To the Graduate Counsel:

I am submitting herewith a thesis written by Paul A. Nagle entitled "An Experimental Investigation of Cavity Aeroacoustics and Control in Subsonic Flows." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Masters of Science, with a major in Mechanical Engineering.

Ahmad D. Vakili

Ahmad D. Vakili, Major Professor

We have read this thesis
and recommend its acceptance:

Roy J. Schulz

Frank G. Collins

Accepted for the Council:

C W Minkel

Associate Vice Chancellor
and Dean of The Graduate School

Statement of Permission to Use

In presenting the thesis in partial fulfillment of the requirements for a Master's degree at the University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Paul a Noyce

Date 4/28/95

An Experimental Investigation of Cavity Aeroacoustics and Control in Subsonic Flows.

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Paul A Nagle

May, 1995

Acknowledgements

My two year experience a the University of Tennessee Space Institute was both challenging and rewarding. I pray that the school will maintain the standards and values that it has demonstrated to the middle Tennessee area.

I would very much like to thank Dr. Ahmad Vakili for his encouragement and friendship. His patience with my short comings was extremely appreciated. Thanks go to my committee members Dr. Frank Collins and Dr. Roy Schultz for their insights and time. I would also like to thank the guys at the Lab. Jim Goodman and especially Ricky Mecker, who taught me the fine art of bondoing and was a whiz at making things work with what was available.

I would also like to thank my parents Rich and Rhoda Bath for their support. But most of all I would like to thank my God the Lord Jesus Christ and for his faithfulness to me. It was through his strength and wisdom that I was able to finish this seemingly overwhelming task. For, "Without him we can do nothing!."

Abstract

Mass injection upstream of a cavity was used to actively control the unsteady pressure oscillations inherent in a cavity at subsonic speeds. High amplitude pressure oscillations result when resonance (matching of frequencies) occurs between the shear layer's unsteady up and down movement and pressure disturbances that *feed back*, upstream, within the cavity. The measurements were performed in a blow down wind tunnel at nominal Mach numbers of 0.5 up to 0.8 and for unit Reynolds numbers between 3 and 7 million per foot. It was shown that mass injection significantly alters the upstream boundary layer and the shear layer over the cavity so that the feed back disturbances do not match with the unsteadiness of the shear layer. Once the two frequencies are shifted, the possibility of resonance interaction can not exist. Upstream mass injection has effectively eliminated the large amplitude oscillations, with acoustic levels which were measured as high as 167.5 dB, that normally exist when mass injection is not present. Sound reductions were as much as 16 dB and 17.3 dB at Mach numbers of 0.5 and 0.8 respectively. Cone probe measurements, over the cavity, have verified the existence of streamwise vortices that are possible contributing mechanisms for reducing pressure oscillations. Water table experiments have also been conducted, and show visually the effects of upstream mass injection on single and double cavity arrangements. This study is a continuation of a systematic study of the attenuation of aeroacoustic oscillations in flows over weapon bay cavities reported by Vakili et al.

Table of Contents

List of Figures

Nomenclature

A_{cavity}	Area of opening of cavity (L X W)
A_{inj}	Area of the total number of holes (Number of holes * $\pi/4$ *D^2)
$A_{pattern}$	Area that just inscribes all holes on mass injection plate
α	Angle of the cutting edge on the water table models
B	Blowing parameter $\frac{\rho_w v_w}{\rho_\infty U_\infty}$
$\mathbf{B}_c$	Cavity blowing parameter ($\mathbf{B}$ * (A_{inj}/A_{cavity}))
$\mathbf{B}_p$	Pattern blowing parameter ($\mathbf{B}$*(A_{inj}/A_{cavity}))
C_f	Coefficient of Friction
D	Depth of Cavity
δ	Boundary layer thickness
δ^*	Displacement thickness
f	Frequency Hz
γ	Ratio of specific heats
H	Shape factor (δ^*/θ)
K_v	Ratio of convected vortex velocity to free stream velocity (empirically equal to 0.57 for L/D = 4)
κ	Phase speed
L	Cavity length
M	Mach number
m	Mode number

μ	Dynamic viscosity
n	Acoustic wave emission delta constant (empirically equal to 0.25 for L/D = 4)
θ	Momentum thickness
p	Pressure
Re	Reynolds number ($Re=\rho U D/\mu$)
ρ	Density
S	Strouhal number (non-dimensional frequency= f*U/L)
T	Temperature
τ	Boundary layer shear stress
u	Local velocity in x-direction
U	Freestream velocity
v	Local velocity in y-direction
ω	Angular frequency of oscillation

<u>Subscripts</u>

e	freestream
o	initial value
w	at or near the wall
x	variable as function of x

Chapter I

Introduction

It has been shown by a number researchers that a high speed flow over a cavity creates extremely unstable conditions within the cavity. Any cavity located on an aerodynamic body that achieves resonance has sound emissions, which are extremely high-pitched tones that radiate outward from the cavity. These tones can be both annoying and detrimental. If a cavity has weapons and/or sensitive instruments within it, the resonance condition can lead to premature failure and/or possible component damage. Krishnamurty[1] was one of the first to investigate cavity flows. Using Schlieren pictures along with frequency and pressure intensity measurements Krishnamurty was able to verify the existence of high frequency sound radiation from the cavity. Krishnamurty also understood that the reaction of the shear layer with the cavity was the source of the oscillations even though he did not know exactly what mechanism was responsible. He determined that the production of the sound from the cavities was associated with the conversion of aerodynamic shear energy into acoustic energy.

Rossiter [2] was another early researcher of cavity flows who introduced the idea of a feed back mechanism between the acoustic radiation emitted and vortex shedding spanning the cavity. Rossiter was able to identify discrete vortical structures from photographs taken of shadowgraph images. The structures were shed at regular intervals from the cavity's leading edge and observed to grow as they convected down stream spanning the cavity. The passage of vortices over the cavity's rear lip was assumed to be responsible for the acoustic radiation expelled from the cavity. The acoustic radiation then travelled back up stream, within the cavity, and then would then initiate vortex shedding from the cavity's leading edge. As discussed by Tam and Block [3] this model was not entirely consistent with other researchers observations in other flow regimes which lead to the conclusion that Rossiter's model did not occur over the entire Mach number range. Rossiter was influential in pointing to a new direction in the understanding of cavity flows as an aero-acoustic feed back process. He also introduced the idea of cavity resonance between pressure oscillations occurring because of the feed back process and natural frequencies of the cavity. Rossiter also recognized that the characteristics of the boundary layer preceding the cavity were important in determining the magnitude of periodic pressure fluctuations.

Research by Heller and Bliss[4] helped to explain some of the observations of Rossiter. They said that interactions between the shear layer over the cavity and the cavity's trailing edge were responsible for the production of pressure oscillations within the cavity. Using water table visualization techniques, Heller and Bliss were able to observe a periodic mass addition and removal process that was attributed to an unsteady shear layer. Figure 1, taken from Heller and Bliss's paper, schematically describes the movement of the shear layer as it goes through one cycle of a mass addition and removal process. Observations indicate that the shear layer periodically moves up and

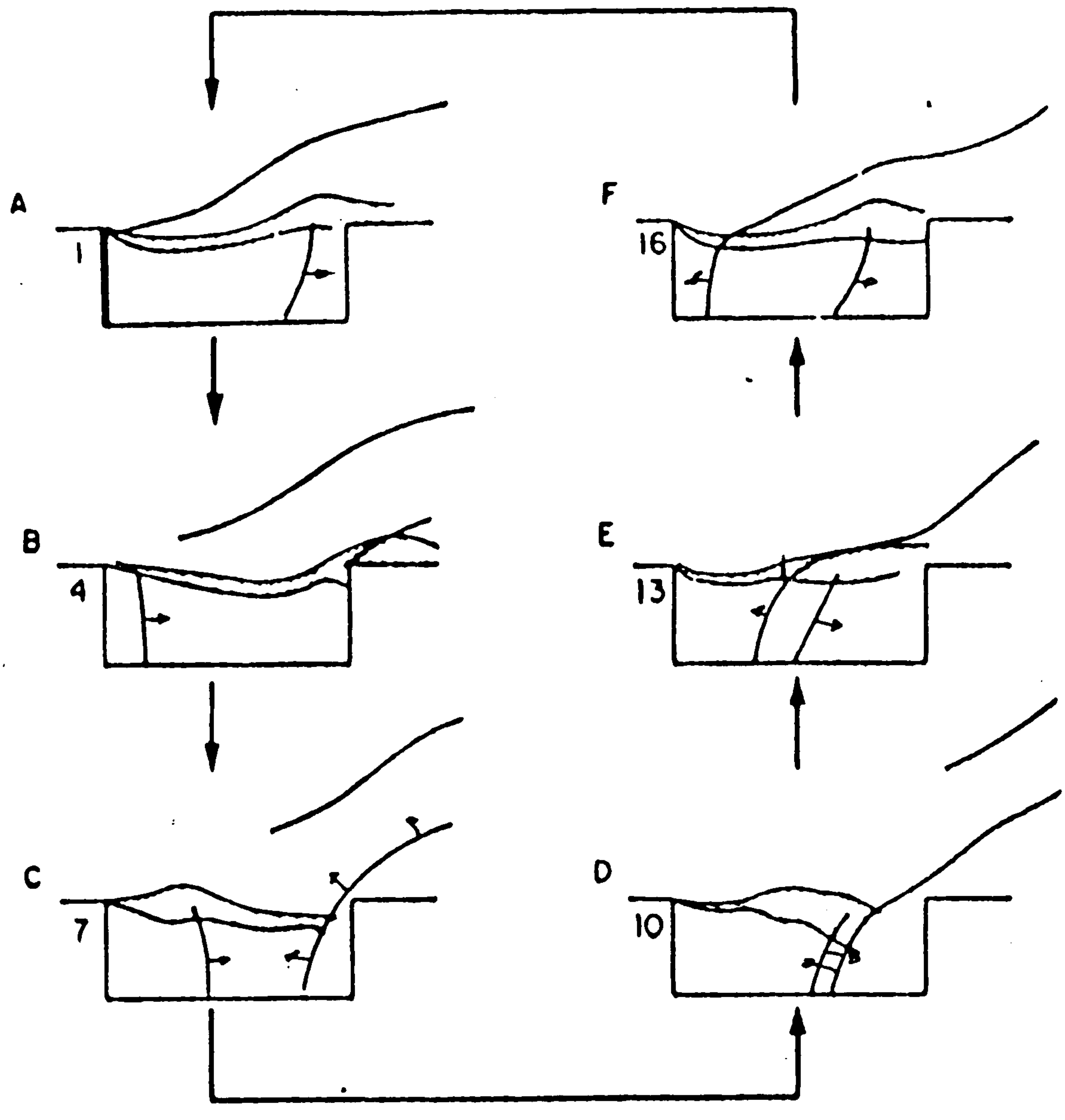


Figure 1: Typical oscillation cycle as described by Heller and Bliss [4] observed in water table studies.

down at the cavity's trailing edge. The unsteadiness of the shear layer lets high energy flow into the cavity when the shear layer is deflected downward (sequence B, C and D of the cycle). Lower energy flow is removed from the cavity when the shear layer is above the cavity's trailing edge (sequence E, F and A of the cycle). When mass is added into the cavity, a cavity wave structure is created (sequence B to C of the cycle). The cavity wave structure is strongly coupled with the oscillations of the shear layer and is what forces the shear layer to be unstable, and thus the concept of a feed back loop.

The above observation of the cavity oscillation mechanism was shown to be consistent with the observations of Rossiter at subsonic speeds. At subsonic speeds the shear layer over the cavity, which was subject to forcing by the cavity internal wave structure, would roll up into distinct vortices. Heller and Bliss concluded that vortex shedding was a "manifestation" of the oscillation process and not "essential" to the basic mechanism.

Heller and Bliss were aware that it was necessary to control the shear layer or the cavity wave structure to reduce cavity oscillations. Their ideas focused on using cowls, spoilers, vortex generators or alterations to the trailing edge geometry. They were able to reduce cavity oscillations but the location of the devices became critical for optimum reduction especially using a cowl.

Tam and Block[3] developed a mathematical model describing the displacement of the shear layer. In their work they were able to find an "amplifying (unstable) wave solution." This solution was based upon an approximation of the shear layer as negligible in thickness. Tam and Block agreed that this approximation was not very accurate and modified the model to take into account a finite shear layer thickness. They felt that to obtain accurate tone frequencies, an adequate estimation of the "dispersion relation" or phase speed was necessary. The initial model's phase speed κ was only a function of ω, the angular frequency of oscillation. To correct the model they substituted a relation for $\kappa=\kappa(\omega,\theta)$, that was derived for a shear layer of finite momentum thickness. The shear layer naturally increases in thickness in the down stream direction. To obtain "reasonable estimates of cavity tone frequencies", the shear layer was stated to have an average momentum thickness θ, over its entire length. Their revised mathematical model showed good agreement with the experimental results of Rossiter and other researchers.

From their work two, new, important parameters in describing cavity flow phenomena were introduced. The first is the ratio of the momentum thickness to cavity length θ/L. This ratio was used to determine what tone Strouhal number $S=fL/U$ would cause the most unsteady frequency of the shear layer over the cavity. The second is the ratio of the length of the cavity to its depth L/D. The L/D ratio becomes important in determining the cavity's own natural frequency. Because of the favorable agreement between the theoretical model and experiment results, Tam and Block felt that their model accounted for most of the important features associated with cavity flow phenomena.

The overall mechanism of cavity resonance may not be fully understood, but most of the essential characteristics that create the mechanism have been identified. In light of the previous research, controlling the unsteadiness of the shear layer has been understood as the means to reduce cavity pressure oscillations. Most researchers understand that altering the boundary layer, preceding the cavity, directly influences the shear layer over the cavity, and changes the shear layer's development and consequently its most unstable frequency. Distancing the shear layer's most unstable frequency from that of the natural frequency of the cavity typically insures that there is no chance of cavity resonance. Averting the occurrence of resonance strengthens the possibility of reducing cavity pressure oscillations.

The present study investigated the use of continuous, uniform, upstream mass injection as a way to control cavity aeroacoustics. The purpose of the work was to measure the shear layer's properties before and after mass injection, and to study the flow interactions over the cavity. Experiments for this work were performed at Mach numbers of 0.5, 0.7, and 0.8. Three different mass injection distributions were used with mass injection rates of 0.05, 0.10, 0.15 and 0.20 lbm/s. The effectiveness of mass injection to reduce cavity pressure oscillations and the associated acoustic noise was evaluated through the use of dynamic pressure measurements, Schlieren imaging and cone probe traversing measurements. Dynamic measurements and Schlieren imaging were performed to show the effect of mass injection on the shear layer spanning the cavity. Cone probe measurements were executed at specific locations over the cavity and velocities vectors perpendicular to the flow were mapped. A qualitative water table investigation on the effects of mass injection on a double cavity arrangement and trailing edge suction was also performed. Results indicate that upstream mass injection is an effective method to reduce cavity resonance.

Chapter II

Literature and Technical Review:

Much of the early work in cavity flows has been summarized in a paper written by Komerath, Ahuja and Chambers[5]. In the paper they discuss issues such as the length to depth ratio, drag, boundary layer characteristics, shear layer growth, Reynolds number and Mach number effects, feed back mechanisms and others. They state that there are some unresolved problems but for the most part there is sufficient understanding of the topic. They also discuss the many forms of aeroacoustic sound suppression techniques. Because of the content of Komerath et. al., this paper will not review all the past work but will focus on specific issues and highlights from various researchers. The interested reader is encouraged to review the paper by Komerath et. al. for some excellent insights into cavity flows.

Factors that influence shear layers:

Methods to reduce cavity resonance focus on changing the characteristics of the boundary layer preceding the cavity. The two dimensional boundary layer equation near the wall, as derived by Roshotko [6], is written as:

$$\mu_w \frac{\partial^2 u}{\partial y^2} = \left(\rho v_w - \frac{d\mu}{dT} \frac{\partial T}{\partial y} \right) \frac{\partial u}{\partial y} + \frac{dp}{dx} \tag{1}$$

the term ρ v_w is the effect of blowing. A change in any of the three terms on the right in equation (4) affects the second derivative of velocity and thus the characteristics of the boundary layer. Any alterations to the boundary layer are paralleled by changes in the shear layer. Rockwell and Naudascher[7] briefly mention some of the parameters that are physically significant in understanding cavity flows such as the Reynolds number, the ratio of the initial displacement thickness to the length of the cavity δ_o^*/L, the ratio of initial momentum thickness to the length θ_o/L, and the length to depth ratio L/D of the cavity.

One boundary layer characteristic that might play a major role in altering the unsteadiness of the shear layer is the momentum thickness. Tam and Block[3] have theoretically shown that the momentum thickness is a key parameter in determining the most unstable frequency of a shear layer. They were able to predict the correct change in the most unstable tone frequencies of a shear layer resulting from a change in θ/L. Vakili and Gauthier[8] have also commented that a substantial increase in the shear layer's initial momentum thickness could result in a reduction of the unsteadiness of the shear layer. They go on to say that the shear layer could possibly span the cavity, without impinging on the cavity's trailing edge, with a sufficient amount of upstream mass injection.

Schatt[9] has performed work at a Mach number of approximately 1.8 with a cavity L/D ratio of 2.54. He used a boundary layer code, which was based upon boundary layer thickness measurements, to generate velocity profiles, momentum thicknesses and other various boundary flow characteristics. Due to inaccuracies in the boundary layer thickness measurement, the results of the code were not as precise and as desired. His results, however, show a trend that with an increase in the θ/D, ratio an increase in the sound pressure level (ΔdB) occurred. This conclusion lends support to the notion that the boundary/shear layer initial momentum thickness θ_0, could be a fundamental parameter in controlling the shear layer and suppressing cavity oscillations.

If momentum thickness is fundamental to the goal of reducing pressure oscillations it then becomes necessary to understand what factors might influence the growth of the momentum thickness of the flow upstream of the cavity. Starting with the boundary layer equations we have:

Continuity as:

$$\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}=0 \tag{2}$$

x-Momentum as:

$$\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}=-\frac{dP}{dx}+\frac{\partial \tau}{\partial y} \tag{3}$$

and using the momentum integral relation method, White [10] has shown that

$$\frac{d\theta}{dx}=\frac{C_f}{2}+\frac{\rho_w V_w}{\rho_e U_e}-\frac{\theta}{U_e}\frac{dU_e}{dx}\left(2+H-M_e^2\right)-\frac{1}{\rho_e U_e^2}\frac{d}{dx}\left(p_e\delta-\int_0^{\delta}p\,dy\right). \tag{4}$$

Here θ is the momentum thickness, H is the shape factor, δ^*/θ and M_e is the freestream

Mach number. From equation (4) we see four terms that could affect the momentum thickness and thus the initial momentum thickness prior to the cavity's leading edge. C_f is the coefficient of friction, $\frac{\rho_w V_w}{\rho_\infty U_\infty}$ is called the blowing parameter **B** and the last two terms are pressure effects.

The coefficient of friction C_f is related to the Reynolds number based on the position x. Generally, boundary layers preceding a cavity are turbulent and therefore, $C_f \sim Re_x^{-1/7}$ or $Re_x^{-1/5}$ depending upon which power law equation best fits the data. Changes in the momentum thickness by changing the Reynolds number are small in turbulent boundary layers unless the Reynolds number change is quite large. It is important to note that Reynolds number effects could possibly become a significant influence in laminar flows because $C_f \approx Re_x^{-1/2}$. Decreasing the Reynolds number by a factor of 1/2, would increase $d\theta/dx$ by approximately 1.414, which is not insignificant. Partial verification of the above statements is contained in the report by Komerath et al.[5], who say that the general conclusion to Reynolds number effects by most researchers was that beyond the transition region, (laminar to turbulent) there was no significant influence of the Reynolds number.

An alternative method would be to change the blowing parameter **B** such as introducing mass upstream of the cavity. Mass injection can be organized into three different categories as described by Fernandez and Zukoski[11]. The first is weak mass injection and affects only the boundary layer's sublayer. The boundary layer is slightly thickened over a long distance and the external flow field is not substantially influenced.

