8-2000

Investigation of aeroacoustics of an axisymmetric cavity

Douglas A. Baker

To the Graduate Council:

I am submitting herewith a thesis written by Douglas A. Baker entitled "Investigation of aeroacoustics of an axisymmetric cavity." I have examined the final electronic 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:

John E. Caruthers

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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INVESTIGATION OF AEROACOUSTICS OF AN AXISYMMETRIC CAVITY

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

Douglas A Baker
August 2000

ACKNOWLEDGEMENTS

From an academic standpoint, the last two years have been an exhilarating experience For this, I would like to acknowledge all my instructors at UTSI for their enthusiasm and dedication to the frustrating profession of educator. I have learned much and appreciate all your efforts to "teach an old dog new tricks".

I especially would like to thank my thesis advisor Dr. Ahmad Vakili for his support and guidance over my time here. His advice and support was very much appreciated. I would also like to thank Dr John Caruthers for his contribution and insight into the slippery world of acoustics.

Of course, nothing is accomplished without doing and in this I send out a thank-you to Jim Goodman, Ricky Meeker, and Keith Walker, whose hard work and imagination was instrumental to the completion of this thesis I would also like to thank Gary Payne, machinist extraordinaire, for his patience and skill in taking funny looking sketches and incomprehensible explanations and creating workable apparatus.

My final and most heartfelt acknowledgement goes to my wife Myrna. Without her love, support, and patience during my long hours hunched over books or staring at a computer screen, none of this could have been possible.

ABSTRACT

Pulsed flow has been recognized as having significant advantages over steady flow in many applications Essential to the implementation of these applications is the creation of a pulsed flow at desired frequencies Therefore, it is necessary to investigate ways of creating pulsed flows efficiently.

The Objective of this research is to investigate the oscillation properties of enclosed cavities. The research consisted of investigating the properties of a cavity axial pulse generator and investigating techniques for active control of the amplitude of the pulses. Firstly, a comparison of two different types of fluidic oscillators is presented, with a discussion of the current models for cavity flow oscillation and their shortcomings, and a discussion of shear layers as applied to jets and jet forcing This leads to a presentation of a method to enhance oscillations in an axisymmetric cavity. Then, the results of an experimental study performed at the University of Tennessee Space Institute Propulsion Lab are presented.

Oscillations were observed in the enclosed cavities that were significantly higher than the calculated Helmholtz frequency of the cavity. The large scatter of the data suggests that the Rossiter equation is not a complete model to use in describing the oscillation characteristics of the cavity Another model considered was that the jet coupling with the acoustic modes of the cavity. The correlation between the predicted acoustic modes of the cavity and the measured cavity data is similar to that for the Rossiter model. This suggests that the oscillations produced by the jet are complex and may involve both coupling with the cavity acoustic modes as well as viscous interaction

of the shear layer with the cavity. As a result, it is recommended that further studies be conducted including measuring the phases and identifying the modes of oscillations.

A significant increase in oscillation amplitude was not observed when a forcing frequency was applied. As a result, it is recommended that further studies be done including flow visualization, quantitative studies of shear layer growth and the effects of increasing the amplitude of the forcing.

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CHAPTER I

INTRODUCTION

BACKGROUND

Pulsed flow has been recognized as having significant advantages over steady flow in many applications. Investigations [1,2,3,4,5,6] on the advantages of pulsed flow have been done in the areas of deep hole drilling, underwater sound generation, jet vectoring, flow attachment over airfoils and combustion chamber mixing. Essential to the implementation of these concepts is the creation of a pulsed flow at desired frequencies. Therefore, it is necessary to investigate ways of creating pulsed flows efficiently.

There exist various pulse generators that normally operate at relatively low frequencies. For certain applications very high frequencies are desirable, in the range of 1kHz to 10 kHz. Currently, fluidic oscillators generate pulse flows with maximum frequencies of nearly 250 Hz. Furthermore, the total pressure loss within these devices can be as high as 60 per cent. In order to create high frequency pulsed flow, it is necessary to investigate fluid flow processes that can support sustained oscillations.

In general, oscillators require two processes in order to function The first is a process that generates a wave and the second is a feedback process. These two processes must be linked in a certain phase relationship in order to ensure the oscillations are maintained

A promising method for pulsed flow generation is to manipulate the passive geometry of an enclosed cavity to tune the interaction of the shear layer with the cavity geometry for maximum amplification of the shear layer instabilities. In examining this method there are two processes that allow self-sustaining oscillations to occur.

The first process is fluid flow over cavities. Fluid flow over cavities is part of a class of flows susceptible to the creation of self-sustaining oscillations. This type of flow occurs in many different applications and the created oscillations have many detrimental effects such as increasing drag, generating noise, and contributing to structural vibration and fatigue. Consequently it has been extensively studied for a number of years[7, 8] and much work has been done in determining how to suppress them[9, 10] These studies have revealed that the oscillations produced in cavities are considered the result of shear layer interactions within the cavity. Disturbances are created when the shear layer interacts with the trailing edge of the cavity. These disturbances travel upstream to the leading edge of the cavity and influence the shear layer development. When these two processes are properly synchronized, self-sustaining oscillations are produced.

The second process is the jet shear layer instability. A shear layer is formed when two streams of different velocities move over each other. Shear layers are naturally unstable to small perturbations through the Kelvin-Helmholtz instabilities. Their growth usually follows two stages. Immediately after the shear layer forms it experiences transverse undulations that grow exponentially at a fundamental frequency. This constant exponential growth at the fundamental frequency continues until the vortices formed in the shear layer begin to coalesce. This coalescence introduces subharmonics into the shear layer, which reduces the growth of the fundamental frequency. The coalescence of vortices leads to the growth of the shear layer Eventually the coalescence deteriorates into small-scale turbulence.

One difficulty in applying the concepts of cavity oscillation to pulsed flow is the fact that the studies done and the models produced involved flow over cavities that are not enclosed. It is unclear whether or not the models for open cavities apply to enclosed cavities.

The second point of interest is that passive cavity tuning relies solely on cavity geometry to produce the required oscillation. It is unclear whether or not the frequency of oscillation can be controlled or the amplitude of the oscillation frequency can be enhanced through external means.

STATEMENT OF OBJECTIVE

The Objective of this research is to investigate the oscillation properties of enclosed cavities. The research is divided into two parts. The first part concentrates on investigating the properties of a cavity axial pulse generator. The second part consists of investigating techniques for active control of the amplitude of the pulses.

The results of this investigation are presented in five chapters. Following this first introductory chapter, Chapter 2 presents a comparison of two different types of fluidic oscillators, a discussion of the current models for cavity flow, a discussion shear layers as applied to jets and jet forcing and finally a proposed technique for amplitude enhancement. Chapter 3 discusses experimental setup and procedures. Chapter 4 presents and discusses results. Chapter 5 outlines conclusions and recommendations

CHAPTER II

TECHNICAL REVIEW

This chapter provides a technical background and analysis for fluidic oscillator properties The chapter starts with a description and comparison of two different types of fluidic oscillators. This discussion reveals that an efficient fluidic oscillator is possible utilizing the properties of fluid flow over cavities. Because of this, cavity flow and cavity flow models are discussed. This discussion reveals that shear layer and shear layer interaction is a fundamental part of oscillations in cavity flow. Consequently, shear layers are discussed with an emphasis on shear layer forcing. Finally, a brief analysis is given that determines the required frequency to enhance the amplitude of cavity flow oscillations.

REVIEW OF FLUIDIC OSCILLATORS

Kowal[11] investigated the properties of a bistable fluidic oscillator that used the Coanda effect. In Kowal's work, the maximum frequency achieved was 110 Hz at .98 Mach. He found that the frequency of the oscillator was controllable with the frequency being a linear function of the supply flow rate. Typical results taken from Kowal's work are shown in Figure 2-1. However, he noted that the device tested had a significant total pressure drop, which makes it an unlikely candidate for use as an efficient source of pulsed flow. The device also produces two pulsed jets from one input jet, thereby decreasing the effectiveness of each output.

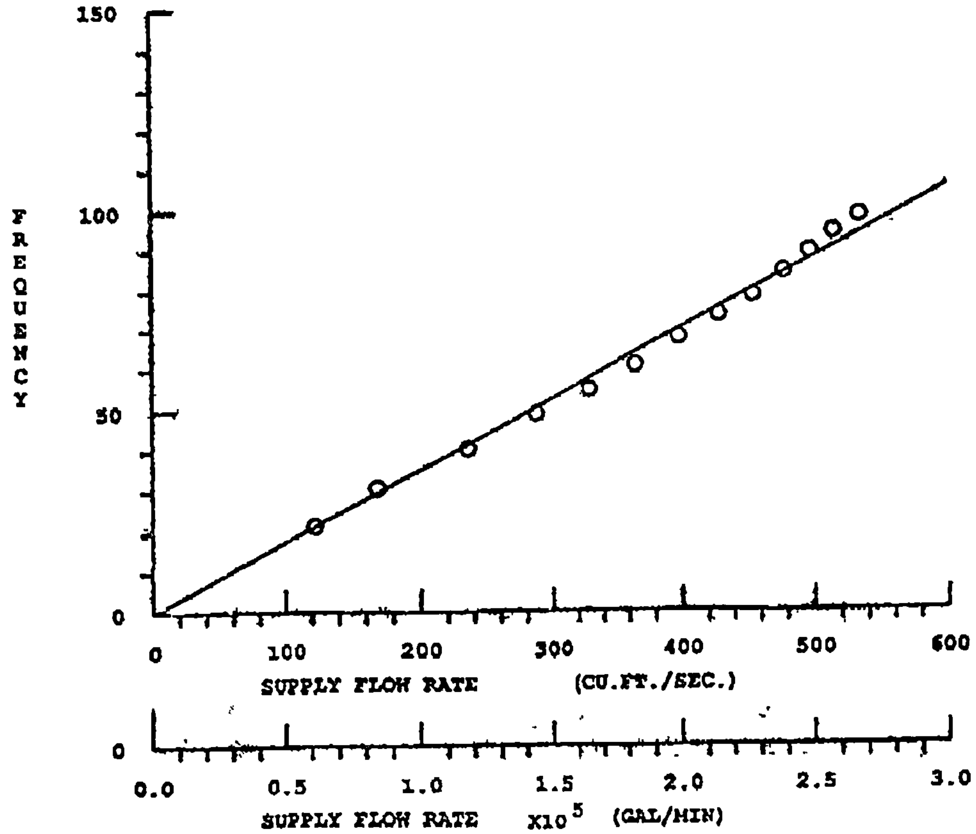


Figure 2-1 Frequency versus Supply Flow Rate for Coanda Oscillator[11]

Morel[12] studied the properties of a Helmholtz resonator driven by a round jet passing through it, which he dubbed a Jet Driven Helmholtz Oscillator (JDHO). A diagram of this device is shown in figure 2-2. A significant point to note is that this device produces only one pulsed flow jet. Morel found that, as the jet velocity increased gradually, the JDHO chamber pressure went though a sequence of oscillations separated by periods of relative quiescence. Morel refers to these periods of oscillations as "modes". For a given mode the frequency of these pressure oscillations increased with increasing jet velocity. Then it reached a maximum at a frequency slightly higher than the Helmholtz frequency of the resonator, and then decayed. The jet Mach number was between .01 and .15 with oscillations in the range of 100 Hz to 300 Hz. The operating frequency of the oscillator was always close to the Helmholtz frequency of the device, which is a function of the cavity geometry.

Morel proposes that the oscillation is a result the following process: The jet entering the cavity contains a low frequency ordered axisymmetric flow. This jet impinges on the exit of the cavity and creates periodic pressure pulses. These pressure pulses are selectively amplified by the Helmholtz resonator geometrical property of the device. The amplified pressure pulses are fed back upstream and cause the jet to fluctuate at the inlet, which induces jet forcing at the frequency of the amplified pressure pulses. The jet shear layer responds to the forcing and amplifies it, which completes the loop.

