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Suppression of Cavity Oscillations Using Upstream Mass Injection

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

Daniel Evan Schatt
August 1992

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ABSTRACT

An investigation was conducted to determine the effectiveness of upstream secondary mass injection in suppressing oscillations that cause acoustic waves in rectangular cavities. The tests were conducted at a Mach number of approximately 1.8, and at a test section Reynolds number of approximately 1.7×10^7/ft. The boundary layer became fully turbulent before reaching the cavity. The mass was injected through a series of holes just upstream of the cavity at several different mass flow rates. Two different hole density patterns (porosities), a high density and a low density, were used in the experiment to judge the relative effectiveness. Turbulent boundary layer characteristics were examined, and frequency spectrums of the cavity oscillations were measured. The results showed significant suppression of sound pressure levels; in the best case, the peak of the frequency spectrum was reduced from 172 dB (no suppression) to 145 dB. In addition, the low density hole pattern was judged to be much more effective in suppression at lower mass injection rates. It was shown that the low density configuration has a larger shear layer momentum thickness, and that the greater suppression is probably caused by this. An attempt was made to develop a nondimensional blowing parameter that could describe suppression effectiveness for any given configuration. It was established that the momentum thickness should be incorporated into the blowing parameter.

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LIST OF SYMBOLS

A	=	area
B	=	blowing parameter
B_{mom}	=	momentum blowing parameter
D	=	cavity depth
L	=	cavity length
M	=	Mach number
S	=	Strouhal number
U, u_e	=	freestream velocity
W	=	cavity width
f	=	oscillation frequency
k	=	vortex convection velocity constant in Rossiter's equation
m	=	mode number of cavity oscillations
$\dot{m}$	=	mass injection
θ	=	momentum thickness
λ_e	=	blowing rate of Fernandez and Zukoski
δ	=	boundary layer thickness, shear layer thickness
γ	=	empirical factor to account for time lag in Rossiter's equation
ρ	=	density

Subscripts

cav	=	cavity
crit	=	point of transition between open and closed cavity flows
e	=	edge of boundary layer
inj	=	injection
w	=	wall

I. INTRODUCTION

Since the advent of high-speed (i.e. transonic and supersonic) flight in the 1940's and 1950's, it has been widely observed that air flowing tangentially over a cavity or cutout is usually unsteady. Cavity flows are of interest because they arise in many applications, such as aircraft weapons bays and wheel wells. Figure 1 shows a typical cavity configuration. Large pressure fluctuations may occur on the walls of the cavity and on surrounding surfaces. These fluctuations are caused by intense flow oscillations within the cavity; they take the form of strong, propagating acoustic waves and are generally detectable as audible tones. In many cases, the acoustic waves are strong enough to cause adverse effects on the cavity and items within, and nearby structural components or sensitive instruments are jeopardized. For example, air flowing externally over aircraft bomb bays and skin openings for probes can cause pressure oscillations of such high intensity as to excite the main flexural or structural modes of the aircraft, causing significant damage. At the very least, the oscillations can cause equipment or instrumentation failure and can cause damage to sensitive stores in the bay; it can also influence store separation or trajectory. The oscillating cavity also causes much greater drag on the body which houses the cavity, as compared to a non-oscillating cavity.

The acoustic phenomena is apparently related to the presence of a shear layer, or turbulent mixing zone, between the external flow and the flow within the cavity. The shear layer appears to undergo coherent oscillations, giving rise to unsteady loading of the edges/surfaces of the cavity. Modeling of these physical features of cavity flow is of fundamental interest, not only because of the rich nature of the flow field and its complexities, but also because of the wide range of applications in which cavity flows and associated oscillations are encountered. For example, pressure vents on the Space Shuttle cargo bay have been observed to cause high internal noise levels during ascent. Cavity flows normally will enhance transition to turbulence, but under certain conditions

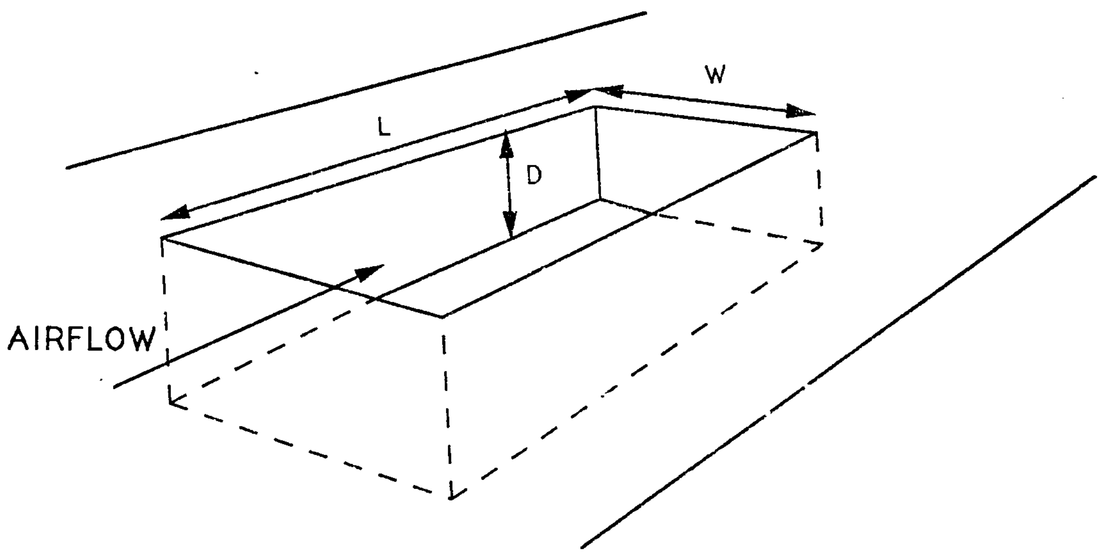


Figure 1. Basic cavity configuration

they can be designed to delay transition. Still other applications include supersonic intakes, landing gear wheel wells, flaps in short-takeoff-and-landing (STOL) aircraft, and cavities/depressions in submarine and ship hulls.

Consequently, it is of considerable interest to understand the mechanisms that cause cavity flow oscillations, which will better enable one to discover practical means to suppress them when necessary. A large amount of research has been devoted to the study of cavity flow over the last several decades. These investigations have been conducted over a speed range from low subsonic to hypersonic Mach numbers, and they have included both theoretical and experimental studies of various cavity configurations. Also, numerous model studies and flight test programs have been conducted. All of these investigations have furthered the understanding of the physical mechanism of the oscillations and provided quantitative information about the relationship of the basic geometric and aerodynamic variables of the acoustic phenomenon. The investigations have also led to empirical relationships that approximately predict the observed frequencies of the oscillations.

Initially, cavity flows were studied experimentally. Due to improvement in experimental techniques, such as optical diagnostics and image processing, some of the important flow features have only recently been observed. In parallel with experimental observations, attempts to provide theoretical understanding of the flow processes have been made. The most successful of these have predominantly been based on linearized analytical descriptions in which it is necessary to employ empirical or semi-empirical parameters. More recently, with the advances in computers, numerical methods and unsteady Navier-Stokes codes have been employed to study the oscillatory flow mechanism. These efforts have met with only partial success.

Previous published work concerned with aerodynamic production of cavity oscillations have been concentrated mainly on two classes of the problem[1], as illustrated in Figure 2:

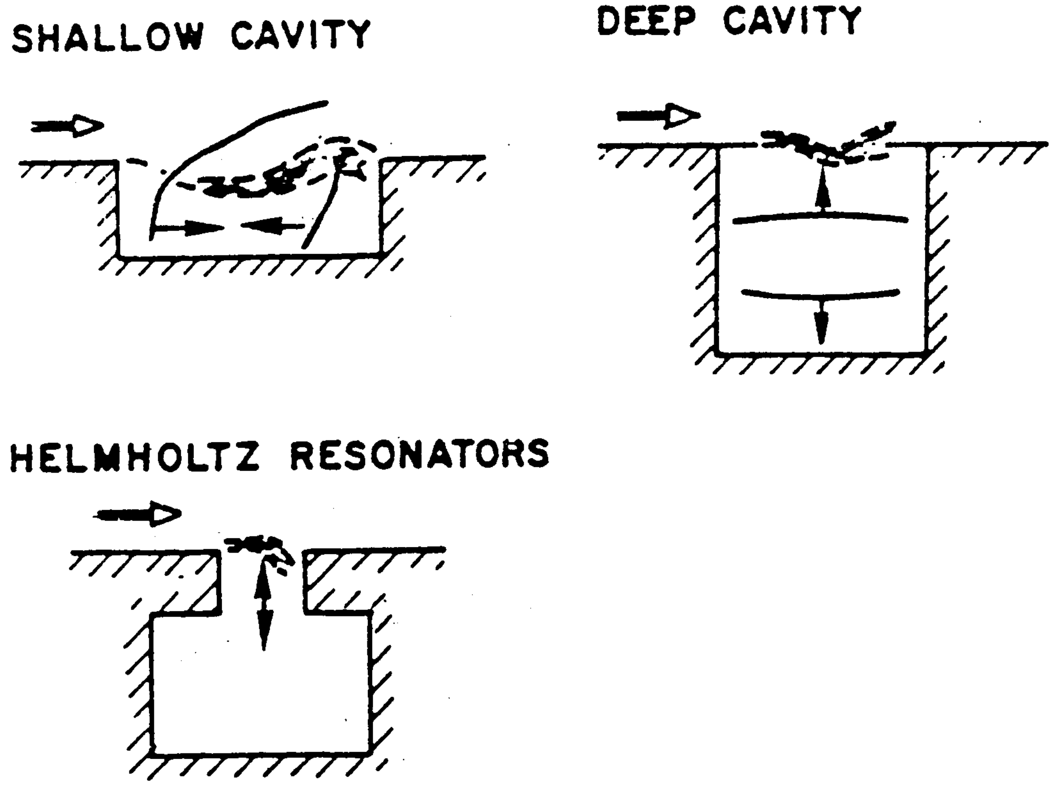


Figure 2. Basic cavity geometries

Source: Rockwell, D. "Oscillations of Impinging Shear Layers". AIAA Journal, May 1983

1) very low speed tests using large enclosures with comparatively small openings which can operate as Helmholtz resonators

2) tests at high speed using small, shallow cavities and shapes relevant to practical problems in aircraft

The Helmholtz resonator type of cavity is distinguished by its very large ratio of cavity volume to cavity orifice area. Consequently, it is possible to generate much lower frequencies as compared to those obtainable with a deep rectangular cavity. This type of oscillation has been documented for flows involving harbors, and compressible flow through ducts.

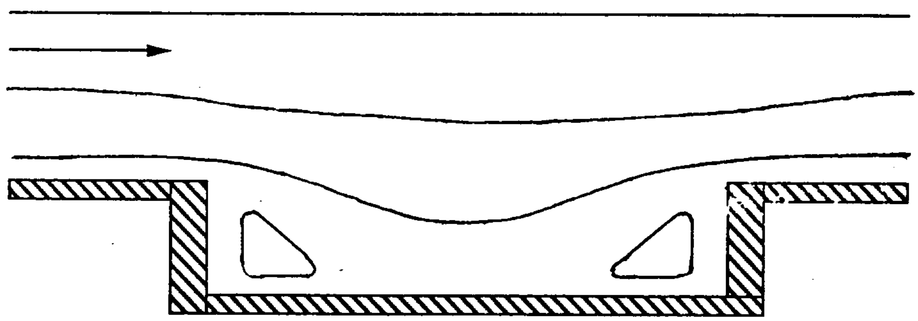
The second class of the problem was the focus of this thesis. The experimental results obtained at supersonic speeds are particularly important for application to cavities on contemporary and future aircraft and missile configurations capable of sustained supersonic speeds. In the critical weapons bay application, current practice may require reduction of aircraft speed prior to opening bay doors, thereby increasing flight time over the target, and increasing vulnerability to enemy countermeasures. The objective of the present study was to investigate the effectiveness of a proposed method of suppressing these cavity oscillations in supersonic flow. Before discussing the suppression method, it will be necessary to provide a fundamental background of the basic flow characteristics.

Data available in the literature show that at supersonic speeds, there are three fundamentally different types of cavity flow fields. These have been classified as open, transitional, and closed cavity flows, as described by Chen.[2] The type of flow field appears to be primarily a function of cavity length-to-depth (L/D) ratio. For $L/D > 13$, the cavity field is generally of the closed flow type. For this case, the shear layer expands over the cavity leading edge, impinges on the cavity floor, and exits ahead of the rear face. At $L/D \approx 12$, the cavity flow field is on the verge of changing from closed cavity flow to open cavity flow, and is referred to as "transitional flow". For this case, the shear layer turns through an angle to exit from the cavity coincident with impinging on the cavity floor, resulting in the impingement shock and exit shock collapsing into a single wave. In some cases, the transitional shear layer may become unstable and alternate between closed and open cavity flow. For $L/D < 10$, the high pressures ahead of the rear face venting into the low pressure region downstream of the front face cause the shear layer to flow over, or bridge, the cavity. This is "open cavity" flow. Figure 3 illustrates closed and open cavity flow.

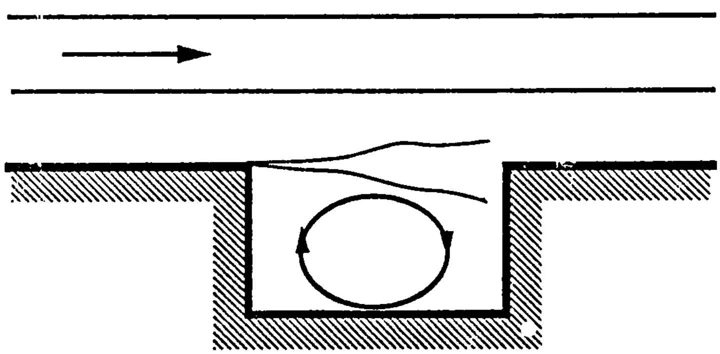
Because of the large differences in the flow fields for open and closed cavity flows and the resulting varied loadings on the cavities and their contents, it is very important to be able to define the L/D boundary that separates the two types of flow fields. This is generally referred to as $(L/D)_{crit}$, which is a function of Mach number. After transition to turbulent flow, the Reynolds number does not appear to play a significant role in cavity flows. Figure 4 provides a visual summary of the classification of cavity flows. The figure illustrates the general region of transition. The Mach number determines the exact point of transition.

