SHEAR LAYER RESONANCE

OVER OPEN CAVITIES

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PREFACE

Self-sustained shear layer oscillations over open cavities beneath a laminar boundary layer were studied experimentally. The cavities were rectangular in cross-section. The research concentrated upon determining the effects of rotating the leading edge of the cavity relative to the flow direction. The leading edge was rotated from an initial position normal to the flow direction to angles up to 30 degrees from the normal. Measurements were performed in an open return wind tunnel with freestream velocities ranging from 20 to 44 m/s. The cavity depth was fixed at 6.35 mm and the streamwise length was varied from 6.55 to 13 mm. Constant temperature hot-wire anemometers together with a dynamic signal analyzer were used to analyze the signals from the shear layer. For a particular cavity size, resonance frequency increased with increasing freestream velocity, while for a fixed freestream velocity as the cavity length was increased, the resonance frequency decreased. As the cavity was rotated, the resonance frequency gradually decreased. Due to inconsistent pattern no general relationship could be developed from the cross-correlation measurements.

I would like to express my sincere appreciation to Dr. F. W. Chambers for his invaluable suggestion, guidance and support as well as the help he provided in each phase of this study as major advisor.

Thanks are also extended to Dr. P. M. Moretti and Dr. R. L. Dougherty for serving on my advisory committee.

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NOMENCLATURE

D	cavity depth in mm
L	cavity length (width) in mm
L'	effective streamwise cavity length (L/Cosϕ) in mm
S	strouhal number (fL/U or fL'/U)
T	time delay in micro seconds
U	mean freestream velocity in direction x (m/s)
Ue	mean freestream velocity at the leading edge of cavity (m/s)
W	spanwise width of the cavity
f	frequency in Hz
n	mode of oscillation
u	convective speed of the disturbances in the cavity shear layer
x	streamwise coordinate
y	transverse coordinate
α	angle of attack in degrees
α_i	amplification factor
α_r	wave number
β	dimensionless frequency ($2\pi f\theta/U$)
$\delta(x)$	shear layer thickness at x
$\theta(x)$	shear layer momentum thickness at x
δ_0, θ_0	characteristic thicknesses at the leading edge

ϕ	angle of rotation in degrees
λ	disturbance wave length

CHAPTER I

INTRODUCTION

The phenomenon of fluid flow over cavities in flat surfaces is of significant importance because of its relevancy to many practical problems. This type of flow occurs in a wide variety of applications of which uncovered cavities on flight vehicles to house optical instruments, landing gear-wells and bomb-bays on aircraft, Helmholtz resonators, ring cavities around projectiles, slotted-wall wind tunnels, continuous laser cavities and cavities in ship hulls and on aircraft wing surfaces are only a few to be mentioned. It is important because the presence of the cavity may cause cavity oscillations which in turn may lead to structural vibration and fatigue, noise generation, drastic changes in mean drag and heat transfer of the body which houses the cavity. The cavity also produces the separated shear layer and an internal recirculating flow. The flow patterns change with changing cavity geometry.

According to Charwat et al. (1961), cavities can be divided into open and closed cavities depending on the cavity length to depth ratio and the flow pattern. For flow over open cavities the boundary layer separates at the upstream corner and reattaches near the downstream corner, while in closed cavities the separated layer reattaches at the cavity bottom and separates again ahead of the downstream wall. They also experimentally found that the dividing line between open and closed cavities at supersonic speeds and for a turbulent boundary layer as ratio of length to depth was L/D = 11. Sarohia (1977) experimentally approximated the demarcation line by L/D = 7 - 8 at low subsonic speed with laminar separation. The nomenclature used is explained in Fig. 1.

Open cavities are further classified into shallow and deep cavities. Cavities are considered shallow for L/D > 1 and deep for L/D < 1, a rough estimate based on experimental findings regarding the mechanism of oscillations produced. (Sarohia, 1977)

Depending on the mechanism of generation, cavity-type oscillations can again be classified into three categories as defined by Rockwell and Naudascher (1978). They define them as, "(a) fluid dynamic, where oscillations arise from inherent instability of the flow; (b) fluid-resonant, where oscillations are influenced by resonant wave effects (standing waves); (c) fluid-elastic, where oscillations are coupled with the motion of a solid boundary." These are represented in Fig. 2, reproduced from Rockwell and Naudascher (1978).

Because of practical importance, many experimental studies have been performed on cavity oscillations covering many different aspects of the flow. However none of these works considered the case of non-parallel flow over rectangular cavities. This report is based on the experimental investigation of resonance characteristics of a shallow, open cavity subjected to low-speed, non-parallel flow.

The following factors were investigated to determine the characteristics :

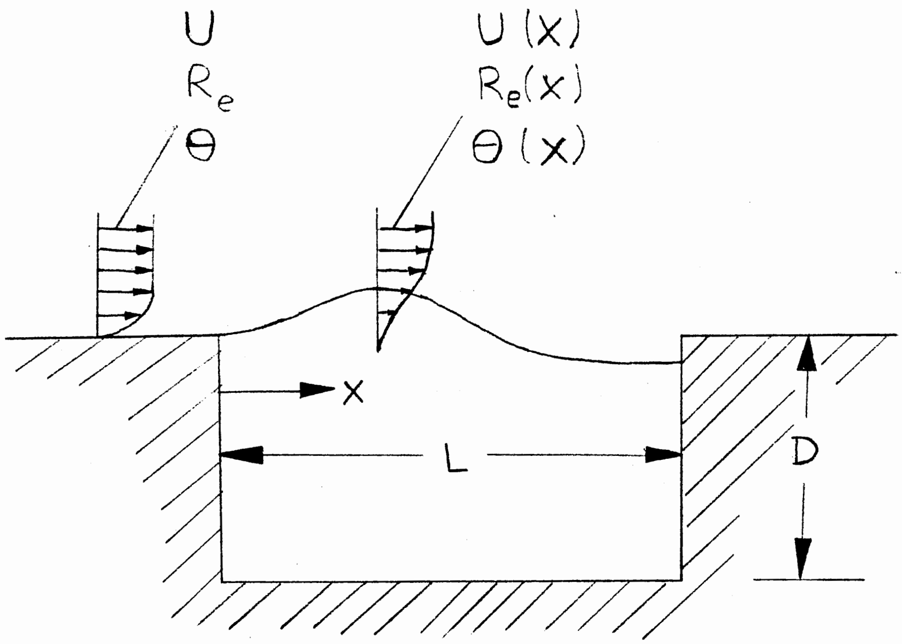

Figure 1. Schematic of separated shear layer flow over a cavity with geometrical and flow parameters

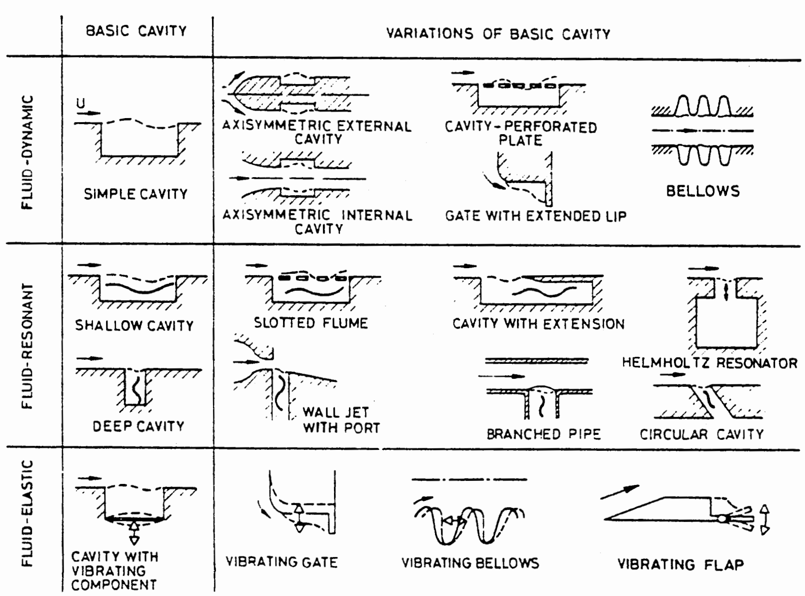

Figure 2. Classification of cavity oscillations (Rockwell and Naudascher, 1978)

1. Mean velocity profile in boundary layer at leading edge.

2. Resonance frequencies at different freestream velocities and angles of rotation.

3. Auto and cross-correlations at different spatial locations for phase measurements of the shear layer velocity fluctuations at different freestream velocities and angles of rotation.

CHAPTER II

LITERATURE REVIEW

Self-sustained oscillations occur for flow over cavities due to the instability of shear layer. Rockwell (1977) suggested that these oscillations involve feedback of a disturbance to the sensitive, initial growth region of the free shear layer. This disturbance is amplified in the streamwise direction causing large amplitude oscillations of the shear layer. Among the three types of oscillations classified earlier, only the fluid-dynamic oscillations are considered in this report. This type of oscillation is controlled by the inherent instability of the cavity shear layer and strongly enhanced by the presence of the downstream edge of the cavity. Depending on the feedback and amplification conditions, certain disturbances are amplified more than others and cause the cavity to oscillate at a resonance frequency.

Referring to Wooley and Karamcheti(1974), Komerath et al (1987) reported that "tones could be generated only at those modes where the integrated amplification was greater than unity and thus provided a criterion for tone selection." Wooley and Karamcheti (1974) described disturbances by a stream function

$$\Psi(x,y,t) = \phi(x,y)\, e^{i[\theta(x) - \omega t]}$$

where

$$\theta(x) = \int [\alpha_r(x) + i\alpha_i(x)]dx$$

is the integrated amplification factor. It was suggested that the main criterion for tone generation is to have an integrated amplification greater than unity. Sarohia (1977) reported that the onset of oscillations in a shallow cavity is accompanied by periodic shedding of vortices from the upstream corner at the frequency of cavity oscillations. But for deep cavities, when vortex shedding frequency is higher than normal mode frequency, the measured frequency approaches the normal mode value. (Buell, 1971)

In this context, one might say that for any system with m degrees of freedom, there are usually m distinct "normal modes", the frequencies of which are solely dependent on the constitution of the system. These are obtained from the analytical solution of

$$\nabla^2\phi + k^2\phi = 0$$

along with the condition $\frac{\partial\phi}{\partial n} = 0$ indicating that velocity component in the normal direction vanishes at the boundary, while the values of k determine the frequency of the respective normal modes. This happens when a wave generated in a closed system is in phase with the reflected wave; the two will reinforce each other. Consequently, there will be a buildup of energy in that mode of wave travel resulting in resonant standing waves. These standing waves are referred to as normal modes of oscillation.

Although many studies have been performed covering different aspects of the oscillation characteristics of cavities, none of those considered non-parallel flow over cavities. Consequently the literature survey has been performed on current literature available on parallel flow over cavities. From those, the most notable contributions of other researchers are discussed below.

The first extensive study on this topic was performed by Karamcheti (1955). He studied the acoustic field of two-dimensional shallow rectangular cavities of different lengths mounted in a blow-down tunnel. The range of Mach number was from 0.25 to 1.5 and schlieren and interferometric techniques were employed for observation. Hot wire anemometry was employed for measurement purposes. He observed that a minimum cavity length is required for the onset of cavity oscillations for a given freestream Mach number and depth. Later Gharib and Roshko (1987) explained that below this minimum width, "the shear layer smoothly bridges over the cavity with no distinct oscillation in it." It was also observed that some combinations of Mach number and cavity length gave rise to two intermittent frequencies. That is, the frequency jumped between two resonant conditions.

Numerous investigations have been made regarding the effects of Mach number on non-dimensional frequency for both laminar and turbulent boundary layers. On the basis of observation of high speed shadowgraphs of cavity oscillations, Rossiter (1966) derived a formula to predict the oscillation frequency. He performed the tests with subsonic and transonic flow ($0.4 < M < 1.2$) over shallow rectangular cavities. This formula is given by

$$S = \frac{fL}{U} = \frac{n - \alpha}{\frac{1}{k_v} + M} \tag{1}$$

where k_V is the vortex convection speed as a fraction of the freestream velocity U, M is freestream Mach number, α is a constant, and n = 1,2,3 etc The mode of oscillation is defined as the value of n.

Rossiter (1966) assumed that the variations in phase difference between pressures along the shear layer with Mach number were due to variations in cavity temperature and hence sound speed. He also assumed that the vortices shed from the upstream cavity corner are convected at a constant phase velocity through the shear layer, resulting in linear phase distribution. The phase velocity of these vortices is independent of the cavity geometry and flow configuration. He observed the principal source of acoustic radiation being located near the trailing edge, which can be effectively suppressed by adding a small spoiler at the trailing edge. However, Rossiter's formula does not predict the mode or modes in which the cavity is most likely to oscillate.

Rossiter's formula was correlated with numerous experimental results obtained from the investigations of Heller et al. (1971). They studied a variable-depth rectangular cavity (length-to-depth ratios from 4 to 7) in the Mach number range from 0.8 to 3. The formula was found to hold well at Mach numbers 0.8 and 1.5, poorly at Mach number 2, and worse at Mach number 3 with α = 0.25 and k_V = 0.57.