The second category is massive mass injection. Massive mass injection significantly alters the external flow so as to lift the boundary layer and external flow up creating a mixing region between the external flow and the injected mass. The momentum of massive mass injection is sufficiently larger than the skin friction effects but less than free stream momentum. The third category is blow off mass injection. Here the momentum is much larger than both skin friction effects and the free stream's momentum. Mass injection efforts used by Vakili et al.[8][21] were in the category of massive mass injection. Vakili has shown that changing the parameter **B** can be enough to change $d\theta/dx$ adequately and thus influence the production of cavity pressure oscillations. The blowing parameter is usually assumed to be much greater than the coefficient of friction ($\mathbf{B} >> C_f$) and by excluding pressure effects equation (4) can be written as $d\theta/dx=\mathbf{B}$. Therefore if mass injection is uniform and continuous, the change in momentum thickness is constant and a simple linear equation can be developed.

Equation (4) also shows that pressure can play a significant role in altering the momentum thickness if there is a dramatic change of velocity in the x direction such as a change in area or some other effect like a shock that the flow must pass. An example of such an influence is the results obtained by Lambert[12]. Lambert's research involved the measurement and evaluation of the shear layer over a cavity at a free stream Mach number of 0.50. Lambert further investigated the influence of mass injection at mass injection rates of 0.05, 0.10, and 0.15 lbm/sec. Prior to mass injection the measured nominal boundary layer thickness δ, was approximately 1 inch. The relatively large thickness was attributed to the design of the tunnel's supersonic nozzle (an upstream area effect), plus the possibility of a shock wave still present in the nozzle. This pressure effect changed the nature of the momentum/boundary layer thickness upstream of the cavity, and influenced the cavity's aeroacoustics in the same way as mass injection. As a result of the already large shear layer momentum thickness, the observed magnitude of cavity oscillations with and without mass injection were very small. The insensitivity of the process to mass injection precludes gaining any understanding of mass addition on cavity aeroacoustics from this reported experiment. Recent, measurements at the same condition has produced a thinner shear layer with a corresponding sound pressure level of 156 dB. The result is approximately 15 dB higher than that reported by Lambert.

Passive suppression methods for control of the shear layer.

Although some applications of cavities are to produce unsteady flow and the acoustic noise associated with them, most research on cavity flows have dealt with trying to suppress the sometimes intense oscillations. Rossiter[2], Heller and Bliss[4], Buell[13], Carr[14], Marquardt [15], Wilcox[16], Franke and Carr [17], Stallings et. al[18] and Shaw[19] have attempted to reduce the oscillations through the use of passive techniques, that is through devices that are fixed and can not adapt to varying flow conditions. The methods were effective in reducing cavity oscillations but were highly dependent upon the location of the devices, cavity geometry and Mach number.

Rossiter[2] used small spoilers to change the boundary layer thickness upstream of the cavity's leading edge. Heller and Bliss[4] suggested the use of cowls, vortex generators or spoilers and/or changing the cavity's trailing edge geometry.

Franke and Carr[17] did extensive research on various cavity arrangements using both water table and air flow studies for cavities with L/D ratios of 2, 3.5 and 4.25. They were able to verify the previously observed phenomena of the up and down oscillation of the shear layer noted by both Heller and Bliss[4] and Tam and Block[3]. Their water table experiments were aimed towards screening the cavity configurations prior to air flow studies. A total of sixty cavity arrangements were evaluated for both single and double cavity configurations using porous vertical baffles, spoilers in the shape of airfoils, ramps and various trailing edge geometries. The effectiveness of many of the configurations were dependent upon the Mach number and cavity length and in some instances actually increased the cavity oscillations. The greatest suppression of cavity oscillations were the arrangements that were able to keep the shear layer out of the cavity. Marquardt[15] did similar tests for cavities with L/D ratios of 2 and 4.25 and confirmed much of Franke and Carr's work.

Stallings et al[18], and Wilcox[16] used passive venting techniques to help control cavity oscillations. The floor of cavities were equipped with different combinations of porous plate, slot vents, pipe vents and lip vent configurations. The idea was that the high dynamic pressures generated at the cavity's trailing wall would be redistributed through the porous plate or vents to the low pressure region upstream at the cavity's forward wall. This redistribution would create a more uniform flow within the cavity and attenuate the dynamic pressure oscillations .

Mass injection as active method for influencing the shear layer.

Since several of today's aircraft rely on stealth technology and many more will in the future, any type of passive, external, suppression devices can be a source of radar signature. This is especially true for attack aircraft that no longer store weapons on the outside. Any external suppression device will also add to the overall drag of the aircraft. Increase in aerodynamic drag may be as much as 250% of steady-state as reported by McGregor and White [20]. Passive suppression devices also limit aircraft to specific flight conditions for proper store separation characteristics. Forcing a combat air craft to meet required flight conditions reduces the aircraft's tactical advantage in the battle field and places the pilot and aircraft in undesirable positions. It becomes advantageous to eliminate resonance and reduce cavity oscillations with other than external, passive, suppression techniques so as to not invoke limitations on the aircraft or disrupt the effects of stealth capabilities.

Vakili et al [8], [21], [22], [23], Schatt [9] ,Taylor[24], Gauthier[25], Lambert[12], and Wolfe [26] have investigated continuous, uniform mass injection just upstream of a cavity to control shear layer unsteadiness. The injected mass changes the shear layer thickness causing it to be more stable and not as susceptible to forcing by the cavity. Their findings have shown a complete elimination of the acoustic oscillations within the cavity. Consistent reductions of up to 27dB were achieved through many experiments. Most of their work was done to show the effectiveness of mass injection and to find the most productive mass injection pattern.

Taylor's [24] efforts were of a qualitative nature. He used water table experiments that focused on reproducing the effects of cavity oscillation and to verify the effect of mass injection as a means to control the unsteady shear layer. The experiments looked at both pulsating mass injection and continuous mass injection upstream of the cavity. Pulsed mass injection was found to disrupt the cavity feed back process only for a time at which point the cavity oscillations actually intensified. Continuous mass injection was found to completely stop the cavity oscillations without returning to an unsteady condition.

Gauthier [25], Schatt[9], and Vakili, Cooper and Schatt [21] focused on extending the study started by Taylor into wind tunnel studies. Gauthier and Schatt did preliminary work with a cavity with L/D ratio of 2.54, at a nominal Mach number of 1.8. They verified that continuous upstream mass injection was able to thicken the cavity shear layer thus increasing its stability. They investigated both a high and low mass injection hole pattern density. The number of injection holes were the same but the injection areas that inscribe all the holes were different. The low density pattern was found to be much more effective at low rates of mass injection. Gauthier and Schatt also introduced two new blowing parameters which were **B** times the ratio of the total injection area (area of a hole multiplied the number of holes) to that of the cavity area, and total injection area to that of the area of the pattern of injection holes or

$\mathbf{B}_c = \frac{\rho_w u_w}{\rho_\infty U_\infty} (A_{inj}/A_{cavity})$ and $\mathbf{B}_p = \frac{\rho_w u_w}{\rho_\infty U_\infty} (A_{inj}/A_{pattern})$.

Vakili, Cooper, and Schatt[21] continued with the results of Gauthier and investigated the influence of various injection patterns with the same cavity and flow characteristics. They verified the results of Gauthier and Schatt that mass injection was able to stabilize the shear layer, and recorded sound pressure level reductions as much as 27 dB with a rectangular hole pattern for mass injection. An explanation of the possible role streamwise vortices may play in stabilizing the flow was developed, based on boundary layer surveys made at various locations around the cavity.

Lambert's[12] work was to conduct cone probe measurements over the cavity and verify explanations given by Vakili, Cooper and Schatt. As previously mentioned, premature thickening of the shear layer induced by pressure effects caused the results of the study to be only partially useful. Velocity vector plots verified the presence of streamwise vortices over the cavity. Cone probe measurements also indicated that the external flow is coupled to the cavity flow.

Research by Wolfe[26] continued with the investigation of cone probe measurements over a cavity at a nominal Mach number of 1.75 with a cavity L/D ratio of 4.33. The cone probe measurements suffered from mass injection effects on the static pressure measurement ports on the probe. Conclusions were that the boundary layer thickness was most affected at high mass injection flow rates. It was also determined that other parameters were of similar or more importance than that the of boundary layer thickness; these being the velocity profile, momentum thickness or other derived parameters.

This thesis is an extension of Lambert's work and a continuation of Wolfe's work. The blow down wind tunnel's supersonic nozzle at the University of Tennessee Space Institute Gas Dynamics Lab was redesigned for subsonic applications. Premature thickening of the boundary layer was not present, and corresponding boundary layer thicknesses δ, upstream of the cavity's leading edge were measured to have heights between 0.25 and 0.3 inches. The magnitude of cavity oscillations were as large as expected, and the effects of mass injection on cavity aeroacoustics were distinct. The purpose of this study was to measure shear layer's properties before and after mass injection, and to study the flow interaction over the cavity. The goal of the work was to :

1) show that mass injection is effective in controlling the shear layer.
2) identify possible mechanisms, resulting from mass injection, that may play a role in shear layer control.

Chapter III

Experimental Procedures:

Tests for this study were performed at the University of Tennessee Space Institute Gas Dynamics Laboratory and consisted of four parts. Part I measured the tunnel flow quality without a cavity installed in the wind tunnel. The measurements of part I consisted of tunnel dynamic pressure measurements, boundary layer measurements and tunnel floor static streamwise distribution measurements. Results from part I were used to evaluate the flow quality of the wind tunnel. Part I was not the focus of the study and therefore results from this section were not included in the experimental results or conclusion of this thesis. Part II measured the cavity baseline response without mass injection. Measurements involved cavity dynamic pressure measurements, tunnel floor static streamwise distribution measurements, and Schlieren pictures showing the boundary and shear layers. Part III measured cavity dynamic pressure responses with varying amounts of upstream mass injection. Measurements included cavity dynamic pressure, tunnel floor static pressure profiles and Schlieren pictures. Part IV measured boundary layer and shear layer thicknesses and mapped flow velocities at specific stations around the cavity with and without mass injection using a five hole cone probe measuring device.

Dynamic Pressure Measurements in the Wind Tunnel :

The research was conducted in a blow down wind tunnel at the University of Tennessee Space Institute Gas Dynamics Laboratories. The wind tunnel test section cross-section was 8 inches by 8 inches and had a total length of 48 inches. The tunnel was equipped with a subsonic nozzle and was able to provide Mach numbers up to 0.8. High pressure air was supplied from eighteen, 5000 psi tanks which are normally only pressurized to 3000 psi for safety reasons. Typical wind tunnel free stream Mach numbers were 0.5, 0.7 and 0.8, at tunnel unit Reynolds numbers between 3 to 7 million per foot. The tunnel's plenum total pressure ranged from 15 to 22 psia at a total temperature of 530 °R.

Figure 2 shows a schematic of the tunnel floor. The rectangular cavity was 6.5 inches long by 1.5 inch deep by 1.5 inch wide. This corresponded to a L/D ratio of 4.33 which is representative of a ratio close to real applications. The cavity and mass injection apparatus were integrated into the floor plate of the tunnel starting approximately 4 inches from the exit of the nozzle. Two dynamic pressure taps were located on the centerline of the cavity floor. Dynamic pressure transducers, associated with channels 0 and 1, were 5.34 inches and 1.81 inches, respectively, downstream from the cavity's leading edge. The dynamic pressure transducers had millivolt measuring accuracies of $\pm 1\%$. A static pressure tap was located on the cavity floor between the two dynamic pressure transducers and also on the cavity's centerline. The static pressure tap on the floor of the cavity could be removed to make cone probe measurements using a vertically traversing probe. Twenty nine tunnel floor static

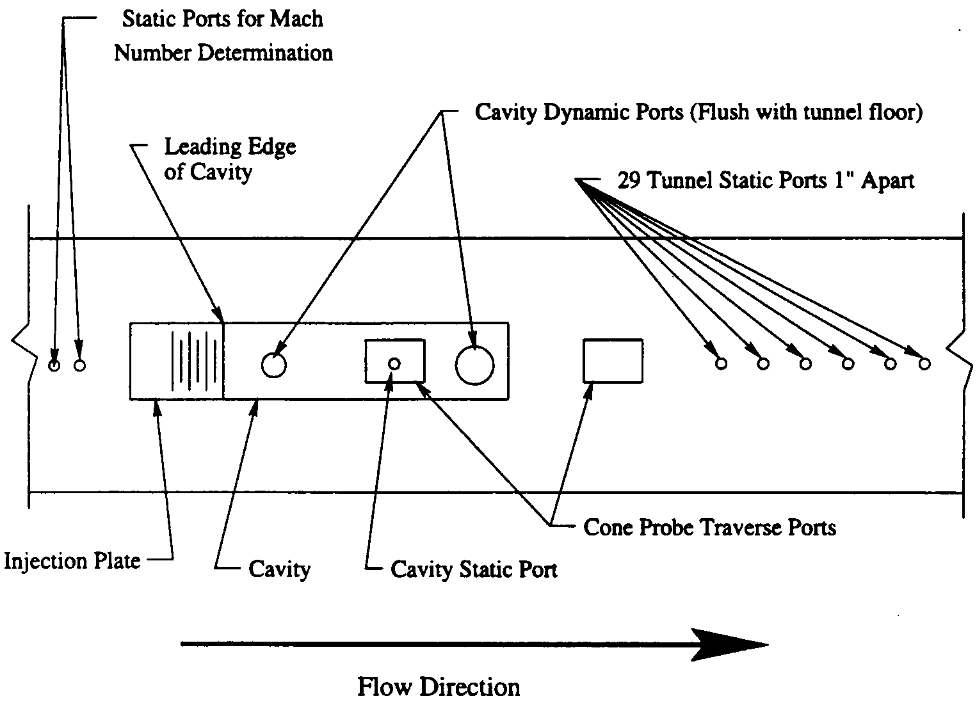


Figure 2: Schematic of the tunnel floor showing the relative placement of the cavity, mass injection, dynamic transducers, cone probe ports, and various other static pressure ports.

pressure ports were located approximately 6 inches downstream from the cavity's trailing edge and were separated from each other by 1 inch to measure tunnel flow uniformity. Two other static pressure ports were located just downstream of the nozzle's throat and were used in conjunction with the total pressure measurement from the plenum of the tunnel to determine the tunnel Mach number.

Different mass injection distributions were provided through three perforated plates as shown in figure 3. Plate 2 had 175, 0.0625 inch diameter holes. Every other hole on plate 2 was plugged for a total of 90 open holes and a corresponding injection area A_{inj}, of 0.276 in^2. The injection pattern for plate 2 had dimensions of 1.75 inches wide and 1.88 inches long, for an injection pattern area $A_{pattern}$, of 3.29 in^2. Plate 4 had 165, 0.03125 inch diameter holes with $A_{inj} = 0.127$ in^2. The injection pattern for plate 4 had dimensions of 1.69 inches wide by 1.88 inches with $A_{pattern} = 3.18$ in^2. Plate 9 had 190, 0.03125 inch diameter holes with an injection area of 0.146 in^2. The injection pattern for plate 9 consisted of three streamwise rows of holes. The two out side rows had pattern dimensions of 0.25 inches wide by 1.88 inches long. The center row had dimensions of 0.44 inches wide by 1.88 inches long. The total injection pattern area for plate 9 was $A_{pattern} = 1.77$ in^2. All injection plates were located with their trailing edges 0.19 inches upstream of the cavity. The injected mass flow was provided by a 1 inch diameter pipe supplied by a 600 psi air tank. The 1 inch diameter supply line was connected to a small plenum just below the injection plates to ensure injected mass uniformity over the injection area. The injected mass flow was measured using an orifice meter in the 1 inch diameter supply line. The injection plenum total pressure and

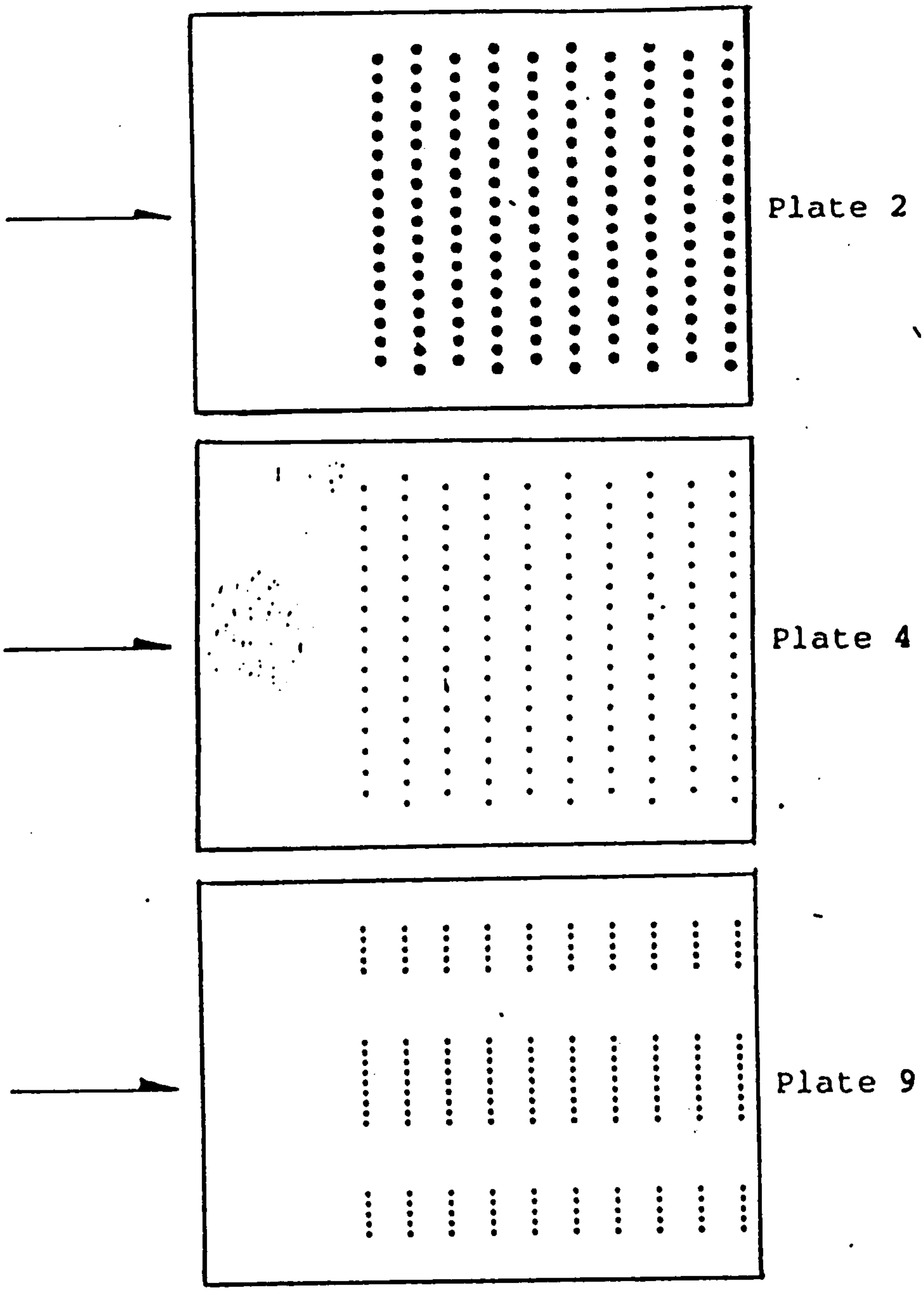


Figure 3: Sketches of mass injection pattern used in study.

tunnel static pressure were used to determine when the holes, through which the injected mass passed, were choked. The choked condition assured that mass injection was uniform. Using isentropic relations a pressure ratio (P_t/P_s) of 1.893 or greater insured uniform mass injection.