In shallow, open cavities--those with an L/D greater than one and with a separated shear layer that spans the cavity--pressure oscillations result from the interaction of the freestream shear layer and the medium within the cavity and involve both acoustic and fluid mechanical mechanisms. Heller and Bliss[3] indicated that the unsteady motion of the shear layer above the cavity results in mass addition and removal at the cavity trailing edge. This will be analyzed in more detail in the next section. Figure 5 shows a schematic of the flow over a shallow cavity

Pressure oscillation amplitudes can be reduced if the shear layer over the cavity can be stabilized so as to prevent the mass addition and removal at the trailing edge. Several geometrical adjustments, such as installation of fences and ramps, have achieved some positive results, as has external forcing of the shear layer. Fluid injection is another possible method. Specifically, bleed injection through a series of holes just upstream of



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



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

Figure 3. Closed and open cavity flows

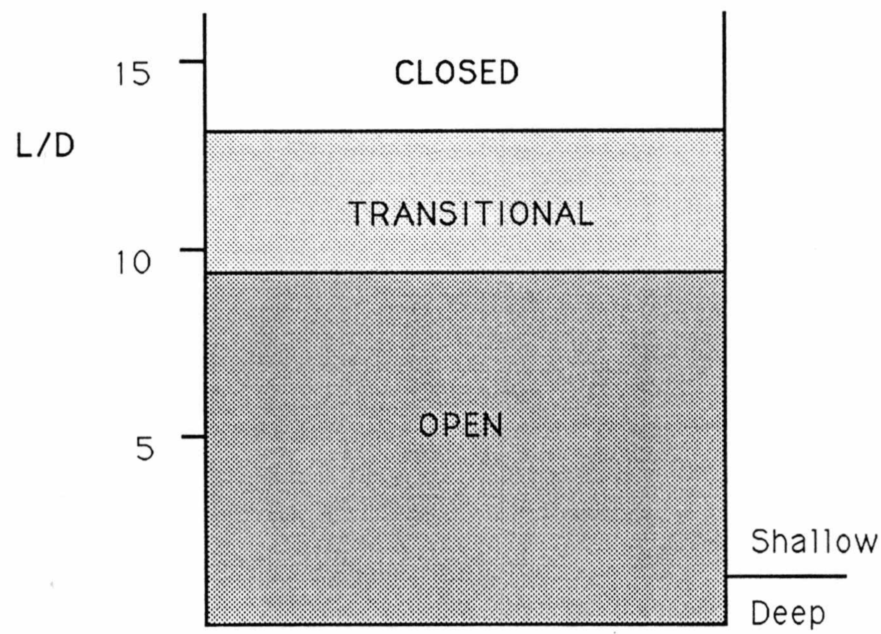


Figure 4. Classification of cavity flows

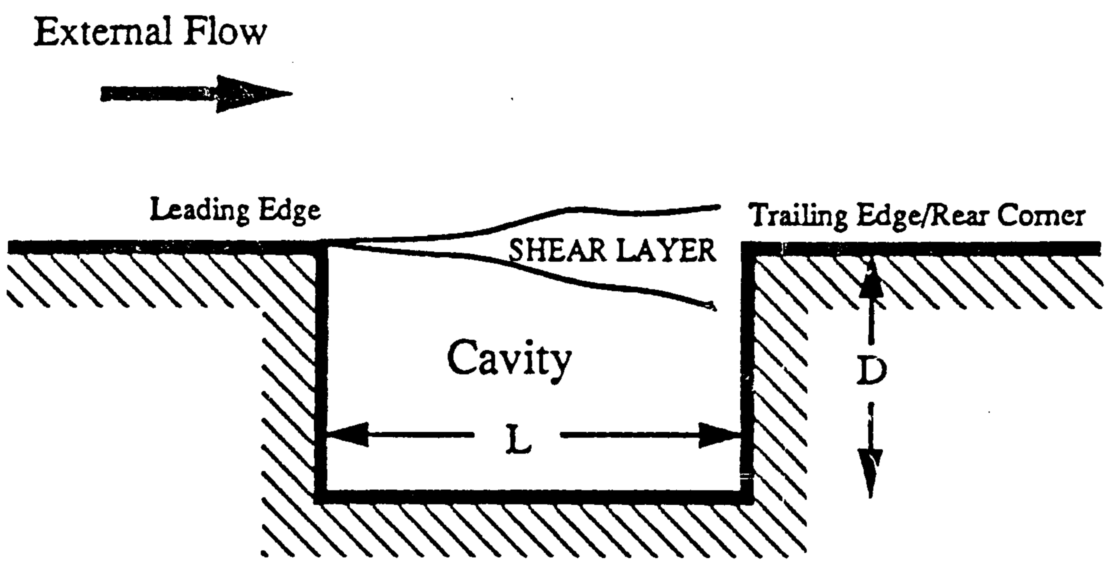


Figure 5. Illustration of shallow cavity flow

Source: Gauthier, C. "Experimental Study of Cavity Flow Oscillations with Upstream Mass Injection". M.S. Thesis, University of Tennessee, Knoxville, December 1990 the cavity will increase both the shear layer thickness and the shear layer momentum thickness. The greater shear layer thickness means there is a reduced probability of a perturbation propagating through the thickness of the shear layer. This will cause it to become more stable by decreasing its response to perturbations. The greater momentum thickness requires that there are lower velocity gradients, which also tends to increase stability.[4] In addition, the shear layer will be blown out of the cavity, and it will have markedly less interaction with the cavity trailing edge. All of these effects will significantly decrease the oscillations. This method of suppression was the focus of the present investigation.

II. THEORY

Fundamentals of Cavity Flow

Many experiments have been completed in studies of the aeroacoustic environment, and a number of theories for predicting oscillation phenomena have been put forward. The experimental study of cavity oscillations stretches all the way back to 1955. In that year, Karamcheti[5] made several important observations for $0.25 < M < 1.25$. He found that the nature of the acoustic field depends not only on the cavity geometry and Mach number, but also on the type of boundary layer (i.e. laminar or turbulent). For given conditions, the acoustic field had much stronger, more discrete tones with a laminar flow. The cavity processes are much more violent when the boundary layer is turbulent, but the generated sound is more broadband. Karamcheti was also the first to realize that vortex motion in the cavity may be an essential feature of the problem.

Relating to geometric properties, Karamcheti observed that the L/D ratio at which sound emission was first noticed depends on Mach number; higher Mach numbers will cause acoustic emission at lower L/D ratios (i.e. deeper cavities). Higher Mach numbers also caused the strength and directionality of the acoustic field to increase. The frequency of the oscillations was observed to increase with freestream velocity and with cavity depth. In short, Karamcheti found that four variables (velocity, Mach number, L/D ratio, and boundary layer type) are most significant in determining the character and intensity of the acoustic field.

In addition, Karamcheti observed that a cavity may oscillate under a broad band of flow situations in a supersonic freestream. Flow oscillations may occur predominantly in the spanwise, longitudinal, or transverse directions. In deeper cavities, longitudinal oscillations are usually predominant. He concluded that the forcing mechanism was associated with the inherent instability of the shear layer, which permits amplification of disturbances.

At the same time, Roshko[6] did a study which focused primarily on aerodynamic factors in cavity flow (i.e. pressure distributions and friction measurements at the base of the cavity). These subsonic measurements allowed Roshko to propose that a system of vortices is a primary component of the flow. He proposed that the periodic acoustic waves may be associated with movements of the vortices, with the frequency being determined by the coupling between the acoustic field and the vortex field.

In 1962, Plumbee, Gibson, and Lassiter[7] took issue with Karamcheti's conclusions about the forcing mechanisms for the phenomena. They hypothesized that conditions inside the cavity must ultimately depend on the characteristic acoustic response of the cavity. In other words, sound generation in a cavity is basically that of an enclosure responding in its normal acoustic modes. The acoustic resonance is excited by the unsteadiness in the turbulent boundary layer approaching the cavity. The theoretical development is somewhat complex, but a simplified model is derived to enable a designer to predict the frequencies that will be observed in a given cavity. Agreement with experiment is good for deep cavities and Helmholtz resonators ($L/D \leq 1$), but not for shallow cavities. At any rate, this scheme gives no indication of the aerodynamic conditions under which resonance will occur.

Rossiter's paper[8] (1966) observed that the theory of Plumbee, et al. is inconsistent with experiment since Karamcheti had shown oscillations were present with laminar boundary layers. Nevertheless, Rossiter agreed with Plumbee that acoustic resonance does play an important role in determining the characteristics of the oscillations, although he suggested the forcing is caused by the flow over the cavity rather than by the boundary layer approaching it. Rossiter offered an empirical formula for generating all the possible frequencies:

$$f = \frac{u}{L} \cdot \frac{m - \gamma}{M + \frac{1}{K}}$$

m = integral number representing the integral acoustic modes

k = ratio of vortex convection velocity to freestream velocity

γ = a factor to account for the the time lag between the passage of a vortex and the emission of an acoustic pulse at the downstream corner of the cavity

The factors k and γ are normally taken to be 0.57 and 0.25 respectively.

Although this formula was developed for subsonic and transonic Mach numbers, they have been used widely in supersonic flows as well. The influence of the shear layer is addressed via the vortex velocity ratio, and cavity shape in the flow direction is acknowledged through the γ term, which Rossiter presents as a function of L/D. This relationship can be displayed graphically; a satisfactory analytical relationship has not been found. The importance of the boundary layer is acknowledged in determining the magnitude of the oscillations; specifically, Rossiter cites the ratio of the boundary layer thickness to cavity depth as the crucial parameter. It should be noted that Rossiter's formula, though widely used, has limitations. Higher mode frequencies are not predicted well, and predicted frequencies are underestimated for high Mach number flows.

Rossiter than suggested a possible physical model of the flow. He proposed a mechanism similar to that producing edgetones, which are the frequencies produced when a wedge is placed in a laminar flow issuing from a narrow slit. The analogy was made because the sequence of frequencies that are experimentally observed are the same in both cases, and acoustic radiation and vortex shedding are common features of both phenomena. The mechanism hypothesizes that the shear layer, which separates the cavity from the external stream, rolls up into discrete vortices which are shed at regular intervals from the front lip of the cavity. There is also an acoustic source at the rear lip. Rossiter assumes the vortices interact with the trailing edge, generating acoustic pulses (pressure waves) which propagate upstream. The pulses deflect the oncoming boundary layer at the leading edge, producing vortices which are shed downstream, thus closing the cycle. Longitudinal oscillations are produced whose frequencies lie in the sequence $(m - \gamma)$. These frequencies, expressed nondimensionally as Strouhal number, are plotted vs. Mach number in Figure 6. The various modes are clearly delineated. These are the dominant frequencies of the shear layer feedback system. When the frequency of one of these components is close to the natural frequency of air in the cavity, resonance occurs. To summarize, it was proposed that the acoustic radiation initiates the vortex shedding, and the passage of the vortices near the rear lip of the cavity is responsible for the acoustic radiation.

Rossiter also made observations concerning the approximation of a 3-D cavity by a 2-D cavity, noting that the flow on the centerline of a 3-D cavity may be similar to the 2-D case, but the flow near the sides and downstream may be quite different. Nevertheless, it has since been shown that the oscillatory characteristics of a supersonic cavity are not influenced significantly by the 3-dimensionality of the cavity.[1]

In the same year, East[1] stated, as had Rossiter, that acoustic tones will only occur when there is resonance between the shear layer pressure fluctuations at particular frequencies and the cavity acoustic modes. East provides an approximate mathematical scheme for predicting the frequencies which will produce this resonance. The theory, in essence, involved the forced acoustic response of a rectangular cavity with five walls having infinite impedance and the sixth having the radiation impedance of the cavity opening. Tones will be produced only when shear layer oscillations are amplified by acoustic coupling between shear layer pressure fluctuations and cavity modes. Shear layer feedback, in turn, causes amplification of certain frequencies which results in the frequencies observed. East's experiments were carried out at very low Mach numbers and with deep cavities, and the frequencies are shown to be consistent with Rossiter's equation.

Heller, Holmes, and Covert[9] (1971) pointed out that Rossiter's equation became worse at $M > 1.5$ because he assumed the speed of sound in the cavity to be the freestream speed of sound. This error became more pronounced at high Mach numbers. They suggested an improvement in the high Mach range by assuming the cavity speed of sound is equal to the freestream stagnation speed of sound. Then:

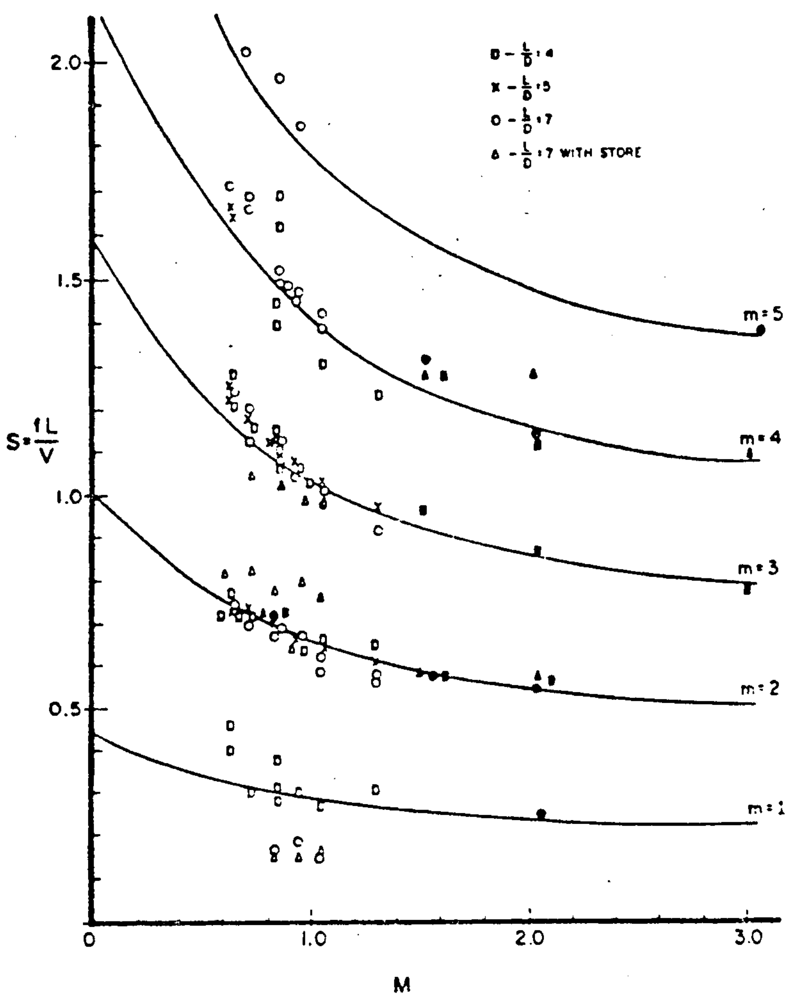


Figure 6. Nondimensional resonant frequencies in a shallow cavity as a function of external stream Mach number

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

$$f = \frac{u}{L} \cdot \frac{m - \gamma}{\frac{M}{\sqrt{1 + \frac{\gamma - 1}{2} M^2}} + \frac{1}{K}}$$

This study then proposed that a shallow cavity does not act as a classical acoustic resonator responding to its normal modes. Shallow cavities resonate poorly, though they may be driven by the freestream at relatively definite frequencies. This is in contrast to deep cavities, which do resonate in their normal modes. The mechanism by which the freestream drives a shallow cavity at definite frequencies appears to resemble an acoustic source close to the trailing edge, and the highest pressure fluctuation levels were observed there.

Heller, et al. also concluded that boundary layer parameters must be included in a complete theory of the response amplitudes of the cavity, and that transition from a laminar to a turbulent boundary layer can greatly affect the cavity response.

Bilanin and Covert[10] (1973) suggested that shear layer instability and interaction with the cavity were required for sustaining oscillations. Specifically, free shear layers have long been known to be susceptible to the so-called Kelvin-Helmholtz instabilities. The model assumes that the shear layer, represented by an infinite vortex sheet which separates the freestream from the quiescent cavity fluid, is disturbed periodically at the upstream lip by a pressure pulse. This excites the Kelvin-Helmholtz instabilities, which grow as they propagate downstream. The fluctuating motion of the shear layer at the trailing edge induces a periodic inflow and outflow, which is the source of acoustic radiation. These acoustic waves, modeled by an acoustic monopole, propagate upstream inside the cavity and give rise to a localized pressure force at the upstream wall which excites the shear layer; this completes the feedback loop (see Figure 7).