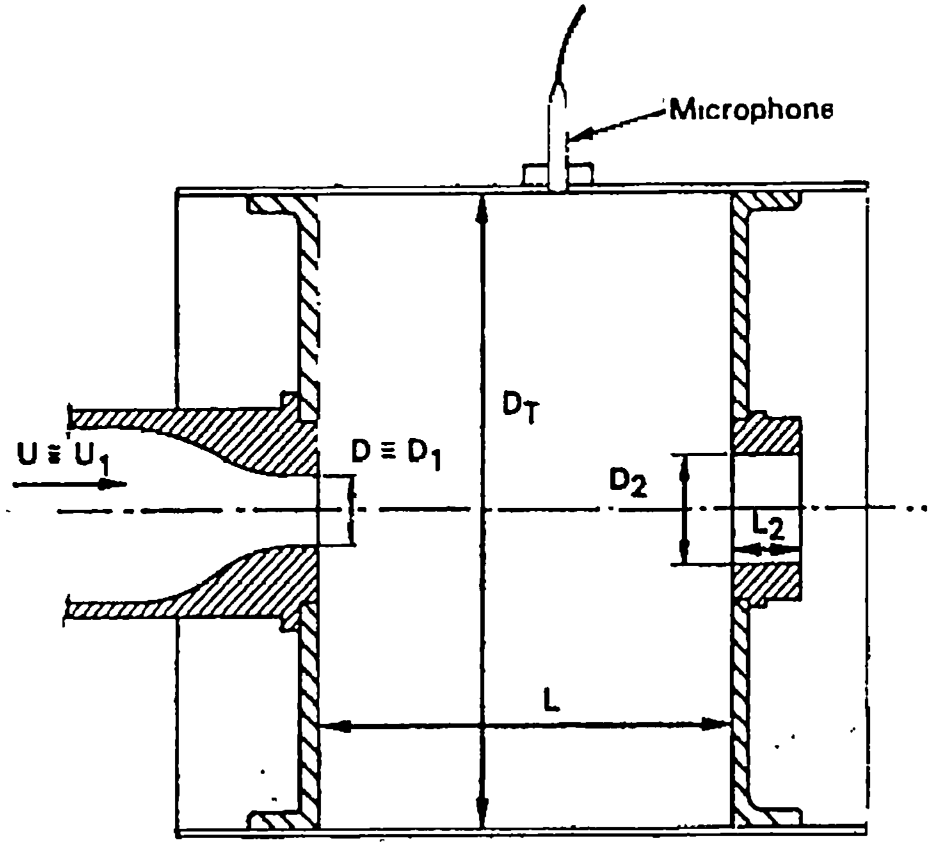


Figure 2-2 Jet Driven Helmholtz Oscillator (from Morel)[12]

The advantage of the JDHO is that it produces a single pulsed jet output with minimal total pressure loss. Because the JDHO pulsed flow is essentially a Helmholtz resonator, the frequency of oscillation is a function of the cavity geometry, which is not as easy to change as the supply volume flow rate, as with the Coanda effect oscillator. However, since the efficiency of producing the pulsed flow is the primary concern the method that seems to provide the most promise is the configuration discussed by Morel.

The Helmholtz resonator is not the only mechanism that can induce oscillation in an enclosed cavity. Another flow mechanisms can generate oscillations at significantly higher frequencies with a given cavity than those produced through the Helmholtz resonator phenomenon. This mechanism utilizes the impingement of shear layers on a downstream obstacle. With this in mind, a review of cavity oscillation models could provide some insight into the operation of this device.

REVIEW OF CAVITY OSCILLATION MODELS

Cavity flow is one of a general class of flows that deal with shear layers impinging on a downstream obstacle. Lucas[13] relates categories of shear layer impingement developed by Rockwell and Naudasacher, which are illustrated in Figure 2-3. Lucas notes that common to all of these different types is the pressure phase relationship between the disturbance created by the shear layer impinging on the downstream obstacle and the convergence of this pressure disturbance upstream in the vicinity of the edge which created the shear layer. This feedback mechanism selectively amplifies frequencies in the shear layer, which produces shear layer fluctuations in a narrow band of frequencies.

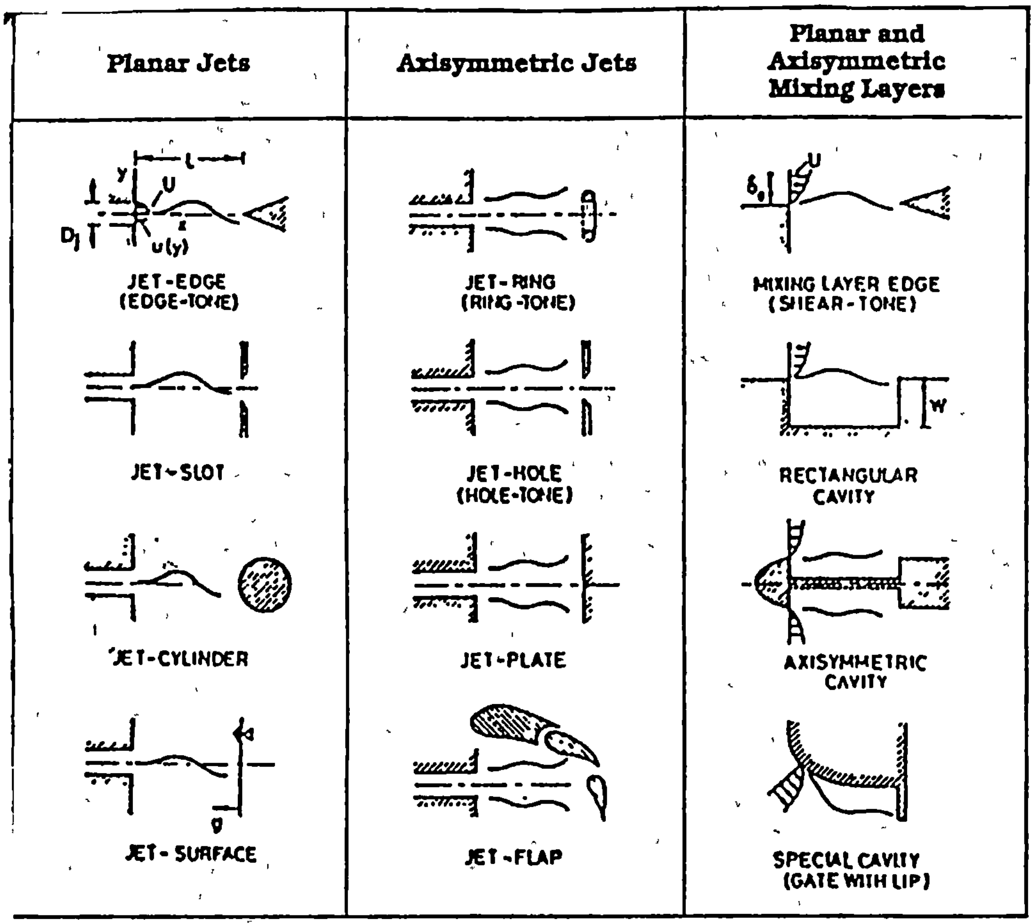


Figure 2-3 Shear Layer Impingement Categories[13]

With regards to flow past cavities, Rockwell and Naudascher[14] categorize this type of flow into three general groups:

a. fluid dynamic, where the oscillation is a result of the inherent flow instability in the cavity shear layer;
b. fluid resonant, where the oscillation arises from resonant wave effects; and
c. fluid elastic, where oscillations occur through coupling with the solid boundary.

Examples of these types of cavities are shown in Figure 2-4.

Fluid dynamic oscillations occur when the ratio of the cavity length to the acoustic wavelength is very small. In these types of oscillations, the primary mechanism for creating the oscillations is the amplification of disturbances in the cavity shear layer. Selective amplification of the shear layer causes certain frequencies to be amplified more than others. This is combined with the feedback from the downstream disturbances enhanced by the cavity trailing edge to create a self-sustaining oscillation.

Fluid resonant oscillations come about when the cavity length is of the same order as the acoustic wavelength. These types of oscillations occur only at certain ratios of wavelength to cavity length corresponding to resonant standing waves in the cavity. Rockwell and Naudascher note however that effects such as the cavity shear layer and mass addition at the cavity trailing edge complicate the predication of these ratios. Fluid elastic oscillations happen when the walls of the cavity deform.

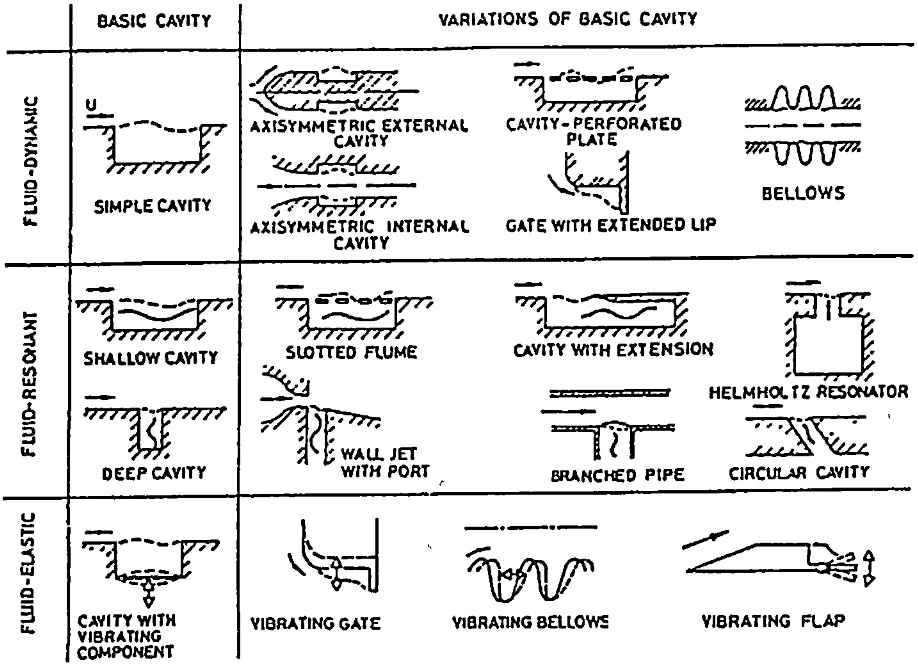


Figure 2-4 Types of Cavity Resonance (from Rockwell and Naudascher)[14]

These discussions indicate that cavity oscillations occur as a result of the interaction of the cavity and the shear layer produced by the flow passing over the cavity. Models that attempt to predict the oscillation frequency of a flow over a cavity therefore must take into account this interaction.

A number of models have been developed the attempt to predict the frequencies of oscillation. Lucas[13] has categorized these models into two general types:

a. Feedback transit time models. These models add the transit time for the vortices moving in the shear layer moving downstream to the transit time for acoustic disturbances produced at the cavity trailing edge to travel upstream to the cavity leading edge; and

b. Acoustic resonance models. These models have an additional criterion in that there must be an acoustic mode excited within the cavity.

Rossiter did a significant study of cavity oscillation in 1964. This study has been referred to in a number of succeeding works, and provided the first model of the behavior of cavity flow. As noted by Gauthier[10], Rossiter observed vortex shedding at the cavity leading edge. The shed vortices, travelling at approximately two-thirds the freestream velocity, grew while spanning the cavity. Upon reaching the trailing edge of the cavity, they interacted with the cavity trailing edge, producing acoustic radiation.

Rossiter's model is a feedback transit time model. It was based upon the times required for (1) the shed vortices to span the cavity, (2) the vortices to interact with the cavity trailing edge and create acoustic waves, and (3) the acoustic waves to reach the cavity leading edge and induce further vortex shedding. This is illustrated in Figure 2-5.

Using these three time scales, Rossiter derived

$$S_m = \frac{fL}{U_\infty} = \frac{m-n}{M + \frac{1}{K}} \qquad (1)$$

where

L = cavity length;

U_∞ = freestream velocity;

$S_m = \frac{f_m L}{U_\infty}$ Is the Strouhal number for a given frequency mode m;

m = an integer number representing the mode of oscillation;

M = the free stream Mach number;

K = the ratio of the shear layer velocity to the free stream velocity; and

n = the phase difference between the (1) upstream arrival of the acoustic wave and the resultant vortex shedding and (2) the downstream interaction of the vortex and the trailing edge and the resultant acoustic wave.

