ACTIVE CONTROL OF CAVITY SHEAR LAYER OSCILLATION

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ABSTRACT

Influence of externally forced initial flow conditions on axisymmetric cavity shear layer were studied. A sinusoidally heated strip upstream of the cavity excited Tollmien-Schlichting waves which, after amplification by the boundary layer, were introduced to the cavity shear layer. By choosing forcing frequencies within the range of shear layer receptivity, it was possible to control frequency and amplitude of the oscillations and consequently control the cavity drag.

INTRODUCTION

As part of a study of the relation between the drag of a cavity and the processes occurring in its separated shear layer, a study was made of the effects of controlled forcing. This is a particularly useful configuration for such a study because, even without forcing, the oscillations in the shear layer tend to be coherent in phase due to the feedback conditions provided by the presence of the downstream edge of the cavity. Because of the presence of these feedback conditions, the cavity shear layer oscillations are self-sustained. A minimum cavity width (b min) is required for the initiation of self-sustained oscillation of the cavity shear layer. The onset of oscillation is associated with a decrease in frequency as the cavity width (b) increases. This trend, then, is interrupted by a jump to a higher frequency and another similar reduction of frequency at a higher mode (Figure 1). The self-sustained oscillation and its associated mode switching phenomena is eventually replaced at a certain cavity width by a wake like flow. In the present study this flow regime will be referred to as wake mode. Flow in the wake mode shows intermittent behavior on a much larger scale. Gharib and Roshko[1] showed that the cavity drag is directly related to the state of the shear layer. The state of the shear layer is determined by the frequency, amplitude of fluctuations (u'or v') and Reynolds stress (u'v') in the layer.

This paper will discuss a series of experiments on the application of a new shear layer forcing scheme to manipulate the state of the cavity shear layer and consequently to control the cavity drag.

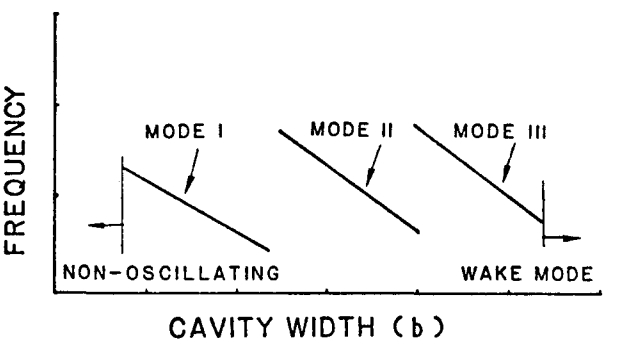

Figure 1. Frequency variation of cavity shear layer with varying cavity width.

Forcing of the Shear Layers

Forcing of the unstable and stable modes of laminar or turbulent shear layers has been the topic of many previous studies. Basically, forcing techniques fall into two catagories:

1. Perturbations to the entire high or low free stream (Miksad[2], Ho and Huang[3], Roberts[4].

2. Localized perturbations in the initial region of the shear layer (Oster and Wygnanski[5]).

In the first type of forcing, e.g., by oscillating one of the streams, the whole streamwise length of the shear layer experiences forcing effects. As a result, no accurate information can be deduced about the influence of perturbations on the initial regions of the shear layer. Oster and Wygnanski showed that forcing effects can be localized by sinusoidal oscillation of a pivoted thin flap at the leading edge of the shear layer splitter plate. Due to the mechanical nature of their technique, an extension of its application to the axisymmetric shear layers is not feasible.

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Shear Layer Forcing Through Tollmien-Schlichting (T-S) Waves

A localized forcing of the shear layers can be obtained through T-S waves. Forcing T-S waves in boundary layers has been practiced for a long time. However, to our knowledge, T-S waves have not been used to force a separated shear layer resulting from such a boundary layer. In the present study, inspired by the experiment of Liepmann, et al.[6], periodic heating of a thin film was used to excite the T-S waves in the boundary layer upstream of the cavity shear layer, benefitting from amplification of the waves before their introduction into the shear layer (Figure 2). One can imagine that the effect of the T-S waves or transverse velocity perturbation (v') at the upstream corner of the cavity would be similar to that of the oscillating flap at the leading edge of the splitter plate in Oster and Wygnanski's experiment. It will be seen later that the frequencies needed to excite the free shear layer are available in the range of boundary layer T-S waves. Thus, a transformation of boundary layer T-S waves to the shear layer Kelvin-Helmholtz waves is possible.

Surface Heating Technique

Liepmann, Brown and Nosenchuck[6] recently showed that time-dependent surface heating can be used to introduce perturbations into laminar boundary layers. Such a technique can be easily adapted to excite T-S waves in an axisymmetric boundary layer such as that of the present study. The idea of periodic heat release into the boundary layer for the purpose of exciting T-S waves was also realized by Kendall[7] in supersonic boundary layers.