Figure 4 shows a schematic layout of the entire experimental setup. The cavity flow oscillations were measured using two Endevco® subminiature piezoresistive dynamic pressure transducers models 8514-10 and 8510-c-15 connected to Validyne SG71 amplifiers. The Endevco® subminiature piezoresistive pressure transducer were connected to a model HP3582a frequency spectrum analyzer and a software package called Labview® on an IBM 486 personal computer. Both devices were used for the purpose of data reduction to provide amplitudes and frequencies of cavity pressure oscillations. Each dynamic measurement collected and averaged 16 sets of 1024 data points. The sample rate was approximately 10,000 points per second. Sound pressure levels measured were accurate to to ±2 dBv, which is defined as:

$$dBv=20\times Log\left(\frac{Volt}{Volt_{ref}}\right) \tag{5}$$

where $volt_{ref}=1$ volt. The dynamic transducer associated with channel 0 was also connected to a Northgate 386 IBM compatible personal computer via an analog to digital converter. The 29 static pressures along the tunnel floor were measured using a 48 channel SCANIVALVE incorporating its own PDCR24 internal pressure transducer. All other time averaged static and total pressures were measured using dedicated Validyne DP15 transducers and Validyne CD19 amplifiers. All time

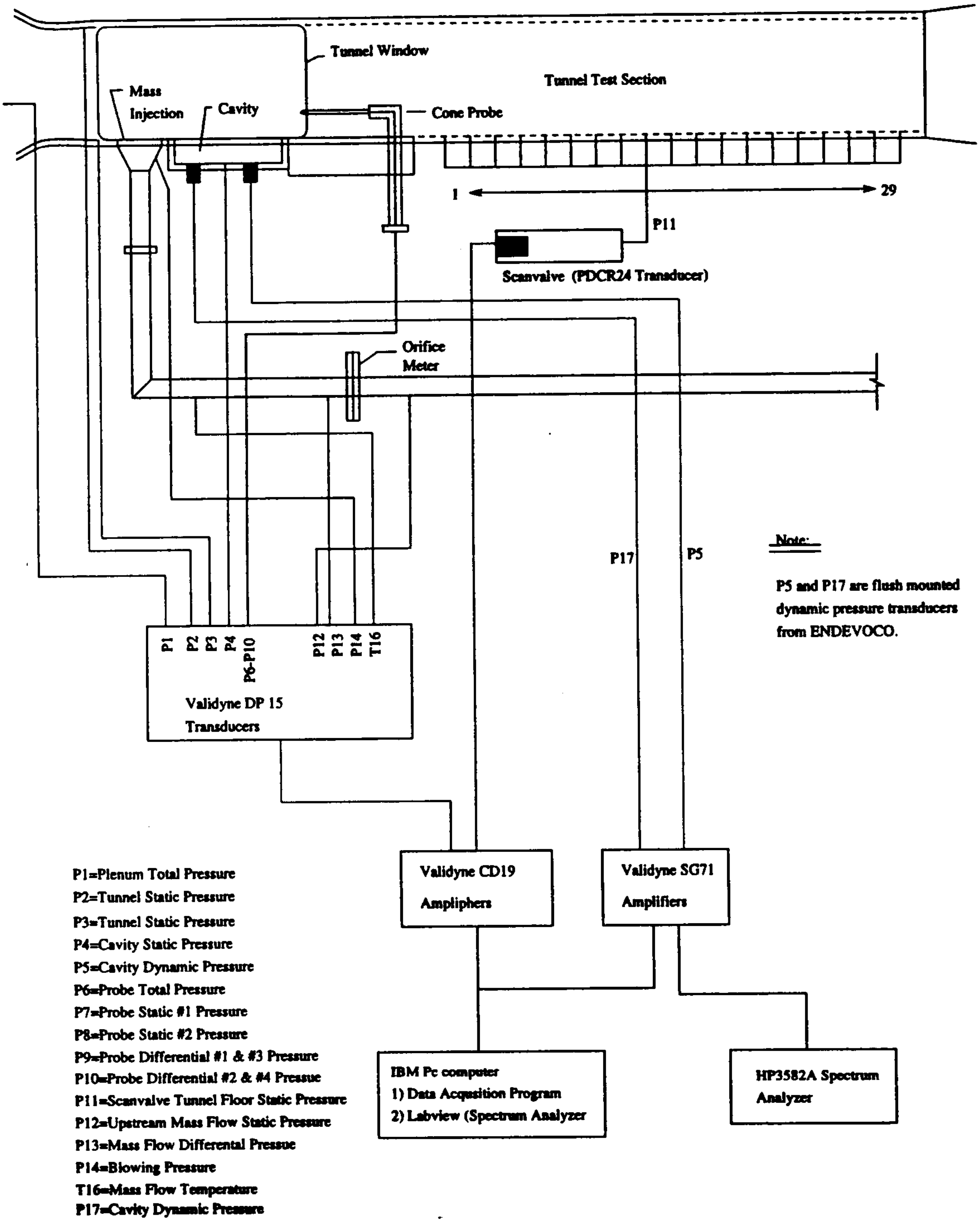


Figure 4: Schematic of experimental setup.

averaged measurements were connected through an analog to digital converter to a Northgate 386 IBM compatible personal computer.

A schlieren video system provided flow visualization of the tunnel flow, the injected flow, the boundary flow, and the shear layer above the cavity. The optical window did not extend deep enough into the cavity to obtain visual details of the flow inside the cavity. Visual observations from the Schlieren photographs showed the effects of mass injection and the increase of shear layer thickness over the cavity.

Testing for parts I, II and III as discussed in the introductory paragraph of this chapter, began by zeroing, as much as possible, the pressure output voltages by adjusting the amplifier's internal variable resistor. The schlieren system was also adjusted at this time, as necessary. A computer program on the Northgate 386 P.C. then took the zeroed values and used them as offset values. The program then returned to a standby window which allowed an operator to view the tunnel's plenum pressure, Mach number and mass injection rate. The standby window allowed the operator to run several data collection procedures once the tunnel was at the test conditions. The operator would control the tunnel's plenum total pressure until the appropriate Mach number was achieved and they would also adjust the mass injection to the desired rate. The operator would then select the appropriate data collection option. When dynamic measurements were taken the spectrum analyzer and Labview® software had to be started by another operator from a cue by the first operator.

Cone Probe Measurements in the Wind Tunnel:

Cone probe measurements were accomplished in Part IV of the testing sequence. All features of part IV were the same as those for Parts I, II, and II except that dynamic pressure measurements were not performed because of the interferences between the probe traversing support and the cavity's wave structure. Also, no Schlieren photography was taken. Figure 5 shows the six locations above the cavity that vertical traverse cone probe measurements were performed. A five hole cone probe was used with Validyne DP15 transducers and CD19 amplifiers for each of the five pressure measurements. The cone probe had a 15° half angle and 5 pressure ports of 0.008 inches in diameter. The probe's movement was controlled by the computer program previously mentioned using the probe measurement option. All aspects of the measuring sequence were the same as discussed in the previous section.

Probe measurements were performed at Mach numbers of 0.5 and 0.7 for mass injection rates of 0.05, 0.10 and 0.15 lbm/sec through mass injection plates 2 and 4. Measurements at Mach 0.8 were not possible because of the probe blockage restricting the flow through the tunnel and the transonic effects taking place.

Water Table Experiments:

Figure 6 is a schematic diagram of the water table used to study qualitatively the effects of mass injection on a double cavity arrangement. Investigations into trailing edge suction were also performed. The difference in settling tank height to flow height were from 0.875 inches to 1.375 inches. Corresponding Froude numbers ranged from

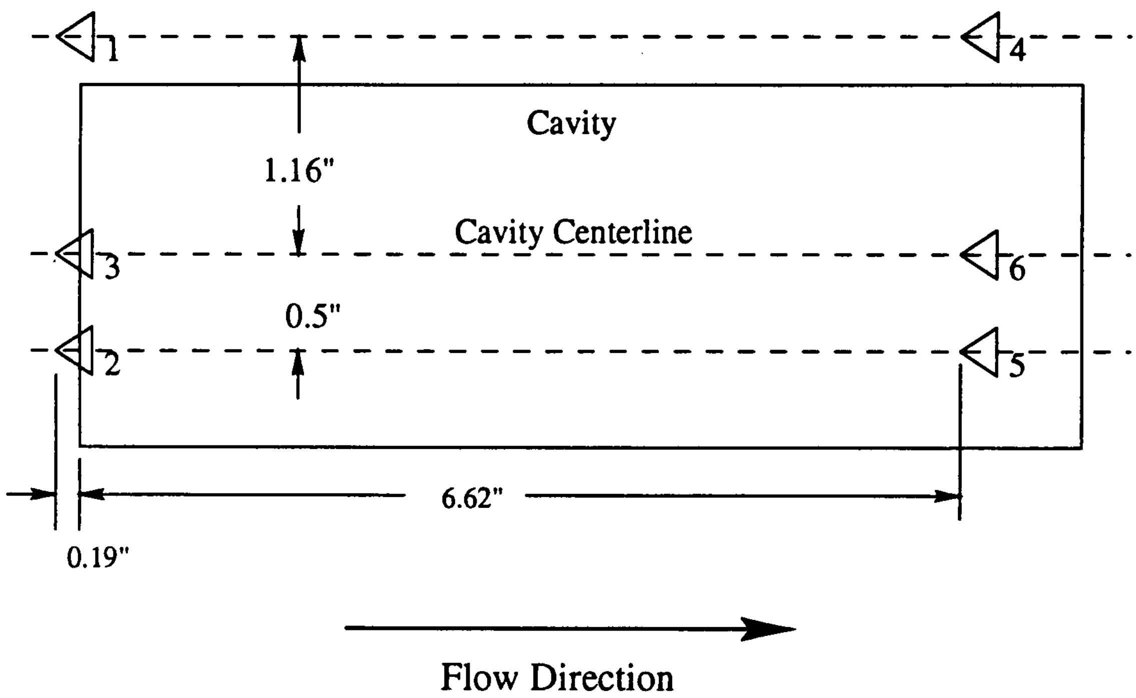


Figure 5: Schematic showing the locations over the cavity where vertical cone probe measurements were performed.

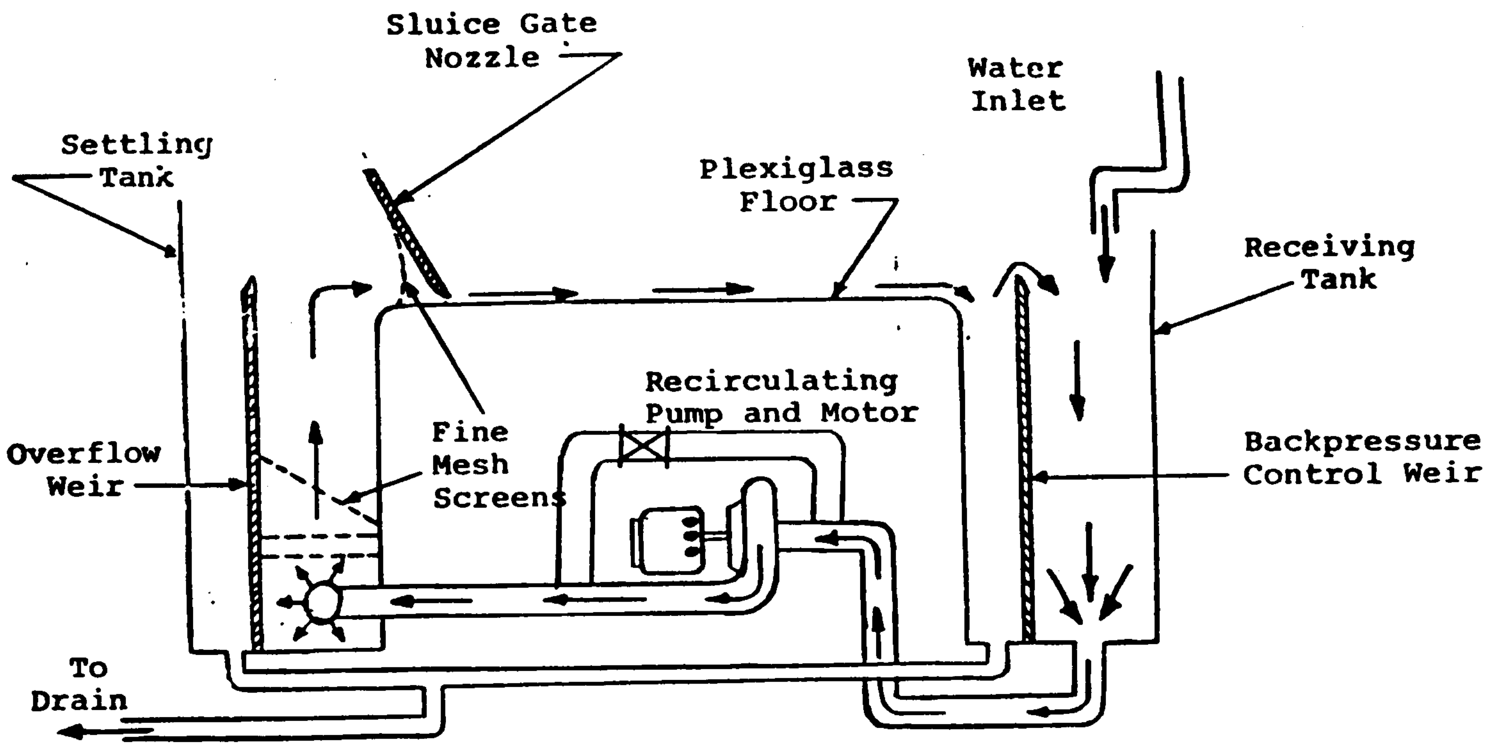
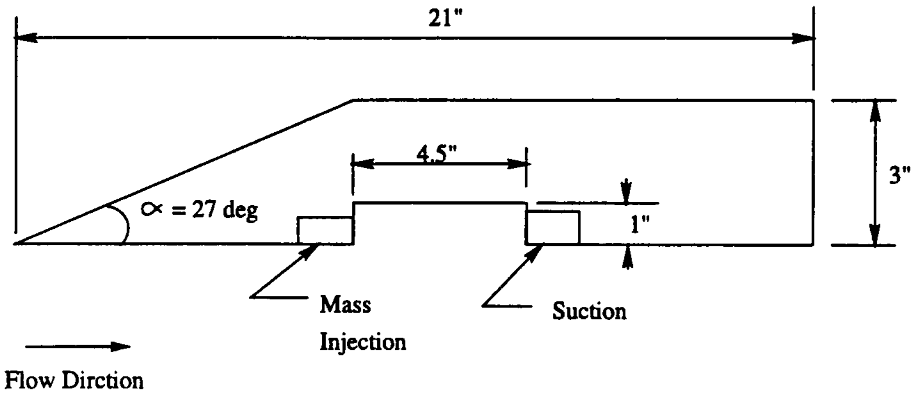
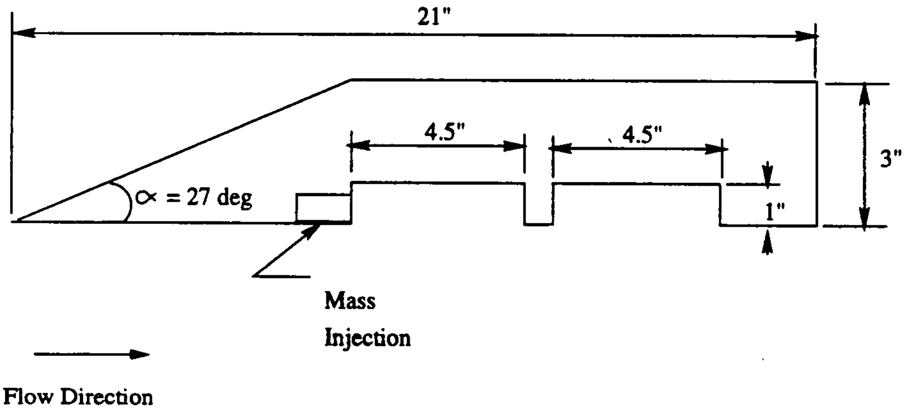


Figure 6: Sketch of water table apparatus.

2.16 to 4.69. Figure 7a and 7b are sketches of the models used in the water table. The dimensions of the cavities were 4.5 inches in length and 1 inch in depth (L/D ratio of 4.5). The models were equipped with an upstream mass injection module for both the single and double cavity arrangements and a mass suction module for the single cavity arrangement at the trailing edge. The single cavity could have either upstream mass injection, down stream suction at the trailing edge, or both.



(a) Single Cavity Arrangement wtih Suction



(b) Double In-Line Cavity Arrangemant

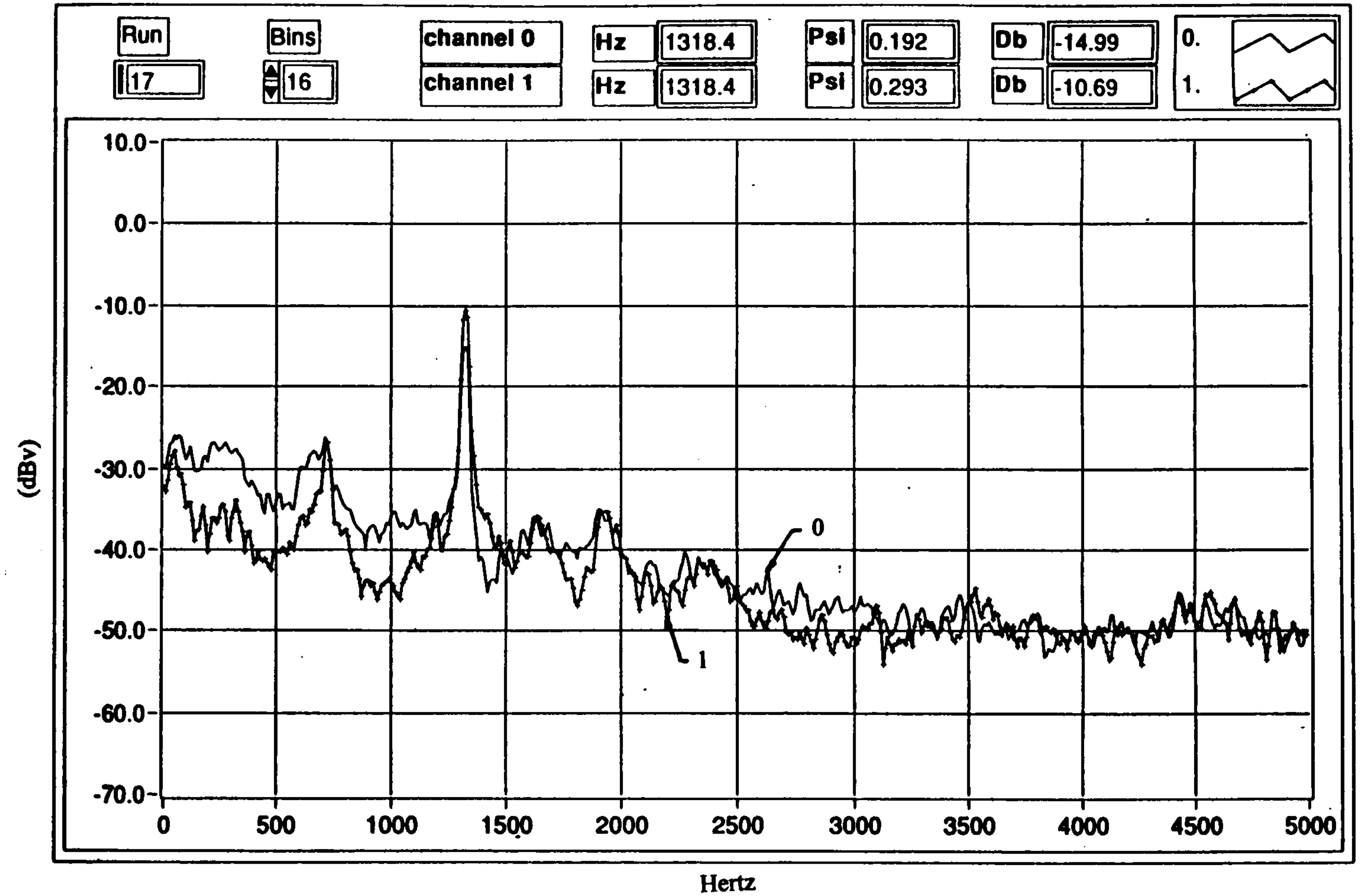
Figure 7: Sketch of models used in water table study.