The values of K and n were determined empirically at 51 and .25 respectively. Gauthier and Lucas note that this model showed good agreement with experimental data in the mid-subsonic range but underestimated the Strouhal number at Mach numbers above 1 5

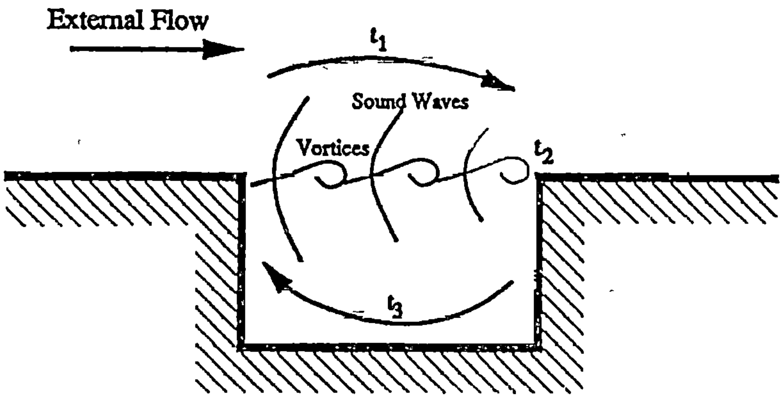


Figure 2-5 Rossiter Cavity Oscillation Model (from Rossiter)[10]

Heller *et al.*[8] proposed a refinement to this model to account for this underestimation of the Strouhal number. In deriving his formula, Rossiter assumed that the speed of sound in the cavity was the freestream speed of sound At high Mach numbers, this assumption is not valid. Heller *et al* found that a correction factor was required. Their equation was

$$S_m = \frac{m-n}{A+\frac{1}{K}}$$

where S_m is as defined above and

$$A = \frac{M}{\sqrt{1+\frac{\gamma-1}{2}M^2}},$$ where M is the freestream Mach number; and

n and K are empirical constants equal to .25 and .56 respectively.

Heller and Bliss[9] proposed a second model. In their investigation, Heller and Bliss did not see the vortex shedding, but rather a sinusoidal amplification of the shear layer as it moved from the leading edge to the trailing edge. This travelling wave motion was a result of amplification of downstream travelling waves inside the cavity. The oscillation process that occurs is the result of a periodic addition and removal of mass at the cavity trailing edge. Their proposed cycle is shown in Figure 2-6. They liken this mass removal and addition to a cavity with the trailing edge wall replaced by a movable wall or piston. An important point to note though is that the process that mechanizes this addition and removal is the unsteady motion of the shear layer rather than the impingement of vortices on the trailing edge.

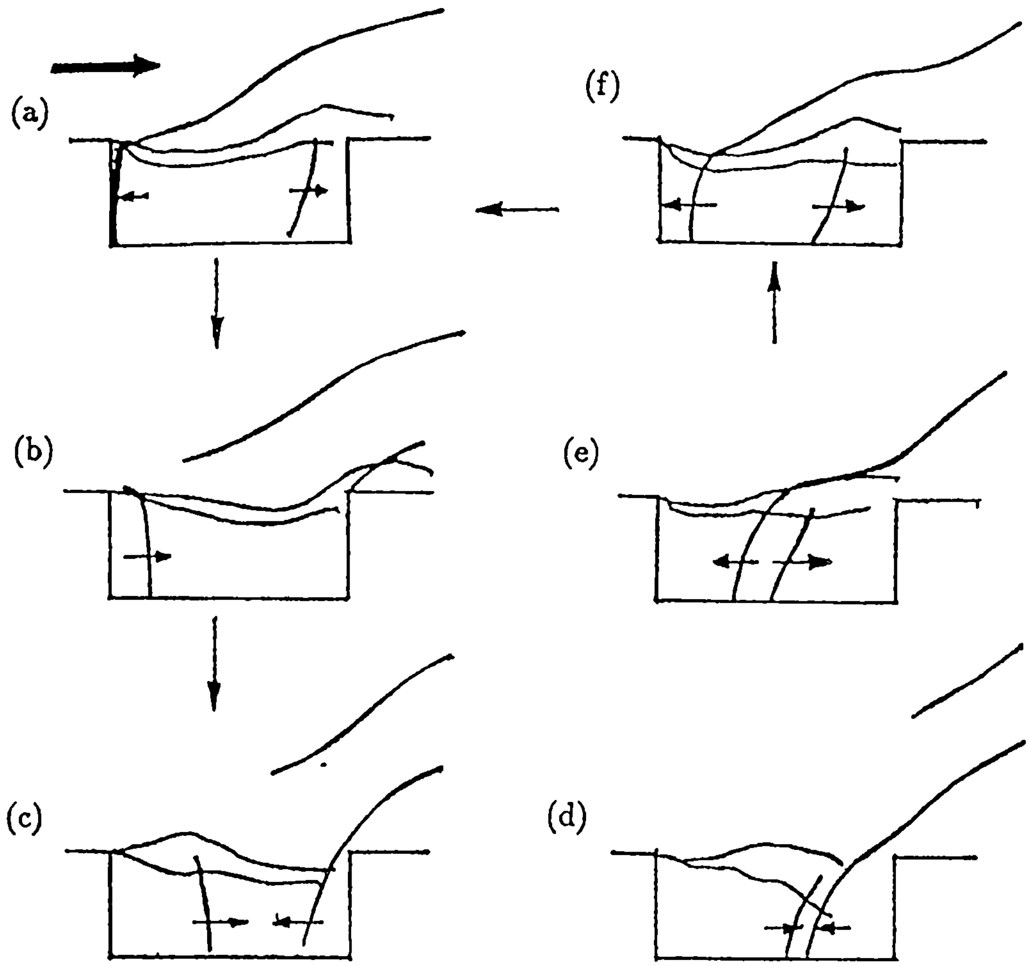


Figure 2-6 Oscillating Shear Layer Model of Heller and Bliss[9]

A third model proposed by Tam & Block[7] also assumed an oscillating shear layer. They noted that the pseudo-piston model of Heller and Bliss failed to predict any discrete oscillation frequency. Therefore, rather than modeling the acoustic wave generation as a pseudo-piston, they introduced an acoustic point source at the trailing edge of the cavity. A diagram of the model of Tam and Block is shown in Figure 2-7. Their argument was that shear layer oscillation creates a periodic shielding and exposing of the trailing edge When the shear layer moves downward, it exposes the trailing edge to the external flow and external fluid flows into the cavity, creating a high-pressure region. Due to the movement of the shear layer, this high-pressure region creates a compression wave. When the shear layer moves upward, it shields the trailing edge so that no compression wave is formed. This produces a continuous train of pressure pulses with a period dependent on the fluctuation of the shear layer. These pressure waves radiate from the trailing edge of the cavity in all directions both inside and outside the cavity. The pressure waves inside the cavity create the standing wave pattern that causes the shear layer oscillation.

Gauthier notes that, although Tam and Block's model was limited and inaccurate at transonic and supersonic speeds, it did allow prediction of the amplitude of oscillation. Hence, the model had value in identifying the importance of the shear layer momentum thickness and cavity depth as well as length in determining the dominant frequencies and amplitudes of oscillation.

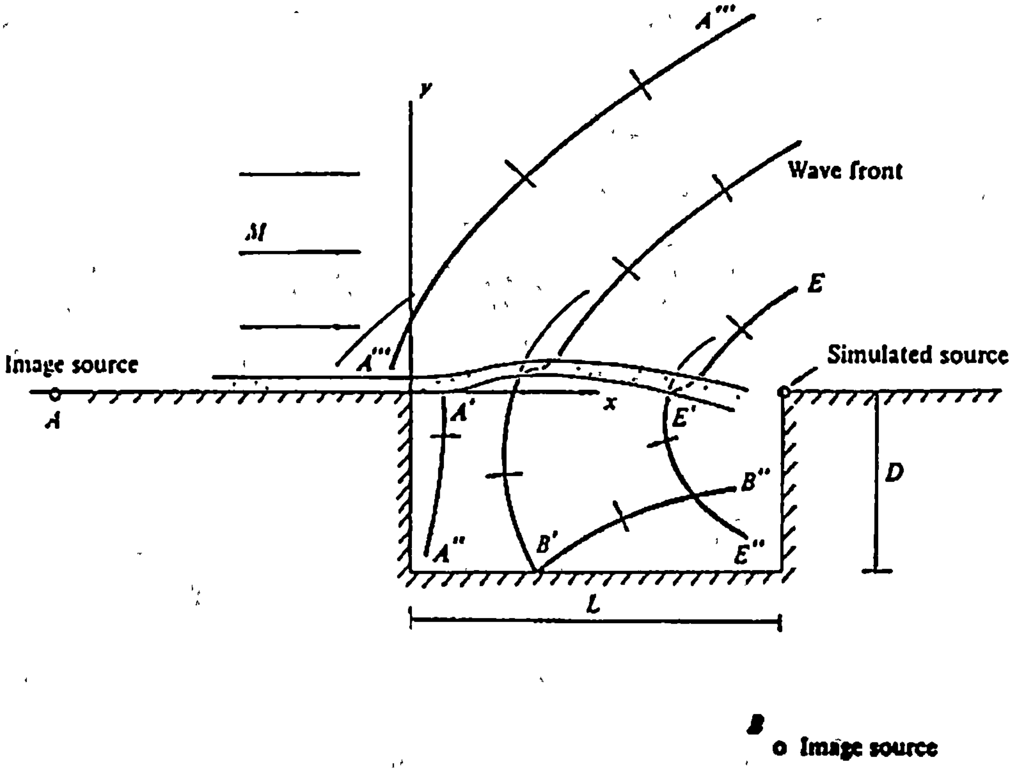


Figure 2-7 Cavity Oscillation Model of Tam and Block[7]

Given the model proposed by Tam and Block[7], the feedback acoustic wave created through the impingement of the shear layer on the trailing edge of the cavity travels both inside and outside of the cavity. In an enclosed cavity, this implies that there could be some cross-interaction of the acoustic waves.

However, Gauthier points out that in supersonic flow the path of the upward travelling acoustic wave can only travel inside the cavity. For an enclosed cavity, this implies that there would be no cross-interaction. The models discussed above would therefore be applicable for predicting frequencies of oscillation in an enclosed cavity.

All of these models indicate that cavity oscillation occurs through the interaction of the shear layer with the trailing edge of the cavity. The frequency of the oscillations is dependent on the cavity length because the acoustic wave travelling from the trailing edge to the leading edge interacts with the shear layer, manipulating it to lock in the acoustic waves.

Examining all of these models of cavity oscillation reveal two important points concerning cavity oscillation frequency:

a. The frequency of the oscillations is dependent on the length of the cavity as well as the Mach number of the flow; and

b. The behavior of the shear layer and its interaction with the cavity play a significant part in determining the frequency and the amplitude of the oscillations produced in cavities.

Therefore, to better understand the mechanics of the oscillation so as to attempt to predict frequencies of oscillation and enhance the amplitudes of the oscillation, it is first necessary to investigate the properties of shear layers and then understand the importance of the cavity length.

SHEAR LAYERS

Previous discussions indicate that the frequency of oscillations in a cavity is dependent on the cavity length and the Mach number of the flow. However, at the heart of the cavity oscillation process is the behavior of the shear layer and its interaction with the cavity. Therefore, an understanding of shear layers is necessary to understand the cavity oscillation process. Free shear layers will be discussed first, followed with a discussion on forced shear layers.

Free Shear Layers

Free shear layers are produced through the merging of two streams initially separated by a thin surface or other obstruction in an environment without boundaries. This lack of boundaries makes free shear layers different than shear layers inside a cavity which are enclosed and impinge on the cavity trailing edge. However, investigating free shear layers provide a starting point for the understanding of shear layer behavior.

The growth of free shear layers is a consequence of the natural instability of the shear layer through the Kelvin-Helmholtz instability. As described by Ho and Heurre[15] and Lucas[16], the shear layer initially undergoes an initial exponential flow growth at some fundamental frequency. At some point the growth at the fundamental frequency lessens as the shear layer begins to roll up into vortices or divide into smaller vortical structures.