For cases in water, Liepmann, et al.[6] show that the effect of heating and cooling of the surface is roughly equivalent to suction and blowing or negative and positive surface displacements. Such an equivalent normal surface oscillation would periodically redistribute vorticity. Depending on the state of the boundary layer, the external perturbations would either be dampened or amplified exponentially.

EXPERIMENTAL SET-UP

The experiments were made in a water tunnel on a 4 inch diameter axisymmetric body with cavity as shown in Figure 3. Velocity fluctuation measurements were made by a two-component laser doppler velocimeter (see Gharib[8] for details of the model and experimental set-up).

Initially three strip heaters were mounted on the ellipsoidal nose of the model (Figure 3) at s = 9.2 cm, 12 cm, and 15.5 cm where s is the distance on the model surface from the nose of the model. Double stick tape was used to electrically isolate heaters from the model. The first and third heaters were stainless steel ribbons 3.7 mm wide, .051 mm thick, wrapped around the front nose of the model. The second heater, also made of stainless steel, was narrower, .08 cm (.2 inch) wide. Each heater entered the model from a flush mounted round adaptor, designed to connect the heaters to the current supply lines. The resistance of the strip heaters was 2 to 4 ohms.

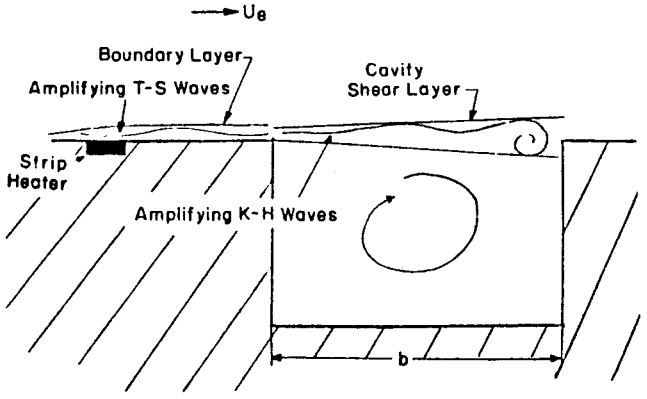

Figure 2. Schematic of cavity flow illustrating the strip heater technique.

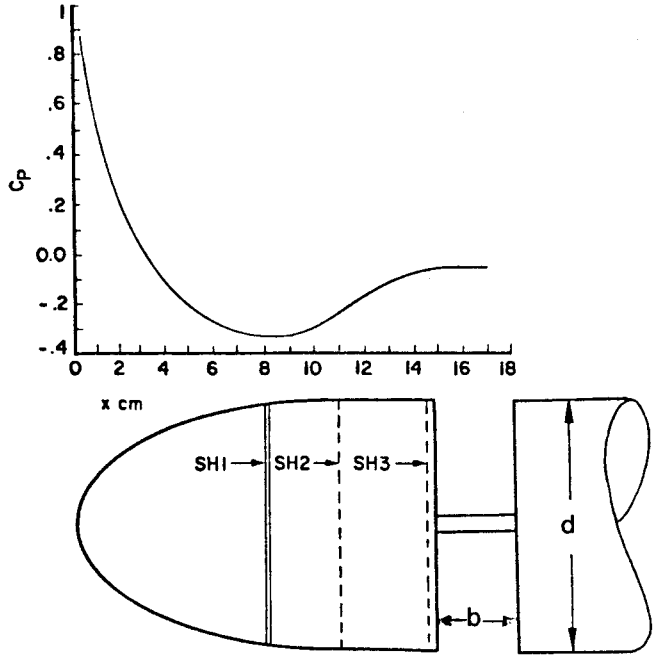

Figure 3. Cavity model and pressure distribution over the ellipsoidal nose cone and respective location of the strip heaters.

A high quality commercial dual channel power amplifier was used to supply current to the strip heaters. A Function Generator was used to provide the selected frequency to the power amplifier. Due to the quadratic dependence of Joule heating on the voltage, the input frequency to the power amplifier had to be half of the desired forcing frequency.

Several parameters are important for the efficiency of a strip heater in forcing both the T-S waves and the shear layer. Liepmann, et al. concluded that Δ/W (where W is the strip heater width and Δ is the boundary layer displacement thickness) is an important parameter in effectiveness of strip heater operation on the local forcing of T-S waves. Our study of the performance of all three strips indicated that the state of the free stream pressuregradient (C_p) is another important factor. In the final version of the experimental model, a single strip heater was flush mounted at $s = 9.2$ cm with $W/\Delta = 5.3$. For this arrangement, external perturbations introduced into the boundary layer benefit the most from adverse pressure gradients (Figure 3).

