted of two distinct procedures, namely cone probe calibration and cavity flow field measurements. An outline of these procedures follows.

Facilities, Installations and Instrumentation

Cone probe calibration was carried out using an open jet calibration tunnel with an exit nozzle diameter of 2.0 inches. The jet operated from two high pressure air tanks operating at 600 psi in a blow down mode. Flow was controlled manually using a pneumatic control valve.

For calibration, the probes were installed in a holder such that the probe tip was centered in the free jet at a position one exit nozzle diameter downstream from the nozzle exit plane. The holder was supported by yoke assembly as illustrated in Fig 3.1 which permitted both yaw and pitch of the probe in 1° increments with a center of rotation about the probe tip. This assured that the probe tip was located at the center of the inviscid core of the jet throughout the entire range of angular displacements used during the procedure. A numerically controlled Vernitron Digital Torqsyn model no. VTSND 23-64B2 was attached to the holder via a tube through the supporting

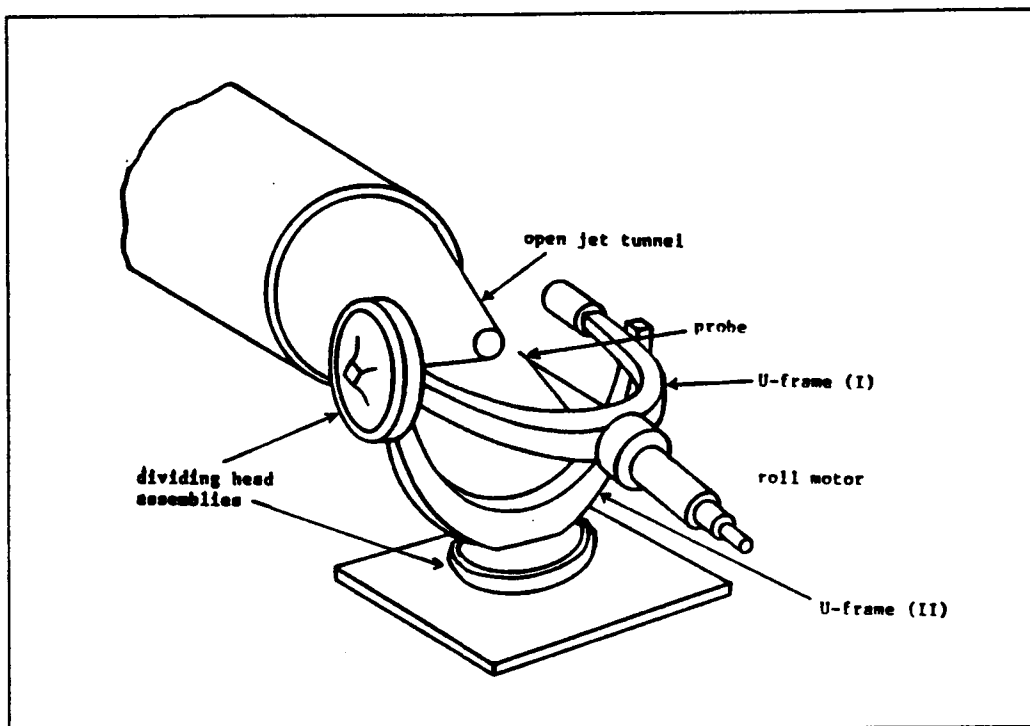


Fig 3.1 Probe calibration stand

mechanism which controlled roll of the probe about it's longitudinal axis. The tunnel total pressure was measured by a pitot probe installed in the stilling chamber and the static pressure port was located in the tunnel nozzle. All pressures were measured using Validyne DP series transducers. The transducer calibrations were: 10 psi for tunnel total; 5 psi for tunnel static, probe total, and probe ports 1 and 2; and 3 psi for differential pressures 1-3 and 2-4.

Cavity flow evaluation was performed in the high speed blow down wind tunnel. The tunnel has an eight inch square test section four feet long and it's converging diverging section was designed for Mach 1.8 operation. A schematic of the tunnel is shown in Fig 3.2. The tunnel operates from two high pressure

(3000 psi) tanks, but for this work maximum tank pressure was kept at 600 psi due to safety restrictions. Flow was controlled manually via a pneumatic flow control valve. A separate low pressure source was used for the mass injection through a plenum located beneath the tunnel floor.

The cavity installed in the test section floor measured 6.5 inches long by 1.5 inches wide by 1.5 inches deep for an L/D ratio of 4.33. The mass injection was provided through a perforated plate with 175 holes 0.0625 inches in diameter in an area 1.0 inches long by 1.75 inches wide which was positioned immediately upstream from and centered on the cavity as shown in Fig 3.3.

The holes were arranged in ten rows of 18 and 17 holes in

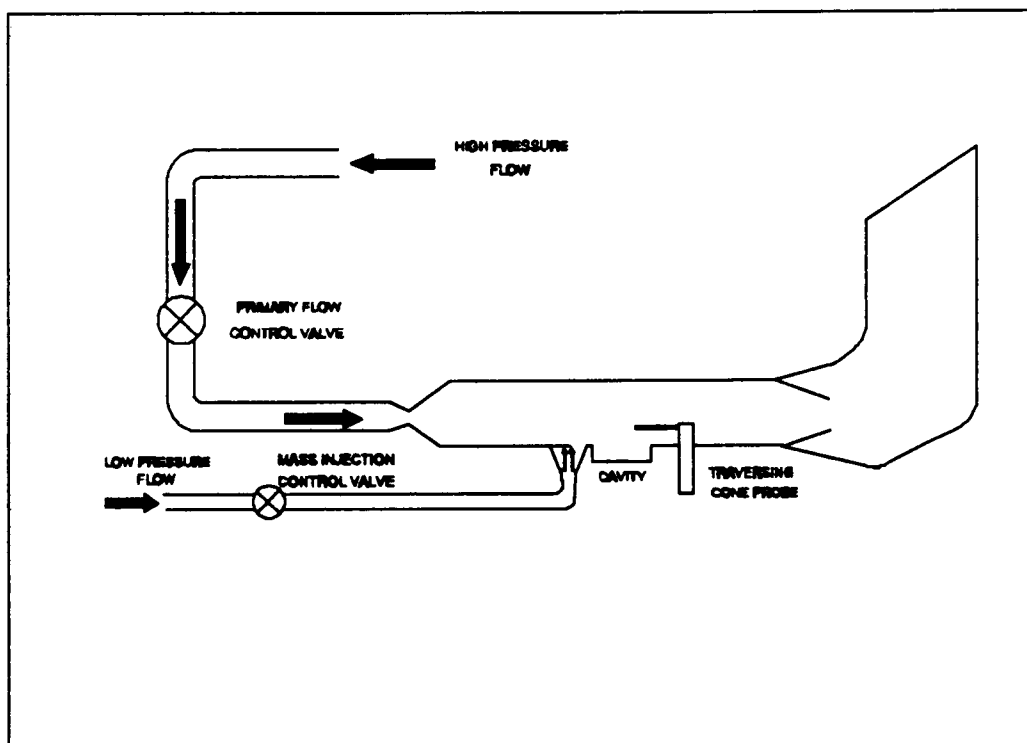


Fig 3.2 UTSI blow down wind tunnel schematic

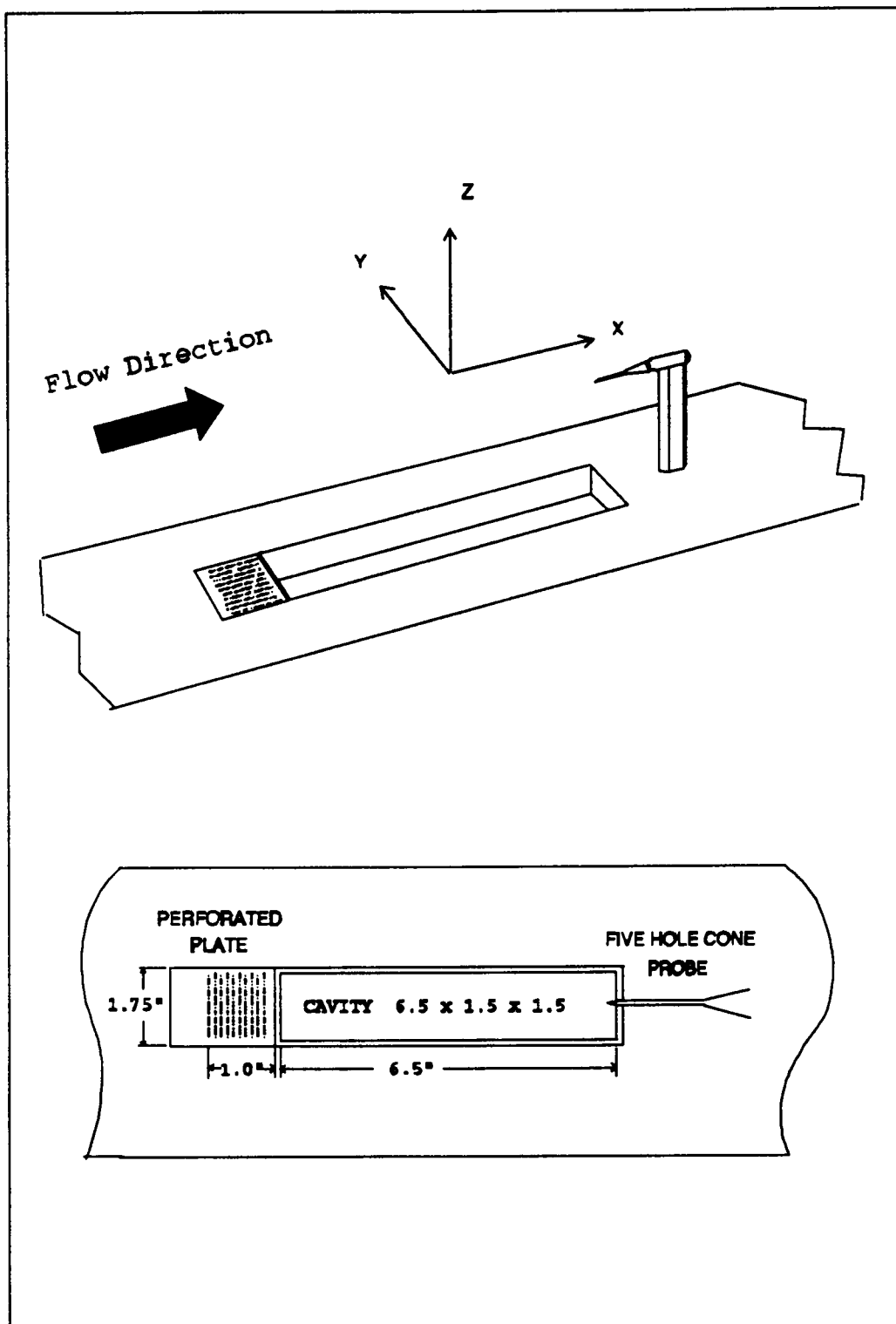


Fig 3.3 Cavity and mass injection layout

an alternating pattern to provide uniform injection. The injected mass flow was provided by a relatively low pressure system through a plenum directly below the perforated plate. The perforated plate used in this work was the same rectangular pattern plate as that used previously by Gauthier [9] and Cooper [4]. Both Gauthier and Cooper reported the greatest cavity pressure oscillation attenuation using this pattern and thus it was the only one studied in the course of this work.

