To the Graduate Council:

I am submitting herewith a thesis written by Michael B. Taylor entitled "Cavity Flow Oscillation Analysis and Water Table Simulation." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

Ahmad D. Vakili, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:

Vice Provost
and Dean of the Graduate School

CAVITY FLOW OSCILLATION ANALYSIS
AND WATER TABLE SIMULATION

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Michael B. Taylor

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ABSTRACT

Under certain conditions, high speed flow over closed cavities becomes unstable, leading to large flow flucuations inside and around the cavities. This phenomenon is simulated for a 1.5-inch deep by three-inch long cavity using a water table. Upstream blowing is used in an attempt to supress the oscillations.

Steady blowing produced total attenuation. Pulsed blowing produces similar attenuation for a few cycles, and then excited the oscillations to higher amplitude.

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CHAPTER I

INTRODUCTION

Under certain conditions, high speed flow over closed cavities becomes unstable, leading to large flow fluctuations inside and around these cavities. These flow disturbances are a large source of difficulty in carrying and separating stores from aircraft weapons bays. The disturbances can cause similar difficulties with submunition separation from missiles.

Flow over cavities may be divided into three categories, according to the cavity length to depth ratio. For deep cavities (region 1 in Figure 1), the free shear layer spans the entire length of the cavity. For shallow cavities (region 3 in Figure 1), the flow attaches to the bottom of the cavity at some point, leaving separated zones at the upstream and downstream ends. Sketches of shallow and deep cavity flow are shown in Figure 2, a and b.

Region 2 represents the transition between deep cavity and shallow cavity flow. This flow exhibits the characteristics of either deep or shallow cavity flow, or it can become unstable and oscillate between the two modes.

This investigation is concerned with the deep

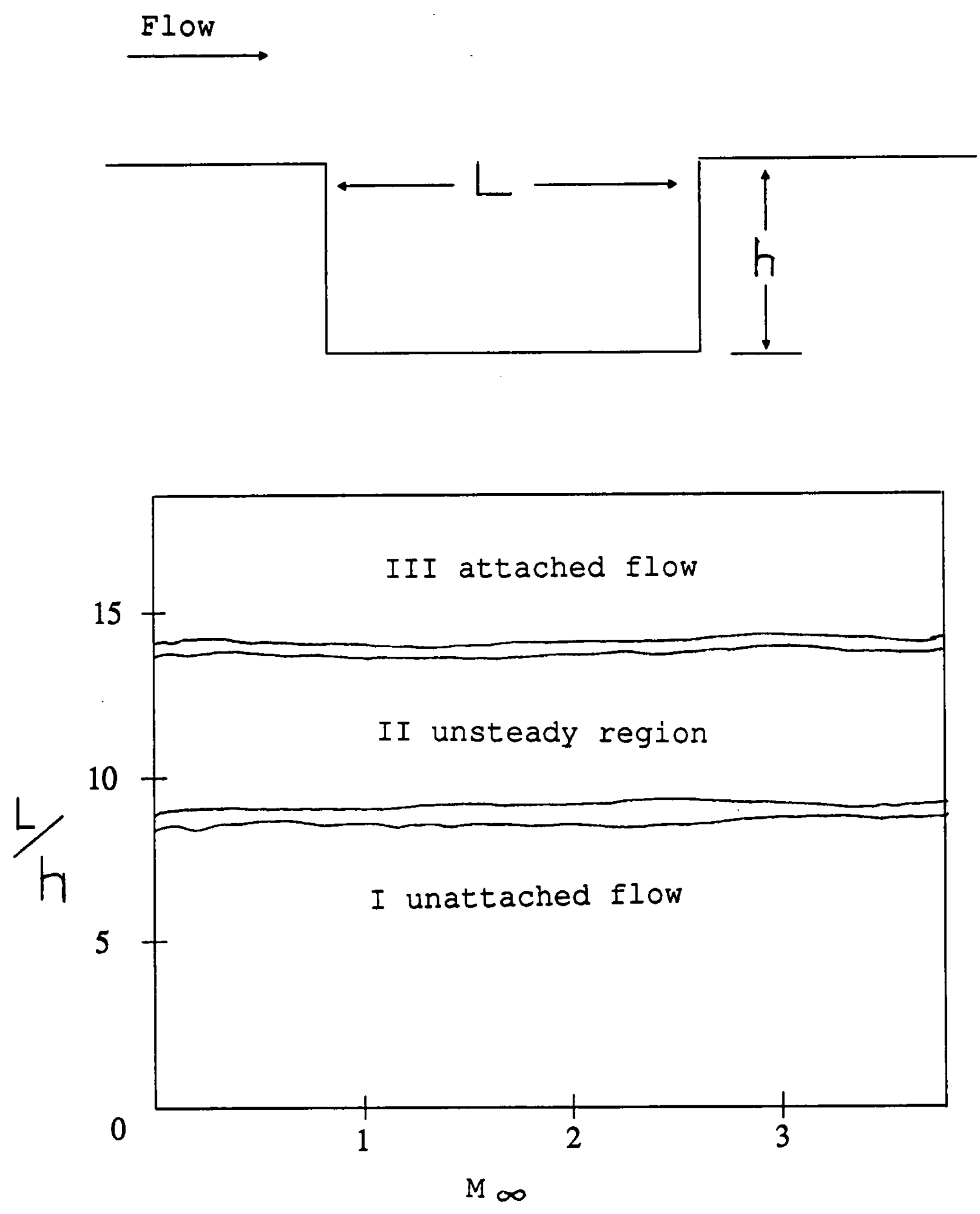
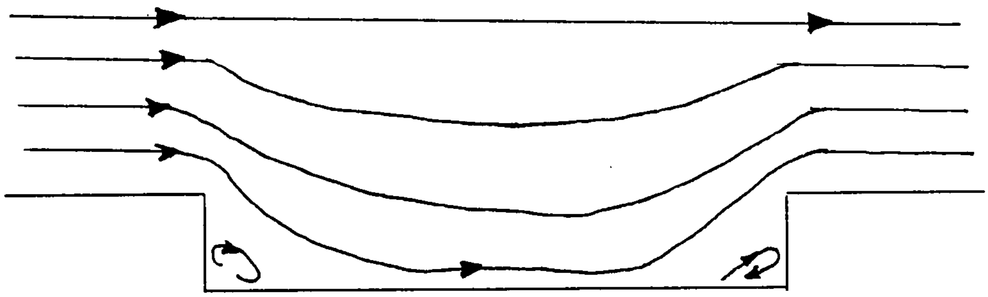
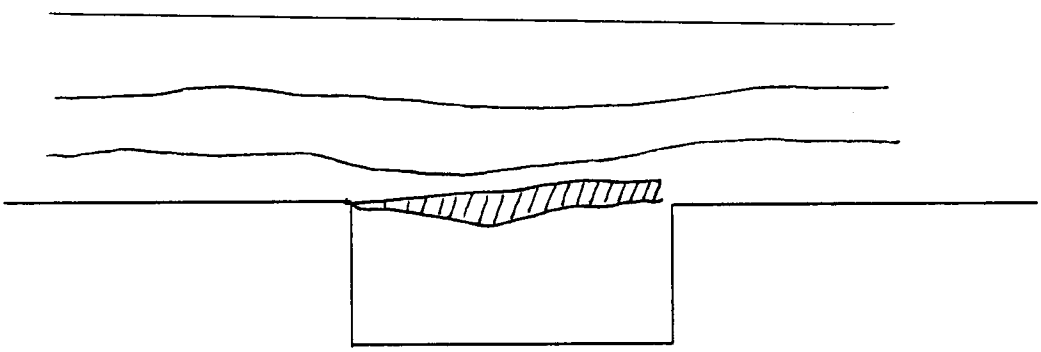


Figure 1. Non-dimensional critical cavity length after Chen



a. Shallow cavity, Region III. Flow attached to the bottom of the cavity.



b. Deep cavity, Region I. Fluid flows over the top of the cavity.

Figure 2. Attached and unattached cavity flows.

cavity flows (region 1) and with region 2 flows when they behave as deep cavity flows. In those flows, the shear layer that spans the cavity does not attach to the bottom of the cavity, but it often oscillates. Large flow fluctuations inside the cavity are associated with these shear layer oscillations. If these flow fluctuations occur inside the aircraft or missile weapon bays, they can hamper safe separation. They can also damage delicate sensors associated with the weapons or even the weapon airframe itself.

Because of this and other applications, oscillating cavity flow has been under investigation for many years. Investigators have sought to understand and model this phenomena sufficiently to enable them to predict it and to suppress or enhance it.

The approach of this study is to simulate an oscillating cavity flow using a water table. This simulation entails numerous assumptions which make direct quantitative comparison with wind tunnel experiments difficult.

However, there are many qualitative similarities between cavity flow experiments using air and the water table simulation. Since water table experiments are much easier to set up and observe than wind tunnel experiments, this technique is useful in the initial evaluation of cavity oscillation suppression concepts.