They noticed that one poor asumption made by Rossiter was a zero cavity recovery factor, i.e. the speed of sound in the cavity was assumed to be equal to the freestream speed of sound. Though this assumption introduced only a small error at low Mach numbers, the error was much greater at higher Mach numbers. Their experimental results indicated a recovery factor close to unity (0.8 - 0.95) rather than to zero. Hence, they modified Rossiter's formula for higher Mach number range assuming the cavity sound speed to be equal to the freestream stagnation sound speed. The improved formula is

$$S = \frac{n - \alpha}{\left\{ \frac{M}{\left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{1}{2}}} + \frac{1}{k_v} \right\}} \tag{2}$$

and n = 1,2,3, . . . etc.

with the restriction of its application to shallow cavities only. The comparison of the two formulae are given in Fig. 3 reproduced from Heller et al. (1971).

Ungar et al. (1977) used Rossiter's modified formula given by Heller et al. (1971) to correlate with their experimental results. Their observation was, "Oscillations begin to appear at low Mach numbers and become most intense slightly above M=1; at very high Mach numbers, say M > 3, the oscillations are often found to decrease." Their results indicate that the modified formula matches best for M > 0.5.

They also reported that for low Mach numbers, the oscillation frequencies for deep cavities (L/D < 2) could be well predicted by

$$f = \left(\frac{2n - 1}{4}\right)\left(\frac{C}{D}\right) \tag{3}$$

with n = 1,2,3, . . . etc.

where C denotes the speed of sound in air.

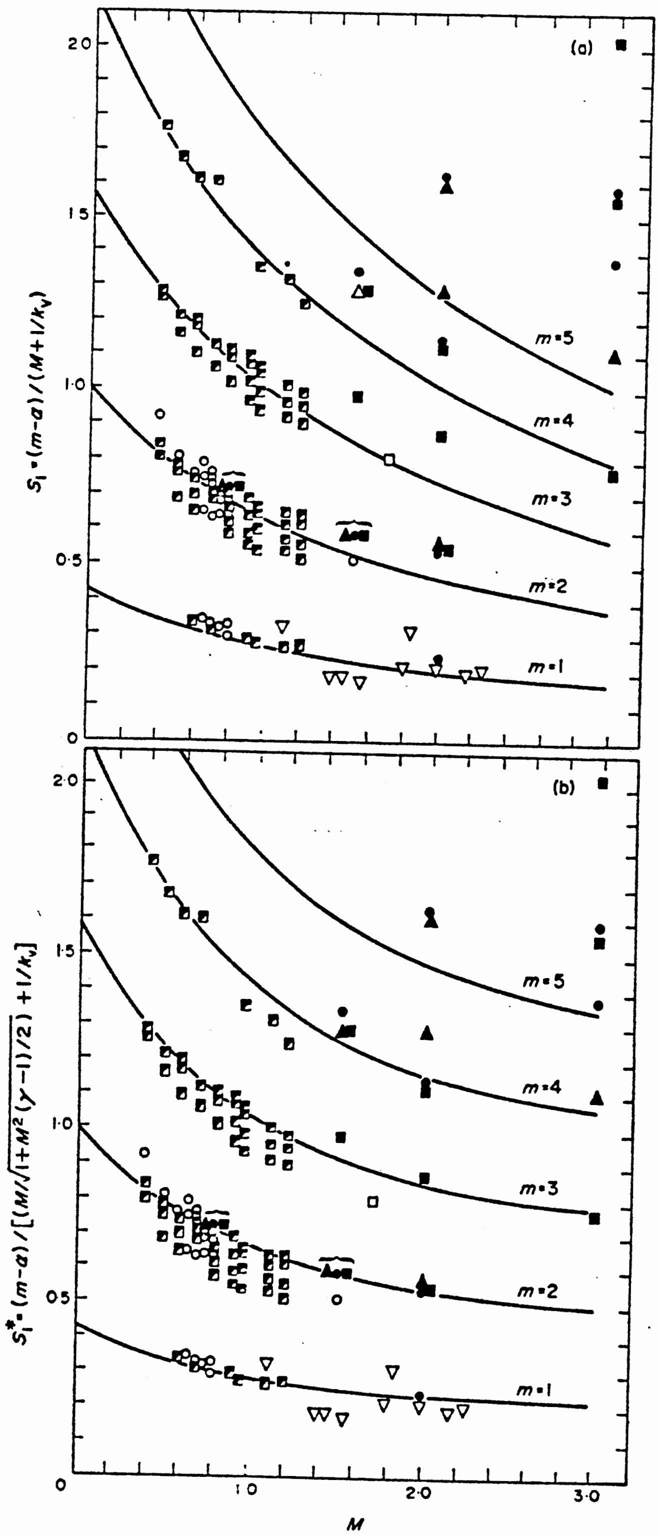

Figure 3. Non-dimensional frequencies as a function of Mach number. (a) Rossiter's formula; (b) Modification of Rossiter's formula. ■ , L/D=4; ▲ , L/D=5.7; ● , L/D=7; ○, Krishnamurty; ◩ , Rossiter; ▽ , White; m=mode of oscillation (Heller et al.,1971)

Deviations from the above equation at higher Mach numbers were attributed to the shear layer over the cavity mouth which might cause an effective stiffening effect at the open end.

Heller and Bliss (1975) suggested that for cavities which are neither shallow nor deep ($1.0 < L/D < 2.0$), frequency prediction is difficult and the occurrence of "shallow" or "deep" cavity behavior depends on Mach number with increasing Mach number tending to make cavities effectively more shallow.

Hence Rockwell and Naudascher (1978) reported that "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 been adequately predicted."

Komerath et al.'s (1987) review indicated that the oscillation frequencies corresponding to the different modes usually are not integral multiples of the frequency of the lowest mode. Generally the values of Strouhal numbers are in bands, the first around 0.6, the second from 0.8 to 1.3, the third from 1.3 to 1.6 and so on (Sarohia, 1977).

They also reported that a predominant frequency is often observed. Rockwell and Naudascher (1978) said that Rossiter investigated the concept of a predominant mode of shallow cavity oscillation. His results are reproduced in Fig. 4 from Rockwell and Naudascher (1978). Referring to Karamcheti (1955), Komerath et al. (1987) said that this is more usual for a laminar boundary layer. For an explanation, they also reported that, "Wooley and Karamcheti, in their study of edgetone generation, have shown that the dominant

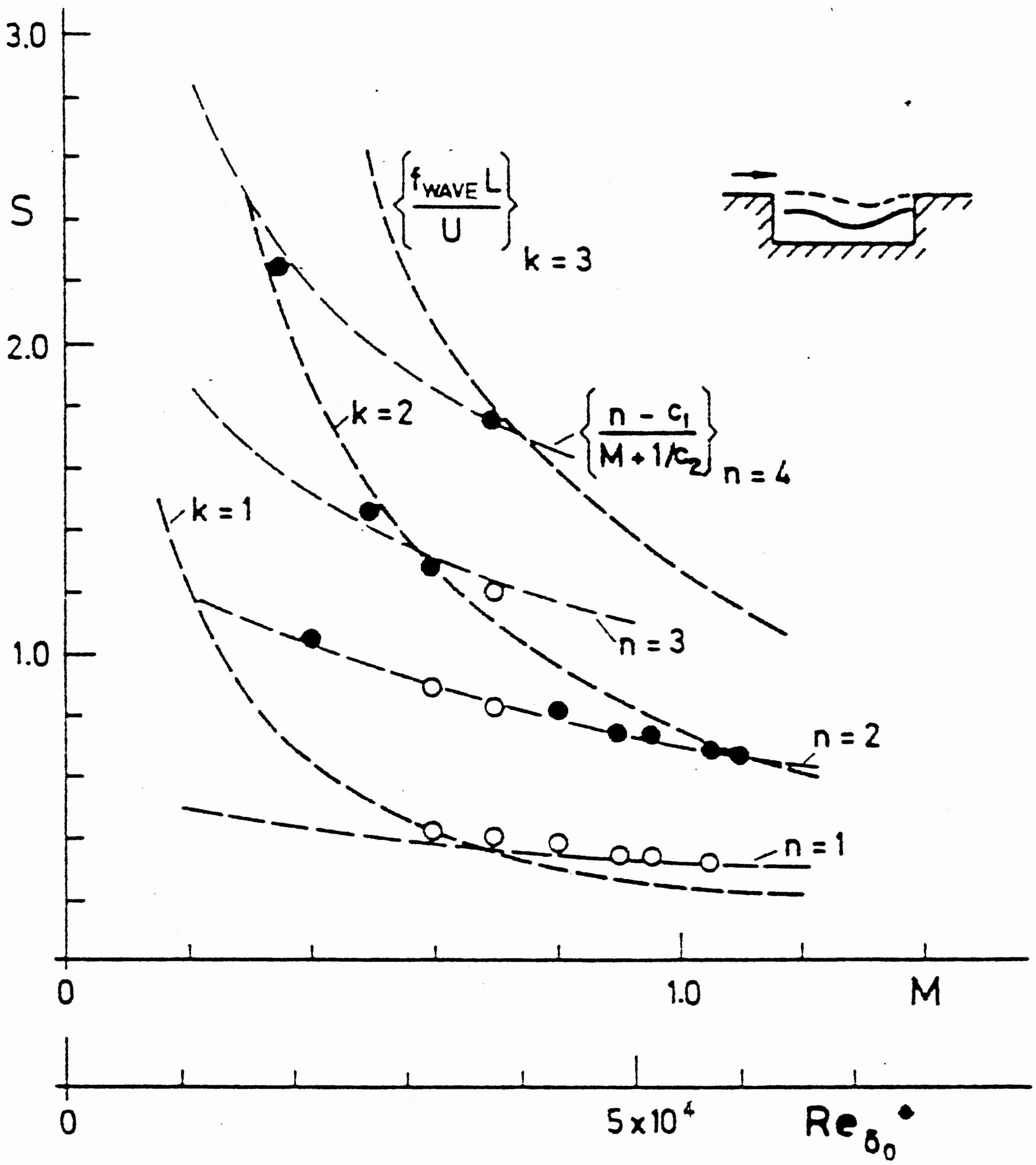

Figure 4. Variation of Strouhal number for flow past a shallow cavity. Dark circles represent amplitudes of predominant modes k=cavity resonance mode, n=semiempirical mode (Rockwell and Naudascher, 1978)

frequency should correspond to the mode receiving the largest integrated amplification. In the absence of any other knowledge of the flowfield, the safest prediction is that the second mode, corresponding to a Strouhal number based on cavity length of approximately 1, is likeliest to be the predominant one. However, the first mode, corresponding to a Strouhal number of approximately 0.5, is likely to be the loudest, if it occurs."

However, Tam and Block (1978) reported that over most of the Mach number range ($M > 0.2$), only one discrete frequency (excluding harmonics) was found for deep cavities. A completely different type of dependence of the Strouhal number was found for $M < 0.2$ which they attributed to tones that are generated by the normal mode resonance mechanism instead of the feedback mechanism. A similar conclusion was drawn by Buell (1971).

From experimental evidence, it has been established that a combination of different parameters (i.e. cavity size and freestream Mach number) are to be satisfied for the onset of cavity oscillations. Covert (1970) analytically showed that there exists a critical value of velocity when the frequency of excitation closely corresponds to the natural frequency without external convection, below which the cavity will not oscillate. His analysis also indicates a constant Strouhal number at the onset of instability. Both results were justified by experimental evidence. However, one limitation of his analysis is its failure to indicate the process by which the oscillations stop at higher velocities.

As most researchers tried to predict oscillation frequency for a given cavity geometry and freestream Mach number, Parthasarathy et al. (1985) investigated using a completely opposite approach. They tried to optimize geometric and aerodynamic parameters to generate some discrete frequencies. The tests were conducted at low Mach number range from 0.12 to 0.24 for deep cylindrical cavities in a flat surface. Using their experimental data for curve fitting, they deduced the following simple relation to determine the resonant frequency given by

$$f = \frac{C}{\{4(1-M)(D+d)\}} \quad (4)$$

where D is the depth, d is the diameter of the cavity and M is the freestream Mach number. The results also indicated multiple peaks of the resonance curve which is consistent with East's results for a rectangular cavity with variable depth as reported by Parthasarathy et al.

Almost all the papers considered so far discussed only high speed flows in the range of moderate subsonic to high supersonic Mach numbers. Sarohia (1977) investigated laminar axisymmetric flows at low subsonic Mach numbers for both variable depth and width of the shallow cavity. Hot wire anemometry, correlation analysis and flow visualization techniques were employed for observation. He reported that cavity oscillation is practically independent of depth unless it is of the order of boundary layer thickness ($D/\delta_0 = O(1)$) of cavity shear flow. This condition delayed the transition of the free laminar shear-layer flow to a turbulent one. He also observed that for a fixed cavity depth and freestream Mach number, as the width was increased oscillations jumped to a higher mode, and at a critical value ($L/\delta_0 =$ 8.15), the two modes occurred alternately but never simultaneously.

According to Buell (1971), this was caused by the increasing difference between shedding and normal mode frequencies which diminished the response amplitude, and finally resulted in a different mode.