Data recorded during the experimental work included tunnel total and static pressures, shear layer total and static pressure profiles, mass injected and cavity acoustic oscillations. Tunnel total pressure was measured using a total pressure probe installed in the plenum and tunnel static was measured from a static port upstream of the model apparatus.

The shear layer pressure profiles were measured using calibrated five hole cone probes. The probe tips measuring 0.070 inches in diameter were manufactured from Incoloy 800 using an Electronic Design Machining process. The pressure orifices were 0.008 inches in diameter drilled normal to the conical surface of the probe. Of the two probes used in this work, one had a 15 degree half angle and the other a 30 degree half angle. The 30 degree probe is illustrated in Fig 3.4.

The five hole probes were traversed through the shear layer using a numerically controlled stepper motor. Two different probe holders were used in this experiment. The first, for cavity centerline measurements has its sting canted downwards 5° from the support as illustrated on page 29. The second, for

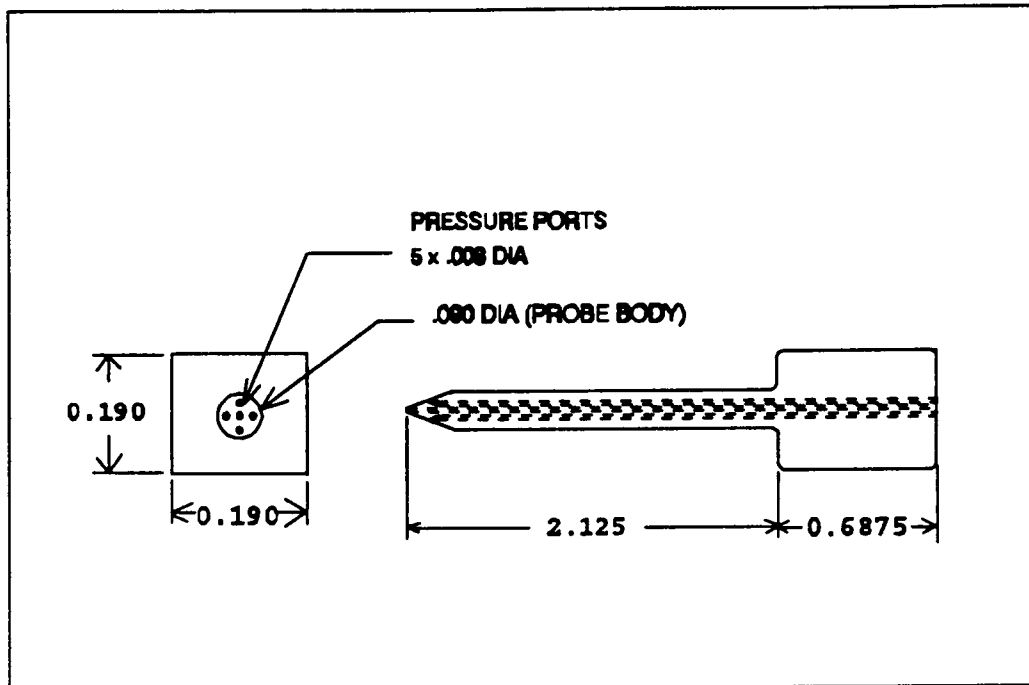


Fig 3.4 Cone probe dimensions

off centerline measurements, was designed with the sting offset such that measurement at 0.50 and 1.0 inches off the centerline could be accomplished by rotating the sting through 90° as shown in Fig 3.5. It also was canted downwards 5°. The probe tip traverse range was from 0.070 to 2.55 inches above the tunnel floor. Probe traverse chordwise stations were 0.5 inches upstream from the cavity leading edge (station 1), at the cavity leading edge (station 2) and at the cavity trailing edge (station 3). Spanwise traverse positions at each station were 0.5 inches to the left of centerline (position b), on the cavity centerline (position a) and 1.0 inches to the right of the centerline (position c). These traverse locations are illustrated in Fig 3.6.

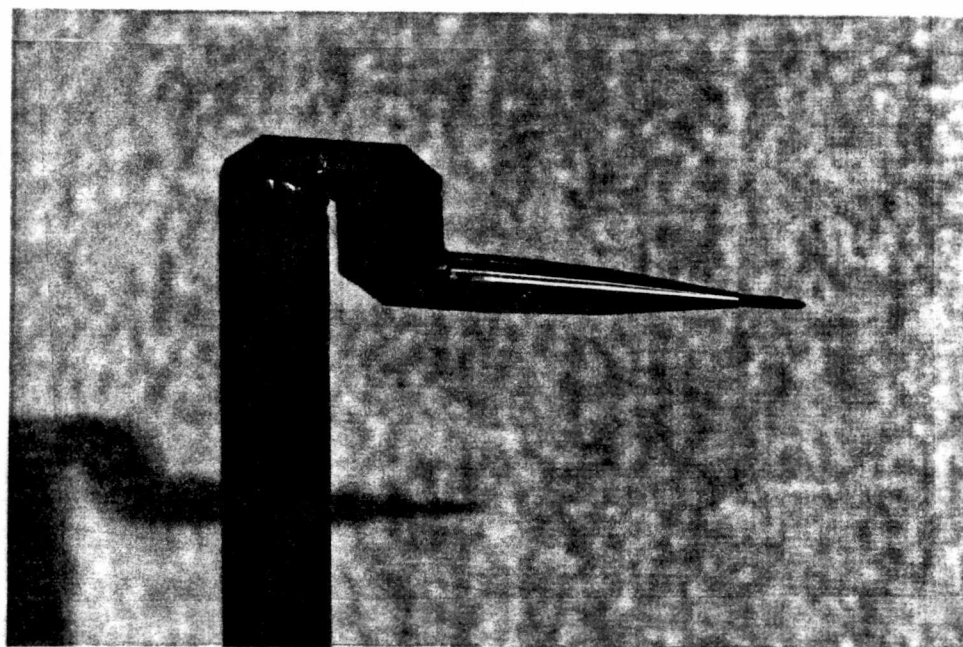
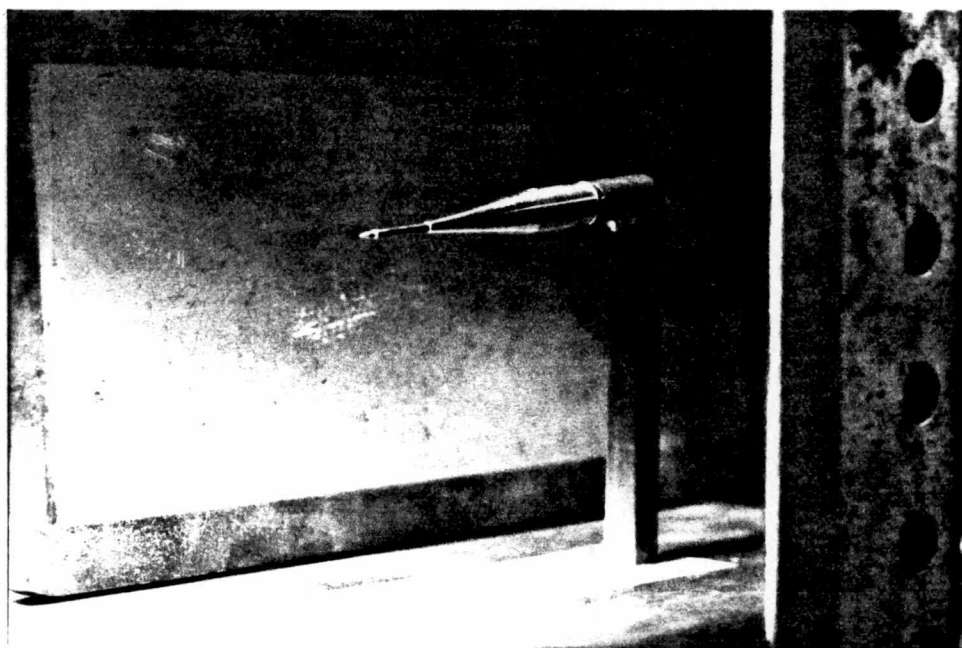


Fig 3.5 Cone probe supports

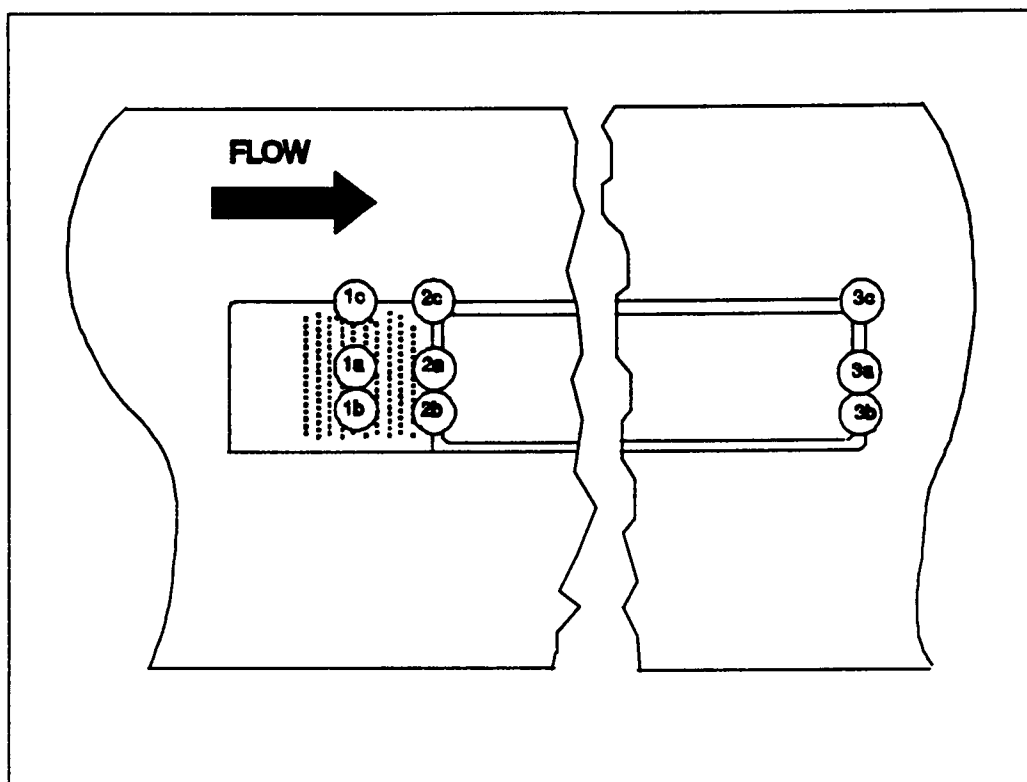


Fig 3.6 Probe tip traverse locations

Cavity acoustic measurements were made using a dynamic pressure sensor installed in the cavity floor. The sensor was an Endevco sub miniature piezoresistive pressure transducer model 8514. The transducer was connected to a Hewlett Packard model HP3582A frequency spectrum analyzer to obtain cavity pressure oscillation amplitude and frequency data.