Chapter IV

Experimental Results:

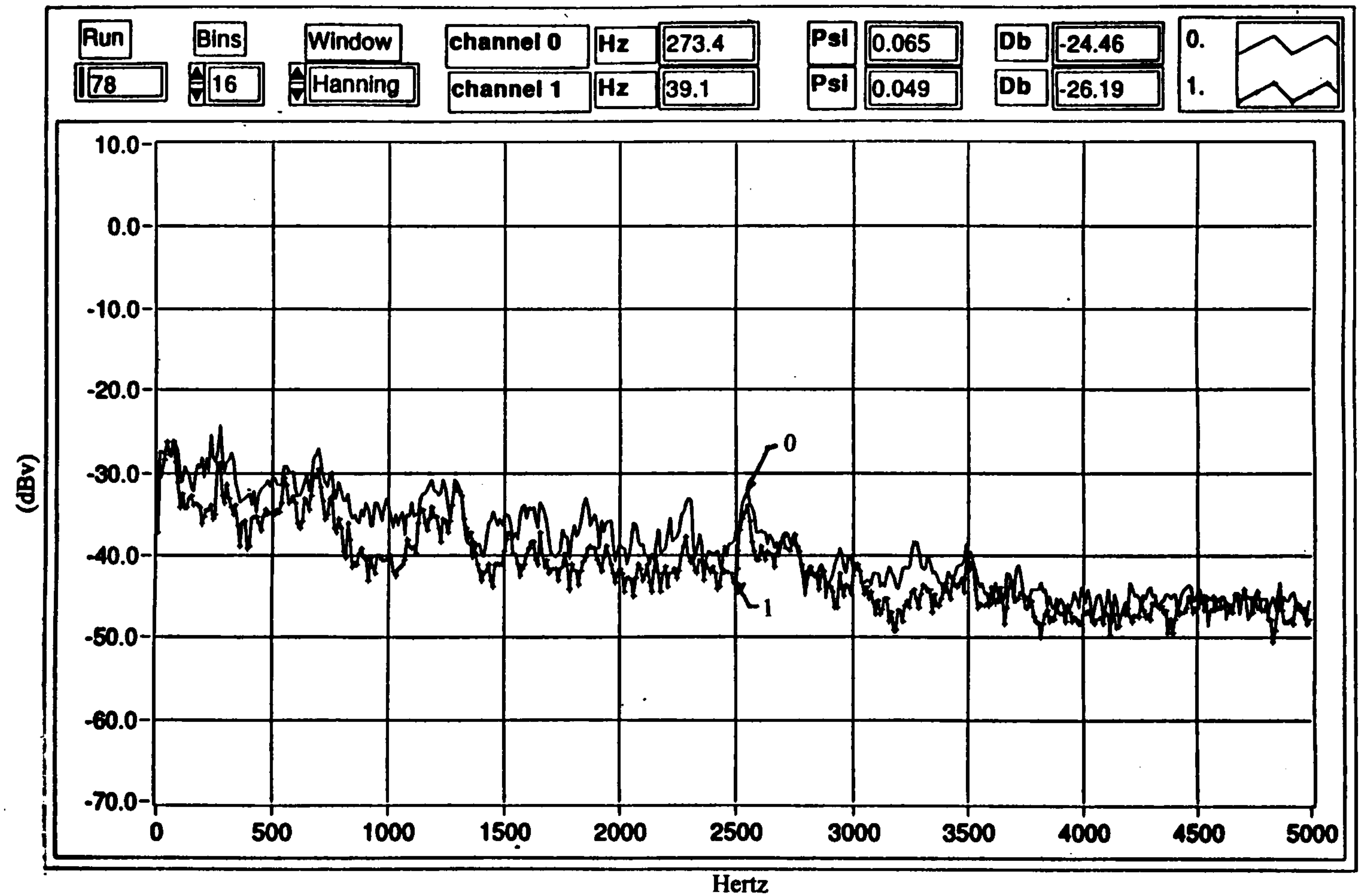
Dynamic Measurements in the Wind Tunnel :

Parts II and III consisted of measuring frequency spectra for the cavity with and without upstream mass injection at Mach numbers of 0.5, 0.7 and 0.8. Figures 8 a and b are the frequency spectra for channel 0 and channel 1 at Mach number 0.5. Channel 0 is output from the dynamic pressure transducer near the downstream wall of the cavity and is associated with P5 in figure 4. Channel 1 is output from the dynamic transducer near the leading edge of the cavity and is associated with P17 in figure 4. Figure 8a is the baseline (cavity without mass injection) measurement and shows a peak amplitude for both channels occurring at a frequency of 1320 Hz with a magnitude of -14.99 dBv (156 dB=log(P/P_{ref}), P_{ref}= 2 x 10^{-4} dyne/cm^2) for channel 0. Figure 8b is a similar frequency spectra taken with 0.10 lbm/sec upstream mass injection (blowing parameter **B**=1.2) for plate 9. Comparing 8a and 8b we see that the result of mass injection is the total reduction of the peak amplitudes in both channels. Another observation, that is not so noticeable, is the slight increase in broadband noise energy with mass injection for frequencies greater than about 2000 Hz. This suggests that some energy is dispersed to the higher frequencies. No explanation of how or why this has occurred has been determined; the effect, however, is not a major concern. Results are similar for plates



(a) Without mass injection (Baseline)

Figure 8: Spectrum results for Mach 0.5

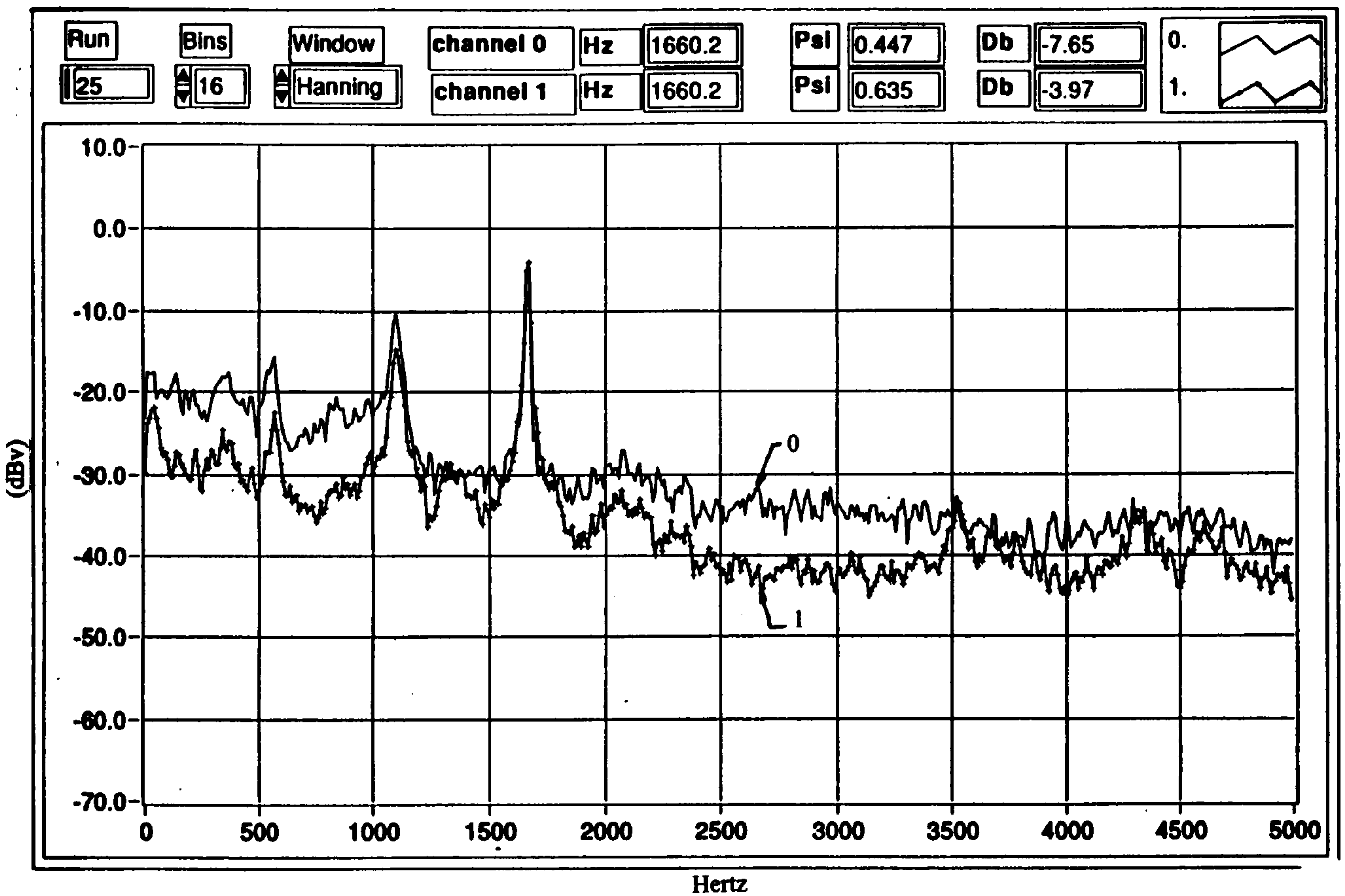


(b) Mach number 0.5 with 0.10 lbm/s mass injection using plate no. 9

Figure 8 (continued)

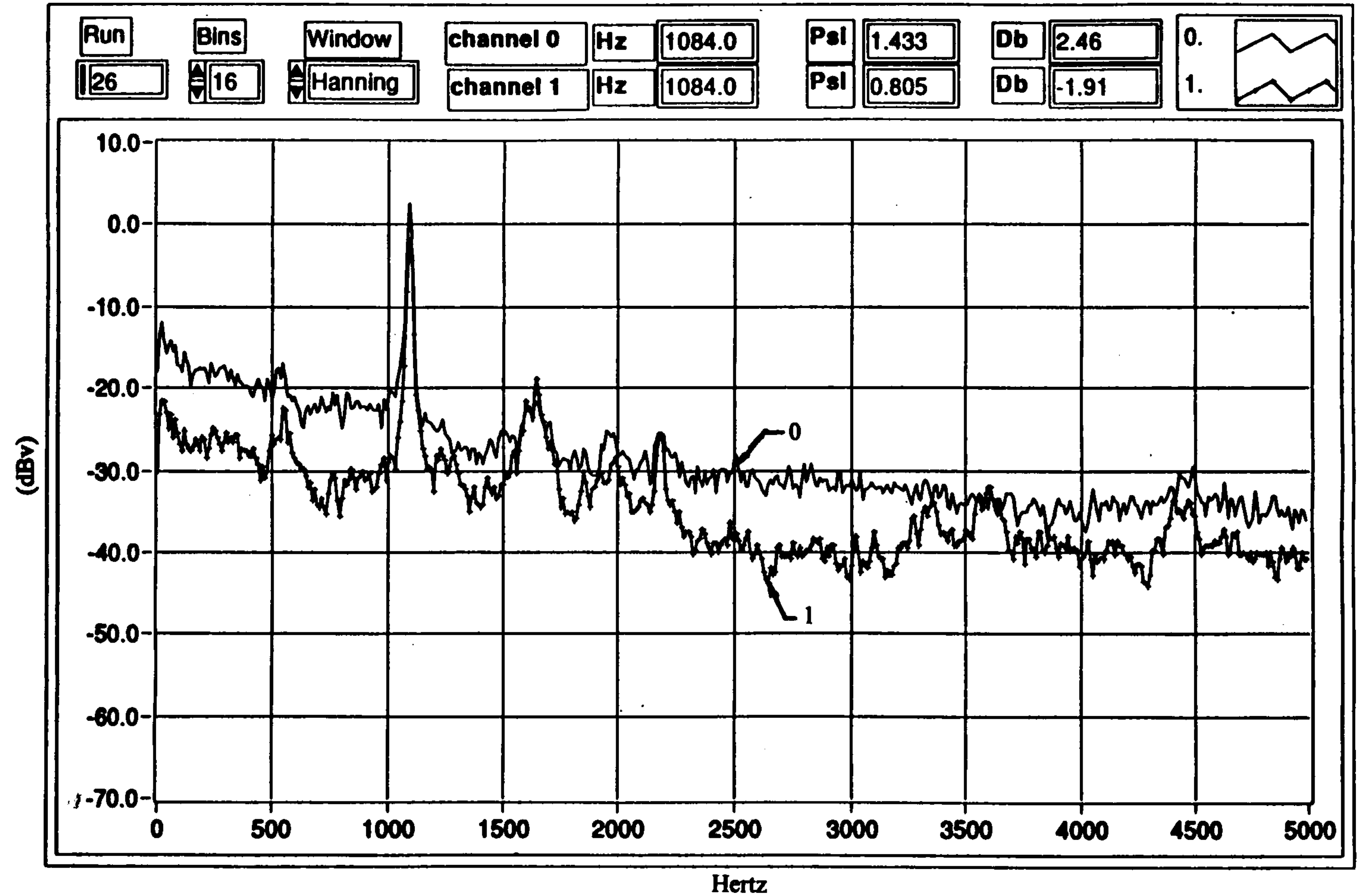
2 and 4 with a reduction of the peak amplitude and an increase in broadband energy above the frequency of approximately 2000 Hz. At a low mass injection rate of 0.05 lbm/s the large peak was reduced but not as much as at higher rates for plates 2 and 4. Plate 9 had the greatest effect of suppressing cavity aeroacoustics at Mach 0.5. Compared to all three plates, mass injection through plate 9 was able to reduce completely the peak amplitude at all mass injection rates. The reduction was due possibly due to a different streamwise vorticy pattern generated by the injection through plate 9, which helped to better control the shear layer.

Figure 9 a, b and c are frequency spectra responses for Mach 0.7. An interesting phenomena of frequency switching occurred for the baseline measurements for a small Mach number range around 0.7. Figure 9a is the baseline representative spectra for the Mach number range of 0.68 to 0.7. Here two peaks are distinguishable with the peak at 1660 Hz being the most prominent. Figure 9b is a baseline frequency spectrum representative for the Mach number range of 0.7 to 0.72. The peak frequency is now switched to 1084 Hz which was previously the weak peak on figure 9a and the peak amplitude at 1660 Hz is significantly reduced. The result can be seen in later figures. It is believed that this switching of mode frequencies could be similar to the observations of Rossiter[2]. At a Mach number of 0.7 for a cavity L/D ratio of 2, Rossiter noticed that there seemed to be no real dominant frequency. Figure 9c is the response with 0.10 lbm/s mass injection from plate 9, and again the peak amplitudes have been reduced. Similar results were obtained for different plates and mass injection amounts. Plate 9 worked best at the low mass injection rate while plate 2 had



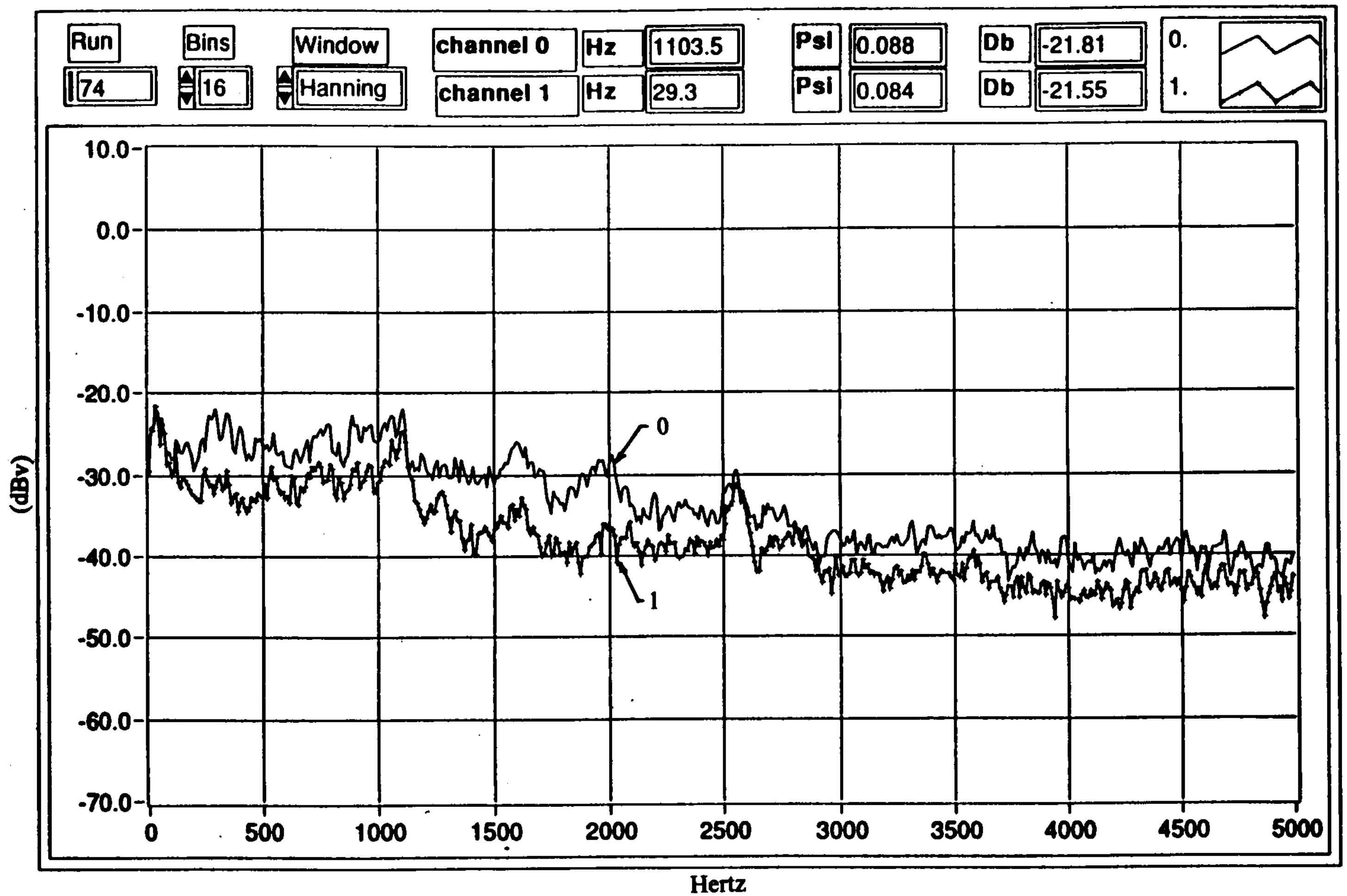
(a) Mach number range between 0.68 and 0.70 with no mass injection (Baseline)

Figure 9: Spectrum results for Mach number 0.7



(b) Mach number range between 0.70 and 0.72 with no mass injection (Baseline)

Figure 9 (continued)



(c) Mach number range between 0.68 and 0.70 with 0.10 lbm/s mass injection using plate 9

Figure 9 (continued)

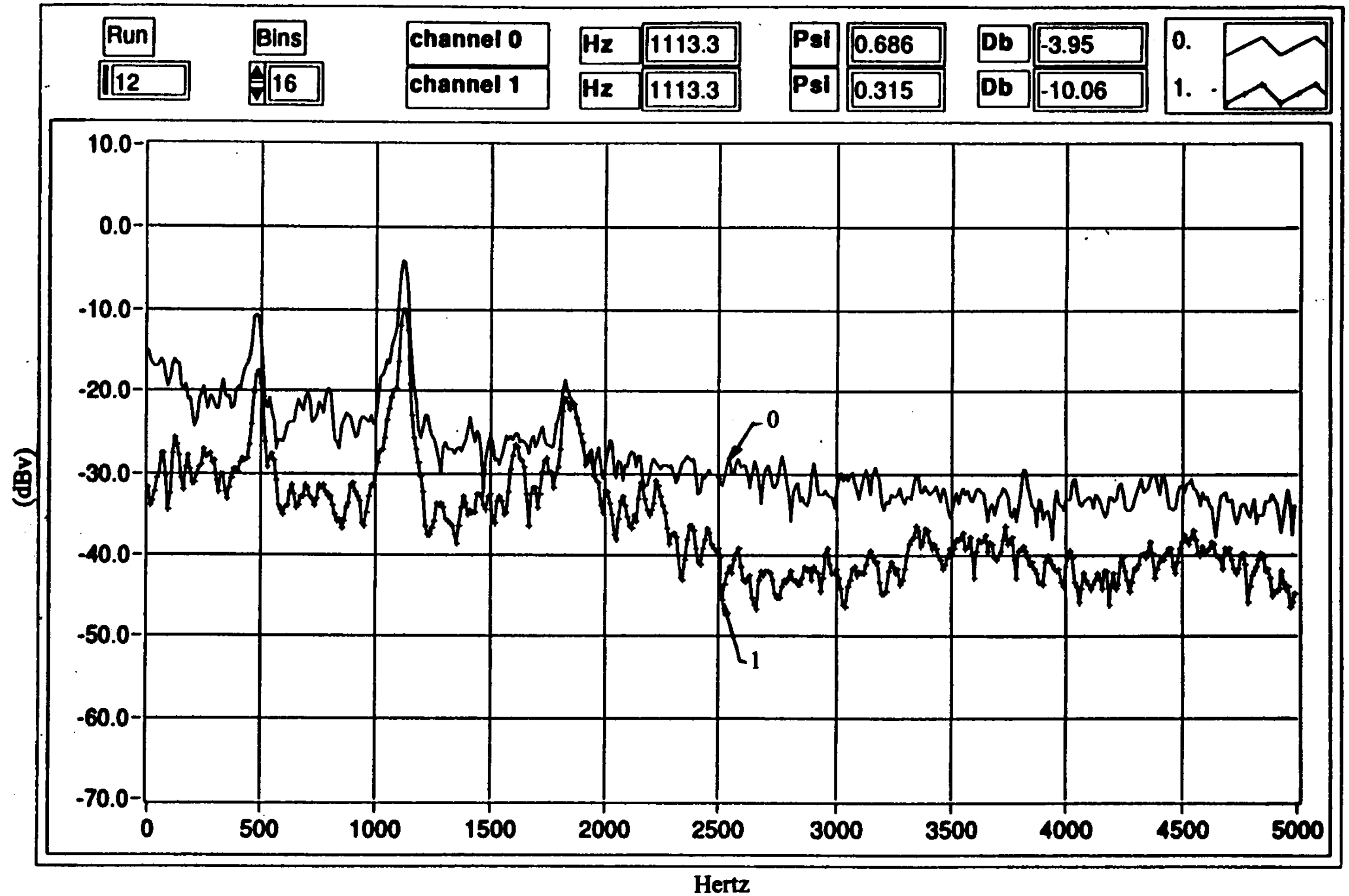
the best results at the higher rates.