Several authors have reported the dependency of oscillation characteristics on shear layer thickness and its growth rate. As the shear layer grows while passing over the mouth of a cavity, characteristic shear layer thicknesses (i.e. δ, δ^*, θ) also increase. Heller and Bliss (1975) reported that for a turbulent shear layer with subsonic flow, this thickness can grow from a small initial value to 20% of the streamwise distance from the cavity leading edge. Rockwell (1977) suggested that momentum thickness growth rate ($\theta(x)$) depends on the time mean Reynolds number, possible turbulent shear stress across the boundary layer, and cavity geometry at and downstream of the shear layer separation as shown in Fig.1. Using a linear growth rate approach he found that an increase in growth rate decreases the predicted value of cavity length required for oscillation. The effects were more severe for higher modes of oscillation. However, the trend was completely opposite for short cavities (i.e. high frequencies) which he attributed to severe decrease in amplification factor in the streamwise direction.

Karamcheti (1955) conducted experiments for both laminar and turbulent boundary layers. He reported that, "While in the laminar case only a single dominant frequency was observed at a given gap width and Mach number, in the turbulent case two frequencies of nearly equal strength were recorded. The higher of these frequencies was nearly twice the other."

Sarohia (1977) experimentally found that the shear layer grows almost linearly in all modes of cavity oscillation. No abrupt increase in growth rate was noticed for increasing cavity width as the cavity flow switched from one mode of oscillation to another. An increase in shear layer thickness at the upstream cavity corner delayed the onset of cavity oscillations. Then comparing with East's results, Sarohia concluded that for a given mode of cavity oscillation, the non-dimensional frequency (Strouhal number) is lower for a turbulent boundary layer separation than for a laminar one.

Cross-correlation of hot-wire signals at different spatial locations in the cavity is the most common technique employed for phase measurements of the shear layer velocity fluctuations. Sarohia (1977) found that at a fixed location as one moves toward the cavity from outside (x/δ_0 = constant), the phase $\psi/2\pi$ (measured in terms of wavelength) decreases until a sharp drop occurs. But further inside the cavity, the phase of the disturbance increased. The phenomenon is clearly shown in Fig. 5.

Gharib and Roshko (1987) suggested that by traversing one probe along the shear layer while keeping the other fixed at one edge it is possible to determine the wavelength and hence the phase velocity u ($u = \lambda f$), since the oscillating frequency is already known. They also presented the following relations

$$\frac{\Psi}{2\pi} = \frac{L}{\lambda} = \frac{fL}{u} = n$$

where n is the number of wavelengths of fundamental frequency contained by the cavity width in the nth mode of oscillation.

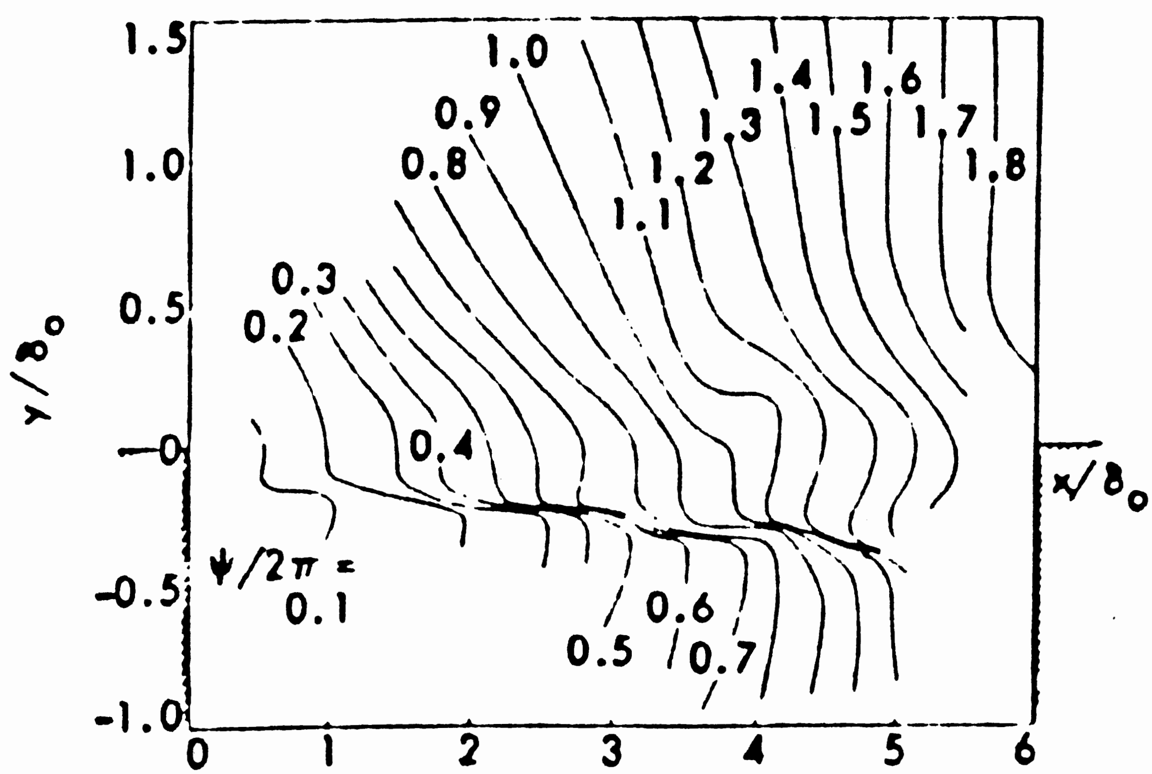

Figure 5. Effect of flow parameters on phase measurement

However, these relations do not hold well as the cavity switches from one mode to another. They also mentioned that the relations are valid for incompressible flow only.

Sarohia gave another approximate integral relation $L/\lambda = (n+1/2)$ where n depends on the mode of cavity oscillation. Another important finding was that as cavity width was increased, the wavelength increased and the frequency dropped; but the phase velocity ($u = \lambda f$) increased steadily without any discontinuity as the oscillation switched modes.

These papers suggest that if the oscillation frequency is known one can calculate the mode of oscillation using Rossiter's modified formula and determine the wavelength and phase difference of the signal from cross-correlation measurements. These parameters could be used to calculate the velocity of the propagating disturbance.

Another important aspect of this type of flow is the measurement of cavity drag. McGregor and White (1970) reported a 250% increase in drag for subsonic internal flow due to cavity oscillations. Also the compressibility effect at high Mach numbers and viscosity effect of real fluids are important. However, these are not discussed in detail as they are beyond the scope of the present investigation.

Thus the literature review contains many results for rectangular cavities subjected to parallel flow. The literature also shows that one can predict frequency using the different formulae provided by different researchers [Rossiter (1966), Heller et al. (1971)] depending on geometric configuration of cavity (shallow or deep) and freestream Mach number. One can also perform measurements to determine the phase difference, wavelength and phase velocity as suggested by Gharib and Roshko (1987). For rectangular cavities in non-parallel flow situations, the literature does not provide experimental results or prediction method. Nor have the above mentioned methods been applied to such cases.

The primary objective in the present case is to be able to predict the different parameters (frequency, wavelength, phase velocity) for non-parallel flow situations. As the cavity is rotated from its axis, the streamwise length of the cavity changes according to $L' = L/\cos\phi$. As mentioned in the beginning, these oscillations involve feedback of a disturbance from the downstream edge of the cavity to the sensitive leading edge. This feedback thus is dependent on the path or cavity length it travels. From the fluid dynamic standpoint, the streamwise length may be assumed to be a significant governing parameter. The pressure wave feedback is not so clearly dependent upon this length. It is expected that as a first approximation, the relations for parallel flow situation will still hold if the effective streamwise length of the cavity is substituted for the actual cavity length.

CHAPTER III

EXPERIMENTAL SET-UP AND PROCEDURE

In the present study, a rectangular model was made from 6.35 mm. aluminium plates. The model had an arrangement for a fixed depth, D, and a continuously varying length, L. The nose of the model was of round shape to avoid flow separation. However, this was not sufficient to resonate the cavity as flow visualization revealed that the flow separated well before it reached the leading edge of the cavity. So the leading edge had to be tilted in the downward direction to avoid flow separation. By trial and error the cavity was found to resonate at an angle of attack of 13 degrees, as measured by a level protractor with an accuracy of 0.5 degrees. Hence throughout the whole experiment, this angle was maintained constant, including cases with rotation. A schematic of the set-up is presented in Fig. 6.

The depth and width of the model were fixed at 6.35 mm and 101.6 mm respectively and the length could be varied continuously from 6.5 mm. to 35 mm. The length could be measured up to an accuracy of 0.0254 mm. To analyze the cavity flow, hot-wire probes were inserted from outside into the shear layer both at the leading and trailing edges. These probes were fixed at particular locations (x = 0 mm and 6.55 mm and y = 1 mm) of the cavity. A schematic of this arrangement is presented in Fig. 7.

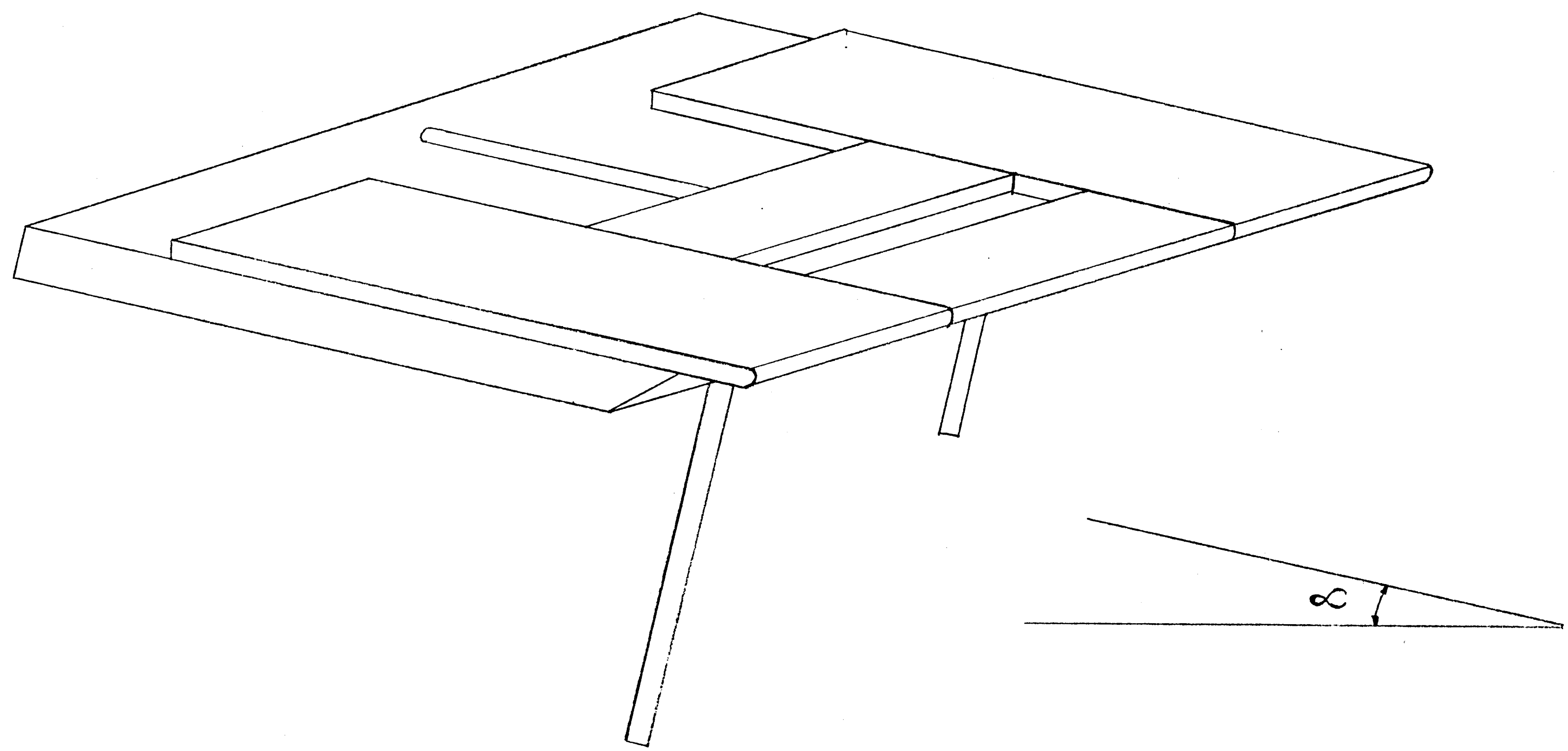

Figure 6. Schematic of the experimental set-up

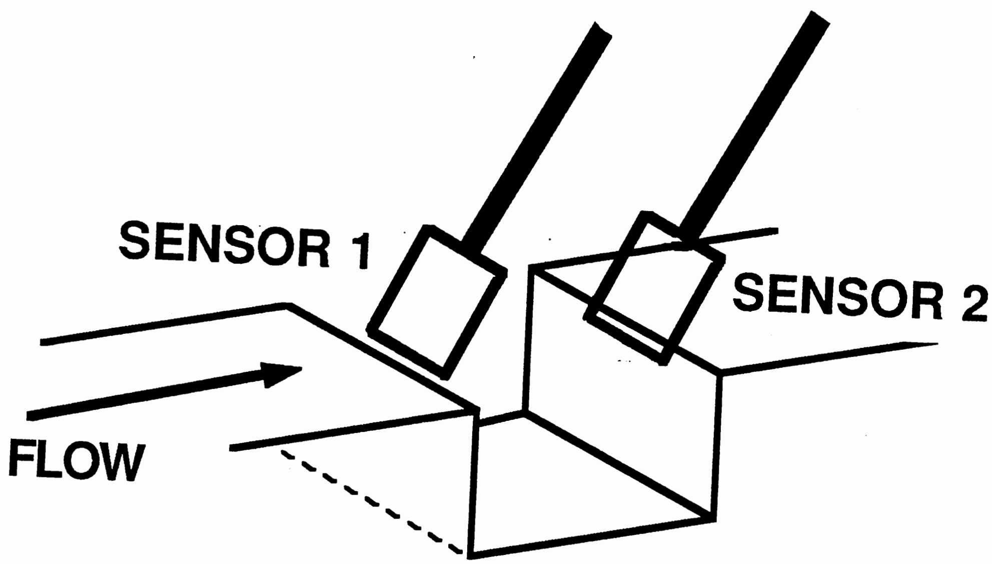

Figure 7. Schematic of the cavity showing cross-correlation technique.