One promising suppression concept is shear layer flow control through upstream blowing. Mass is injected into the flow directly upstream of the cavity. The effects of this is easily observed in the water table experiments by using dye.

Both steady and pulsed upstream blowing was tried. The steady blowing thickened the cavity shear layer and in most cases attenuated the cavity oscillations. The pulsed blowing attenuated the oscillations, depending on the phase relationship between the blowing and initial cavity oscillations. These experiments indicate that upstream blowing is a promising technique and should be explored further.

Previous efforts to attenuate the amplitude of weapons bay cavity oscillations have centered around the use of passive means, such as vortex generators. These devices work by affecting the shear layer across the mouth of the cavity, changing its natural frequency. Such devices are only effective within a narrow range of flow parameters for which they are designed. The goal of this work is to explore the active blowing upstream of the cavity to accomplish the same end for a wide range of flow parameters.

CHAPTER II

TECHNICAL REVIEW

One of the earliest investigators of the cavity flow ocsillations phenomenon is Krishnamurty (1955). Krishnamurty experimented with a variable length cavity in a small transonic wind tunnel. He took schlieren photographs of the acoustic field radiated from the cavity. He also measured the frequencies of these fields using hot wire anemometry. Krishnamurty found that intense, directional acoustic fields radiated from the cavities. He also found that at a given freestream flow condition, the frequency of the sound emissions is inversely proportional to the cavity length. Krishnamurty did not attempt to explain or model the phenomenon.

Rossiter (1964) proposed a feedback model for the phenomenon. According to his model, vortices are shed at the upstream lip of the cavity. These vortices are convected downstream in the free shear layer which spans the cavity opening. Upon reaching the downstream lip of the cavity, the vortices interact with the lip to produce acoustic pulses. These pulses travel upstream inside the cavity. They interact with the shear layer at the upstream lip to produce new vortices, thus closing the loop. Rossiter derived the following semi-empirical equation for tone frequencies

$$\frac{fL}{U} = \frac{m - n}{M + 1/k} \qquad (1)$$

where f=tone frequency, L=length of cavity, U=free stream velocity, M=Mach number, m is an integer mode number and k and n are empirical constants.

Heller and Bliss (1975) studied this phenomenon using a water table simulation. Their observations indicated a significant periodic inflow and outflow at the downstream edge of the cavity. They modeled this effect and the acoustic waves produced by the cavity with a piston at the rear bulkhead.

Tam and Block (1978) proposed a detailed mathematical model based on a feedback coupling between the upstream portion of the shear layer and an acoustic source at the downstream lip of the cavity. They accounted for the effects of shear layer thickness and cavity depth, which previous investigators had neglected.

First they derive their mathematical model assuming that the thickness of the shear layer is negligible, just as Rossiter and other investigators had done. Then they enhance their model to account for the shear layer thickness. The enhanced model predicts oscillation frequencies significantly better and over a wider range of conditions than Rossiter's much simpler model.

Tam and Block point out that the shear layer thickness is a significant fraction of cavity length in some of Rossiter's experiments ($\Theta/L=0.081$). They believe that some of the apparent data scatter in those experiments is due to variations in shear layer thickness. They also identified some serious difficulties in completely modeling the shear layer thickness. The shear layer spanning the mouth of the cavity grows in thickness in the streamwise direction. The rate of growth of the shear layer depends upon the growth of the large scale coherent structures contained within. These are affected by and also affect the oscillation of the shear layer. Tam and Block resolved this problem by assuming a constant momentum thickness across the mouth of the cavity.

CHAPTER III

WATER TABLE THEORY

A water table is a flat table with a smooth, nearly level surface over which a thin sheet of water is made to flow at a uniform speed. Any object placed on the surface of the table will generate standing waves. The waves in this sheet of water are analogous to shock waves in a supersonic wind tunnel. The analogy between water table flow and two-dimensional supersonic flow is fairly extensive. There are relationships between the height of the water on the table and the enthalpy of flowing gas, between the velocity of the surface waves of the water and the velocity of sound waves in a gas, and between the Froude number in water table flow and the Mach number in gas flow.

The analogy between water surface height in water table flow and enthalpy in gas is derived as follows: Consider a sheet of water emanating from a large reservoir as shown in Figure 3. The Bernoulli equation for steady, incompressible flow applies and can be used to relate any two arbitrary points in the flow:

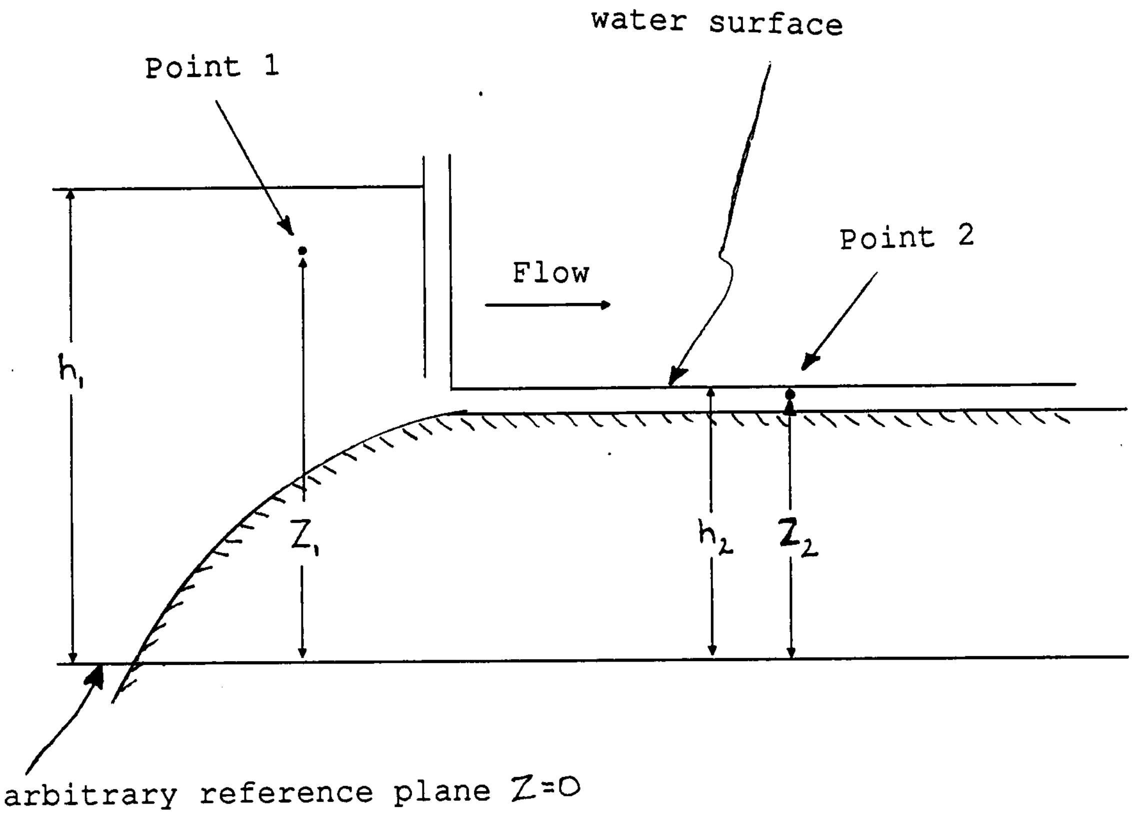


Figure 3. Water table analogy.

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho g z_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g z_2 \qquad (2)$$

where the subscripts denote the properties at points 1 and 2, P is pressure, ρ is density, V is velocity, g is the acceleration of gravity and z is the height above an arbitrary reference plane.

If we choose the ambient atmospheric pressure as a zero reference, then we can write:

$$P = \rho g (h - z) \qquad (3)$$

where h is the height of the free surface of the water above the arbitrary reference plane. Substitute (3) into (2) and discard the V_1 term since V_1 is approximately zero. After algebraic rearrangement, the result is

$$\frac{V_2^2}{2g} = h_2 - h_1 \qquad (4)$$

Note that equation (4) has the same form as the energy equation for steady, adibatic, isentropic, compressible gas flow:

$$\frac{V^2}{2} = H_0 - H \qquad (5)$$

where specific enthalpy is designated by H to distinguish it from the surface height h.

Equation (4) can be made more useful by dropping some of the generalities we have maintained up to now. First, fix the arbitrary reference plane to the flow surface of the table. Second, use subscript "o" to denote conditions in the reservoir and no subscript to denote flow properties on the flow surface. We now have:

$$\frac{V^2}{2g} = h_o - h \qquad (6)$$

It is convenient to apply the term "stagnation height" to h_o as suggested by the analogy between h_o and H_o.