Figure 10 a, b, c and d are frequency spectra for Mach 0.80. Figure 10a is the baseline spectra and shows the peak frequency to be at 1113 Hz, with minor peaks at frequencies of about 500 Hz and 1800 Hz. Unlike the responses for plates 2 and 4 at the other Mach numbers, the effect of mass injection at Mach 0.80 was different. Figure 10b shows that at a low mass injection rate of 0.05 lbm/s through plate 2, the peak amplitude actually increases. As the mass injection rate was increased to 0.15 lbm/s and higher the peak amplitudes began to be reduced. Figure 10c shows the spectra for Mach 0.80 at a mass injection rate of 0.15 lbm/s using plate 2. Higher mass rates were not obtainable. The larger plenum pressures needed, for the higher mass flow rates, blew out seals around the mass injection apparatus. The result gave false readings about the amount of mass actually involved in changing the boundary layer structure in the tunnel. Figure 10d shows the results of the frequency spectra for plate 9 at 0.05 lbm/s. Plate 9 was the exception in that at the low mass injection rate of 0.05 the peak amplitude was reduced, but at higher injection rates the response was again an increase in peak amplitude.

Figure 11 is a plot showing the baseline peak amplitude frequency for each Mach number compared to the empirical values of frequency given by the modified Rossiter's equation,

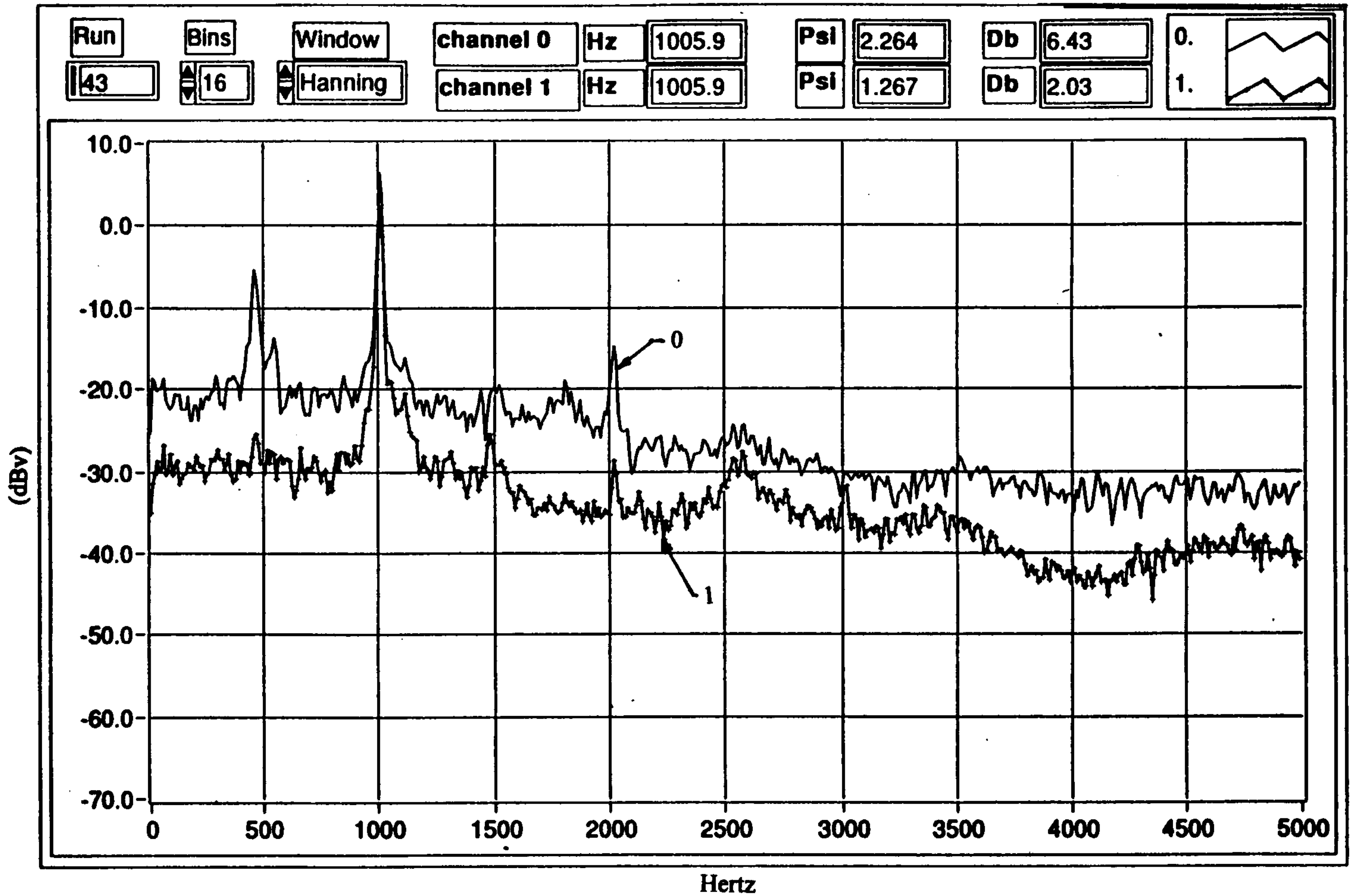
$$Str = f\frac{U}{L} = \frac{m-n}{\dfrac{M}{\sqrt{1+\frac{\gamma-1}{2}M^2}}+\dfrac{1}{K_v}} . \tag{6}$$

Here m is the mode 1,2 3, and so on, K_v is the ratio of convected vortex velocity to



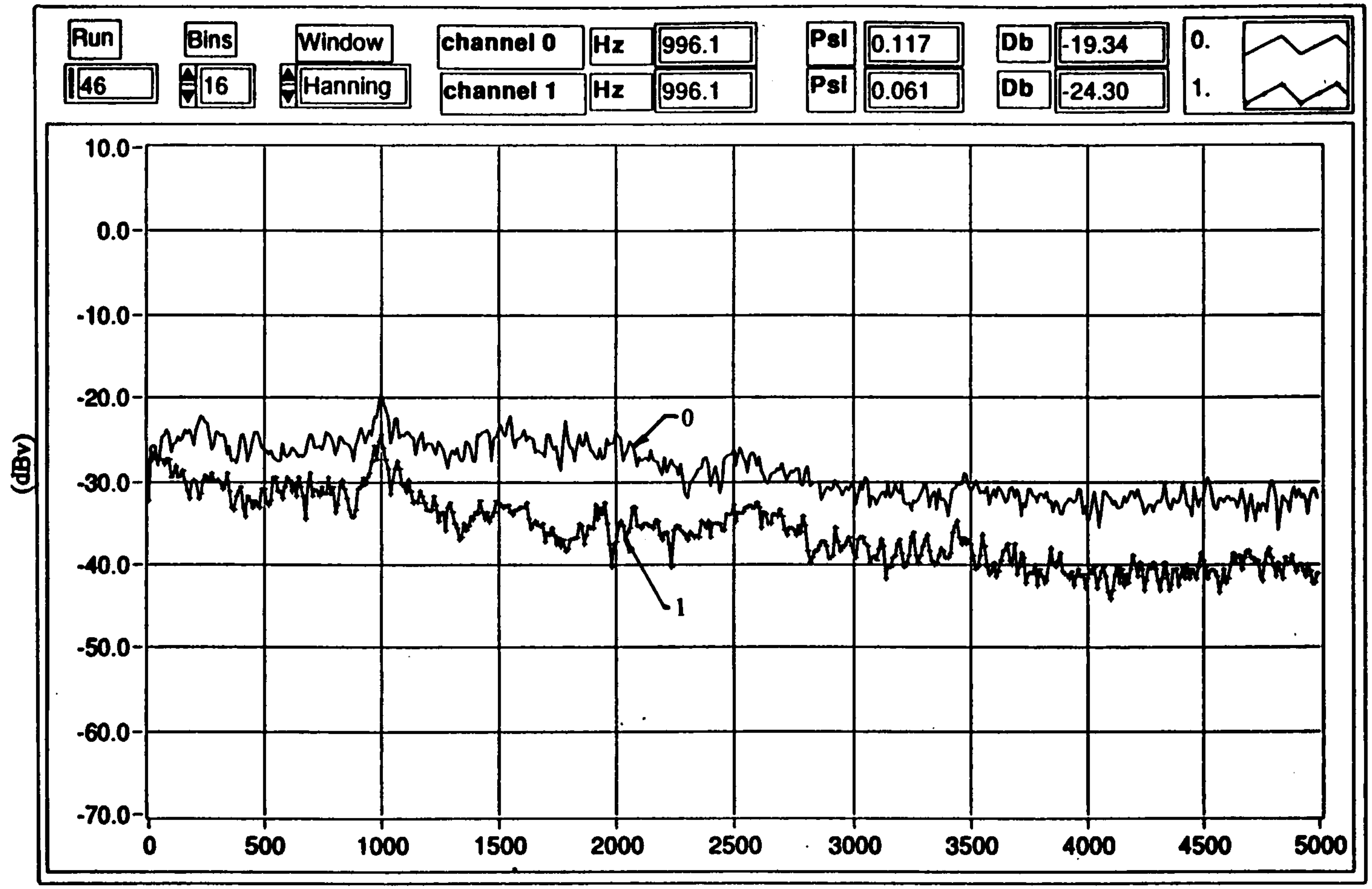
(a) Without mass injection (Baseline)

Figure 10: Spectrum results for Mach number 0.80



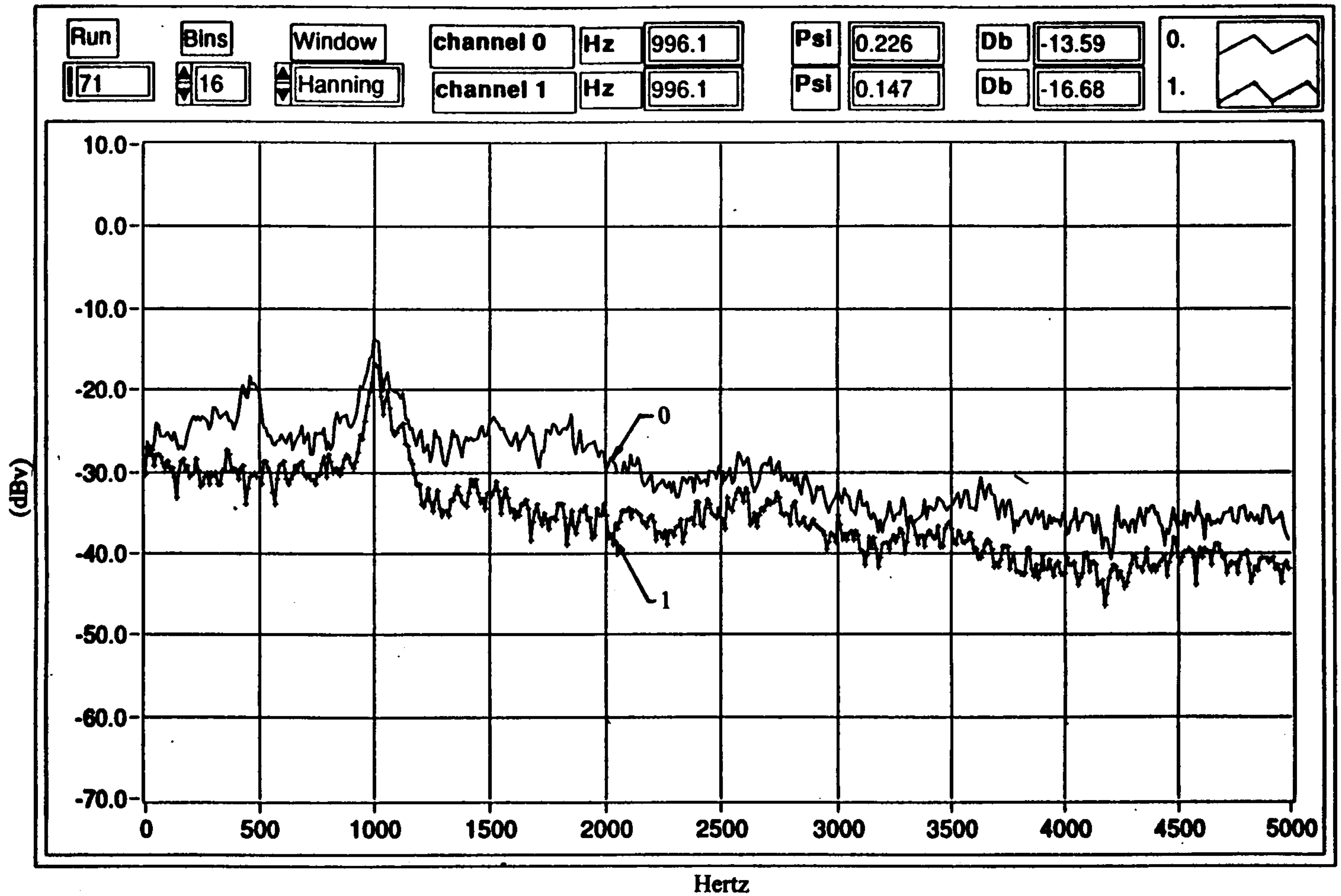
(b) Mach number 0.80 with 0.05 lbm/s mass injection using plate 2

Figure 10 (continued)



(c) Mach number 0.80 with 0.15 lbm/s mass injection using plate 2

Figure 10 (continued)



(d) Mach 0.80 with 0.05 lbm/s mass injection using plate 9

Figure 10 (continued)

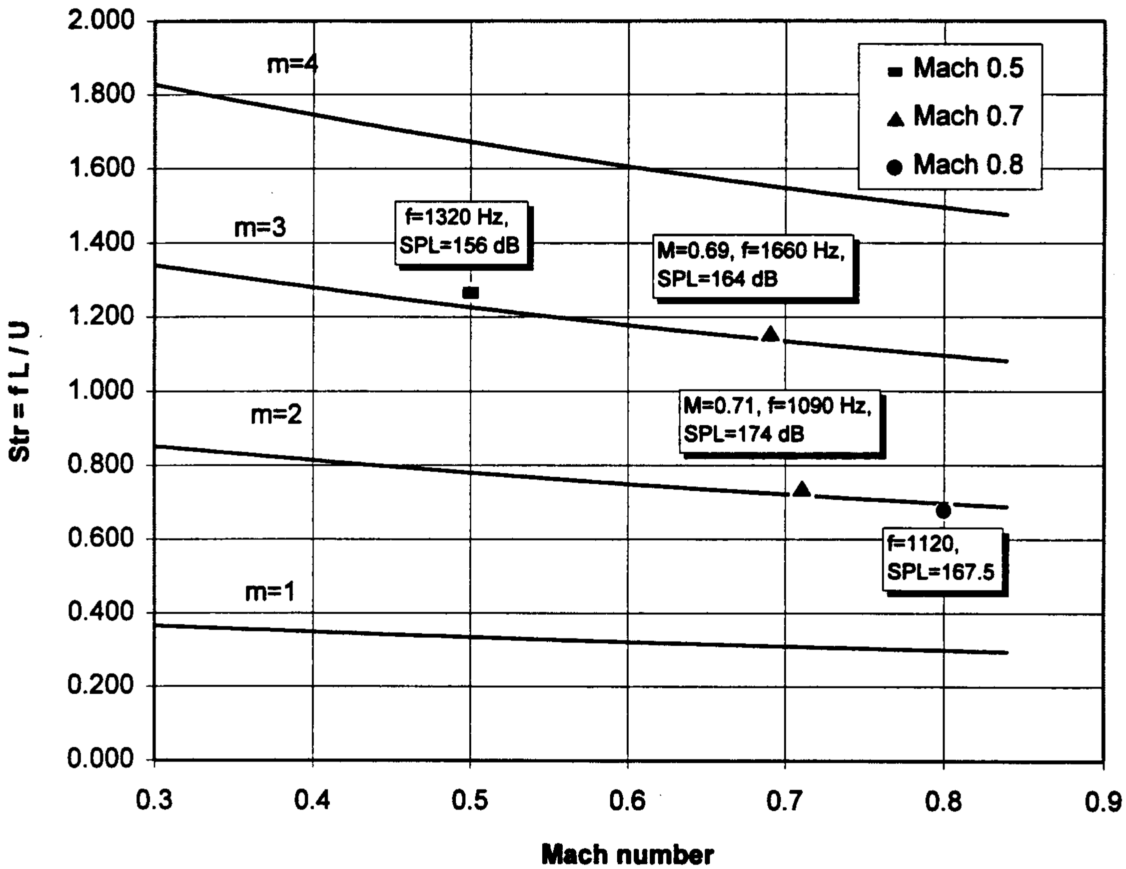


Figure 11: Comparison of experimental baseline peak amplitude frequencies to peak amplitude frequencies predicted by the modified Rossiter's equation.

free stream velocity and n is the acoustic wave emission delay constant. K_v and n are empirically derived and are equal to 0.57 and 0.25, respectively, for an L/D ratio of 4. The present experimental results are in good agreement with the empirical equation, with only a 3% difference. However, compared with the experimental data of Rossiter[2] at each Mach number the frequency mode numbers corresponding to aeroacoustical peak frequencies did not coincide. Dissimilarities in frequency mode numbers were attributed to the difference between Rossiter's cavity (L/D=4) and the cavity in this study (L/D=4.33). The mode value is not predictable and depends upon the cavity and flow conditions.