RESULTS AND DISCUSSION

External Forcing of the Non-Oscillating Cavity Flow

For small values of cavity width to depth ratio b/d, for which the flow does not oscillate naturally, periodic oscillations could be induced by forcing with the amplified T-S waves.

The receptivity of the cavity shear layer in the non-oscillating regime to externally imposed disturbances was studied. Two different cavity widths were examined, with corresponding $b/\theta_o = 66 < b/\theta_o|_{min}$ and $b/\theta_o = 77 < b/\theta_o|_{min}$, where θ_o is the momentum thickness at the separation point.

Throughout this section these selected widths will be referred to as case A and B respectively. In both cases edge velocity (velocity outside the boundary layer at the separation point) was fixed at $U_e = 22$ cm/sec. Cavity flow response was measured in terms of the maximum Reynolds stress that was developed in the shear layer at a station .254 cm upstream of the downstream corner.

Spectral analysis of the response velocity fluctuations indicated a one to one relation between forcing and the response frequency. For Case A, Figure 4 presents the response of the cavity shear layer to a wide range of the forcing frequencies at different levels of forcing power. The results indicate that the amplitude level of shear layer response increases as the forcing power increases. For forcing levels above 9 watts, resonance peaks appear at the forcing frequency of 7.2 Hz.

An overall phase measurement revealed that Case A at the resonance (F = 7.2 Hz) satisfies the phase criterion $\phi/2\pi = Fb/U_c = 2$, where ϕ is the overall phase difference between two corners, F is the response frequency, b is the cavity width and U_c is the phase velocity. In this study each mode has been identified by the integer value of the Strouhal number ($Fb/U_c = N$). Therefore, case A at the resonance simulates the second mode of the oscillations. Removing the forcing caused the resonance mode to disappear, thus showing that the flow oscillations were not self-sustaining. Figure 4 also shows that the existence of resonance depends on a minimum amplitude threshold.

Figure 5 presents the response of the cavity shear layer for Case B at a fixed forcing level of 9 watts. This case shows a resonance peak at the forcing frequency of 6.2 Hz with $\phi/2\pi = Fb/U_c = 2$. Appearance of a resonance peak for Case B at a lower forcing level than that of case A, indicates that the threshold level decreases as b/θ_0 increases. In Case B, the effect of initial lower amplitude of the forcing was compensated by longer cavity length in such a way that reduced the required forcing level for the resonance condition. The effect of higher forcing power on the exponential growth of the perturbations was to increase the general level of Reynolds stress (Figure 6a). Figure 6b presents the growth behavior of the different frequencies for a fixed forcing level (9 watts) for Case B.

It can be concluded that external frequencies can be imposed on naturally non-oscillating cavity flows, within the receptivity range of the shear layer. These frequencies can cause the cavity flow to resonate if they satisfy the following conditions:

1) $\phi/2\pi = Fb/U_c = N$ for the given width (b); and

2) $A > A_{Th}$ where A is the amplitude of external frequency at the downstream corner and A_{Th} is the threshold amplitude.

It is logical to propose that as the cavity width increases, the threshold level decreases to such an extent that a flow background frequency, which satisfies the phase criterion and has sufficient amplitude, will initiate the self sustained oscillation. In this study the natural self-sustained oscillations always started at the second mode. It is now clear that due to the insufficient cavity width and the absence of proper frequencies in the flow background, the first mode did not appear naturally in this study. However, by selecting a proper forcing frequency and initial amplitude, the first mode of oscillations, $\phi/2\pi = Fb/U_c = 1$, was simulated for Case A. This was accomplished at a forcing

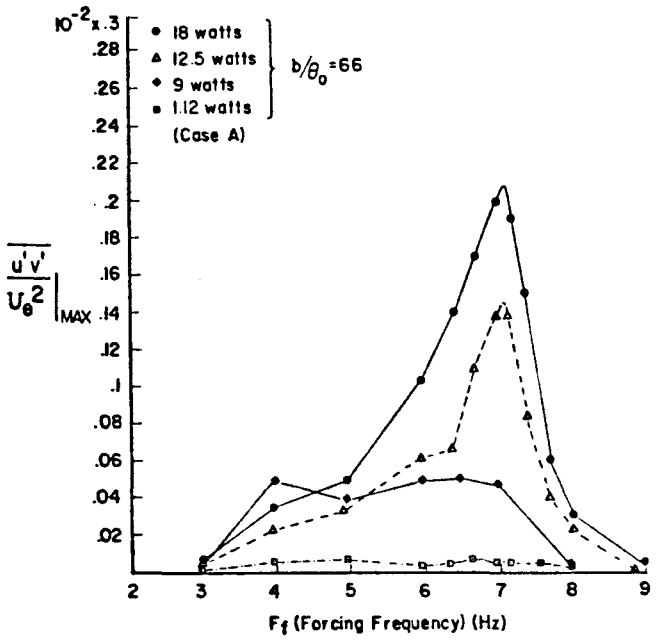

Figure 4. Variation of maximum Reynolds stress with forcing frequency at four different forcing power levels (Case A).