To measure the velocity profile, a hot-wire probe was installed at the leading edge of the cavity which could be moved with 0.0254 mm accuracy across the shear layer. Measurements were made at an interval of 0.127 mm with a sampling frequency of 2000 samples per second and a record length of 5000 samples.

Constant temperature hot-wire anemometry was used to measure both mean and fluctuating velocity components in streamwise direction. Measurements were made by data acquisition through a 12-bit A/D converter (Metrabyte model DAS-16G1) and a 386-33 MHz IBM compatible personal computer. Frequency spectrum measurements were made using both a Spectral Dynamics SD 345 spectrum analyzer and a HP 35665A two channel dynamic signal analyzer. Cross-correlation measurements were made through the two channel dynamic signal analyzer. The output of the power spectrum and cross-correlation measurements were displayed on the screen and printed.

For all measurement purposes the set-up was AC coupled. For frequency measurements, the instrument range was fixed from 0 to 10 (12.8 in HP 35665A) KHz and an average of 50 samples were taken giving a total record length of 1.562 seconds (HP 35665A). Measurements were made both for leading and trailing edge probes simultaneously to ensure consistency of measurements using the dynamic signal analyzer.

In cross-correlation measurements, the phase difference was measured in terms of time delay. The instrument range was from 0 ms to 3.9 ms and an average of 100 samples were taken giving a total record length of 0.7812 seconds. To avoid wrap around error, a correlation weighing function was chosen which suppresses the first and last quarter of the time record, and passes the center part of the time record. This is required to avoid amplitude inaccuracies in cross-correlation measurements. Also the signals were constantly monitored through an oscilloscope. The flow was found to be intermittently turbulent with comparatively higher turbulence intensities at lower speeds. Flow visualization techniques, using tufts and surface oil flows were employed to ensure that the flow remained unseparated until it reached the leading edge of the cavity.

CHAPTER IV

RESULTS

The resonant condition was achieved by tilting the set-up downward, giving an angle of attack of 13 degrees. This ensured a laminar boundary layer with intermittent turbulence and it remained unseparated until the leading edge of the cavity. This condition was chosen after a series of diagonostic tests.

It was experimentally observed that for a given set of flow conditions, a minimum cavity length is necessary for the onset of cavity oscillation. As reported by other researchers, it was also observed that for a given cavity, there exists a minimum velocity below which no cavity oscillation occurs. However, no demarcation line was determined, as this was not the main objective.

The resonance characteristics of a shallow, rectangular cavity subjected to non-parallel flow were investigated in detail in the present study. Fig. 8 shows typical power spectrum measurements as observed on HP 35665A screen. The spectra were formed from the signals of hot wire anemometer probes located at 0 mm and 6.55 mm positions at a vertical distance of approximately 1 mm above the plate. The upper half shows a distinct resonant peak (7456 Hz) at the leading edge. The lower half shows a resonant peak (7456 Hz) at the trailing edge. Measurements were made at both ends to check

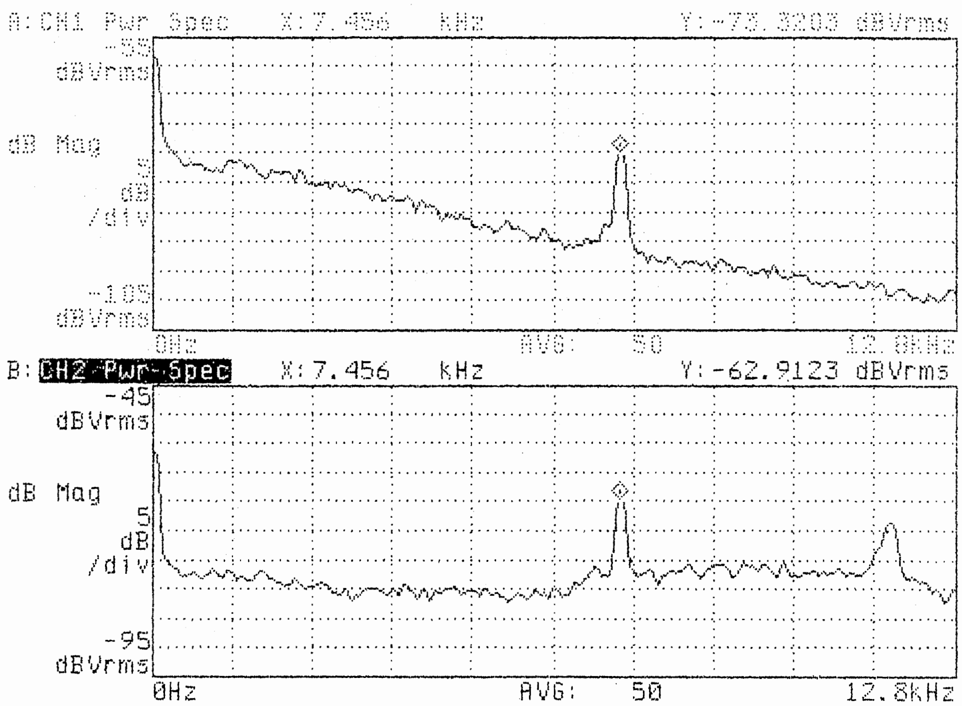

Figure 8. A typical power spectrum measurement

consistency of results. The resonance frequency of the hot-wire signal was determined from the spectra measured by fast Fourier transform (FFT) analysis. This was non-dimensionalized by converting it into Strouhal number (S=fL/U) and was plotted against non-dimensional width (L/θ) of the cavity.

Considering flow over an inclined plate, the Falkner-Skan solution was used to calculate the estimated momentum thickness, which was very thin and difficult to measure. Details of the solution are presented in Appendix B. The Falkner-Skan flow is a boundary layer similarity solution assuming the freestream velocity over the plate $U(x) = Kx^{m/(2-m)}$, where K is a constant. The parameter m is a measure of the pressure gradient, with a positive m indicating a favorable pressure gradient. However, the experimental flow was not rigorously compared to this solution.

Measurements were made both for fixed cavity lengths (7 to 13 mm) and for fixed free-stream velocities (20 to 44 m/s). For a given cavity size, resonance frequency was found to increase with increasing freestream velocity. On the other hand, for a fixed speed of the freestream the resonance frequency decreased as the cavity length was increased. This phenomenon can be observed from Fig. 9. Also, as the cavity was rotated from its axis, the resonance frequency dropped gradually. These results are presented in Fig. 10 and 11 in non-dimensional form. In Fig. 10 absolute cavity length L was used, while in Fig. 11, L was replaced by effective streamwise length $L' = L/\text{Cos}\phi$. In Fig. 11 first mode of oscillation occurred at a non-dimensional frequency about 0.9 which slowly increased with increasing L/θ. At a value of L/θ = 49.8, the oscillation jumped to the