There is also a strong analogy between the continuity equations for water table flow and two-dimensional gas flow. It can be easily shown by writing a mass balance equation for an incremental element of volume that:

$$\frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \qquad (7)$$

where u is the component of velocity in the x direction and v is the component of velocity in the y direction. Comparing equation (7) with the continuity equation for two-dimensional gas flow

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \qquad (8)$$

we see that h corresponds to density, ρ . It has already been shown that h also corresponds to H. If we assume that the flowing gas is perfect and has constant specific heats, then h also corresponds to temperature, since $H = c_p T$. The relationship between density, temperature and the corresponding stagnation properties in a perfect gas is

$$\frac{\rho}{\rho_0} = \left(\frac{T}{T_0}\right)^{\frac{1}{\gamma-1}} \qquad (9)$$

where γ is the ratio of specific heats.

It is obvious then, that water height h corresponds simultaneously to density and temperature of a perfect gas only if $\gamma = 2$. This is physically impossible for an actual gas. The ratio of specific heats ranges from a high value of about 1.67 in monatomic gases to a value approaching 1 for very large molecules.

The above results are not intended to be an exhaustive explanation of the water table analogy. This is available from several sources. An excellent example is references Loh (1969). These results are intended to illustrate some of the limitations and assumptions inherent in the water table analogy. The following points have significant implications for cavity flow simulation:

1. Water table flow is two-dimensional; hence it can only simulate two-dimensional gas flow.

2. Water table flow simulates a gas with $\gamma = 2$. For many gases of interest, for example air, $\gamma = 1.4$.

3. The water table simulates the shock waves and density changes found in supersonic flow. The technique is not applicable to subsonic flow.

4. The equations used to derive the water table analogy assume invicid flow. Some of the undesired viscous effects can be minimized by tilting the table, but they cannot be eliminated. Viscous effects also cause the water height drop across a simulated weak shock to be greater than a corresponding enthalpy drop in a gas flow.

CHAPTER IV

CAVITY FLOW ANALYSIS

One of the earliest investigators of this phenomenon, Krishnamurty (1955), showed that there is a strong, linear correlation between cavity length and the frequency at which the cavity oscillates. Krishnamurty made numerous runs in which he varied only cavity lengths. He measured the frequency of the cavity's acoustic emissions using hot wire anemometry and a wave analyzer. For a given run, he plotted frequency against the reciprocal of the cavity length. The data for a given run nearly always falls on a straight line, which, when extended, passes through the origin. Lines for different Mach numbers form a narrow fan. Subsequent investigators have confirmed this finding.

Investigators after Krishnamurty frequently presented their data as plots of nondimensional frequency, or Strouhal number, $S=\frac{fL}{U}$ where f is frequency, L is cavity length, and U is freestream velocity. Thus the strong dependency of frequency on cavity length is well established. Later researchers (Rossiter, Plumbee, et. al., and Tam and Block) customarily presented their data as plots of Strouhal number against other parameters such as freestream Mach number or cavity depth. These plots showed that there is definite, but much weaker, dependence of frequency upon these parameters.

Although factors other than cavity length and freestream velocity are weak determiners of frequency, they can be strong determiners of the amplitude of the acoustic emissions from the cavity. Krishnamurty noted that some combinations of cavity geometry, freestream Mach number and flow character (laminar vs. turbulent) yielded much stronger emissions than others. This point is clearly illustrated by his excellent schlieren photographs.

The importance of cavity geometry in determining the amplitude of the cavity oscillations can be explained by a feedback model. The feedback concept is illustrated by Figure 4. Instabilities in the shear layer grow in the downstream direction (A). Upon reaching the downstream lip of the cavity (B), the shear layer oscillations have reached their largest amplitude. The shear layer reacts with the downstream lip to produce disturbances, which are convected upstream inside the cavity. These disturbances excite the upstream portion of the shear layer at (C). This basic mechanism has been suggested by many authors, including Heller and Bliss, Tam and Block, Ho and Nossier and Yu, et al (1987).

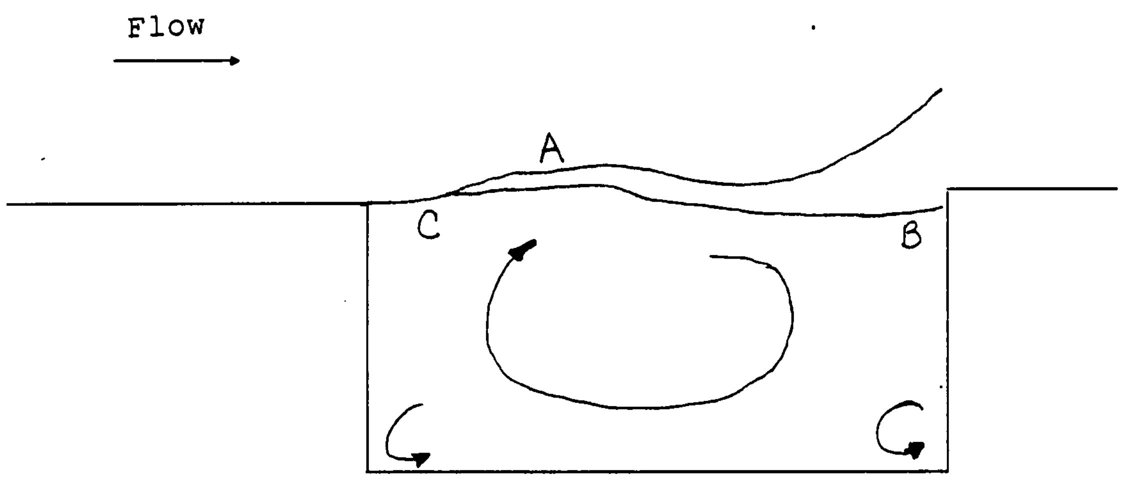


Figure 4. Convective feedback.

For supersonic freestream flow, it is obvious that the feedback path must be inside the cavity. Since the flow is supersonic outside the cavity, disturbances cannot propagate upstream there. For the same reason, disturbances would propagate much more readily inside the cavity even if the freestream flow was high subsonic.

If this feedback model describes the phenomenon reasonably well, one would expect the amplitude of the oscillations at any given conditions to depend largely on the effectiveness of the feedback process. This would depend largely on two factors:

1. the efficiency of the feedback path inside the cavity;

2. the receptivity of the upstream portion of the shear layer to excitation at the downstream frequency.

The efficiency of the feedback path inside the cavity should be a strong function of the cavity geometry. The effective geometry, as Tam and Block point out, would be influenced by the thickness of the shear layer. The local shear layer thickness is strongly influenced by the boundary layer thickness at the upstream lip and by the freestream Mach number.

It would be useful at this point to examine the growth of free shear layers. The shear layer that spans the cavity does not behave in exactly the same manner as a free shear layer, but free shear layers have been studied extensively and serve as a useful starting point.

Ho and Huerre (1984) present growth rate data for incompressible free shear layers taken by a number of researchers as a plot of the growth rate of the momentum thickness in the streamwise direction, θ , vs. R, where R is a simple function of the velocities of the two streams:

$$R = \frac{U_1 - U_2}{U_1 + U_2} \qquad (10)$$

In physical terms, R is a ratio of the amount of shear present (velocity difference in the numerator) to the average velocity. Ho and Huerre's plot shows that the growth rate can be approximated as a linear function of R:

$$\frac{d\theta}{dx} = .45R \qquad (11)$$

Messersmith, et. al. (1988) present a similar plot using slightly different nomenclature. The slope of their plot is comparable to Ho and Huerre's.

Compressible free shear layers generally grow at a slower rate than the incompressible case. A particular shear layer can be characterized as compressible or incompressible through the use of a convective Mach number. The concepts of convective velocity and convective Mach number are widely used in the analysis of high speed shear layers. The definitions given here follow the development of Messersmith, et. al.

The convective velocity is the speed at which the large scale structures of the shear layer move with respect to a stationary frame of reference. It can be shown that the convective velocity, U_c, is equal to the average of the freestream velocities weighted by the roots of the freestream densities:

$$U_c = \frac{U_1\sqrt{\rho_1} + U_2\sqrt{\rho_2}}{\sqrt{\rho_1} + \sqrt{\rho_2}} \qquad (12)$$

Note that U_c is simply the average of the freestream velocities when both streams are of the same fluid and their freestream Mach numbers are sufficiently low. Convective Mach numbers can be defined for each stream, using the velocities of the streams with respect to the convective velocity:

$$M_{c,1} = \frac{U_1 - U_c}{c_1} \quad ; \quad M_{c,2} = \frac{U_c - U_1}{c_2} \qquad (13)$$

where c is the speed of sound.

Messersmith, et. al. combine these two stream convective Mach numbers in a geometric average to give a general convective Mach number:

$$M_c = \frac{M_1\sqrt{\frac{\rho_2}{\rho_1}}\left(1-\frac{U_2}{U_1}\right)}{\sqrt{\frac{\gamma_2}{\gamma_1}}\left(\sqrt{\frac{\rho_2}{\rho_1}}+1\right)} \qquad (14)$$

Messersmith, et. al. formulated the above equation to cover the general case of two possibly different fluids mixing. Since the two streams of interest in cavity flow are of the same fluid, the above equation can be simplified. Using

$$\frac{U_2}{U_1} = \sqrt{\frac{\rho_1}{\rho_2}} \qquad (15)$$

one can obtain:

$$M_c = M_1 R \qquad (16)$$

where R is the velocity ratio function defined by equation (10).