Figures 12 and 13 are Schlieren photographs taken from a VCR camera and frame grabbed using a Data Translations® frame grabbing board installed in a 486 PC. Figure 12 shows the boundary and shear layer over the cavity at a Mach number of 0.7. There is no mass injection present upstream. The first vertical line from the right would be the start of the mass injection area. The second vertical line is the location of the leading edge of the cavity. The third vertical line just visible in the left corner of the photograph is the location of the cavity's trailing edge. The four horizontal marking dashes just downstream of the second vertical line are approximately 0.25 inches apart with the bottom line the same distance from the floor of the tunnel. It is observed that the boundary layer is approximately 0.2 to 0.3 inches thick. The ratio of the boundary layer thickness to cavity length and depth are $\delta/L=0.046$ and $\delta/D=0.2$, respectively. Figure 13 is a similar photograph to that of figure 12 except with mass injection present. It shows the effect of a mass injection rate of 0.10 lbm/s from plate

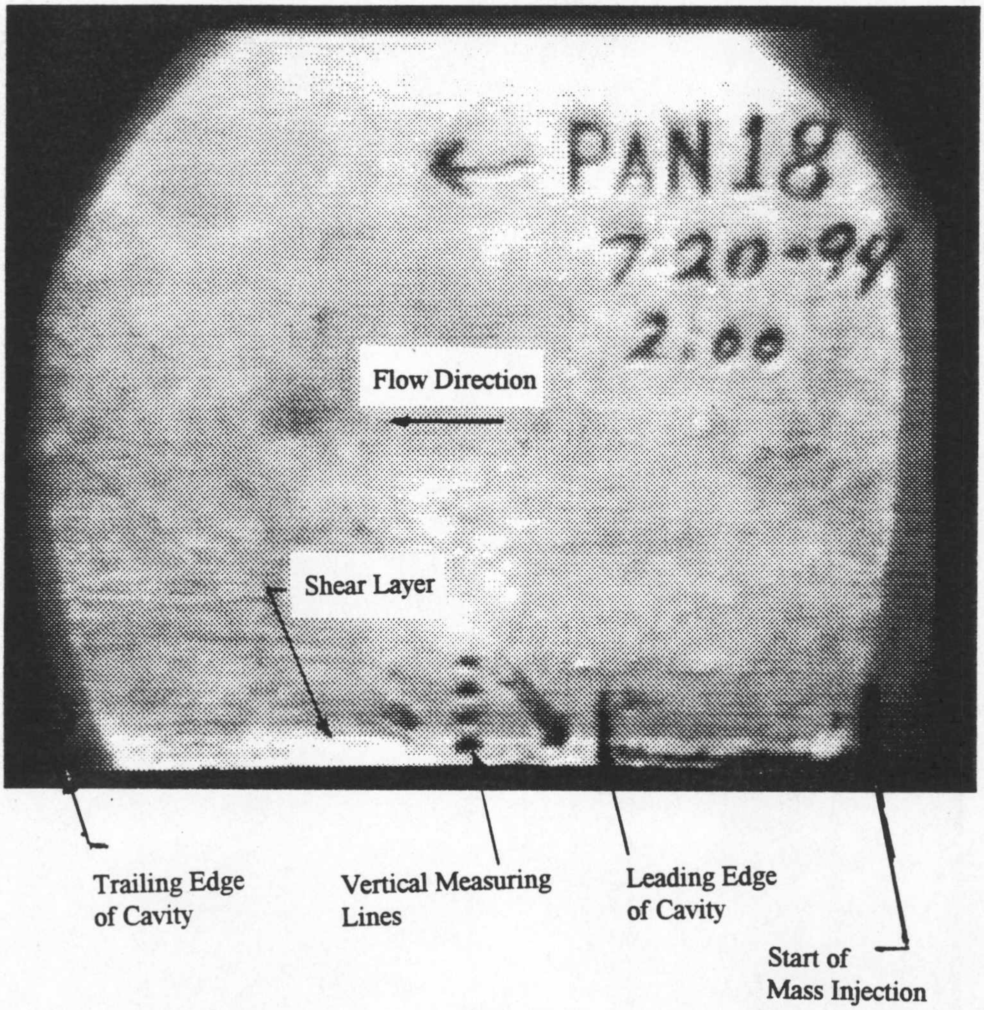


Figure 12 Schlieren photograph of the boundary and shear layers over the cavity at Mach 0.7 and no mass injection.

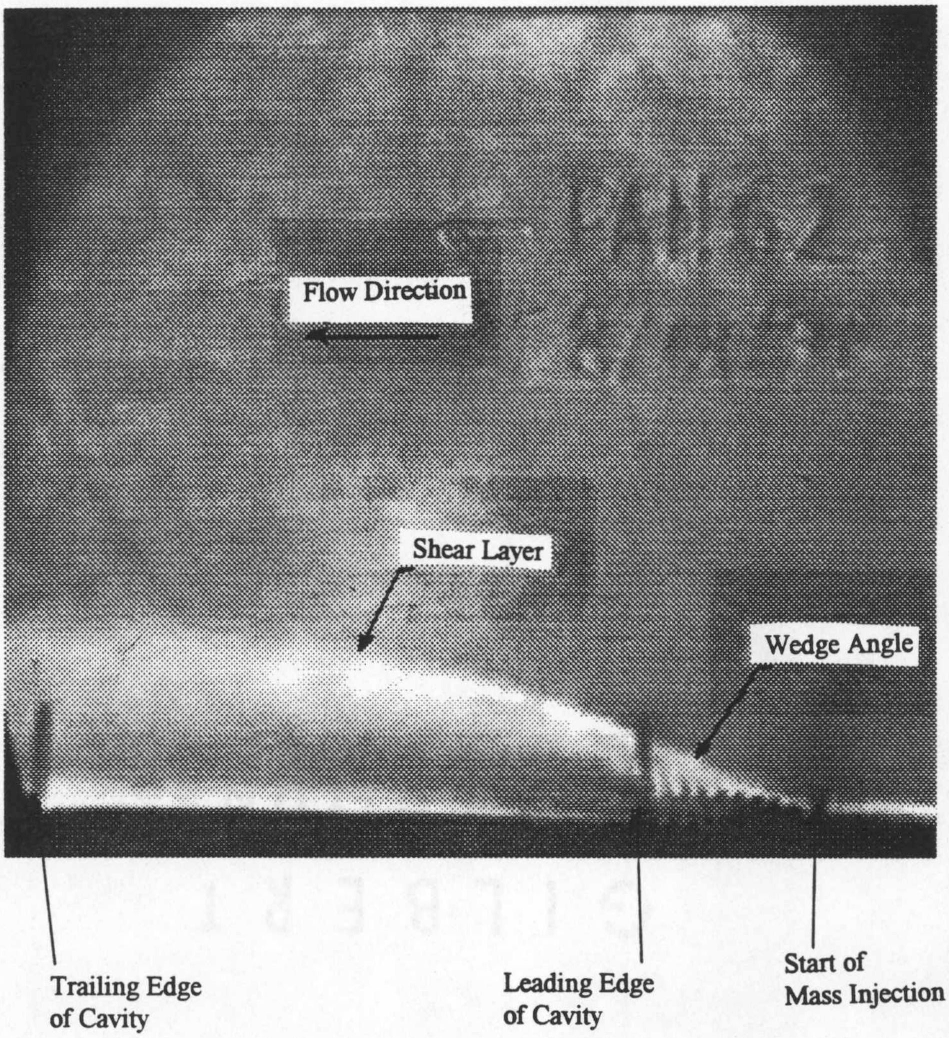


Figure 13 Schlieren photograph of boundary and shear layers over a cavity at Mach 0.7 and 0.10 lbm/s mass injection using plate 4.

4 on a Mach 0.7 free stream flow. The shear layer is thickened over the cavity so that it does not interact with the cavity or the trailing edge. The boundary layer thickness to Length and Depth ratios are estimated to about twice as large as with no mass injection.

Figures 14, 15 and 16 are plots of sound pressure level reduction versus mass injection rate for the various Mach numbers. The greatest amount of reduction shown in figure 15 is for a Mach number of 0.7 with a mass injection of 0.1 lbm/s, using plate 2. The greatest reduction for all plates occurs around 0.1 lbm/s of mass injection for Mach numbers of 0.5 and 0.7. Figure 16 shows that at Mach 0.8 the greatest reduction of sound pressure level occurs at higher mass injection rates, with an increases in peak amplitude occurred at 0.05 lbm/s mass injection. From figure 16, Plate 9 shows a range of mass injection where there is reduction in peak amplitude around the mass injection rate of 0.05 lbm/s. The magnitude of reduction decreases and then again increases at 0.2 lbm/s. One of the possible explanations for this is transonic effects. These test conditions were run several times to assure that there was not any problems with the measuring instruments. Each measurement was consistent with the previous measurement, which was a measure of repeatability of the data gathered. Figure 17 through 19 are similar plots of peak amplitude reduction in acoustic sound pressure levels versus the blowing parameter $\mathbf{B}^*(A_{inj}/A_{pattern})$ for plates 2, 4 and 9..

Table I is a summary of the maximum reduction of cavity oscillations for each plate, Mach number, and mass injection rate tested. Observations of the blowing parameter show ranges where injection was most effective. The effective range of the

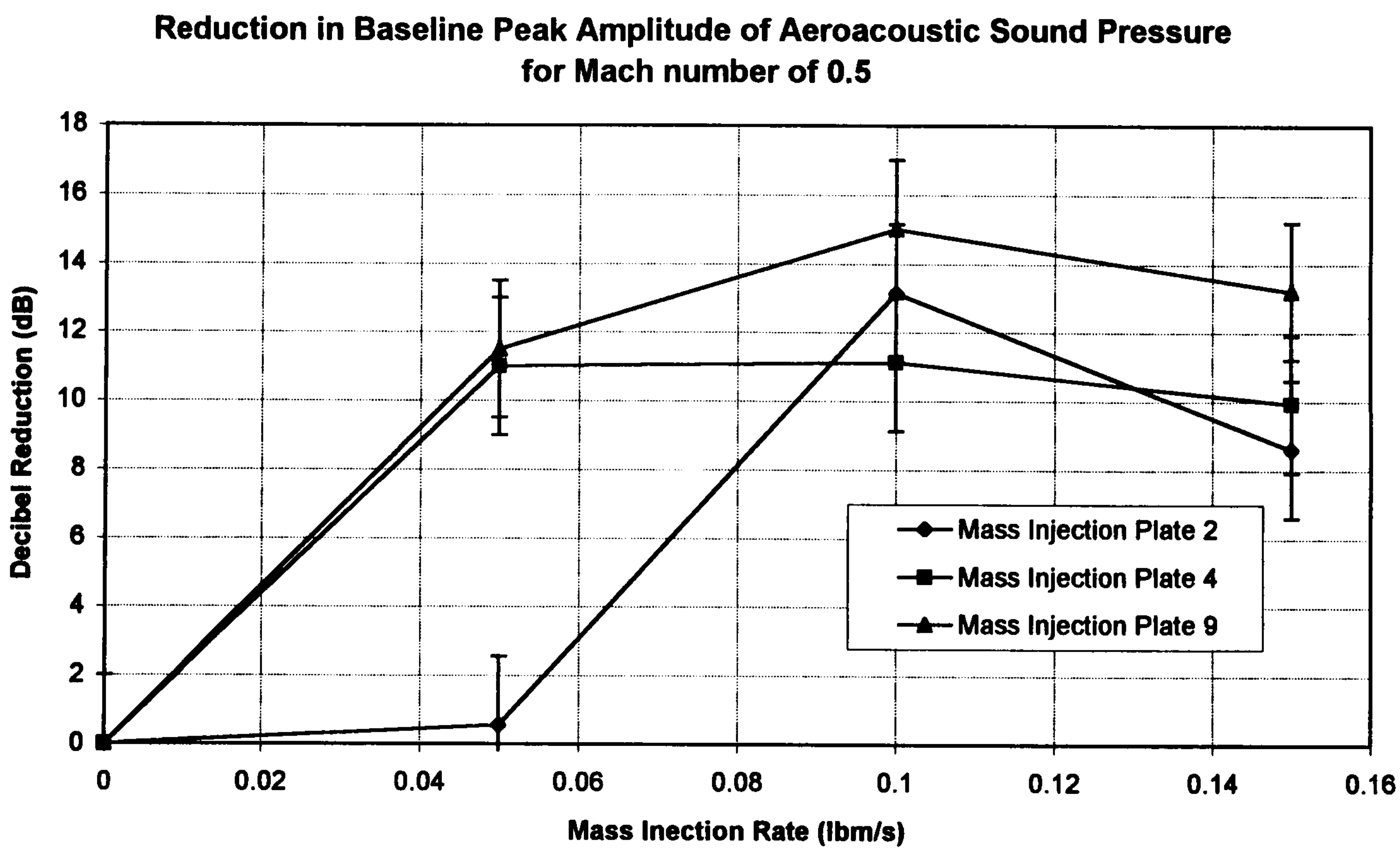


Figure 14: Plot of sound pressure level reduction for Mach number 0.5 versus mass injection rate for plates 2, 4, and 9.

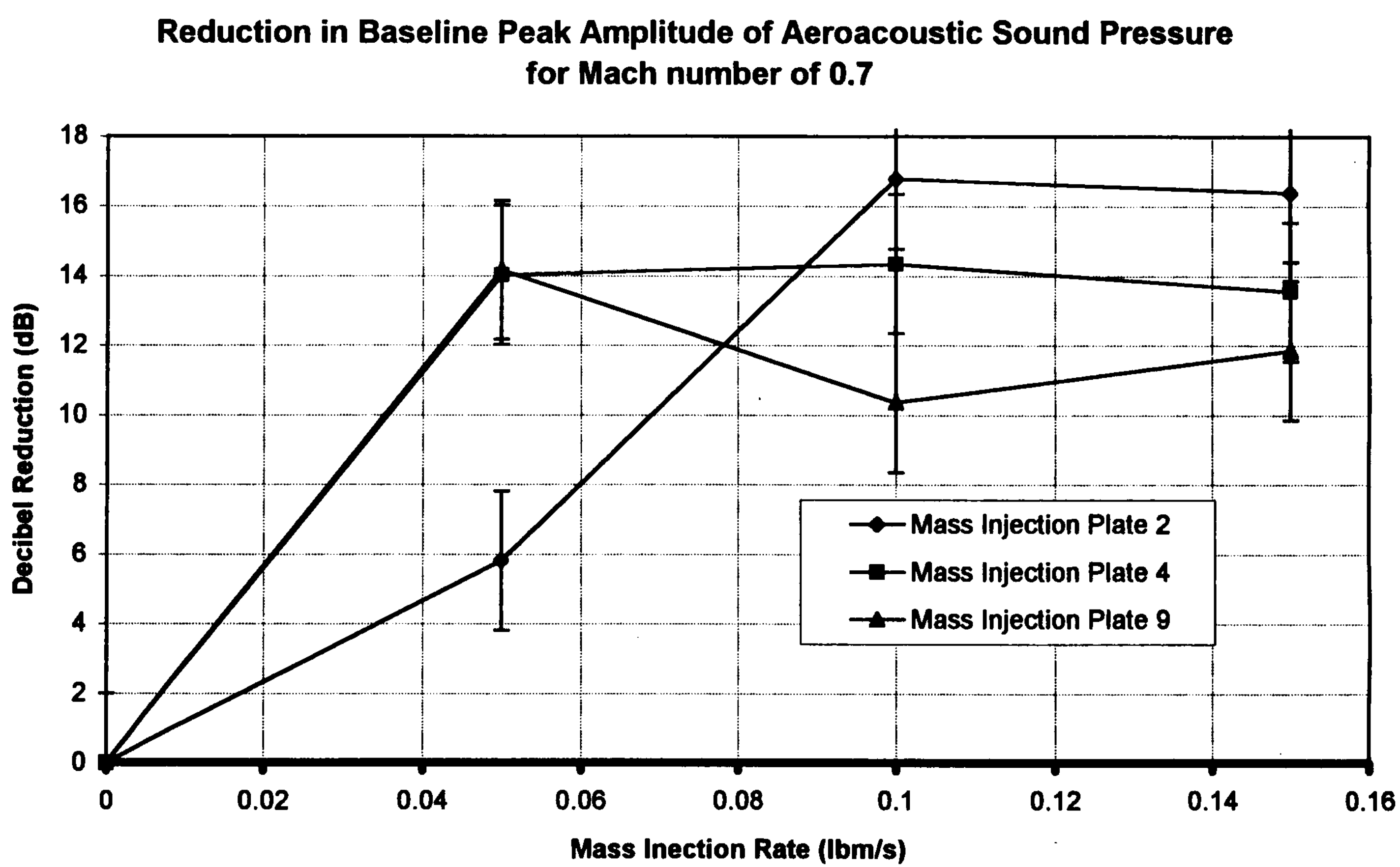


Figure 15: Plot of sound pressure level reduction for Mach number 0.7 versus mass injection rate for plates 2, 4, and 9.

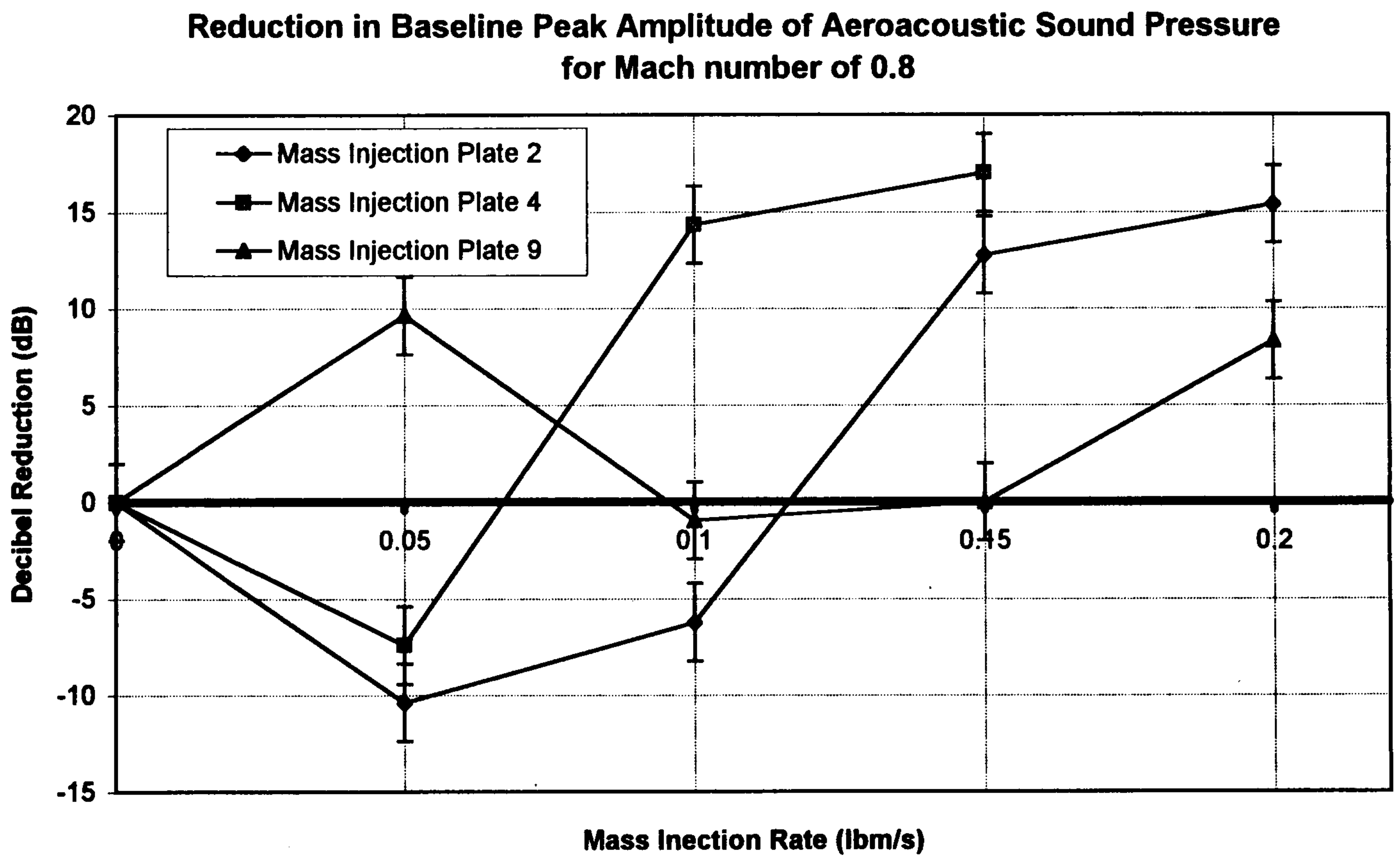


Figure 16: Plot of sound pressure level reduction for Mach number 0.8 versus mass injection rate for plates 2, 4 and 9.