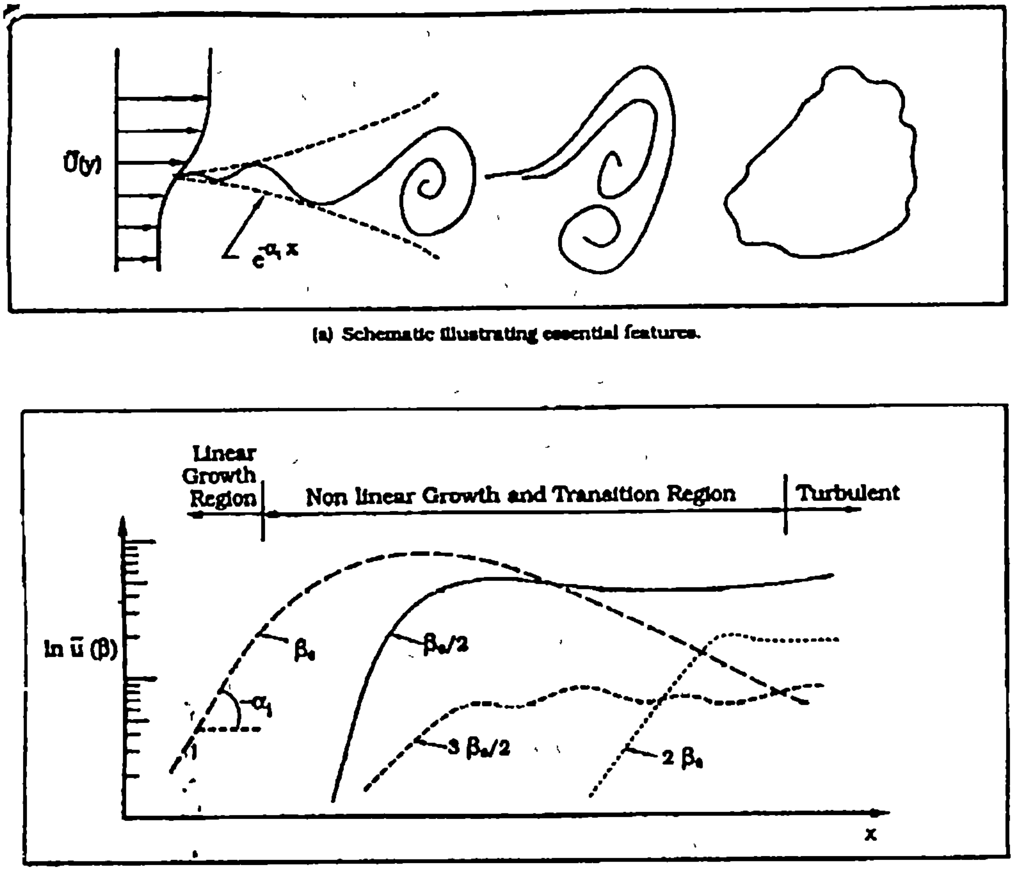
The energy transfer between the fundamental frequency growth and other harmonics are the cause of the reduction in the growth of the fundamental frequency. These vortices coalesce, which introduces growth at additional frequencies, usually harmonics of the fundamental frequency. This evolution is illustrated in Figure 2-8.

The value of the fundamental frequency can be determined mathematically through the solution of the Orr-Sommerfield equation (or, in the inviscid limit, the Rayleigh equation). Ho and Heurre point out however that there is no satisfactory nonlinear theory that describes the growth of the shear layer. In the absence of such a theory, they outline two different approximate models. The first model is phenomenological where the momentum thickness increases due to vortex pairing taking place at fixed distances downstream. The momentum thickness is constant between parings and doubles instantaneously at the location of pairings. This simplified model gives the following relationship for the growth of the shear layer.

$$\frac{d\theta}{dx} = \frac{(-\alpha_i\theta)_{\max}}{\ln G} \approx 0.12\frac{R}{\ln G}$$

where G is a constant growth factor and R is the convective velocity ratio $R = \dfrac{U_1 - U_2}{U_1 + U_2}$.

Another model utilizes the fact that there exists a global feedback mechanism in a free shear layer. This feedback occurs as a result of the sudden change in circulation during vortex merging. The merging vortices create an upstream travelling acoustic wave which, when in the proper phase relationship with the initial instability of the shear layer, influences the development of the shear layer.



(a) Schematic illustrating essential features.

(b) Streamwise disturbance growth rates.

Figure 2-8 Shear Layer Growth (from Lucas)[16]

In both of these models, Ho and Heurre indicate that the lengthwise growth of the free shear layer momentum thickness is related to the convective velocity ratio R In this case, U_1 is the velocity of one flow and U_2 is velocity of the other flow. Experimental data shows that the momentum thickness growth rate in free shear layers is related to the velocity ratio through $\frac{d\theta}{dx} = 0.045R$. Gauthier provides an analysis that shows that, once compressibility is accounted for, the compressible shear layer growth rate for cavity flows is approximately two to five times greater than that for free shear layers. This indicates that the feedback mechanism is forcing the cavity shear layer.

In an enclosed cavity, the flow will be represented as a jet rather than a mixing layer. Jets are different than mixing layers in that they have a second length scale, the jet diameter D (for axisymmetric jet) or slot height H (for planar jet). These produce two different frequencies of importance. The first is the shear layer mode frequency, which is associated with the most amplified wave of the initial velocity profile. In this case the dimensionless frequency uses the momentum thickness as length scale and is represented as $\frac{f\theta}{U}$, where θ is the thickness of the shear layer. The second frequency is called the preferred mode frequency. This frequency is a measure of the passage frequency of the vortices at the end of the potential core This frequency uses the jet diameter as length scale so the dimensionless frequency in this case is $\frac{fD(orH)}{U}$.

This discussion of free shear layers reveal that they are naturally unstable and their growth is a result of flow instabilities and vortex coalescence. A feedback process determines the natural frequency of shear layer oscillation. The shear layer growth is related to a dimensionless parameter called the convective velocity ratio. Experimental data has shown that the growth rate in cavity shear layers is significantly larger than that of free shear layers, which indicates some sort of forcing is occurring in the cavity shear layer.

Forced Shear Layers

Forcing a shear layer means introducing a disturbance into the shear layer. This disturbance, properly applied, will organize the vortex formation and coalescence that causes the shear layer to grow at a faster rate.

Forcing can be introduced into a shear layer through a number of methods. Ho and Heurre[15] distinguish two basic methods: 1) mechanically, using vibrating ribbons or flaps, 2) acoustically, through a loudspeaker. Vakili *et al.*[17] used periodic injection of fluid as a method of forcing. The main condition of the forcing is that it must be spatially coherent.

There are a number of parameters that, when properly implemented and applied, will cause shear layer forcing. These parameters are discussed below separately although they cannot in reality be separated from each other:

a. Frequency. Using frequency as a method of forcing is quite effective in manipulating the shear layer. In frequency forcing shear layers can be manipulated effectively with very low forcing levels, provided that the excitations is applied at the proper frequency[13]. This occurs due to what Ho and Heurre call subharmonic forcing. This entails introducing frequencies into a shear layer at specific subharmonic ranges of the fundamental frequency of the shear layer. In specific frequency ranges this forcing can cause simultaneous merging of a number of vortices, thereby increasing the shear layer growth rate.

For forcing frequencies much lower than the shear layer natural frequency and large forcing amplitudes, the initial vortices at the shear layer natural frequency rapidly form large vortices at the forcing frequency. This process has been called collective interaction and has been identified in a number of experiments, one of which was the forced-jet investigation of Crow and Champagne[18].

b. Phase. The relative phase of the forcing and natural frequency of a shear layer can have a significant effect on the growth of the shear layer. Numerous studies have indicated that the smaller the initial phase difference between the natural frequency disturbances and the frequency of the forcing, the faster the vortices will coalesce[15]. With a phase difference of π, the growth of the shear layer can actually be retarded because vortex formation is suppressed due to the phase difference.

c. Amplitude. Amplitude as a mechanism to force a shear layer is the least efficient of the techniques described here. However, as identified earlier, collective interaction usually requires a relatively large amplitude wave to force the shear layer. Therefore, amplitude can be effective when used in collaboration with other forcing parameters.

Shear layer forcing in Cavities

In light of the discussions of shear layers and shear layer forcing, cavity oscillation can now be reexamined.

Unlike free shear layers, cavity shear layers are bound by the trailing edge of the cavity. As stated earlier, free shear layers undergo forcing as a result of a feedback from the acoustic waves created by the merging of downstream vortices. This effect is replaced by the disturbance waves generated when a shear layer impinges on a downstream surface such as the trailing edge of a cavity. The effect of this impingement is to create a source of acoustic waves that travel upstream to affect the shear layers. The forcing is accomplished through impingement of the shear layer on the trailing edge of the cavity.

Impingement, that is allowing the shear layer to hit a downstream obstacle, can be considered a mechanism that implements frequency forcing of the shear layer. In forcing a free shear layer, the shear layer adjusts to the forcing frequency. In an impinging shear layer the distance from the shear layer origin to the impinging surface controls the frequency, for a given flow velocity ratio.

The experiments of Crow and Champagne[18] and Chan[19] indicate that external forcing allows initial vortices to coalesce faster and cause a greater growth in the shear layer. If the external forcing were coincident to the cavity resonant frequency, higher amplitude self sustained oscillations would result.

AMPLITUDE ENHANCEMENT OF CAVITY OSCILLATIONS

One of the objectives of this investigation was to examine the effect of external forcing to enhance the amplitude of the resonant oscillation in an enclosed cavity. From examining the mechanism of cavity flow, this would be best accomplished through interactions with the shear layer. In previous discussions on forcing it was noted that the most efficient way to manipulate the shear layer is through frequency forcing[15].

To investigate the effectiveness of external forcing on enhancing the cavity oscillation amplitude, it is necessary to determine a forcing frequency that will enhance the cavity oscillations. The problem is to match the forcing of a jet, which is controlled by the forcing frequency, with the natural forcing of the cavity, which is controlled by the cavity geometry. This matching can be accomplished by utilizing the work done by Chan[19]. His investigation on frequency forcing in a jet indicated that the maximum amplification of an induced pressure disturbance in the shear layer was relatively independent of the Strouhal number based on the jet diameter (St_D) and occurred at a Strouhal number based on length (St_L) of .92. His results are shown in Figure 2-9. This St_D independence with maximum amplification at a constant St_L provides the matching between the jet frequency forcing and the forcing controlled by cavity geometry.

Assume that the Rossiter equation is a representative model of the oscillation mechanism inside the enclosed cavity. The Rossiter equation can then be used to find a Mach number and jet velocity that would result in maximum amplification of the pressure disturbances. Inserting $St_L = .92$ into the Rossiter equation and rearranging gives

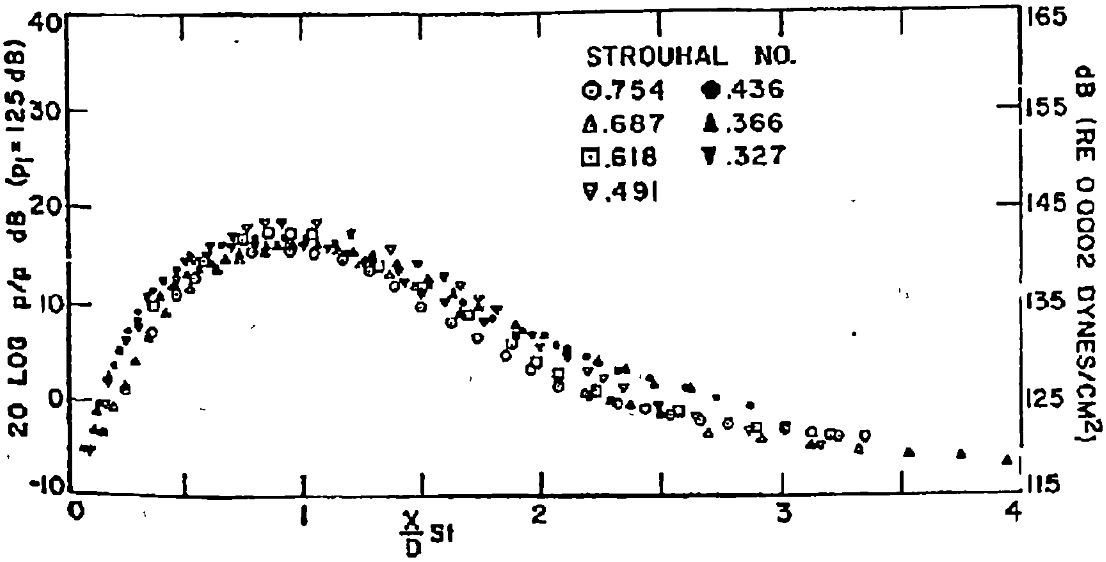


Figure 2-9 Pressure Distributions in a Jet (from Chan)[19]

$$M_{max} = \frac{m-n}{.92} - \frac{1}{K}$$

Using this relationship with the definition for the speed of sound will give the jet velocity. Table 2-1 gives the results for modes 1 to 3

Table 2-1 Mach number for first three modes with St_L of .92

Mode	Mach number	Jet Velocity (ft/sec)
1	-0.97	-305.54
2	0.116	39.91
3	1.203	363.69

Table 2-1 shows that mode one is clearly not physically realistic. Mode 2 is in the jet velocity range of Morel's investigation. Mode 3 occurs in the transonic range and so is applicable to this study. Using the dimensionless frequency values from figure 2-9 gives values for the forcing frequency. Using these forcing frequencies and the St_L =. 92 give values for cavity length. These frequencies and lengths are shown in Table 2-2 along with the associated St_D.