Messersmith et. al., present an empirical curve fit which relates the growth rate of a compressible shear layer to the growth rate of an equivalent incompressible shear layer:

$$\frac{\left(\frac{d\theta}{dx}\right)_{comp}}{\left(\frac{d\theta}{dx}\right)_{incomp}} = 0.7\exp(-2M_c^2)+0.3 \quad (17)$$

As one would expect, the expression yields a value of 1.0 for $M_c = 0$. The curve decreases smoothly to a value of 0.4 at $M_c = 1.0$ and 0.3 at $M_c = 2.0$. The curve is valid between $M_c = 0$ and $M_c = 2.0$.

For a given cavity flow, a certain amount of circulation exists inside the cavity. The circulation is sustained by slow-moving cavity fluid being entrained by faster moving fluid in the shear layer. If one assumes that the fluid inside the cavity moves about one-fourth as fast as the freestream velocity outside the cavity, then the value of R is 0.6. Using equation (11), the growth rate of an incompressible shear layer would be $\left(\frac{d\theta}{dx}\right)_{incomp} = 0.027$. One can then use the empirical curve fit given by equation (14) to calculate a factor to account for compressiblity effects.

The result of these calculations is the rate at which a cavity shear layer would grow in the absence of any feedback mechanisms. Feedback mechanisms are active, however, and they will generally cause the shear layer to grow at a rate greater than the nominal rate specified by the preceding equations.

Small disturbances of the proper frequency, acting on the upstream portion of the shear layer, are amplified, producing large-scale coherent structures in the downstream portion. As mentioned earlier in this section, in order for the feedback mechanism to be effective, there must be an efficient path for disturbances to propagate upstream inside the cavity, and the upstream portion of the shear layer must be sensitive to the particular disturbances which are propagated upstream. Some dimensional analysis might help identify the parameters which determine when these conditions occur.

For high subsonic flows and for supersonic flows, the growth rate of the shear layer is relatively small and very small, respectively. Therefore, the coupling which naturally exists between the shear layer frequency and the cavity natural frequency would be expected to be present. For these cases, the energy in the flow can be periodically fed into the cavity at the rear bulkhead where the shear layer instabilities have their maximum amplitude. And as a result, there will be large amplitude pressure oscillations.

These observations have led to the application of the upstream blowing (or other means) to change the characteristic frequency of the shear layer through modifications of its thickness. As a result of the thickening of the shear layer, its stability properties are changed as well. To detail the above, a qualitative order of magnitude discussion with respect to frequency follows.

A Strouhal number, S, based on cavity length, b, has already been discussed. It is possible to reconstruct another Strouhal number using the momentum thickness of the shear layer as the characteristic length scale. It has been thoroughly established that shear layers may be excited by perturbations at a particular frequency, and that frequency is a linear function of shear layer thickness (e.g. Liu (1988) and Ho and Heurre (1984)).

Under the proper conditions, the frequency associated with the cavity length will correspond to the characteristic frequency of the shear layer. This will occur at some ratio of the shear layer Strouhal number, S_θ, and the cavity length Strouhal number, S_b. This ratio, S_θ/S_b, reduces to $\frac{\theta}{b}$. Thus $\frac{\theta}{b}$ is an important parameter for determining when the shear layer will oscillate at large amplitude.

It has also been observed that the length to depth ratio of the cavity, $\frac{b}{d}$, is an important parameter, for two reasons. First, a relatively shallow cavity may tend to confine the oscillations of the shear layer, suppressing their amplitude. The experiments of Fiedler, et. al. (1988) support this conclusion.

Second, the length to depth ratio will influence the recirculation patterns inside the cavity. This will determine the phase of the excitation delivered to the upstream layer.

Earlier in this chapter, it was assumed that the recirculation velocities inside the cavity are a significant fraction of the freestream velocity. If this is true, the recirculation velocities inside the cavity are also a significant fraction of the speed of sound in all but low Mach number flows. These velocity fields would in part determine the amount of time required for an acoustic disturbance produced at the downstream lip of the cavity to reach a particular upstream location. For a given frequency, this time determines the phase. If an oscillation is reinforced in the proper phase, it will grow in magnitude.

Obviously, the shape of the cavity will affect the flow field inside it. Examples of some possible recirculation patterns are shown in Figure 5.

The freestream Mach number will influence the recirculation velocity inside the cavity. Following an argument similar to the previous one, the freestream Mach number also affects the phase of the upstream propagated disturbances.

To summarize these discussions, the following conceptual model of large amplitude cavity oscillation is proposed. A feedback loop locks at some point in the

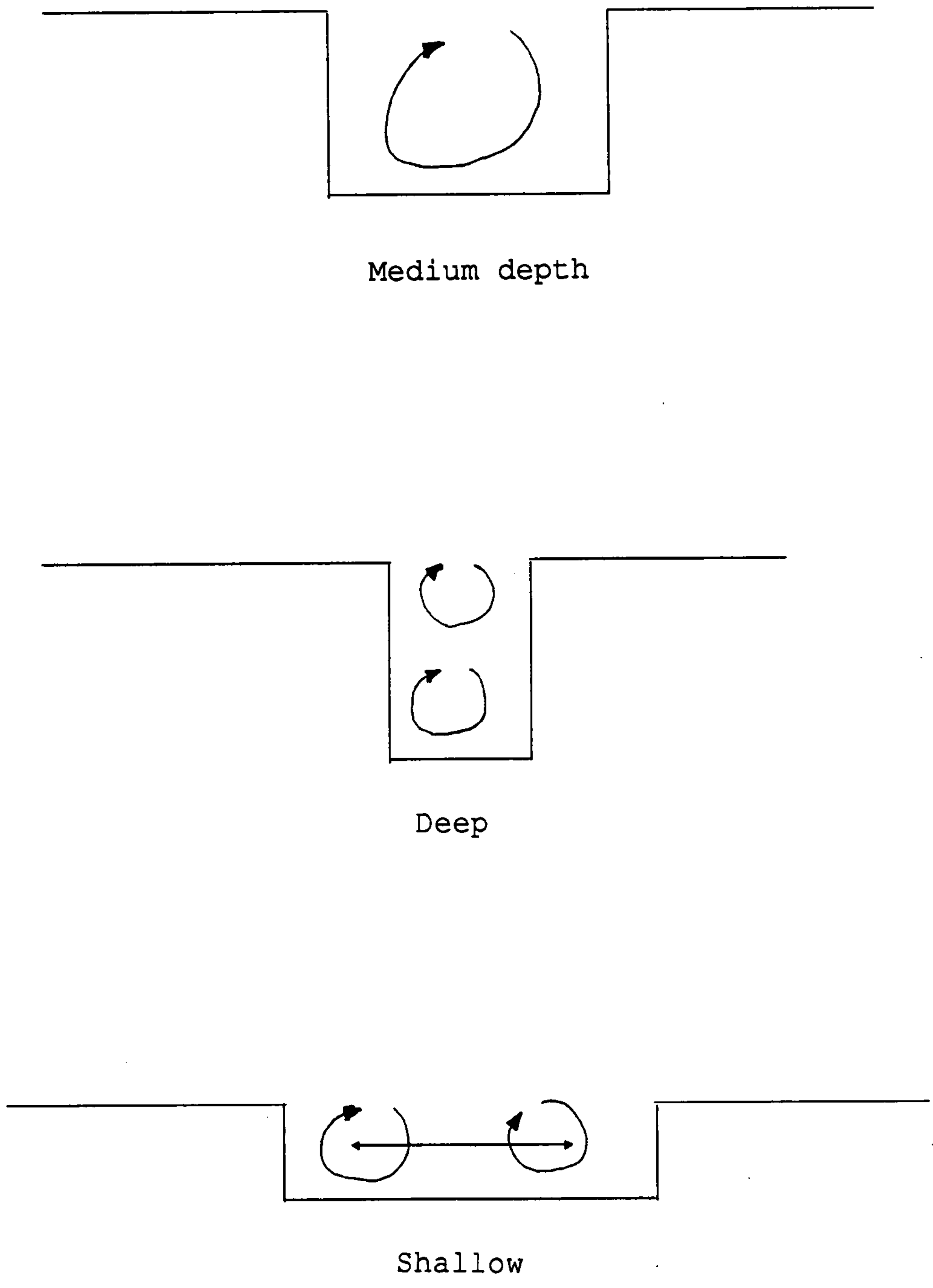


Figure 5. Recirculation patterns.

upstream portion of the shear layer. The characteristic frequency of the shear layer at the lock point is determined by the shear layer thickness, which in turn is determined by the initial shear layer thickness and the growth rate. Large-scale coherent structures are produced which travel downstream at the convective velocity of the shear layer. Pressure disturbances are produced at the downstream lip as a result of interactions between the large scale coherent structures and the cavity lip. These disturbances propagate upstream inside the cavity, aided or hindered by the velocity field inside the cavity. If the disturbances arrive at the lock point with the proper phase, the cavity oscillations will reach a large amplitude.