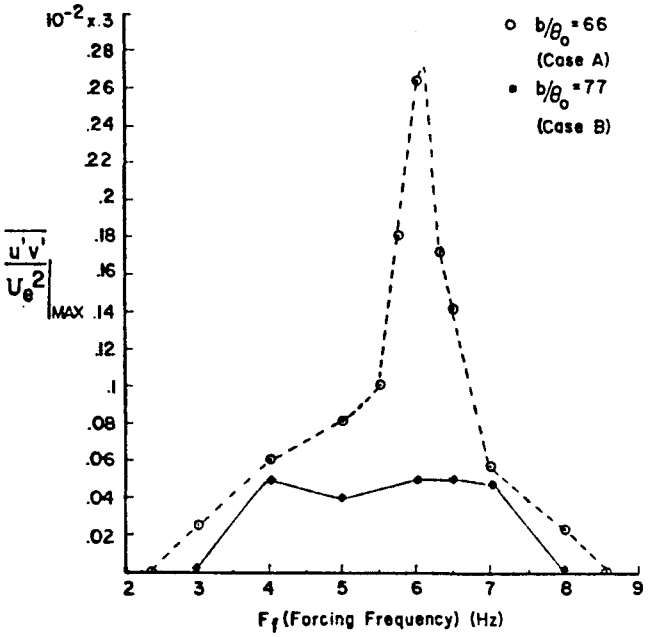

Figure 5. Variation of the maximum Reynolds stress with forcing frequency, constant power.

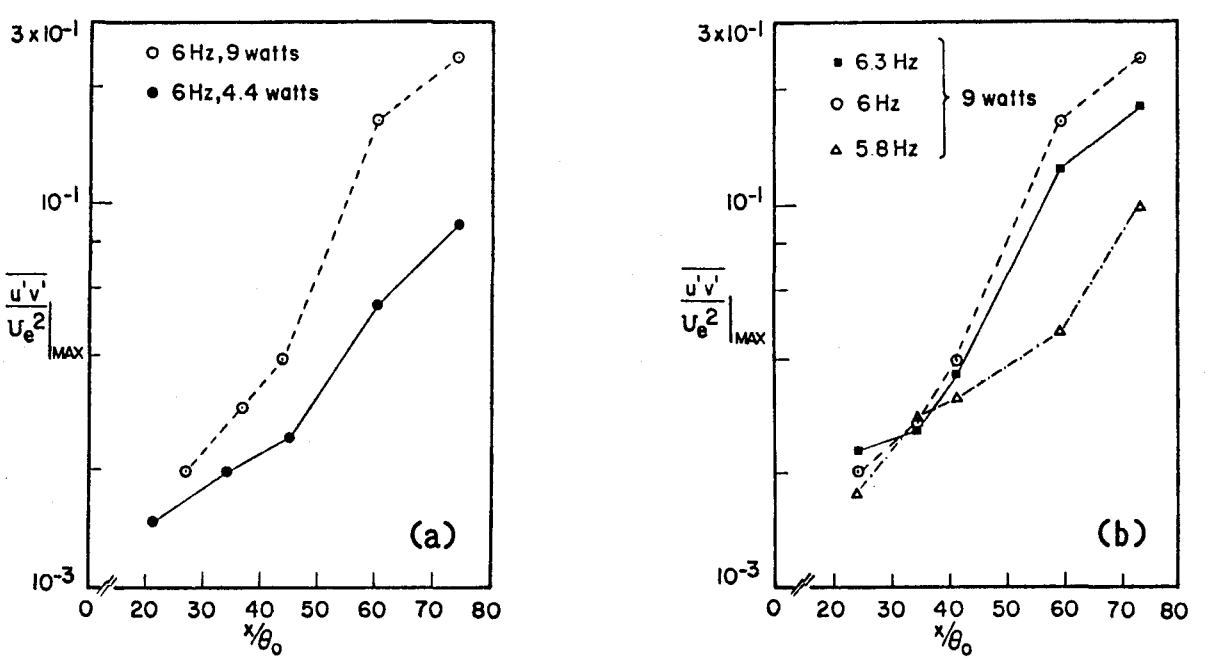

Figure 6. Distribution of the maximum Reynolds stress with the streamwise distance, a)two different forcing powers, constant frequency, b) three different forcing frequencies, constant power.

frequency of 4 Hz, and a power level of 35 watts. A flow visualization of this case is shown in Figure 7b. Comparison to the unforced case shown in Figure 7a reveals two noteworthy features. The first is the appearance of a small amplitude wave in the shear layer of the forced case. The second is the interaction of this wave with the downstream corner and the resultant strong recirculating flow inside the cavity.