The involved model, similar to Rossiter's but with no empirical constants, includes an equation that describes the allowable frequencies. Though many simplifying assumptions are made, there is general agreement with experimental data for

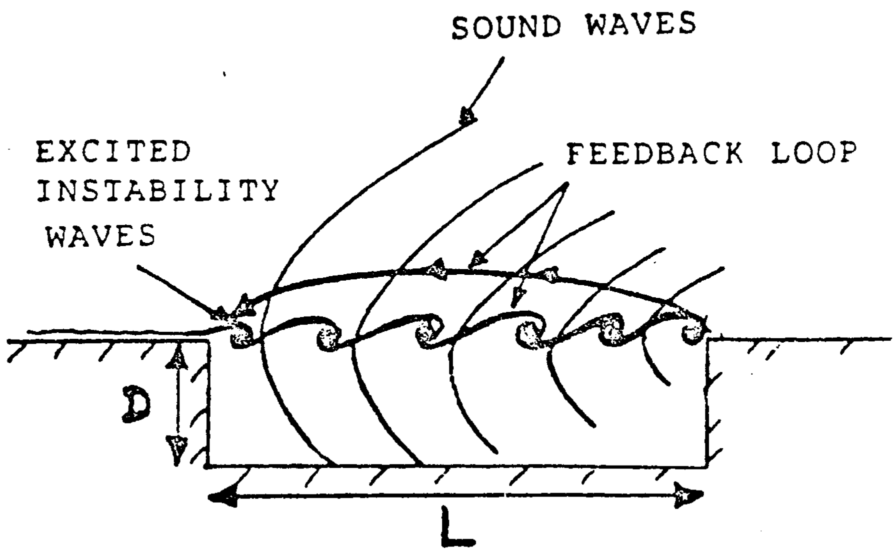


Figure 7. Feedback loop responsible for cavity oscillations

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

$0.8 < M < 3.0$. This agreement would seem to indicate that the flow contains many of the features that the model assumes, which are similar to the mechanisms underlying edgetone production. Bilanin and Covert also made the important observation that the unsteady motion in cavities may be treated as if it were 2-D (i.e. the oscillations are independent of the transverse or spanwise directions).

Soon after, Heller and Bliss[3] (1975) published a paper which proposed a physical mechanism and analytical model for pressure oscillations at transonic and supersonic speeds. They suggested that the cause is an interaction of the free shear layer and the cavity internal medium, involving both acoustic and hydrodynamic mechanisms.

They postulated that the unsteady shear layer motion leads to a periodic mass addition and removal at the trailing edge, which produces an effect similar to replacing the rear bulkhead with an oscillating piston. This creates forward traveling waves which reflect from the front bulkhead and become rearward traveling waves, as illustrated in Figure 8. The resulting wave structure in the cavity forces the shear layer in an unsteady motion over the cavity, which is responsible for the trailing edge mass addition and removal that initially produced the traveling waves; thus the loop is complete. It is observed that the wave motion of the shear layer and the wave structure within the cavity are strongly coupled and cannot be considered separately. This view is analogous to the shedding-of-vortices view; Heller and Bliss state that the shear layer, subjected to forcing by the cavity internal wave structure, would roll up into discrete vortices.

Tam and Block's study[11] (1978) focused on oscillations in wheel wells, and therefore on shallow cavities ($L/D \geq 1$) in the low subsonic range. Nevertheless, some important observations were made which apply throughout the entire Mach number range.

Tam and Block pointed out several shortcomings in Rossiter's model. They state that there is not necessarily good agreement with the experimental data of others, particularly at Mach numbers outside his range. Furthermore, they note that some experimental observations, particularly by Karamcheti, and Heller and Bliss, did not

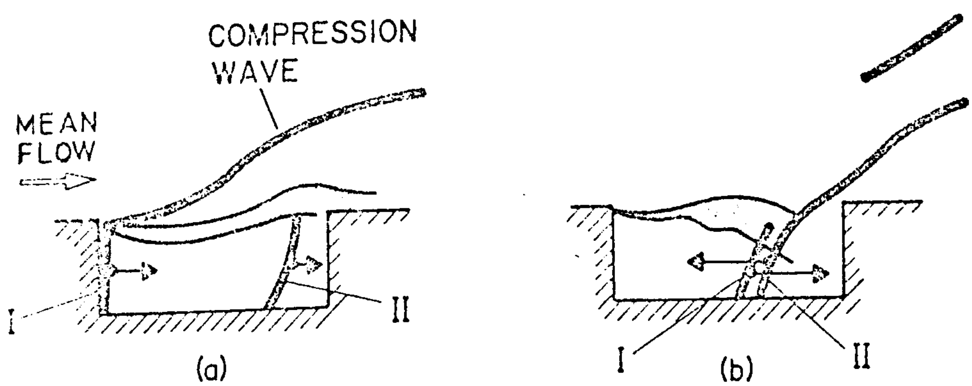


Figure 8. Illustration of wave motion in a cavity, after Heller and Bliss
Source: Rockwell, D. and Naudasher, E. "Review--Self-Sustaining Oscillations of Flow Past Cavities". Transactions of the ASME, Vol. 100, June 1978

indicate vortex shedding. This would seem to indicate that vortex shedding is not essential to producing oscillations. Finally, the Rossiter model does not explain how acoustic disturbances are generated and how they excite the shear layer.

In addition, Tam and Block express reservations about Bilanin and Covert's model, although they acknowledge an improvement over Rossiter. The Bilanin and Covert model is in poor agreement with data at low Mach numbers, and in addition, there is concern over the modeling of the shear layer as an infinitesimally thin vortex sheet. There is still no explanation of how the acoustic disturbances interact, and how they excite the flow instabilities.

Tam and Block proposed a detailed linearized model which attempts to take into account the shear layer thickness, and an analysis of the excitation process is put forth. Some of the simplifying assumptions in previous models were removed, and some features in Bilanin and Covert's model are incorporated.

A vortex sheet is used to simulate the shear layer. The fluctuating interaction between the shear layer and the cavity trailing edge is simulated by an imaginary line source, and the fluctuation of the vortex sheet (shear layer) due to the resulting pressure field is solved with linearized theory. Figure 9 shows the Tam and Block model. In this theory, the oscillation occurs when the pressure radiation from the trailing edge forms a closed loop with the transverse velocity fluctuation at the leading edge (Figure 10). This is achieved in the form of an expression which implies that the largest radiated pressure at the trailing edge is reached when the negative deflection of the shear layer at the leading edge reaches its extreme.

Tam and Block obtained good agreement with Rossiter's data ($0.4 < M < 1.2$) and also with their own data ($M < 0.4$). This last agreement suggests that these particular tones are generated by normal mode resonance mechanisms. Other oscillations are stated to be caused by excitation of instabilities in the shear layer.

The Tam and Block model was extended into the supersonic regime in Zhang.[12] Zhang modified Tam and Block's theory to obtain best agreement with supersonic data by

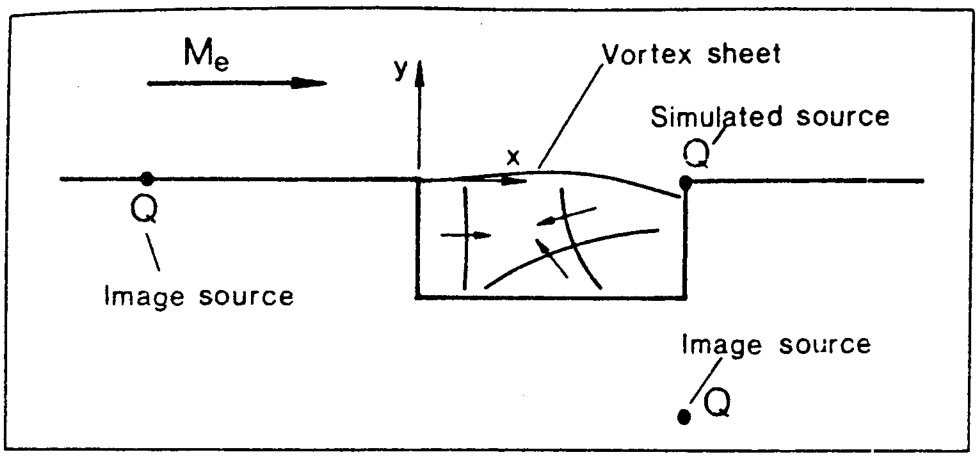
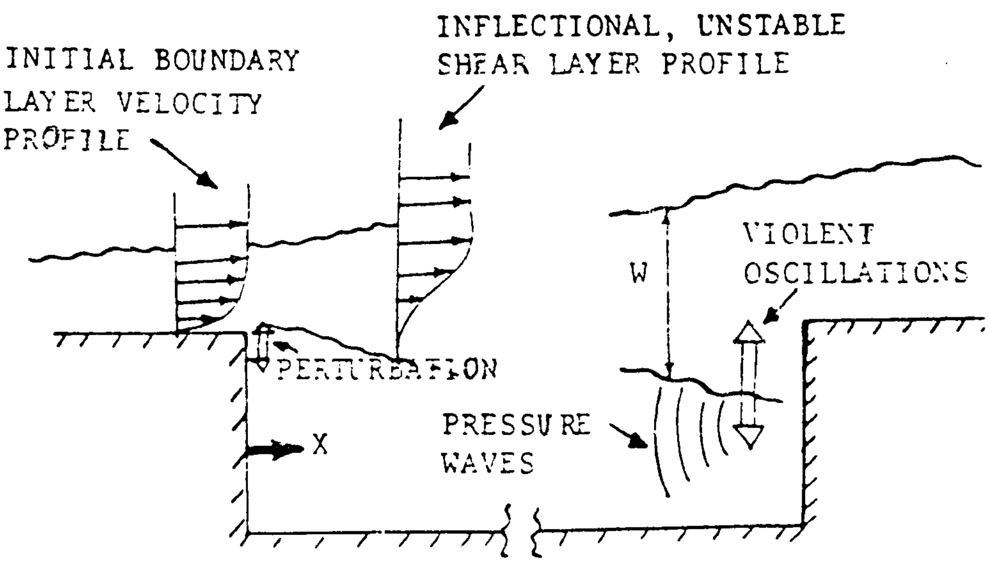


Figure 9. Schematic of Tam and Block analytical model

Source: Zhang, X. and Edwards, J.A. "An Investigation of Supersonic Oscillatory Cavity Flows Driven by Thick Shear Layers". Aeronautical Journal, December 1990



$W = K\,(X - X_0)$

WHERE

- W = Shear layer width
- K = Widening Rate (constant)
- X_0 = Effective Origin

Figure 10. Shear layer growth characteristics

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

introducing a certain phase or time lag between the transverse velocity fluctuation and the pressure pulse radiation at the trailing edge. The overall results of the modified theory show good agreement with experiment.

Rockwell and Naudasher[13] (1978) reported that self-sustaining oscillations can be grouped in three categories:

1) fluid dynamic--these are caused by the selective amplification of instabilities (disturbances) in the cavity shear layer, and a feedback condition is present due to the upstream propagation of disturbances, which is enhanced by the presence of the cavity trailing edge

2) fluid resonant--these are caused by resonant wave phenomena (standing waves)

3) fluid elastic--these are coupled with the oscillations of a solid boundary and are dependent on the elastic, inertial, and damping properties of the structural system

Purely fluid-dynamic oscillations can occur if the acoustic wavelength is very large compared to the cavity length. The condition of selective amplification, which causes certain disturbances to be amplified more than others, must be present. Also, there must be an effective feedback mechanism; the feedback is basically an upstream propagation of disturbances which is enhanced by the downstream presence of the cavity trailing edge.

Fluid-resonant oscillations are self-sustaining oscillations that are strongly coupled with resonant standing wave effects within the cavity. The frequencies are sufficiently high that the acoustic wavelength is of the same magnitude or smaller than the cavity length. If L/D is large, longitudinal standing waves exist, and shallow cavity behavior ($L/D > 1$) is exhibited. If L/D is small, transverse waves are present, and we observe deep cavity behavior ($L/D < 1$).

Rockwell and Naudasher pointed out the difficulties of predicting the exact wavelengths at which these standing waves will occur. Some complications include existence of the shear layer, mass exchange at the trailing edge, and other effects which can produce deviations from ideal resonator behavior of rectangular enclosures. Some features of pure fluid-dynamic flows, such as upstream propagation of pressure waves, can also exist in fluid-resonant flows.

If one or more walls of a cavity undergo displacement that is large enough to exert feedback control on the shear layer perturbations during the cavity oscillation, the excitation is defined as fluid-elastic. It can be assumed that the structural oscillator has much the same function that the resonator wave has in fluid-resonant oscillations. Then the resonator wave frequencies are replaced by the natural frequencies of the structural oscillator. This flow phenomenon is made quite complex by the interaction of structural and flow dynamics.

In many practical cases of cavity oscillations, the basic excitation mechanisms already discussed may occur in a number of possible combinations. In the present study, the oscillations contained features of both fluid-dynamic and fluid-resonant models. Although the effect of this coupling can substantially alter the overall nature of the oscillations, much insight can be gained by categorizing in this manner.

In 1980, Clark, Kauffman, and Maciulaitus[14] investigated sound pressure levels (SPLs) in cavities over a wide range in Mach number. They observed that SPL values are reasonably constant or reach a minimum value in the front half of the cavity, increase steadily towards the rear, and then rise rapidly near the rear face. Maximum SPL levels were measured as occurring at $M \approx 1.5$. This maximum level in turn was weakly dependent on L/D, exhibiting the greatest amplitude at L/D = 5.6. They suggested modifying Rossiter's equation by replacing the constant for ratio of vortex to freestream velocity with ratios experimentally determined as a function of Mach number.

Komerath, Ahuja, and Chambers[15] (1987) presented an excellent summary of the great variety of issues in cavity flows, as well as previous work in the field. Komerath, et al. pointed out one of the major observations that have been made regarding modes of oscillations: the wavelength of oscillation modes tends to occur in integral submultiples or multiples of the cavity dimensions, and the mode corresponding to the largest dimension usually predominates. In general only the first three modes are observed, beyond which broadband fluctuations obscure distinctions between modes. In addition, although the possible modes are easy to predict, the determination of which will actually occur is not trivial. The accurate prediction of the mode, or frequency, which is observed requires sophisticated modeling of the feedback mechanism and flow conditions, as well as instabilities. The frequencies of the modes as a function of Mach number were illustrated previously in Figure 6. The mode frequencies have also been observed to change with L/D. This tendency is illustrated in Figure 11.

Komerath, et al. discussed the difficulty of predicting the amplitude of oscillation. This is extremely difficult to predict theoretically because of the variety of processes involved, as well as the great range of observed amplitudes. At present, there is no satisfactory method.

The proposed mechanisms of sound generation were then examined. These include vortex shedding at the leading edge, edgetones generated by the shear layer, and the "pseudopiston" effect of periodic mass exchange at the trailing edge.

Mach number effects are also a factor, as explained by Komerath. As stated previously, the modal frequencies increase with Mach number. As compressibility effects come into play, the feedback process is altered, and the formation of shock patterns has large effects on the shear layer deflections. Many prediction schemes have been deficient with respect to modeling the part played by the shear layer in cavity oscillations. Attempts that ignored the details of the shear layer have succeeded in situations where it isn't the controlling factor, such as deep cavities and Helmholtz resonators.