CHAPTER V

APPARATUS AND PROCEDURE

The water table used in this study is located in The University of Tennessee Space Institute Gas Dynamics Laboratory. The water table assembly consists of a settling tank, an adjustable sluice gate nozzle, a 3/4 inch thick plexiglass flat test section 45 inches wide by 72 inches long, five inch high plexiglass sidewalls and a discharge tank. A schematic of this water table is shown in Figure 6.

As shown in the figure, the water from the discharge tank is pumped into the settling tank and recirculated. The pump is driven by a constant speed motor. The effective pumping rate may be controlled by opening or closing a bypass valve.

The speed of the water sheet traveling over the test section is controlled by controlling the height of the water surface in the settling tank (the stagnation height, h_o, from the previous section). This can be controlled by either:

1. varying the amount of water recirculated. As more water is recirculated, the stagnation height increases accordingly in the settling tank. The recirculation is varied by using the bypass valve. Care

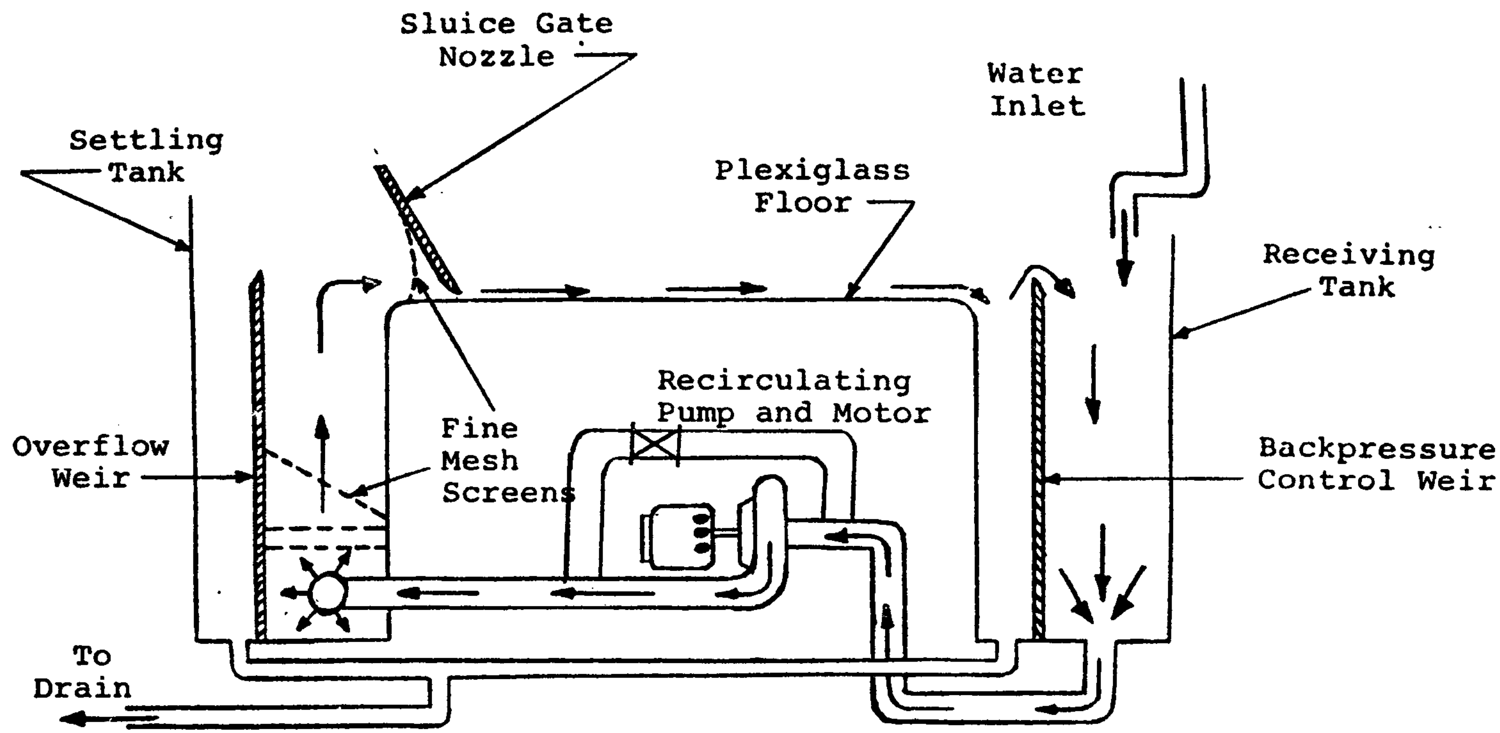


Figure 6 Schematic Diagram of Water Table.

must be taken to allow h_o to settle to equilibrium before running experiments.

2. varying the height of an adjustable overflow bulkhead in the settling tank. As long as there is sufficient recirculation flow, the stagnation height will rise or fall to match the height of the bulkhead, with the excess spilling over the top into the overflow weir.

The second method was found unsatisfactory due to the uneven flow caused by the overflow and by leakage at the seals of the adjustable bulkhead. The adjustable bulkhead was fixed in place and caulked. The bypass valve was used to regulate the stagnation height for most of the experiments.

The Froude number (the water table analog of Mach number) was measured by inserting pointed instrument into the water a few inches downstream of the sluice gate. This was done in order to create a disturbance analogous to a Mach cone. A protractor was used to measure the resulting wave half angle. The error resulting from this method is judged to be about ten percent.

Alternative methods for deducing the Froude number are measuring the stagnation height in the settling tank or measuring the velocity of the water sheet directly. Peele (1968) made an experimental comparison of the stagnation height method and the wave angle method. His results are presented in Figure 7.

The accuracy and repeatablility of the Froude number measurements probably could have been refined by an order of magnitude by measuring the velocity of the water sheet directly. However, the extra accuracy would not have contributed significantly to the experiment. As pointed out in the previous section, the limitations and assumptions inherent in the water table analogy make precise, quantitative modeling of the cavity flow impossible. Only qualitative results are sought or expected.

The main test article for this experiment is shown in Figure 8. The 1.5 inch by 3 inch cutout simulates a two-dimensional cavity with a length to depth ratio of 2.0. The article was fabricated from one-inch thick plexiglass stock.

The particular length to depth ratio of this article was selected as one likely to produce high amplitude oscillations. The most pronounced oscillations were produced at a simulated Mach number of 2.0 and a ten degree angle of attack.

The first frequency measurements were made using hot film anemometry. The hot film probe was placed in the lower rear corner of the cavity. A DISA model 55D01 hot wire controller was used with a TSI 1212-60W hot

