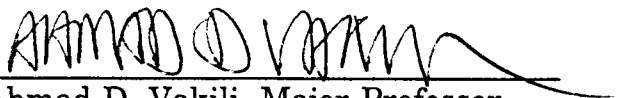
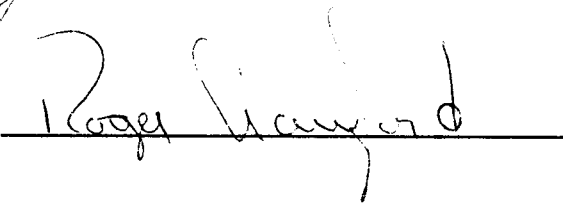


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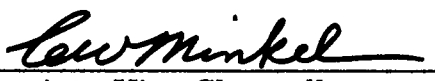
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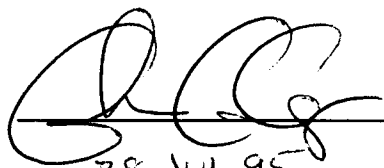

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**AN EXPERIMENTAL STUDY
OF MASS INJECTION PATTERN EFFECTS
ON CAVITY OSCILLATIONS**

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

Glenn Christopher Cooper
August 1995

DEDICATION

This thesis is dedicated to my true and faithful friend, Beth, who is also my beautiful wife. Her unwavering love is the source of my strength.

ACKNOWLEDGMENTS

To merely acknowledge my major professor, Dr. Ahmad D. Vakili, does not do justice to all of his gracious contributions. The guidance, foresight, encouragement and seemingly limitless patience he has provided are the primary impetus behind the completion of this work. He has my deepest admiration and appreciation.

ABSTRACT

An experimental study was performed to investigate the effects of mass injection on the suppression of aeroacoustic interaction in an open, rectangular cavity in supersonic flow. The oscillatory behavior of flow over a cavity can induce substantial pressure fluctuations and result in a potentially detrimental environment. Through the use of upstream mass injection, boundary layer and shear layer growth were enhanced, and the aeroacoustic effects were attenuated and, in some cases, virtually eliminated.

The injectant was introduced perpendicular to a supersonic freestream through a series of small holes. Freestream Mach number was held constant at a nominal $M=1.8$. Additionally, the pattern of the injectant holes was varied to study three-dimensional and various vortical interactions induced by the hole patterns. Acoustic data and boundary-layer surveys were obtained for each injectant model and for various injectant flow rates.

Mass injection upstream of an open cavity was shown to be an effective method of attenuating cavity aeroacoustics. Variation of the injectant hole patterns demonstrated that three-dimensional interactions can also be an effective means of aeroacoustic suppression; however, the hole pattern which most closely approximates a two-dimensional injectant/freestream interaction produced the maximum attenuation of the patterns considered.

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LIST OF SYMBOLS

B_c	- Cavity blowing parameter
D	- Cavity depth
K_v	- Constant for convective velocity in Rossiter's model
L	- Cavity length
L/D	- Cavity length-to-depth ratio
ℓ	- Length of mass injection
M	- Mach number
S	- Strouhal number
U	- Velocity
f	- Frequency
m	- Mode number for cavity oscillations
$\dot{m}$	- Mass flow rate
n	- Constant for interaction delay in Rossiter's model
δ	- Boundary layer thickness
ρ	- Air density
θ	- Momentum thickness
γ	- Specific heat ratio

Subscripts

c	- Cavity
$cavity$	- Cavity
e	- Outer edge of boundary layer
Inj	- Injection
o, ∞	- Freestream
w	- Wall

CHAPTER I

INTRODUCTION

BACKGROUND

Throughout the evolution of aircraft design, higher performance has always been the driving motivation behind expanding technological horizons. Reduction of aerodynamic drag, as a result, became a primary consideration in the design process. The most obvious method to obtain such decreases in drag is to streamline the vehicle by internally carrying all hardware not essential to a given mode of flight, such as landing gear, fuel tanks, cargo, ordnance, and other mission-oriented equipment.

While the subject equipment is not in use, the spaces in which it is stowed are enclosed by streamlined doors and fairings; however, at some time during flight operations, the concealed hardware is usually deployed into the air flow immediately surrounding the vehicle. The aerodynamically protected storage spaces then become open cavities exposed to the freestream environment. This subjects the stowed equipment to a wide range of aerodynamic flow and pressure fluctuations that could potentially impede the proper deployment and operation of the hardware at the least, and be destructive to vehicle integrity at worst.

As the cavity is exposed to the external flow, the development of a shear layer ensues and the contents of the cavity are subsequently subjected to a highly dynamic environment of fluctuating pressures. Depending on the freestream conditions and the cavity geometry, the shear layer's flow structure is modified and externally forced, developing oscillatory fluctuations

with natural, or preferred frequencies. These fluctuations often excite the natural acoustic frequencies of the cavity, resulting in acoustic resonance. This is referred to as cavity aeroacoustics.

Many investigations have been performed in an attempt to understand the dynamics of flow over an open cavity. Covert (Ref. 1) gives a historical perspective of cavity-flow research, referencing scientific efforts dating as far back as the 1870's. Stallings and Wilcox (Ref. 2), on the other hand, offer a summary of more recent efforts.

Efforts to reduce acoustic radiation and other adverse effects, such as aerodynamic drag and vehicle structural fatigue, have been almost as extensive as the studies of cavity flow. A wide range of flow regimes has been examined, from low subsonic speeds oriented toward the operation of landing gear, to high transonic and supersonic speeds where effects on ordnance delivery and the deployment of mission-critical equipment are important concerns. Recent examples of such equipment include aircraft-borne telescopes utilized by NASA for deep-space investigative studies, and United States Air Force over-the-horizon infrared tracking devices.

The most effective method of controlling the cavity shear layer and, subsequently, its behavior in the cavity environment, is to enhance its growth. Shear-layer forcing, or sharply defining and organizing the flow structures within the shear layer, can create this effect. Ho and Huerre (Ref. 3) divided forcing methods into five categories. They are, in order of decreasing effectiveness: frequency control, mode switching control, phase control, streamwise-vortices control, and amplitude control. Frequency control is the method most often studied, since it is far and above the most effective means of suppressing cavity aeroacoustics. Control of streamwise vortices has also

received some attention.

Numerous techniques to obtain frequency control and, thus, acoustic suppression have been investigated. Most efforts have focused on the use of mechanical devices and cavity modifications. Examples include boundary-layer fences (both static and oscillating), various shapes of cavity doors, leading and trailing-edge ramps, and sloped surfaces instead of corners at the cavity edges. Considerable effort has also gone into using sawtooth spoilers and vortex generators as methods of controlling the shear layer. These devices generate streamwise vortices which, in turn, couple with the spanwise vortical structures within the shear layer. The interaction results in enhanced shear layer growth.

The methods of acoustic suppression listed above have shown some success. Their primary shortcoming, though, is that they tend to be "point" designs. In other words, while they may be effective in a given flow environment for a given cavity geometry, the effectiveness can be diminished or completely eliminated if the freestream conditions change, that is, a different flight condition is encountered. This logically leads to the need for an actively controlled suppression method.

GENERAL OBJECTIVE

Initially, the use of mass injection in association with cavity flow was utilized primarily for reducing aerodynamic drag (Ref. 4). The favorable results from these efforts point logically toward the hypothesis that corresponding reductions in cavity acoustic levels were also achieved.

Efforts aimed at specifically decreasing the aeroacoustic environment have involved a wide variety of mass-injection methods. These include

introducing the injectant within the cavity along its floor (Ref. 5), at the cavity's leading edge (Ref. 6), and upstream of the cavity itself (Refs. 7, 8, 9, and 10). Each method obtained some measure of success at attenuating acoustic levels within the cavity.

In the experimental study presented here, the primary means of achieving the desired results was control of the shear layer which develops across the cavity opening. Specifically, the boundary layer upstream of the cavity was modified by mass addition, or blowing, and the shear layer growth and stability were controlled through variation of the upstream injection. This concept was investigated by Vakili et al. (Ref. 7) and Taylor (Ref. 8) using a water table. Gauthier (Refs. 9, 10) expanded on their work by investigating the effects of upstream mass-addition in supersonic flow. Using a uniform, two-dimensional injection pattern, Gauthier attained significant sound pressure level (SPL) reductions. A natural experimental progression would suggest investigating the effects of three-dimensional injection patterns on cavity aeroacoustic attenuation.

The work presented here includes a limited reproduction of Gauthier's experimental data, and an expansion of his work through the use of five mass-injection patterns. The "baseline" acoustic data were gathered without any mass injection. Data obtained using the two-dimensional injection pattern were compared to Gauthier's experimental data for determination of replication accuracy. Finally, the three-dimensional models were investigated and the effectiveness of each was compared to the two-dimensional results.

CHAPTER II

SHEAR LAYER FLOW DISCUSSION AND TECHNICAL REVIEW

The major thrust of this work is to investigate the use of upstream mass injection and the resulting three-dimensional disturbances to reduce the amplitude and, ideally, the formation of resonant acoustic frequencies in supersonic flow over a slender cavity. Accordingly, emphasis will be placed on reviewing previous research into suppression of the aeroacoustic oscillations associated with cavity flow.

DISCUSSION OF SHEAR LAYER FLOW

Kelvin-Helmholtz instabilities begin to develop almost immediately downstream from the leading edge in a free shear layer, and are the primary impetus behind its growth (Ref. 3). Downstream, the instability waves eventually develop into coherent spanwise vortical structures (Fig. 2.1). These large-scale structures create their own local shear layer interactions with the freestream flow, which results in small-scale vorticity sub-structures (Ref. 9). This brings about the dispersion of the shear layer's organized structures further downstream, and the shear layer subsequently degenerates into a turbulent wake.

If the shear layer's convective Mach number is supersonic, the vortical instabilities will remain small and cause little shear layer growth. This is primarily due to the lack of any feedback mechanism through which the effects of the downstream perturbations can influence shear layer development. That

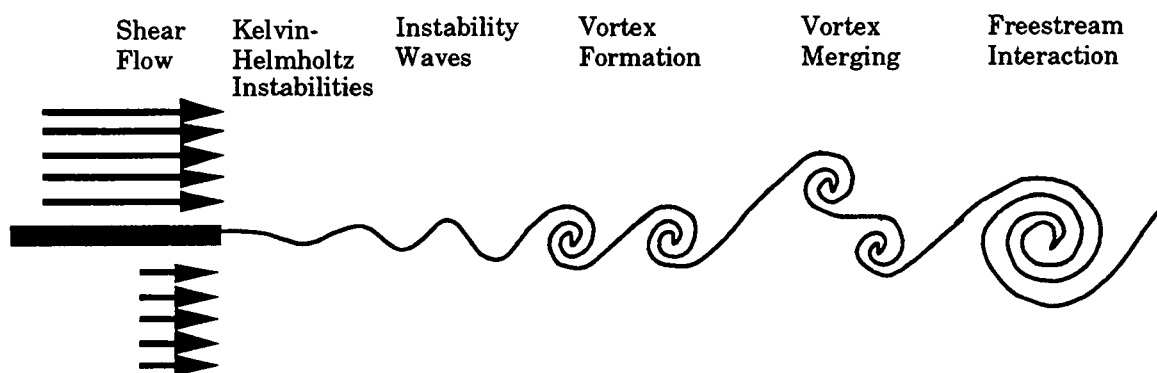


Figure 2.1. Development of a Free Shear Layer (Ref. 9)

is to say, since the shear layer is supersonic, downstream disturbances cannot propagate upstream. As a result, the coherent vortical structures actually remain relatively small.

For shear layer flow with a subsonic convective Mach number, as is the case with supersonic flow over a cavity with subsonic flow inside the cavity, the feedback mechanism does exist. Any disturbances generated by the large or small-scale structures propagate upstream to the shear layer's origin as pressure waves in the subsonic flow, thus modifying the development of the ensuing vortical structures. The shear layer continually self-adjusts in this manner until it arrives at its natural, or preferred modes of oscillation.

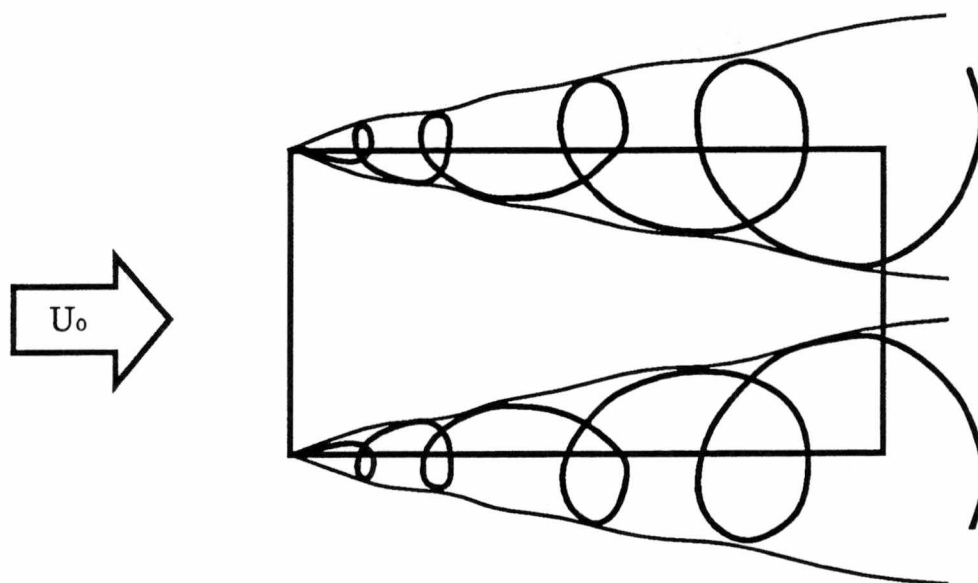
Shear layer development over a cavity is different from that of a free shear layer, but its fundamental behavior is similar. The primary differences lie in that the cavity acts as a forcing mechanism, which organizes a sharper definition of the vortical structures and enhances their growth. The impinging surface of the cavity's downstream edge provides an additional, powerful source of downstream disturbances which are, in turn, fed back to the shear layer's origin. The cavity channel, itself, is a confined pathway of relatively low-speed, subsonic flow, creating an environment conducive to the

propagation of the downstream perturbations. Additionally, as the freestream conditions change and the shear layer develops under the influence of the cavity's presence, resonance can result if the shear layer's preferred frequencies approach the natural acoustic frequency of the cavity.

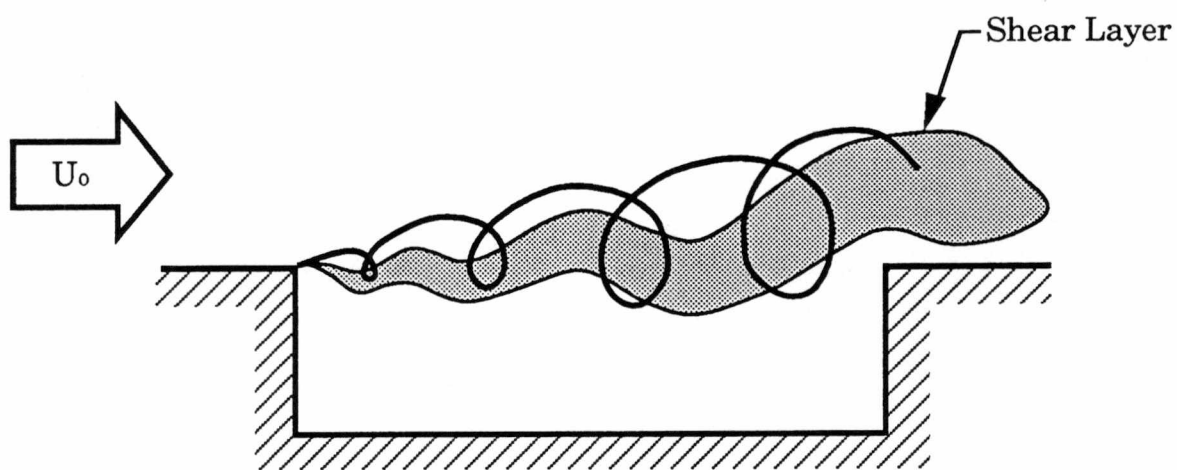
The impingement surface, or the downstream cavity edge, is the primary source of large-amplitude oscillatory motion in the cavity flow environment. It augments shear-layer-flow structural organization, making it similar to an external forcing mechanism. The shear layer's natural feedback mechanism is enhanced by the impingement surface, and the structural development of the shear layer, therefore, is essentially amplified by the cavity's downstream bulkhead (Ref. 9). There are two interpretations of the feedback mechanism at the impingement surface, both of which are dependent on the Mach number of the external flow.

The first is described by Tam and Block (Ref. 11). They observed that streamwise vortices begin forming at the corners of the cavity leading edge in low-speed subsonic flow. The vortices interact with the shear layer's spanwise vortical flow, and complex coupling ensues (Fig. 2.2). The upstream perturbations result from the splitting of these large-scale vorticity structures.

The second interpretation pertains to supersonic flow. In this instance the shear layer's natural sinusoidal motion is the predominant factor in causing impingement on the trailing edge. The large mass exchange proposed by Heller and Bliss (Ref. 12) permits the high-energy external flow to impinge upon the rear bulkhead in an oscillatory manner, creating strong disturbances which are fed upstream through the cavity to the leading edge. This is representative of a fluid-resonant-type flow, which will be discussed below. With either interpretation, the cavity's acoustic properties are the primary



Top View



Side View

Figure 2.2 Streamwise Vortical Flow Interaction

cause of the shear layer's specific structural modification.

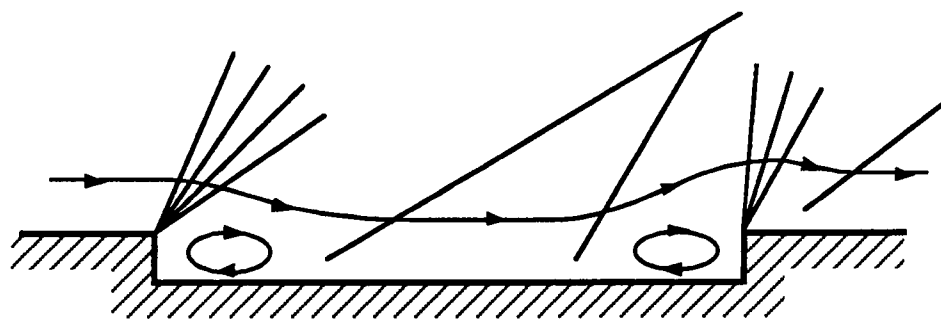
CAVITY FLOW REVIEW

Extensive research and analysis of flow past cavities have been performed, and a very brief review is presented here. A thorough technical review of this field was compiled by Komerath, et al. (Ref. 13), while more recent efforts at modeling supersonic flow over shallow cavities have been summarized by Stallings and Wilcox (Ref. 2).

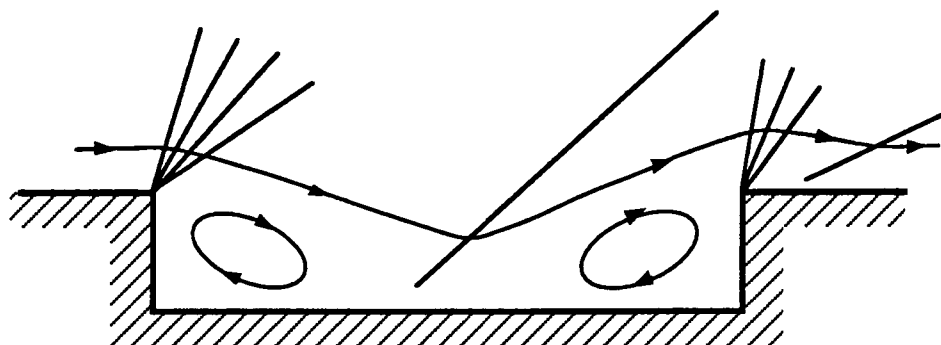
Chen (Ref. 14) divided cavity flow into three general categories. Defining a "shallow" cavity as one with a length-to-depth ratio (L/D) greater than one, the flow categories are as follows (Fig. 2.3):

- 1) "Closed" cavity flow - the shear layer reattaches to the cavity floor, and a second separation occurs at the cavity trailing edge. This is associated with high L/D cavities.
- 2) "Transitional" cavity flow - the shear layer may reattach at any point on the cavity floor, trailing edge or farther downstream, or any combination of the three.
- 3) "Open" cavity flow - the shear layer reattaches at or downstream of the cavity trailing edge, typically seen in flow over low L/D cavities.

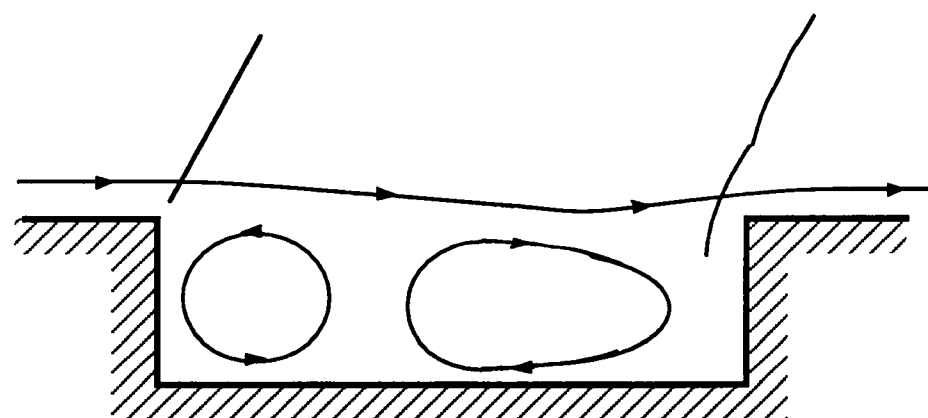
Open cavity flow can be further subdivided into flows dominated by longitudinal (lengthwise) and normal (depthwise) disturbances. Longitudinal disturbances consist of a system of streamwise vortices generated at the cavity leading edge. Krishnamurty (Ref. 15) proposed that these vortical structures produce regular, periodic, high-intensity sound waves by coupling



Closed Cavity Flow



Transitional Cavity Flow



Open Cavity Flow

Figure 2.3 Cavity Flow Field Models (Ref. 2)

with the shear layer's spanwise vortical fluctuations, resulting in strong acoustic radiation.

Rossiter (Ref. 16) divided cavity flow into two components, random and periodic. As L/D decreases from 4, he found that the periodic component dominates the cavity oscillations, and that random fluctuations dominate flow over cavities with L/D larger than 5. He theorized that vortex shedding from the cavity leading edge augments instabilities in the shear layer, which causes high-energy external flow impingement at the trailing edge (Fig. 2.4). This results in a perturbation which travels upstream through the cavity and reflects off the forward bulkhead. The reflected acoustic wave enhances the leading edge vortex shedding, and the process becomes self-sustaining.