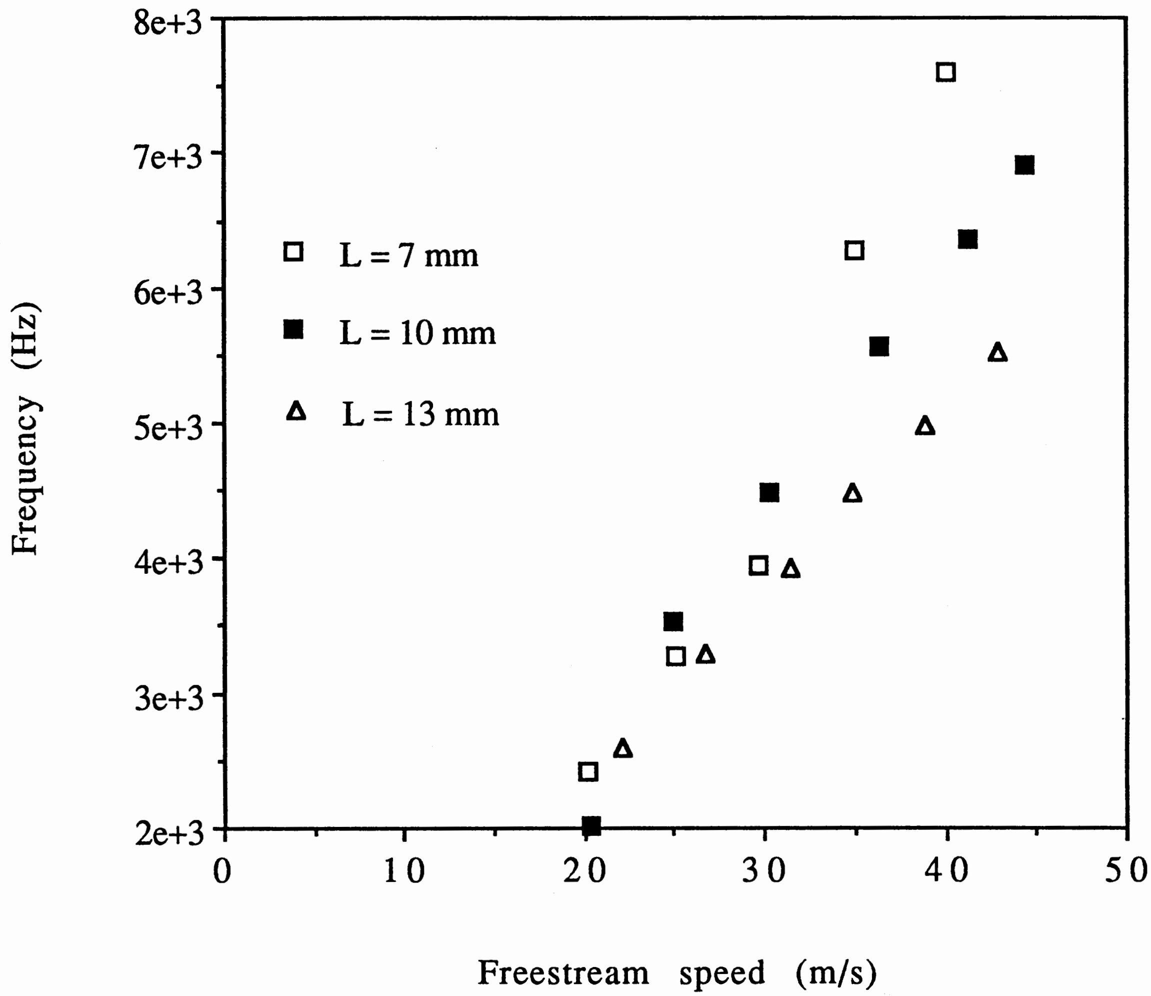

Figure 9. Dependence of frequency on cavity lengths

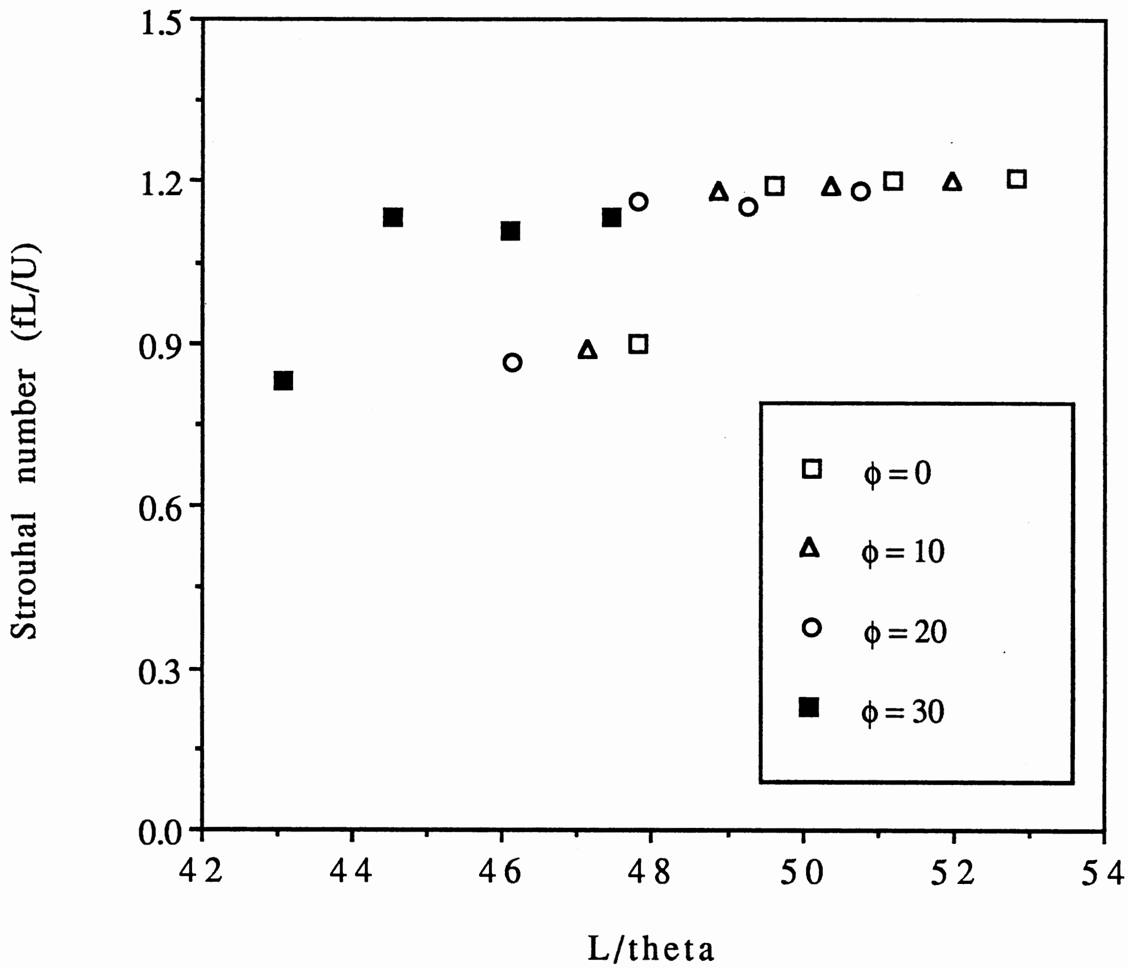

Figure 10. Effect of length on non-dimensional frequency

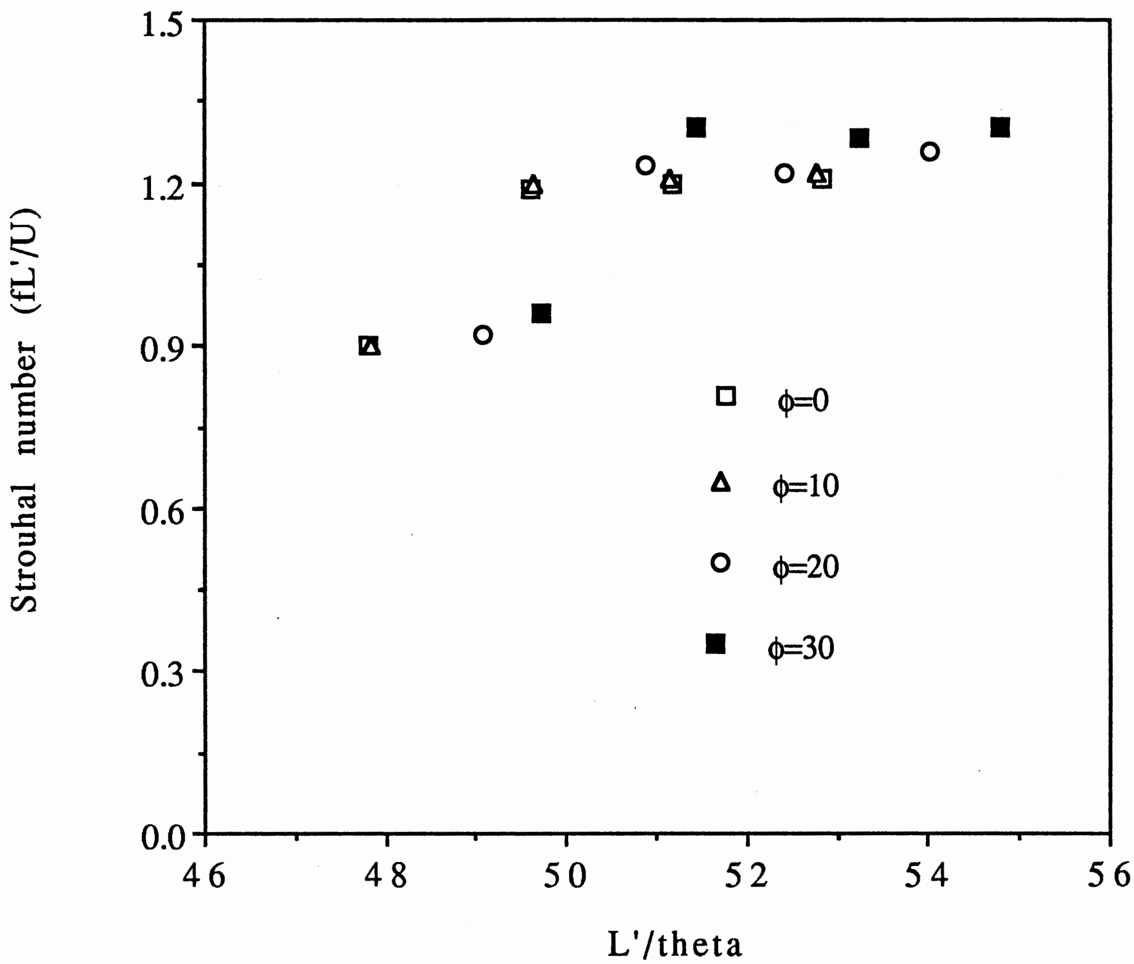

Figure 11. Effect of streamwise length on non-dimensional frequency

second mode and the cavity was found to oscillate at a Strouhal number of about 1.2. The oscillation mode was determined from the simple relation $n=L/\lambda$, while the method of computing λ is described in the following paragraphs.

Figure 12 shows the variation in frequency with the angle of rotation for different freestream speeds. For a given speed the frequency dropped with increasing angle.

Phase difference and wavelength of the propagating disturbance were measured by cross-correlating the hot-wire signals at two different spatial locations in the cavity. Measurements were made for a fixed cavity size (L = 6.55 mm) but for freestream speeds ranging from 35 to 44 m/s and for angles of rotation ranging from 0 to 30 degrees.

The phase difference was measured in terms of time delays observable as absolute maxima in the cross-correlation measurements. Figure 13 and 14 shows two typical cross-correlation measurements. In Fig. 13 a distinct peak is observable indicating the time delay. Fig. 14 shows multiple peaks which was common to most of the cases during the experiments. Since one could not arbitrarily choose the proper peak, several peaks were used to calculate the different parameters. Since the delay T was known, hence the convective velocity $u = L'/T$ could be computed. Also from the measured oscillating frequency f, wavelength λ was computed from $u = \lambda f$. Though the exact reasons for multiple peaks could not be determined, the presence of intermittent turbulence in the boundary layer flow ahead of the cavity and vibration of the set-up are possible causes.