Experimental Procedures

Probe Calibration

The five hole cone probes required calibration for Mach no and flow angularity. The process commenced with nulling the differential pressures at α and $\Phi = 0^\circ$ at a free stream Mach

number of 0.5. This assured that the probe longitudinal axis was aligned with the free stream.

Once nulled, the calibration consisted of pitching the probe to obtain angles of attack from -35° to $+35^{\circ}$ in 5° steps. At each angle of attack the probe was rolled about it's longitudinal axis from -90° to $+90^{\circ}$ in 10° steps. For each roll, data was obtained for Mach no from 0.4 to 0.6 in .05 steps. Probe roll angle and data collection was controlled by an AT PC via an analogue to digital interface. Collected data was then reduced using the software discussed previously to obtain the calibration constants for the probe. The procedure was then repeated for the second probe.

Cavity Flow Evaluation

This portion of the experiment consisted of investigating of tunnel nominal flow conditions and how these flow conditions were modified first by the introduction of the cavity and then by the addition of mass injection over the cavity. The acoustic oscillation frequencies and amplitudes within the cavity were also investigated as was the effect of mass injection in their suppression. The free stream Mach number for all test runs was 0.5.

A major assumption made throughout the experimentation was that the flow was symmetric with respect to longitudinal vertical plane through the middle of the test section. Therefore, to determine flow conditions at a given station, the data from the probe traverses was treated as symmetrical and

thus yielded shear layer flow condition predictions at five spanwise positions which included the cavity centerline, the cavity side edges, and the midpoints between the cavity centerline and edgepoints.

For nominal test section flow conditions, probe traverses were made at station 3 only. In the absence of the cavity and blowing, the results from the measurements at this station were considered a good representation of flow conditions throughout the test section. Also, to ensure the nominal flow was not separated due to the off design point operation of the tunnel, a surface oil flow visualization was carried out.

With the cavity installed, probe traverses were made at station 3 at the three test positions and at stations 1 and 2 on the cavity centerline (position a). Here again, upstream of the cavity the measurements on the centerline were considered a good representation of the spanwise flow conditions within the region of interest. In addition to the time averaged probe traverse measurements, acoustic dynamic measurements were made inside the cavity.

With the cavity and blowing configuration, probe traverses were made at all three test positions at stations 2 and 3 using mass injection rates of 0.05, 0.10 and 0.15 lb/s. Again dynamic acoustic measurements of the pressure oscillations inside the cavity were made with the dynamic transducer for the three mass injection rates.

CHAPTER IV

EXPERIMENTAL RESULTS AND ANALYSIS

Calibration

The calibration data for the two probes were reduced using the computer codes of Hatcher [7] and Strike [8] discussed previously. A direct application of Strike's Mach number code yielded very good results. Table 1. lists the calibration constants, the sum of the residual errors between calculated and measured data, and the standard deviation of the errors for each probe calibration. When considering the sum of the residuals, it is worth noting that the input data for each probe was approximately 1300 data points, thus the curve fit was quite good. As expected, it was found that PAVG is not strongly dependant upon α as shown by the plot of PAVG vs α at constant Mach number and roll angle in Fig 4.1. Fig 4.1 also illustrates the dependence of PAV (average of the sensed static pressures) normalized by the measured static pressure to angle of attack. Using PAV as the sensed static pressure yields errors of less than 4% in worst cases and thus it can be used as a reasonable measure of local static pressure.

The data reduction for flow angularity calibration began with Hatcher's misalignment program. It was found however, that for this application the program gave a reasonable initial guess of the misalignment angles, but the graphic resolution was insufficient to accurately determine these values. Spreadsheet software was used to fine tune these angles using a trial and

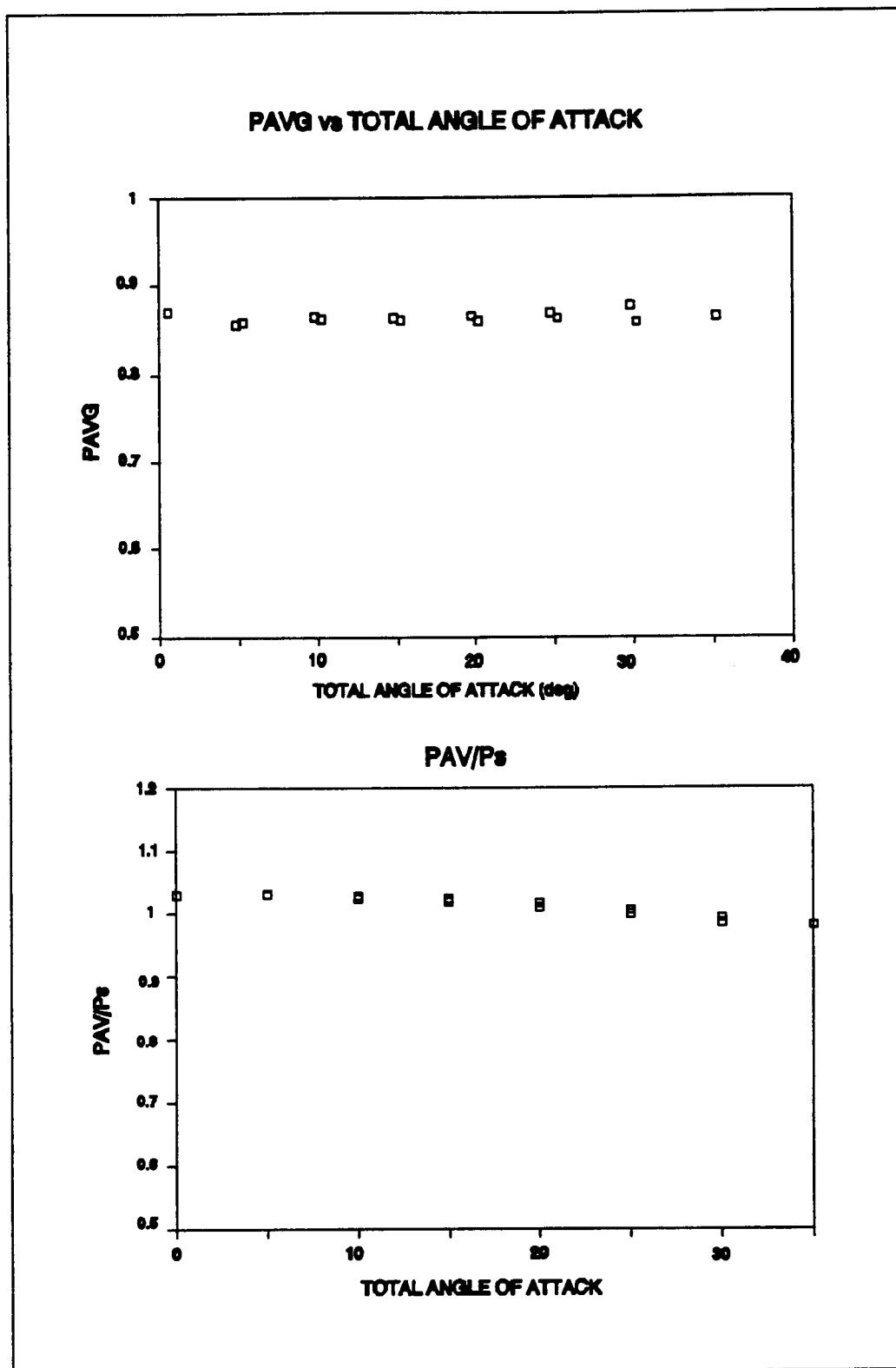


Fig 4.1 Comparison of PAVG vs α_t and PAV vs α_t . Probe #1, $M = 0.50$

error method - changing the misalignment angles one at a time and replotting DPSQP vs α_t . This step was necessary because Strike's angularity calibration program is very sensitive to the accuracy of these angles.

Once the misalignment angles were determined, the angularity calibration program yielded reasonable results. The calibration constants, sum of residuals and standard deviation of the errors are given in table 2. At first it appears that the curve fits are not very accurate, but again the number of calibration data points yielding the residuals must be considered. Also, it must be remembered that five hole cone probes are typically accurate to angles of attack of $\pm 27^\circ$ []. Due to the relatively large angles of attack expected when dealing with mass injection, the calibration was carried out up to $\alpha = \pm 35^\circ$ and therefore some minor disagreement was expected at the higher angles of attack. This is shown graphically in Fig 4.2 which plots the angularity parameter DPSQP vs α_t .

The overall calibration results were as expected and considered reasonable.

The time constant for the probes was determined to be approximately 0.8 seconds. A plot of the pressure sensed by the probe vs time is shown in Fig 4.3 compared with the time response of the Endevco dynamic transducer. The time response is the primary weakness of small cone probes, but in this experiment the lengths of the pressure transmission lines from the probe to the transducers were kept as short as physically possible, and the results seem quite good. It was noted that the

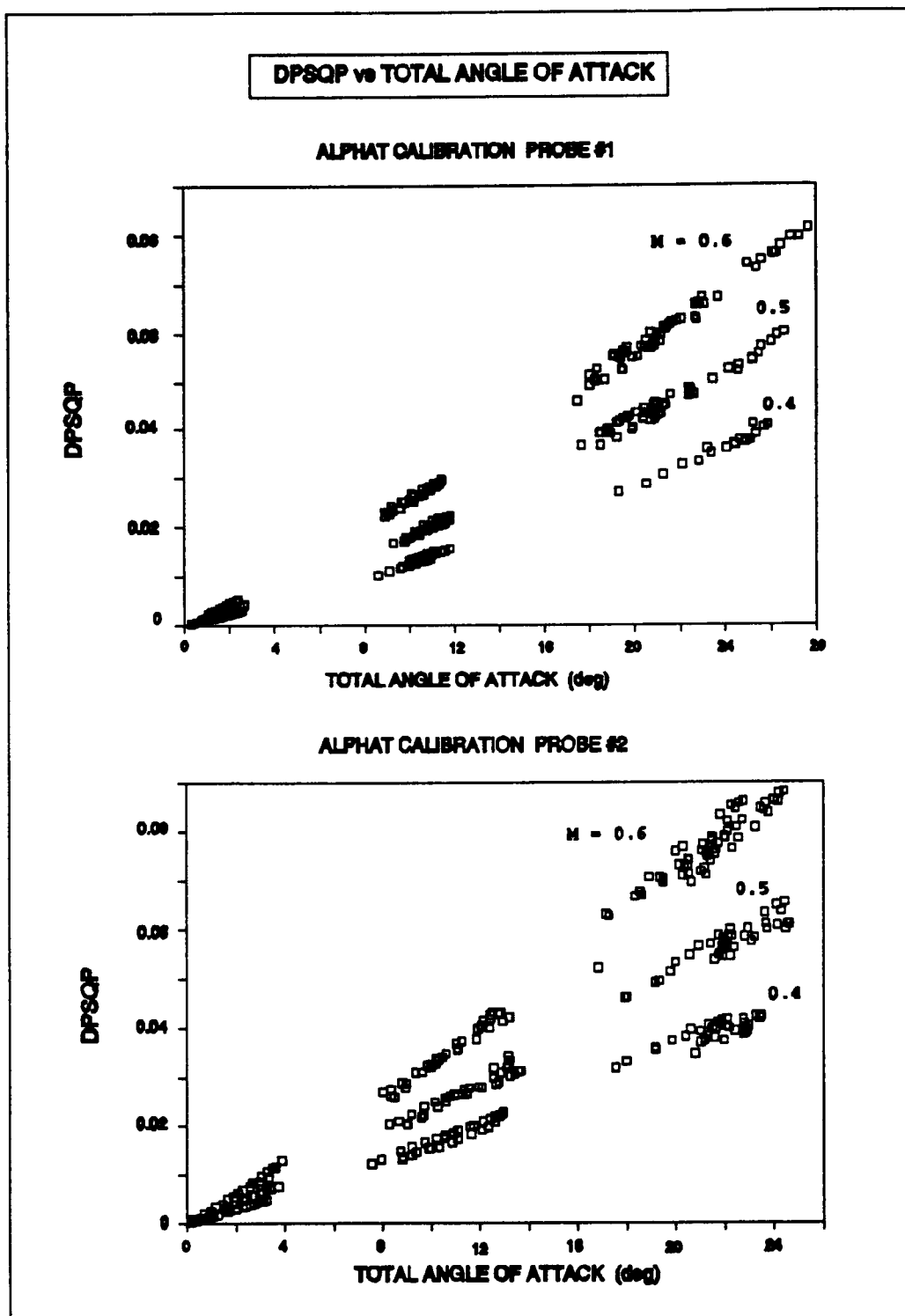


Fig 4.2 DPSQP vs α_t . (Number of data points reduced for clarity).