With the tremendous growth of computing power in the 1980's, computational solutions of cavity flows became more feasible. A recent paper by Dix and Butler[16] reported on attempts to utilize computational fluid dynamics in predicting flow fields in

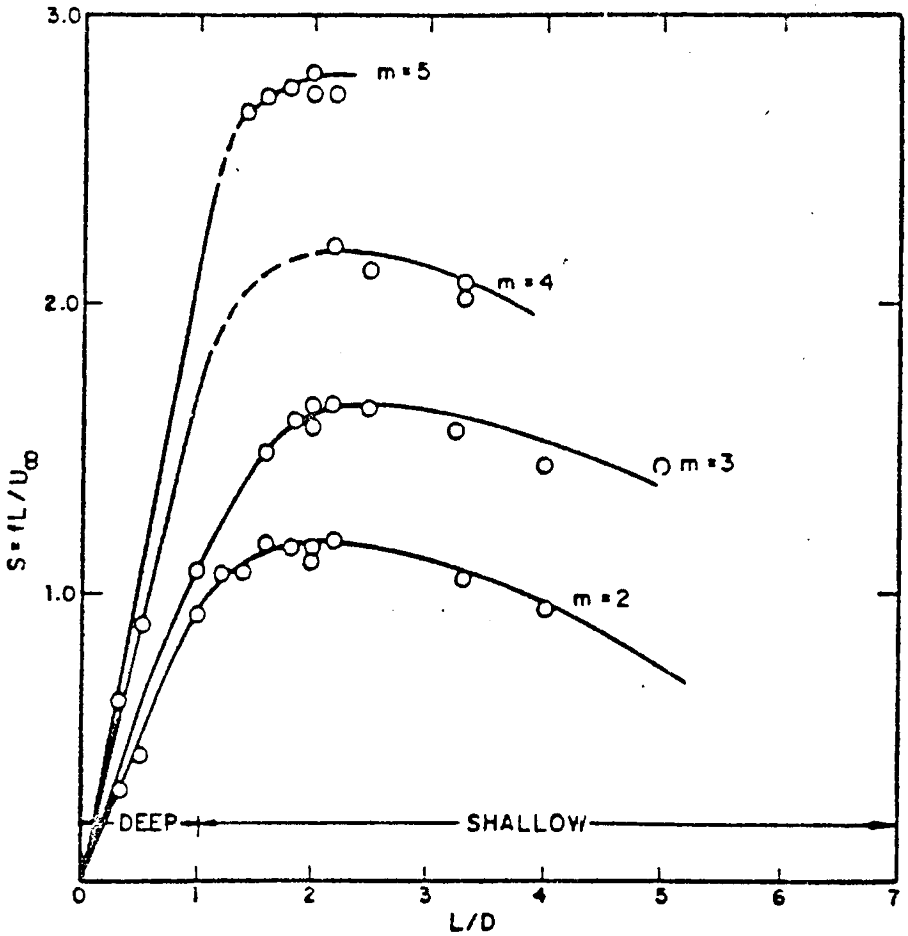


Figure 11. Length-to-depth ratio dependence of nondimensional resonant mode frequencies at M_e= 0.22 for several values of mode number

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

cavities; these attempts have met with moderate success. For example, Suhs[17] (1987) presented a 3-dimensional grid scheme using a Navier-Stokes solver in an attempt to predict the flow field in a 3-D cavity. The results show relatively good agreement, and addition of viscous terms was stated as a future goal. There have been additional CFD efforts to predict cavity flow, such as those by Rizzetta[18], and Hankey and Shang.[19] However, it should be noted that the computational requirements are enormous. For example, in Suhs' study, 10 to 20 hours of computing time were required on a Cray XMP. Some CFD schemes require up to 100 hours on these machines. Hence, at this time, such an approach is somewhat impractical.

Bauer and Dix[20] proposed a semi-empirical model to predict frequency spectrums in cavity flows, which also could include the effects of fluid injection. The objective was to allow the prediction of frequency *and* amplitude of cavity oscillations using only the modest computational capability of a personal computer. The model assumes that the shear layer over the cavity generates a continuous spectrum which excites "edgetone" frequencies (i.e. frequencies of vortex shedding). The model incorporates a damping term which is a function of the characteristic acoustic frequencies of the cavity and the edgetone frequencies. The damping term determines the amplitude of the excited edgetones that are observed. Estimations of frequency and amplitude obtained with the model agree reasonably well with experimental results in the subsonic and low supersonic regimes. In the mass injection model, the assumption is made that all injected mass is entrained in the shear layer.

There are some other current developments in the diagnostic area that are of interest. In the 1970's, Roshko[21] identified vortical structures in high Reynolds number free shear flows. This started intensive efforts in shear layer instability, and has resulted in significant changes in diagnostic methods. There are now techniques in data acquisition, such as the automated interferometry technique and laser doppler velocimetry, which allow point measurement capability over the entire flow field in high speed flows.

In summary, the cause-and-effect relationship between the shear layer and acoustic frequency fluctuations in the cavity has been studied extensively, but is still not completely understood. It is established, however, that the frequency and dominant mode are a strong function of Mach number and L/D ratio. In the analysis area, successful semi-empirical prediction of frequencies of oscillation has been carried out by Rossiter, Tam and Block, and others. Mechanisms of sound production that have been proposed include vortex shedding, edgetones generated by the shear layer, and the "pseudopiston" effect of periodic mass exchange at the trailing edge. Figure 12 is from Clark, et al.[14] It compares their test data, and the predictions of modal frequencies of their method, with the predictions of other theories. It is conceivable that these various models all have elements of truth, with the differences attributable to viewing the physical phenomena from different perspectives. Difficulties can arise because oscillations at high Mach numbers appear to have a different driving mechanism than those at lower Mach numbers. For lower Mach numbers, oscillations seem to be caused by excitation of shear layer instabilities, while at higher Mach numbers the cause is apparently related to the appearance of standing waves.

In general, the prediction techniques have the same general form and require two empirical constants. They are based on simplified descriptions of the downstream movement of the shear layer vortices and the internal (cavity) wave system. Key empirical constants defining the phase between the vortices and waves, and the propagation speed of the vortices, must be determined.

Analyses of shallow cavity oscillations, which are the focus of this study, generally treat the cavity shear layer as infinitesimally thin in order to accommodate the essential features of the oscillation (i.e. wave structure, elastic effects, fluid-mass exchange at the trailing edge) while keeping the analysis tractable. In general, the frequencies of cavity oscillations seem to be predictable on a purely theoretical basis for some cases, and on a semi-empirical basis for all cases. Amplitudes of cavity oscillations, however, have not yet been adequately treated.

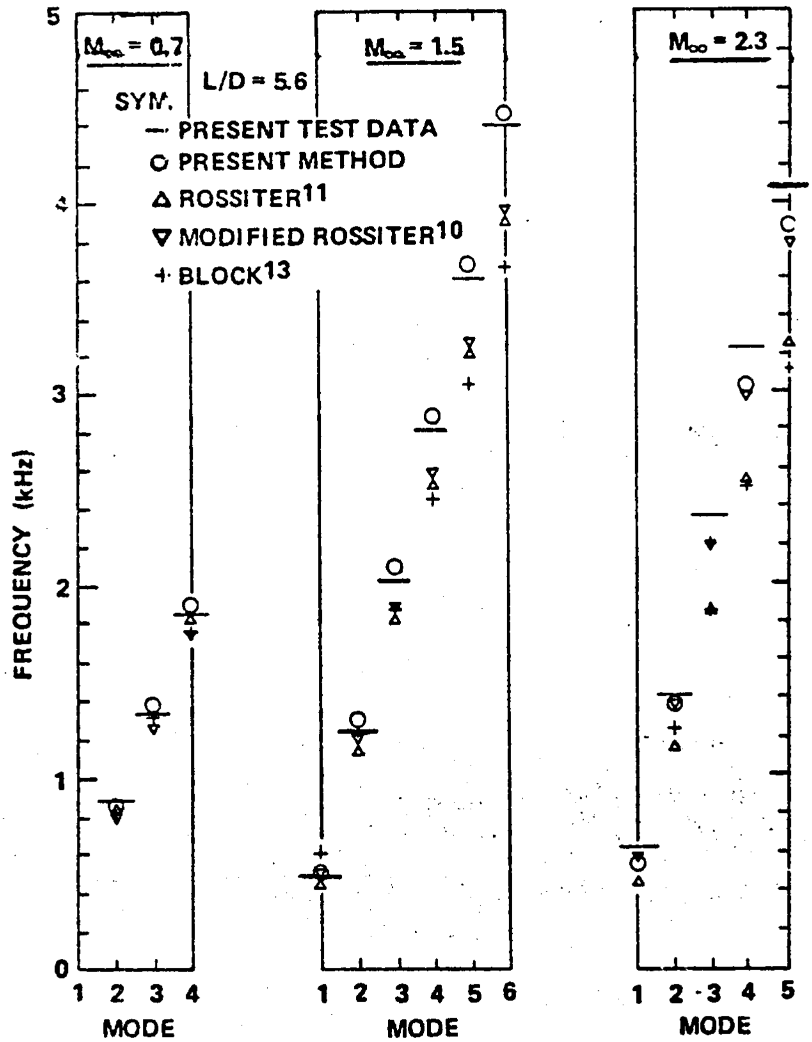


Figure 12. Comparison of various prediction methods for cavity oscillation modes

Source: Clark, R.L., Kauffmann, L.G., and Maciulaitus, A. "Aeroacoustic Measurements for Mach 0.6 to 3.0 Flow Past Rectangular Cavities". AIAA-80-0036, 1980

Suppression of Oscillations

Geometrical Adjustments

There have been rather comprehensive studies of the effectiveness of various techniques of controlling the cavity aeroacoustic environment. Most attempts to suppress oscillations have focused on geometric modifications. These suppression devices are designed to interfere with the acoustic feedback loop by deflecting the shear layer out of the cavity.

There are various approaches to suppressing oscillations through geometry adjustments, and numerous studies have been carried out. Among these are Rossiter, who successfully reduced oscillations with several spoiler configurations, and Heller and Bliss, who showed that the fluctuating shear layer could be stabilized through the use of various baffles in the cavity and bulkhead edge shaping. As discussed previously, Heller and Bliss indicated that the unsteady motion of the shear layer above the cavity results in mass addition and removal at the cavity trailing edge. The important role played by mass exchange at the trailing edge would explain why alteration of cavity trailing edge geometry is often effective in suppression. Studies have shown that pressure oscillation amplitudes can be reduced if the shear layer over the cavity can be stabilized so as to prevent the mass addition and removal process.

Two other prominent investigations should be noted. Franke and Carr[22] (1975) found that certain geometries, such as ramps at the leading and trailing edges, and spoilers and baffles, were effective in reducing oscillations under certain conditions. Franke and Sarno[23] (1990) investigated the use of fences in front of the cavity. Both static and pulsed fences were tried. The static fence showed mixed results, being more effective at higher Mach numbers. The effectiveness of pulsing the fence was limited. The pulsing did force the shear layer, since the frequency of the pulse was clearly evident in the frequency-amplitude plots. However, it caused sound pressure levels that were comparable in magnitude to those at higher frequencies that were to be suppressed.

As a result of these studies, conclusions can be drawn regarding the suppression effectiveness of passive methods. Numerous configurations of ramps, upstream spoilers or deflectors, and fences have been tested and have shown some promise, with some configurations giving substantial attenuation of cavity oscillations. The effectiveness of any particular suppression device is usually Mach number-dependent. In addition, effectiveness varies widely depending on the test configuration, and is different for different frequency components; certain configurations can actually increase SPL, as noted by Clark, Kauffman, and Maciulaitus.[14]

Mass Injection Approach

Acoustic, pneumatic, or mechanical forcing of the shear layer at the leading edge of the cavity provides another means of preventing the mass addition and removal process. In shallow cavities, cavity oscillations and associated noise arise due to instability of the cavity shear flow. Therefore, one can, in principle, reduce cavity noise by modifying the stability characteristics of the cavity shear flow.

In the previous section, suppression was achieved through alteration of the cavity geometry; thus it can be shown that suppression depends largely on the development of the shear layer. It has been demonstrated that cavity oscillations can be delayed by the introduction of a small quantity of air into the cavity flow. This causes the shear layer to be effectively blown out of the cavity, which reduces the interaction with the downstream cavity corner. Consequently, cavity oscillations are reduced. Figure 13 provides an illustration of the basic features of a mass injection flow.

The mechanism can also be viewed in the following manner. The mass entrained by the shear layer from the main flow may cause the large trailing edge mass exchange postulated by Heller and Bliss. When the cavity begins to oscillate, a large increase in

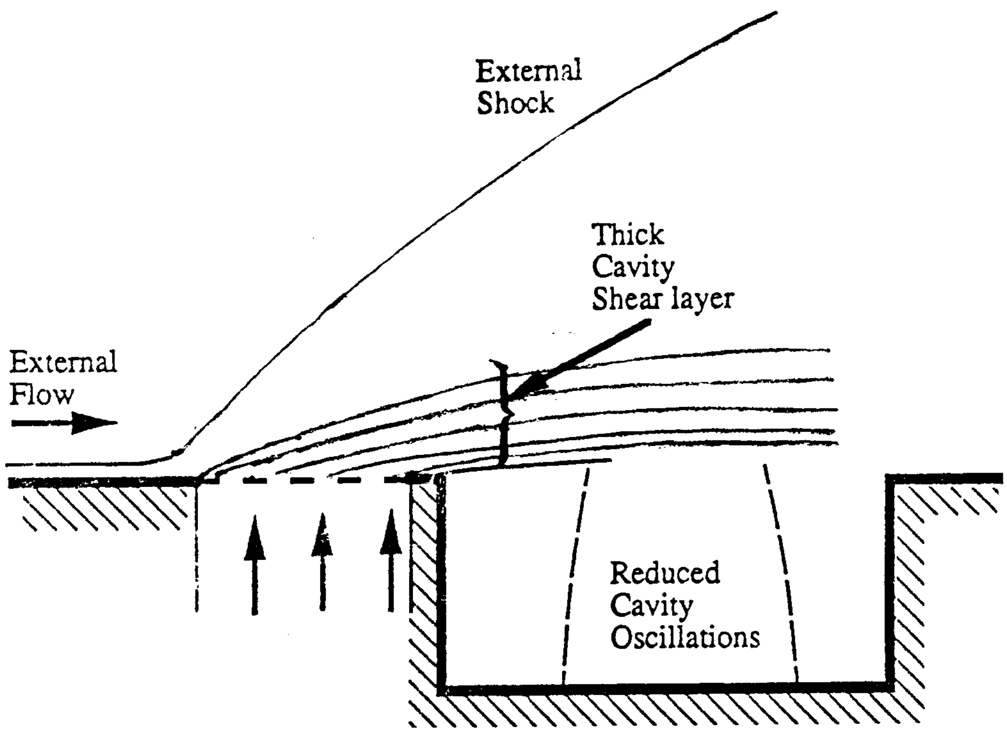


Figure 13. Schematic of the mass injection flowfield

entrainment occurs because of the fluctuation of the shear layer. Mixing caused by the mass injection will reduce the velocity gradient in the region near the wall (i.e. increases momentum thickness). This reduced velocity gradient will reduce the amount of entrainment by the shear layer which, in turn, will reduce the mass exchange at the trailing edge. This will neutralize the acoustic feedback cycle, which will reduce cavity noise.

Yet another interpretation of the suppression phenomenon is provided by a consideration of shear layer instability. An explanation of the fundamentals of shear layer flow is required. The behavior of free shear layers is heavily influenced by the Kelvin-Helmholtz instabilities referred to previously. These Kelvin-Helmholtz instabilities develop downstream into coherent structures (spanwise vortices). These, in turn, produce disturbances which are fed back to the origin of the shear layer. The presence of natural frequencies in the free shear layer has been associated with this feedback process.

The effect of shear layer forcing is to organize the shear layer flow and to enhance the momentum thickness growth rate. An impingement surface in a cavity affects the shear layer in a similar manner to external forcing. Just as forced shear layers adjust to the forcing frequencies, the impinging shear layer adjusts to natural frequencies dictated by the cavity geometry. Hence, the shear layer feedbacks are enhanced by the presence of an impingement surface which increases the intensity of the upstream perturbations. The response of the cavity shear layer can be substantially reduced by increasing its stability. As stated previously, this can be accomplished with mass injection ahead of the cavity. This will reduce the velocity gradient, increase the initial momentum thickness, and therefore lead to greater stability, as explained by Ho and Huerre.[4]

Several notable investigations on mass injection were performed. Fernandez and Zukoski[24] (1969) studied mass injection through a uniformly porous plate into a turbulent boundary layer. The experiments were performed at a Mach number of 2.6. They defined three regimes, depending on the degree of mass injection:

1) Skin-friction term is comparable to or larger than the injectant term; they both influence the problem. Boundary layer theory is applicable.