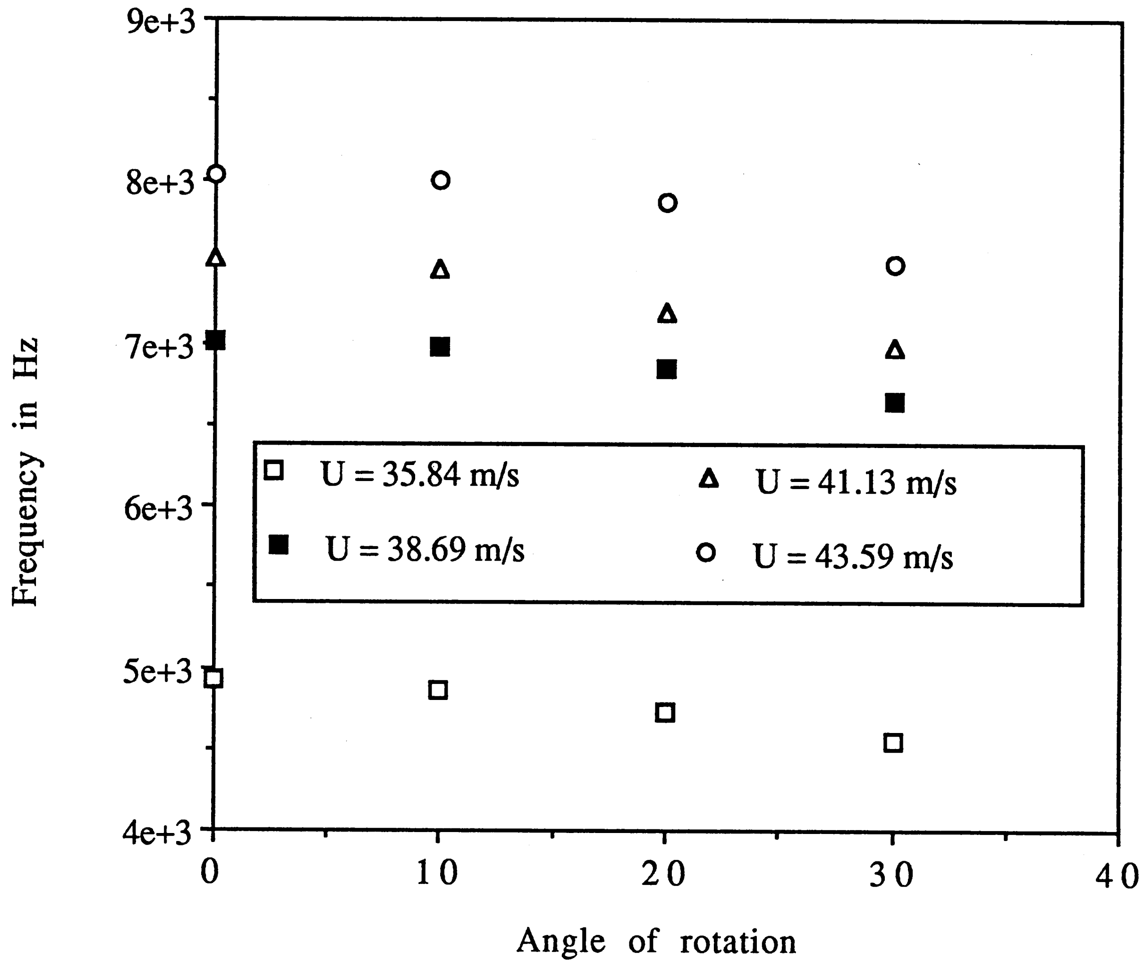

Figure 12. Effect of angle of rotation on frequency

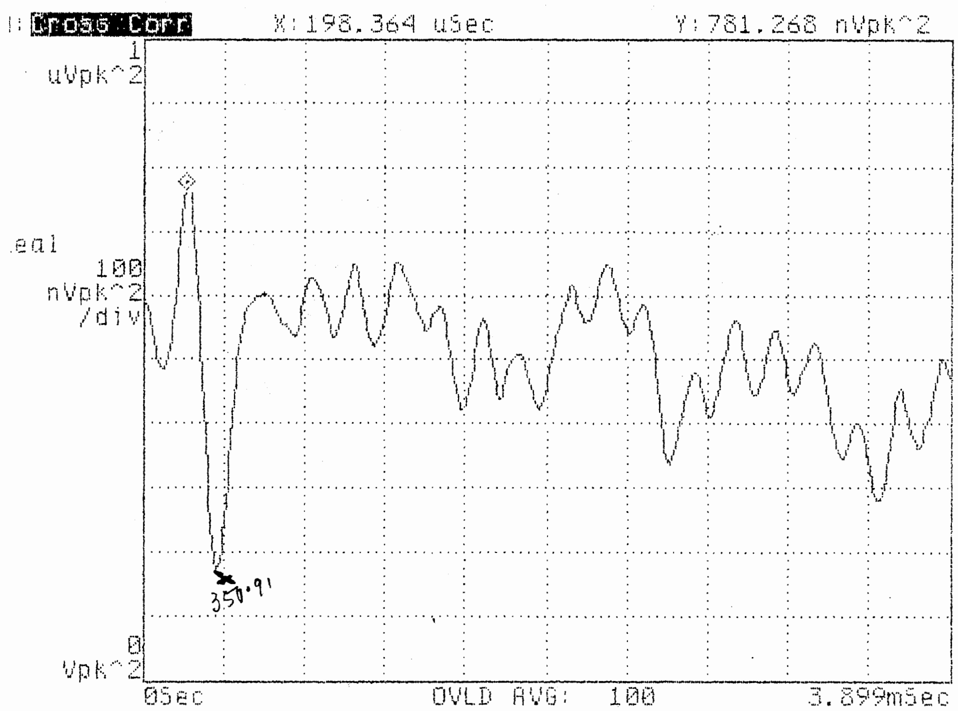

Figure 13. A typical cross-correlation measurement - ideal case

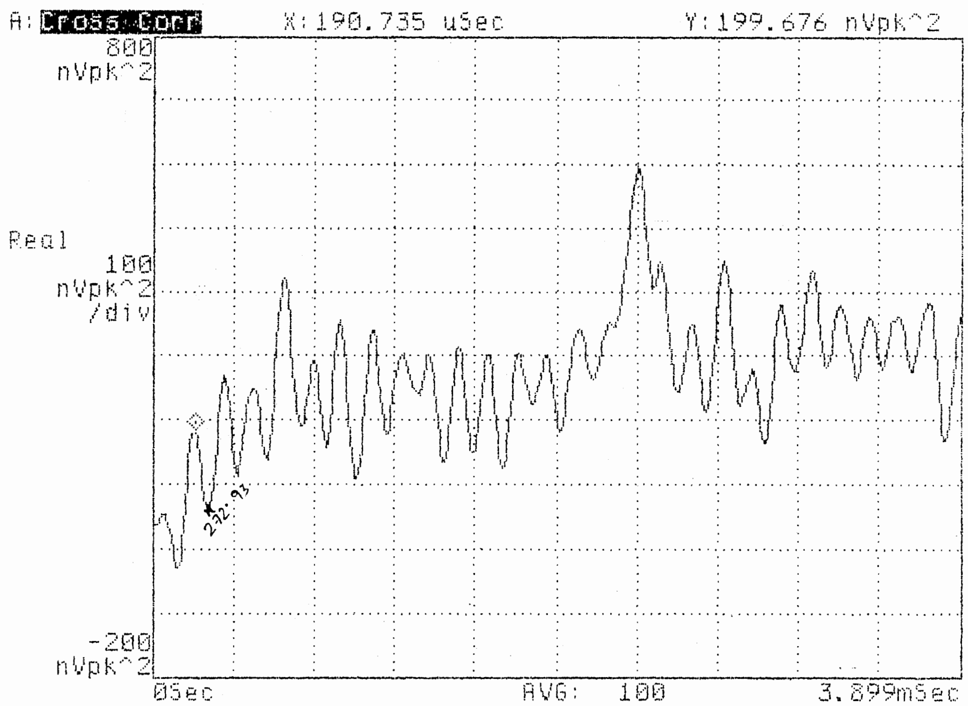

Figure 14. A typical cross-correlation measurement - worse case

Cross-correlation measurements were also performed using a longer recording length of 1 second, instead of 7.812 ms. An average of 50 samples were taken and the output is presented in Fig. 15. It indicates a sinusoidal frequency of 20 Hz which remained constant throughout the experiment and matched the constant wind tunnel blower shaft rpm (1200). So it was independent of the freestream speed. These low frequency oscillations resulted in waviness observed in short time correlation measurements.

The effect of angle of rotation on convective velocity for different freestream speeds is presented in Fig. 16. Measurements did not indicate any consistent pattern of dependency of the convective velocity on either parameter.

From Fig. 17 to Fig. 20, the variations in calculated convective velocity for a given set of flow conditions are presented as the cavity was rotated from 0 to 30 degrees. These ranges in the convective velocity result from using all of the multiple peaks in the cross-correlations in calculating the convective velocity. No arbitrary judgement was made as to which was the "true" peak. Other researchers observed the ratio u/U to vary from 0.4 to 0.6. In the present study the different peaks yielded values from 0.3 to 0.9.

Figure 21 represents attempts to measure velocity profile at the leading edge of the cavity. These measurements were made for two different freestream velocities. Using the Falkner-Skan solution, the boundary layer thickness was estimated to be slightly less than 1 mm (0.04 in.) for the higher velocity case and over 1 mm for the lower velocity case. The profile indicates that for the higher velocity case, freestream speed was attained at a height of about 0.8 mm