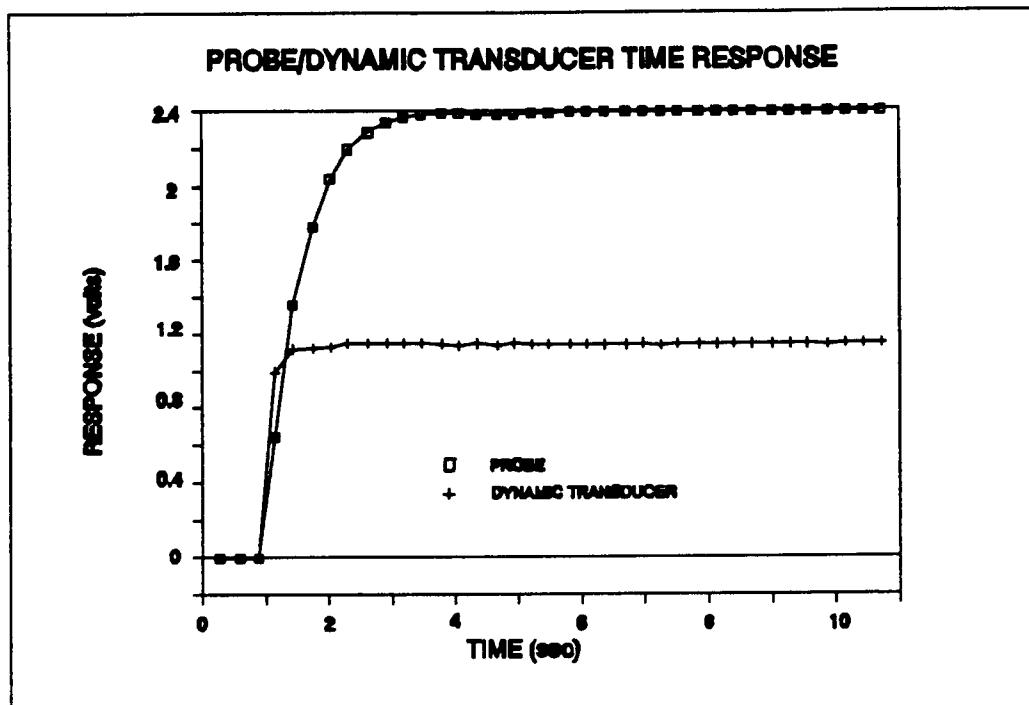


Fig 4.3 Probe and dynamic transducer time response

time response of the probes falls off rather dramatically as the length of the transmission lines is increased - even by just a few inches.

Cavity Flow Evaluation

Nominal Tunnel Flow Conditions

The results of the probe traverse at station 3a revealed a boundary layer thickness of approximately one inch, using $M/M_e = 0.99$. This was considered very large for this tunnel, but the tunnel was designed for supersonic operation and thus was being operated far from design conditions. The boundary layer profile is illustrated in Fig. 4.4. The results found previously during supersonic flow experiments was typically 0.25 inch

boundary layer thickness. It was believed that there may be a possibility of flow separation in the nozzle leading to a thickening of the boundary layer.

The results of the surface oil flow visualization indicated there were no flow separation regions external to the cavity in the absence of mass injection. Fig. 4.5. illustrates this as well as the reverse flow streaklines on the side and floor of the cavity.

Acoustic oscillation measurements of the cavity flow using the dynamic pressure transducer showed peak amplitudes at 350, 1130, 1420 and 1630 Hz. The largest magnitude was -31.0 dB at 350 Hz. as shown in Fig 4.6. This corresponds to approximately 0.05 psi and thus is very insignificant. The reason for this is

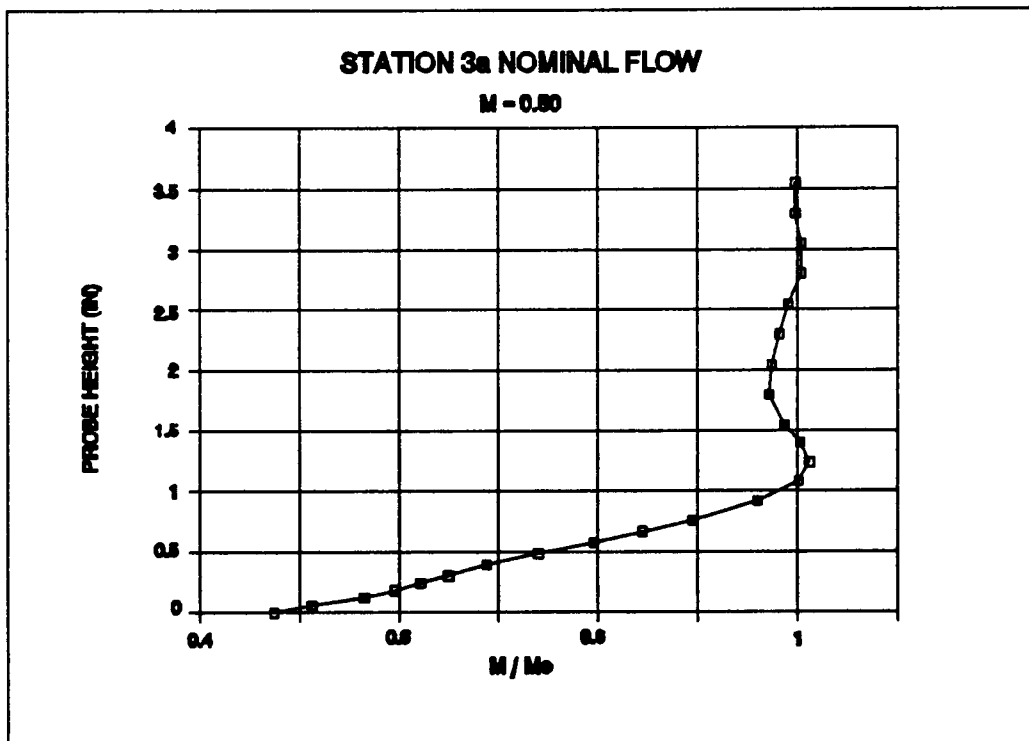


Fig 4.4 Boundary layer profile for nominal flow conditions

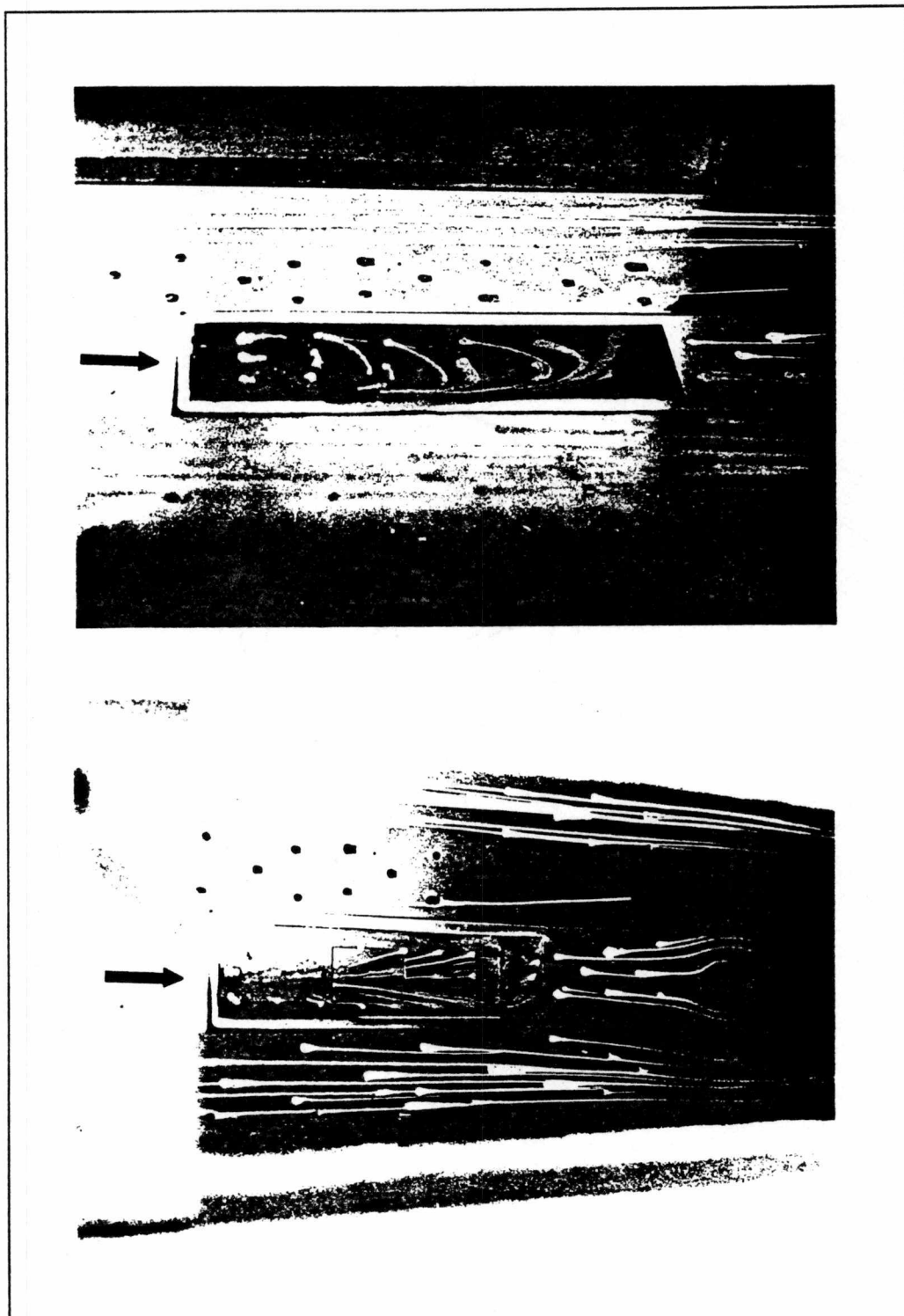


Fig 4.5 Flow visualization of cavity flow with no mass injection

that a shear layer with an inflection point is hydrodynamically unstable and develops Kelvin - Helmholtz instabilities downstream. The distance downstream that these instabilities occur depends on the initial thickness of the shear layer. The coupling between these instabilities and the natural acoustic frequencies of the cavity leads to resonance with peak amplitudes in the cavity. In the current study the shear layer was too thick to develop instabilities over the cavity and therefore no large acoustic oscillations existed. This observation appears to confirm the postulation of Vakili, Gauthier and Cooper that increasing the shear layer thickness over a cavity increases it's stability thus reducing the amplitude of the acoustic oscillations in the cavity.