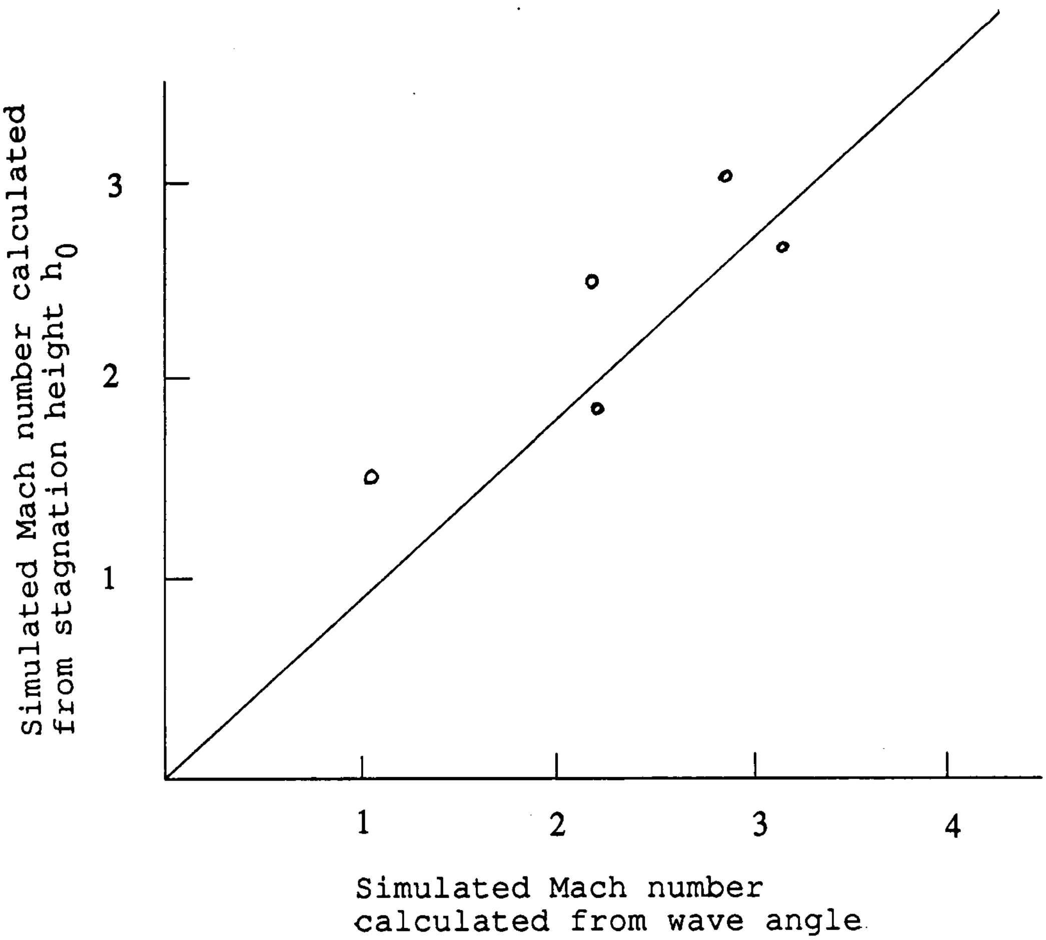


Figure 7. Comparison of two methods for measuring Mach number. Ref. Peele

1 required
Use 1" thick plexiglass provided.
Cut 1" x 2" cavity from smoothest,
straightest edge.

Top view

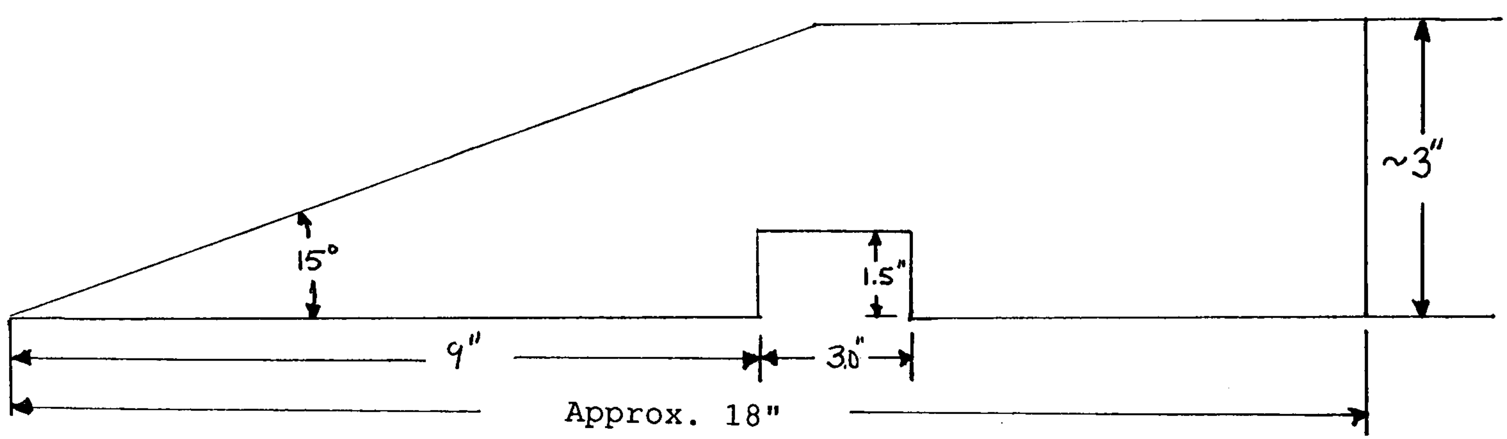


Figure 8. A water table.

film probe tip. The overheat ratio was 1.10, and the resistance was set at 4.89 ohms. Since low frequency signals were to be measured, frequency compensation was not needed. Since frequency measurements, rather than absolute velocity measurements, were desired, no velocity calibration was performed.

The resulting signal was fed into a Hewlett Packard model HP3582A spectrum analyzer. The unit displays results on a CRT as a plot of signal strength in dBV vs. frequency in hertz. A sample display is shown in Figure 9. Note the peak at 3.04 hz and a secondary peak at the first harmonic of this frequency. A plot of Strouhal number versus Mach number is shown in Figure 10.

Although this method produced several successful frequency measurements, it has a few drawbacks. One drawback is high wear and tear on probe tips. Despite the best attempts to keep the water in the water table circuit clean, debris tended to accumulate on the hot film probe tip. As the debris accumulated, the performance of the probe deteriorated. Eventually it became difficult to distinguish the peaks on the spectrum analyzer display from the noise. Attempts to clean the probe tip did not yield much improvement.

Because of the debris and other drawbacks on the hot film method, an alternative method was tried. An electrically conducting probe was positioned in the

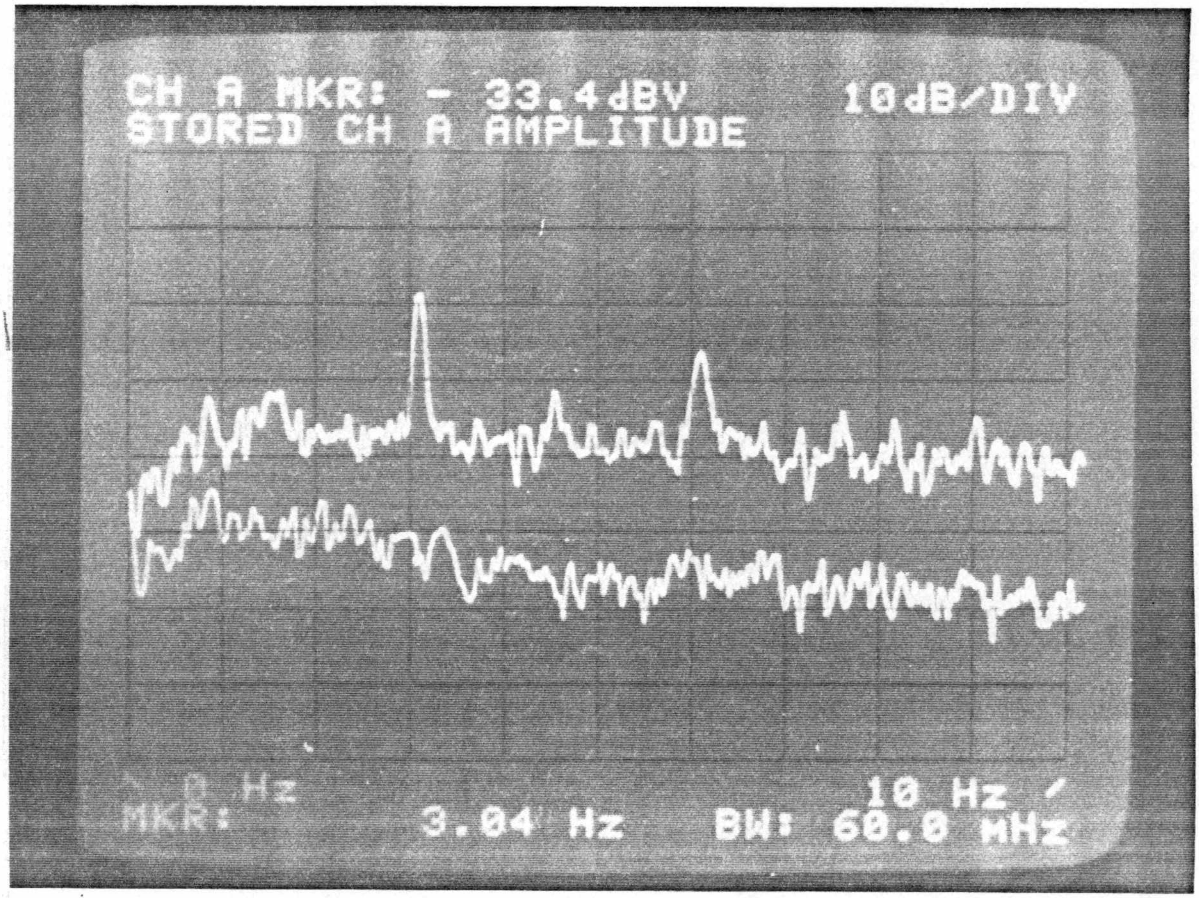


Figure 9. Sample display of frequency signal.