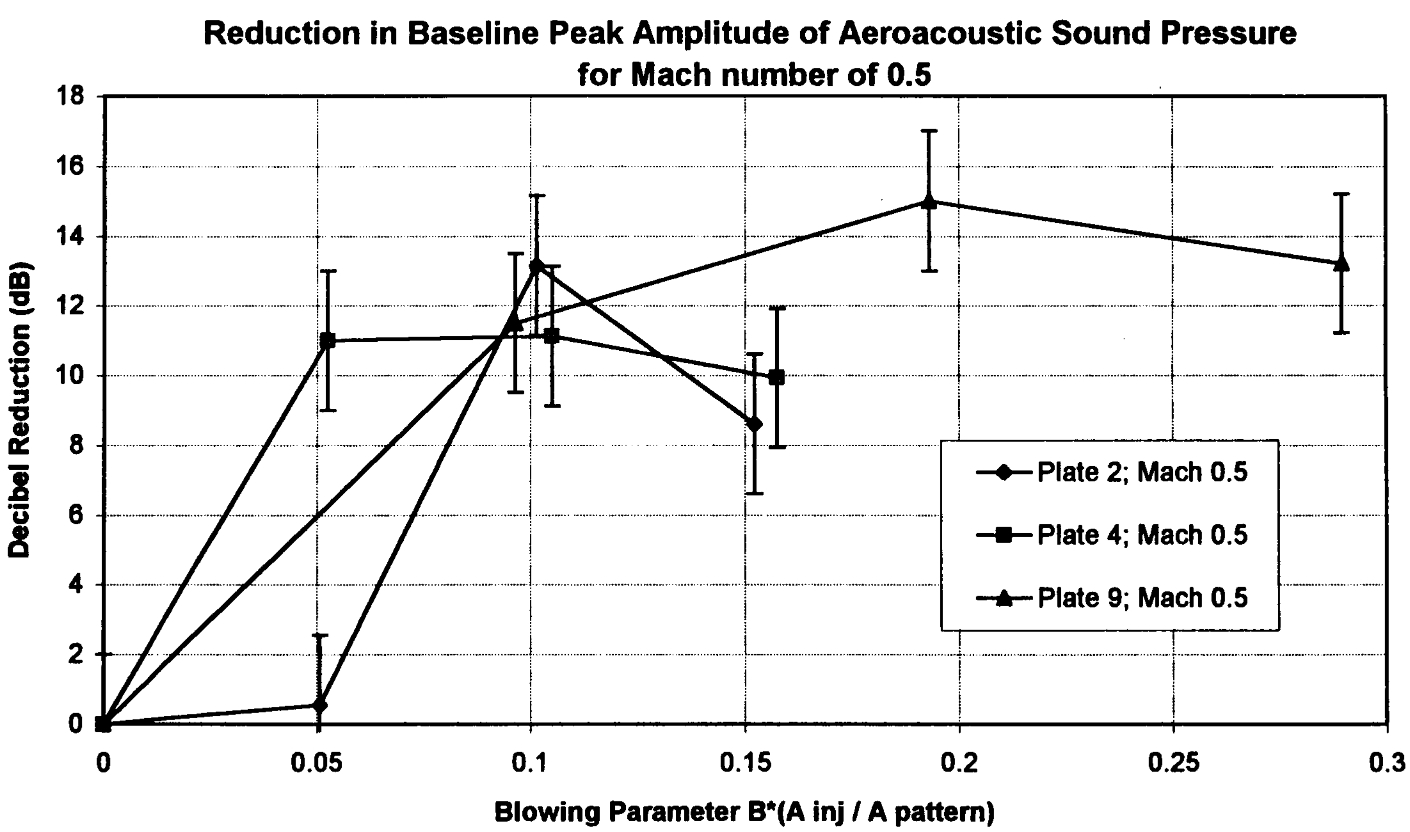


Figure 17: Plot of sound pressure level reduction for Mach number 0.5 versus blowing parameter $B^*(A_{inj}/A_{pattern})$ for plates 2, 4 and 9..

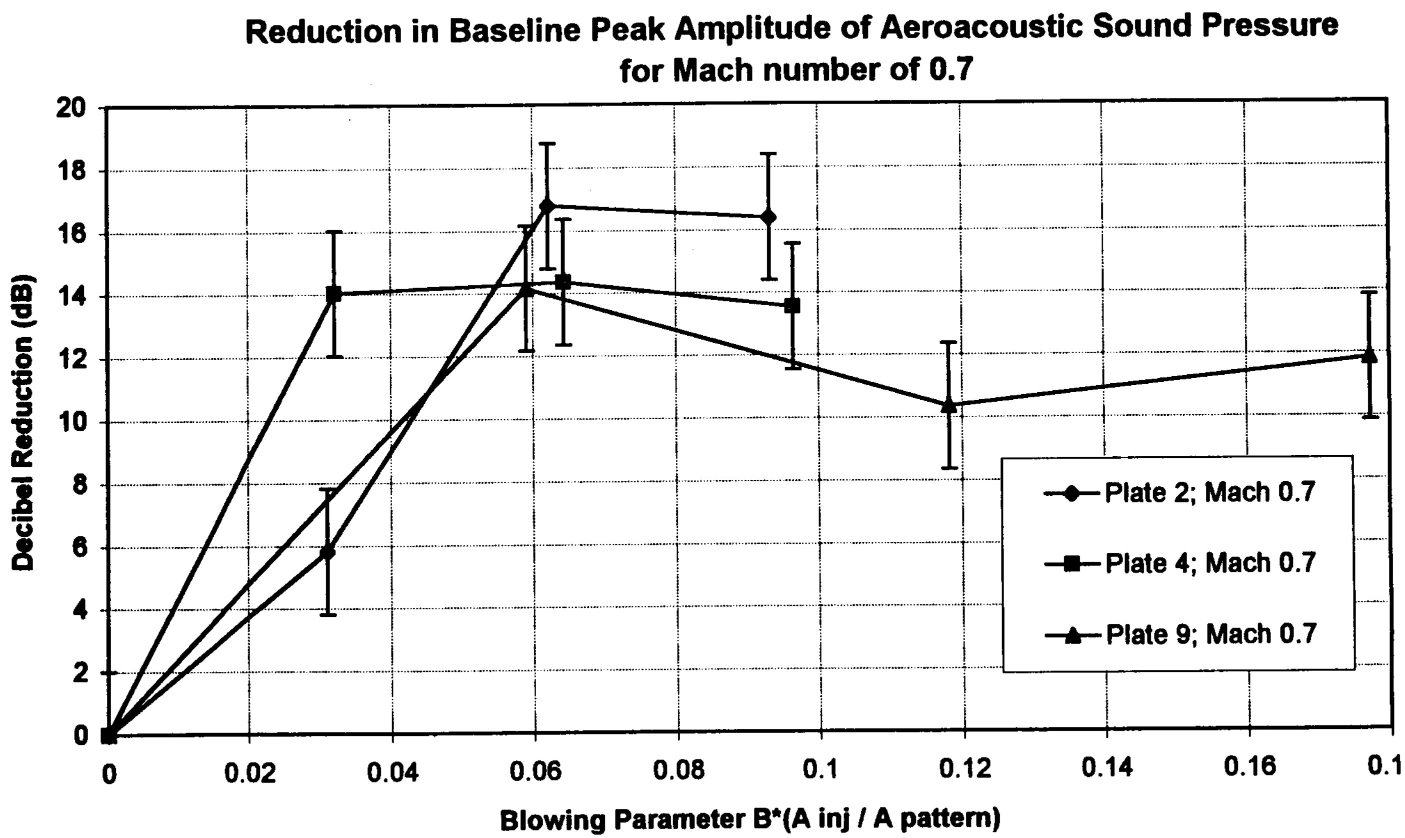


Figure 18: Plot of sound pressure level reduction for Mach number 0.7 versus blowing parameter $B^*(A_{inj}/A_{pattern})$ for plates 2, 4 and 9.

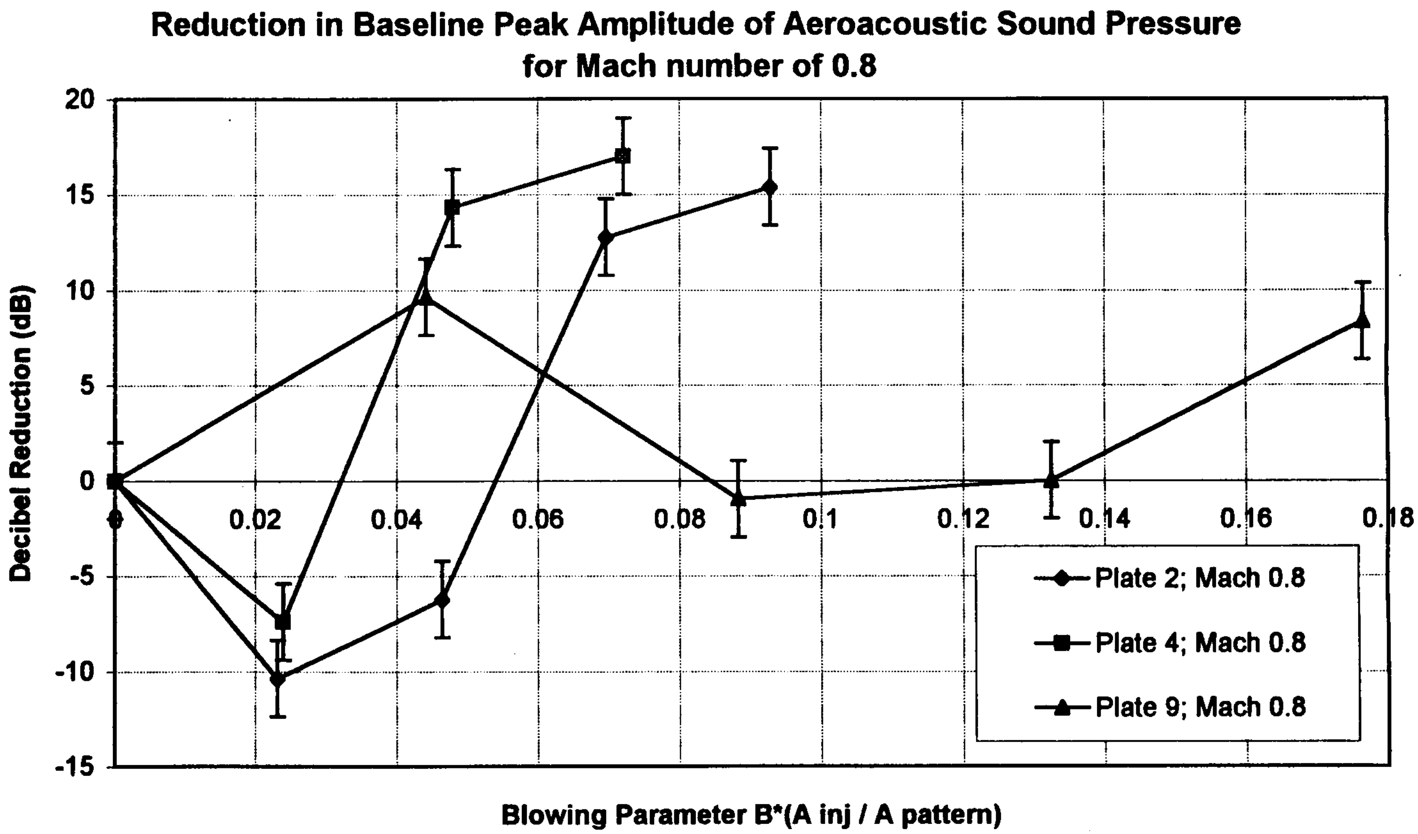


Figure 19: Plot of sound pressure level reduction for Mach number 0.8 versus blowing parameter $B^*(A_{inj}/A_{pattern})$ for plates 2, 4 and 9.

Table I: Summary of maximum amplitude reduction of Aeroacoustic Sound Pressure Level for plates 2, 4 and 9 at Mach numbers of 0.5, 0.7 and 0.8

Mach 0.5	Plate #	Mass Injection Rate	Blowing Parameter B*(Area inj / Area Cavity)	Amplitude Reduction (dB)
	2	0.1	0.1015	13.15
	4	0.1	0.1050	11.12
	9	0.1	0.1931	15
Mach 0.7	Plate #	Mass Injection Rate	Blowing Parameter B*(Area inj / Area Cavity)	Amplitude Reduction (dB)
	2	0.1	0.0622	16.78
	4	0.1	0.0643	14.35
	9	0.05	0.0591	14.16
Mach 0.8	Plate #	Mass Injection Rate	Blowing Parameter B*(Area inj / Area Cavity)	Amplitude Reduction (dB)
	2	0.2	0.0929	15.39
	4	0.15	0.0721	17
	9	0.05	0.0441	9.64

blowing parameter for the Mach number of 0.5 was around 0.1 to 0.2 and for the Mach number of 0.7 the range was 0.06 and 0.07, for all mass injection plates. An effective range of the blowing parameter for the Mach number of 0.8 was not as distinct. The level of blowing seemed to be dependent upon the distribution of the injection pattern. As previously stated, for a Mach number of 0.8 higher mass injection rates worked well with plates 2 and 4, and for plate 9 a low injection range between 0.05 to 0.06 lbm/s was more effective.

Cone Probe Measurements in the Wind Tunnel :

Figures 20 through 23 are vector plots of velocity in the shear layer over the cavity. As shown in figure 5, only three station over the cavity could be measured at both the leading and trailing edge of the cavity. The cone probe support device did not allow any other positions to be measured. To obtain a better understanding of the flow over the cavity, the mirror image of the data measured at stations 1, 2, 4 and 5 was incorporated into plot. The scale vector is equal to a Mach number of 0.25. Like Wolfe[26] the static pressure measurements of the cone probe were influenced by the mass injection process and at times were greater than the local total pressure measurement. Some sections of the data were not reducible and gaps can be seen on the plot.

Figures 20 and 21 are surveys of the shear layer at the leading and trailing edge respectively for a Mach number of 0.7 with no mass injection present. The centerline traversing survey, in figure 20, shows that a very small amount of cross flow was

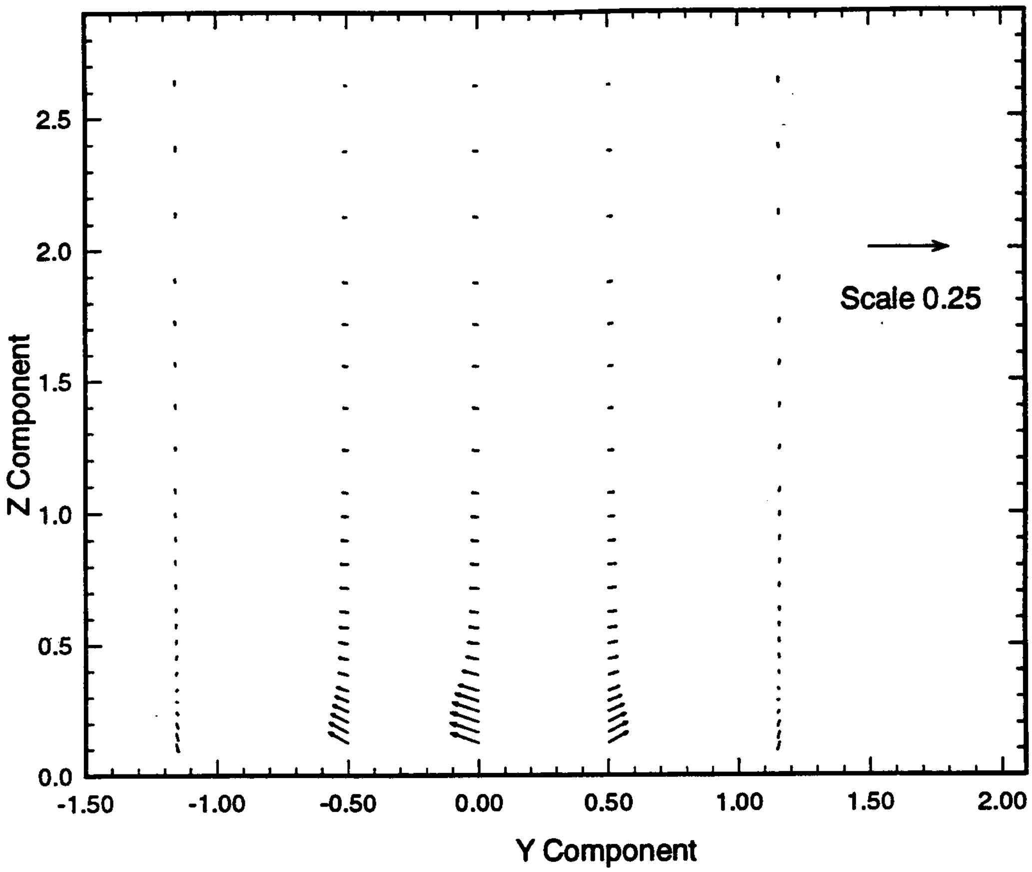


Figure 20 : Cone Probe velocity vector plots at the cavity's leading edge for Mach number of 0.7 and no mass injection.

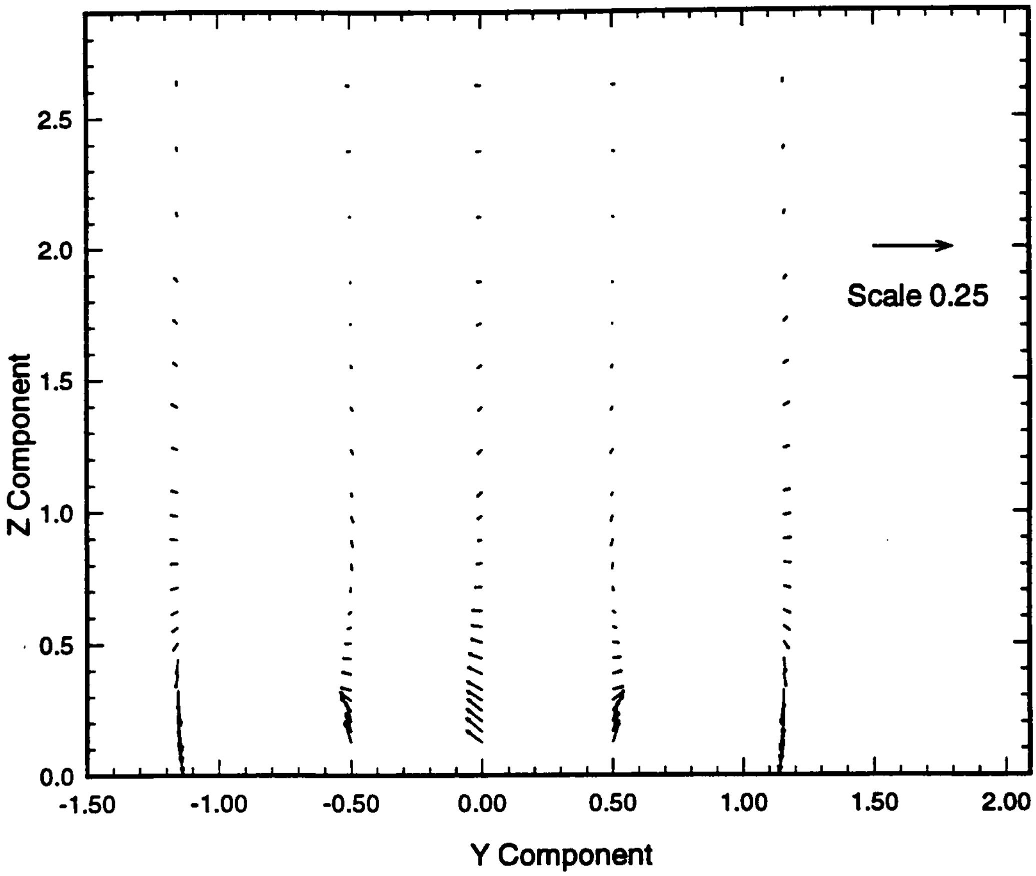


Figure 21 : Cone Probe velocity vector plots at the cavity's trailing edge for Mach number of 0.7 and no mass injection.

measured. Theoretically this cross flow should not exist because of the assumption that the tunnel flow has a mid-plane symmetry. The probe may not have been exactly lined up with the centerline of the tunnel flow, or the cavity giving measurements off the plane of symmetry. Figure 21 shows that a small amount of rotation is in the flow near the trailing edge possibly due to flow entrainment caused by the unsteady nature of the shear layer.

Figures 22 and 23 are vector plots at the same Mach number as figures 20 and 21, but with a mass injection rate, through plate 4, of 0.1 lbm/s. Figure 22 displays the measurements at the upstream location, and shows streamwise, rotational structures starting to develop above the cavity. These structures occur at approximately 0.5 inches above the floor of the tunnel. Although, there are no measurements to indicate such, the height that the vortex structures are observed in figure 22, seem to coincide with the point were the probe left the injection wedge as shown in figure 13. Vakili et al[21] had previously suggested the existence of the streamwise vortices and their relative positions above the cavity. Their suggestion was based upon the results of their study, which evaluated the effectiveness of several mass injection distributions to reduce cavity aeroacoustic oscillations .