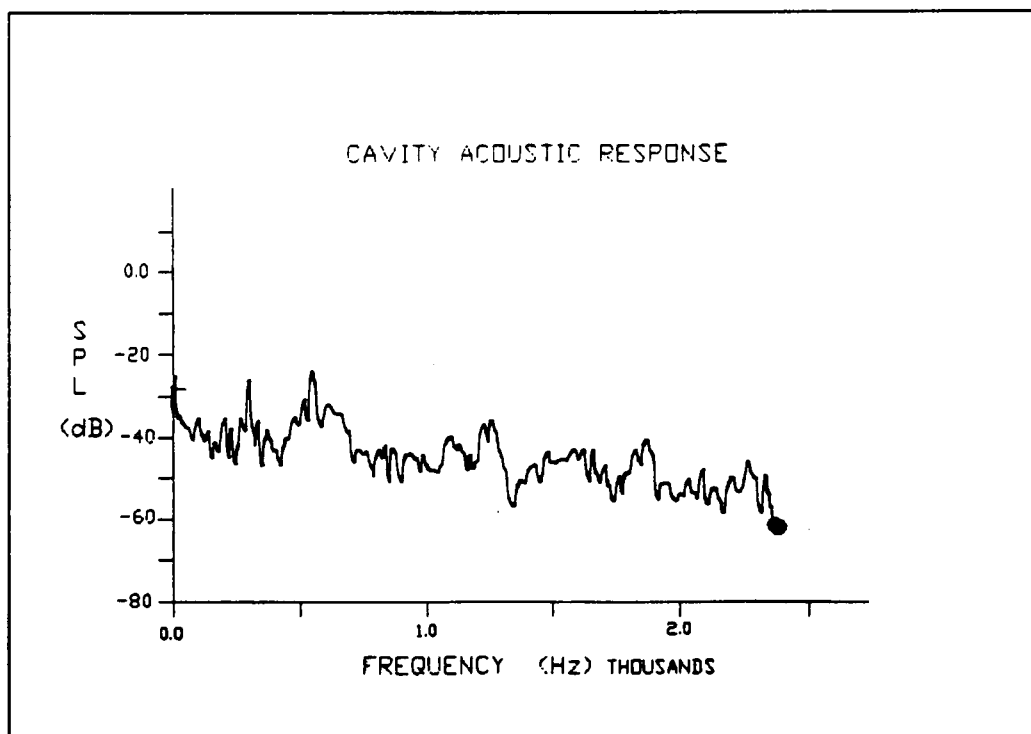


Fig 4.6 Cavity acoustic frequencies - no mass injection

Mass Injection Effects

The shear layer profile on the cavity centerline and the spanwise velocity vector plots for stations 2 and 3 (cavity leading and trailing edges respectively) are illustrated in Fig 4.7. The increase in shear layer thickness with mass injection is obvious from these figures. It can also be seen that there is a region of unsteady or reversed flow in the vicinity of the tunnel floor at both stations. The five hole cone probes can not provide any useful results when the free stream is not impacting the probe on it's nose, thus data gathered in these regions is meaningless.

It can also be seen that the existing edge vortices generated by the cavity are modified significantly by the injected mass, and the effects increase with mass injection flow rate. The shear layer thickness over the cavity in the absence of mass injection was too thick for any significant acoustic oscillations to occur and therefore acoustic suppression could not be studied in this experiment. It follows that acoustic measurements taken from the cavity indicated that the peak amplitudes and frequencies did not vary significantly through all the runs either with or without mass injection. The frequency plots for runs conducted with mass injection are shown in Fig 4.8.

One of the main reasons for carrying out this experimental work was to confirm the postulations of the researchers mentioned previously. In fact it was found that the static

STATION 2 POSN a (cavity, $\text{mdot} = 0.05$)

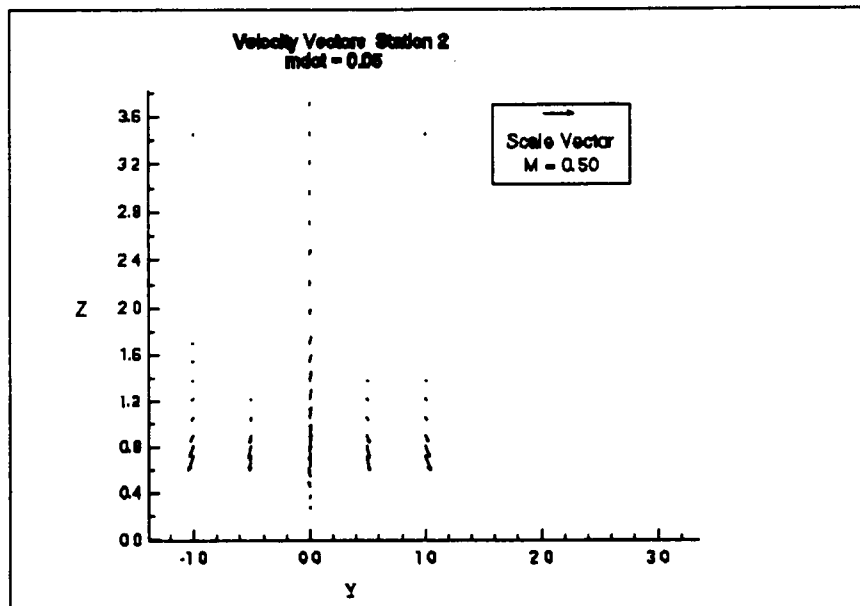
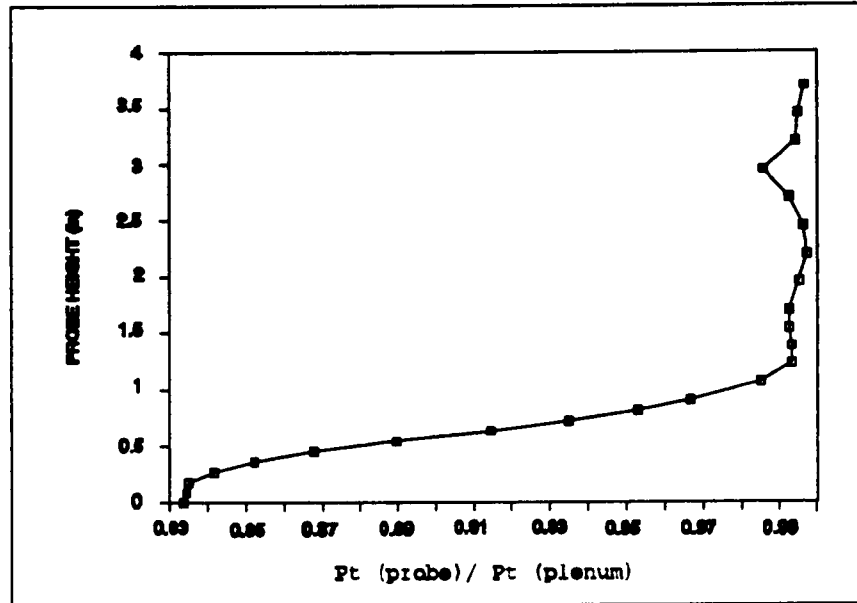


Fig 4.7 Shear layer profile and spanwise velocity vector map

STATION 2 POSN a (cavity, $\dot{m} = 0.10$)

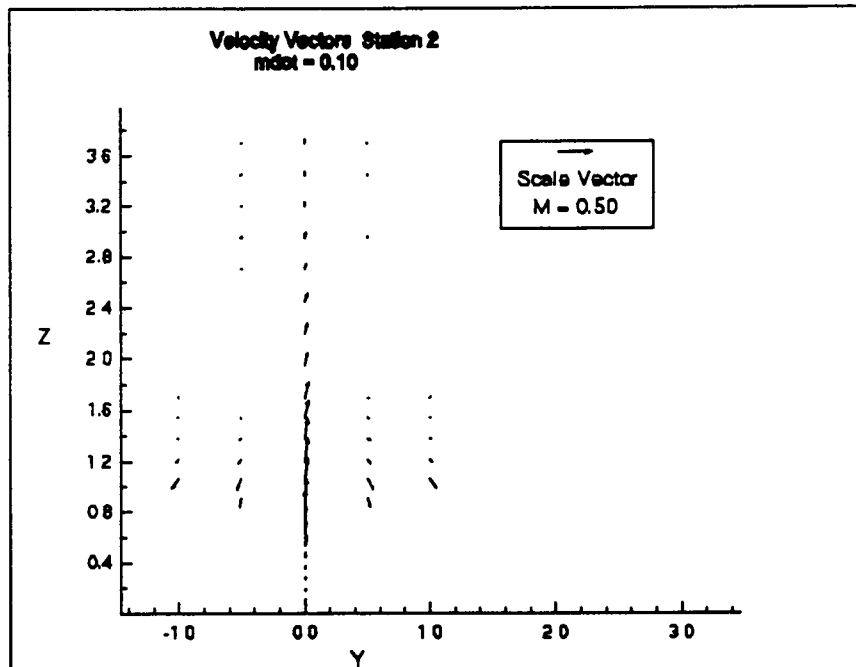
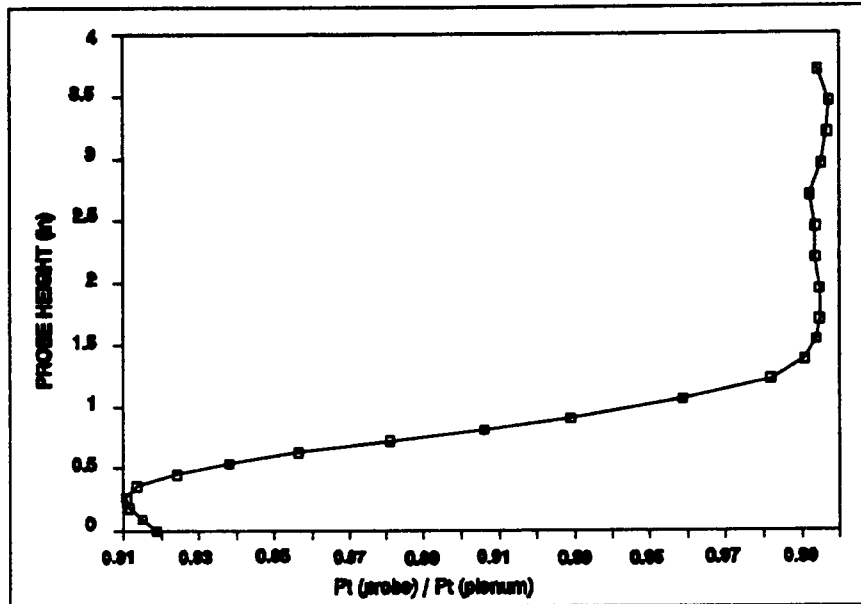