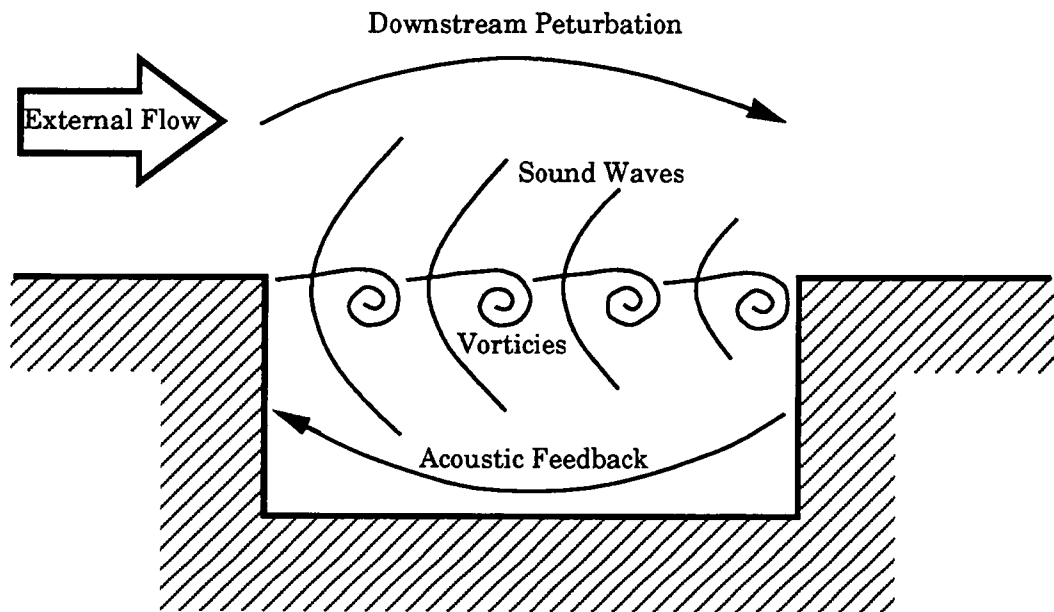


Figure 2.4 Rossiter's Open Cavity Flow Model (Refs. 9 & 16)

Taking into account the time for the entire process to complete one cycle, Rossiter was able to formulate the following equation yielding all possible

excitation frequencies.

$$S = \frac{fL}{U_0} = \frac{(m-n)}{M + \frac{1}{K_v}} \quad (2.1)$$

where S is the Strouhal number, L is cavity length; U_0 is the freestream velocity; m is the integer mode; n is an empirical constant that accounts for the phase shift between vortices and acoustic-pulse time delays from flow interactions with the cavity's rear corner; M is the freestream Mach number; and K_v is an empirical constant representing the ratio of the speed of convection of the vortices to the freestream flow speed. Rossiter's equation produced fairly accurate predictions for all possible frequencies at subsonic and transonic conditions.

Through the use of water table experiments Heller and Bliss (Ref. 17) and Heller et al. (Ref. 18) proposed that shear layer oscillatory motion for flow over a cavity was caused by mass addition and removal. Figure 2.5 shows a detailed sequence of the shear layer/pressure wave interaction (Ref. 12). Reflection of the waves caused by shear layer impingement on the trailing edge travel upstream and reflect off the forward bulkhead. The acoustic wave interacts with the shear layer causing oscillatory disturbances that, in turn, result in mass addition/removal at the trailing edge.

In developing his equation to predict cavity excitation frequencies, Rossiter assumed that the speed of sound in the cavity to be the same as the free-stream speed of sound. This introduces substantial errors at supersonic Mach numbers. Heller, Holmes and Covert (Ref. 19) modified Rossiter's equation to improve its applicability at supersonic speeds.

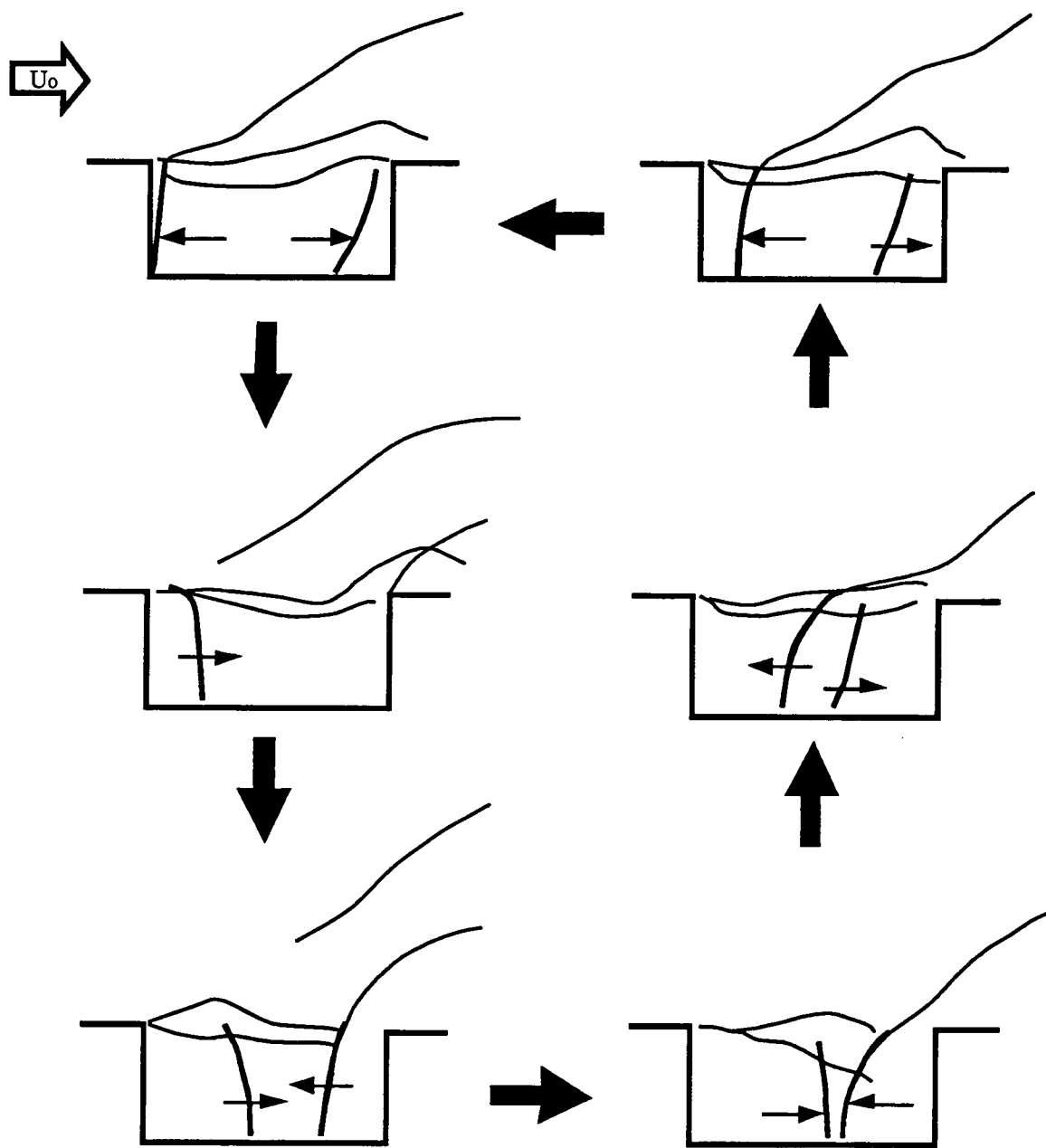


Figure 2.5 Heller and Bliss's Mass Addition and Removal Model (Ref. 17)

$$S = \frac{fL}{U_0} = \frac{(m-n)}{\left[\frac{M}{\sqrt{1 + \frac{(\gamma-1)}{2} M^2}} + \frac{1}{K_v} \right]} \quad (2.2)$$

Also taking issue with the substantial limitations of Rossiter's work, Tam and Block (Ref. 11) developed a mathematical model accounting for cavity dimensions and shear layer development. Although their work was limited to fairly low subsonic speeds, they were able to model the high energy impingement on the cavity trailing edge corner and resulting pressure wave. They were not successful, however, in modeling shear layer development over the cavity.

The mechanisms that support self-sustaining oscillations in cavity flow were grouped into three categories by Rockwell and Naudascher (Ref. 20). They are:

- 1) Fluid dynamic - typically associated with low speeds, the oscillations are caused by shear layer instability and vortex shedding. Large-scale coherent structures are thought to be important in the development of this type of flow.
- 2) Fluid resonant - the flow is dominated by acoustics and resonant wave propagation, and is usually seen at higher Mach numbers.
- 3) Fluid elastic - flow oscillations are coupled with system oscillations (elastic cavity boundaries).

The work reported here is concerned with fluid resonant flow.

Although numerous other investigations have been extensive (Ref. 2, 21, 22), a complete and thorough understanding of cavity flow has not been formulated. Several computational fluid dynamics efforts have also been initiated (Ref. 23, 24, 25). Suhs (Ref. 26) demonstrated results that compared well to wind tunnel data for Mach 0.74. The results for Mach 1.5 compared reasonably with experimental data except at the cavity trailing edge, where the lack of modeled viscous effects in the computer code caused the quality of the results to deteriorate. It should be noted that even with the use of super computers, these codes can take tens of hours of CPU time, thus demonstrating the need for further analytical and experimental work in cavity flow.

AEROACOUSTIC SUPPRESSION TECHNIQUES REVIEW

Suppression techniques typically attempt to reduce cavity-flow acoustic effects through modification of the shear layer development. By altering the upstream characteristics of the shear layer, its preferred frequencies can also be altered; therefore, it becomes possible to avoid excitation of the cavity's natural frequency response. Stabilization of the shear layer reduces the mass addition/removal process, and, consequently, the oscillatory behavior of the cavity flow as well. To this end, two major categories have emerged: the use of hardware and cavity geometry modification, and the use of an injectant inside or upstream of the cavity.

Mechanical and geometric modifications

Most mechanical modifications, sometimes referred to as passive methods, involve the use of spoilers and fences upstream of the cavity to

promote shear layer growth or merely deflect the shear layer away from the cavity downstream edge. The primary objective is to stabilize the shear layer vorticity characteristics and to enhance shear layer growth, $d\theta/dx$. Shear layer frequency forcing has also been attempted through the use of devices such as oscillating fences and pulsating injectants.

Cavity modifications, on the other hand, do not attempt to modify the shear layer's impact on the cavity trailing edge; rather, they are designed to lessen the effect of the impinging shear layer and the resulting perturbations. Such modifications typically include leading and trailing-edge ramps, or sloped surfaces in place of a sharp corner at the impingement point.

Heller and Bliss (Ref. 12) employed spoilers, or vortex generators, immediately upstream of the cavity in an attempt to increase the boundary layer momentum thickness and augment the three-dimensional instabilities inherent in the shear layer. They also used a slanted cavity trailing edge to eliminate the sharp corner onto which the shear layer could impinge. Mach number was varied from 0.8 to 2.0. At supersonic speeds, they were able to achieve a maximum acoustic reduction of 10 dB.

At about the same time, Franke and Carr (Ref. 27) performed a water table experiment to determine the effects of cavity geometry on flow-induced pressure oscillations. The most successful modifications were subsequently tested in wind-tunnel experiments at Mach 1.75 and 2.35. The double-ramp configuration shown in Figure 2.6 reduced the most severely resonant frequency by almost 25 dB.

Shaw (Ref. 28) used combinations of spoilers, ramps, and acoustic coatings to suppress the acoustic environment. At subsonic speeds (Mach 0.6 to 0.75), he was able to achieve an acoustic pressure reduction of 43 dB by

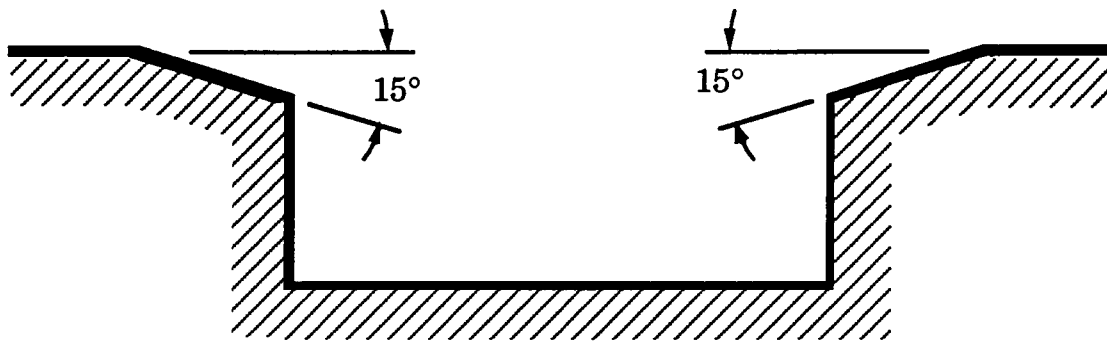


Figure 2.6 Leading- and Trailing-Edge Ramps (Ref. 27)

using a porous spoiler upstream of the cavity and coating the cavity walls with polyurethane foam.

A series of experiments were conducted by Clark (Ref. 29). He used sawtooth fences as acoustic suppression devices for several cavities of various L/D dimensions. The test was conducted at Mach numbers between 0.6 and 3.0. Clark noted that the baseline acoustic pressure increased in magnitude with Mach number, peaking at Mach 1.5 with readings on the downstream bulkhead. The noise subsequently decreased somewhat with increasing Mach number. Typical acoustic reductions due to the sawtooth fence were 10-12 dB.

Franke and Sarno (Ref. 6) experimented with three suppression devices: a static fence upstream of the cavity, a pulsating fence, and mass injection at the cavity leading edge. The Mach number was varied from 0.6 to 1.6. The mass injection portion of their experiment will be discussed in the next section.

It was determined that neither fence was effective at reducing the second-mode oscillations, but that the static fence did suppress the first mode. The oscillating fence was intended to mechanically force the shear layer, thus preventing it from achieving its own natural oscillation frequencies. Although successful at doing just that, the acoustic readings showed significant peaks at

the frequency of the fence oscillation; as a consequence, this was determined to have little positive effect on the aeroacoustic environment.

More recently, Dix and Butler (Ref. 22) amassed a large data base of cavity-flow parameters using numerous cavity configurations at Mach numbers ranging from 0.6 to 3.0. A vast array of bay doors, spoilers, and sawtooth fences were tested as suppression devices. These investigations found that leading edge spoilers are effective only in the subsonic and transonic regimes. The number of teeth on the sawtooth fence also proved to be important at subsonic speeds; this, however, was not a pertinent factor in supersonic flow. Indeed, at supersonic speeds, the fences had only limited effectiveness.

Dix and Butler did not explore cavity geometry modifications such as ramps and slanted edges. Their work was closely oriented toward the industry of aircraft design and development; consequently, they dismissed such alterations, noting that they place undue limits on aircraft designers and significant restrictions on the usable size of the weapons bay.

Instead of spoilers or fences, Smith, Gutmark, and Schadow (Ref. 30) conducted an experiment using patterns of small pins upstream of the cavity. Several pin configurations were tested, as were numerous pin diameters and heights. The experiment was performed at two Mach numbers, 1.8 and 2.6. Reductions of acoustic pressures were similar to those achieved with fences, approximately 10-12 dB.

The preceding examples of acoustic suppression efforts have primarily explored shear layer manipulation and growth as a means of damping cavity shear layer oscillation. The methods have included the addition of hardware and cavity geometry modifications to promote shear layer growth, modified

frequency response, and reduction of the energy imparted by shear layer impingement.

Kaufman, Maciulatis and Clark (Ref. 31) performed a similar experiment, but also made some noteworthy conclusions. Using the modified Rossiter's equation (Ref. 12), they determined that the constant, K_v , which is the ratio of vortex to freestream velocities, could be replaced with ratios experimentally determined as a function of Mach number. Improved results were achieved in the prediction of the first six modes for Mach numbers 0.7, 1.5, and 2.3. They encountered asymmetric flow within the cavity for certain flow conditions and cavity geometry, and noted the need for further investigation of the effects on side wall static pressures.

Their most significant observation, though, was the need for better methods of predicting sound pressure levels (SPL) of modal peaks in order to avoid a trial-and-error approach to acoustic suppression. This observation points to the shortcomings of cavity geometry modification and passive suppression devices. Such techniques are very dependent on Mach number, flow conditions, and specific cavity geometry, thus making them "point" designs. That is to say, while a given hardware addition may be adequately effective for a certain point in the flight profile, it may have no effect whatsoever if the flight conditions are changed even slightly. Indeed, Clark et al. found that certain fence configurations actually increased the SPL. This demonstrates the need for a method of actively controlling shear layer development over a cavity.

Injectant modifications

In order to prevent acoustic resonance in cavity flow, the shear layer

must be modified so that its preferred frequencies fall outside the cavity's natural frequency. Mass injection has been investigated as a method to stabilize shear layer oscillatory characteristics, and a review of those efforts follows.

Although he did not specifically use an injectant as a suppression device, Wilcox (Ref. 4) modified the cavity to make use of the oscillatory pressure fluctuations. Interested in decreasing cavity-induced drag, he performed an experiment with a porous cavity floor. Mach number was varied from 1.60 to 2.86. The high-pressure area caused by shear layer impingement on the trailing edge/corner was relieved through a series of holes at the downstream end of the cavity floor. The high-pressure air was then piped to the upstream portion of the cavity, where a relatively low pressure existed below the cavity leading edge. The resulting flow pattern is shown in Figure 2.7.

Wilcox states that through this technique he was able to cause a high L/D cavity to behave as though it had a lower L/D ratio; that is, certain cavities that naturally exhibit closed cavity flow can produce open cavity flow characteristics. Although drag reduction was the primary focus of this study, it seems reasonable to hypothesize that the magnitude of the cavity's acoustic environment was also reduced.

An experiment using a mass injectant as an aeroacoustic suppression device was performed by Sarohia and Massier (Ref. 5). Although the freestream Mach number of the experiment was low ($M=0.1-0.35$), they did achieve a significant reduction in shear layer fluctuation amplitudes by injecting air into the bottom of the cavity model.

Franke and Sarno (Ref. 6) introduced injectant air at the cavity leading edge at a 45-degree upward angle (into the freestream) and also parallel to the

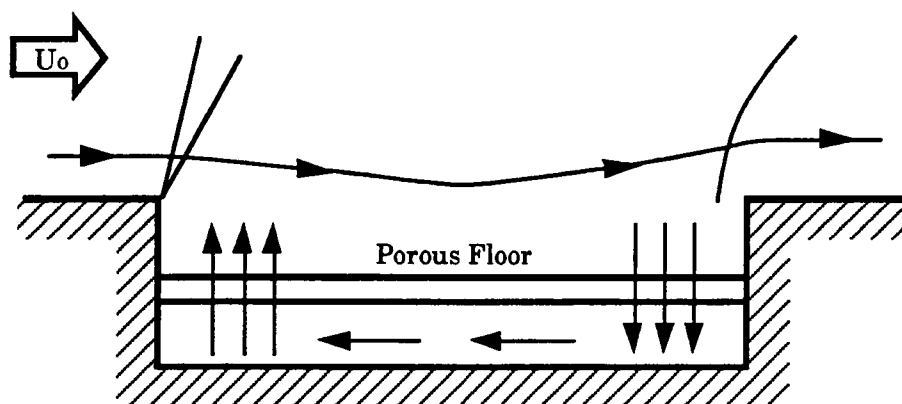


Figure 2.7 Porous Floor Cavity Flowfield (Ref. 4)

freestream. The angled flow had some success at attenuating both the first- and second-mode oscillations, reducing them by as much as 8 dB. The parallel flow, conversely, had little effect on the cavity acoustics. In fact, it was noted that with no external freestream flow, the parallel flow of injectant tended to excite the cavity acoustics in a fashion similar to the freestream with no suppression devices; that is, the injectant, itself, excited the cavity's natural modes of oscillation.

Attempting to simulate an ablative thermal protection system, Voorhees and Bertin (Ref. 32) used mass injection upstream of a cavity. Although not concerned with acoustic effects, their major conclusion was that a cavity with upstream mass injection exhibited the qualities of a shorter cavity without mass injection. In other words, like Wilcox's experiment, a cavity that naturally produced closed flow was shown to behave like a cavity with open flow.

Aeroacoustic control with upstream mass injection

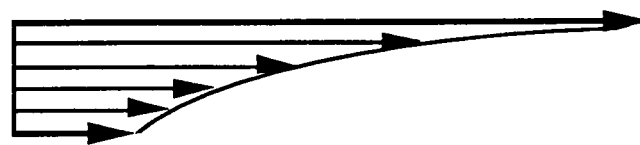
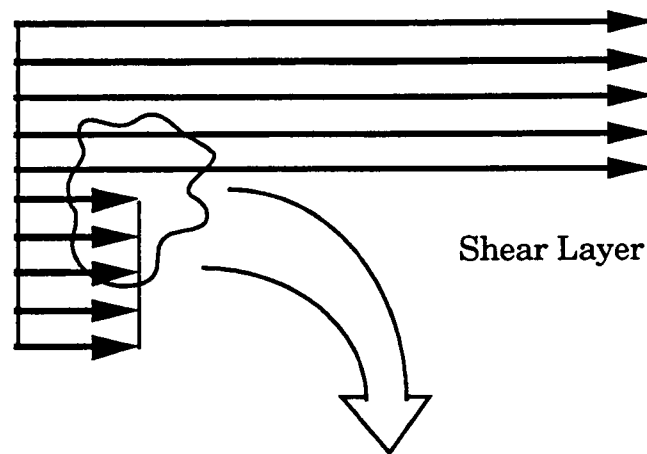
Another method of stabilizing the shear layer is to increase its

momentum thickness. The thicker shear layer has a weaker or smaller velocity gradient between the two flows which are, in this case, the freestream and the ambient cavity environment (Fig. 2.8). Since the gradient slope is less steep, the shear layer is inherently more stable. This, in turn, modifies the preferred frequencies.

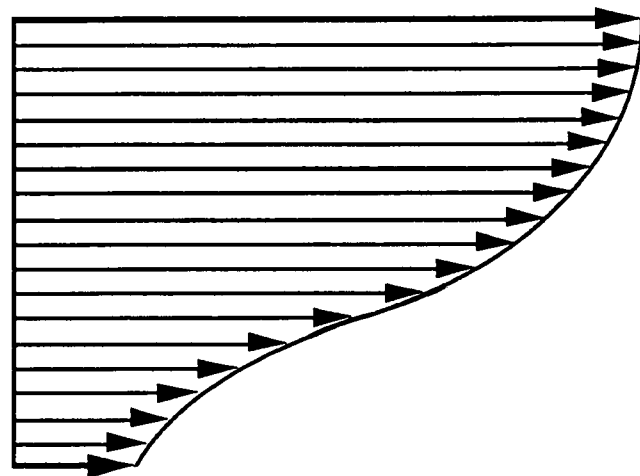
By injecting additional mass into the boundary layer upstream of the cavity, the shear layer's growth, or thickness, is enhanced and its responsiveness to perturbations is reduced (Fig. 2.9). An optimum mass-injection rate would prevent cavity resonance with a minimum amount of blowing. As freestream conditions change, however, so too would the ideal flow of injectant. In addition, it can be hypothesized that certain mass flow rates would adjust the shear layer's preferred frequencies to a harmonic of the cavity's natural frequency, again resulting in resonance. This stresses the need for active control of shear layer characteristics, and one in which upstream mass injection lends itself to a practical application.

The use of mass injection, or blowing, upstream of the cavity was initially investigated by Vakili et al. (Ref. 7) and by Taylor (Ref. 8). Taylor performed a water table experiment in which steady upstream blowing completely eliminated cavity-flow oscillations. Pulsed, out-of-phase mass injection was also investigated with limited success. The oscillations were initially attenuated, but subsequent to a frequency response shift, an increase in amplitude was observed.