2) Injectant term is large compared to the skin friction but the injectant momentum flux is small compared with the freestream momentum flux. The boundary layer approach is still valid.

3) The momentum flux of injectant and freestream are comparable. Boundary layer theory is no longer applicable.

The mass flow rates used in these experiments fall into the second regime. Fernandez and Zukoski observe that a natural value for the blowing rate is:

$$\lambda_e = \frac{\rho_w u_w}{\rho_e u_e}$$

ρ_w = density at wall

ρ_e = density at edge of shear layer

u_w = velocity of mass injection flow through each hole

u_e = velocity of freestream

Different values of λ_e generate a range of velocity profiles at a given downstream station. Fernandez and Zukoski state that despite the great changes in profile shape, the boundary layer thickness, nondimensionalized with respect to the momentum thickness, doesn't change greatly. However, since the momentum thickness does markedly increase with greater blowing, the boundary layer thickness does increase in absolute terms.

Voorhees and Bertin[25] (1969) investigated how upstream mass injection affects cavity flow fields at a Mach number of approximately 1.95. Several significant observations were made:

1) Injection of air into the boundary layer significantly decreases the velocity and velocity gradient near the wall. Consequently, the boundary layer thickness increases with mass injection rate.

2) The ratio of momentum thickness to boundary layer thickness increases.

3) The critical closure ratio $(L/D)_{crit}$ increases with mass injection (because of momentum thickness increase).

4) The flowfield in a cavity with upstream mass injection appears similar to that for a shorter cavity without mass injection.

These last two observations lead one to conclude that the effect of mass injection is to shorten the apparent length of the cavity to the oncoming flow.

Sarohia and Massier[26] (1977) performed one of the few investigations specifically addressing the use of mass injection to suppress cavity noise. It was done at low Mach numbers (up to 0.5) with axisymmetric cavities. They observed that the mass injection at the base of the cavity virtually eliminated the periodic oscillations for certain conditions and, consequently, the radiated noise. Observations also indicated a decrease in the periodic velocity fluctuations in the shear layer (which cause instabilities). Oscillations reappeared when cavity length or Mach number was increased, but these could be delayed by an addition of mass. They defined a nondimensional mass injection parameter:

$$\sigma = \frac{\dot{m}}{\pi D\, b_{min}\, \rho\, u_e}$$

b_{min}= length below which no oscillations occur, for given conditions

They noted that, in general, as σ increased, b_{min} increased. Under certain conditions of flow and geometry, mass addition had a negligible reduction and even an enhancement of noise. This was believed to be caused by mass injection perturbations, which in turn were caused by inducing a change of modes. Depending on the cavity configuration and flow, the mass flux, $\rho_w u_w$, required to suppress the cavity flow noise was 5-15% of the freestream mass flux. Required mass injection varied with flow conditions and geometry, but effective suppression was achieved with a very small fraction of the mass flow past the cavity.

Franke and Sarno[23] (1990) did some experimentation with mass injection, which involved steady and pulsating secondary flow injection at the cavity leading edge. The pulsation was attempted because of the suggestion that the shear layer could be forced at a frequency different from the resonant frequency in order to reduce the oscillation amplitude. The tests were conducted at two flow injection angles (parallel to the flow and at 45° to the flow in a downstream direction) at M = 1.28. The flow injection was somewhat effective. Suppression of sound pressure level was better at 45° flow injection than with parallel flow injection. Pulsing the flow injection had little effect on suppression.

The work done by Gauthier[27] (1990) and Vakili and Gauthier[28] (1991) served as a foundation for the present study. Their experiments were done at an L/D ratio of 2.54 and at a Mach number of 1.8.

Gauthier experimented with a single configuration of holes for secondary mass injection. He observed that the effect of mass injection was to significantly increase the thickness of the oncoming boundary layer (or cavity shear layer). Due to these effects, the amplitude of cavity oscillations was significantly reduced, from 174 dB to 147 dB. As mass injection flow increased, the SPL of the cavity oscillations decreased sharply at first and leveled off at the larger rates.

Vakili and Gauthier experimented with two different hole configurations (low density pattern and high density pattern) to judge the relative effectiveness of each; the low density pattern was judged as more effective. It should be noted that the predictions of the model of Bauer and Dix, discussed earlier, show a similar trend to these experimental results.

A nondimensional cavity blowing parameter was used in both of these data analyses to measure injection mass flow:

$$B = \frac{\rho_w u_w}{\rho_e u_e} \cdot \frac{A_{inj}}{A_{cavity}}$$

where A_{inj} is the total cumulative area of the injection holes. The area ratio is included to account for the influence of the hole configuration on the injection characteristics.

The primary objective of the present study was to validate, and expand on, the results of Gauthier and Vakili. An effort was made to determine the cause of the greater suppression effectiveness of the low density hole pattern. In addition, a different blowing parameter was used in an attempt to more accurately reflect the influence of the hole pattern geometry:

$$B = \frac{\rho_w u_w}{\rho_e u_e} \cdot \frac{A_{inj}}{A_w}$$

where A_w = area of rectangular pattern of injection holes.

The cavity area is not used here because it is assumed to have a negligible effect on the blowing characteristics.

III. EXPERIMENTAL METHOD

Experimental Apparatus

This experiment was conducted in the supersonic blowdown wind tunnel of the University of Tennessee Space Institute Gas Dynamics Laboratories at a Mach number of approximately 1.8, and at a test section Reynolds number of approximately 1.7 x 10^7/ft. The square test section duct is 8" x 8" and is approximately four feet long. The test conditions in the tunnel are continually monitored as the test proceeds and manual adjustments to the primary flow control valve are required to maintain given conditions.

The cavity and mass injection installations are located near the beginning of the test section. The L/D ratio is 2.54 (3.8125" long, 1.5" deep, 1.5" wide) which is categorized as shallow open cavity flow. The injected mass flow is provided through 175 holes. They are arranged into ten rows of 18 and 17 holes alternately with the rows of holes offset to provide a more uniform injectant flow. The holes are 0.062 inches in diameter, and are separated by 0.031 inches in each row.

Two different geometries were tested. In the high density geometry, the holes cover an area of 1 inch long and 1.75 inches wide just upstream of the cavity, with the rows separated by 0.031 inches. In the low density geometry, the rows are separated by twice as much, or 0.062 inches, so the area covered by the hole pattern is twice as much (see Figure 14 for illustration). In terms of porosity (ratio of injection area to area of hole pattern), the high density hole pattern had a porosity of 0.3, while the low density porosity was 0.15. The thickness of the perforated plate, (length of the hole) is 0.26 inches.

The injected mass flow is provided by a secondary low pressure reservoir which also requires continuous adjustments. A one inch pipe provides the injectant flow, which is expanded into a relatively large plenum chamber just before reaching the perforated plate to enhance the injected flow uniformity. The flow through the holes is choked to

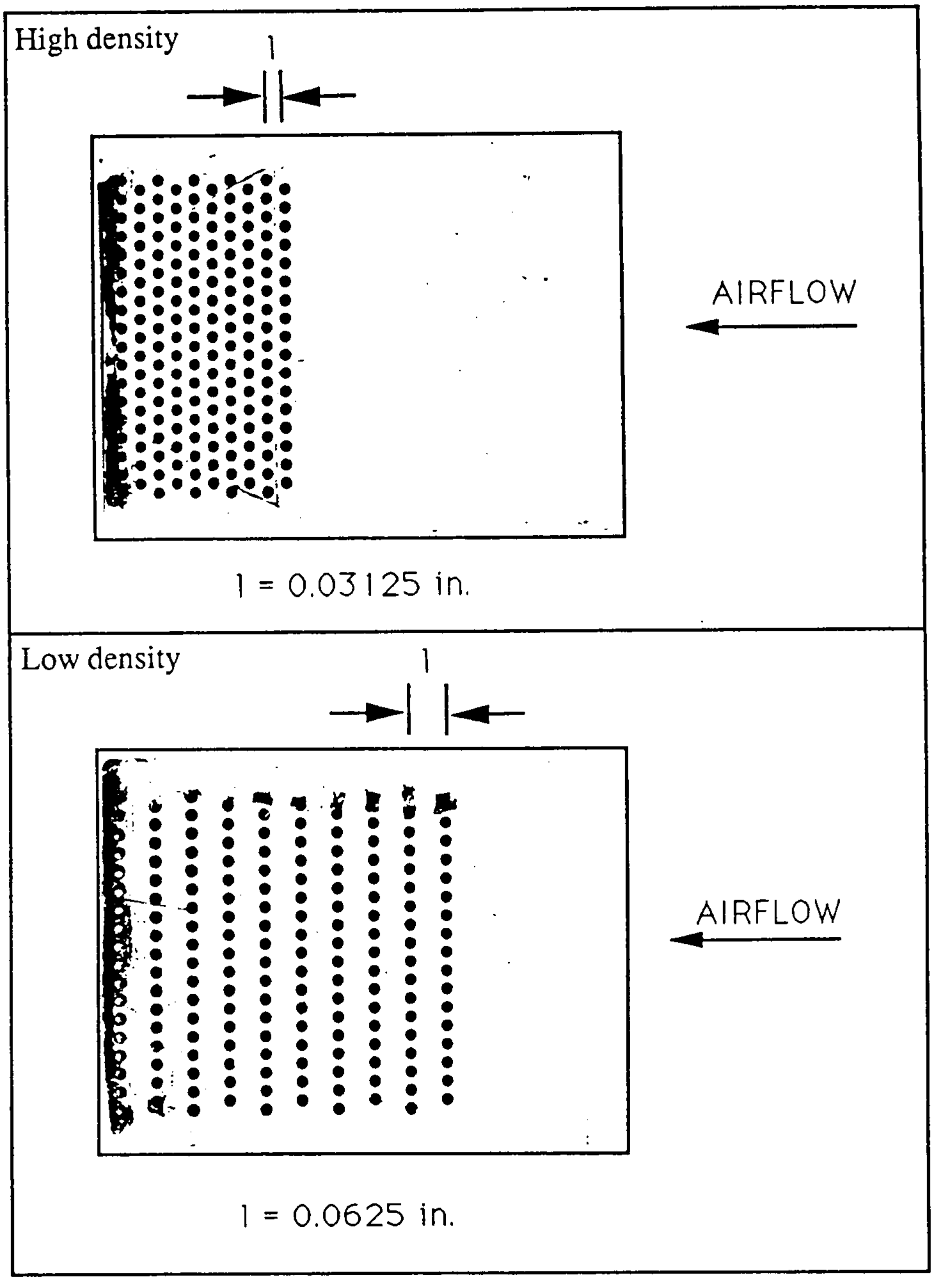


Figure 14. Geometric distribution of mass injection holes (actual size)

further enhance flow uniformity. The injectant flow is measured with an orifice meter.

The quantities measured in this experiment are: frequency and amplitude of cavity oscillations, total pressure through the boundary layer, and static pressures along the floor of the tunnel. In addition, a Schlieren system provides flow visualization. The measuring instruments are described below.

The cavity flow oscillations were measured with a dynamic pressure sensor installed at the rear of the cavity floor. The Endevco subminiature piezoresistive pressure transducer model 8514 transmitted its output to a Hewlett-Packard model HP3582A frequency spectrum analyzer. The transducer was positioned at an x/L of 0.944 with respect to the length of the cavity. The analyzer provided plots of the frequencies and amplitudes of the cavity oscillations.

The total pressures across the boundary layer were measured using a computer-controlled traversing pressure probe. The movable traversing mechanism was in turn connected through the tunnel wall to a computer controlled motor. The probe itself consisted of a 0.04 inch internal diameter tube. Two types of traversing probe tips were used: a short probe tip and a long probe tip. The short probe measured boundary layer characteristics at the downstream station (trailing edge of the cavity). The long probe extended horizontally from the traversing mechanism in order to measure boundary layer characteristics at the upstream station (leading edge of the cavity). These measurements provided useful information on shear layer growth along the length of the cavity. Figure 15 shows the entire experimental setup, including the traverse probe.

A reference static pressure is normally located on a tunnel wall at the same measuring location, and the static pressure is assumed constant through the boundary or shear layer. However, under massive injection, a pressure gradient is believed to exist within the flow. Therefore, strictly speaking, the reference static pressure should be measured directly on the total pressure probe to assure accurate results. In this case, the reference pressure was located to the side of the cavity. This introduces some level of inaccuracy into the results, especially at high blowing rates.

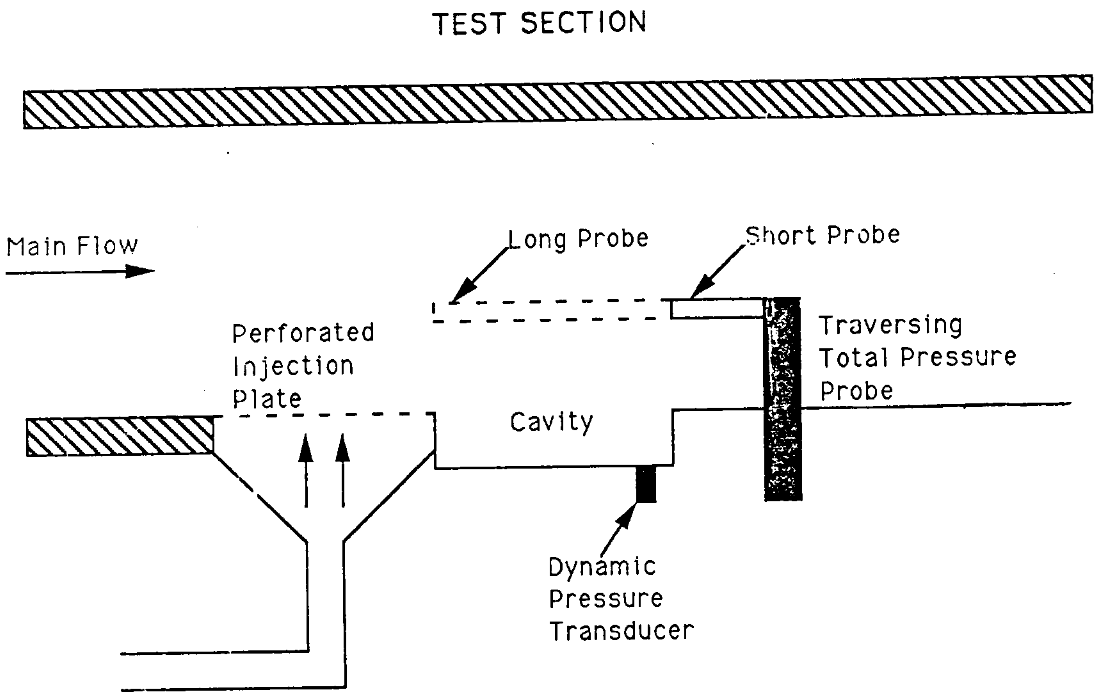


Figure 15. Schematic diagram of the experimental setup

Numerous static pressure ports were located along the tunnel floor, and the static pressures were read in sequence during the run by use of a scanning valve.

In addition, a Schlieren video provided flow visualization of the injected flow, the boundary layer, and the shear layer above the cavity. However, it was impossible to obtain visual details of the flow inside the cavity with the experimental setup since the flow visualization did not extend inside the cavity.

Test Conditions

In general, the tunnel Mach number of 1.8 was maintained approximately constant throughout each run; the variation was within 2% throughout the test. However, the tunnel reference pressure, used to control the tunnel, was noted to vary slightly during each run. These variations occurred because the manually controlled primary valve had to be continually adjusted as the reservoir pressure decreased.

In a similar fashion, the mass injected flow was continuously adjusted by controlling the injection plenum pressure, which was noted to vary slightly during each run. By installing more sensitive transducer diaphragms allowing greater control, this error was reduced significantly.