Fig 4.7 (cont) Shear layer profile and spanwise velocity vector plot

STATION 2 POSN a (cavity, $\dot{m}=0.15$)

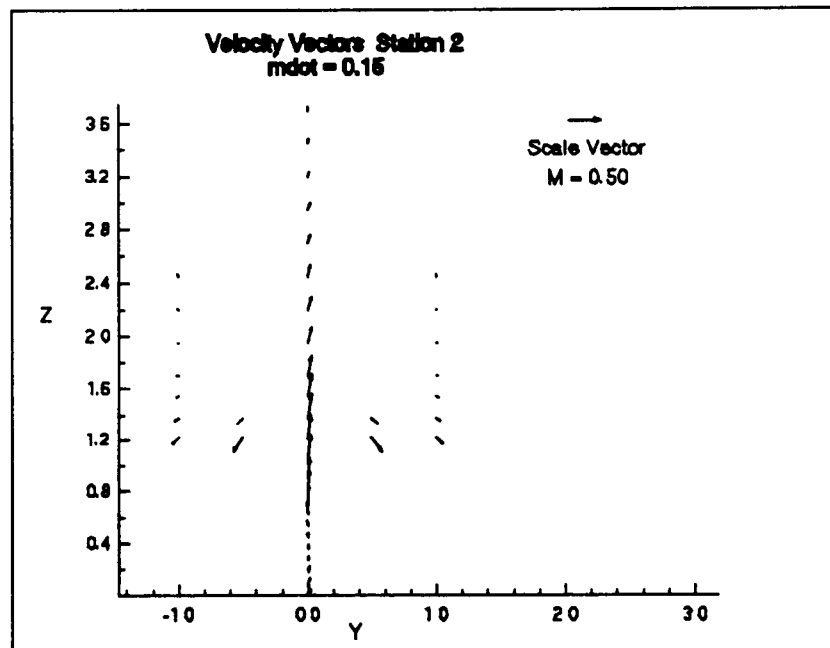
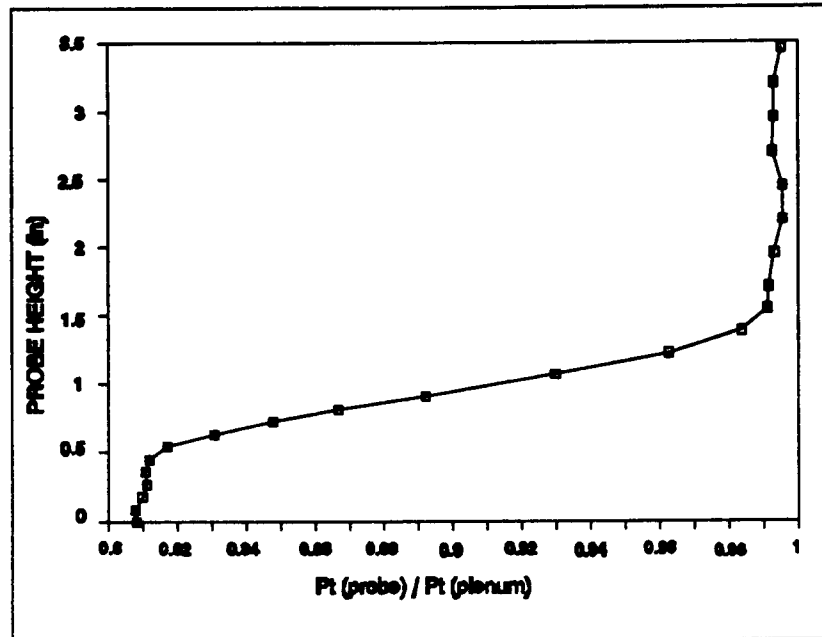


Fig 4.7 (cont) Shear layer profile and spanwise velocity vector map

STATION 3 POSN a (cavity, $\dot{m}=0.05$)

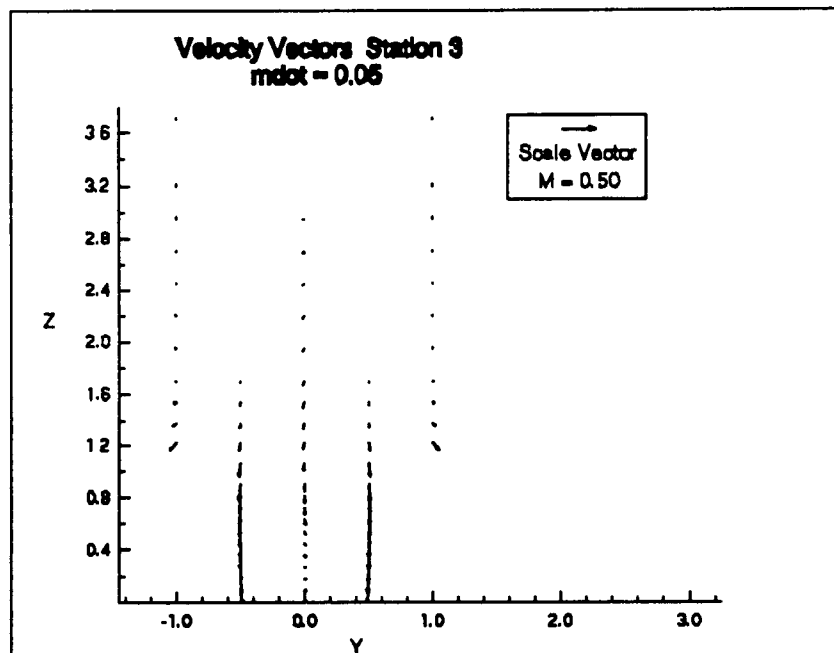
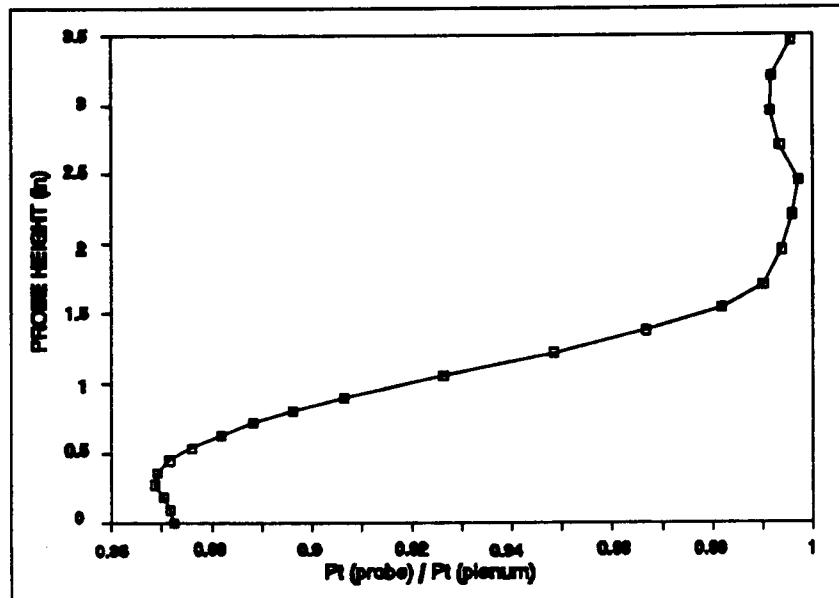


Fig 4.7 (cont) Shear layer profile and spanwise velocity vector map

STATION 3 POSN a (cavity, $\dot{m}=0.10$)

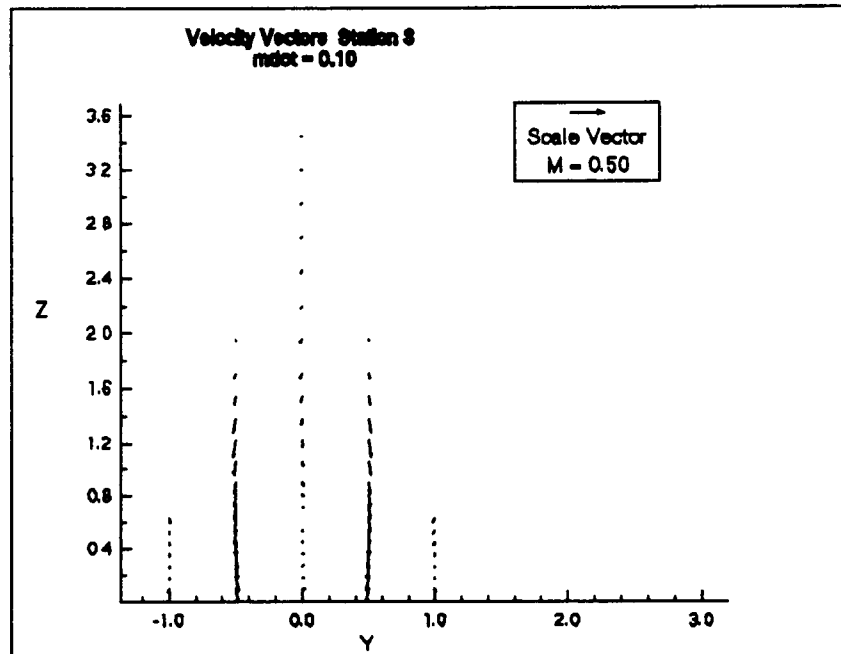
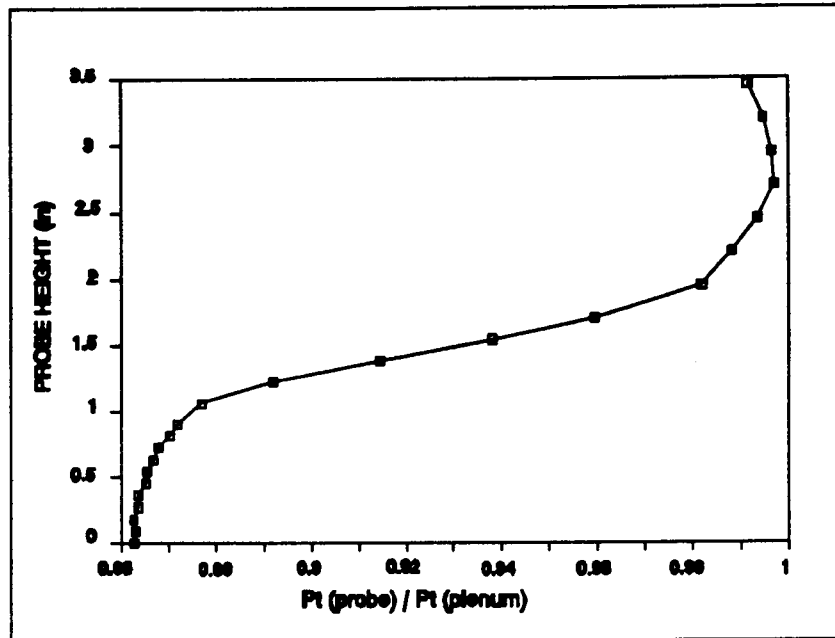