It is interesting to note that the response of the cavity flow to external forcing is not instantaneous. Figure 8 presents traces of the velocity fluctuations taken at a station with $x = 60\ \Theta_o$, where x is the downstream distance. The cavity was in the non-oscillating mode with $b/\Theta_o = 66$. Figure 8a indicates that for an external forcing frequency of 7.2 Hz, simulating Mode II, it takes 3 cycles of the oscillation before the peak amplitude establishes itself. When the forcing is turned off it takes many more cycles for the amplitude of oscillations to diminish, indicating that resonance occurring in the system through the feedback mechanism slows down the amplitude decay.

Generating Drag Through Forcing

Drag coefficient of the cavity was determined by integrating the mean and turbulent momentum transfer terms ($\bar{u}\bar{v} + \overline{u'v'}$) along a straight line that connects two corners of the cavity (see Gharib[8] for details). Case B, at the resonance, had a drag coefficient of 0.0012. This drag coefficient was one order of magnitude higher than that of the unforced case. Distributions of $\bar{u}\bar{v}/U_e^2$, and $\overline{u'v'}/U_e^2$ along the line that connects two corners for both the forced and unforced cavity are given in Figures 9a and 9b. These figures show that the difference in the drag coefficient of forced and unforced cases can be attributed to the development of a strong Reynolds stress level in the forced case.

External Forcing Effects on a Naturally Oscillating Cavity Flow

Once the cavity flow had established the self-sustained oscillations, $b/\Theta_0 > b/\Theta_0|_{min}$, the flow resisted any other external disturbances. Therefore, it was expected in order to interact with the flow oscillations, the amplitude level of external forcing must be comparable to that of the self-sustained fluctuations in the flow.

A non-dimensional cavity width of $b/\Theta_o = 95$ was selected for an external forcing experiment. The cavity flow was oscillating at 5.4 Hz in Mode II. An external forcing frequency of 6 Hz was introduced to the shear layer. Depicted in Figures 10a through 10g are the spectral distributions of velocity fluctuations for several levels of forcing as the forcing power was changed from 2 to 27 watts.

Spectra show that as the amplitude of the forcing increases, the amplitude of natural oscillation decreases and eventually disappears. At the forcing power of 40 watts, the forced frequency becomes the dominant frequency of the oscillations. Oscilloscope traces of the signal for the case when both natural and forced frequency have the same amplitude, as seen in Figure 10d, are given in Figure 10h. Strong modulation of the signal indicates that both frequencies are present simultaneously. Note that in the co-existence region, Figures 10b through 10f, the peak amplitude of both frequencies is lower than that of the single frequency regions of Figures 10f and 10g.

Miksad[9] in his study of dual excitation of a free shear layer observed a similar interaction of two frequencies. He reported that if the excitation amplitudes were adjusted so that both disturbances reached a finite amplitude together, the final amplitudes of both components tended to be reduced, but not as strongly as when one component was clearly dominant. Miksad concluded that the distortion of the mean flow by the stronger frequency made the velocity field unsuitable for the growth of the weaker frequency. Similar behavior had also been observed by Sato[10] in symmetric wakes.

Important to our study is the fact that the amplitude of the forced frequency in Figure 10g, where natural frequency just disappears, is equal to the amplitude of the natural frequency in the absence of the forced frequency (Figure 10a). This fact establishes the amplitude of the natural frequency as the level which should be exceeded by the amplitude of forced frequency to change the frequency of the oscillations. With this rule it is possible to impose forced frequencies on the cavity shear layer within the receptivity range of the shear layer. These forced oscillations are not, in general, self-sustained.

During the mode switching region (hysteresis region), self-sustained oscillation in a desired mode could be achieved by providing a proper frequency within the hysteresis region of that mode. Thus, the mode switching phenomena could be eliminated by external forcing. Also, transition to the wake mode could be prevented by enhancing the amplitude of the natural frequency through external forcing. It is possible to extend Mode III, last mode in this study, by 20 momentum thickness through external forcing. Drag measurements indicated a low cavity drag in the extended mode. This fact supports the conclusion of Gharib and Roshko[1] that self-sustained oscillation is the main reason for the existence of the low-drag regimes of the cavity.