A new test section was used in the wind tunnel and, therefore, the aerodynamic quality of the tunnel test section was evaluated. Throughout the test section, the wall static pressure was basically constant along the length, and pitot surveys did not indicate any nonuniformities. Therefore, the velocity was judged sufficiently uniform for the present experiments. Schlieren visualization also indicated acceptable flow uniformity.

Experimental Procedure and Data Analysis

The tests performed in this study can be categorized into three types. First, the tunnel was run for the flat plate case (i.e. without cavity or mass injection plate). The aerodynamic quality of the test section flow was confirmed by measuring the static pressures along the test section, and by calculating the velocity profiles using static and total pressure measurements. In addition, the Schlieren video was used to corroborate aerodynamic quality.

Then, the mass injection plate was installed without the cavity and a series of runs was made. Next, the cavity plate was installed by itself and baseline frequencies and amplitudes of cavity oscillations were obtained. Finally, both the cavity and the mass injection apparatus were installed and the effects of mass injection upon the cavity oscillations were documented for numerous runs with various mass-injection rates.

Data reduction was accomplished using a turbulent boundary layer code developed at the Arnold Engineering Development Center Propulsion Wind Tunnel Facility.[29] The boundary layer code was necessary in order to provide a temperature profile through the boundary layer or shear layer. This allowed velocity to be calculated from Mach number. The standard Rayleigh-Pitot equation is used to obtain the Mach number profile, but the code incorporates some unique features in deriving the velocity profile and the other boundary layer parameters. The interested reader is referred to the report for details. The code was run for steady, adiabatic flow of a calorically perfect gas with a Prandtl number of unity. The code is strictly applicable only to wall boundary layers, and not to free shear layers. Therefore, quantitative information obtained with this code at the downstream end of the cavity (free shear layer) could have significant error. However, since the Prandtl number is assumed to be one (constant total temperature), the velocity profile through the shear layer is uniquely determined by the measured total pressure profile. Although the velocity profile shape and the measured total pressure profile shape will differ, both will produce the same shear layer thickness.

The boundary layer thickness is critical to this analysis and, therefore, an explanation of the determination of this quantity in this experiment is warranted. The boundary layer code just described was used to generate velocity profiles for the various cases. Due to certain inaccuracies (primarily the static pressure measurement at the tunnel floor rather than on the total pressure probe), the code's strict definition of the boundary layer thickness (vertical measurement at which $u = 0.995u_e$) was often not workable. Therefore, the boundary layer thickness was measured manually from the velocity profile plots. The vertical distance at which the steep velocity gradient of the shear layer suddenly terminated was used as the boundary layer thickness. In most cases, this point on the profile was quite evident.

Some basic assumptions and simplifications were required to keep the analysis tractable. First and foremost, 3-D effects in the the cavity flow and injected flow are not accounted for. However, the oscillatory characteristics of the cavity are not significantly affected by the spanwise dimension.[1]

IV. RESULTS AND DISCUSSION

Baseline Cavity Oscillations

This was the control test, carried out with no mass injection and no traverse probe present. The frequency-amplitude spectrum showed three very distinct peaks, as shown in Figure 16. These three peaks correspond approximately to the first, second, and third modes, as predicted by Rossiter's modified formula. The second mode is clearly predominant over the others, reaching a peak SPL of 172 dB at a frequency of 2640 Hz.

Effects of Upstream Mass Injection

Mass injection was used in order to control shear layer properties and reduce shear layer interaction with the cavity trailing edge.

The low density configuration is much more effective at reducing the sound pressure level at lower mass flow rates. The decrease in sound pressure level (ΔdB) with mass injection is shown for both geometries in Figure 17, and the difference is evident. Here, the SPL is taken as the maximum amplitude of the frequency spectrum. The greatest decrease attained is 27 dB; this decrease is from 172 dB (pressure fluctuation of 1.5 psi) to 145 dB (pressure fluctuation of 0.07 psi). Also note that there is no further decrease in SPL past a certain mass injection rate. This can be attributed to the separation of the shear layer upstream of the cavity at that mass injection rate. This essentially means that the shear layer no longer emanates from the leading edge of the cavity, but begins separation at a position upstream of the cavity. Since the greater portion of the shear layer no longer interacts with the cavity leading and trailing edges, additional mass injection (which influences the shear layer) has a negligible effect on the cavity

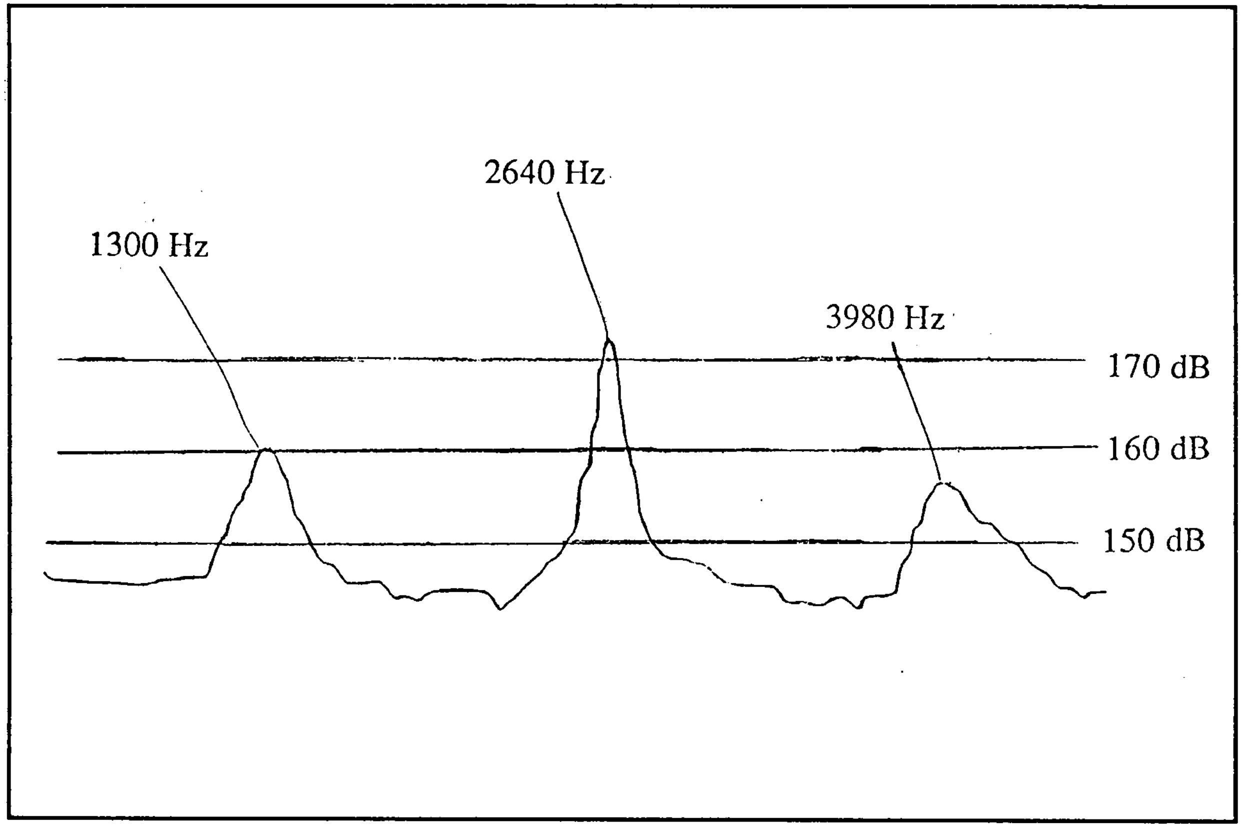


Figure 16. Baseline frequency-amplitude spectrum

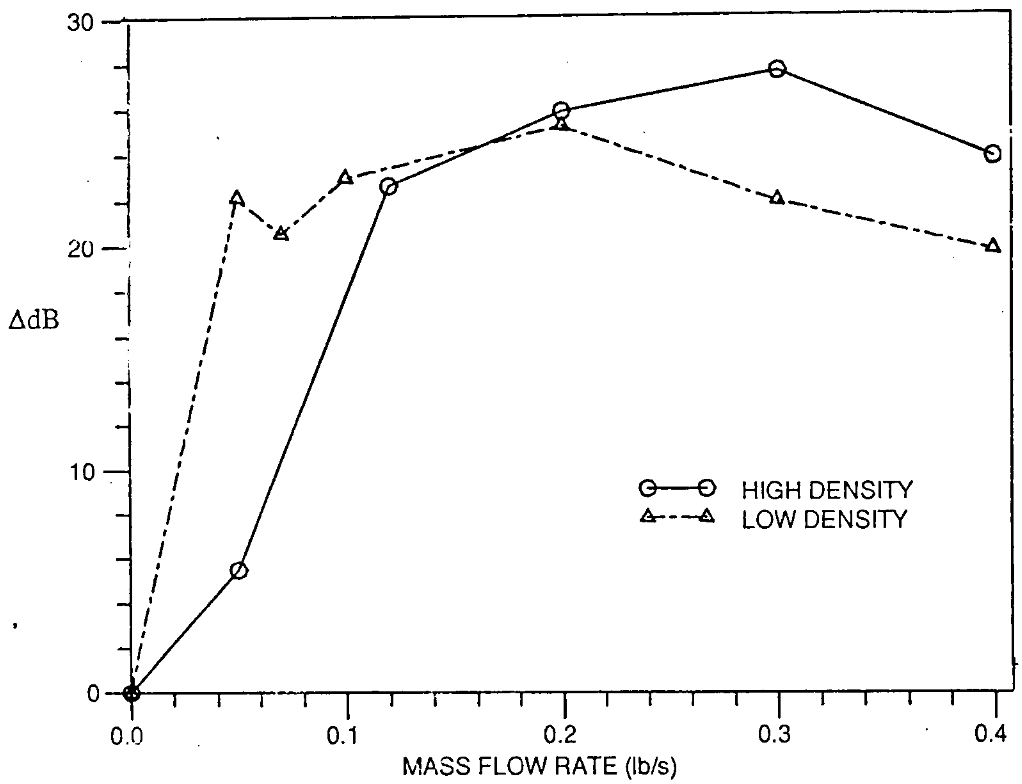


Figure 17. Comparison of ΔdB with mass injection for high and low density injection

oscillations.

Figure 18 shows that both configurations had approximately the same boundary layer thicknesses at the upstream and downstream stations for a given mass injection. Flat plate configurations (no cavity) were also run with the high density geometry. With the long probe, there was little difference in the boundary layer thickness, as seen in Figure 19. This indicates minimal influence of the cavity on the upstream boundary layer.

In each case it was apparent that SPL significantly decreases as boundary layer thickness increases (mass injection increases) at a given station. This decrease was quite apparent in the initial stages of boundary layer thickening; the SPL then leveled off, and in fact there was a slight increase at higher boundary layer thicknesses, which correspond to higher mass injection rates. This tendency is seen in Figure 20. Here, the boundary layer thickness is nondimensionalized with respect to the cavity depth. Figure 20 also shows that a given boundary layer thickness does not correspond to the same SPL for both configurations. The high density hole configuration tends to have higher sound pressure levels at a given boundary layer thickness, especially at relatively low thicknesses. Since different sound pressure levels are generated for each blowing configuration in the case where mass flow rate and shear layer thickness are nearly the same, this would seem to indicate the importance of including the effects of injection geometry in the blowing parameter.

The nondimensional cavity blowing parameter referred to previously was used to describe blowing rates. Here, the area of the hole pattern is incorporated into the formula. This parameter was varied between 0 and 0.25 for the high density configuration and between 0 and 0.5 for the low density configuration. Figures 21 through 23 are similar to Figures 17, 18, and 19 respectively, except the blowing parameter is the independent variable instead of mass flow rate. The purpose of the blowing parameter is to provide a single nondimensional number to describe the suppression effectiveness of any given configuration and set of flow conditions. In this

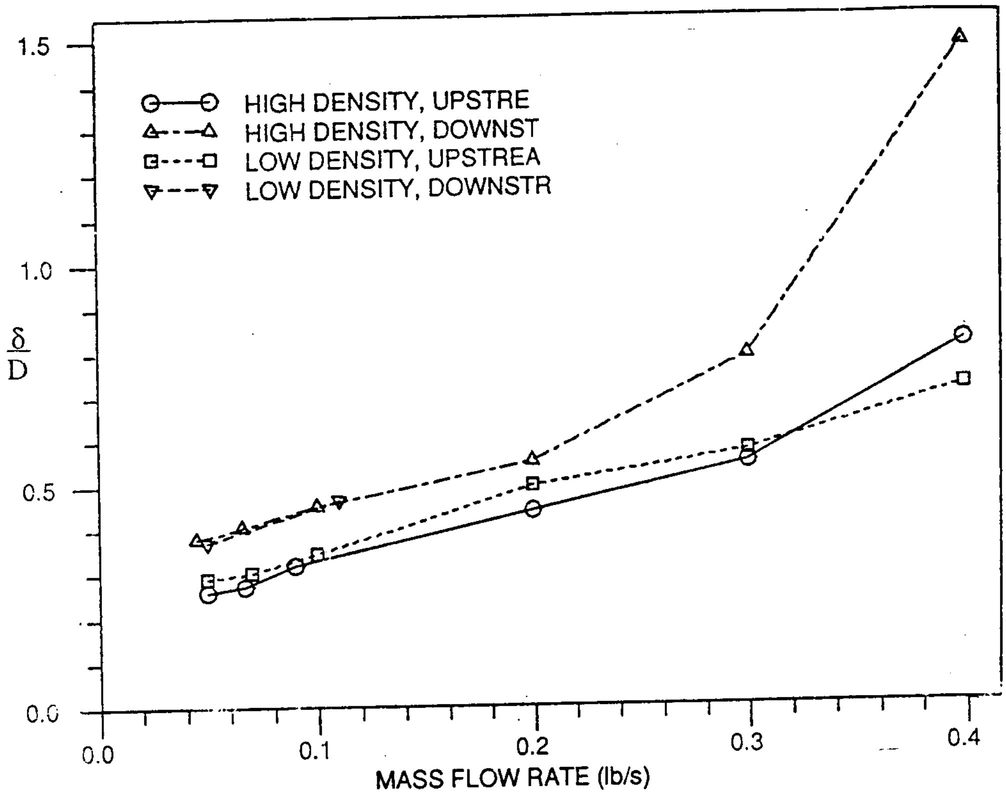


Figure 18. Mass injection rate vs. boundary layer thickness (high density vs. low density)