In logical progression, Gauthier (Ref. 9) investigated the effects of upstream mass injection in supersonic air flow by installing a porous plate upstream of the cavity. The injection area was roughly the shape of a rectangle in order to achieve an essentially uniform, two-dimensional



Small Momentum Thickness
and Steep Velocity Gradient



Large Momentum Thickness
and Shallow Velocity Gradient

Figure 2.8 Effect of Thickness on Shear-Layer Velocity Gradient

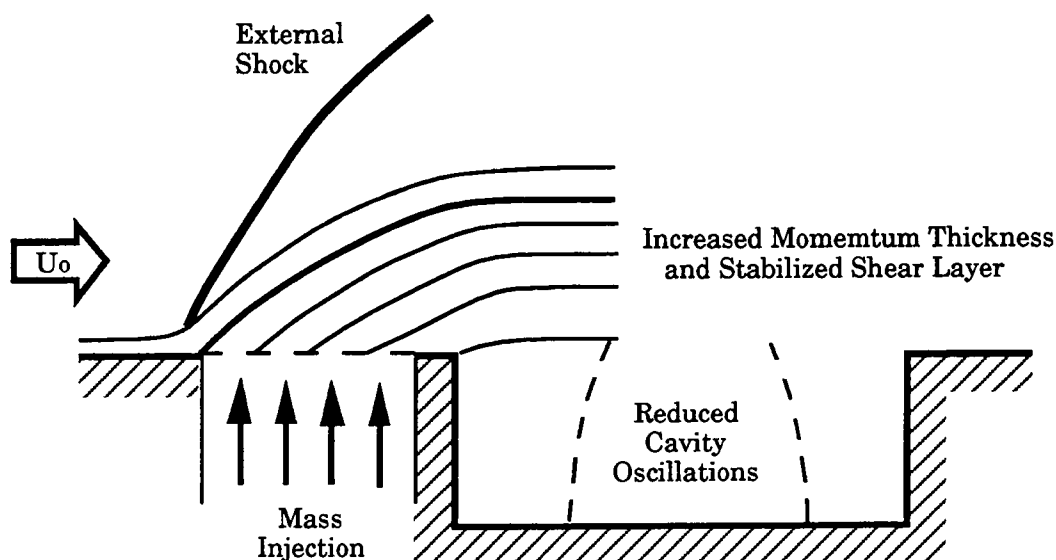


Figure 2.9 Shear-Layer Thickening through Upstream Mass Injection (Ref. 9)

distribution of injectant. As documented by Vakili and Gauthier (Ref. 10), significant acoustic attenuation was achieved for a cavity of $L/D=2.54$ at Mach 1.77 (Fig. 2.10). Virtual elimination of all primary frequency peaks was achieved (attenuation as high as 27 dB), while background noise was also significantly reduced.

Gauthier compared his results to predictions based on Fernandez and Zukoski's model (Ref. 33). He used the massive mass-injection model for his predictions. That is, enough mass is injected to result in large external-flow deflections; the skin friction is negligible when compared to the injectant momentum; the injectant momentum is small when compared to the freestream momentum; the injectant fluid lifts the boundary layer and external flow; and the two fluids form a mixing layer. A significant point in the Fernandez model, also, is that it assumes a two-dimensional flow. Except for very small blowing rates, the data from the experiment presented in this report, as well as Gauthier's experimental results, demonstrate large flow

curvature and flow separation. As a result, neither set of data correlates very well with Fernandez's predictions.

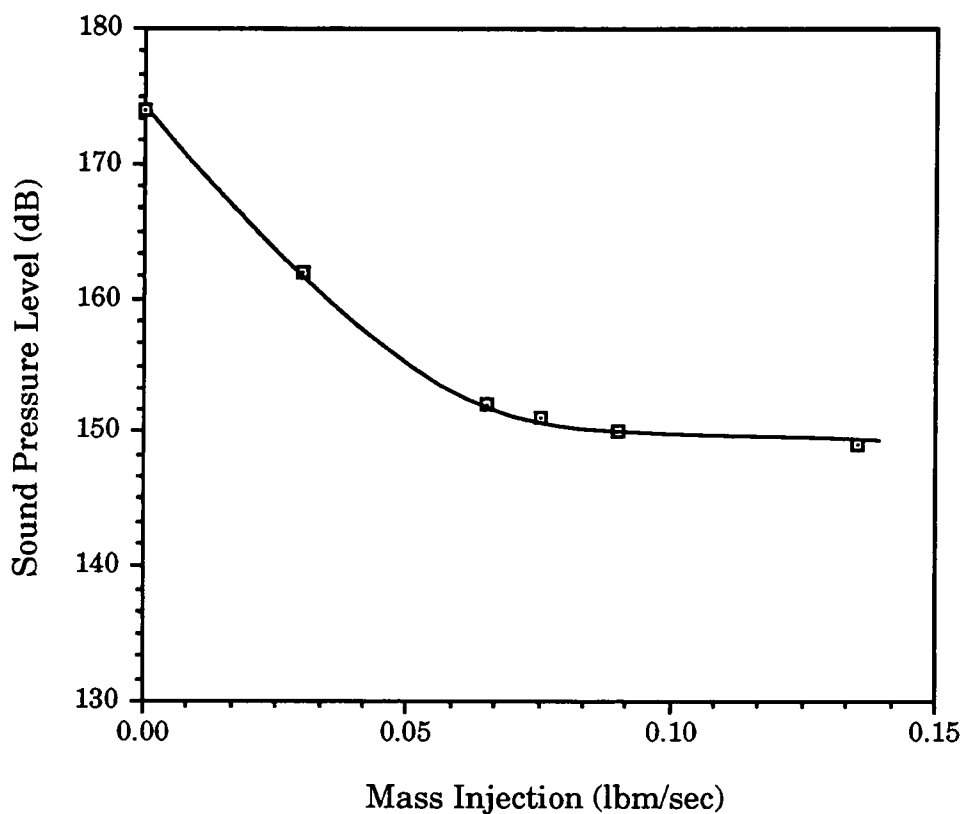


Figure 2.10 Cavity Oscillation Amplitude vs. Mass Injection (Ref. 9)

Fernandez developed a blowing parameter, which Gauthier, in turn, modified. The blowing coefficient, B_c , for the cavity is:

$$B_c = \frac{\rho_w u_w A_{inj}}{\rho_\infty u_\infty A_{cavity}} \quad (2.3)$$

where ρ_w and u_w are flow density at the wall surface, A_{inj} is the total area of the injectant holes, ρ_∞ and u_∞ are the freestream density and velocity, and

A_{cavity} is the area of the cavity. Gauthier used the parameter as another method of comparing the effectiveness of various mass flow rates.

The major conclusion drawn was that the cavity feedback mechanisms were restrained through the use of mass injection, although further investigation was required to determine the cause. Gauthier also noted a sharp initial reduction in the SPL. At higher injectant flow rates, though, the reduction became essentially constant.

It should be noted that the use of massive upstream mass injection not only modifies the boundary layer, but actually changes it into a shear layer before reaching the cavity environment. The injectant is introduced into the boundary layer in a direction perpendicular to the freestream, and the boundary layer accordingly develops a shear layer with the injectant; consequently, flow curvature and separation ensue. As a result, the flow that initially encounters the cavity environment is actually already a modified shear layer. The effects of this are discussed in Chapter IV. For clarity, the flow upstream of the cavity will be referred to as a boundary layer to prevent confusion with the shear layer that develops over the cavity.

The present study reported herein is founded on the work of Gauthier. Several injection plates with different hole patterns were tested at various mass-flow injection rates. The plates were designed with the specific intent of introducing three-dimensional blowing characteristics into the boundary layer upstream of the cavity, the effects of which were measured and analyzed.

CHAPTER III

EXPERIMENTAL METHODS AND PROCEDURES

This chapter will describe the wind tunnel facility used during the experiment, followed by a discussion of the test conditions. Wind tunnel flow quality is addressed, and finally, the procedures of the experiment are presented.

FACILITY DESCRIPTION

The study was performed in the University of Tennessee Space Institute Gas Dynamics Laboratories. The wind tunnel used is a blow-down facility with a nominal freestream Mach number of 1.8 (Fig. 3.1). The test section is eight inches square and approximately four feet long. The tunnel air supply is obtained from three 3000-psig storage tanks, which are filled with ambient air.

The mass injectant was supplied through a separate, small plenum chamber located immediately below the installed injection plate (Fig. 3.2). The source of this air is also separate from the tunnel air supply and is from a relatively low-pressure reservoir.

MODEL DESCRIPTION

The cavity model and injection plate were recessed into the test section floor immediately downstream of the tunnel nozzle exit (Fig. 3.2). The rectangular cavity dimensions are 3.813-in. long by 1.500-in. wide by 1.500-in. deep, giving an L/D value of 2.54.

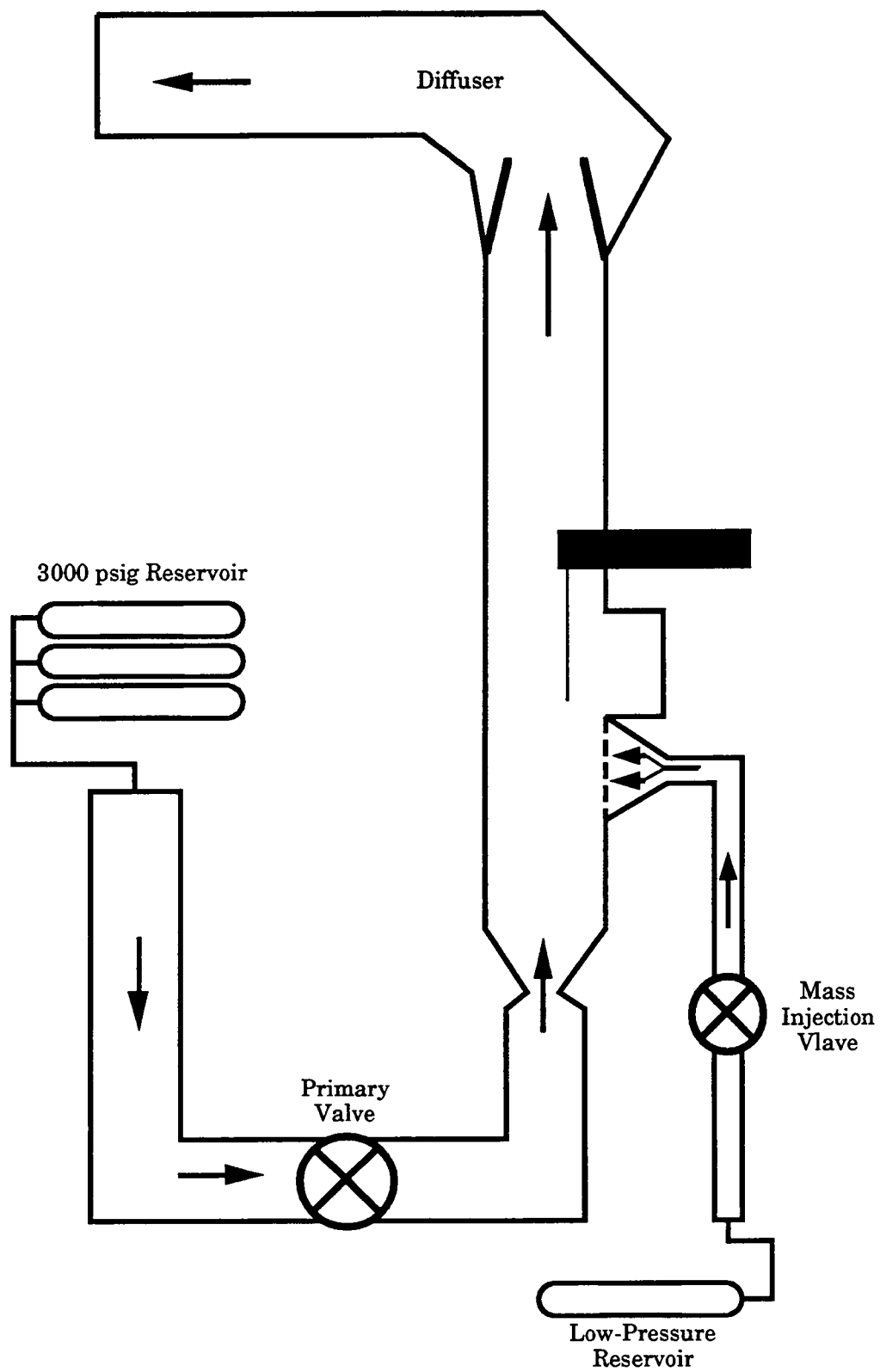


Figure 3.1 Schematic of Wind Tunnel

Each of the injection plates was perforated in one of six hole patterns, through which the air mass flow was injected. Figure 3.3 shows the various hole patterns; they will be referred to as the Rectangle (Ref. 9), Triangle, Inverted "T", Double Triangle, Inverted Triangle, and Inverted Trapezoid. Each plate at its widest (spanwise) point is slightly wider (1/16 inch on either side) than the cavity. The streamwise injection-area length, ℓ , was nominally equivalent for each of the models. Normalized with the cavity length, L , the Rectangle model, $\ell/L=0.509$, was used as a comparison baseline. The other models were designed to minimize injection length variation. Their injection lengths are as follows: the Triangle and Inverted Triangle both measure $\ell/L=0.544$; the Inverted "T" is $\ell/L=0.544$; and the Double Triangle measures $\ell/L=0.491$.

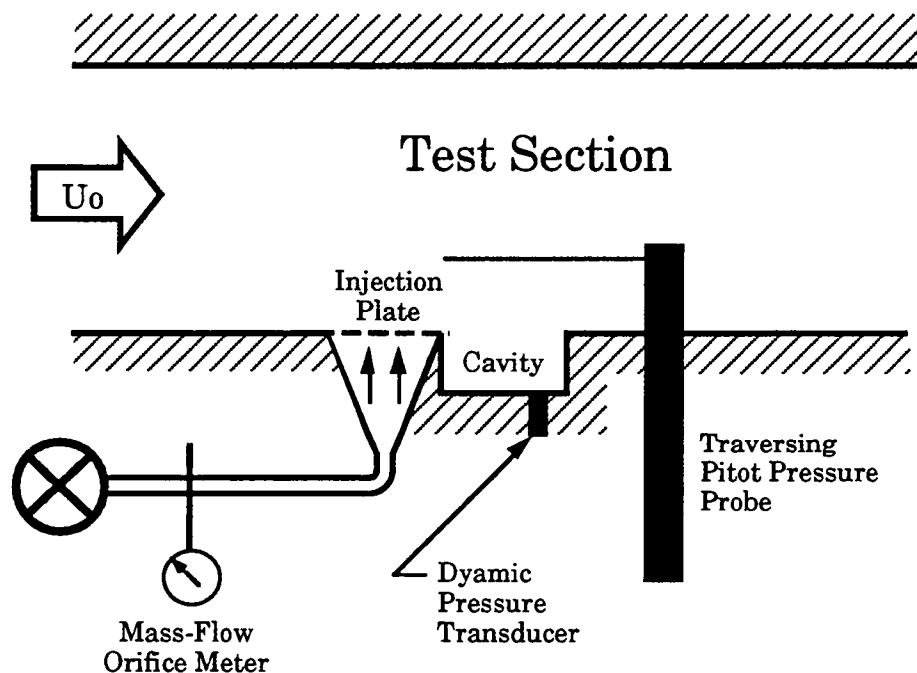


Figure 3.2 Schematic of Wind-Tunnel Test Section

The Inverted Trapezoid is the exception. It was designed to investigate the effects of terminating mass injection farther upstream from the cavity leading edge than the others; consequently, its injection length is $\ell/L=0.333$. The distance from the Inverted Trapezoid's injection pattern leading edge to the cavity leading edge was held equal to those of the two Triangle models.

It should be noted that Gauthier evaluated two hole "densities;" that is, the same number of holes were used in both of his injection plates, but the injection length was varied from $\ell/L=0.509$ (referred to as a "low density" pattern) to $\ell/L=0.255$ ("high density"). Since substantially greater acoustic attenuation was achieved with the low-density model, it alone is considered in this study. Indeed, the injection length of the plates fabricated for this test was also selected based on the improved results of the low-density model.

Individual hole dimensions remained consistent for each model; all holes were 1/32-in.-diam., and the relative position of the holes to one another was the same for each injection plate (Fig. 3.4). The hole dimensions were selected to provide uniform injectant flow and to remain consistent with Gauthier's work; thus, the only geometric parameter to be varied during the experiment was the overall hole pattern and, consequently, the number of holes per plate (area of injection).

The effect of varying the injection area was not determined during this study. An analysis of the influence of injection area would require injection plates with identical shapes but of differing areas. Since this experiment sought to primarily evaluate the effects of varying the injection area pattern, the acquired data do not lend themselves to a meaningful analysis of the effects of injection area variance.

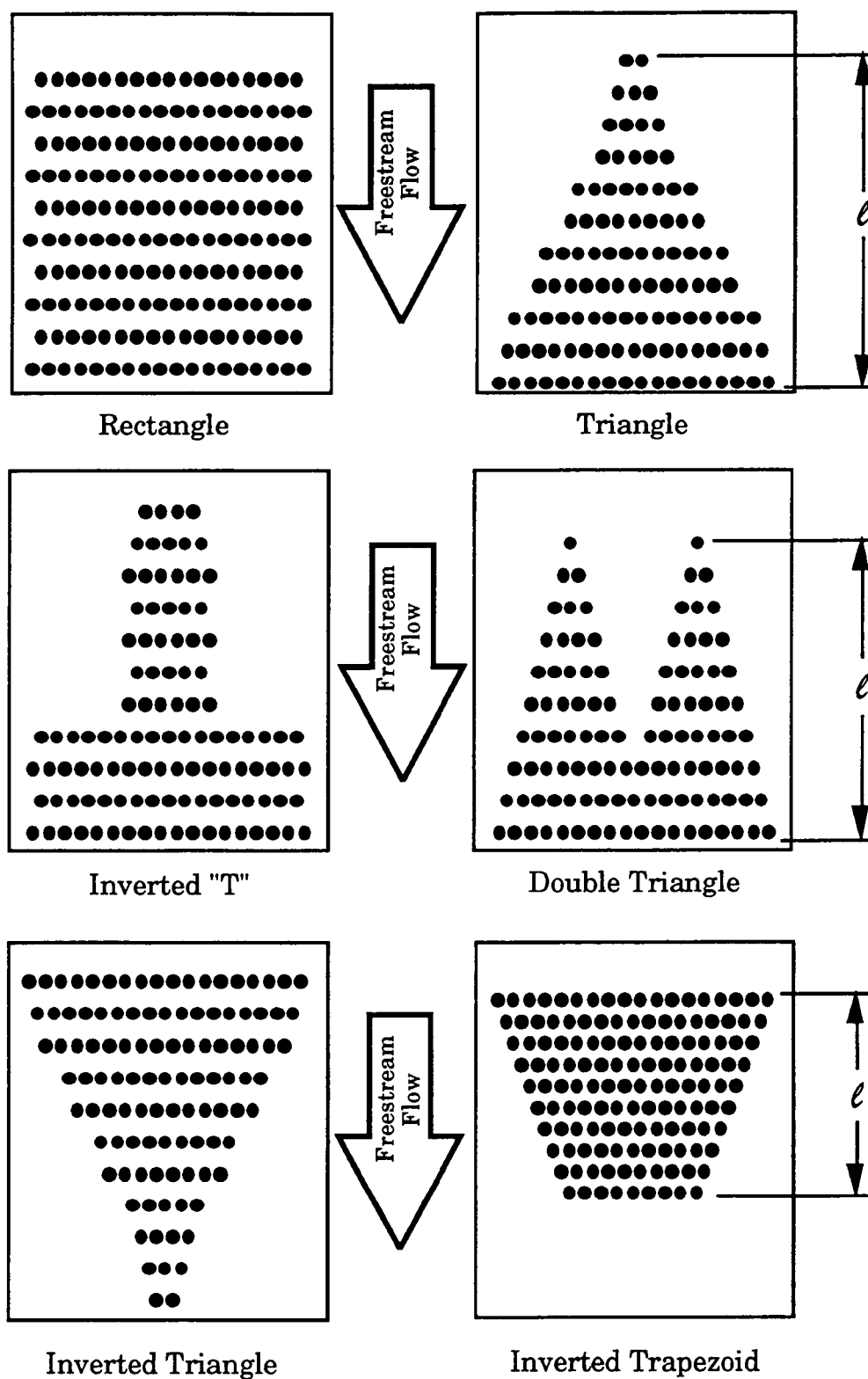


Figure 3.3 Mass-Injection Model Hole Patterns

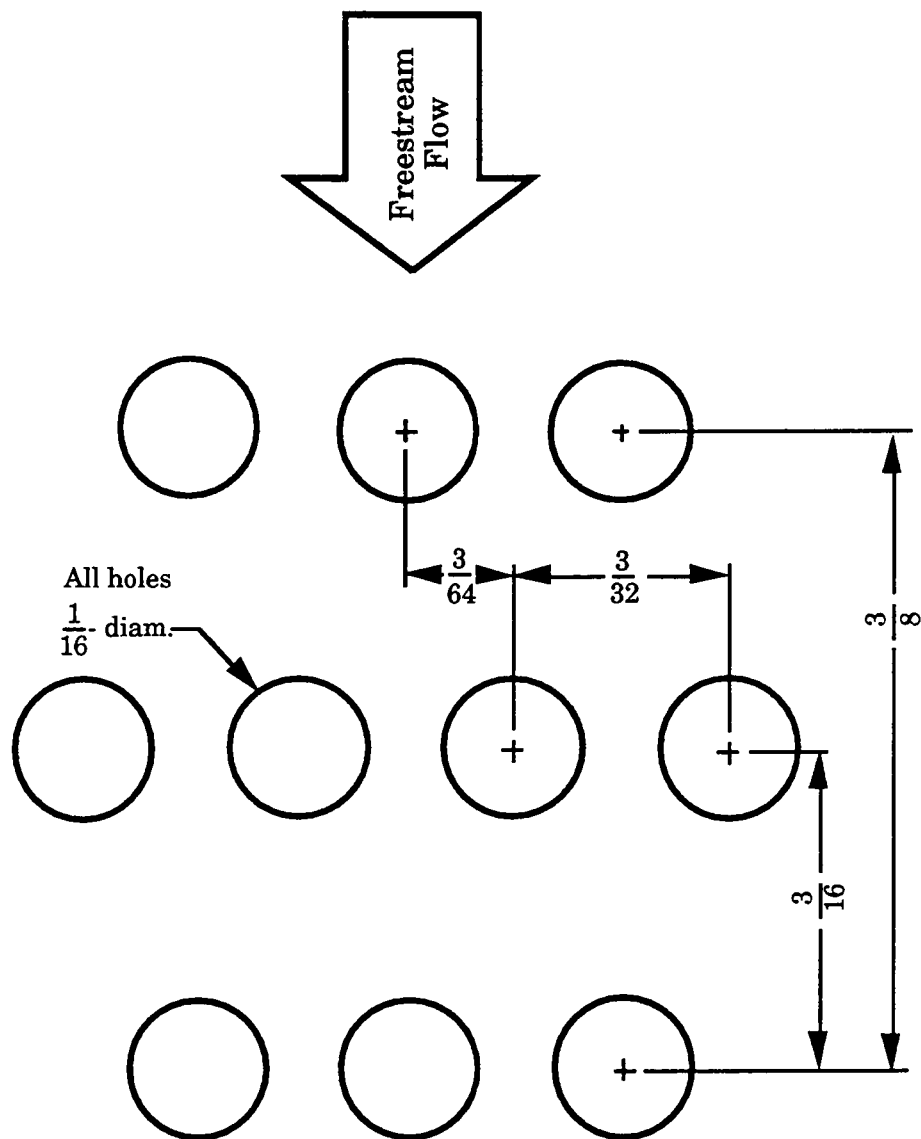


Figure 3.4 Hole Pattern Dimensions

Uniformity of the mass flow over the entire injection area was achieved by ensuring choked flow conditions through the injection holes.

TUNNEL INSTRUMENTATION

Experimental data were obtained for the following parameters: cavity acoustics (sound pressure level, SPL), injected mass flow rates, boundary layer

pressure profiles, and tunnel flow and freestream conditions. Figure 3.5 shows the location of the various static pressure ports, thermocouples, and the dynamic pressure transducer.