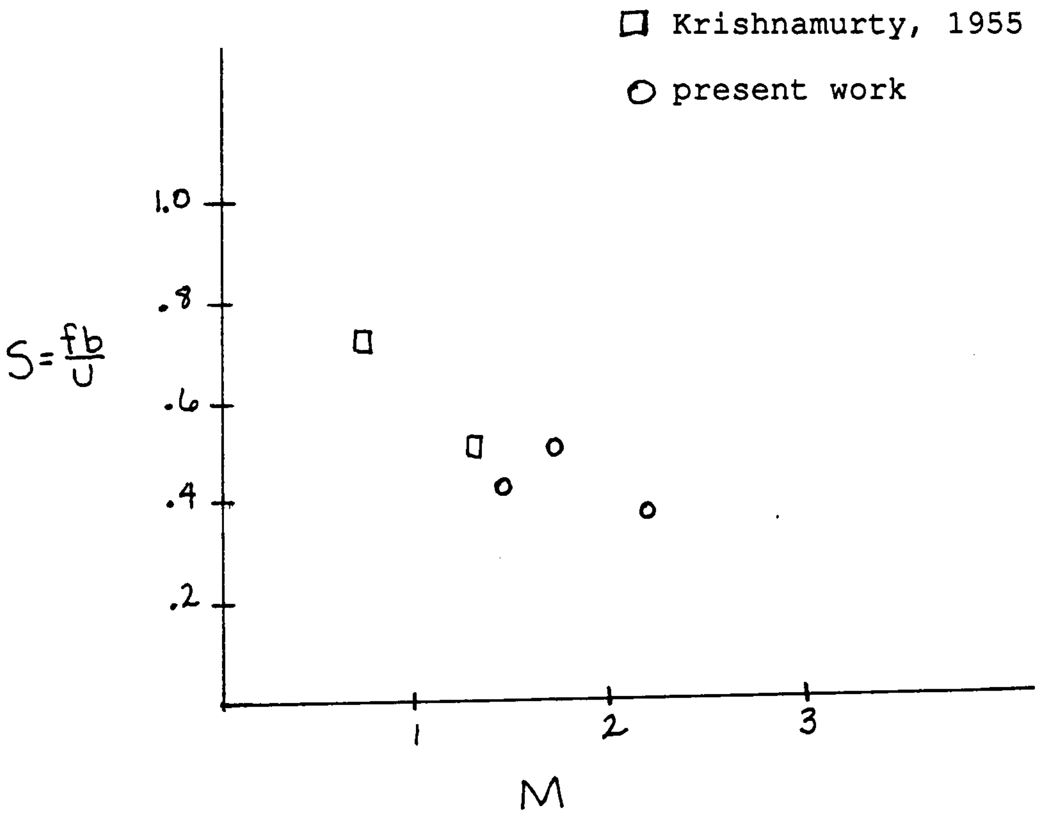


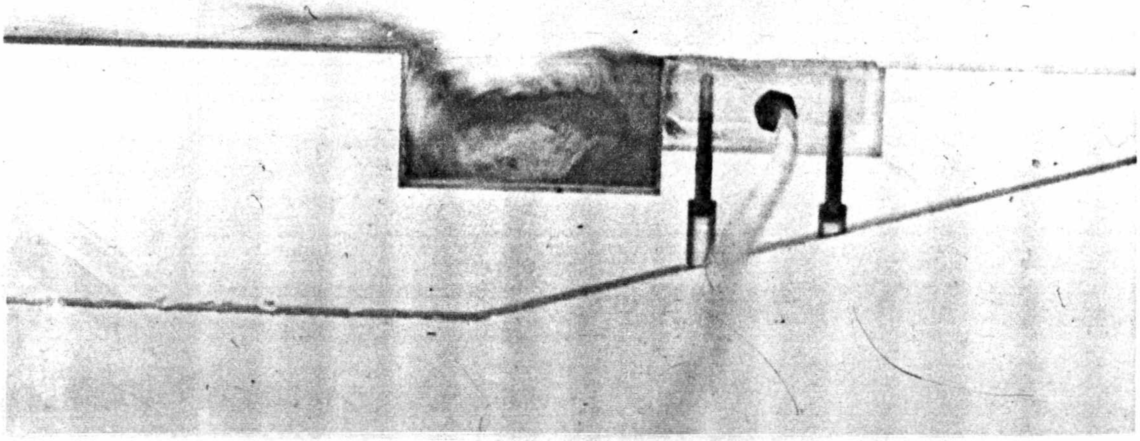
Figure 10. Stroughal number vs. Mach number.

cavity such that it was partially wetted. As the water level rises and falls in and around the cavity due to cavity flow oscillations, different amounts of the probe surface area are wetted. Another electrode was placed away from the cavity so that it remains submerged and completely wetted at all times. A constant voltage power supply was connected to the probe and the submerged electrode. A small current flowed through the water. This current was a function of the wetted area of the probe, and therefore of the height of the water surface. A voltage, measured between the probe and the electrode, was fed to the spectrum analyzer.

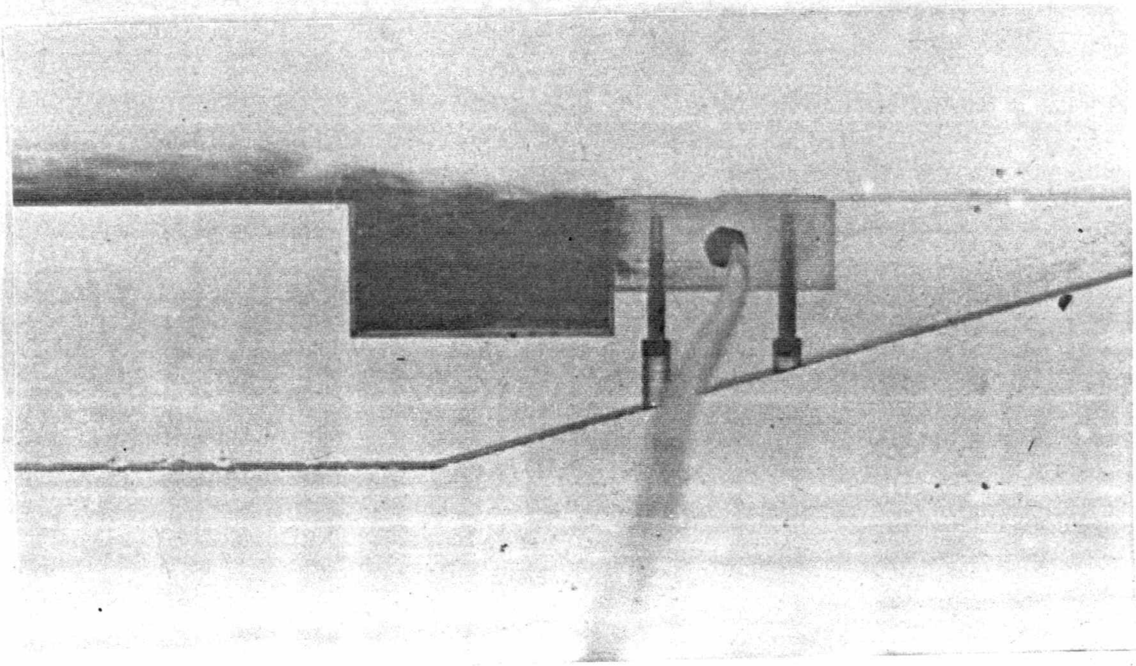
This method worked fairly well also. It was less sensitive than the hot wire technique, but it did not suffer from the debris contamination problem.

The cavity shear layer was made visible by injecting food coloring periodically into the cavity, as shown in Figure 11. This worked well because the freestream water outside the cavity moved much faster than the diffusion rate of the dye. Several video tapes were made demonstrating this technique.

To facilitate shear layer manipulation, the test article was modified. A small section, upstream of the cavity's upstream lip, was cut out and replaced with a mass injection module. This assembly is shown in Figure 12. Tap water is supplied to the top of the module



a. Typical flow in a cavity oscillating due to external flow, without control.



b. Controlled flow in the cavity stablized by the upstream blowing.

Figure 11. Flow over cavity with and without flow control.