Water Table Experiments :

Figure 24 and 25 are VCR images photographed in the water table and then image grabbed using the technique as previously described. They show the effects of mass injection on both a single and double cavity arrangement. The flow conditions

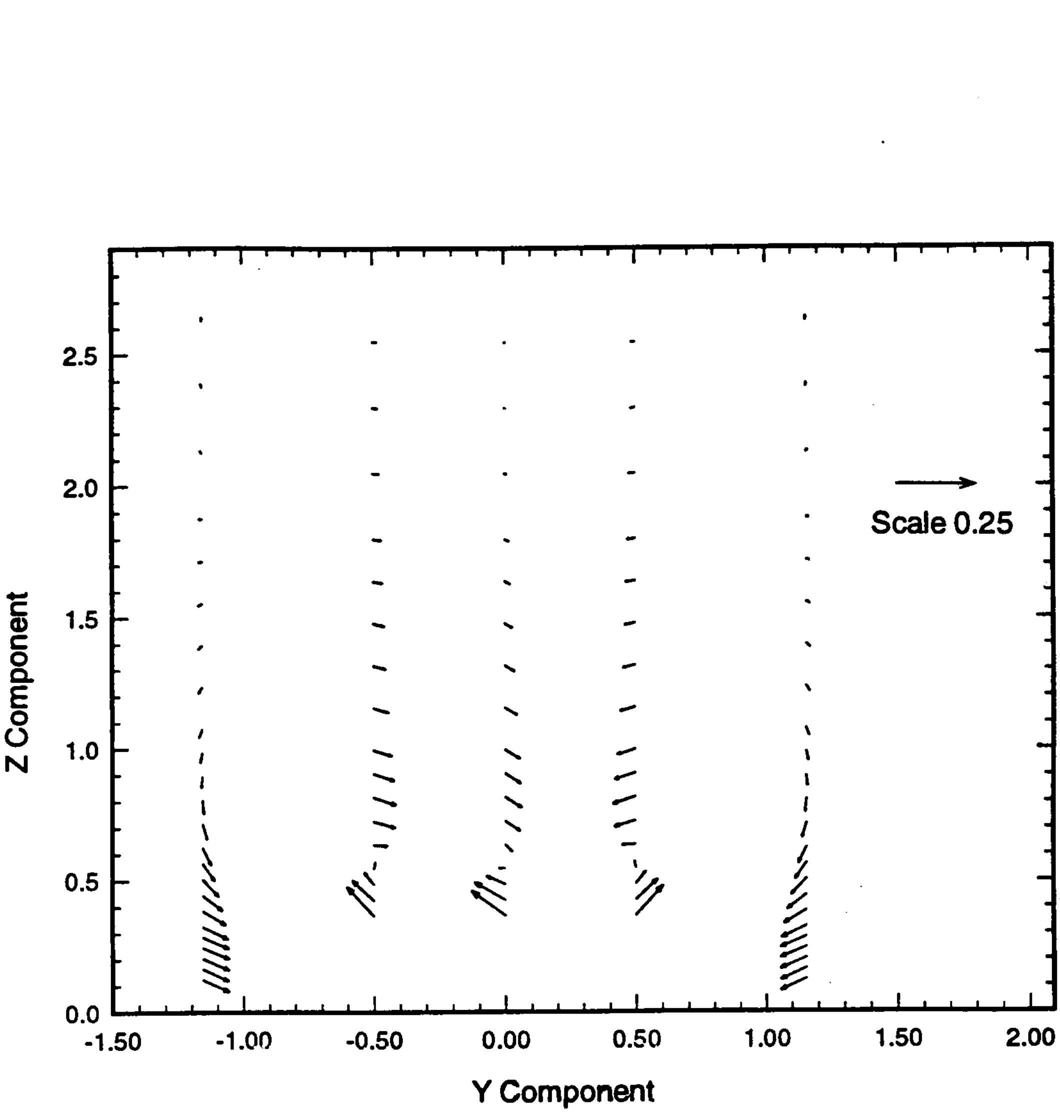


Figure 22 : Cone Probe velocity vector plots at the cavity's leading edge for Mach number of 0.7 and 0.10 lbm/s mass injection using plate 4.

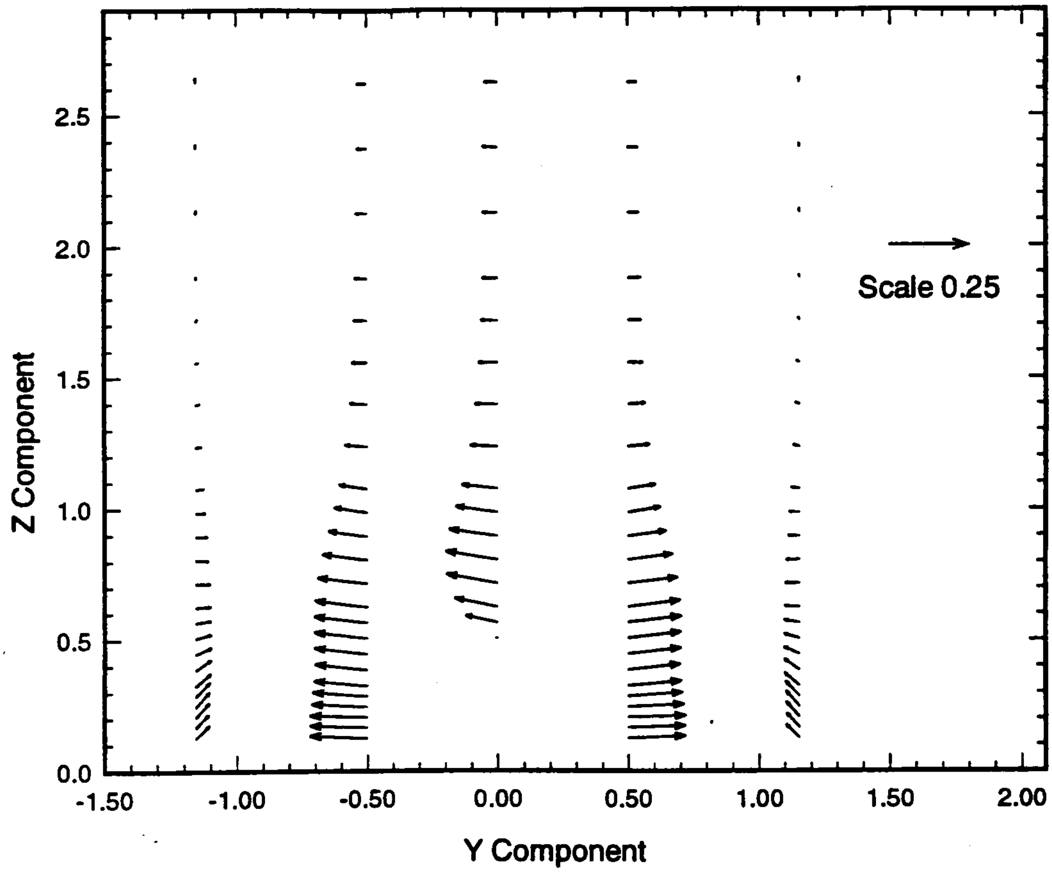
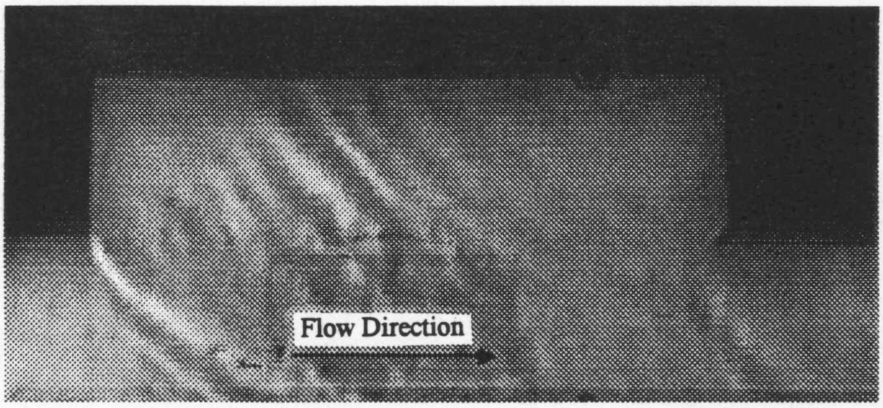
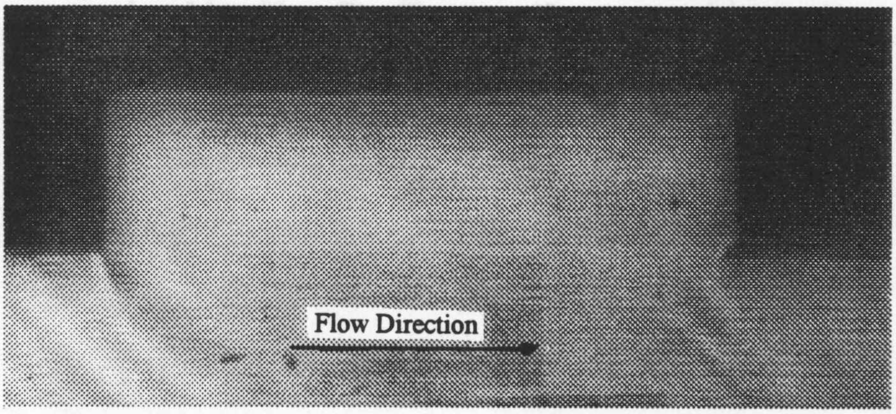


Figure 23 : Cone Probe velocity vector plots at the cavity's trailing edge for Mach number of 0.7 and 0.10 lbm/s mass injection using plate 4.



(a) Without Upstream Mass Injection

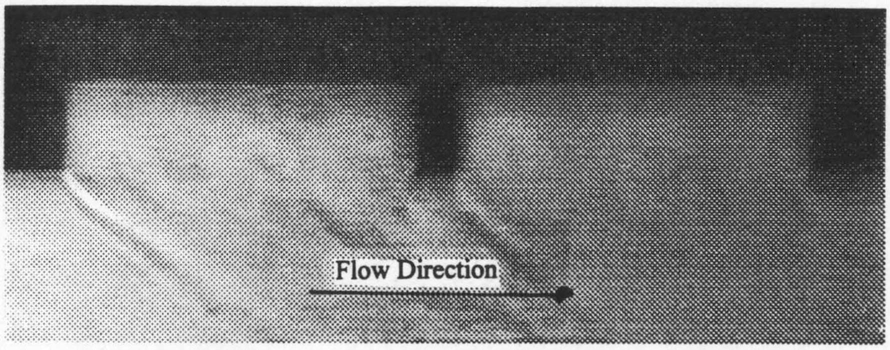


(b) With Upstream Mass Injection (4 gal/min)

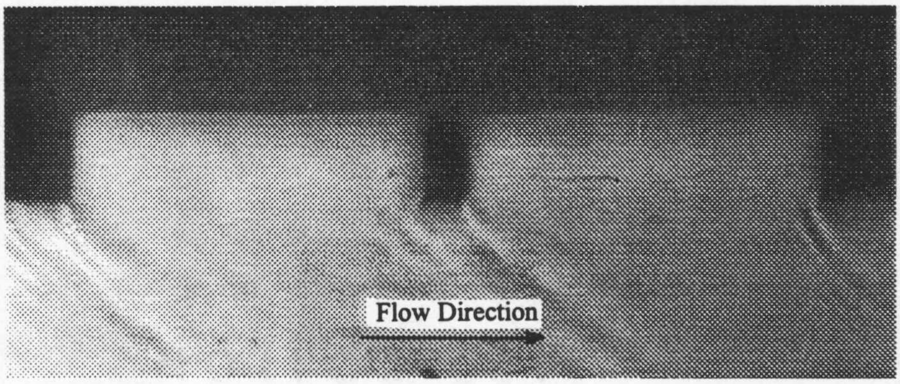
Figure 24: Photographs of water table single cavity arrangement.

represent a Froude number of 2.16. Figure 24 dramatically shows the effects of mass injection on a single cavity. In figure 24a, the wave pattern is reflecting downward into the cavity and later bounces off the floor and interacts with the shear layer near the trailing edge, something that Tam and Block[3] said could be a significant influence. Figure 24b shows how a mass injection rate of 4 gallons/min (0.56 lbm/s) affects the cavity flow. The flow is much smoother and much less chaotic. For a single cavity, with suction at the trailing edge, the pressure oscillations were still prevalent in the cavity.

Figure 25 shows how mass injection influences a double cavity arrangement. Close observations of figure 25a show that the leading cavity is perturbed, while the second cavity's pressure oscillations are not as severe. At higher mass injection rates figure 25b shows that both cavities seem to be less unsteady . Qualitatively this indicates that mass injection may also be sufficient to reduce cavity pressure oscillations in both single and double in-line cavity arrangements.



(a) Without Upstream Mass Injection



(b) With Upstream Mass Injection (4 gal/min)

Figure 25: Photographs of water table with double in-line cavity arrangement.

Chapter V

Conclusions

An experimental study of mass injection effects on cavity aeroacoustics has been performed for subsonic Mach numbers of 0.5, 0.7 and 0.8. Mass injection rates of 0.05, 0.10, 0.15 and 0.2 lbm/s were used with three different mass injection patterns. The following conclusions have been drawn:

- With a sufficient amount of upstream mass injection the attenuation of cavity pressure oscillations were between 12 and 17 dB.
- For a small range of Mach number between 0.68 and 0.72, the frequency of the peak amplitude was observed to switch between modes 3 and 2, respectively. The measured frequencies were in good agreement with predicted values calculated with the modified Rossiter's equation.
- Cone probe measurements indicate the presence of streamwise vortices, which may play a strong role in controlling the unsteadiness of the shear layer and reducing cavity pressure oscillations.
- The mass injection pattern of distribution played a critical role at Mach number 0.8 in amplitude reduction of pressure oscillations. This may be related to transonic effects and to differences in the way the streamwise vortices and transverse vortices interact with each other at the higher flow speeds.

- Preliminary flow visualization studies in a water table show that mass injection may also attenuate the aeroacoustics in a double in-line cavity arrangement. Also, suction at the trailing edge of the cavity was appears to be much less effective in reducing cavity pressure oscillations.

List of References

References

1. Krishnamurty K., "Acoustic Radiation from Two-Dimensional Rectangular Cutouts in Aerodynamic Surfaces", National Advisory Committee For Aeronautics TN 3487, August 1955.

2. Rossiter J.E., "Wind Tunnel Experiments on the Flow over Rectangular Cavities at Subsonic and Transonic Speeds," Royal Aircraft Establishment ARC R&M 3438, 1966.

3. Tam, C. K. W. and Block P. J. W. , "On the Tones and Pressure Oscillations induced by Flow Over Rectangular Cavities," *J. Fluid Mech.* (1978), vol 89, pp. 373-399.

4. Heller H.H. and Bliss D., "The Physical Mechanism of Flow Induced Pressure Fluctuations in Cavities and Concepts for their Suppression," AIAA Paper 75-491, 1975.

5. Komerath, N.M., Ahuja, K.K., and Chambers, F.W., "Prediction and Measurement of Flows Over Cavities - A Survey," AIAA Paper 87-0166, 1987.

6. Reshotko, E., "Stability and Transition, How Much Do We Know," ASME, New York, 1987, pp. 412-434.

7. Rockwell, D. and Naudascher, E., "Review - Self Sustaining Oscillations of Flow Past Cavities," ASME Journal of Fluids Engineering, Vol. 100, NO. 2, June 1978, pp. 152-165.

8. Vakili, A.D. and Gauthier C., "Control of Cavity Flow by Upstream Mass Injection," AIAA Journal of Aircraft, Vol. 31, No.1, Jan-Feb 1994, pp 169-174.

9. Schatt, D.E., "Suppression of Cavity Oscillations Using Upstream Mass Injection," M.Sc Thesis, The University of Tennessee, Knoxville, Tennessee 1992.

10. White, F.M., *Viscous Fluid Flow*, McGraw-Hill, Inc., Second Edition, ©1991, pg 524.

11. Fernandez, F.L., and Zukoski, E.E., "Experiments in Supersonic Flow with Large Distributed Surface Injection," *AIAA Journal*, Vol. 7, No. 9, 1969, pp. 1759-1767.

12. Lambert, E.P., "Measurement of the Shear Layer Over a Cavity with and without Upstream Mass Injection," M.Sc. Thesis, The University of Tennessee, Knoxville, Tennessee, 1993.

13. Buell D.A.,"An Experimental Investigation of the Airflow Over a Cavity with Antiresonance Devices", NASA TN D-6205, 1971.

14. Carr D.L.,"An Experimental Investigation of Open Cavity Pressure Oscillations," M.Sc. Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, GAE/AE/74S-1, 1974.

15. Marquardt M.F.,"An Experimental Investigation of Pressure Oscillations in Two-Dimensional Open Cavities,", M.Sc. Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, GAE/AE/75D-14, 1975.

16. Wilcox F.J. Jr., "Experimental Measurements of Internal Store Separation Characteristics at Supersonic Speeds," NASA Langley Research Center, Hampton, Virgina, Presented at the Store Carriage, Integration, and Release Conference, Organized by the Royal Aeronautical Society, Bath, England, April 4-6, 1990.

17. Franke, M.E. and Carr, D.L., "Effect of Geometry on Open Cavity Flow-Induced Pressure Oscillations," AIAA paper 75-492, 1975.

18. Stallings R.L., Plentovich E.B., Tracey M.B., and Hemsch, M.J., "Effect of Passive Venting on Static Pressure Distributions in Cavities at Subsonic and Transonic Speeds," NASA TN 4549, June 1994.

19. Shaw L.L., "Suppression of the Acoustic Environment in an Irregularly Shaped Cavity with an Opening exposed to Subsonic Flow," Annual Symposium on Aerospace Science and Technology 10th Proceedings (A4-38876, 18-01), New York, AIAA, 1984, pp 331 to 335.

20. McGregor O.W. and White R.A., "Drag of Rectangular Cavities in Supersonic and Transonic Flow Including the Effects of Cavity Resonance", AIAA Journal, Vol. 8, No. 11, November 1970, pp 1959-1964.

21. Vakili, A.D, Cooper, G.C., and Schatt, D.E., "Effect of Upstream Mass Injection Patterns on Cavity Flow Aeroacoustics," Experimental Heat Transfer, Fluid Mechanics and Thermodynamics 1993, pp 1157-1164.

22. Vakili, A.D., Wolfe R., Nagle, T., and Lambert, E., "Active Control of Cavity Aeroacoustics in High Speed Flows," AIAA paper 95-0678, 1995.

23. Vakili, A.D., Wolfe R.C., and Nagle, P.A., "Active Control of Cavity Aeroacoustics," The University of Tennessee Space Institute, To be presented in Germany June 1995.

24. Taylor M., "Cavity Flow Oscillation Analysis and Water Table Simulation," M.Sc. Thesis, The University of Tennessee, Knoxville, Tennessee, 1989.

25. Gauthier, C.R.,"Experimental Study of Cavity Flow Oscillations with Upstream Mass Injection," M.Sc. Thesis, The University of Tennessee, Knoxville, Tennessee, December 1990.

26. Wolfe, R.C., "An Investigation of the Effects of Upstream Mass Injection on Cavity Aeroacoustics," M.Sc Thesis, The University of Tennessee, Knoxville, Tennessee, May 1995.

Vita

Paul Anthony Nagle was born on the 4 of September 1968 in Portland, Oregon. He attended High School at Post Falls High School and graduated in 1987. He spent three years at George Fox College in Newberg, Oregon where he was enrolled in a 3-2 pre-engineering program. His 3-2 program turned into a 3-3 while he attended Washington University in St. Louis, Missouri. In 1992 he received a B.S in Applied Science from George Fox College and a year later in 1993 he graduated from Washington University with a B.S. in Mechanical Engineering.

In the summer of 1993 he entered the Graduate school at the University of Tennessee Space Institute. In the spring of 1995 he became employed at Sverdrup Technology in Tullahoma, Tennessee and in May of the same year graduated with a Masters of Science degree in Mechanical Engineering from the University of Tennessee Space Institute under the tutelage of Dr. Ahmad Vakili.