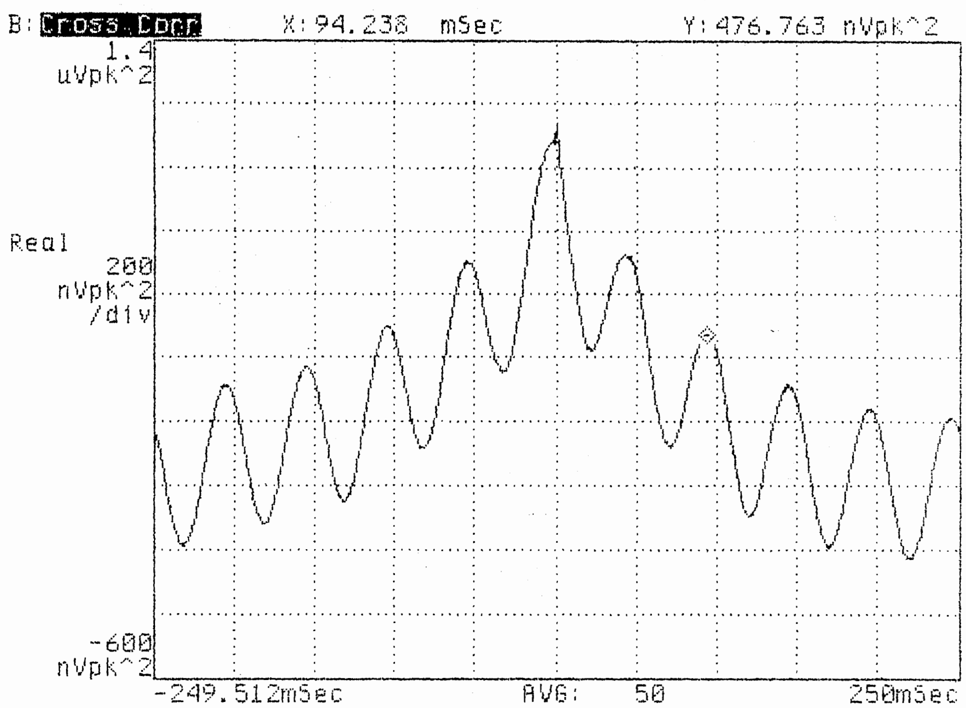

Figure 15. Cross correlation measurement with long time record

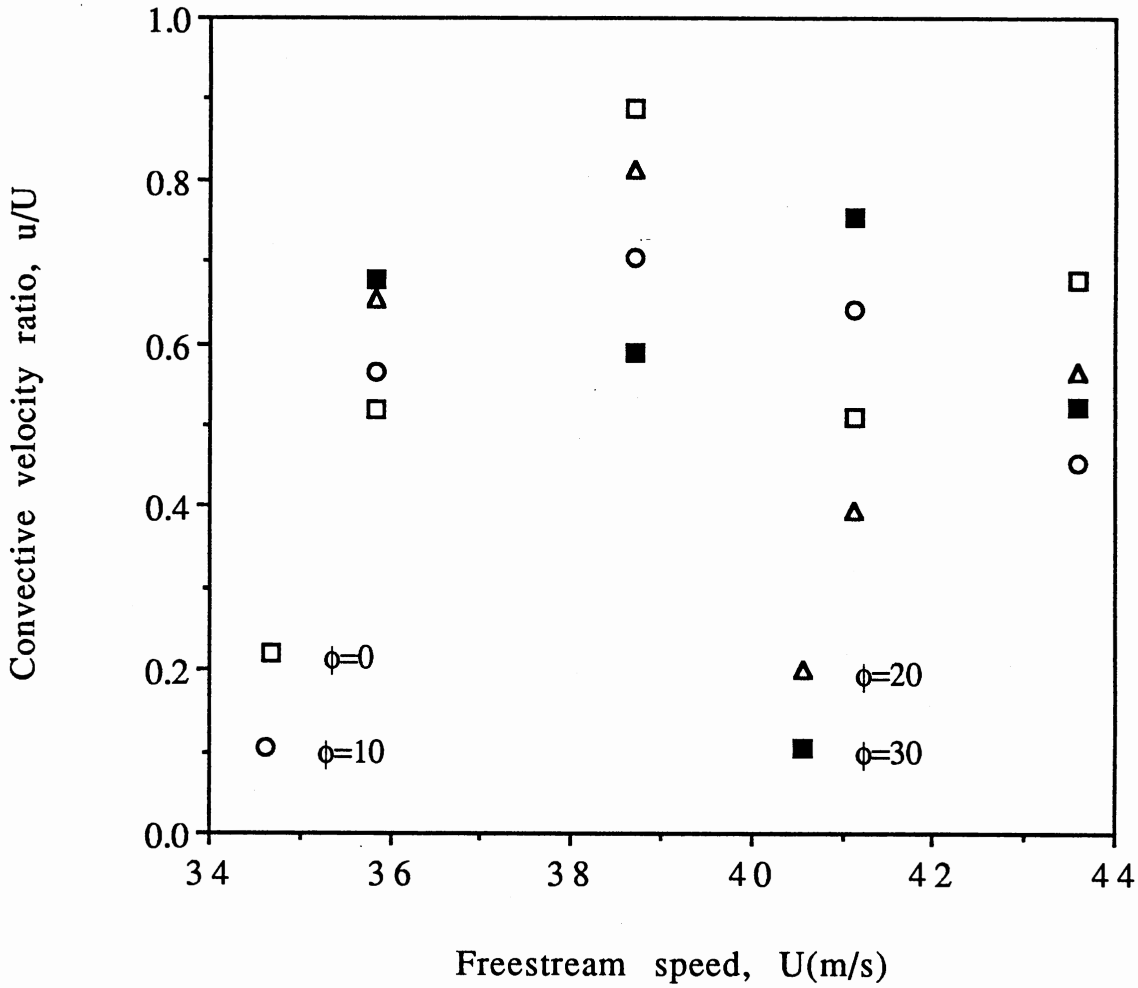

Figure 16. Effect of angle of rotation on convective velocity

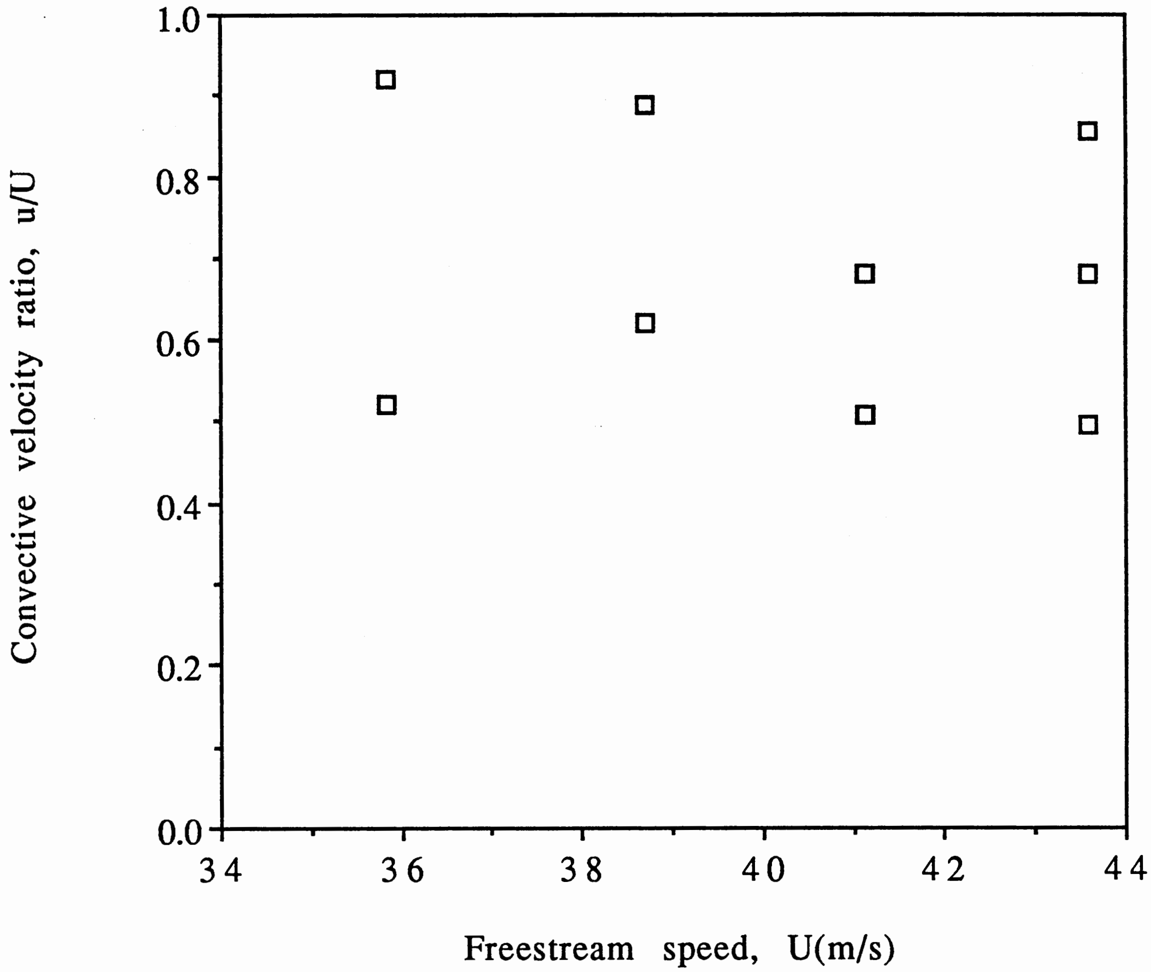

Figure 17. Dependence of convective velocity on freestream speed at phi=0

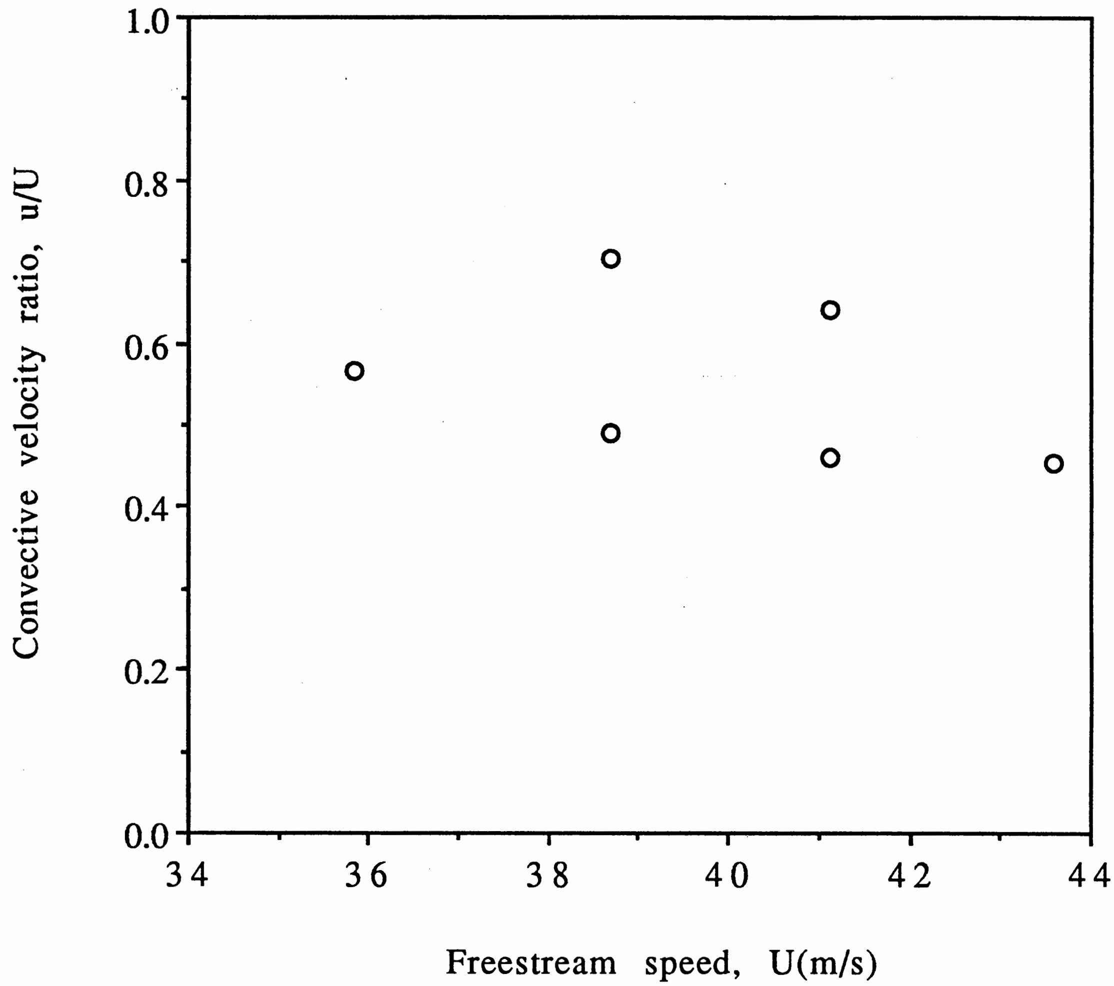

Figure 18. Dependence of convective velocity on freestream speed at phi=10

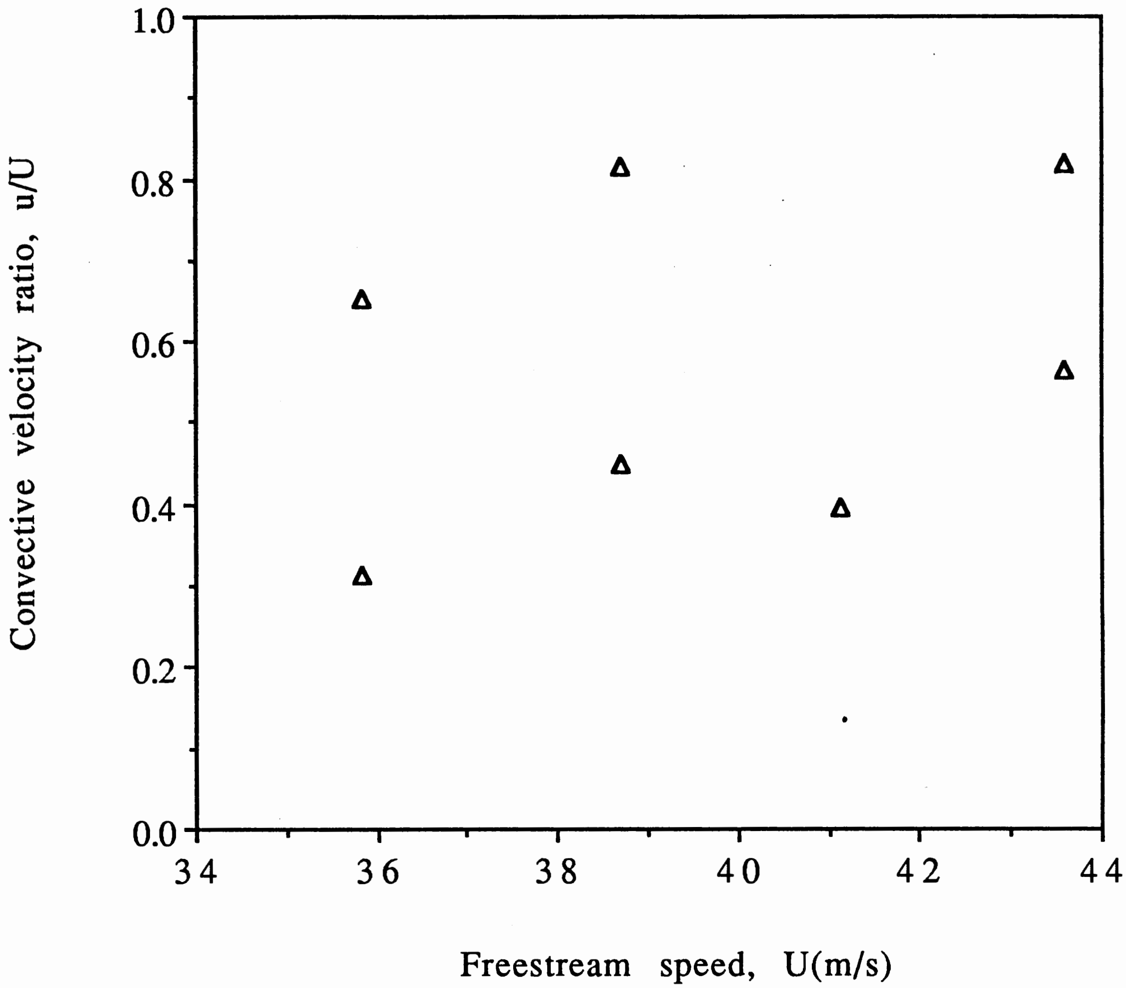

Figure 19. Dependence of convective velocity on freestream speed at phi=20

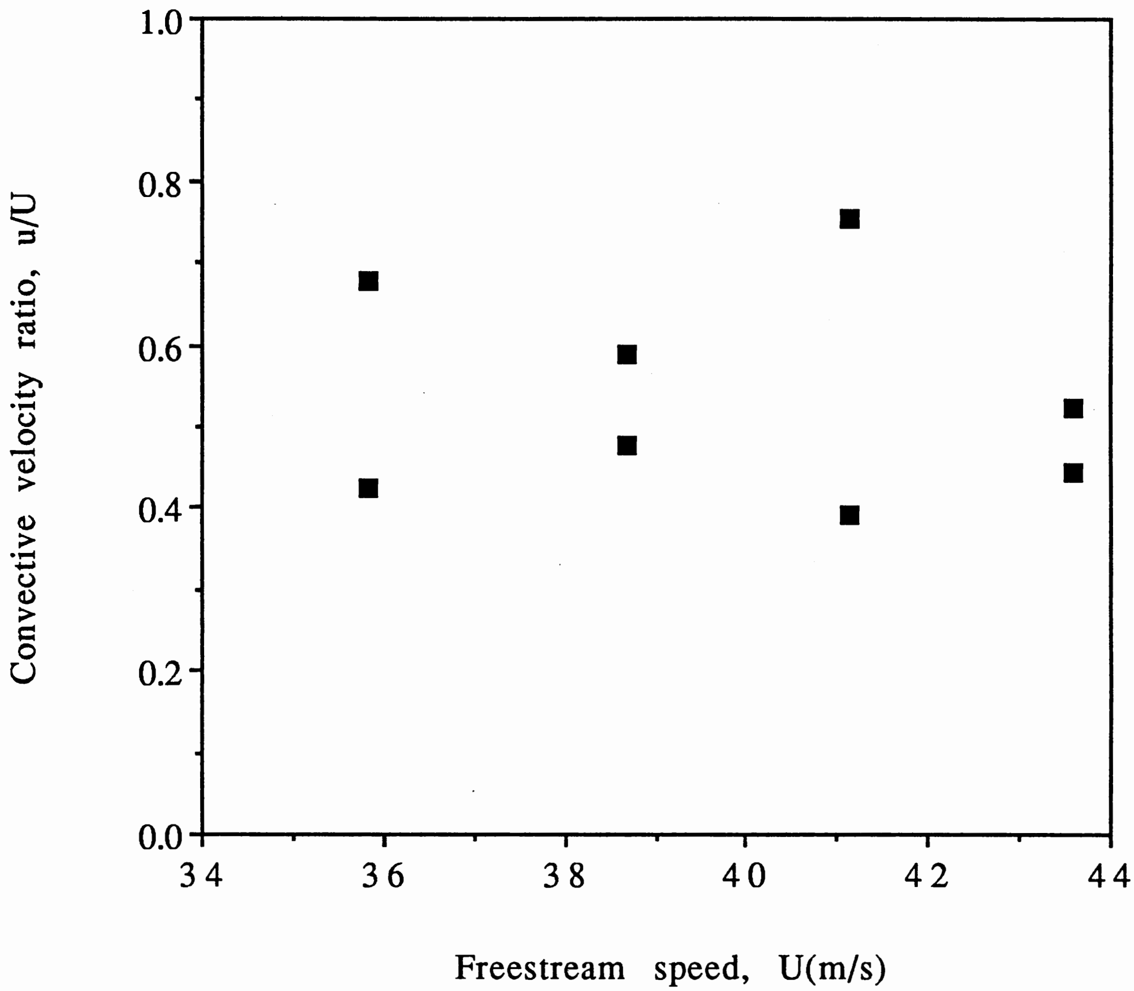

Figure 20. Dependence of convective velocity on freestream speed at phi=30

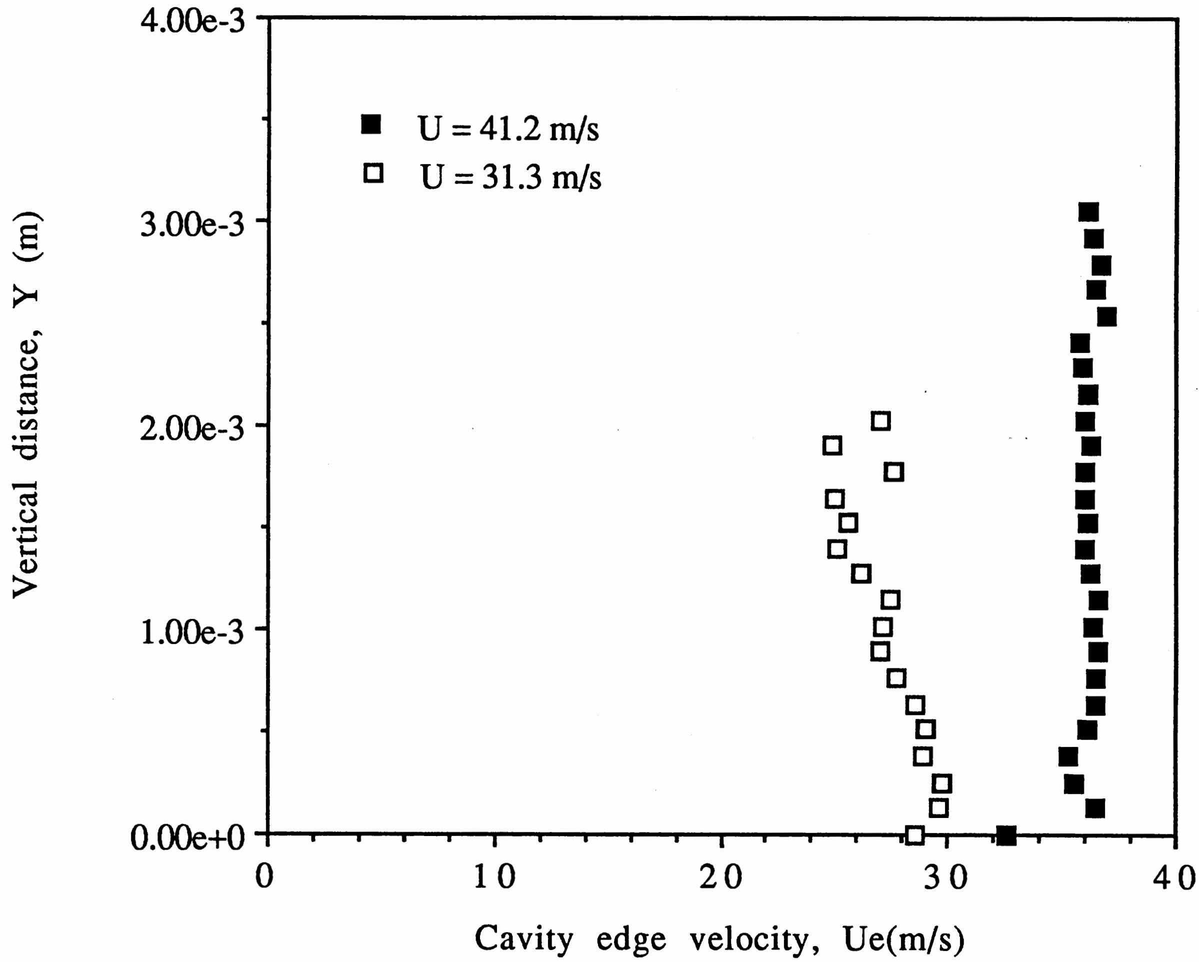

Figure 21. Mean velocity profile at the leading edge of the cavity

above the leading edge. For the higher velocity case the profile is quite unusual. This likely is explained by the fact that the measurements were complicated by probe vibrations and the intermittent appearance of turbulence, drastically changing the measured profile. It would be expected that transition would be more likely to appear at the higher velocity.

CHAPTER V

DISCUSSION

Two bands of non-dimensional frequencies were observed ranging from 0.90 to 0.96 and 1.2 to 1.3 indicating two different modes of oscillation. It was assumed that the frequency response would be governed by the effective streamwise length ($L' = L/\cos\phi$) of the cavity as substituted in Rossiter's modified equation. But those substitutions resulted in oscillation modes halfway between two integers while one would expect an integer value. This trend was observed for all but 30 degree cases. It was probably because for small angles of rotation, the effective streamwise length did not vary that much in comparison to the frequency measured. It is appropriate to mention again that the literature (Heller et al., 1971) indicates that the modified equation matches best for $M > 0.5$ which is much higher than the experimental Mach number ($M = 0.122$). Complete comparisons for the case with $U = 42.32$ m/s and $L = 7$ mm have been presented in Table I. Moreover, it might be possible that as the cavity was rotated, the streamlines did not necessarily maintain the original direction but deviated following the leading edge of the set-up and made a different angle than anticipated.

These results, however, did not indicate any significant improvement when compared with the results obtained using the

TABLE I

COMPARISON OF RESULTS USING ROSSITER'S MODIFIED EQUATION

Angle (phi)	f (Hz)	L' (mm)	Mach no.	n (S=fL/U)	n' (S=fL'/U)
0.000	7875.000	7.000	0.122	2.680	2.680
5.000	7850.000	7.027	0.122	2.680	2.690
10.000	7850.000	7.108	0.122	2.680	2.720
15.000	7800.000	7.247	0.122	2.660	2.750
20.000	7675.000	7.450	0.122	2.626	2.780
25.000	7525.000	7.724	0.122	2.580	2.820
30.000	7425.000	8.083	0.122	2.550	2.900

Note: These results were obtained for a freestream speed of U = 42.32 m/s. The cavity length was fixed at L = 7 mm. The experiment was performed at an atmospheric pressure of P = 731.4 mm of mercury and at a room temperature t = 29.5^0 C. The last two columns give a comparison between mode of oscillation using absolute and effective streamwise length of the cavity respectively.

actual length in the equation (see Table I). Note that these results give n = 2.55 - 2.68. So it was concluded that Rossiter's modified equation can not be applied to either parallel or non-parallel flow situations for this case.

Hence an effort was made to correlate the results with other prediction methods. Current experimental results indicate that it is more appropriate to use Michalke's (1965) solution of the Orr-Sommerfeld equation for a free shear layer to determine the wavelength and mode of oscillation. Using a non-dimensional frequency of $\beta=2\pi f\theta/U$, the number of waves α_r contained within the cavity was obtained from the numerical solution presented by Michalke. Using the simple relation $\lambda=2\pi\theta/\alpha_r$ (Rockwell, 1977), the associated wavelength and mode of oscillation $n=L/\lambda$ were computed. These results were found to be very close to an integer. θ was estimated from a solution for Falkner-Skan flow. This introduced some error due to its limitation to specific type of velocity profile which did not exactly match the experimental velocity profile. For calculation parameters and results readers are referred to Table II.

However experimental values were mostly higher than theoretical values which might be attributed to the fact of deviation of the experimental condition from the theoretical one. For example the solution was derived approximating an inviscid shear layer with a hyperbolic tangent velocity profile. One major limitation of this method is its incapability of predicting the frequency which needs to be experimentally determined. So further investigation is necessary to find an alternate method to overcome this limitation.

TABLE II

RESULTS FROM MICHALKE'S SOLUTION

U (m/s)	Angle (phi)	Frequency(Hz)	T (micro sec)	Theta (mm)	Beta	Wave no.	Lambda (mm)	n (theory)	n (expt.)
35.840	0.000	4928.000	198.364	0.137	0.118	0.176	4.890	1.340	0.978
	10.000	4864.000	328.064	0.139	0.119		4.970	1.340	1.590
	20.000	4736.000	297.546	0.142	0.118		5.070	1.370	1.400
	30.000	4544.000	311.920	0.152	0.121		5.430	1.390	1.420
38.690	0.000	7008.000	190.735	0.132	0.150	0.235	3.530	1.850	1.340
	10.000	6976.000	244.141	0.134	0.152		3.580	1.860	1.700
	20.000	6848.000	221.252	0.137	0.152		3.660	1.950	1.520
	30.000	6656.000	331.415	0.147	0.159		3.930	1.920	2.200
41.130	0.000	7520.000	312.805	0.128	0.147	0.235	3.420	1.920	2.350
	10.000	7456.000	251.770	0.130	0.148		3.480	1.910	1.880
	20.000	7200.000	152.588	0.133	0.146		3.560	2.000	1.100
	30.000	6976.000	244.141	0.142	0.151		3.800	1.990	1.700
43.590	0.000	8032.000	221.252	0.124	0.143	0.235	3.310	1.980	1.780
	10.000	8000.000	335.693	0.126	0.145		3.370	1.970	2.680
	20.000	7872.000	282.288	0.129	0.146		3.450	2.020	2.200
	30.000	7496.000	331.415	0.138	0.149		3.690	2.050	2.480

Note: These results were obtained using Michalke's solution of Orr-Sommerfeld equation. The experimental conditions were same as provided in Table I. The last two columns compare the mode of oscillation using Michalke's solution and experimental results respectively.