Fig 4.7 (cont) Shear layer profile and velocity vector map

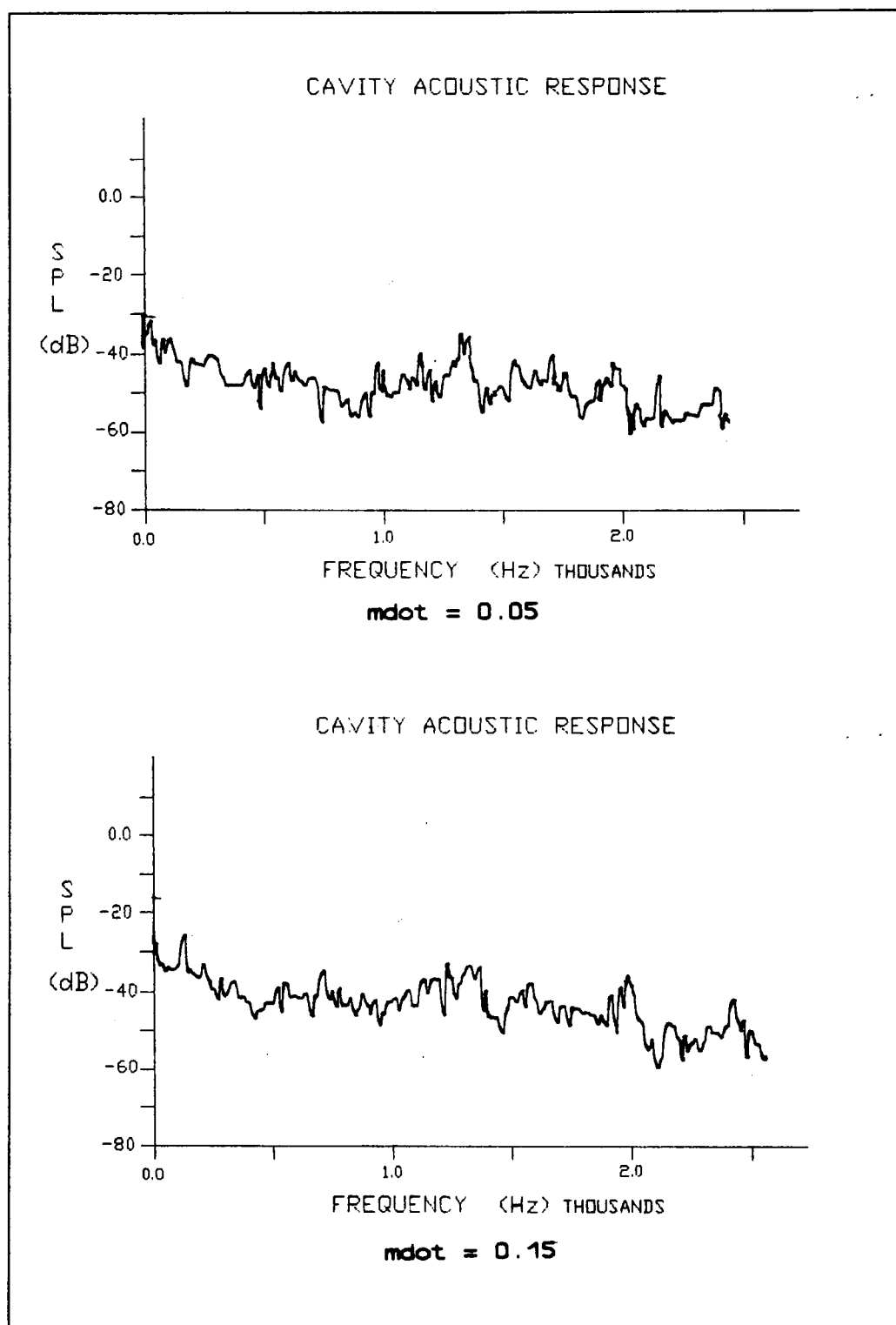


Fig 4.8 Cavity oscillation frequency plots.

pressure did vary though the shear layer as shown by the profiles illustrated in Fig 4.9 of the traverse profiles at the cavity leading edge. Vortical flow patterns were also observed, but a greater number of traverse locations would be required to gain a more comprehensive outline of these patterns.

It must be emphasized that in order to confirm these postulations the use of cone probes was required. The use of the cone probes resulted in substantial data reduction, but the effort has demonstrated the suitability and versatility of using these probes for research in this area, and has yielded more insight on the understanding of cavity flow phenomena.