SPL data were gathered with an Endevco subminiature piezoresistive pressure transducer, model 8514, which was located on the downstream portion of the cavity floor at an $x/L=0.744$. The transducer was connected to a Hewlett Packard model HP3582A frequency (spectrum) analyzer for acquisition and analysis of cavity acoustic frequency spectrum and amplitude data. A sample of these data is shown in Figure 3.6.

Boundary layer surveys were obtained with a total pressure probe. The probe traversed the tunnel flow in the vertical (depthwise) direction relative to the cavity. A computer-controlled electric stepping motor drove the probe traversing mechanism during the boundary-layer surveys.

Six probes were used, one for each survey station. Figure 3.7 shows the probe geometry. Each probe consisted of a 0.040-in. internal diameter stainless steel tube, which was supported by a 0.250-in. outside-diameter rigid tube. The larger tube was connected to the traversing mechanism. The end of each probe was slightly flattened to facilitate data acquisition close to the model surface.

The smaller-diameter tubes were cut to different lengths and bent according to each singularly assigned survey station. Boundary layer pressure profiles were obtained at six locations. The pitot probe was placed at three locations 0.125 inches upstream of the cavity's leading edge: on the cavity longitudinal centerline, and at 0.250 and 0.500 inches from the centerline. In a similar manner, pressure surveys were taken at three corresponding locations 0.125 inches downstream of the cavity trailing edge.

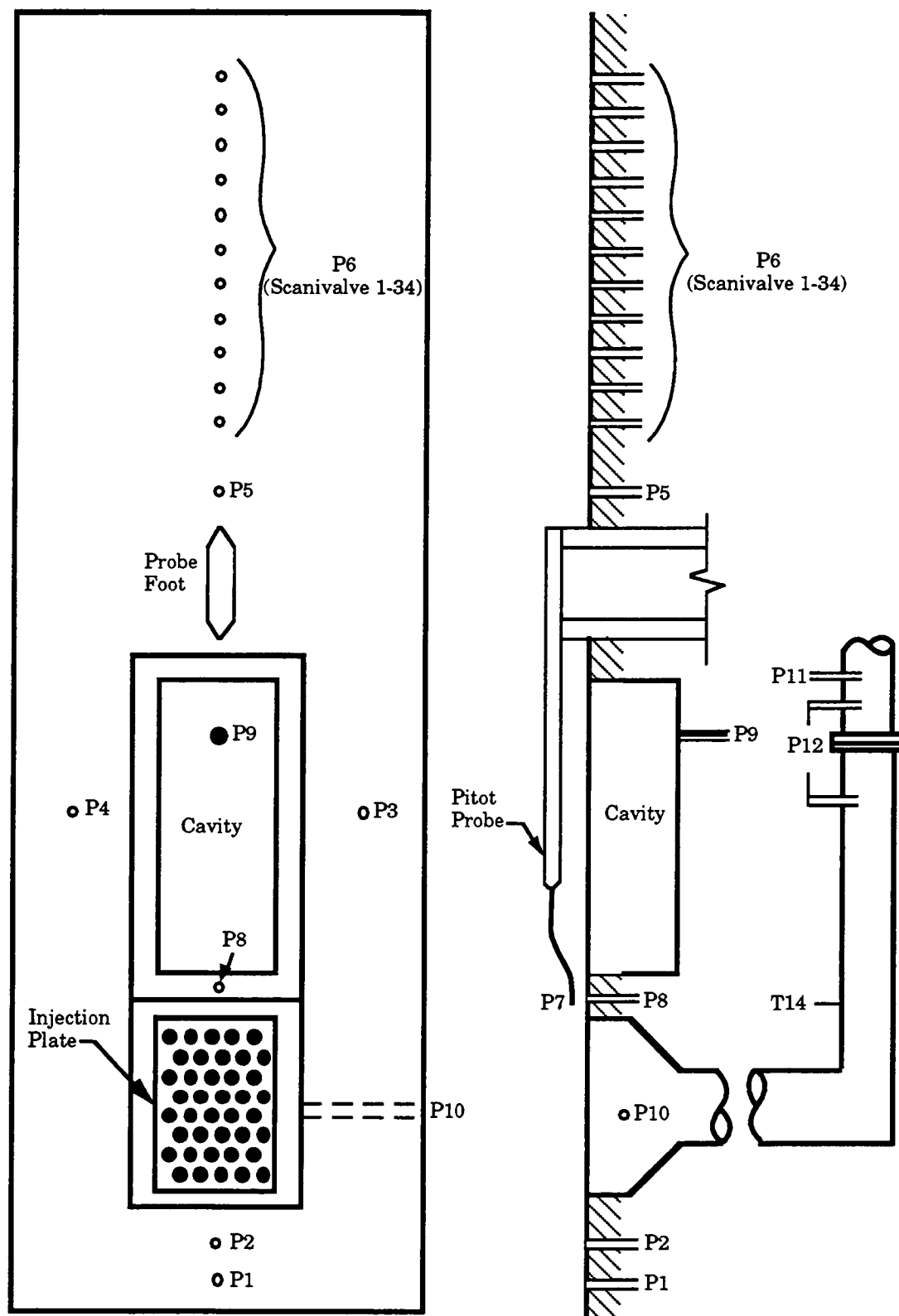


Figure 3.5 Tunnel Instrumentation Locations

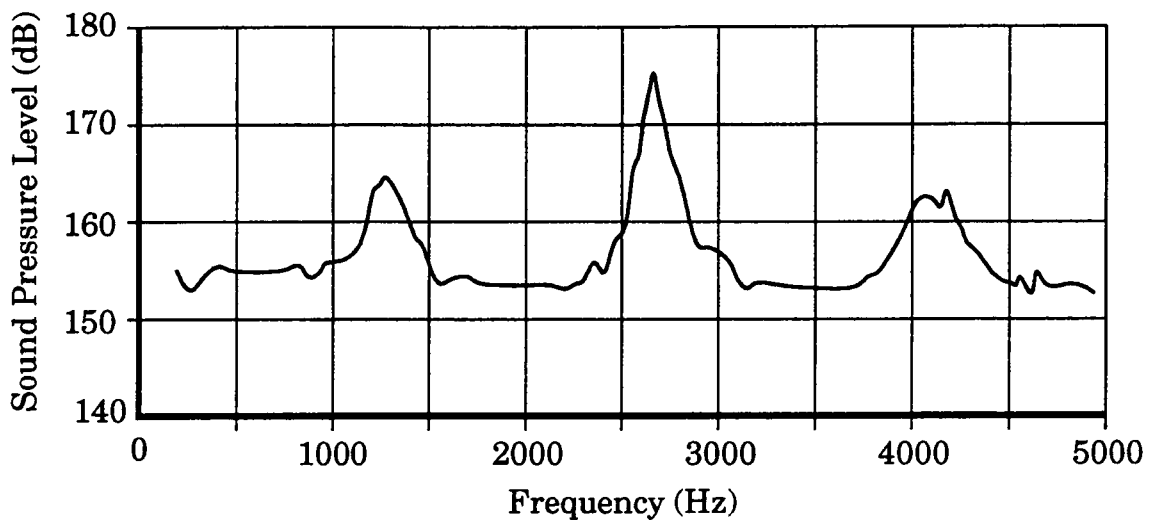


Figure 3.6 Sample Cavity Acoustic Frequency Spectrum Data

The traversing mechanism drove each total pressure probe from the model/tunnel surface to a height of approximately four inches into the tunnel flow. This profile ensured that the survey obtained pressure data through the entire boundary and shear layers and into the tunnel freestream.

Since the probe was traversing a shear layer and, in particular, a shear layer with mass addition, the static pressure throughout the survey is thought to vary substantially (Ref. 34). Ideally, a static pressure measurement should be made in the immediate vicinity of the pitot measurement, such as might be achieved with a Mach-flow angularity probe. The static pressure source used for this experiment was located on the tunnel floor halfway along the cavity length (Fig. 3.5).

The mass flow injection system was controlled by manually varying the plenum inlet valve to maintain a constant plenum pressure and mass-flow rate. Uniform flow through each of the equal-diameter holes was obtained by keeping the pressure ratio across the injection plate high enough to ensure the flow was choked.

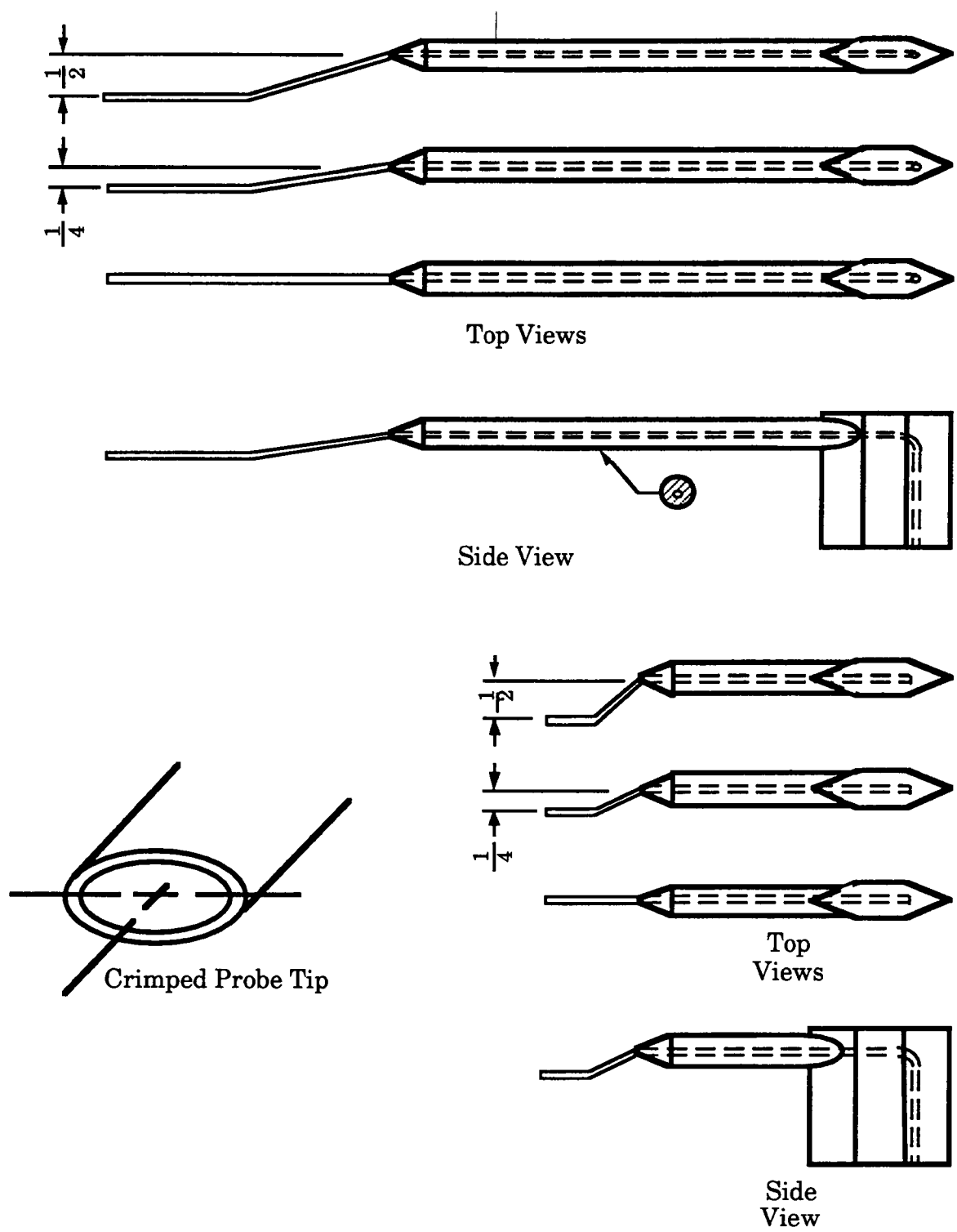


Figure 3.7 Boundary-Layer Survey Probe Geometry

Wind tunnel conditions were monitored by measuring total pressure and temperature in the tunnel stilling chamber. Freestream flow parameters were determined through adiabatic flow calculations. Like the mass injection system, the tunnel total pressure was also manually held constant by manipulating the primary flow control valve from the tunnel air reservoir tanks.

A series of 34 static pressure ports were located longitudinally along the test section floor downstream of the cavity model. All pressure data were obtained with a 48-channel scanning valve.

Freestream flow conditions were qualitatively evaluated through a Schlieren optical system. The data were recorded on videotape at a shutter speed of seven microseconds. No large tunnel-induced flow disturbances were evident. Due to limitations of the tunnel windows and the model design, the Schlieren system was not used to evaluate the flow within the cavity. The line of tunnel-floor-based static ports indicated a fairly uniform, low-turbulence flow with essentially constant static pressure along the length of the test section. No further attempt was made, however, to evaluate the tunnel freestream turbulence. Any tunnel turbulence effects on the responsiveness of the cavity shear layer were reduced and, at higher mass flow rates, were essentially eliminated by the flow of injectant over the cavity.

TEST METHODS

The experiment was performed in four distinct sections. First, the tunnel freestream conditions were quantified by acquiring static pressure data throughout the test section without the cavity model installed. Boundary layer surveys were performed to quantify the tunnel conditions at the locations

where similar surveys would be performed during the cavity portion of the test.

The second section of the test involved installing the cavity model only, with a nonporous flat plate upstream of the cavity. Again, boundary layer surveys were performed immediately upstream and downstream of the cavity. Additionally, baseline acoustic data were gathered.

Two mass flow rates were selected for the boundary layer surveys performed throughout the remainder of the test. The values were chosen as representative of two significant points of acoustic attenuation (Fig. 3.8). The first, $\dot{m}=0.110$ lbm/sec, is the mass flow beyond which little additional acoustic attenuation was observed with any additional injected mass. The second, $\dot{m}=0.050$ lbm/sec, was chosen as a representative "midpoint" between the acoustic levels observed, that is, with no mass flow and the maximum attenuation achieved for any given injection plate configuration.

For the next portion of the experiment, the low density injection plate used by Gauthier, or the Rectangle, was installed. Acoustic measurements were made at several mass flows in order to duplicate Gauthier's results. Boundary layer surveys were made at the two designated mass flows.

Finally, in the fourth portion, and main thrust of the experiment, the five injection plates with various hole patterns were tested to (1) evaluate the acoustic attenuation of each pattern, and (2) investigate the effects of purposely introducing three-dimensional effects into the shear layer. Boundary layer surveys were performed at the two previously-mentioned mass flow rates, upstream and downstream from the cavity.

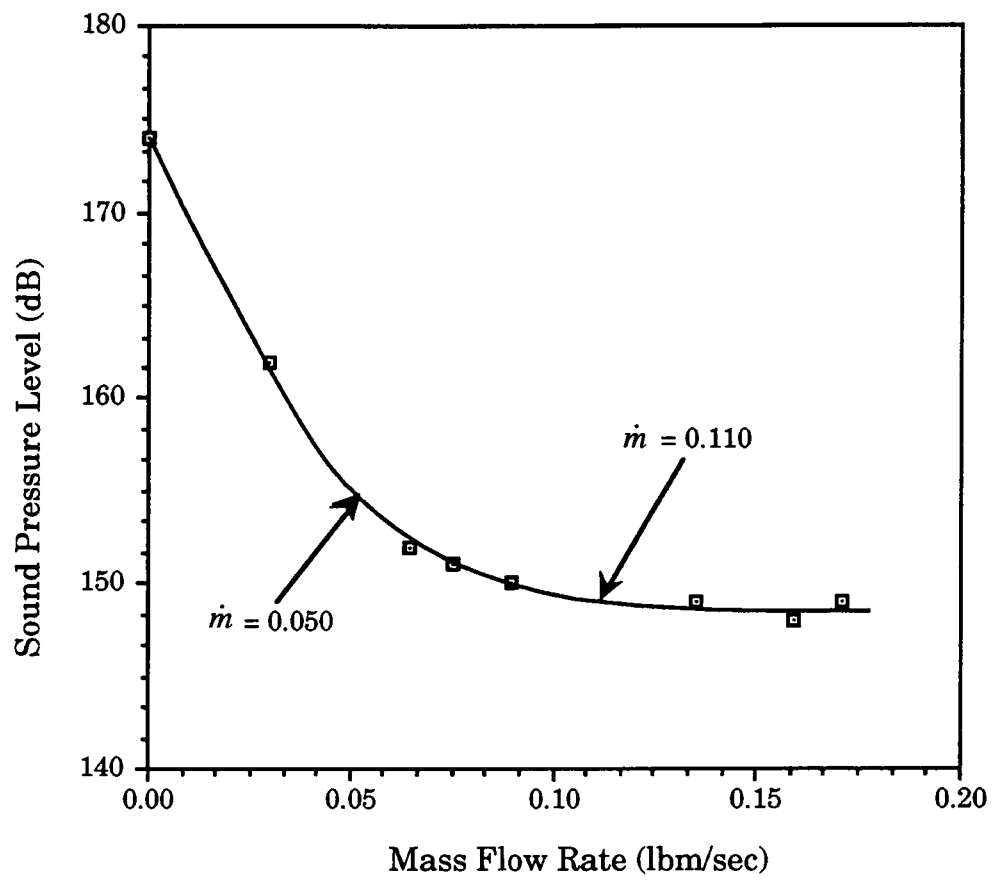


Figure 3.8 Acoustic Attenuation with Increased Mass Addition

CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

The data obtained through this study will be presented in four sections, corresponding to the aforementioned four sections of the experiment. First the tunnel flow characteristics are shown, followed by the baseline cavity flow and acoustic characteristics. Next, Gauthier's data and data acquired under duplicated flow conditions are compared. Finally, data from the five injection plates are presented.

TUNNEL FLOW CHARACTERISTICS

Static pressure readings along the tunnel test section floor indicated fairly uniform flow with no cavity model hardware installed (Fig. 4.1). The

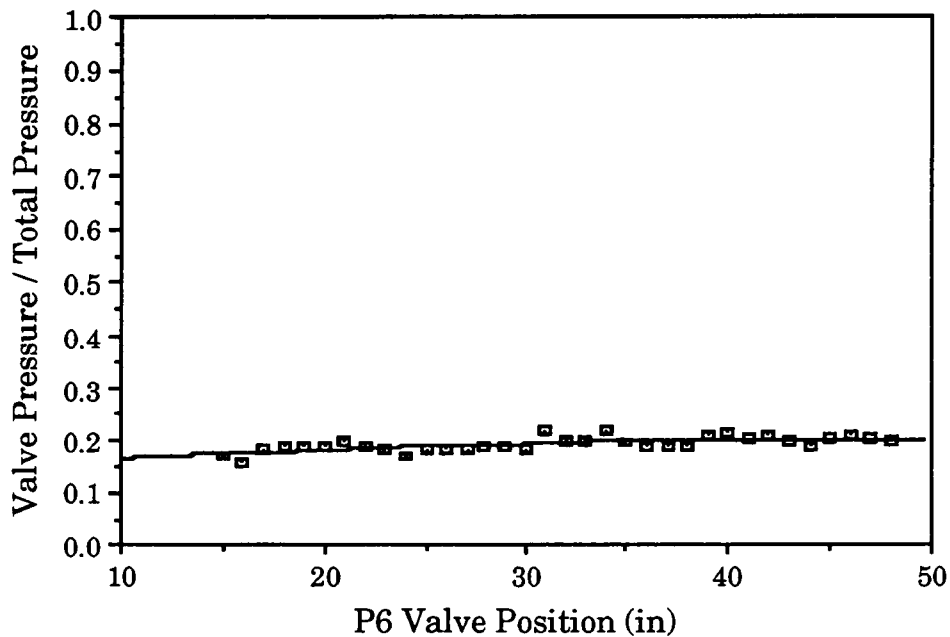


Figure 4.1 Test-Section Static Pressure without Cavity Model

static pressure readings were within two percent of each other for the entire test section length. Static pressures were normalized by the stilling chamber pressure, and are presented graphically for each run.

Again, with no cavity model hardware installed, boundary layer surveys were performed at the two centerline stations, 0.125-in. both upstream and downstream of the where the cavity's leading and trailing edges would be located after the cavity model was installed. Both indicated smooth total pressure profiles with no noticeable disturbances (Fig. 4.2). The total pressure data were analyzed and velocity profiles were calculated (Fig. 4.3). Boundary layer thickness was 0.25-in. and 0.30-in. at the respective survey stations. This concurs with the visual data obtained with the Schlieren system. The primary medium for the Schlieren data was a video tape.

Boundary-layer profile data were obtained at six points, three upstream of the cavity and three downstream (Fig. 4.4). Each location is identified by a reference number, 1 through 6.

BASELINE CAVITY DATA

The maximum Sound Pressure Level (SPL) measured for the cavity without mass injection was 176 dB at 2660 Hz. Secondary peaks were 165.8 dB at 1320 Hz and 162.7 dB at 4120 Hz (Fig. 4.5). This was for the cavity with a solid, flat, flush-mounted plate placed immediately upstream in place of the injection plates.