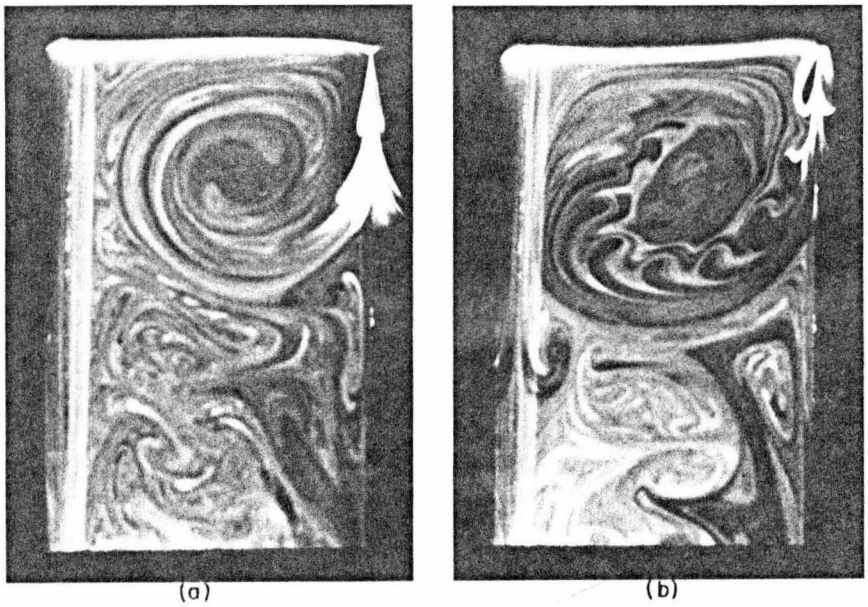

Figure 7. Flow visualization of a naturally non-oscillating cavity flow, $b/\theta_o = 66$ a) unforced, b) forced.

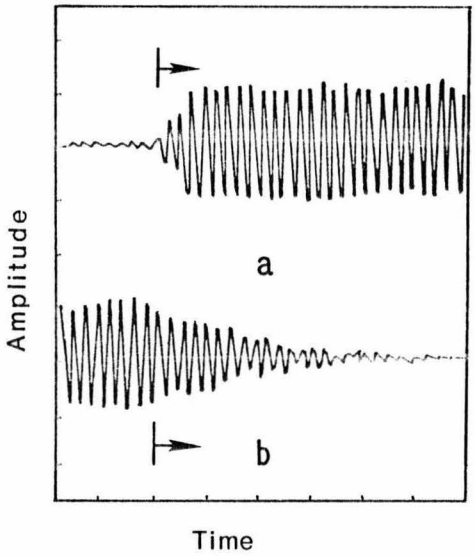

Figure 8. Oscilloscope traces of forced fluctuation, a) turn on, b) turn off.

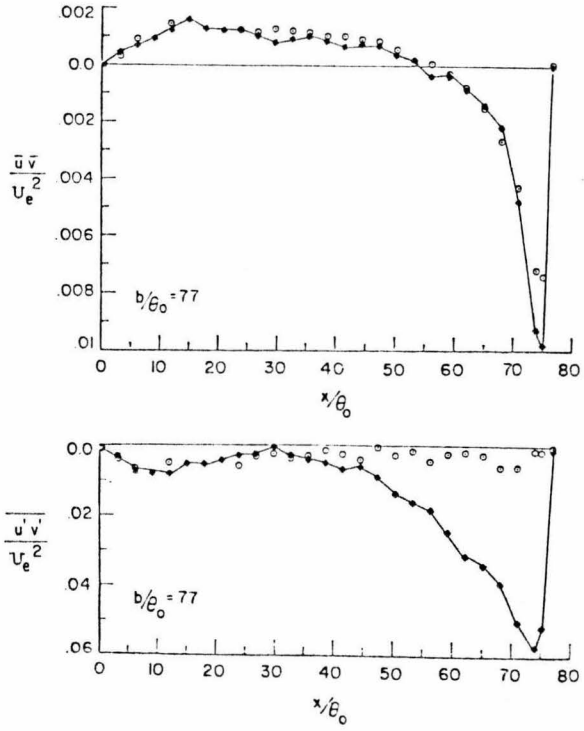

Figure 9. Distribution of a) $\bar{u}\bar{v}/u^2$ term, b) Reynolds stress,
⊙ unforced ◆ forced