As observed in Fig. 17 to 20, the convective velocity was found in some cases to be higher than the typical values, (0.4-0.6) reported by other researchers. This difference may have been caused by the location of the fixed hot-wires used in the cross-correlation measurements. Changing flow parameters, such as the initial boundary layer thickness and the shear layer thickness likely have very strong effects on phase measurements, as evidenced by Sarohia (1977). He showed that for a fixed x location of the cavity as one moves along non-dimensional vertical distance y/δ_0, the phase drastically changes. This is shown in Fig. 5. Since the experiment was conducted for different velocities, for changing y/δ_0, at different velocities measurements were presumably made at different phases as sensed by the hot-wires.

To see the effect of the leading edge probe on the trailing edge probe, cross-correlation measurements were made with the cavity completely covered. Measurements did not indicate any interference sensed by the trailing edge probe caused by the leading one. This conclusion was reached from the fact that no distinct peak was observed in the cross-correlation display.

Current experimental results indicate that Rossiter's modified equation can not be applied to the present case. Michalke's solution indicated some improvement with the limitation of predicting the frequency as mentioned earlier. The multiple peaks observed in cross-correlation measurements yielded some convective velocity ratios (0.3 - 0.9) ususally higher than reported by other researchers (0.4 - 0.6). So further investigation is necessary to find a suitable prediction method for non-parallel flow cases.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this investigation was to get an idea about the oscillation characteristics of a shallow open cavity subjected to non-parallel flow. Based on the research findings the following conclusions were drawn:

1) Weak dependence of frequency response on the angle of rotation was observed.

2) No general relationship could be developed between convective velocity and freestream velocity or angle of rotation.

Rossiter's method could not be applied to the present case. Michalke's solution indicates some improvement with the limitation of frequency prediction.

A question was encountered during the course of the work. This is "The effect of low-frequency noise of the wind tunnel itself on the results."

For extensions of this research, it is recommended that improving measurement technique is required so that the hot-wires sense unchanged flow parameters under different test conditions during phase measurements or to traverse the hot wire to see phase changes with locations.

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APPENDICES

APPENDIX A

DATA FOR DIFFERENT CAVITY LENGTHS

L = 7 mm U(m/s)	L = 7 mm f(Hz)	L = 10 mm U(m/s)	L = 10 mm f(Hz)	L = 13 mm U(m/s)	L = 13 mm f(Hz)
20.200	2425.000	20.320	2025.000	22.060	2600.000
25.090	3275.000	24.930	3525.000	26.770	3300.000
29.610	3950.000	30.280	4475.000	31.400	3925.000
35.000	6275.000	36.340	5550.000	34.940	4475.000
40.080	7600.000	41.220	6350.000	38.880	4975.000
		44.360	6900.000	42.870	5525.000

DATA FOR DIFFERENT ANGLES OF ROTATION

U (m/s)	Angle (phi)	Frequency(Hz)	T (micro sec)
35.840	0.000	4928.000	198.364
	10.000	4864.000	328.064
	20.000	4736.000	297.546
	30.000	4544.000	311.920
38.690	0.000	7008.000	190.735
	10.000	6976.000	244.141
	20.000	6848.000	221.252
	30.000	6656.000	331.415
41.130	0.000	7520.000	312.805
	10.000	7456.000	251.770
	20.000	7200.000	152.588
	30.000	6976.000	244.141
43.590	0.000	8032.000	221.252
	10.000	8000.000	335.693
	20.000	7872.000	282.288
	30.000	7496.000	331.415

APPENDIX B

FALKNER-SKAN SOLUTION

Falkner-Skan solution is a boundary layer similarity solution for wedge flows. The most common form of the equation is

$$f''' + ff'' + m(1 - f'^2) = 0$$

where the parameter m is a measure of the pressure gradient. A positive m indicates a favorable pressure gradient while a negative m denotes an unfavorable pressure gradient. The boundary conditions are given by

$$f(0) = f'(0) = 0 \quad \text{and} \quad f'(\alpha) = 1$$

where $\frac{U(x)}{U} = f'(\eta)$, $\eta = y\sqrt{\left(\frac{r+1}{2}\frac{U(x)}{\nu x}\right)}$, and $m = \frac{2r}{1+r}$

However, to apply this solution the freestream velocity distribution is required to be $U(x) = Kx^{m/(2-m)}$, where K is a constant. Given an angle of attack α, $m = 2\alpha/\pi$. In the present case, for an angle of attack of 13 degrees m = 0.144. With this value of m, the equation was solved by Runge-Kutta iterative process to satisfy the boundary conditions for given values of f''(0). As the cavity was rotated(ϕ) from 0 to 30 degrees, the effective angle of attack changed ($\tan\alpha' = \tan\alpha/\cos\phi$) to some extent. Considering this for different angles of rotation the following values were obtained.

TABLE III

RELATIONSHIP BETWEEN ANGULAR
ROTATION AND f"(0)

ϕ	f"(0)
0	0.63261
10	0.63562
20	0.63562
30	0.65435

From these values, the shear layer momentum thickness θ can be determined using the relation

$$\theta = \frac{f''(0)}{\left[\frac{U \cos\phi}{2\nu x}\right]^{\frac{1}{2}}}$$

where for experimental conditions of temperature $t = 29.5^0$ C and atmospheric pressure of P = 731.4 mm of mercury, kinematic viscosity ν = 1.656 E-5 m^2/s and x = 0.0508 m indicating the distance between the leading edge of the cavity and the leading edge of the set-up. The results presented in the tables were obtained under these conditions.

In the Falkner-Skan velocity equation, assuming K to equal to the freestream speed, for experimental freestream speeds different cavity leading edge velocities were computed. This is presented in the following table :

TABLE IV

RELATIONSHIP BETWEEN FREE STREAM SPEED AND EDGE VELOCITY

U m/s	Ue m/s
35.84	32.2
38.69	34.77
41.13	36.96
43.59	39.17

This table gives an idea as to how the edge velocity varies with the freestream speed. All Strouhal numbers are calculated based on the free stream speed.

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