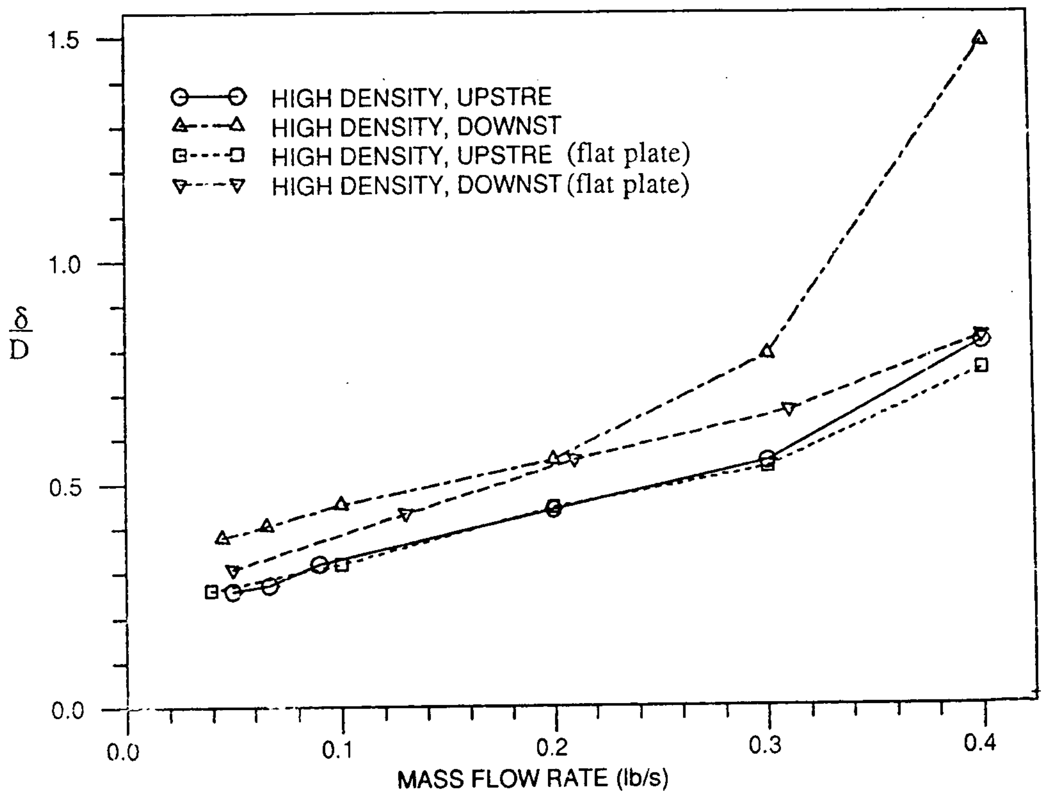


Figure 19. Mass injection rate vs. boundary layer thickness (flat plate vs. cavity)

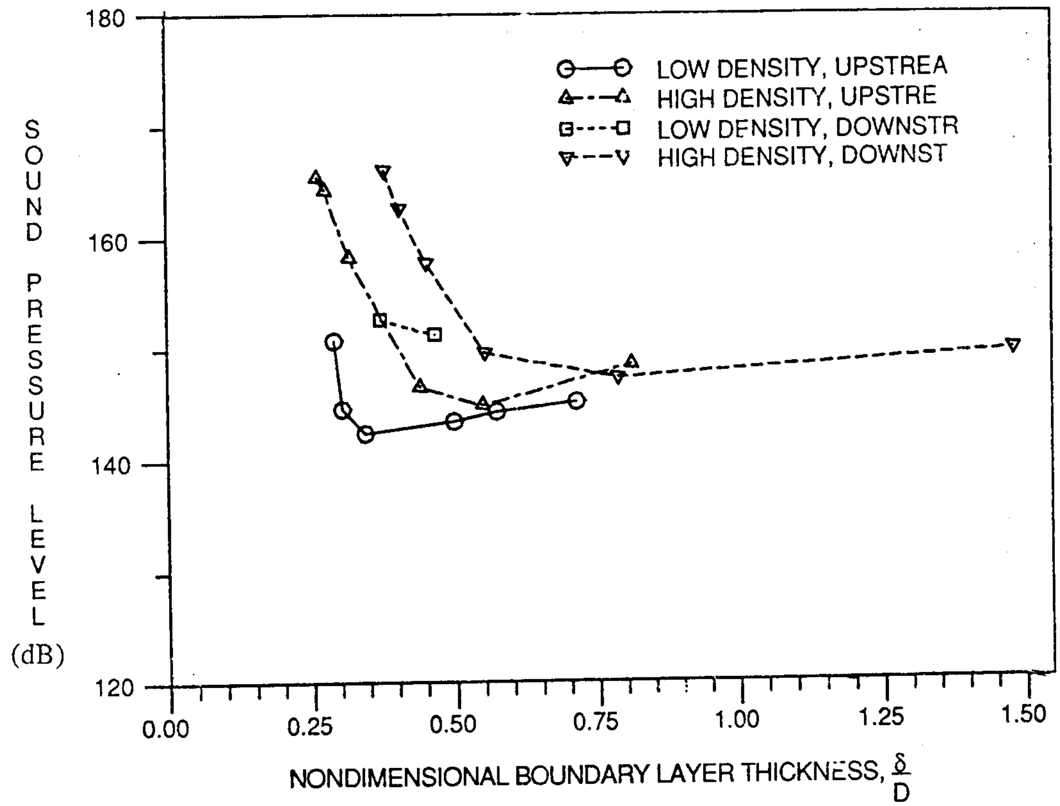


Figure 20. Boundary layer thickness vs. sound pressure level

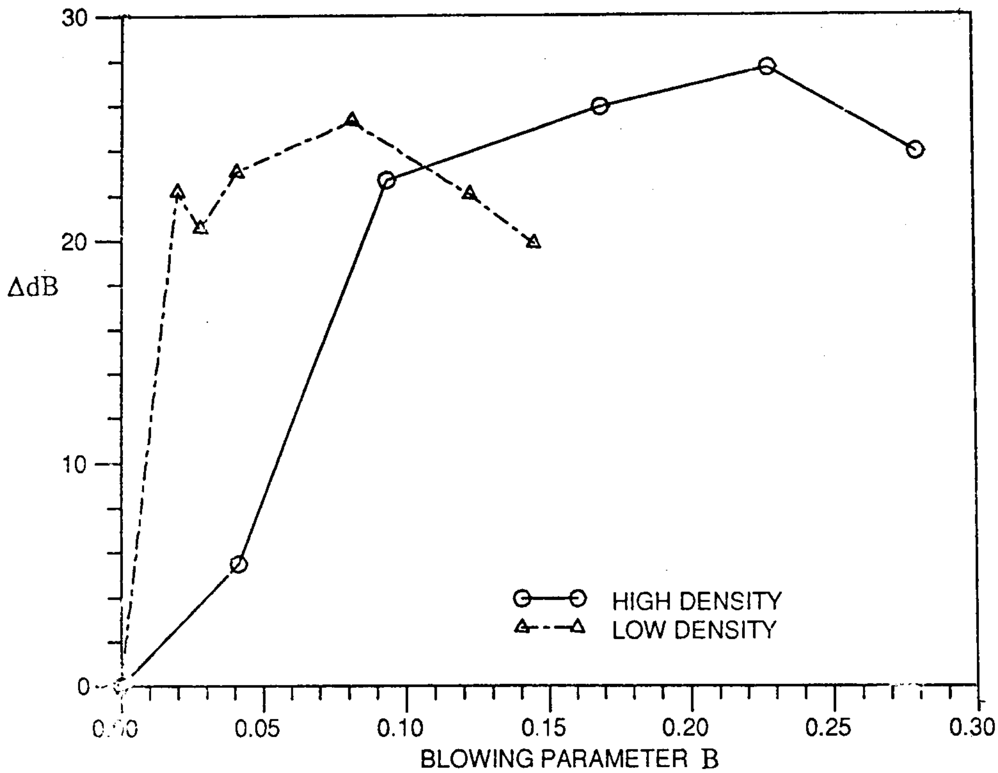


Figure 21. Blowing parameter vs. sound pressure level attenuation

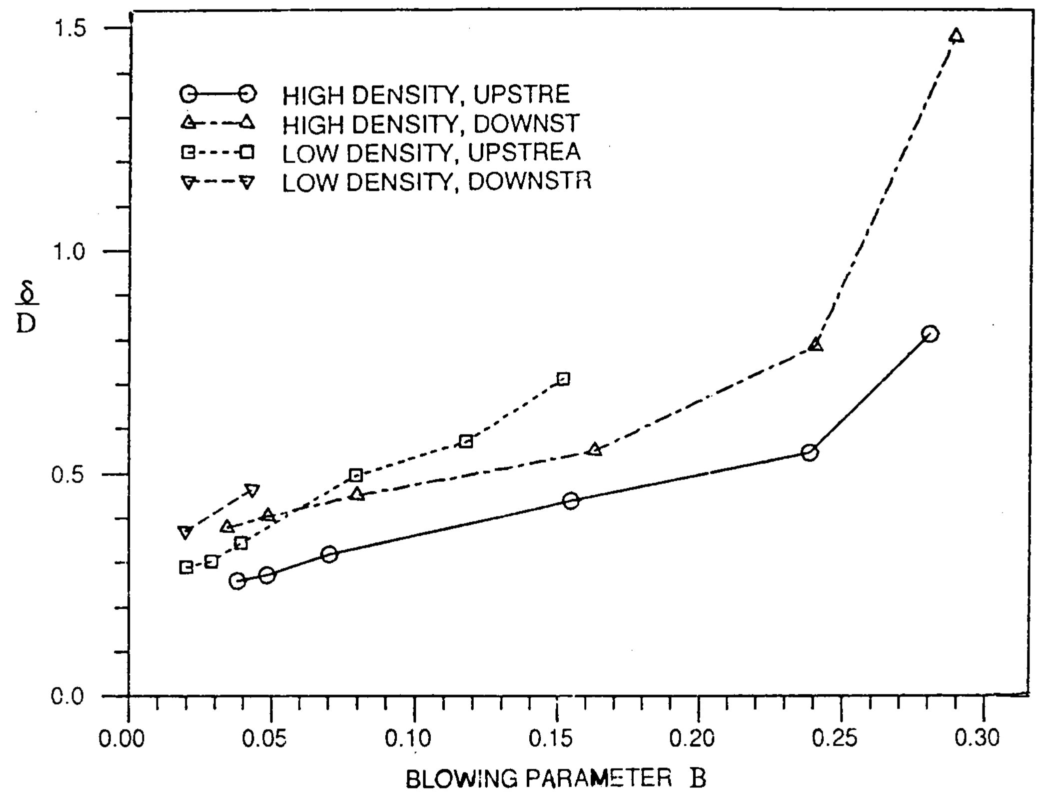


Figure 22. Blowing parameter vs.boundary layer thickness (high density vs. low density)

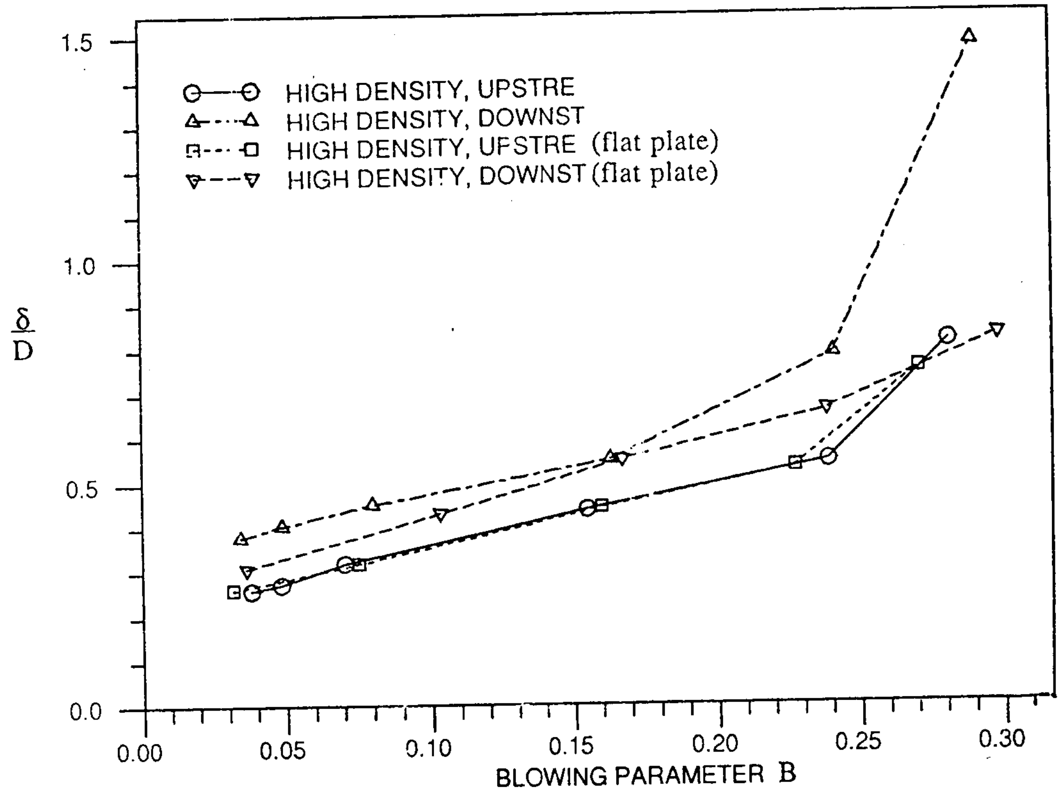


Figure 23. Blowing parameter vs. boundary layer thickness (flat plate vs. cavity)

respect, Figure 21, showing the blowing parameter vs. ΔdB, is particularly important. Ideally, a given blowing parameter, for any configuration, should always correspond to a certain ΔdB. The figure indicates that this is far from the case. Therefore, one can conclude that there is one or more critical variables missing from the correlation parameter. This point will be returned to shortly.

Since there is little, if any, difference in shear layer thicknesses, this cannot be the cause of the difference in suppression. The cause may be related to a difference in momentum thicknesses between the two configurations. The low density hole pattern injects over a greater area. This could induce greater mixing with the main flow, causing an increased momentum thickness. Shear layers with a greater momentum thickness have lower velocity gradients, which increases the stability of the shear layer. This makes it less susceptible to instabilities[4], which will decrease the measured intensity of the oscillations. Figure 24 shows that the low density pattern does indeed produce somewhat higher momentum thicknesses at the cavity leading edge than the high density hole pattern. The plot shows momentum thickness, nondimensionalized with respect to the cavity depth, as a function of mass flow rate.

The momentum thickness is apparently intimately related to suppression effectiveness. Therefore, it should also be related to any correlation parameter designed to describe suppression effectiveness. Figure 25 shows ΔdB as a function of the nondimensionalized momentum thickness at the upstream station. The high and low density configurations exhibit the same trend, which is further evidence of the importance of the momentum thickness. It is probable that the momentum thickness is the missing factor in the correlation parameter; further research should attempt to incorporate it.