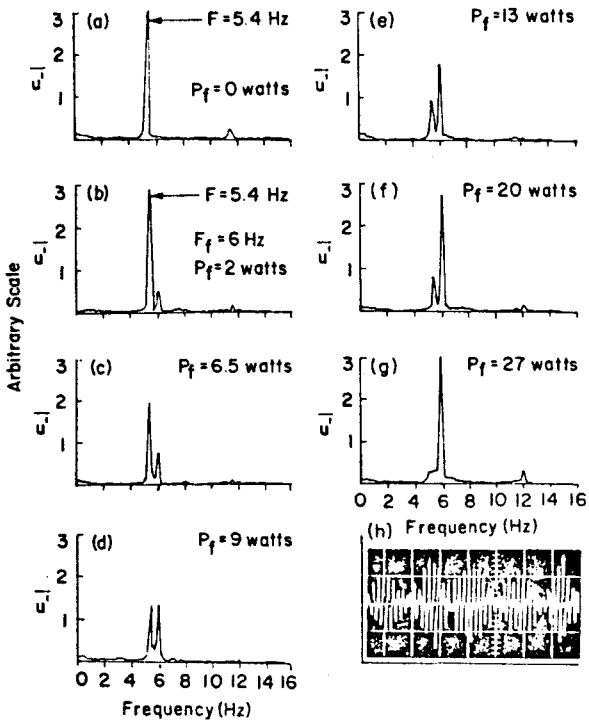

Figure 10. Velocity fluctuation spectra of the natural and forced frequencies interaction, (h) scope trace of case (d).

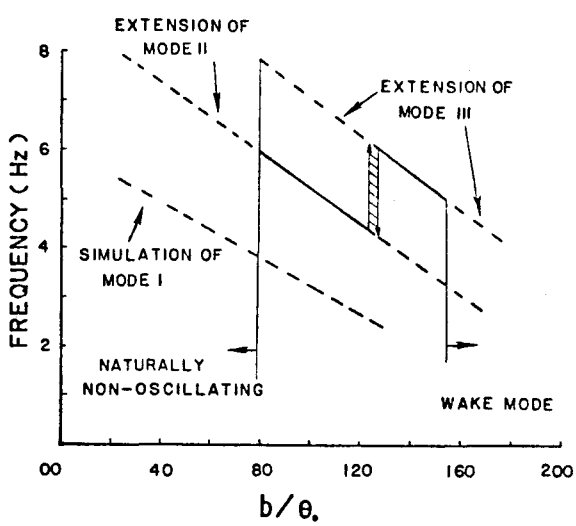

Figure 11. Possible interactions with the cavity flow through external forcing
1) Extension of Mode II and and III
2) Simulation of Mode I
3) Delay of the wake mode.

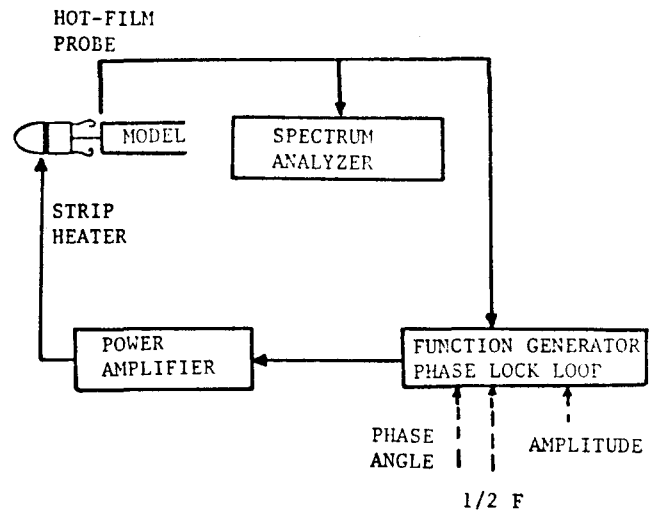

Figure 12. Schematic of cancellation set-up.

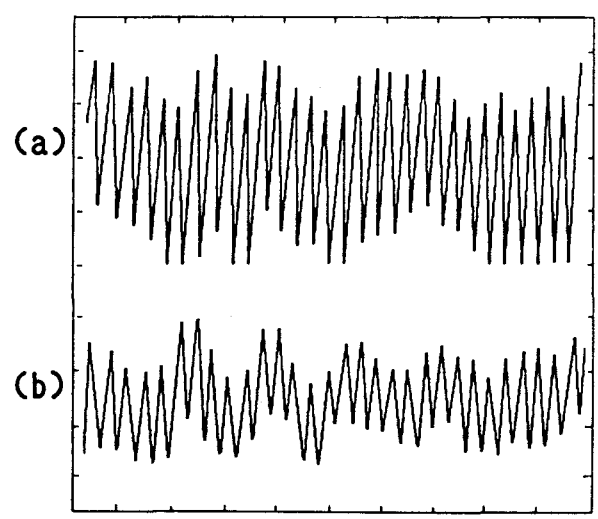

Figure 13. Damping of natural oscillations
a) natural oscillation
b) strip heater on

However, once the cavity entered the wake mode, it was not possible to re-establish cavity flow oscillations by external forcing.

A map of possible interaction with the cavity flow oscillations observed in this experiment is given in Figure 11.