Table 2-2 Forcing Frequencies and Cavity Length

St_D	Forcing Frequency (Hz)	Cavity Length (in)
0.754	19629 4	0.671088
0.687	17885.1	0.736536
0.618	16088.8	0.81877
0.491	12782.5	1.03055
0.436	11350.7	1.16055
0 366	9528.31	1.38251
0.327	8513	1.5474

CHAPTER III

EXPERIMENTAL SETUP AND PROCEDURES

This chapter contains a description of the experimental installation and procedures used to obtain the data. The first part is a description of the experimental setup.

This experiment was conducted at the University of Tennessee Space Institute Propulsion Laboratory. The apparatus consisted of a high-pressure air source that fed a settling chamber consisting of a 3 inch diameter pipe approximately thirty feet long. Valves controlled the pressure within the settling chamber. A reducer allowed the connection of the cavity with the settling chamber. The total pressure in the settling chamber controlled the jet speed.

The cavity used was cylindrical with a length to depth ratio (L/D) between .813 and 1.63. Varying the cavity length through a moveable piston wall changed the L/D. A diagram of the cavity is shown in Figure 3-1. The moveable piston wall had a removable faceplate to allow for different jet exit configurations. The jet faceplate used in this experiment had a smooth convergent-divergent nozzle designed develop fully expanded flow at a jet exit Mach number of 1.23, the flow condition calculated for amplification. This faceplate was designed with a pressure tap at the nozzle exit. The static pressure at the jet exit was measured using this pressure tap. A diagram of the faceplate is shown in Figure 3-2.

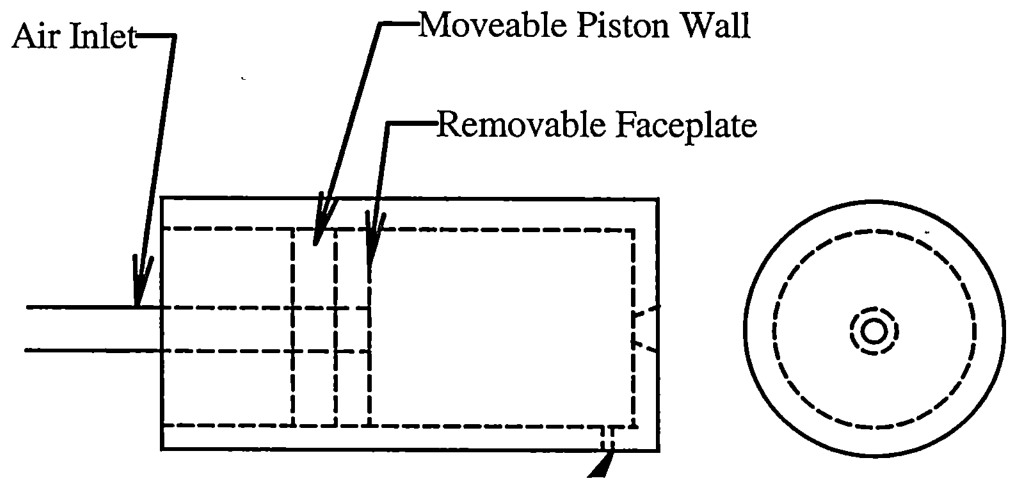


Figure 3-1 Diagram of Axial Pulsing Device

The pressure inside the cavity was measured using a Kulite XSL-7-093-25D miniature pressure transducer mounted flush on the cavity wall adjacent to the exit. The static pressure of the jet exit was measured using a KuliteXCS-093-25D miniature pressure transducer mounted at the outlet of the pressure tap on the removable faceplate as seen in Figure 3-2. The output from these transducers was fed into a Bridgeview PC based data collection system. The output of the cavity pressure transducer was also displayed on a HP spectrum analyzer. The frequency spectrum of the collected cavity pressure data was then calculated using MATLAB. The static pressure at the jet exit and the total pressure in the settling chamber were used to determine the jet Mach number using the isentropic expansion relations for pressure The temperature at the jet exit was determined by first measuring the temperature in the settling chamber. Then, knowing the Mach number, the temperature at the jet exit could be found using the isentropic expansion relations for temperature The temperature at the jet exit and the jet Mach number were then used to find the jet velocity.

For a given cavity length, the jet speed was varied until tones could be heard from the cavity, at which time data was collected. The frequency peaks were then determined from the spectrum data. These frequencies were used to calculate the Strouhal number. To provide jet forcing a speaker was installed in the settling chamber approximately 28 inches from the jet exit. The speaker was directed towards the jet exit and was hooked up to a frequency generator and amplifier. A diagram of the experimental apparatus is shown in Figure 3-3. The amplifier output was adjusted to approximately 17 volts RMS as measured on a voltmeter, which was the highest input

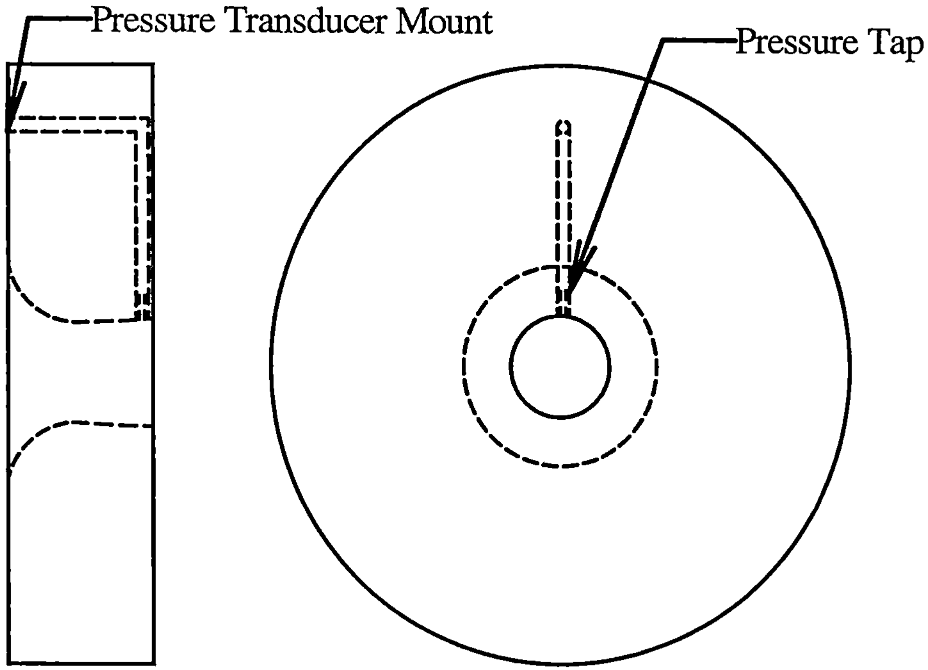


Figure 3-2 Axial Pulse Device Moveable Wall Faceplate

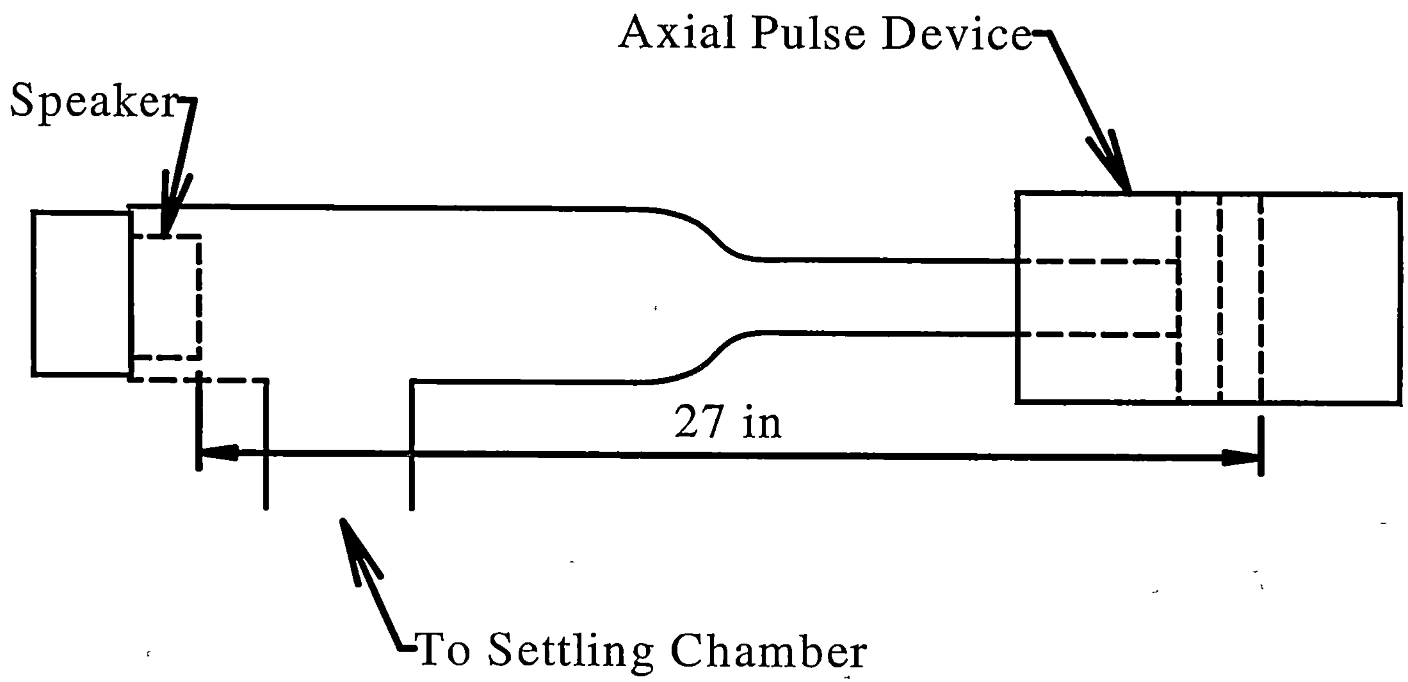


Figure 3-3 Speaker Installation for Frequency Forcing

amplitude that the speaker could maintain. Due to the frequency response of the speaker, the only condition that could be investigated was with a cavity length of 1.5474 inches and a forcing frequency of 8513 Hz. The actual frequency was 8520 Hz as measured by the HP spectrum analyzer A frequency plot of the speaker output with no flow through the cavity is shown in Figure 3-4.