It was hypothesized that a momentum-related blowing parameter of the form:

$$B = \frac{\rho_w u_w}{\rho_e u_e} \cdot \frac{u_w}{u_e} \cdot \frac{A_{inj}}{A_w}$$

could prove useful if the injection velocity increases for higher mass injection rates. This

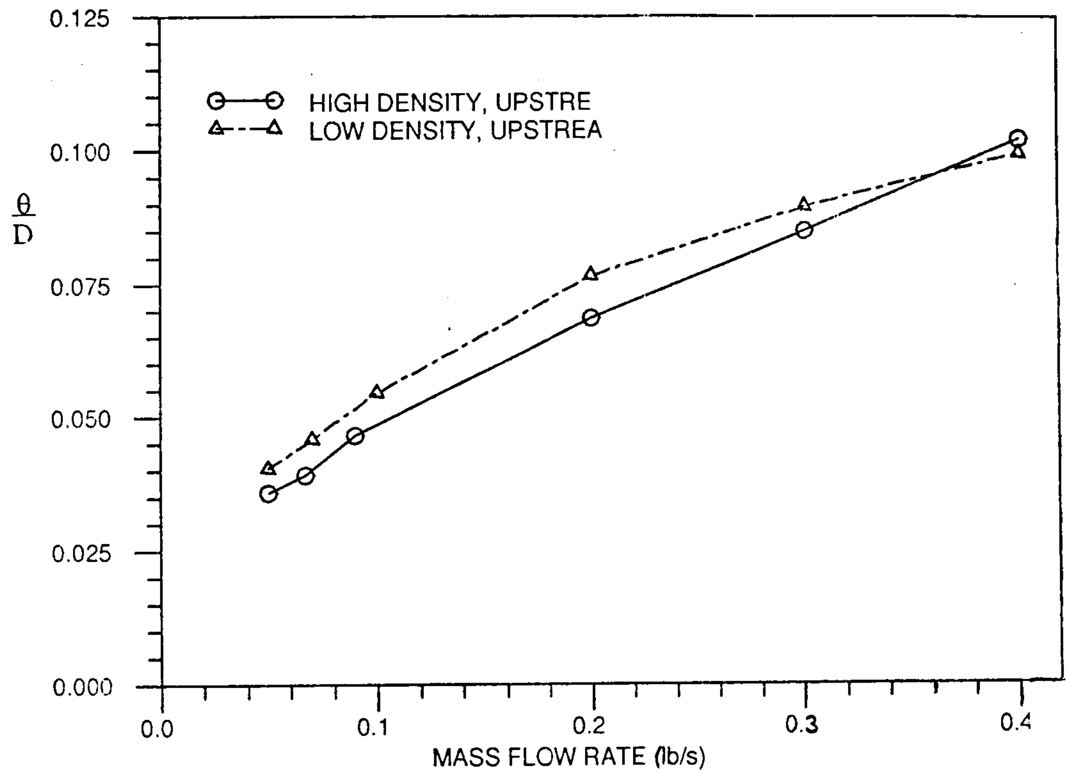


Figure 24. Mass injection rate vs. momentum thickness

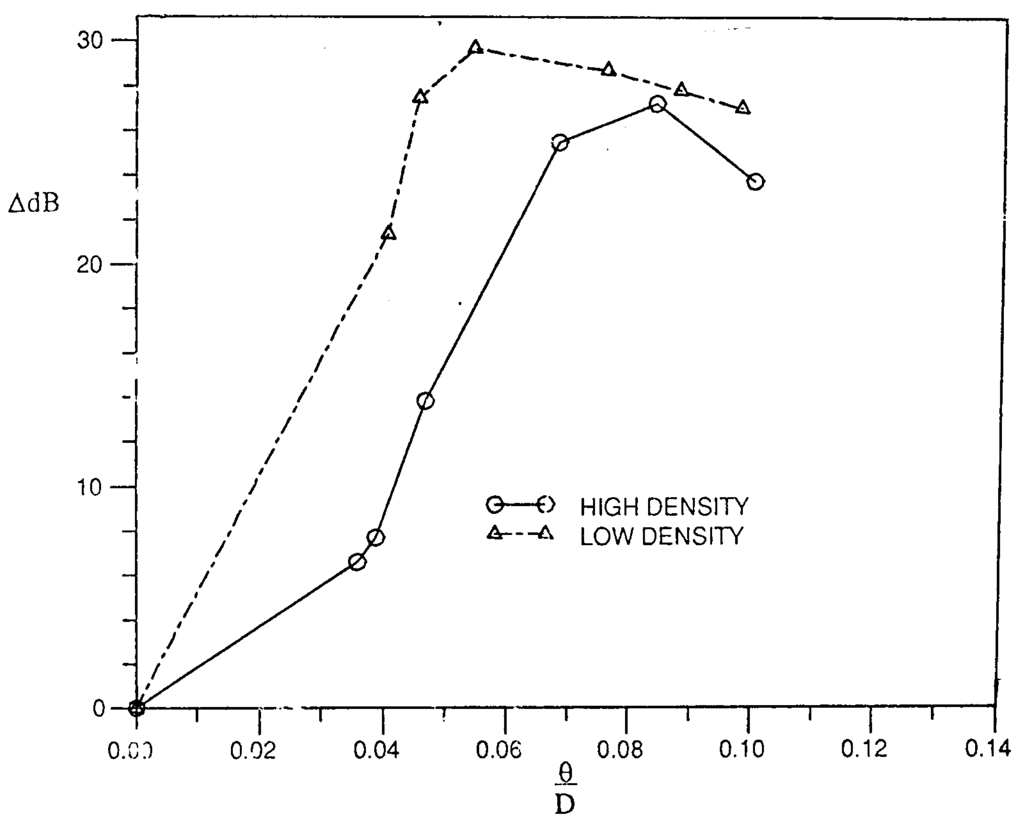


Figure 25. Momentum thickness vs. sound pressure level attenuation

could be a subject for future investigation.

Some general trends were observed in the frequency-amplitude spectrum for all cases. The first and third modes tend to fade and disappear with very slight blowing. The always-dominant second mode would decrease quite drastically and suddenly at slightly higher blowing rates. All modes would then gradually fade into the background noise as blowing increased. The background noise was generally between 140 and 150 dB. At the same time, the overall broadband spectrum of the SPL decreased, and there are slight frequency shifts. Since the frequencies of the dominant modes in shallow cavities are closely related to cavity length, these frequencies should be affected by mass injection.

In Figure 26, the frequency spectrum of a baseline run is superimposed on a frequency spectrum of a mass flow of 0.2 lbm/sec (most effective) through the high density hole configuration. At this mass flow rate, the effectiveness of high and low density configurations are similar. The greater effectiveness of the low density hole pattern can be seen at the lower mass injection rates. Figure 27 illustrates the frequency spectrum of the baseline along with high and low density configurations at 0.05 lbm/sec. The peaks of the low density spectrum are significantly lower.

The Schlieren videos clearly illustrate some of the basic features of the flow. Figure 28 shows the flow of the low density hole configuration with intermediate mass injection. An oblique shock is generated by the interaction of the oncoming flow with the secondary injection. Note the thick dark area at the base of the shock. This is caused by the onset of separation when the flow near the wall encounters the mass injection flow. A shock is, of course, generated at that point. The separated flow then merges with the shock farther away from the wall. The shear layer can be seen as the lighter area emanating from the base of the shock. It is clearly thicker and more distinct than in the baseline run.

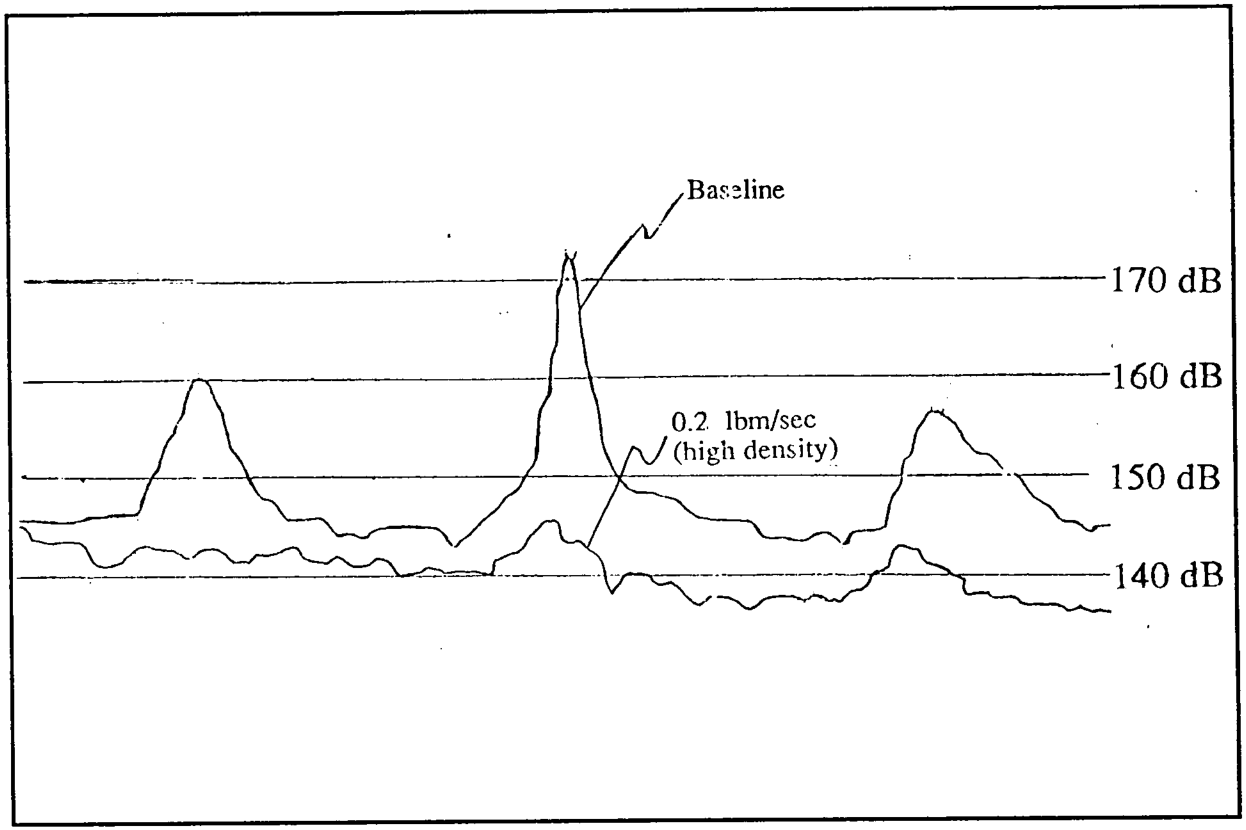


Figure 26. Frequency-amplitude spectrum (0.2 lbm/sec)

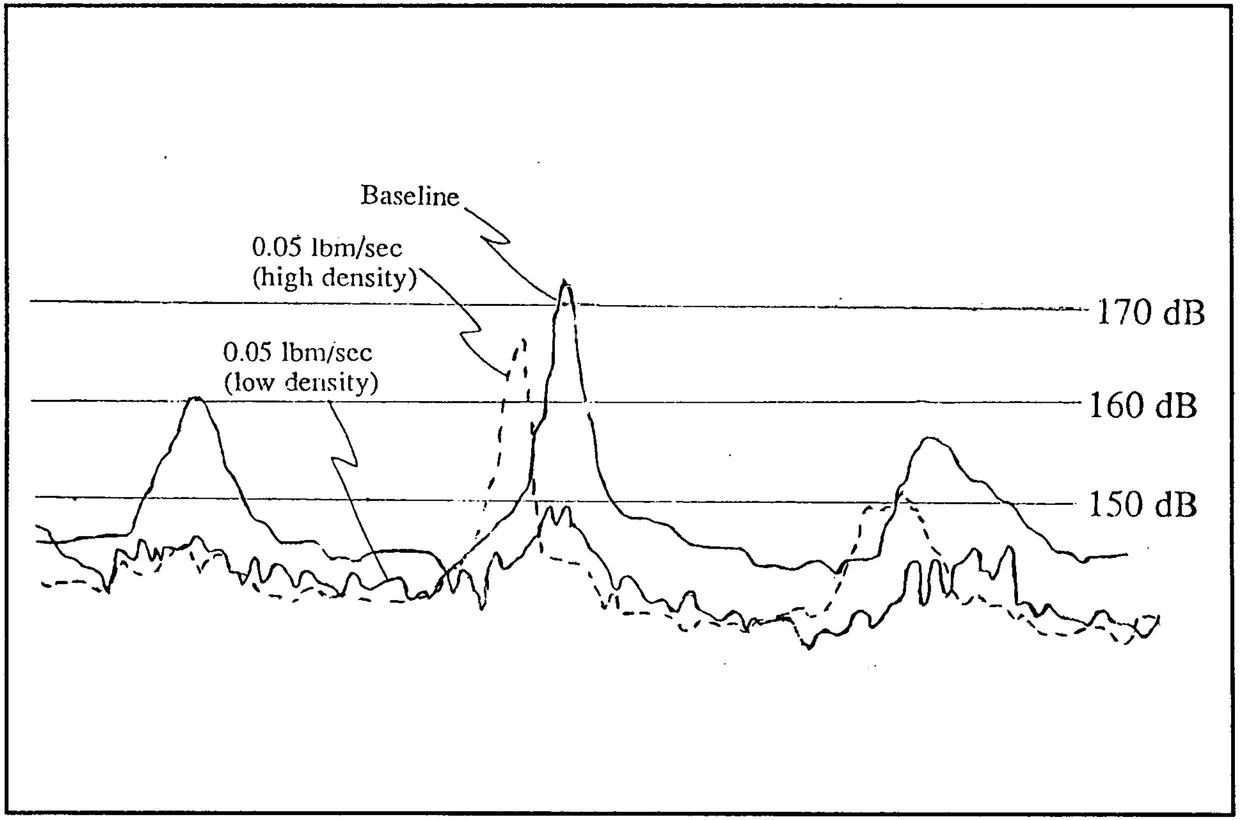


Figure 27. Frequency-amplitude spectrum (0.05 lbm/sec)

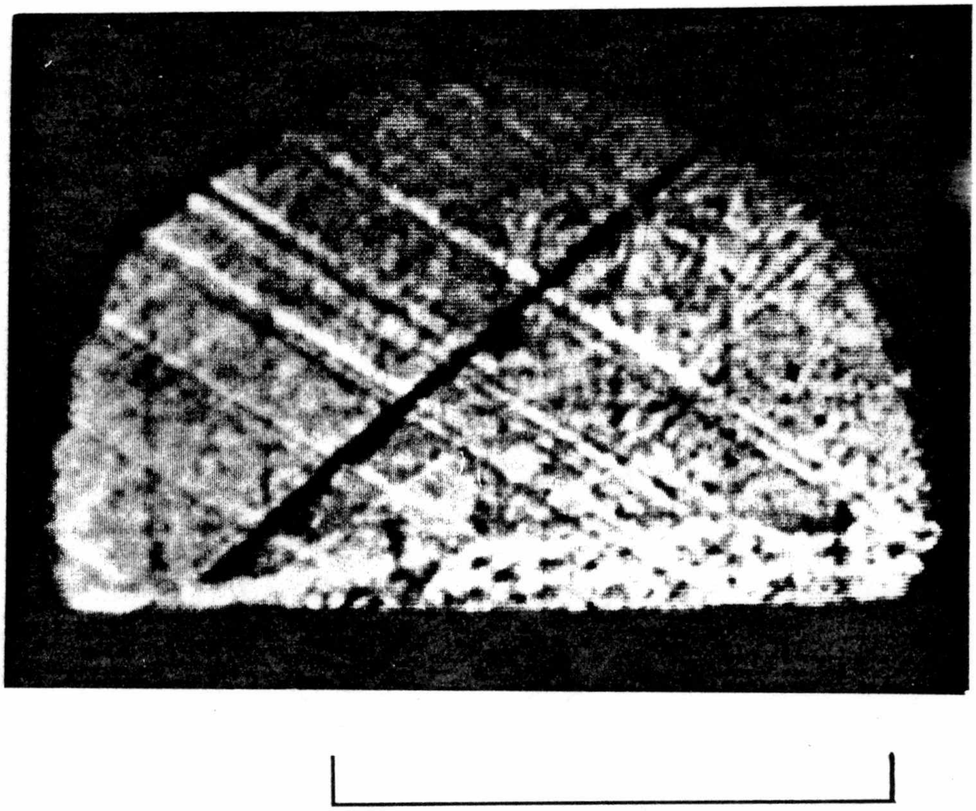


Figure 28. Typical schlieren photograph with mass blowing (low density hole pattern)

V. CONCLUSIONS

In summary, the following conclusions can be drawn from the experiments carried out during this study:

1) Mass injection upstream of the cavity significantly decreases sound pressure levels with relatively small blowing rates (0.05 lbm/s). The greatest SPL reduction is 27 dB from the initial baseline of 172 dB (at an intermediate blowing rate of 0.2 lbm/sec).

2) Low density hole configurations (porosity of 0.15) apparently are more effective than high density hole configurations (porosity of 0.3) in altering shear layer stability characteristics at low mass flow rates since greater reductions in sound pressure level are achieved.

3) Sound pressure level stops decreasing at higher mass injection rates. This is due to the displacement of the shear layer away from the cavity, which prevents any further modifications in the shear layer interaction with the cavity.

4) The blowing parameter correlation B did not accurately reflect experimental results. The momentum-related parameter B_{mom} should be investigated in the future.

5) Additional further work is recommended to:

a) develop a new nondimensional blowing parameter (probably incorporating the momentum thickness), which also incorporates both the geometry of the hole pattern and the density of the pattern.

b) verify the physical cause for the greater effectiveness of the low density configuration in suppressing acoustic levels.

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