Pitot pressure profiles indicated a slight thickening of the boundary layer upstream of the cavity, specifically, to 0.30 inches (Fig. 4.6). Immediately downstream of the cavity, evidence of the shear layer was observed as the boundary layer increased by approximately 150 percent to 0.75 inches. Table

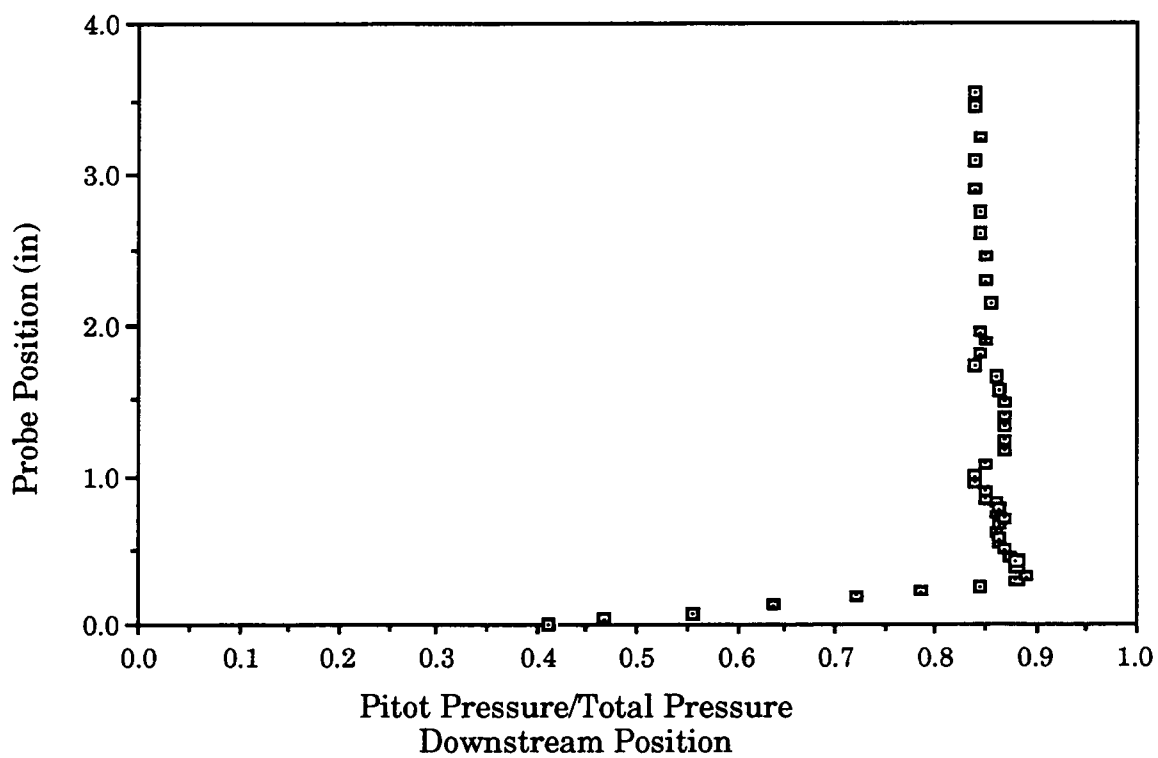
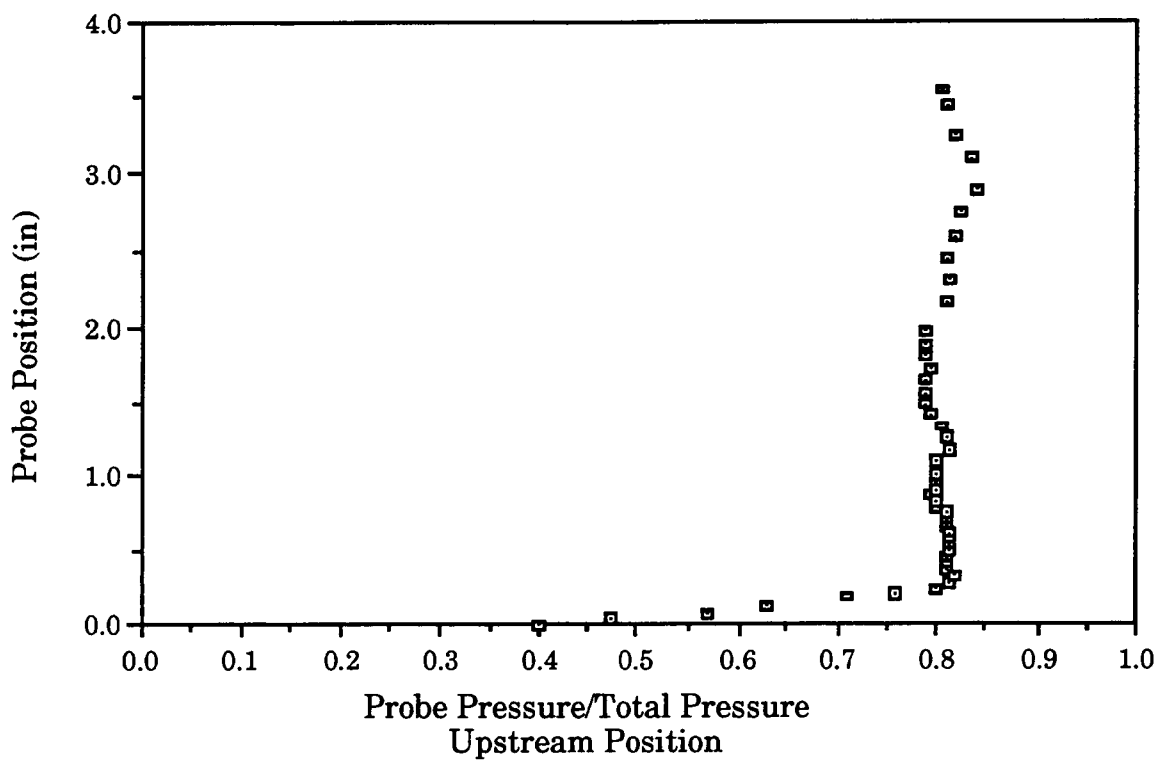


Figure 4.2 Boundary-Layer Survey Pressure Data

Cavity Model Installed, No Mass Injection

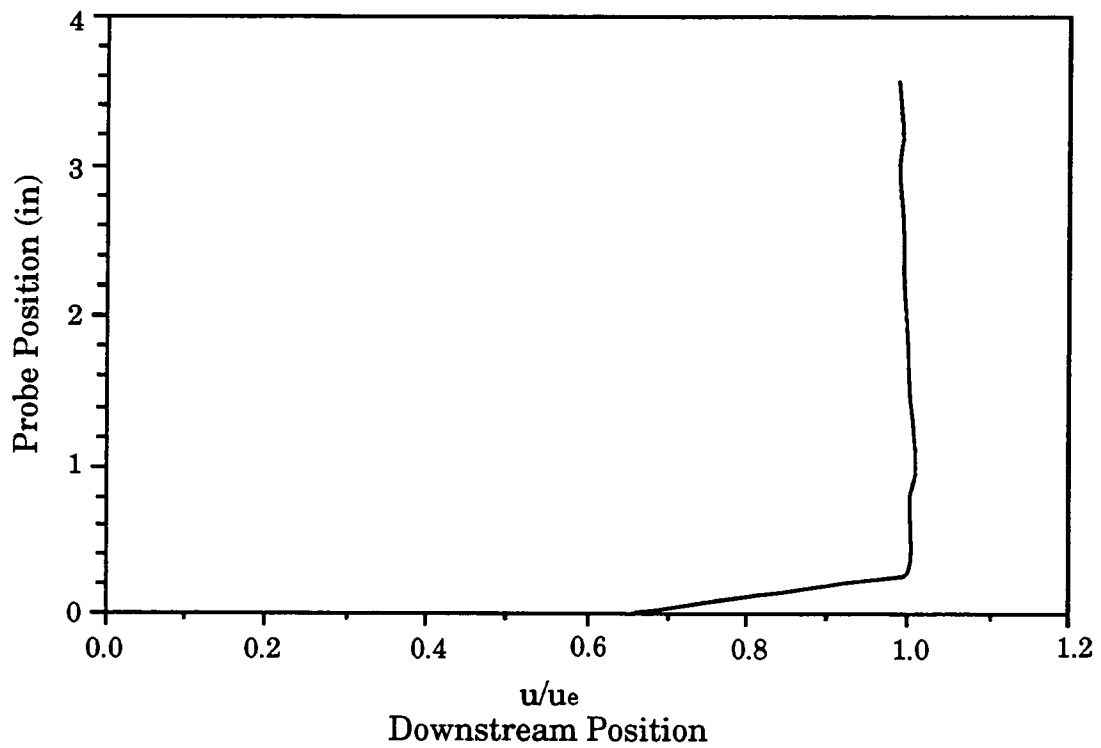
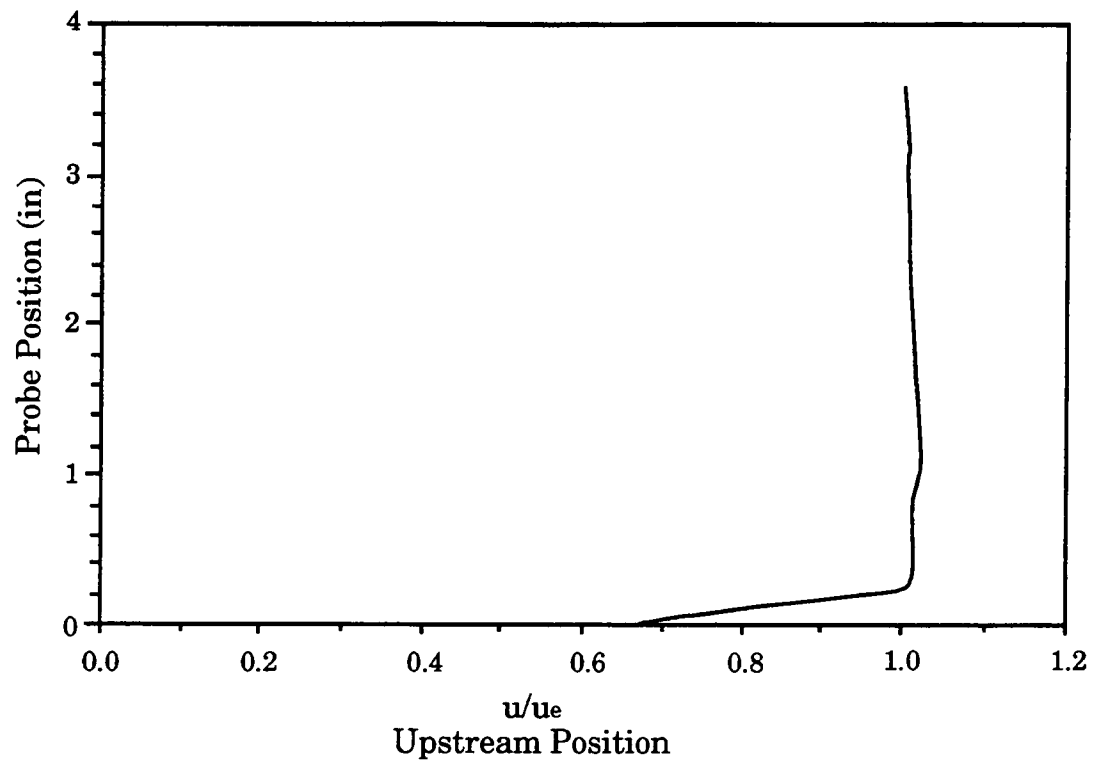
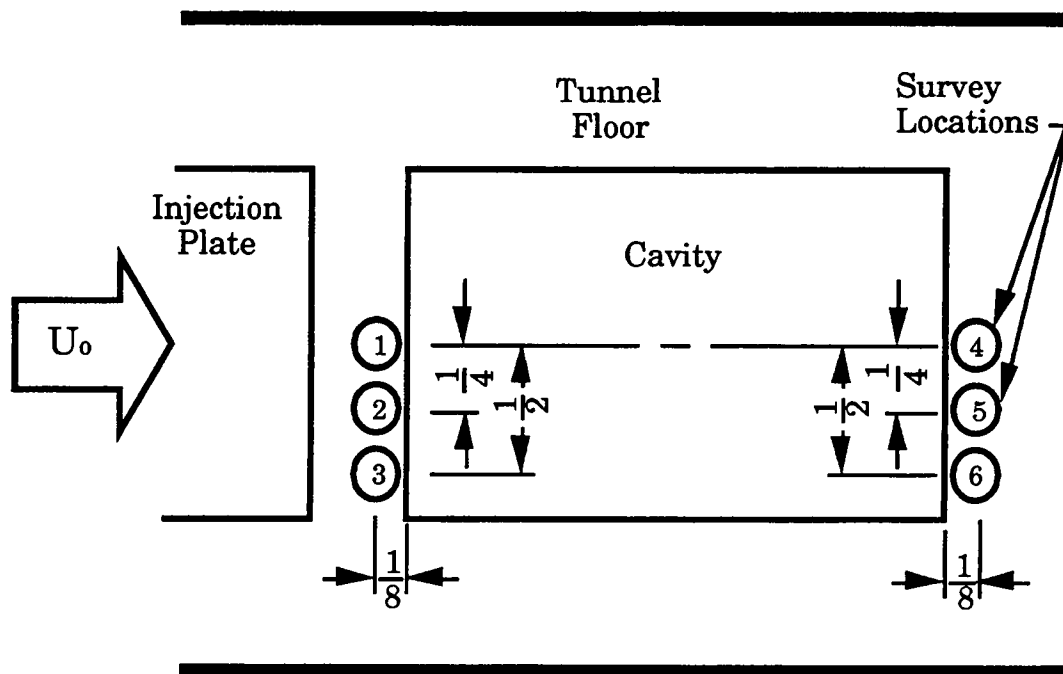


Figure 4.3 Calculated Boundary-Layer Velocity Profile

Cavity Model Installed, No Mass Injection



Top View of Wind Tunnel Test Section

Figure 4.4 Probing Locations for Boundary-Layer Profiles

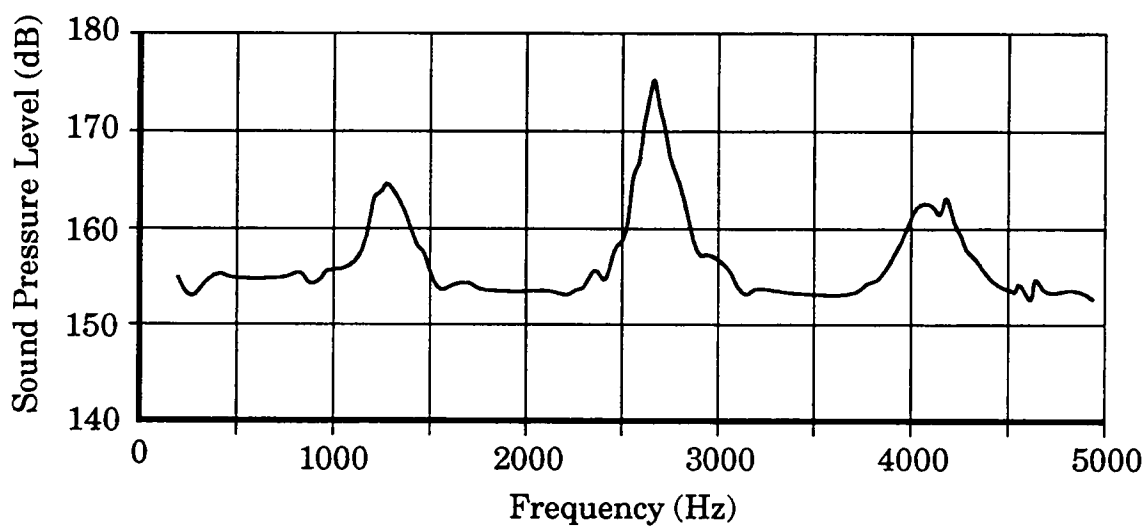


Figure 4.5 Baseline Acoustic Frequency Spectrum Data, No Mass Injection

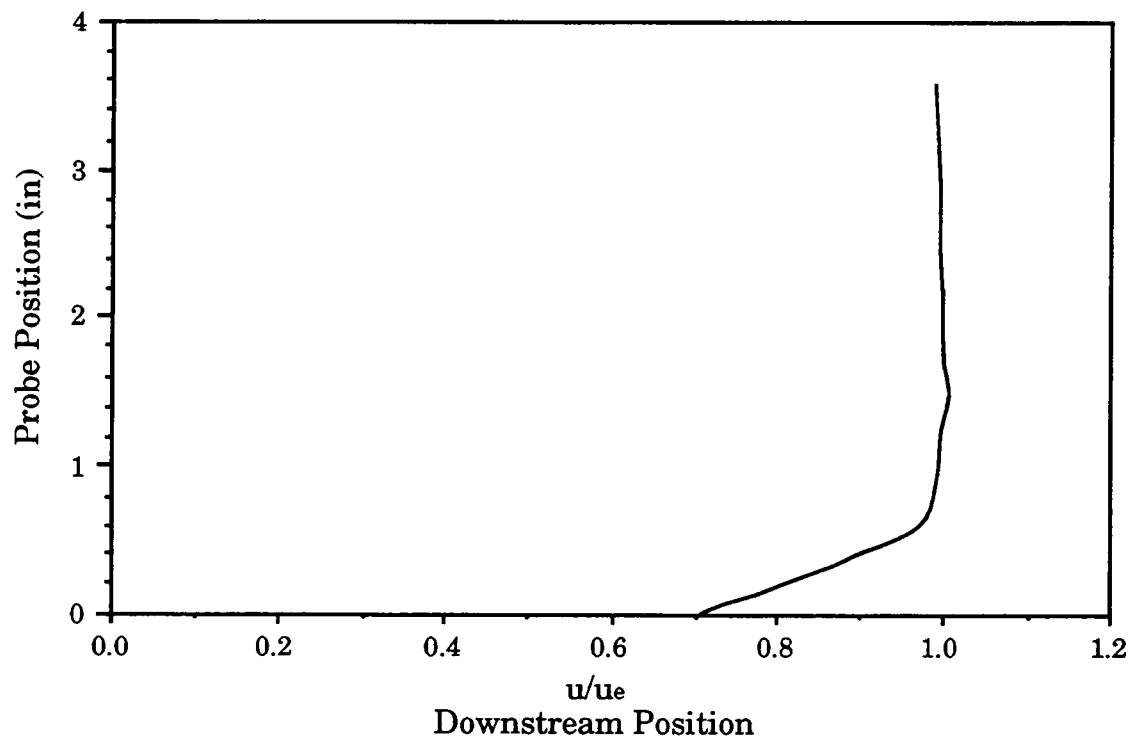
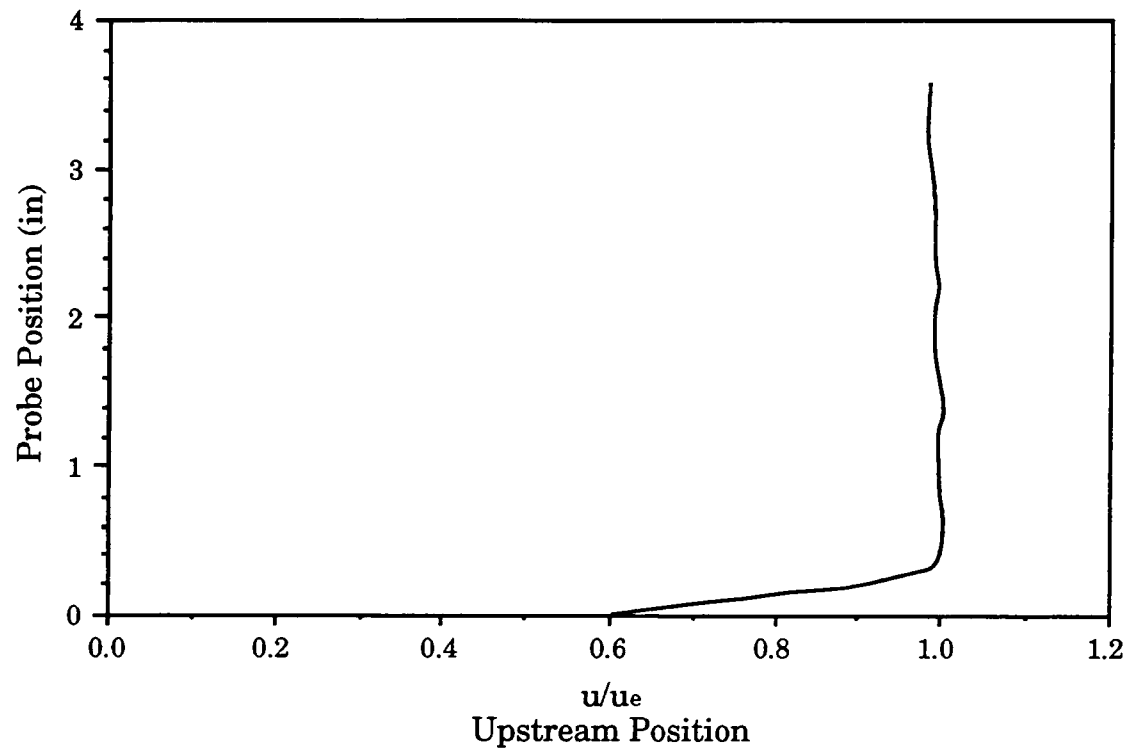


Figure 4.6 Sample Boundary-Layer Velocity Profile with Mass Injection

4.1 summarizes the data obtained for the flat-plate model configuration.

Velocity profiles could not be calculated with great accuracy from the pitot pressure probe data obtained from the cavity model configurations. This is due to the lack of a relevant static pressure source; that is, the total pressure probe did not have a local static pressure source while traversing the boundary and shear layers. Despite the shortcomings of the data acquisition system, the computer calculations indicated boundary and shear layer thicknesses in concurrence with those seen on the Schlieren system.

Table 4.1 Baseline Cavity Test Data

Run Number	Mass Flow (lbm/s)	Blowing Parameter B_c	Sound Pressure Level (dB)	Acoustic Attenuation (Δ dB)	Boundary Layer Thickness δ (in)	$\frac{\delta}{\delta_o}$	Probe Position
10213	N/A	N/A	176.0	0.0	N/A	N/A	N/A
10215	N/A	N/A	175.1	0.9	0.30	1.00	1
10214	N/A	N/A	175.3	0.7	0.75	1.00	4

The Schlieren data showed a weak expansion fan at the cavity leading edge, and a fairly noticeable oscillating flow structure across the cavity. Some rear corner impingement was observed, although sharp camera focus was not available at that portion of the model.

DUPLICATION OF DATA

The blowing parameter, B_c , discussed in Chapter II (Equation 2.3) was modified for the data analysis of this experiment.

$$B_c = \frac{\rho_w u_w A_{inj}}{\rho_\infty u_\infty A_{cavity}} = \frac{\dot{m}_{inj}}{\rho_e u_e A_{inj}} \frac{A_{pattern}}{A_{cavity}} \quad (4.1)$$

The modified blowing parameter permits the inclusion of each model's specific geometry, or the area of the entire injection pattern vice only the sum of the individual injection holes.

Figure 4.7 shows a comparison of Gauthier's acoustic data and the data acquired during this experiment at duplicated flow conditions. There is some mismatch of acoustic attenuation at lower mass flows. A possible cause is mass flow rate fluctuations. That is to say, the natural pressure differential across the injection plate caused by the freestream induced a mass flow of approximately 0.20 lbm/sec. This made it exceptionally difficult to manually hold low mass flow rates constant. In contrast, the data agree well at higher injection rates. Indeed, the overall trend is very similar for the entire range of mass flows, confirming the test method duplication.

When compared to the baseline cavity data (no mass flow), significant acoustic attenuation was observed during the present study at a mass flow of 0.050 lbm/sec ($B_c=0.117$), the large peak being reduced by 24.3 dB (Fig. 4.8). As mass flow was increased to 0.110 lbm/sec ($B_c=0.214$), the large peak shifted by 200 Hz to 2460 Hz and was reduced by 26.6 dB. This corresponds directly to Gauthier's data of an acoustic decrease of 27 dB and 2530 Hz. Gauthier also experienced a peak frequency shift of 200 Hz when compared to his zero-flow data.