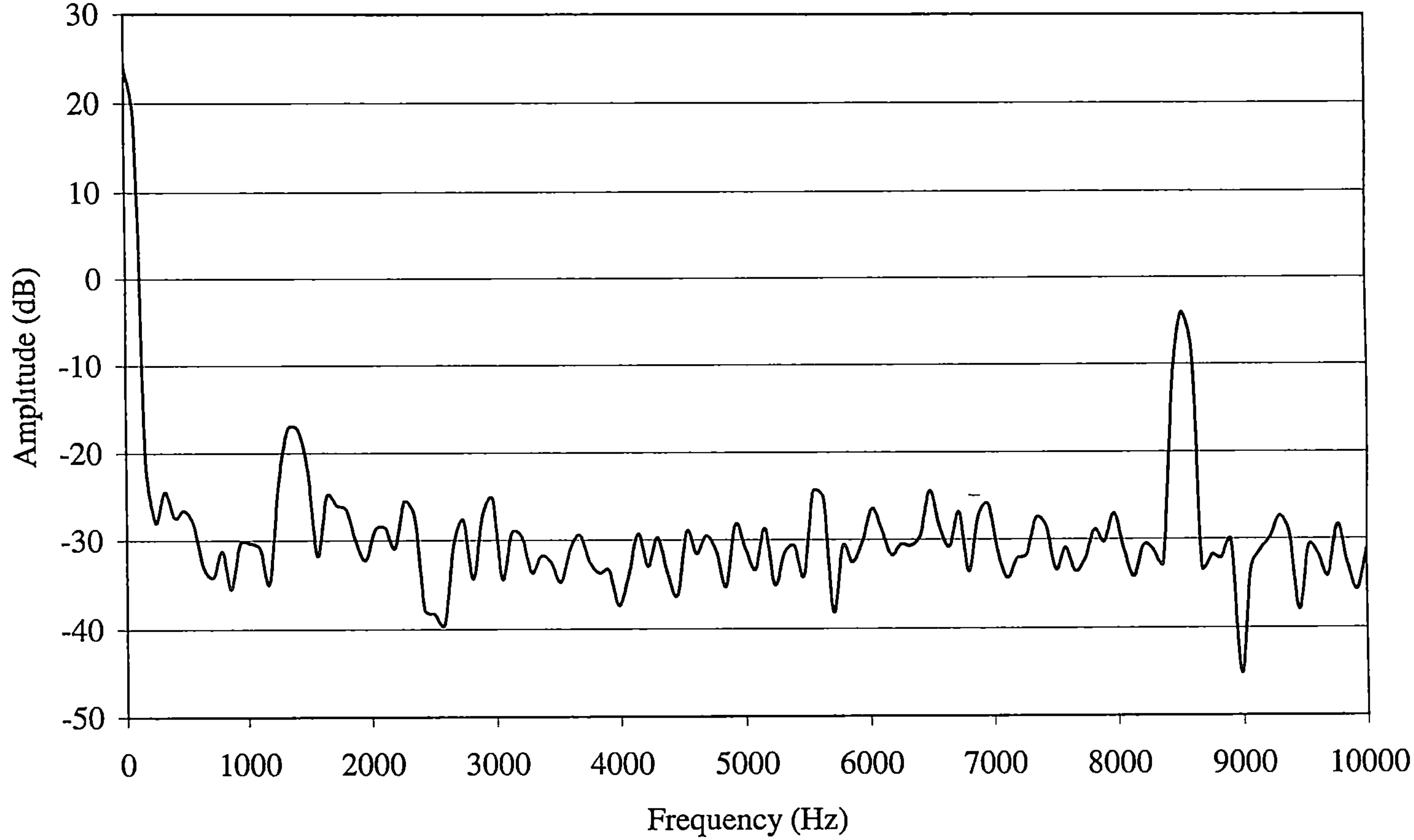


Figure 3-4 Speaker output with no cavity flow

CHAPTER IV

EXPERIMENTAL RESULTS

PROPERTIES OF CAVITY OSCILLATIONS

When pressure was increased slowly, the cavity emitted high-pitched "whistles" at certain pressures. When these whistles were heard, a resonant peak was observed on the spectrum analyzer. At pressures below approximately 15 pounds per square inch (psi), the frequency of these whistles would change suddenly at certain pressure settings. This indicated that there was some sort of mode switching occurring as the jet speed increased. Unlike Morel's observations, the observed frequencies were different. Above 15 psi, the observed peak frequency remained constant as the pressure was increased, but changed in amplitude. The observed frequencies changed for different cavity lengths for a given same pressure setting. At cavity lengths above approximately 3 inches however no oscillations were observed at any pressure setting. In all cases the observed resonant peaks were at frequencies significantly higher that the predicted Helmholtz oscillator frequencies for the cavity under examination. This indicated that a mechanism other than the Helmholtz oscillator phenomenon was causing the resonant peaks.

The spectral data given in Figures 4-1 to 4-4 shows this frequency change with changing total pressure for the different cavity lengths. The values of the observed resonant peaks indicate that the resonance is not the result of the Helmholtz property of the cavity. The resonance peaks were identified from each and the Strouhal number was calculated. Figure 4-5 shows the Strouhal number versus Mach number for all data. The data trend indicates that Rossiter's model spans the range of frequencies obtained for the