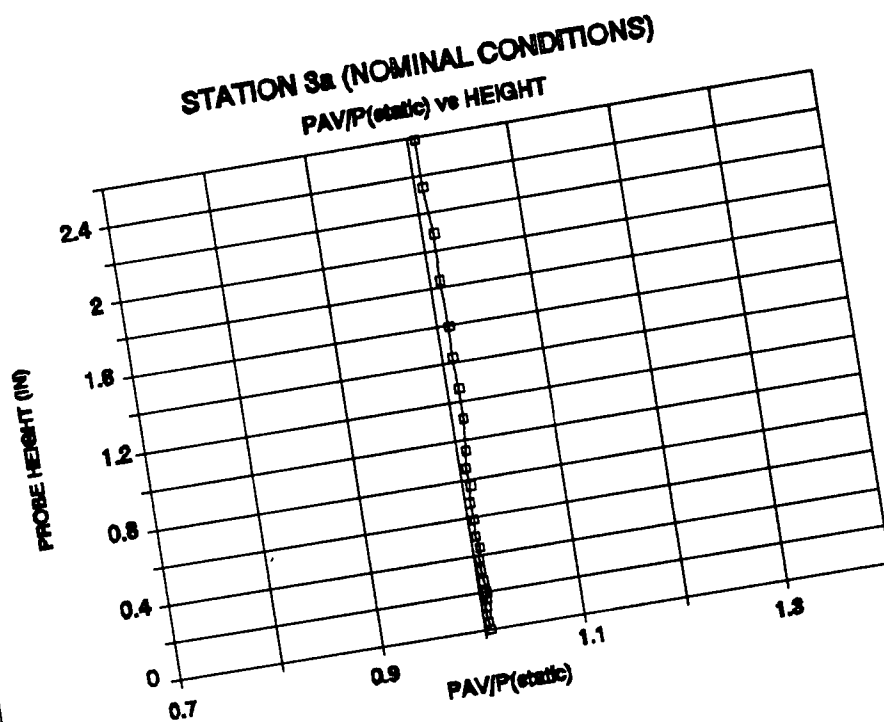


Fig 4.9 Sensed static pressure traverse profile

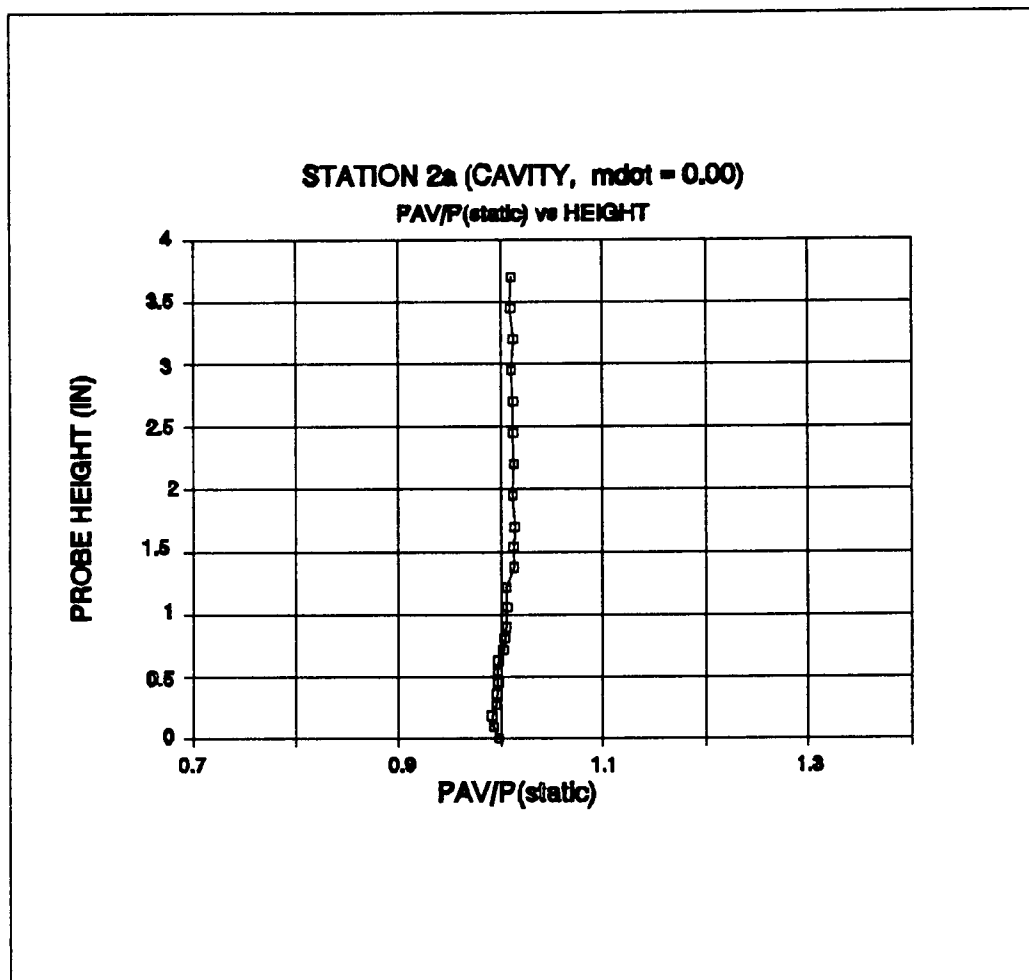


Fig 4.9 (cont) Static pressure traverse profiles

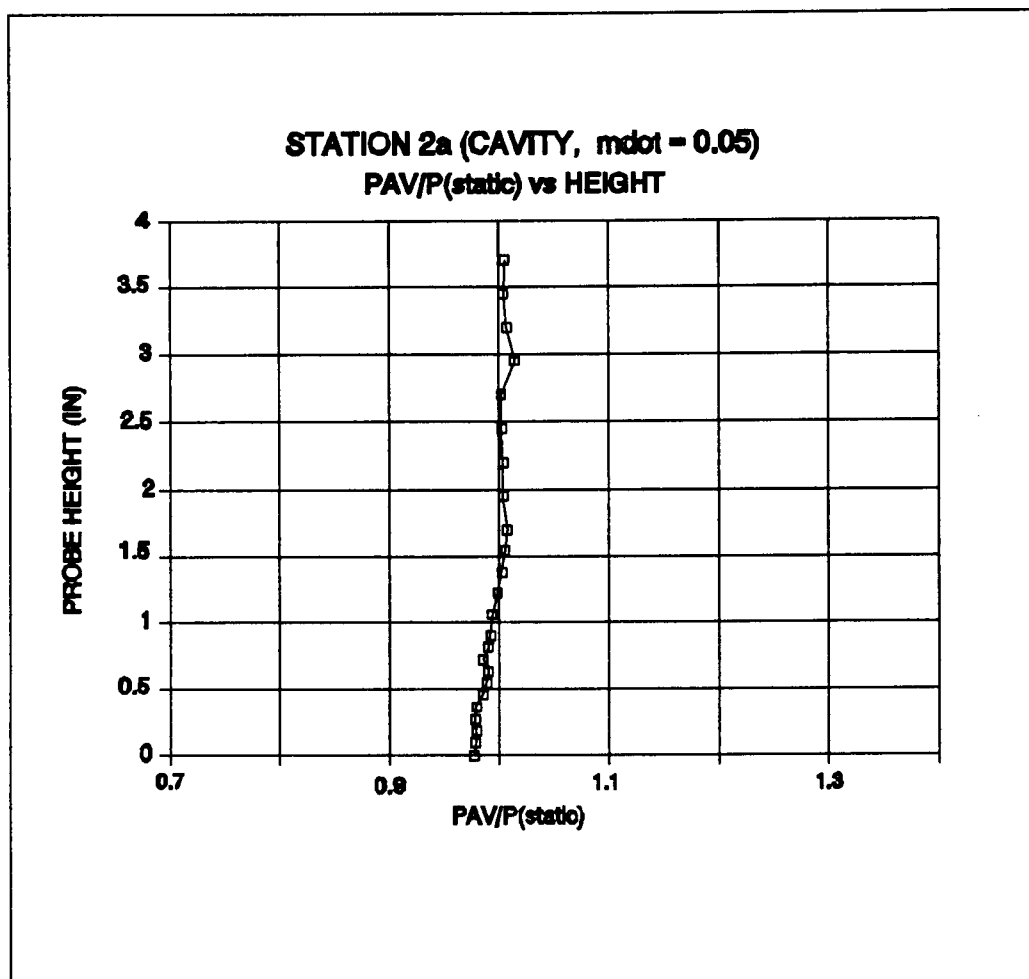


Fig 4.9 (cont) Static pressure traverse profile

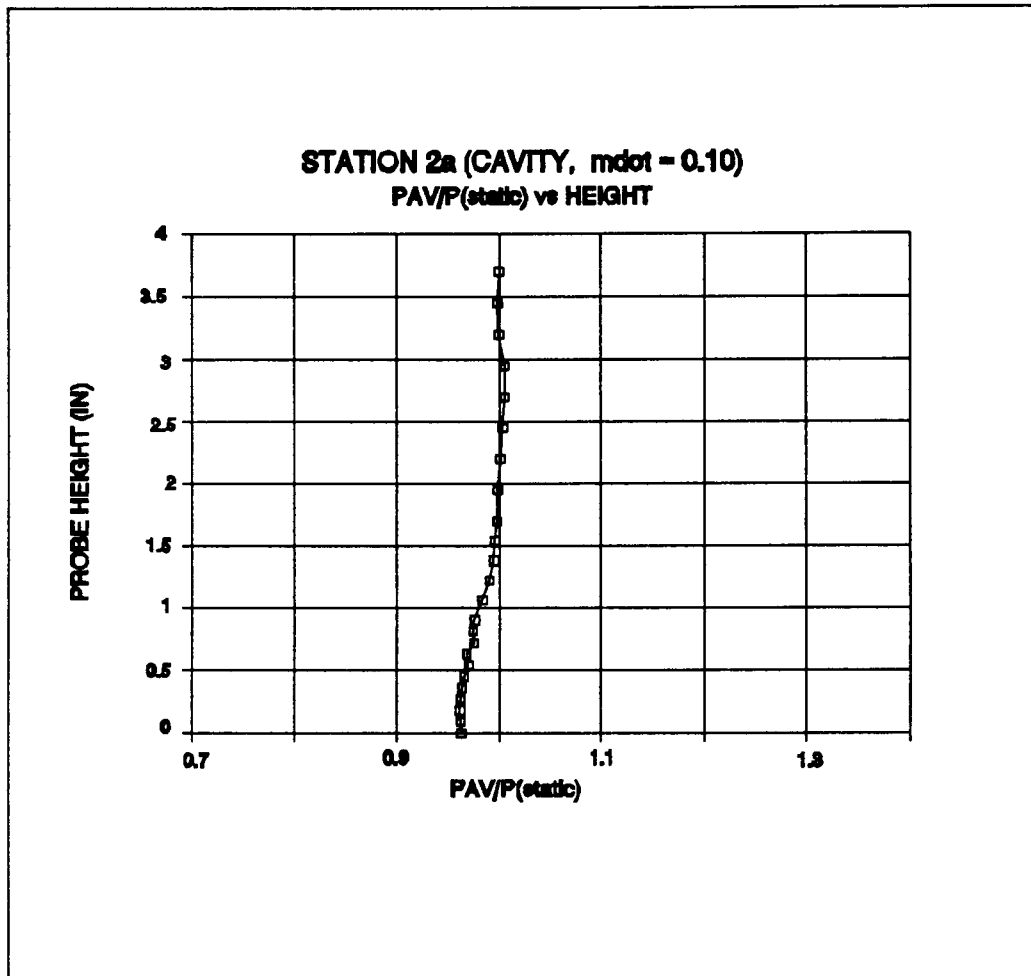


Fig 4.9 (cont) Static pressure traverse profile

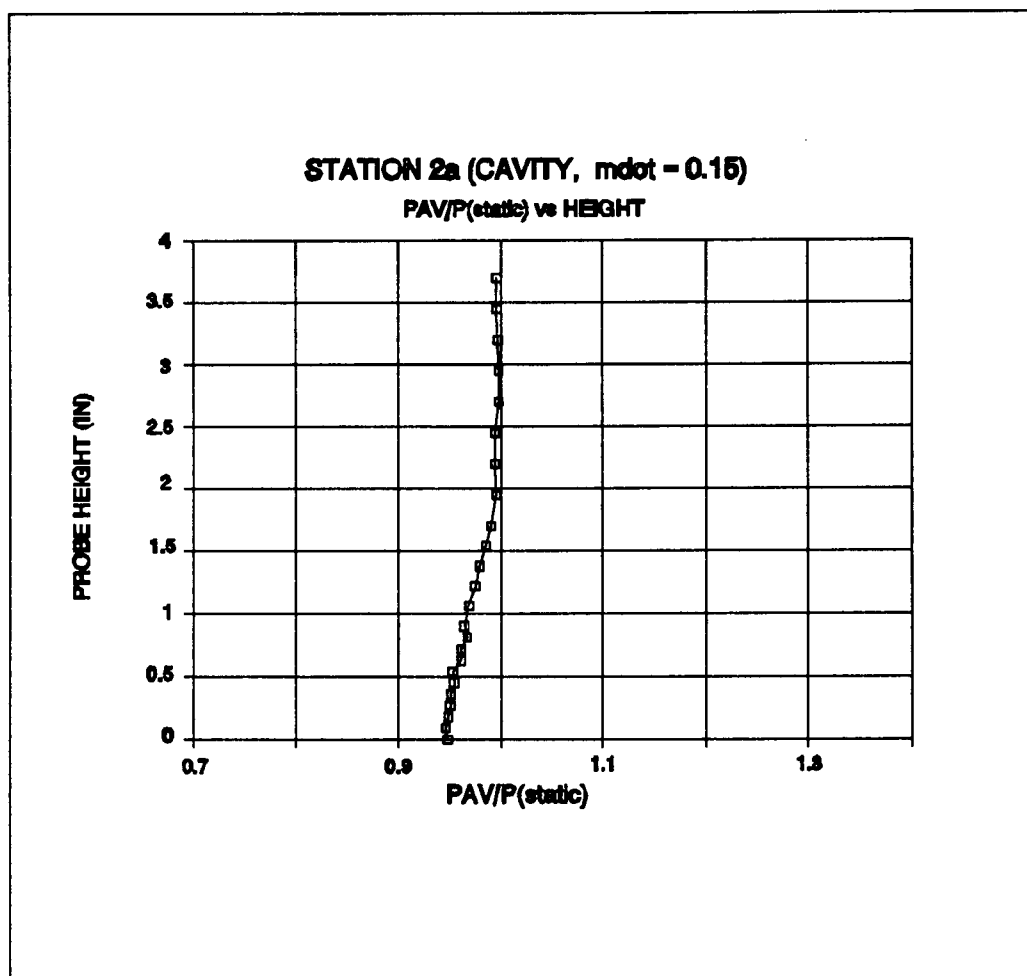


Fig 4.9 (cont) Static pressure traverse profile

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This experiment was carried out to measure the local flow parameters of shear layer total and static pressure profiles using traversing 5 hole cone probes and the acoustic oscillations excited in a cavity by the shear layer. From these measurements the following conclusions were drawn:

1. The tunnel off design operation conditions resulted in a very thick boundary layer, and therefore some of the aspects of the intended work could not be carried out.
2. The cavity acoustics observed with this thick boundary layer (one inch thick) supported the work previously carried out by Vakili, Gauthier, Schatt and Cooper.
3. Cone probe measurements indicated that the external flow is coupled to the cavity flow.
4. Due to the thickness of the shear layer over the cavity, mass injection did not alter the cavity acoustics significantly. This is consistent with Gauthier's results which indicated that there was a point above which further increases in mass injection rates did not cause any greater reduction in acoustic oscillation amplitudes.
5. The static pressure measurements indicated that with mass injection the static pressure traverse profiles were not constant.
6. It was observed from the local velocity vectors that the

flow exhibited vortical flow patterns over the cavity.

7. It is recommended that this experimental work be repeated at supersonic speeds such that the full scope of the intended work may be completed.

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APPENDIX

PROBE CALIBRATION CONSTANTS

TABLE 1.
MACH NUMBER CALIBRATION CONSTANTS

	PROBE #1	PROBE #2
C1	0.0000000	0.0000000
C2	-28.5977228	300.257927
C3	127.361703	-138.759796
C4	-206.676050	245.247197
C5	149.527565	-190.705186
C6	-40.6210398	55.1852622
C7	0.0000000	0.0000000
C8	43.4299540	48.1477756
C9	-49.2200800	-58.1333059
C10	0.0000000	0.0000000
C11	0.0000000	0.0000000
C12	0.0000000	0.0000000
C13	0.0000000	0.0000000
C14	-423.512944	-417.855628
C15	0.0000000	0.0000000
C16	0.0000000	0.0000000
C17	0.0000000	0.0000000
C18	0.0000000	0.0000000
C19	533.024684	876.719086
RMS DEVIATION	.37415E-02	.41235E-02

TABLE 2
ANGLE OF ATTACK CALIBRATION CONSTANTS

	PROBE #1	PROBE #2
A1	-6566.563	4023.2602
A2	26764.854	-10775.922
A3	-38168.546	6760.9196
A4	19772.450	1265.036
A5	6385.1674	3156.5066
A6	-8776.4458	-4347.0648
RMS DEVIATION	1.53768	2.15423

VITA

Edward Paul Lambert was born on 11 September 1956 in St. John's, Newfoundland. He graduated from high school in 1974 and enrolled in the Canadian Armed Forces. In August 1983 he was selected for the University Training Plan and enrolled in the Mechanical Engineering program at the University of Ottawa. Upon graduation he was commissioned as an Aerospace Engineering Officer.

He was subsequently employed as the Maintenance and Engineering Officer at CFB Goose Bay's Rescue Flight. While there he was selected for the Post Graduate Training Plan and enrolled in the University of Tennessee Space Institute's Aerospace Engineering program in August 1991. He graduated with a Masters of Science Degree in Aerospace Engineering in August 1993.