Boundary layer thickness increased to 0.70 inches at the upstream centerline position for the higher mass flow rate, and to 0.75 inches at the downstream position (Fig. 4.9). This shows a dramatic initial thickening of the

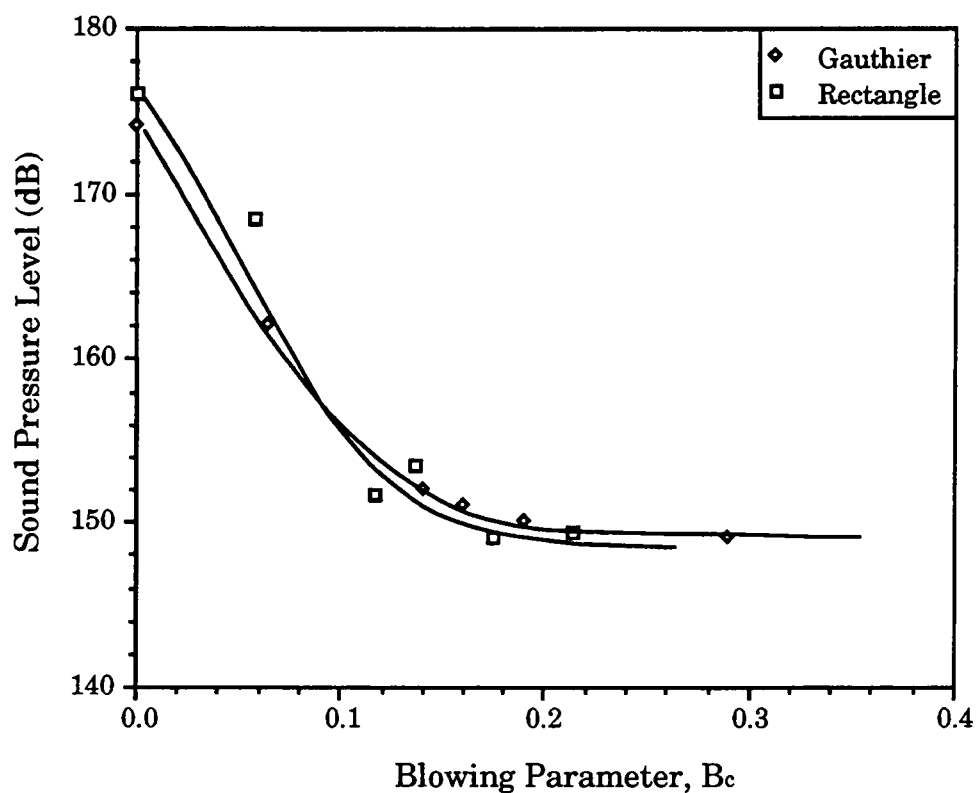


Figure 4.7 Comparison of Duplicated Data

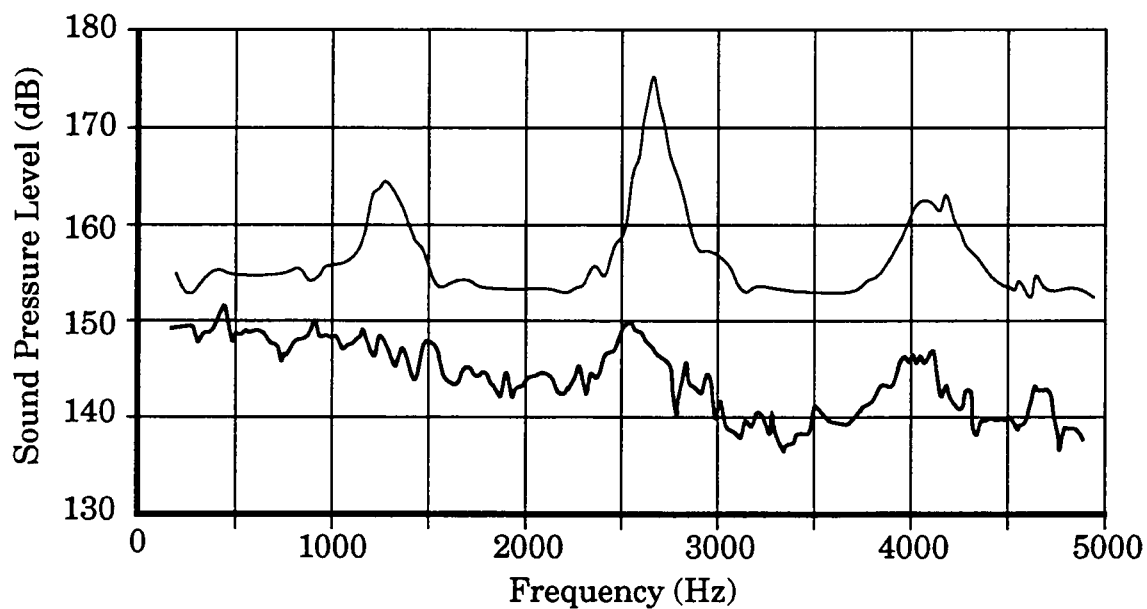


Figure 4.8 Acoustic Pressure-Level Reduction for the Rectangle Model

boundary layer (no mass flow, $\delta=0.30$), but not much growth of the shear layer over the cavity. The Schlieren system confirms the survey data, showing a stable, thick shear layer over the cavity.

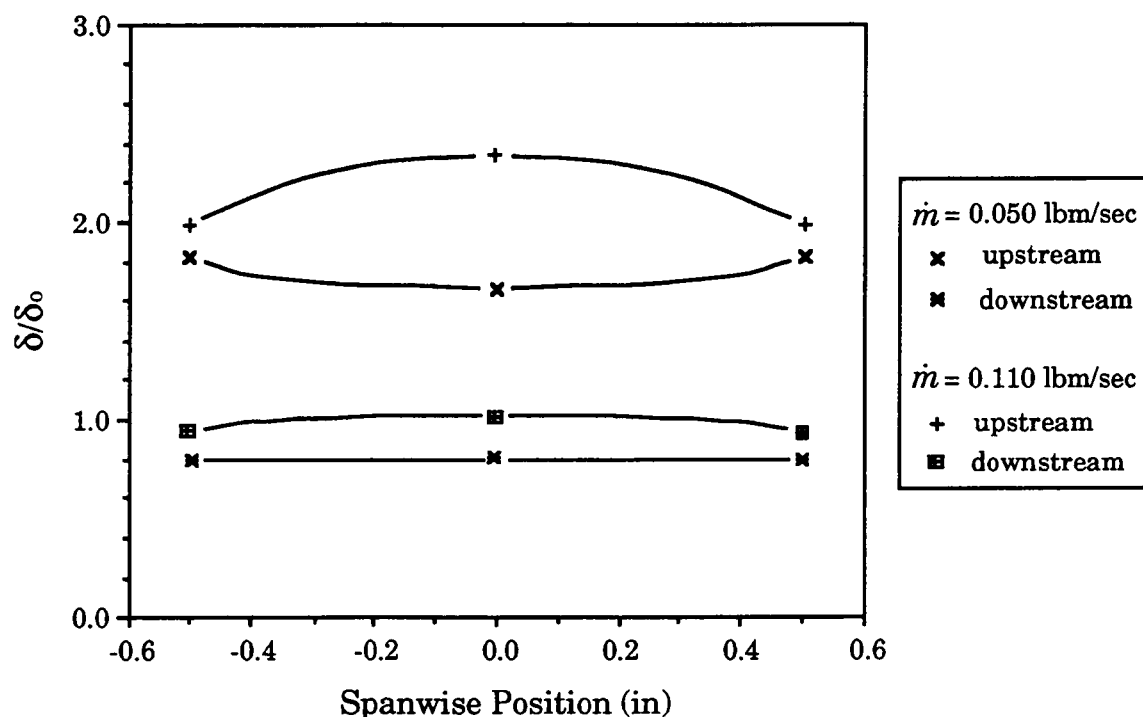


Figure 4.9 Spanwise Boundary-Layer Thickness for Rectangle Model

The boundary layer thickness was almost constant in the spanwise direction. This also seems to indicate a fairly stable and uniform shear layer.

A summary of the data obtained for the Rectangle model is shown in Table 4.2.

INJECTION PLATE DATA

The acoustic attenuation data are shown for each injection plate in Figure 4.10. Data from Gauthier's study are not included.

Table 4.2 Rectangle Model Data

Run Number	Mass Flow (lbm/s)	Blowing Parameter B_c	Sound Pressure Level (dB)	Acoustic Attenuation (Δ dB)	Boundary Layer Thickness δ (in)	$\frac{\delta}{\delta_0}$	Probe Position
10315	0.030	0.058	168.4	7.6	N/A	N/A	N/A
10303	0.050	0.116	151.7	24.3	N/A	N/A	N/A
10304	0.070	0.136	153.5	22.5	N/A	N/A	N/A
10305	0.090	0.175	149.0	27.0	N/A	N/A	N/A
10306	0.110	0.214	149.4	26.6	N/A	N/A	N/A
10307	0.150	0.291	147.8	28.2	N/A	N/A	N/A
10308	0.050	0.116	N/A	N/A	0.50	1.67	1
10309	0.110	0.214	N/A	N/A	0.70	2.33	1
103010	0.050	0.116	N/A	N/A	0.55	1.83	3
103011	0.110	0.214	N/A	N/A	0.60	2.00	3
10311	0.050	0.116	N/A	N/A	0.60	0.80	4
10312	0.110	0.214	N/A	N/A	0.75	1.00	4
10313	0.050	0.116	N/A	N/A	0.60	0.80	6
10314	0.110	0.214	N/A	N/A	0.70	0.93	6

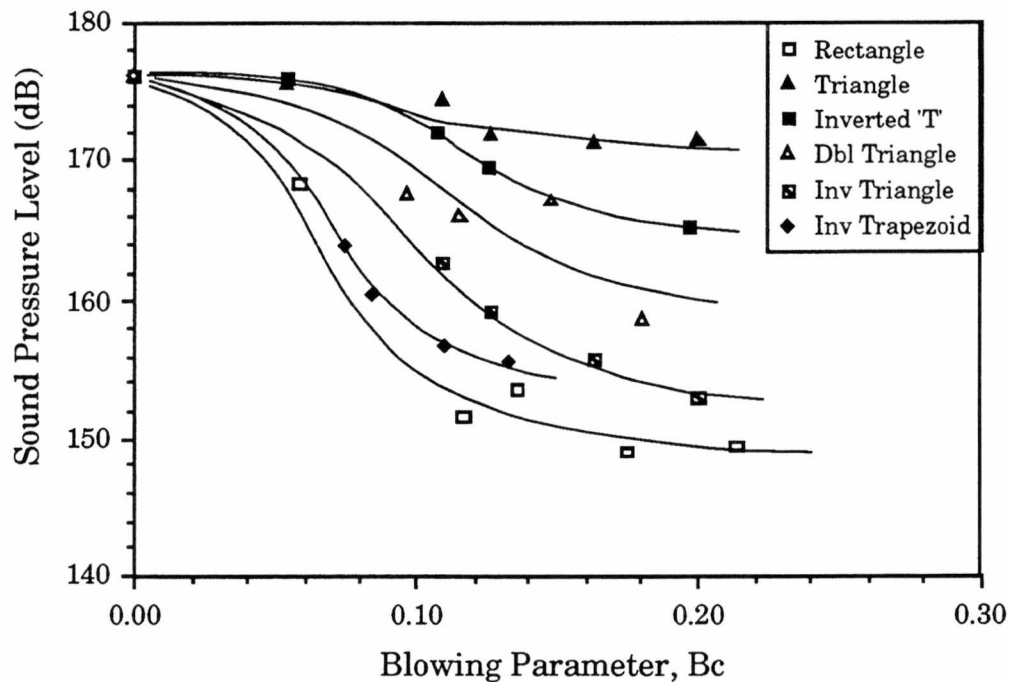


Figure 4.10 Acoustic Attenuation Data for All Injection Patterns

Triangle

The Triangle was the least effective of the injection plates tested. The maximum peak reduction was only 5 dB (Fig. 4.11). No boundary layer surveys were obtained (Table 4.3).

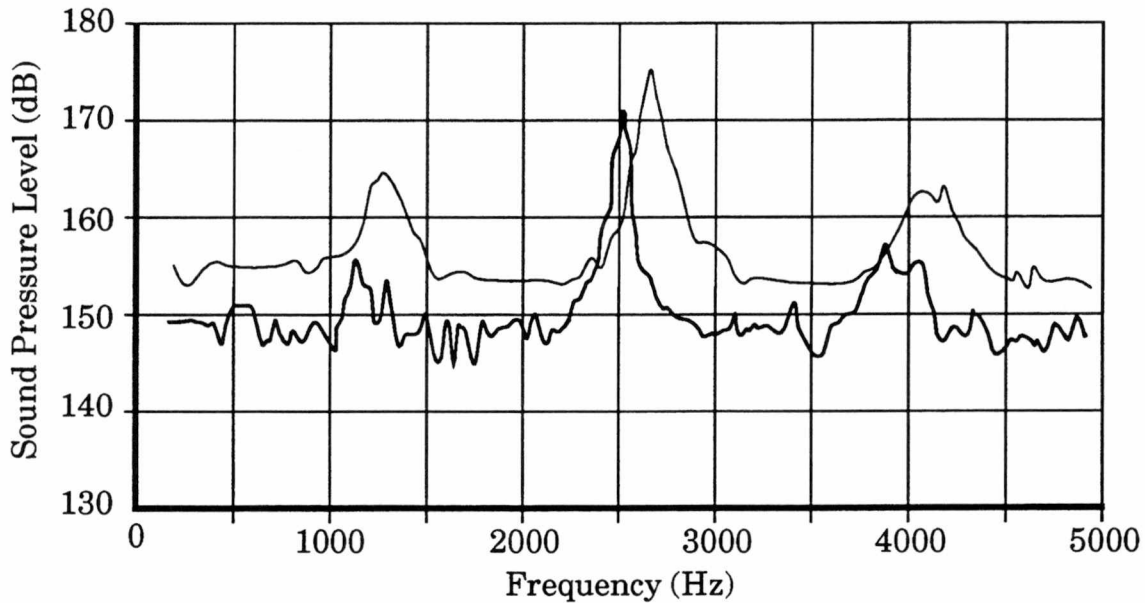


Figure 4.11 Acoustic Pressure-Level Reduction for the Triangle Model

Table 4.3 Triangle Model Data

Run Number	Mass Flow (lbm/s)	Blowing Parameter B_c	Sound Pressure Level (dB)	Acoustic Attenuation (Δ dB)	Boundary Layer Thickness δ (in)	$\frac{\delta}{\delta_0}$	Probe Position
10216	0.030	0.054	175.5	0.5	N/A	N/A	N/A
10221	0.040	0.082	174.3	1.7	N/A	N/A	N/A
10222	0.050	0.109	174.4	1.6	N/A	N/A	N/A
10223	0.060	0.118	172.8	3.2	N/A	N/A	N/A
10224	0.070	0.127	171.7	4.3	N/A	N/A	N/A
10225	0.090	0.163	171.1	4.9	N/A	N/A	N/A
10226	0.110	0.200	171.4	4.6	N/A	N/A	N/A

The Schlieren system shows almost no growth of the upstream boundary layer, and substantial oscillatory motion of the shear layer. Shear layer impingement at the rear corner is clearly evident.

Inverted "T"

Acoustic attenuation was substantially greater for the Inverted "T". Figure 4.12 shows a maximum peak reduction being 13.2 dB. This attenuation is about the same magnitude observed for most mechanical, or passive suppression devices.

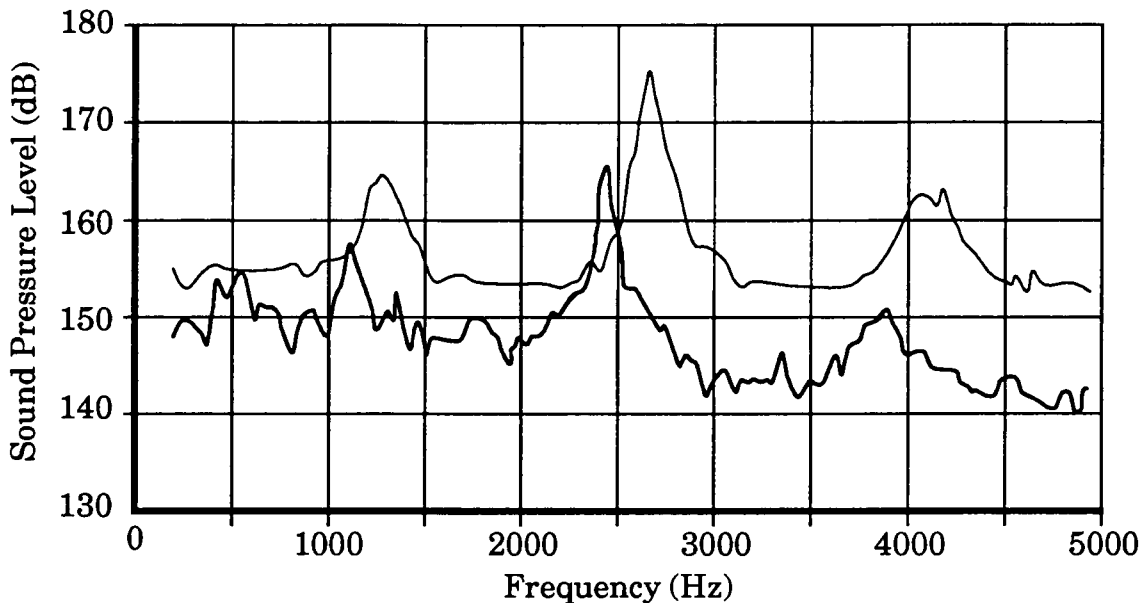


Figure 4.12 Acoustic Pressure-Level Reduction for the Inverted "T"

Although the shape of the injection area's effective leading edge is normal to the freestream flow, only one-third of that edge is followed by the full length of injection area; the remaining two-thirds of the leading edge is followed by a relatively short injection area close to the cavity's lip (Fig. 3.3). This is almost equivalent to having a thin Rectangle that is only a third as wide as the

cavity. This model was created to promote three-dimensional vortical interactions using the basic Rectangle design.

Centerline probing data indicate a moderate-to-large boundary layer thickness increase (Fig. 4.13), resembling the data from the Rectangle model.

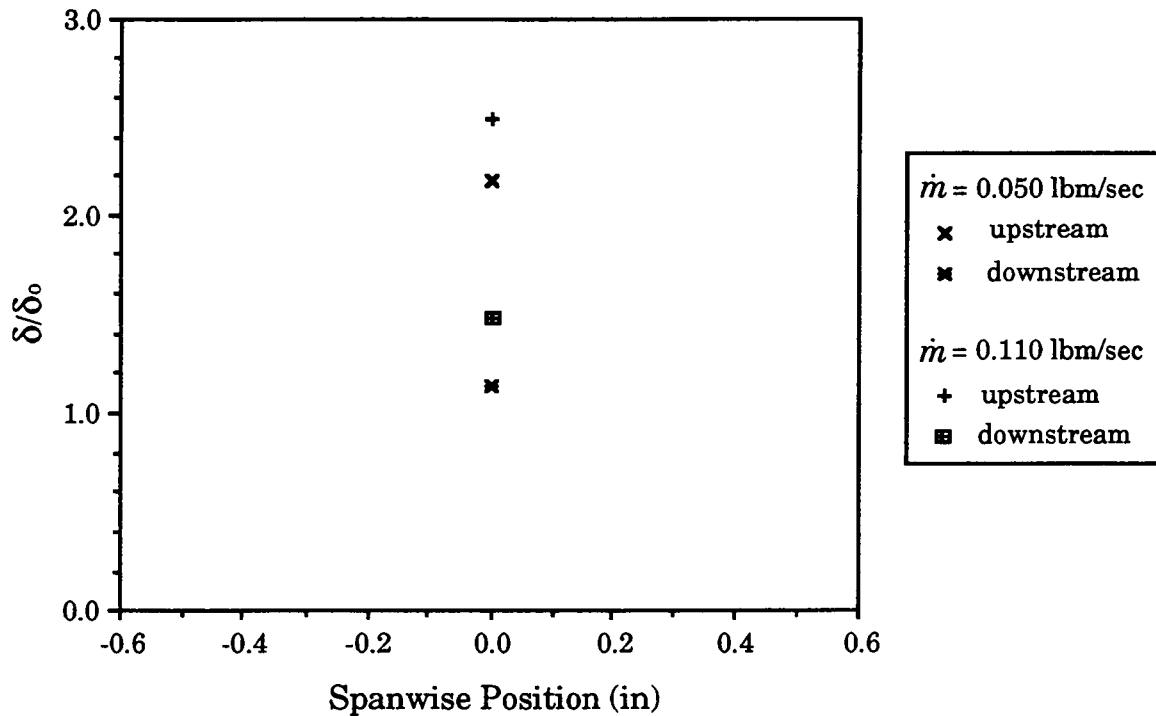


Figure 4.13 Streamwise Boundary-Layer Thickness for the Inverted “T”

Since no significant acoustic attenuation was observed (relative to the Rectangle), off-centerline probing data were not obtained (Table 4.4).

Double Triangle

Maximum attenuation of the largest frequency peak for the double triangle was 17.4 dB (Fig. 4.14). The shock pattern was similar to that of the Triangle, but the two shocks that developed toward the cavity centerline interacted, creating a stronger pressure rise.

Table 4.4 Inverted "T" Model Data

Run Number	Mass Flow (lbm/s)	Blowing Parameter B_c	Sound Pressure Level (dB)	Acoustic Attenuation (Δ dB)	Boundary Layer Thickness δ (in)	$\frac{\delta}{\delta_0}$	Probe Position
10231	0.030	0.054	168.4	0.1	N/A	N/A	N/A
10232	0.040	0.081	151.7	2.4	N/A	N/A	N/A
10233	0.050	0.107	153.5	4.0	N/A	N/A	N/A
102310	0.070	0.125	149.0	6.5	N/A	N/A	N/A
10234	0.110	0.197	149.4	10.9	N/A	N/A	N/A
10235	0.150	0.269	147.8	13.2	N/A	N/A	N/A
10239	0.050	0.107	N/A	N/A	0.65	2.17	1
10236	0.110	0.197	N/A	N/A	0.75	2.50	1
10238	0.050	0.107	N/A	N/A	0.85	1.13	4
10237	0.110	0.197	N/A	N/A	1.10	1.47	4

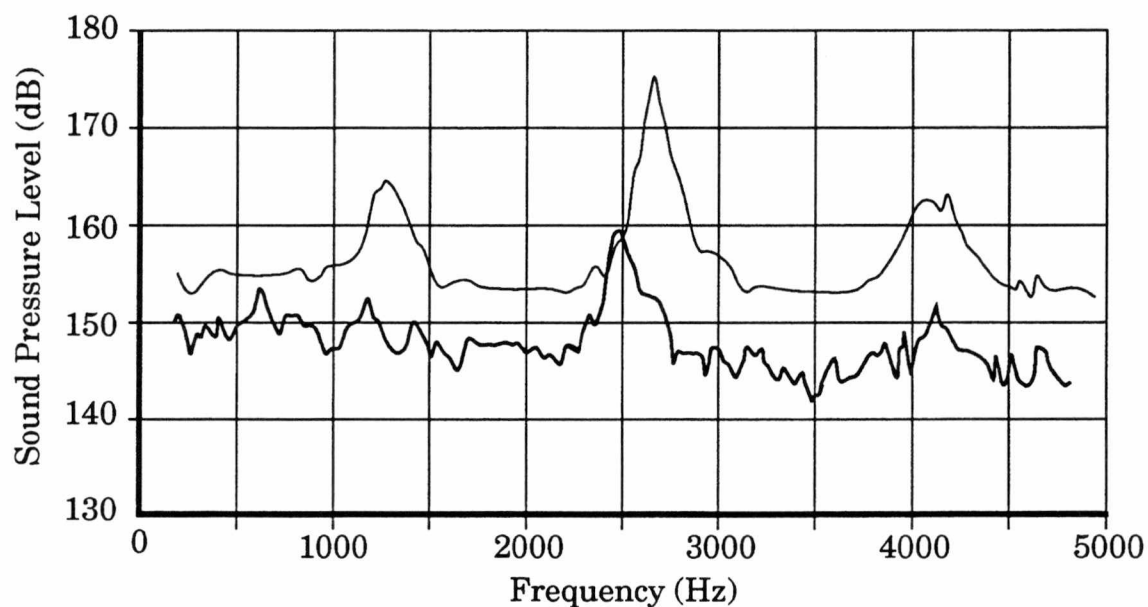


Figure 4.14 Acoustic Pressure-Level Reduction for the Double Triangle

The boundary layer survey data show a significant growth off-centerline (Fig. 4.15). The thicknesses are greatest downstream of each triangle's apex, and taper off to either side and the center.

The data obtained for the Double Triangle are summarized in Table 4.5.