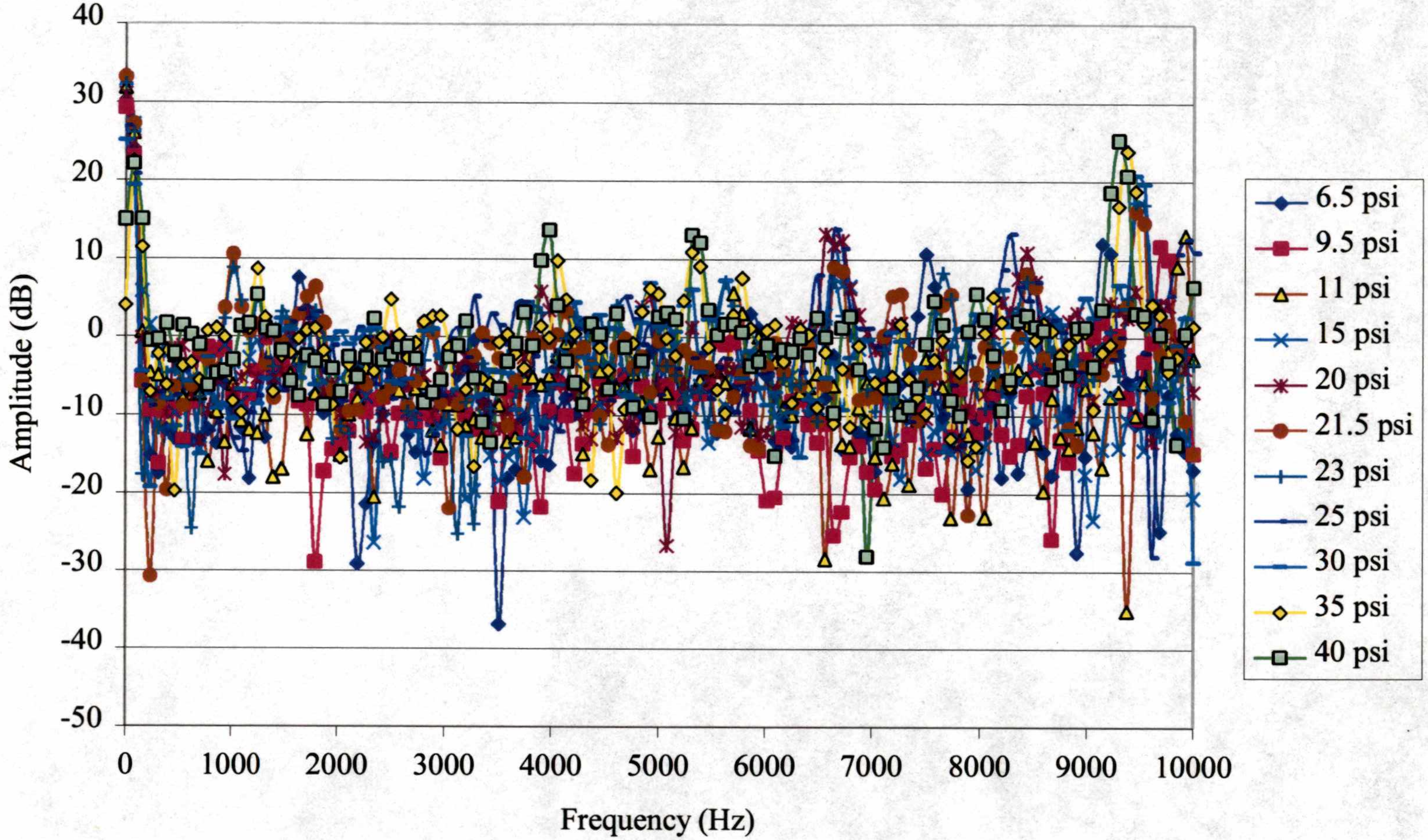


Figure 4-1 Cavity Resonance Spectrum Cavity L/D = .813

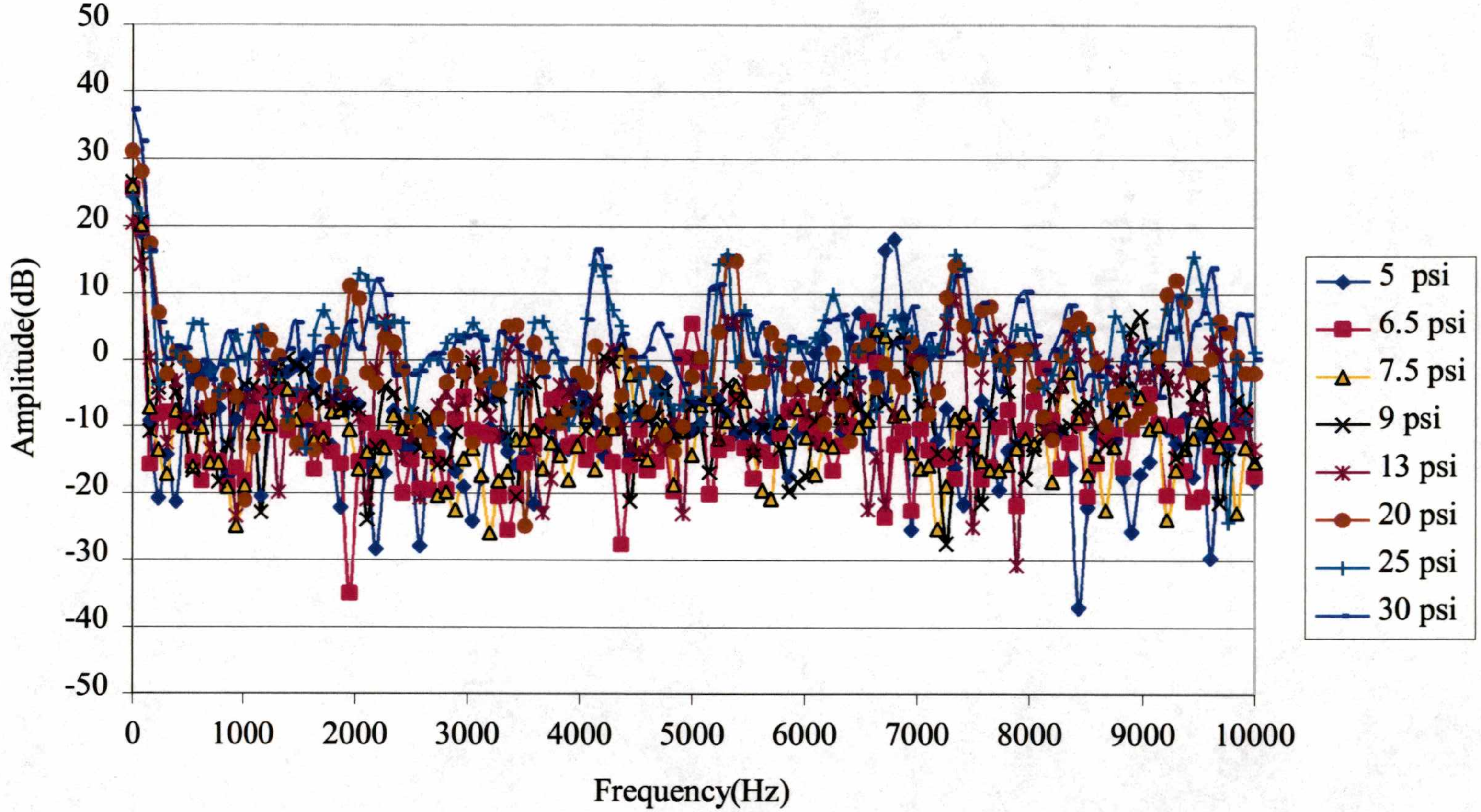


Figure 4-2 Cavity Resonance Spectrum Cavity L/D = 1.22

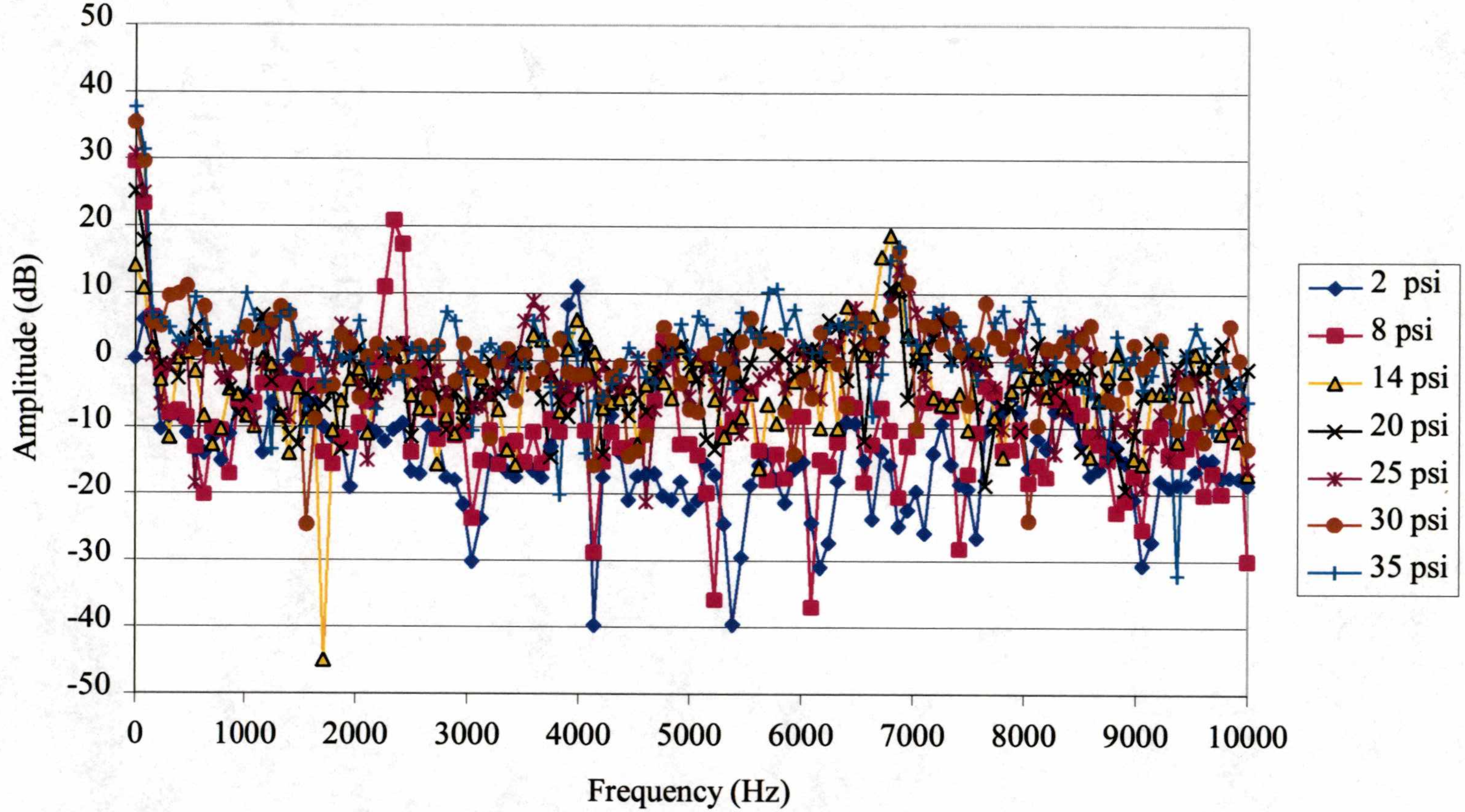


Figure 4-3 Cavity Resonance Spectrum Cavity L/D = 1.43

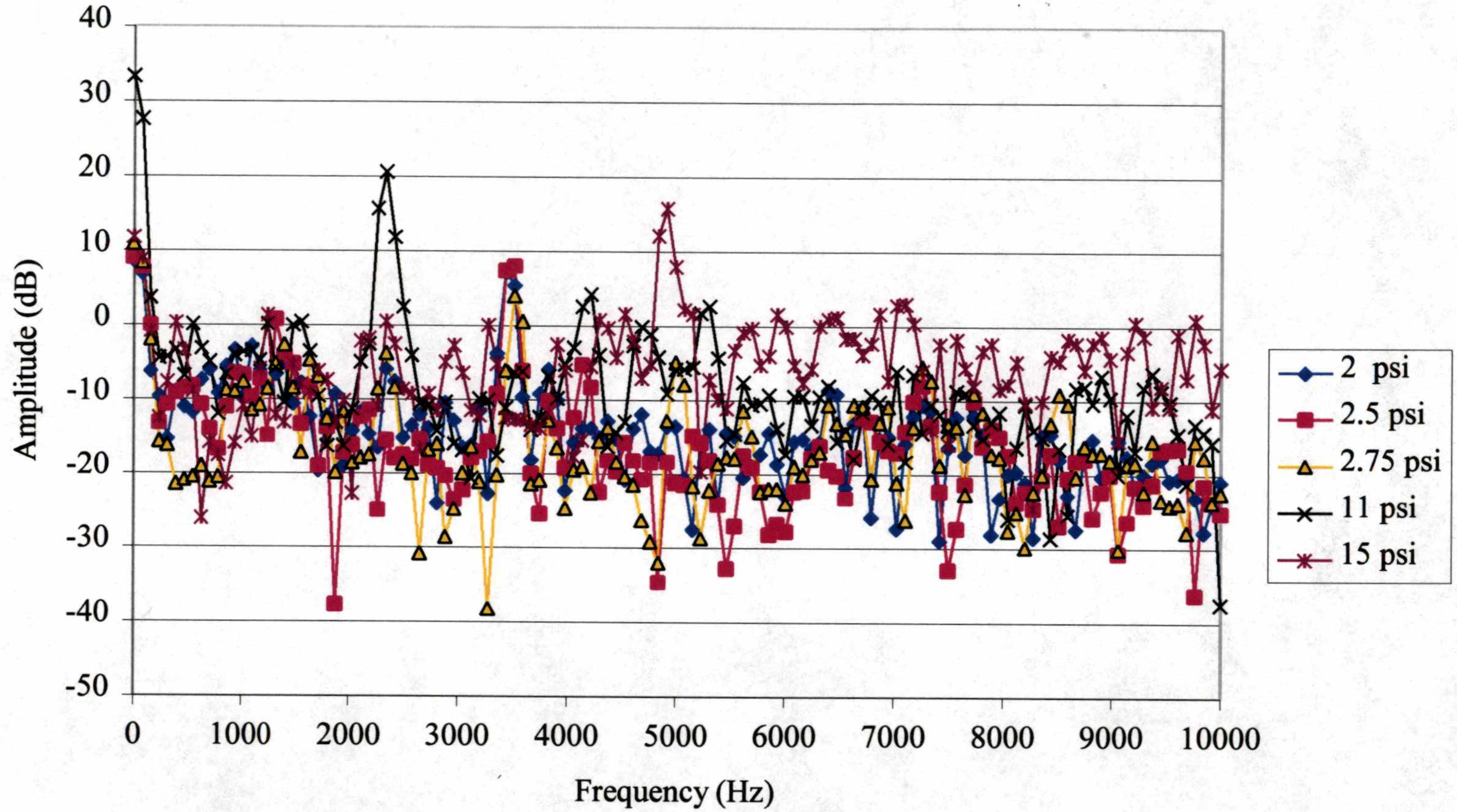


Figure 4-4 Cavity Resonance Spectrum Cavity L/D = 1.63

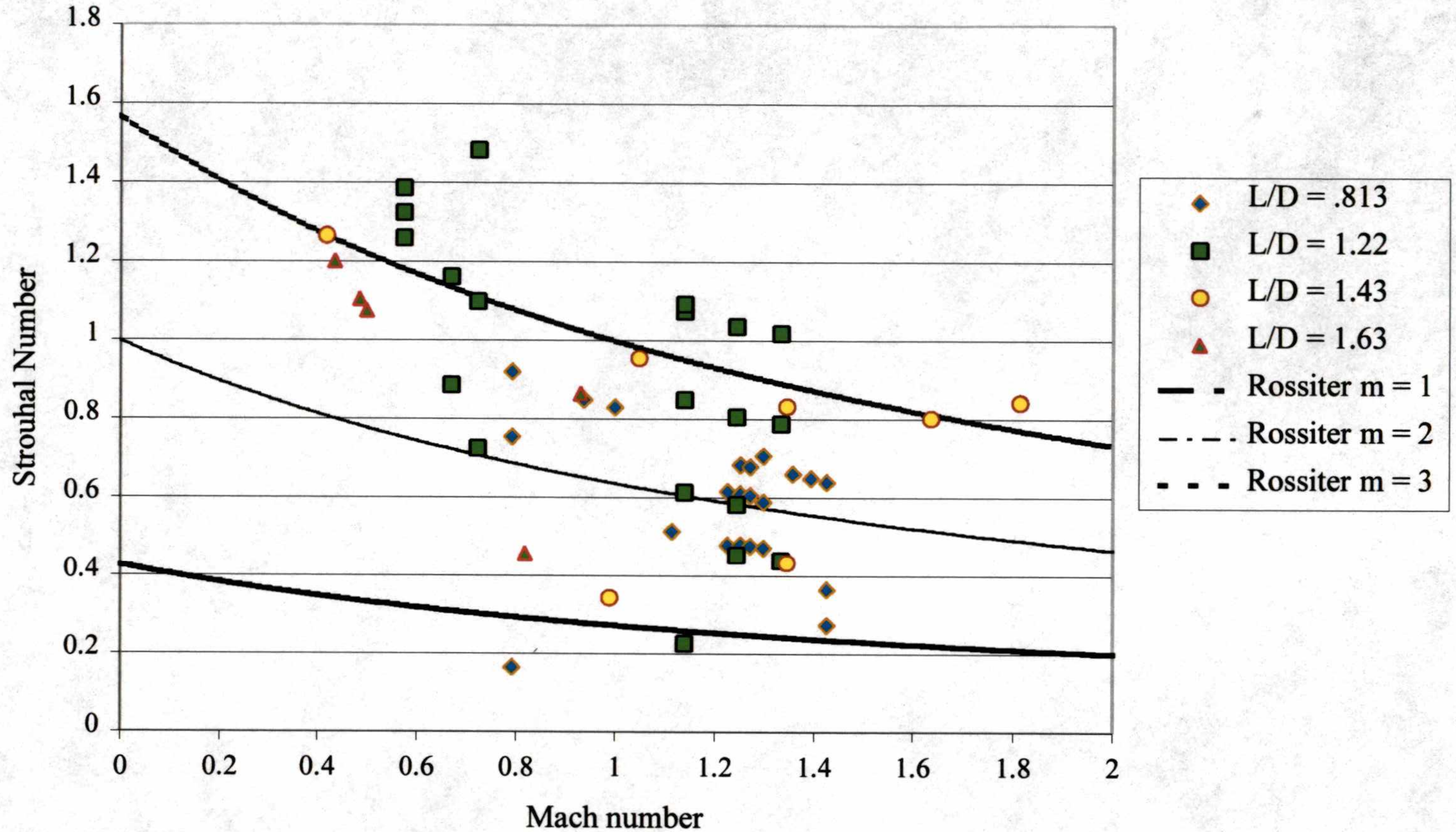


Figure 4-5 Comparison of Rossiter Equation with Cavity Resonance Data

enclosed cavity in this jet velocity range. The large scatter of the data suggests that the Rossiter equation is not a complete model to use in describing the oscillation characteristics of the cavity.

Because of these results, it was necessary to find other possible models to explain the cavity oscillation mechanism Another model considered was that the jet might have been coupling with the acoustic modes of the cavity. To determine if this was the case, the modes of the cavity had to be determined. This was done by solving the wave equation for a cylindrical cavity, with the boundary conditions of zero velocity at the cavity wall and finite velocity at the cavity center. Graphs of the resulting acoustic modes for each L/D are shown in Figures 4-6 to 4-9 along with the cavity data measured. These graphs indicate that the correlation between the predicted acoustic modes of the cavity and the measured cavity data is similar to that for the Rossiter model. This suggests that the oscillations produced by the jet are complex and may involve both coupling with the cavity acoustic modes as well as viscous interaction of the shear layer with the cavity.