Cancellation Experiment

The cavity shear layer differs from a free shear layer by its imposed boundary condition at the downstream corner. Studies of Gharib and Roshko as well as previous studies indicate a strong phase coherence throughout the shear layer, which is considered to be the result of the downstream corner feedback through the shear layer. This phase stability is responsible for the appearance of a sharp peak in the power spectrum of velocity fluctuation. The velocity power spectrum of an unforced free shear layer does not have such a distinct, sharp peak, but rather a broad band around the natural frequency(Browand[11]).

The phase stability of a cavity-controlled shear layer makes the possibility of active control of the oscillation quite appealing. This section describes an effort to reduce the amplitude of the oscillations by implementing the cancelling effect of two similar waves with finite phase difference. A cavity width of $b/\theta_0 = 82$, with frequency of 6 Hz, was selected for the cancellation experiment. The signal from a downstream location was fed to a function generator which had a built-in lock loop. It was possible to lock to lower harmonics of the input signal. Phase variation of the output signal with respect to the first subharmonic of the input signal was possible through an independent manual adjustment knob. The power amplifier was then supplied by the output of the function generator. The experimental set up is sketched in Figure 12.

Due to small drift in phase of the cavity flow oscillation, it was not possible to maintain a phase lock situation for an extended period of time. Occasionally a correct phase angle could be found where the forced and natural frequencies would interact in such a way that wide band rms fluctuations were reduced. A sample of such a cancellation is shown in Figure 13. A reduction of rms fluctuation by a factor of 2 was achieved during 30 cycles of the cavity shear layer oscillations. This corresponds to a drag coefficient reduction by a factor of 10. Liepmann and Nosenchuck[12] reporta factor of 2-3 in the reduction of rms fluctuations of the natural (T-S) waves in the flat plate boundary layer.

CONCLUSION

This study shows that control of the cavity flow oscillation, in the frequency and the amplitude domains, is possible by external forcing of the cavity shear layer. It is shown that excited Tollmien-Schlichting waves can be used to force the shear layer generated after separation of a boundary layer, that is, a transformation of the T-S waves of the boundary layer to Kelvin-Helmholtz waves of the shear layer is possible for some range of frequency.

Through the study of cavity shear layer response, it is found that minimum cavity length required for the onset of oscillation strongly depends on the turbulent content of the flow background. Different mode extension and simulation is possible by providing the proper forcing frequency and amplitude to the cavity shear layer. The most important result of external forcing is the ability to control established self-sustained oscillations. A 40% reduction in amplitude of oscillation was obtained through active interaction of external and natural perturbations.

On the important problem of active interaction with the natural oscillation, there remains much to be done. More understanding of the precise role of phase difference between natural and external perturbations, especially subharmonics, is needed.

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REFERENCES

1. Gharib, M. and Roshko, A., "The Effect of Flow Oscillations on Cavity Drag," 1985, in preparation for publication in JFM.

2. Miksad, R. W., "Experiments on the Nonlinear Stages of Free Shear Layer Transition." J. Fluid Mech., 56, 1972, p. 695.

3. Ho, C. H. and Huang, L. S., "Subharmonics and Vortex Merging in Mixing Layers." J. Fluid Mech., 119, 1982. pp. 443-473.

4. Roberts, F. A., "Effect of a Periodic Disturbance on Structure and Mixing in Turbulent Shear Layers and Wakes," PhD Thesis. California Institute of Technology, 1985.

5. Oster, D. and Wygnanski, I., "The Forced Mixing Layer between Parallel Streams." J. Fluid Mech., 123, 1982, pp. 91-130.

6. Liepmann, H. W., Brown, G. L. and Nosenchuck, D. M., "Control of Laminar-Instability Waves using a New Technique." J. Fluid Mech., 118, 1982 pp. 187-200.

7. Kendall, J. M., "Supersonic Boundary Layer Stability Experiments." Proc. of Boundary Layer Transition Study Group Meeting, II, 1967, Aerospace Corp., San Bernardino, CA.

8. Gharib, M., "The Effect of Flow Oscillations on Cavity Drag and a Technique for their Control," PhD Thesis, California Institute of Technology, 1983.

9. Miksad, R. W., "Experiments on Nonlinear Interactions in the Transition of a Free Shear Layer." J. Fluid Mech., 65, 1973, p. 695.

10. Sato, H., "An Experimental Study of Non-Linear Interaction of Velocity Fluctuations in the Transition region of a Two-Dimensional Wake." J. Fluid Mech., 44, Part 4, 1970, pp. 741-765.

11. Browand, F. K., "An Experimental Investigation of the Instabilities of an Incompressible, Separated Shear Layer." J.Fluid Mech., 26, 1966, pp. 281-307.

12. Liepmann, H. W. and Nosenchuck, D. M., "Active Control of Laminar-Turbulent Transition." J. Fluid Mech., 118, 1982, pp. 201-204.