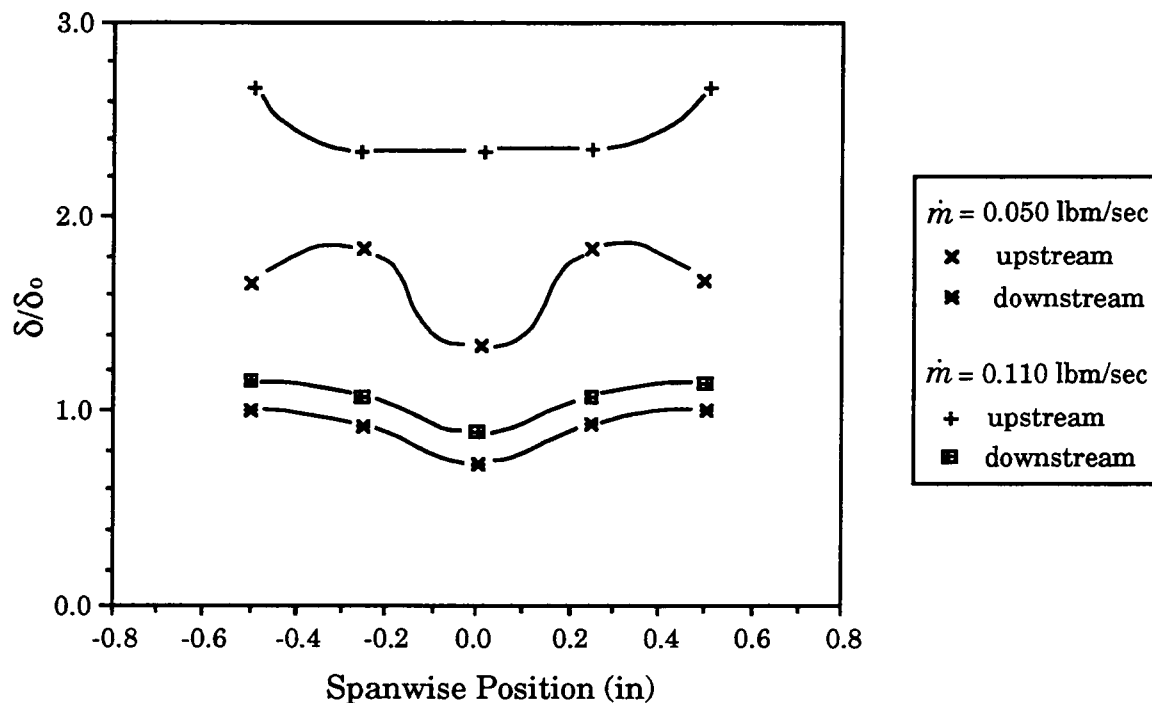


Figure 4.15 Spanwise Boundary-Layer Thickness for the Double Triangle

Inverted Triangle

The Inverted Triangle proved to be the most effective of the five nonrectangular injection plates. Maximum peak acoustic attenuation was 23.1 dB (Fig. 4.16).

The boundary layer data show a large increase in thickness along the centerline (Fig. 4.17). In the spanwise direction, the thickness decreases. This is logical due to the geometry of the injection area being longest on centerline.

Table 4.5 Double Triangle Model Data

Run Number	Mass Flow (lbm/s)	Blowing Parameter B_c	Sound Pressure Level (dB)	Acoustic Attenuation (Δ dB)	Boundary Layer Thickness δ (in)	$\frac{\delta}{\delta_0}$	Probe Position
10242	0.050	0.097	167.6	8.4	N/A	N/A	N/A
10241	0.070	0.115	165.9	10.1	N/A	N/A	N/A
10245	0.080	0.132	166.8	9.2	N/A	N/A	N/A
10243b	0.090	0.148	167.1	8.9	N/A	N/A	N/A
10243a	0.100	0.164	164.2	11.8	N/A	N/A	N/A
10244	0.110	0.181	158.6	17.4	N/A	N/A	N/A
10246	0.150	0.247	161.6	14.4	N/A	N/A	N/A
10255	0.050	0.097	N/A	N/A	0.40	1.33	1
10247	0.110	0.115	N/A	N/A	0.70	2.33	1
10252	0.050	0.097	N/A	N/A	0.55	1.83	2
10251	0.110	0.115	N/A	N/A	0.70	2.33	2
10254	0.050	0.097	N/A	N/A	0.50	1.67	3
10253	0.110	0.115	N/A	N/A	0.70	2.67	3
10256	0.050	0.097	N/A	N/A	0.55	0.73	4
10248	0.110	0.115	N/A	N/A	0.65	0.87	4
10281	0.050	0.097	N/A	N/A	0.70	0.93	5
10282	0.110	0.115	N/A	N/A	0.80	1.07	5
10283	0.050	0.097	N/A	N/A	0.75	1.00	6
10284	0.110	0.115	N/A	N/A	0.85	1.13	6

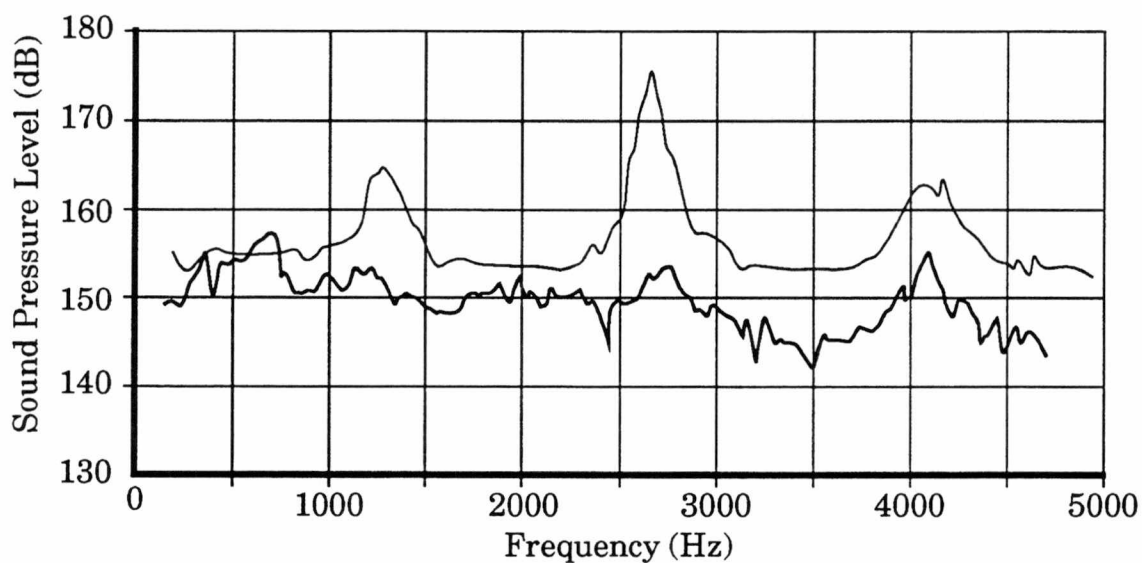


Figure 4.16 Acoustic Pressure-Level Reduction for the Inverted Triangle

The spanwise decrease in boundary-layer thickness is reversed, however, at downstream locations for high mass flow rates.

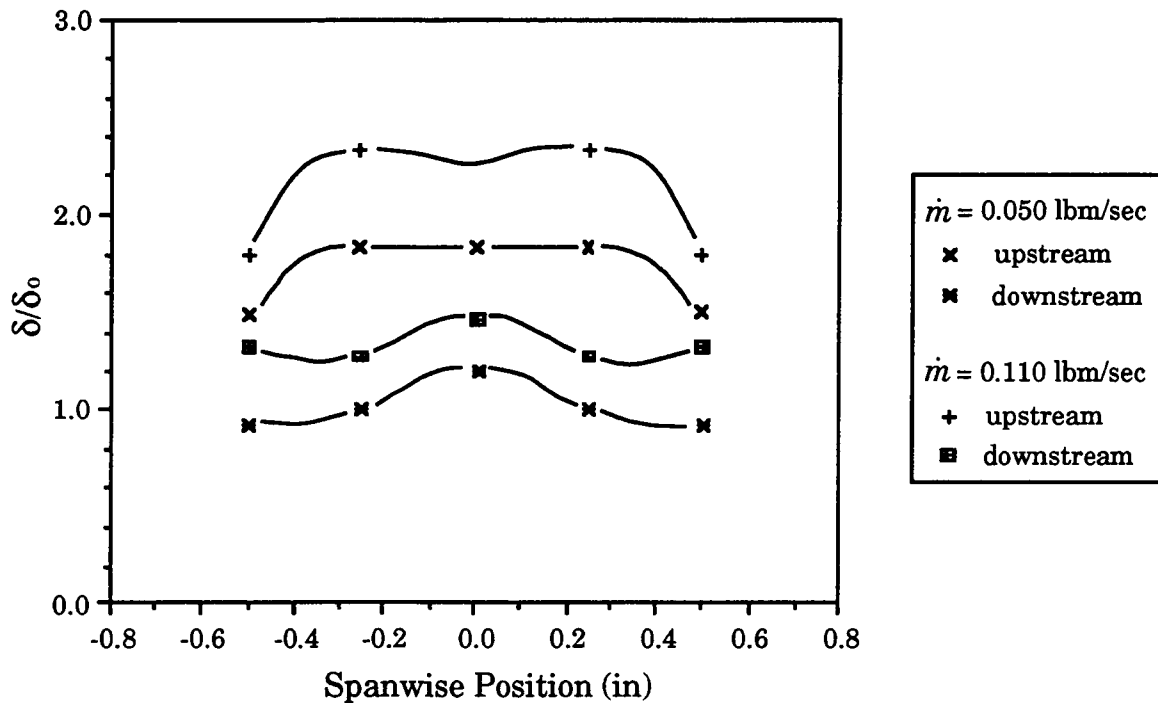


Figure 4.17 Spanwise Boundary-Layer Thickness for the Inverted Triangle

Table 4.6 is a summary of the data obtained for the Inverted Triangle.

Inverted Trapezoid

The Inverted Trapezoid was designed to measure the effect of injection length, but not in the same manner as Gauthier. The plate is essentially the same as the Inverted Triangle, but the hole pattern ends at two thirds the standard injection length. The first row of upstream holes is located at the same distance from the cavity leading edge as the Inverted Triangle.

Like the Inverted Triangle, the Inverted Trapezoid has a full - width

Table 4.6 Inverted Triangle Model Data

Run Number	Mass Flow (lbm/s)	Blowing Parameter B_c	Sound Pressure Level (dB)	Acoustic Attenuation (Δ dB)	Boundary Layer Thickness δ (in)	$\frac{\delta}{\delta_0}$	Probe Position
10286	0.050	0.109	162.8	13.2	N/A	N/A	N/A
10287	0.070	0.127	159.2	16.8	N/A	N/A	N/A
10288	0.090	0.163	155.8	20.2	N/A	N/A	N/A
10285	0.110	0.200	152.9	23.1	N/A	N/A	N/A
10302	0.150	0.272	153.3	22.7	N/A	N/A	N/A
10289	0.050	0.109	N/A	N/A	0.55	1.83	1
102811	0.050	0.109	N/A	N/A	0.55	1.83	2
102812	0.110	0.200	N/A	N/A	0.70	2.33	2
10291	0.050	0.109	N/A	N/A	0.45	1.50	3
10292	0.110	0.200	N/A	N/A	0.55	1.80	3
10293	0.050	0.109	N/A	N/A	0.90	1.20	4
10294	0.110	0.200	N/A	N/A	1.10	1.47	4
10295	0.050	0.109	N/A	N/A	0.75	1.00	5
10296	0.110	0.200	N/A	N/A	0.95	1.27	5
10297	0.050	0.109	N/A	N/A	0.70	0.93	6
10301	0.110	0.200	N/A	N/A	1.00	1.33	6

leading edge perpendicular to the freestream. The acoustic reduction was expected to be the most effective nonrectangular design, but was actually almost identical to the Inverted Triangle. Figure 4.18 shows a maximum peak reduction of 20.2. The boundary layer survey data, on the other hand, indicate that the various spanwise thicknesses for the Inverted Trapezoid are not similarly identical to its triangular counterpart (Fig. 4.19). The shear layer thickness is not as large, either, yet the acoustic attenuation was substantial.

The Inverted Trapezoid data obtained are shown in Table 4.7.

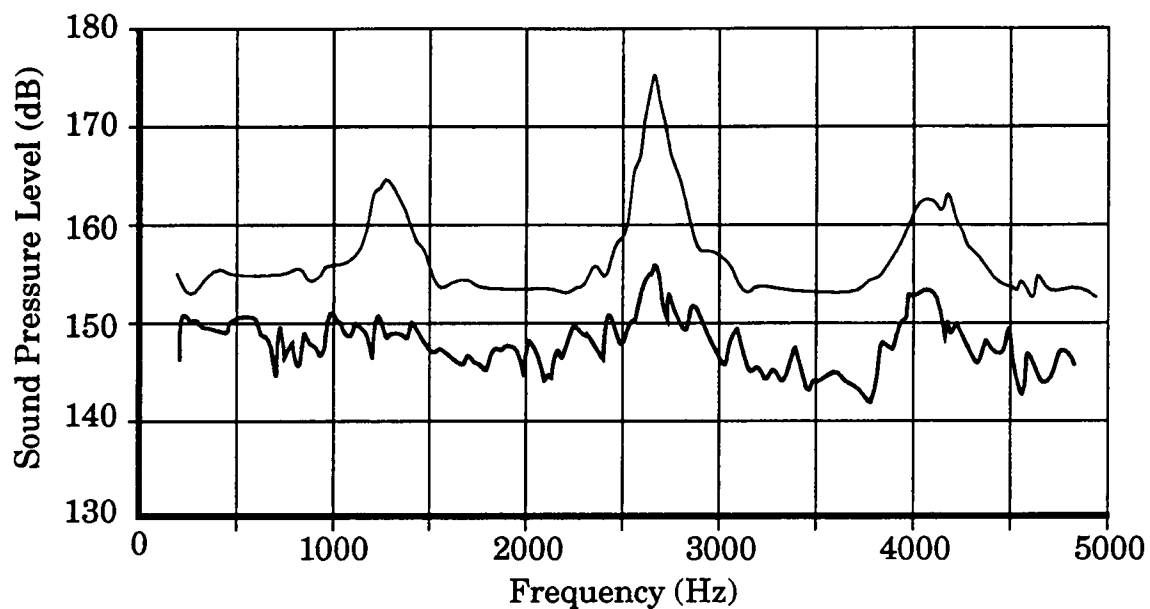


Figure 4.18 Acoustic Pressure-Level Reduction for the Inverted Trapezoid

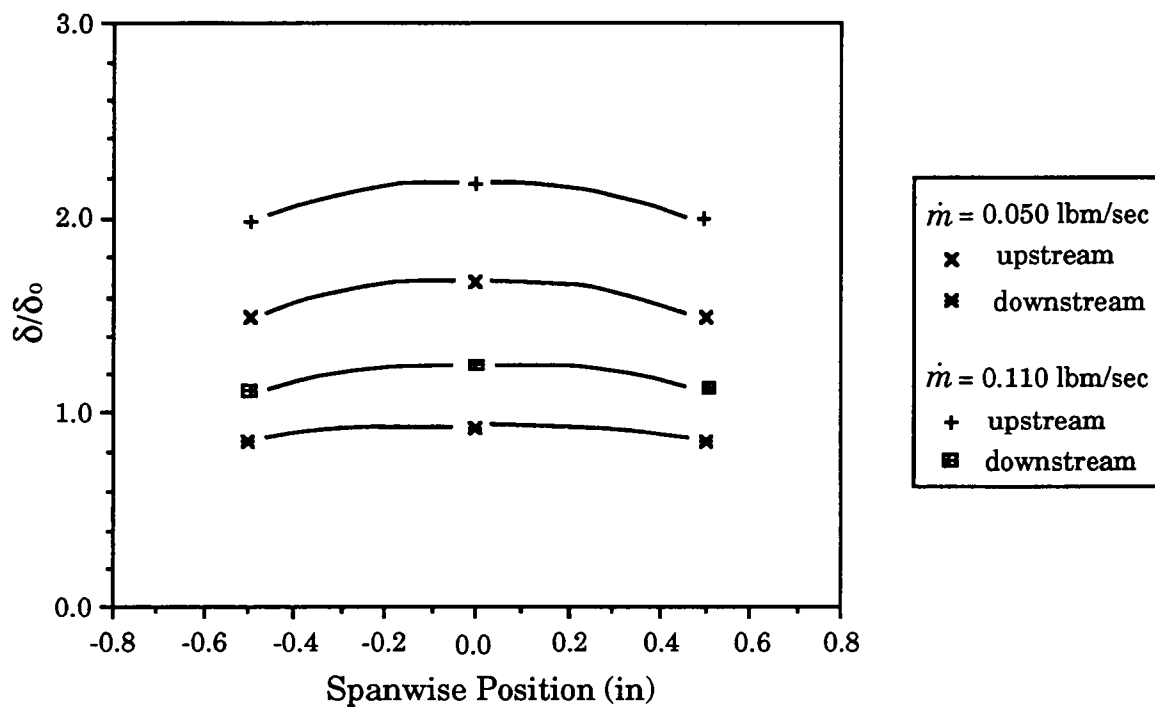


Figure 4.19 Spanwise Boundary-Layer Thickness for the Inverted Trapezoid

Table 4.7 Inverted Trapezoid Data

Run Number	Mass Flow (lbm/s)	Blowing Parameter B_c	Sound Pressure Level (dB)	Acoustic Attenuation (Δ dB)	Boundary Layer Thickness δ (in)	$\frac{\delta}{\delta_0}$	Probe Position
10316	0.050	0.075	163.8	12.2	N/A	N/A	N/A
10317	0.070	0.085	160.2	15.8	N/A	N/A	N/A
10318	0.090	0.109	156.7	19.3	N/A	N/A	N/A
10319	0.110	0.133	155.8	20.2	N/A	N/A	N/A
103110	0.150	0.181	152.3	23.7	N/A	N/A	N/A
11011	0.050	0.075	N/A	N/A	0.50	1.67	1
11012	0.110	0.133	N/A	N/A	0.65	2.17	1
11013	0.050	0.075	N/A	N/A	0.45	1.50	3
11014	0.110	0.133	N/A	N/A	0.60	2.00	3
11015	0.050	0.075	N/A	N/A	0.70	0.93	4
11016	0.110	0.133	N/A	N/A	0.95	1.27	4
11017	0.050	0.075	N/A	N/A	0.65	0.87	6
11018	0.110	0.133	N/A	N/A	0.85	1.13	6

DISCUSSION OF RESULTS

Tunnel and cavity baseline measurements

The tunnel and cavity baseline data show no unexpected trends. The Schlieren system indicates that the freestream has no major disturbances, showing only minor Mach lines throughout the test section. The cavity's acoustic characteristics agree well with the baseline data obtained during Gauthier's experiment. Similarly, the boundary layer thicknesses at either end of the cavity are supported by previous measurements.

Equation 2.2 was used to compare Rossiter's predictions to the data obtained. The cavity's baseline frequency spectrum (Fig. 2.2) indicates three significant modes. The first three modes predicted by Rossiter and the three

observed modes are presented in Table 4.8.

Table 4.8 Predicted and Observed Cavity Frequency Modes

Mode	Predicted Frequency (Hz)	Observed Frequency (Hz)
1	1046	1320
2	2441	2660
3	3836	3980

Duplication of previous results

The acoustic-attenuation data acquired from the Rectangle show very close agreement with Gauthier's data (Fig. 4.7). The data at higher mass flow rates are nearly duplicated. This validates the basis for comparison of the test results to the previous data.

Injection Plates

Expounding on the purpose for this study as discussed in Chapter III, the primary objectives for using upstream mass injection as a suppression device are to stabilize the shear layer by enhancing its growth, $d\theta/dx$, and, hence, also modify its preferred instability modes such that resonance with the cavity's natural acoustic frequencies is eliminated or reduced. In addition, if it can be accomplished more efficiently, the secondary objective is to create fluid "ramps" that prevent shear layer interaction with the cavity leading edge.

It should be noted that off-centerline boundary layer data were obtained only to one side of centerline. The data are presented graphically assuming symmetric flow about the vertical center plane of the tunnel.

Table 4.9 contains the observed frequency modes for the cavity alone, that is to say, with no blowing, and for each model with a mass-flow rate of 0.110 lbm/sec. The first mode for the Rectangle, Double Triangle, Inverted Triangle and Inverted Trapezoid were not apparent in the frequency spectra.

Model	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)
Cavity	1320	2660	3980
Rectangle	not observed	2460	4080
Triangle	1160	2460	3880
Inverted "T"	1200	2440	3880
Double Triangle	not observed	2480	4060
Inverted Triangle	not observed	2740	4040
Inverted Trapezoid	not observed	2680	3940

Table 4.9 Observed Frequency Modes for All Injection Models

Several possibilities exist which may explain this phenomenon. One is that the first mode, having the smallest magnitude of the three observed modes, simply becomes "buried" under other frequency interactions in its immediate vicinity. Similarly, out-of-phase interactions may interfere with the first mode. Still another possibility is that the model mass-flow injection may cause radiation boundary conditions which dampen the first mode enough to suppress it into the surrounding noise.

The Rectangle was the most effective acoustic suppression design. The height of the boundary and shear layers was the most uniform in the spanwise direction (Fig. 4.9). This is indicative of the ideal mass injection previously mentioned. The shear layer is stabilized, it is less responsive to upstream perturbations, and its preferred frequencies have been adjusted to fall outside the natural acoustic frequency of the cavity. The virtual elimination of shear-

layer impingement on the cavity trailing edge was directly responsible for the reduction of downstream perturbations. Additionally, the injection pattern design reduced flow interactions with the cavity sides. That is to say, the rectangular pattern prevented the freestream from encroaching laterally into the cavity environment (Fig. 4.20). This augmented the effects of the shear layer stabilization, resulting in the most effective acoustic attenuation injection configuration.

The Rectangle design was modified to investigate the use of three-dimensional effects to meet the objectives listed above. It was hypothesized that streamwise vortical flow could be used to reduce the edge interactions between the freestream and the cavity environment. It was also hypothesized that streamwise vortices could result in stabilizing the shear layer's inherent instabilities, thus modifying the preferred frequencies and enhancing acoustic attenuation.

The physical explanation behind the ineffectiveness of the Triangle was the shock wave system that developed upstream of the injection area. The shock pattern was somewhat like a diamond, not only oblique in the spanwise direction, but also in the streamwise. The pressure rise across this shock system was much smaller than that caused by the Rectangle; consequently, the momentum thickness of the shear layer was not greatly enhanced, making it more responsive to perturbations.

Figure 4.21 shows the hypothesized streamwise vortical flow pattern. It is important point to note the proximity of the vortices to the cavity edge. In this instance, the vortical flow actually entrained high-energy flow into the cavity, resulting in an increase in the amplitude of the pressure fluctuations.