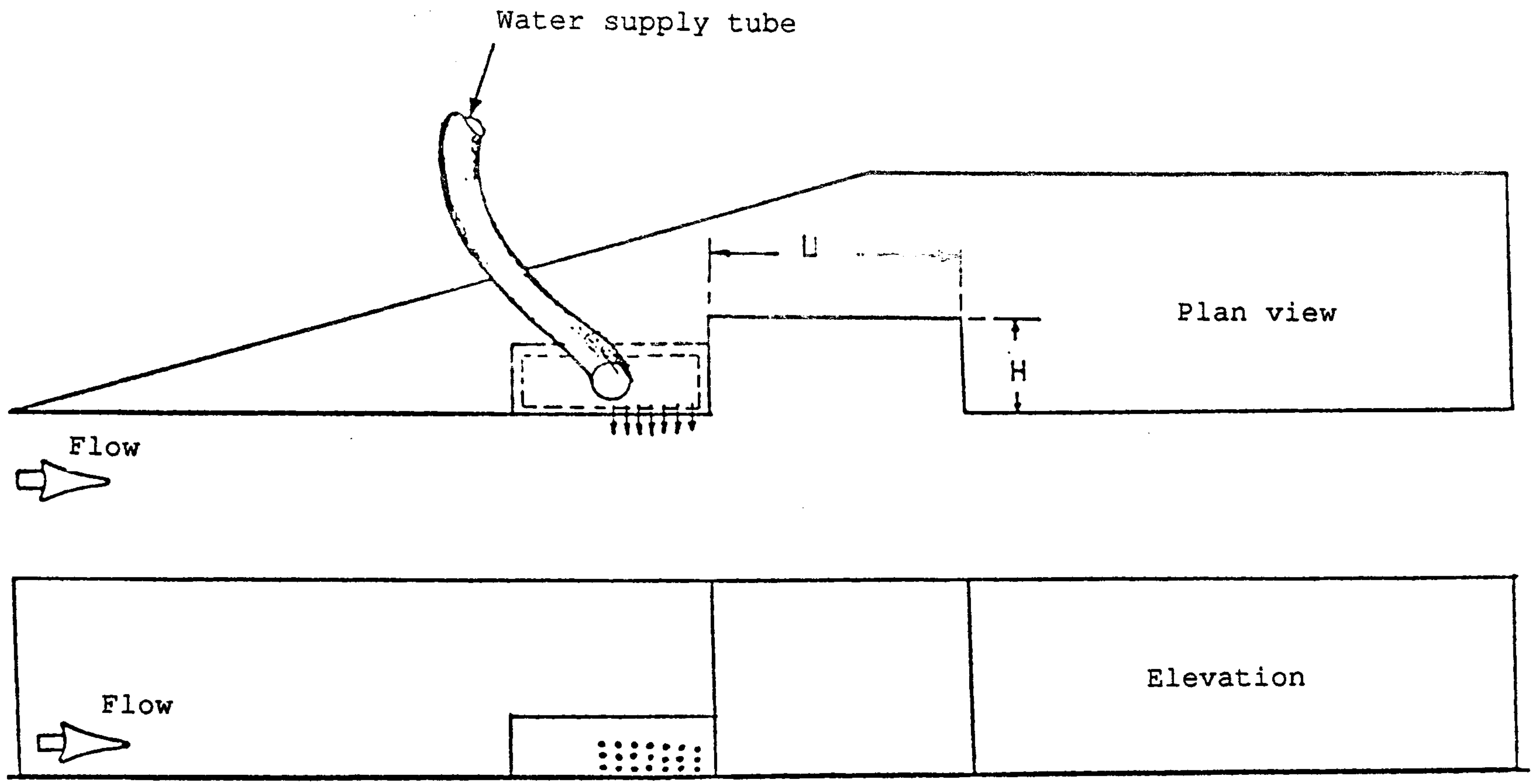


Figure 12. Schematics of the generic cavity model.

through a nylon tube. The water flows into a manifold inside the module and out the 35, .040-inch diameter, holes into the water table flow. Since the module is located just upstream of the cavity, the module flow should influence the shear layer.

Experiments were performed using pulsed flow controlled by a solenoid valve, by steady flow and by a combination of both. This apparatus is shown in Figure 13. The pulsed flow seemed to affect the cavity oscillations the most. By pulsing at the cavity's measured oscillating frequency, it was sometimes possible to excite the oscillations to very high amplitudes. By starting the pulsing at the proper time, it was also possible to attenuate the cavity's oscillations for a few cycles. After a few cycles, the phase of the cavity's oscillations adjusted to match the phase of the pulsing, and high amplitudes resulted. Reinforcement, rather than attenuation, appeared to be the stable mode in every case.

This observation is explained as follows. The oscillation frequency of the cavity was measured with no flow through the module. When the pulsing was started, the shear layer was thickened, changing the oscillation frequency of the cavity. Since the frequency of the pulsing is slightly different from the cavity oscillation frequency, the phase differently between

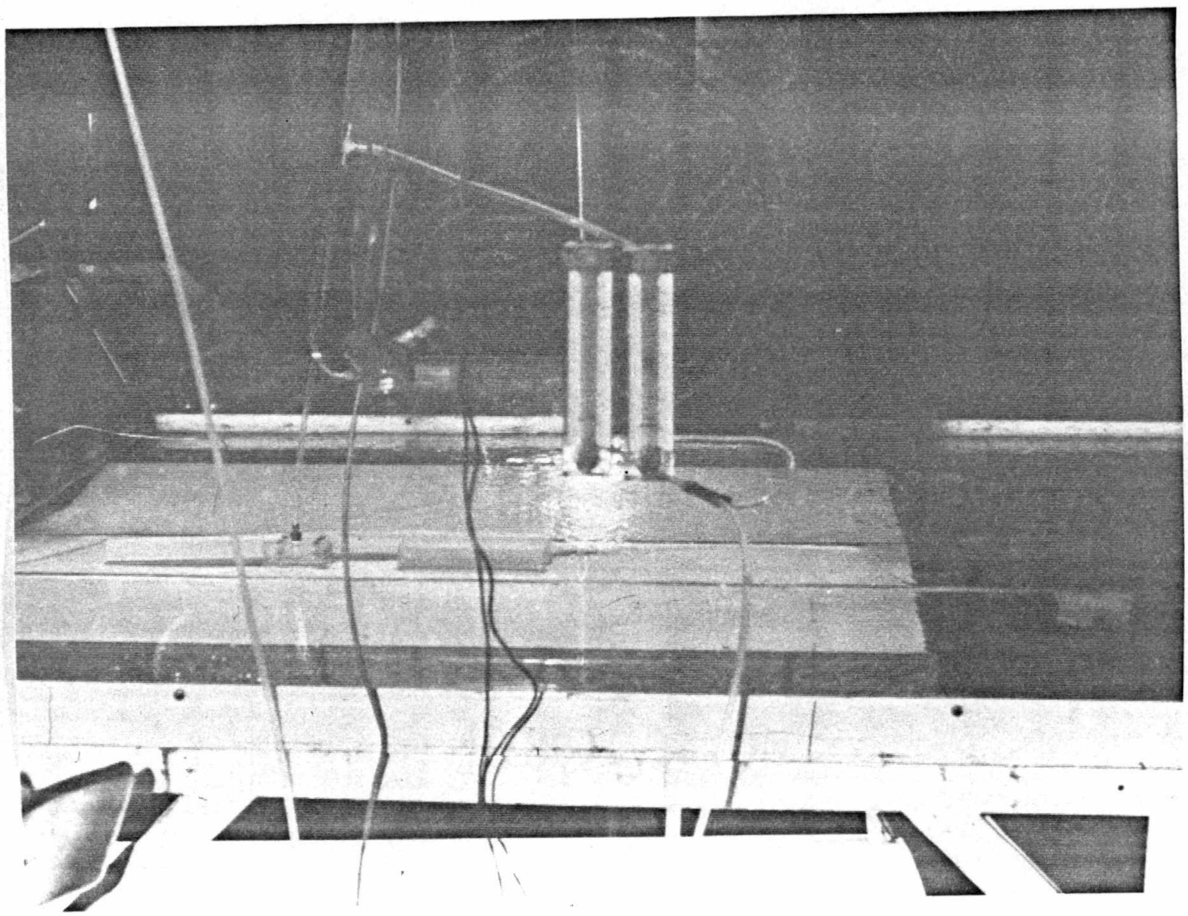


Figure 13. Pulse flow apparatus.

them will change with each cycle. If the pulsing is initiated exactly out of phase with the cavity, the oscillations will be canceled on the first cycle. With each succeeding cycle, however, the waves will drift more into phase.

After several cycles, the pulsing will reinforce the cavity oscillations, exciting them to large amplitudes. Since these large amplitude oscillations are occurring at a frequency close to the preferred mode of the cavity, they are stable. If the above explanation is correct, it should be possible to cancel the cavity oscillations for as long as desired if a feedback control system were used to lock the phase of the pulsing.

The results for steady flow through the module were not as dramatic. Dye seed runs indicated that the thickness of the shear layer at the upstream lip of the cavity was definitely increased by steady module flow. In all cases observed by the author, steady flow through the module provided some attenuation.

CHAPTER VI

CONCLUSIONS

Flow in and around the cavities with an aspect ratio in the range which represent unstable and unsteady flow have been studied. An experiment simulating two-dimensional supersonic flow over a cavity with a length to depth ratio of two has been conducted on a water table.

A qualitative analysis of the flow instabilities have been performed verifying the experimental observations. Several important conclusions have been drawn.

First, a water table can be used to simulate the supersonic flow instabilities over and in cavities.

Second, distributed steady blowing upstream of the cavity results in the thickening of the boundary layer just upstream of the cavity, which consequently becomes a thick shear layer over the cavity.

Third, as a result of thickening of the boundary layer, the characteristic instability frequency of the shear layer is altered and the interactions between the shear layer and the cavity flow is significantly decreased or completely eliminated.

Fourth, manipulation of the shear layer in the form of periodic blowing can be used to accomplish the same results as in conclusion three, or to further the level and amplitude of interaction between the shear layer and the cavity.

Finally, further work is recommended. Wind tunnel tests are needed to complement the present study and to obtain quantitative measurements needed to identify parameter ranges for design and implementation purposes.

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VITA

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