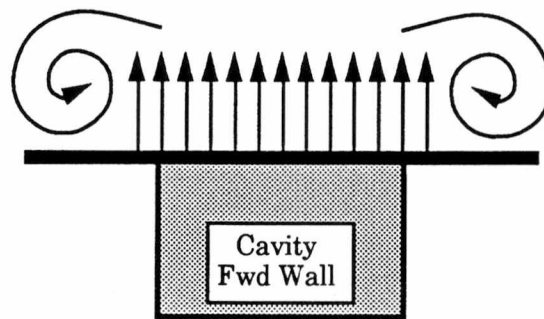
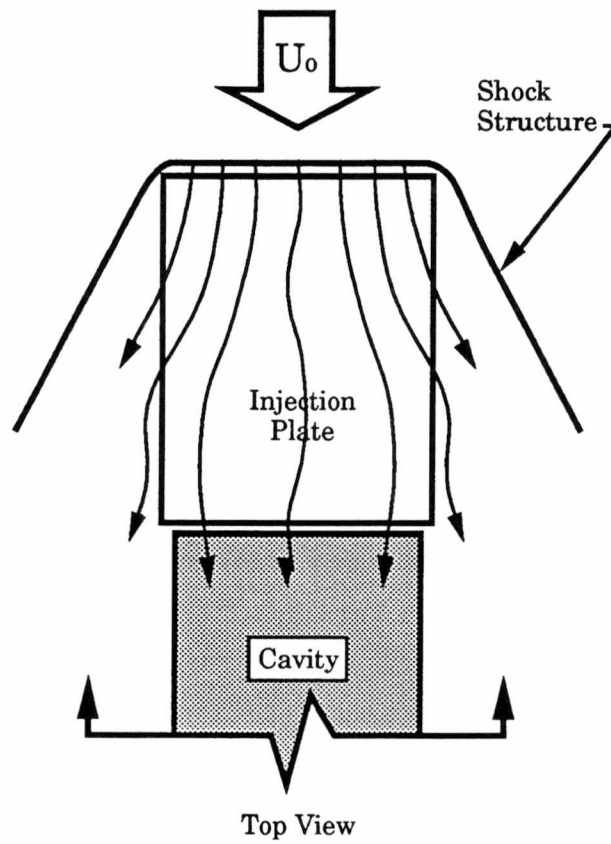


Figure 4.20 Flow Diagram of the Rectangle Model

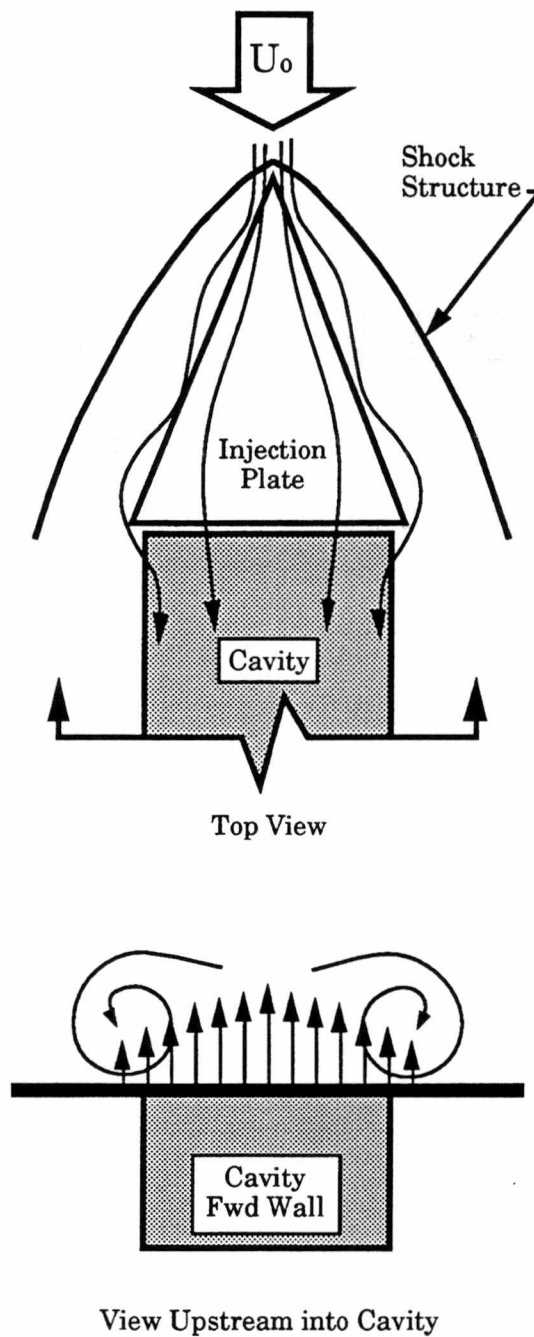


Figure 4.21 Flow Diagram of the Triangle Model

The shock system created by the Inverted "T" injection pattern was more abrupt than the Triangle's. Both the leading edge of the "T" and the two side bars were normal to the freestream, and the resulting shock wave pattern

(and higher pressure increase across the shocks) was more conducive to shear layer growth. This is evidenced by the significant improvement in acoustic attenuation.

The flow over the middle "stem" portion of the "T" was similar to the Rectangle (Fig. 4.22). The streamwise vortical development along this portion of the plate was then interrupted by the flow over the sidebars. Due to the relatively short injection length, the sidebars alone could not enhance shear layer growth. The ensuing complex interaction of that flow and the vortical flow from the stem resulted in the limited entrainment of external flow and associated disturbances.

The design could possibly be improved by lengthening the side bars; that is to say, if the side bars had more injection length, the interactions of the shear layer with the lateral edges of the downstream cavity corner may be further reduced and overall acoustic attenuation could be improved.

Like the Triangle, the outside edges of the Double Triangle injection pattern provided some means of redirecting the freestream flow (Fig. 4.23). The injection pattern downstream of each apex created a full injection length over which the boundary layer's momentum thickness was substantially increased, thus providing the means for stabilizing the shear layer over the cavity. The area between the two apexes produced an environment of complex flow interaction.

It is hypothesized that the shock waves created by the "inward" sides of the two triangles interacted with one another, creating a shock system with a pressure rise much more substantial than that experienced behind one of the shocks alone. There was little, if any, injectant present between the apexes; consequently, minimal boundary layer growth occurred in the immediate

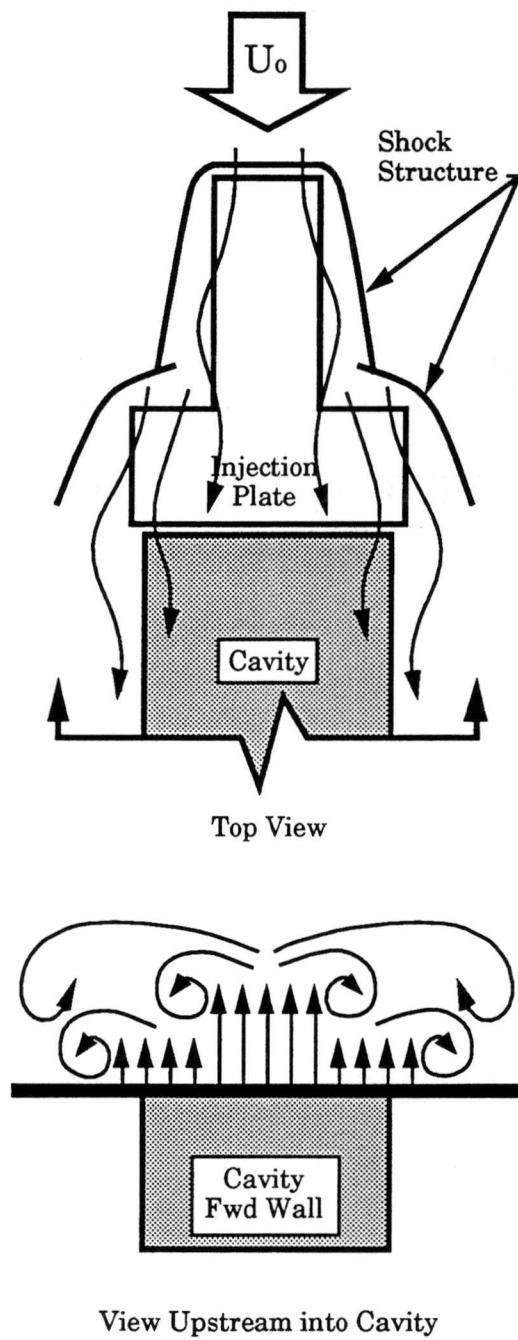


Figure 4.22 Flow Diagram of the Inverted "T" Model

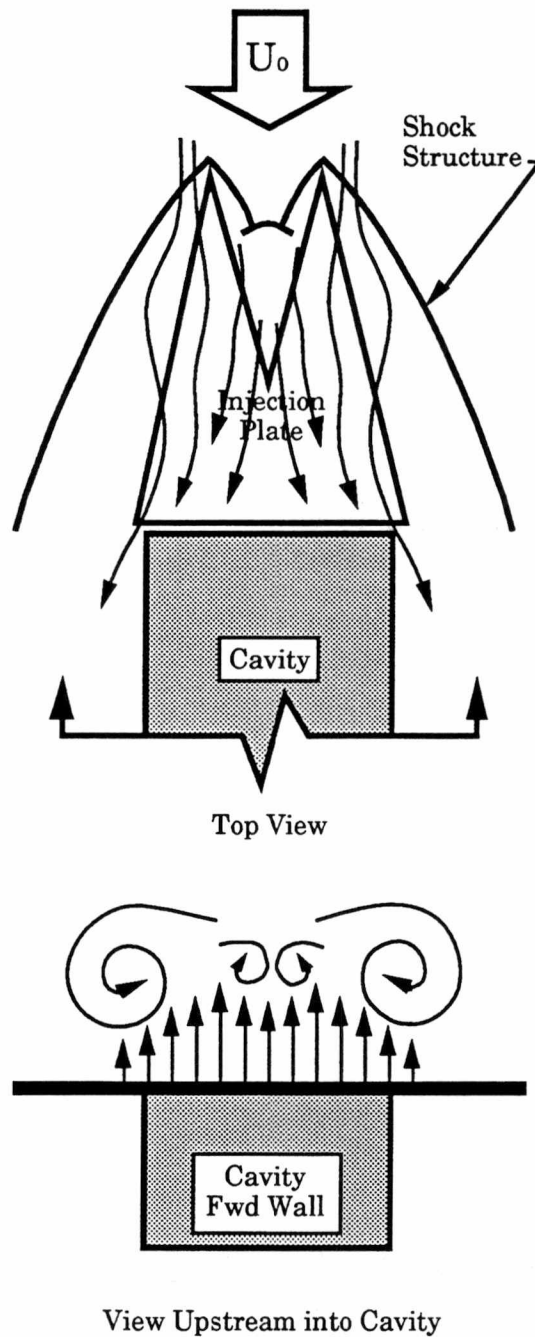


Figure 4.23 Flow Diagram of the Double Triangle

vicinity. The pressure rise due to the shock interaction, however, laterally expanded into the adjacent area of mass injection and boundary layer interaction. This had two effects: first, the shear layer thickness increased

laterally as it progressed downstream; thus, interaction with the cavity edges and the corners of the trailing edge were reduced. Second, the relatively smaller boundary layer upstream of the cavity at the centerline position created a similarly smaller shear layer over the cavity. The result was some entrainment of the freestream high-energy flow and, consequently, limited shear layer interaction at the center portion of the cavity trailing edge. This effect may be reduced with the addition of injection holes between the apexes, the extreme resulting in a trapezoidal pattern.

The design of the Inverted Triangle was intended to enhance the development of streamwise vortices in a different direction. The leading edge of the hole pattern was oriented normal to the freestream to maximize the pressure increase across the shock system and, subsequently, enhance growth of the momentum thickness.

The physical explanation of the observed effects of this injection pattern was that the receding downstream edges of the hole pattern entrained the freestream flow, and result in the formation of streamwise vortices (Fig. 4.24). The vortical structure would then interact with the cavity shear layer, modifying its development such that large-scale instabilities would not be created. The significant difference between the vortical flow developed by the Inverted Triangle and the Triangle is the proximity of the vortices to the cavity. In this case, the vortical core is farther away from the cavity than the Triangle instance. As a result, the ability to entrain external flow is substantially reduced, while, conversely, shear layer stabilization seems to occur through streamwise vortical interaction.

Although it is difficult to prove this hypothesis with the available data, Figure 4.17 shows noteworthy trends in the boundary and shear layer

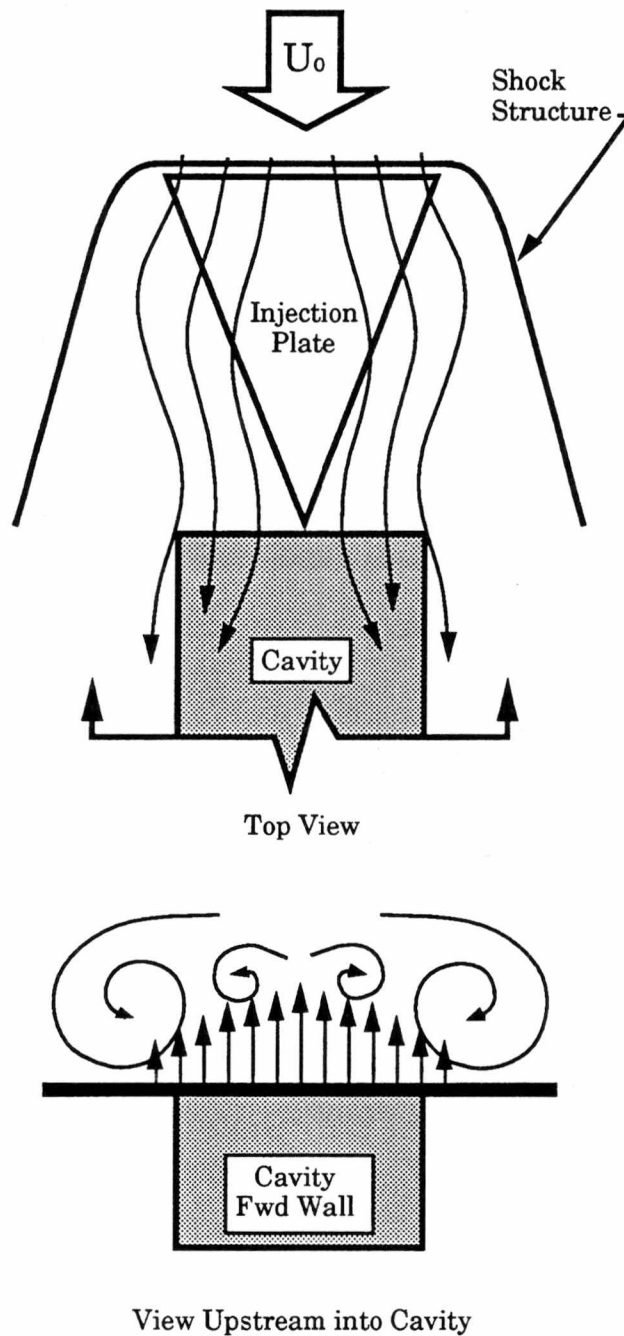


Figure 4.24 Flow Diagram for the Inverted Triangle

thicknesses. Focusing on the higher mass flow rate, it can be seen that the boundary layer thickness dropped off toward the sides of the cavity at the leading edge. This trend is actually reversed at the trailing edge, indicating an

influence other than the mass injection on the shear layer development. The acoustic attenuation effectiveness of this design warrants further investigation of the resulting cavity flow. In particular, extensive three-dimensional flow measurements should be acquired.

The Inverted Trapezoid design was to investigate the effects of commencing mass injection at the same upstream location as the other models, but truncating it farther upstream from the cavity leading edge. Figure 4.18 shows a mild spanwise decrease in boundary layer thickness which is slightly amplified at the downstream survey stations. Despite these differences in boundary and shear layer thicknesses, the acoustic attenuation of the Inverted Trapezoid was only slightly less effective than the Inverted Triangle.

The Schlieren data show a relatively stable shear layer; however, there is a disturbance in the area between where the hole pattern stops and the cavity leading edge. Some form of wave instability fluctuates immediately upstream from the cavity leading edge, but is not consistently present. No such disturbance was observed for the other configurations. Two possible physical explanations have been formed concerning its nature.

The first theory postulates that the mass injection lifts the boundary layer off of the tunnel floor, and when the injection ceases at the end of the hole pattern, the boundary layer tries to reattach itself to the tunnel floor surface upstream of the cavity (Fig. 4.25a). The geometry of the injection plate is such that the reattachment point is approximately where the cavity shear layer originates, or at the cavity's leading edge. As a result, the disturbance is periodic and has little effect on the cavity aeroacoustics.

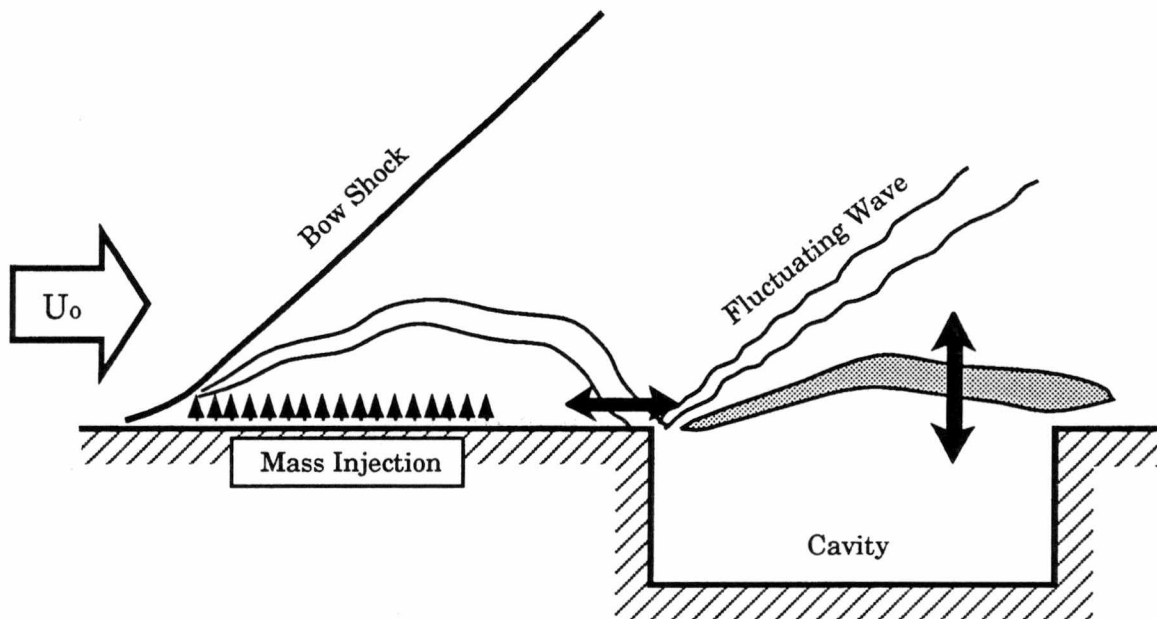


Figure 4.25 Flow Diagram for the Inverted Trapezoid

a. Boundary Layer Reattachment

Another possibility is that after the mass injection ceases, a new boundary layer forms underneath the newly-developed shear layer consisting of the original boundary layer and the injected mass (Fig. 4.25b). The “new” boundary layer interacts with the suspended shear layer, and the flow that is introduced over the cavity is a complex combination of the two. The cavity environment is thus “insulated” from the freestream not just by the mass injection, but by the new boundary layer as well. This changes the effective depth of the cavity further, since the high-energy flow of the freestream is now even farther above the cavity floor; as a result, the L/D ratio of the cavity is changed, and the likelihood of the shear layer spanning the cavity is greater.

The aforementioned pressure fluctuation may result from the increased oscillatory nature of the shear layer; that is to say, the hypothesized boundary/shear layer unique to this design may have relatively small

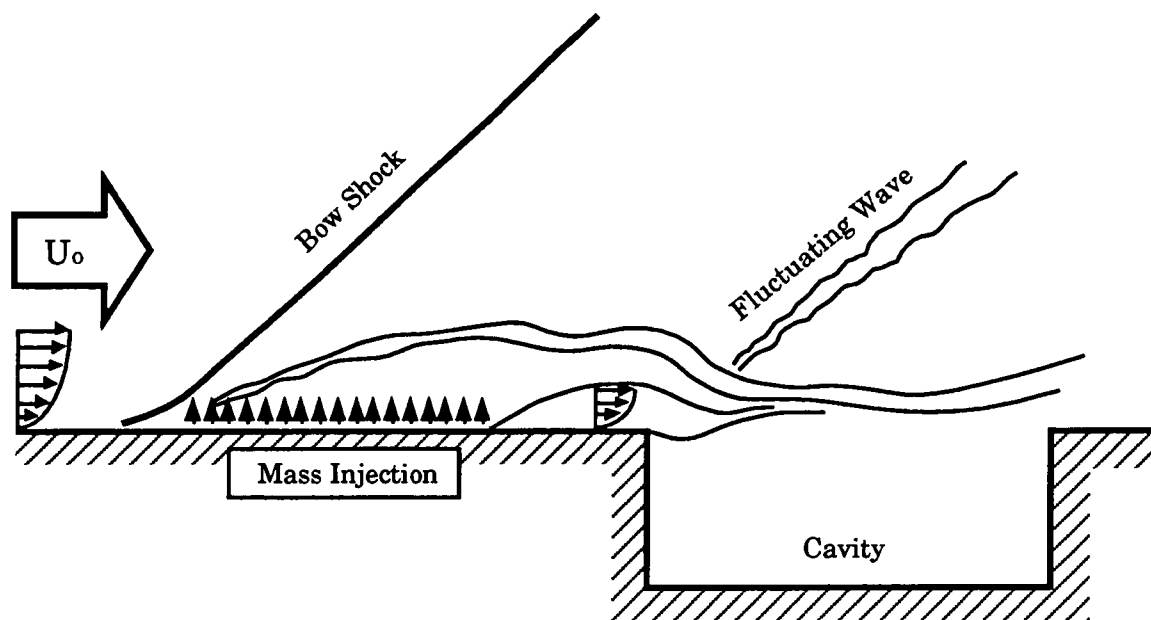


Figure 4.25 (continued)

b. Secondary Boundary Layer Formation

amplitude fluctuations which, in turn, interact with both the cavity environment and the freestream. These fluctuations could cause minor shock waves as the entire complex cavity shear layer develops over the cavity. Farther downstream, the characteristics of the overall shear layer will overcome the less powerful fluctuations of the smaller shear layer that developed upstream of the cavity.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The effects of mass-injection patterns upstream of a cavity were experimentally studied. Various injectant hole patterns were used to introduce three-dimensional disturbances into a shear layer created over a rectangular cavity with $L/D=2.54$, in a supersonic freestream at $M=1.8$.

The injectant was expected to help stabilize the shear layer and, thus, reduce any aeroacoustic effects which naturally occur in cavity flow. By varying the pattern of the injectant area, streamwise vortical interactions were altered, and their effect on shear layer stabilization and aeroacoustic attenuation was studied. Based the results obtained, the following conclusions were drawn:

- As was established by Gauthier (Ref. 9) and duplicated in this experiment, mass injection upstream of the cavity enhances boundary layer growth and, consequently, shear layer growth.
- While holding the net injection area constant it was determined that varying injection patterns does indeed influence shear layer development differently for each case studied. Effective acoustic attenuation also varied considerably.
- Three-dimensional interactions resulting in streamwise vortical interaction has been shown to be an effective acoustic attenuation device in some cases.

- The rectangular pattern, or that which most closely approximates a two-dimensional injection pattern, appears to result in the maximum attenuation of the patterns considered.

Additionally, the conclusions drawn indicate the need for further research in this field; hence, the following recommendations are offered.

- A basic, more fundamental study of cavity flow with upstream mass injection is needed.
- Dynamic three-dimensional measurements, including local static pressures within the shear layer and the injection area, need to be acquired.
- A nondimensional quantity more descriptive of the injection flow physics needs to be identified. Parameters such as streamwise injection length, porosity, and possibly injection pattern need to be incorporated into its formation.

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VITA

Glenn Christopher Cooper was born on May 26, 1962 in Pittsburgh, Pennsylvania to Bernice B. and William J. Cooper. He attended the public schools of Mount Lebanon School District and graduated from Mount Lebanon Senior High School in June 1980. After a year spent learning to fly, he entered Virginia Polytechnic Institute and State University. In June 1985, he received a Bachelor of Science degree in Aerospace and Ocean Engineering.

For the next three years, he worked for Calspan Corporation as a wind tunnel project engineer at the Arnold Engineering Development Center in Tullahoma, Tennessee. He specialized in the study of aerothermodynamic heating of bodies in hypersonic flow. During that time, he attended the University of Tennessee Space Institute as a part-time graduate student.

Eventually Glenn's love of flight called him to another career. In November 1988, he entered Aviation Officer Candidate School, was commissioned as an Ensign in the United States Navy four months later, and entered flight training. On June 6, 1990 he completed his first aircraft-carrier landings, thus qualifying as a "Tailhooker." Glenn received his wings of gold on February 8, 1991 and was designated a Naval Aviator.

Before beginning the next phase of flight training, he re-entered UTSI, again on a part-time basis. In August 1995 he was awarded a Master of Science degree in Aerospace Engineering.

Glenn is presently flying the Grumman A-6E Intruder from the USS Independence somewhere between the Pacific Ocean and the Persian Gulf. His home port is Naval Air Facility Atsugi near Tokyo, Japan.