AMPLITUDE ENHANCEMENT

The spectral data given in Figure 4-10 compares the forced spectrum with the unforced spectrum at a measured Mach number of 1 20 and a forcing frequency of 8520 Hz. The graph indicates that no increase in the amplitude of oscillation occurred when the forcing was applied To determine if resonance occurred at a different frequency, a frequency sweep was performed from 1 kHz to 10 kHz.

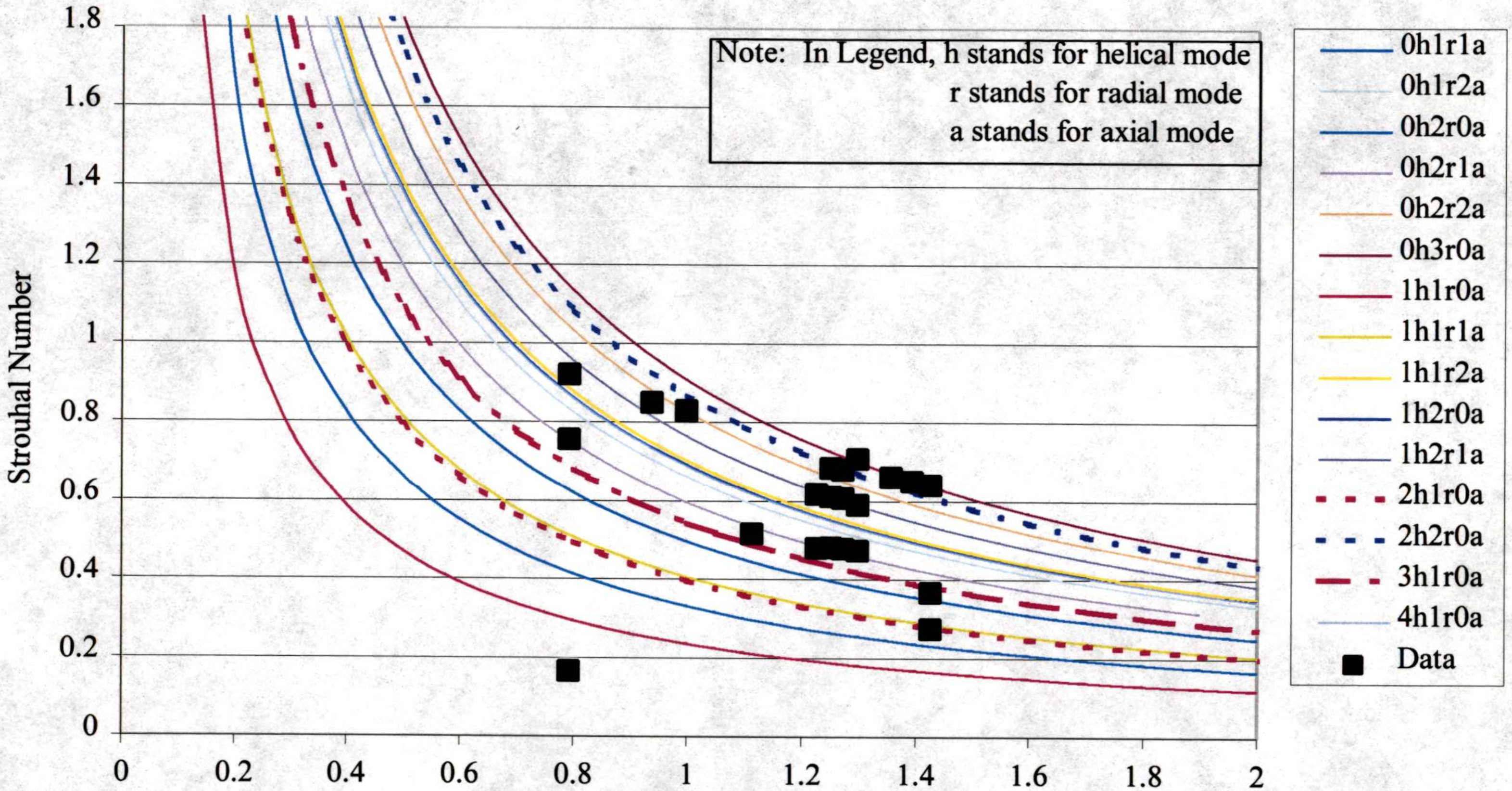


Figure 4-6 Comparison of Cavity Acoustic Modes with Cavity Resonance Data L/D = 0.813

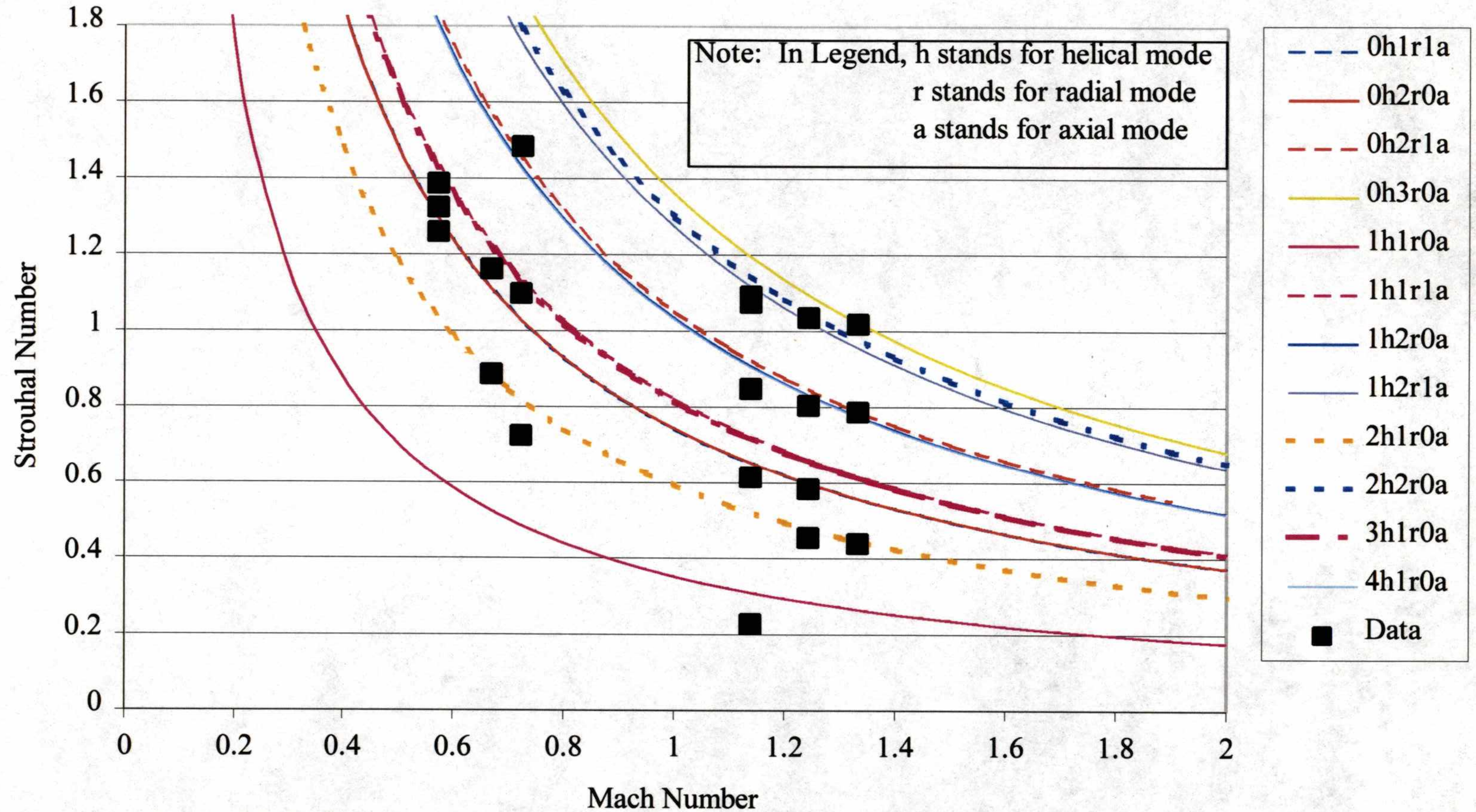


Figure 4-7 Comparison of Cavity Acoustic Modes with Cavity Resonance Data L/D = 1.22

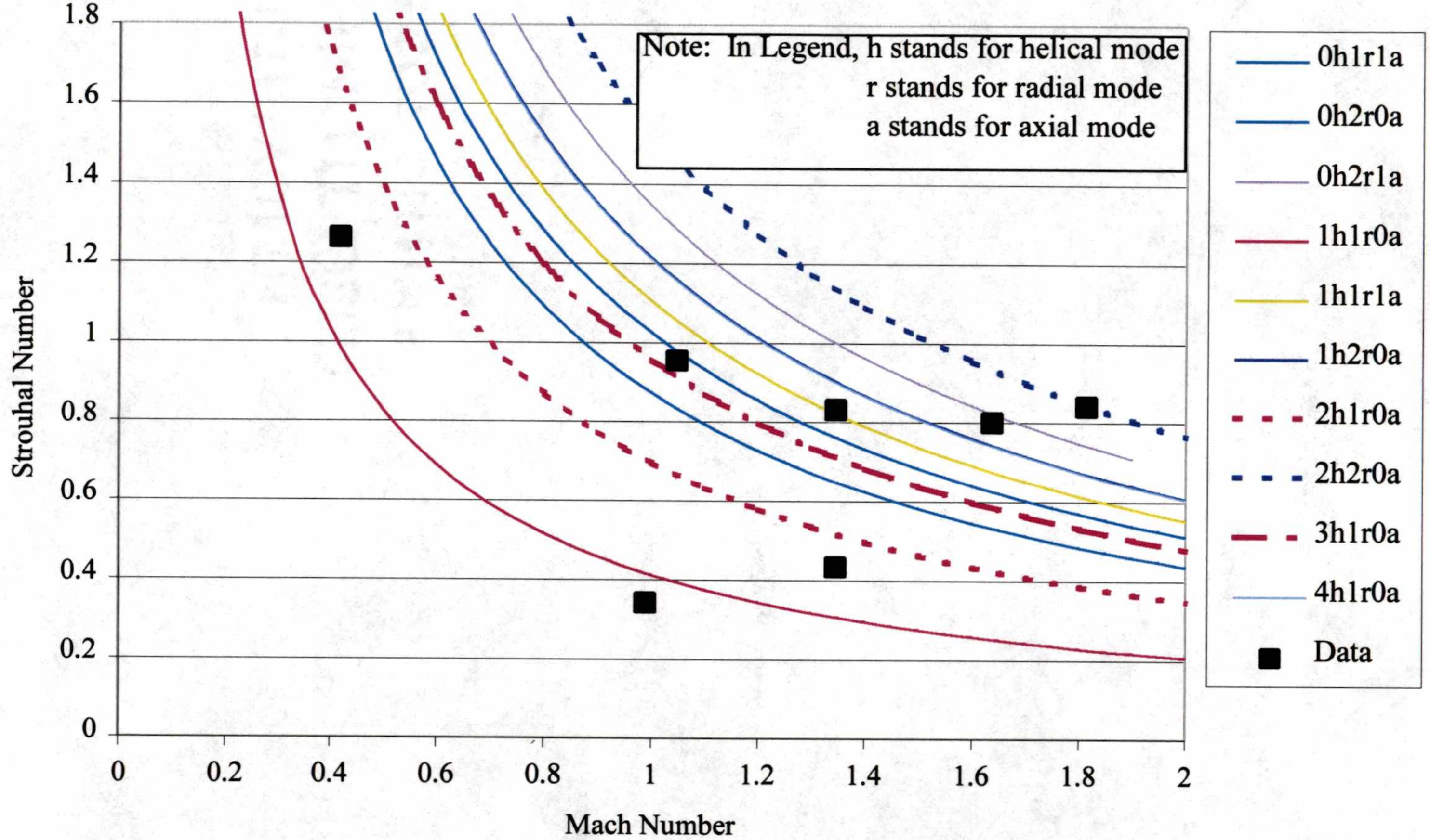


Figure 4-8 Comparison of Cavity Acoustic Modes with Cavity Resonance Data L/D = 1.43

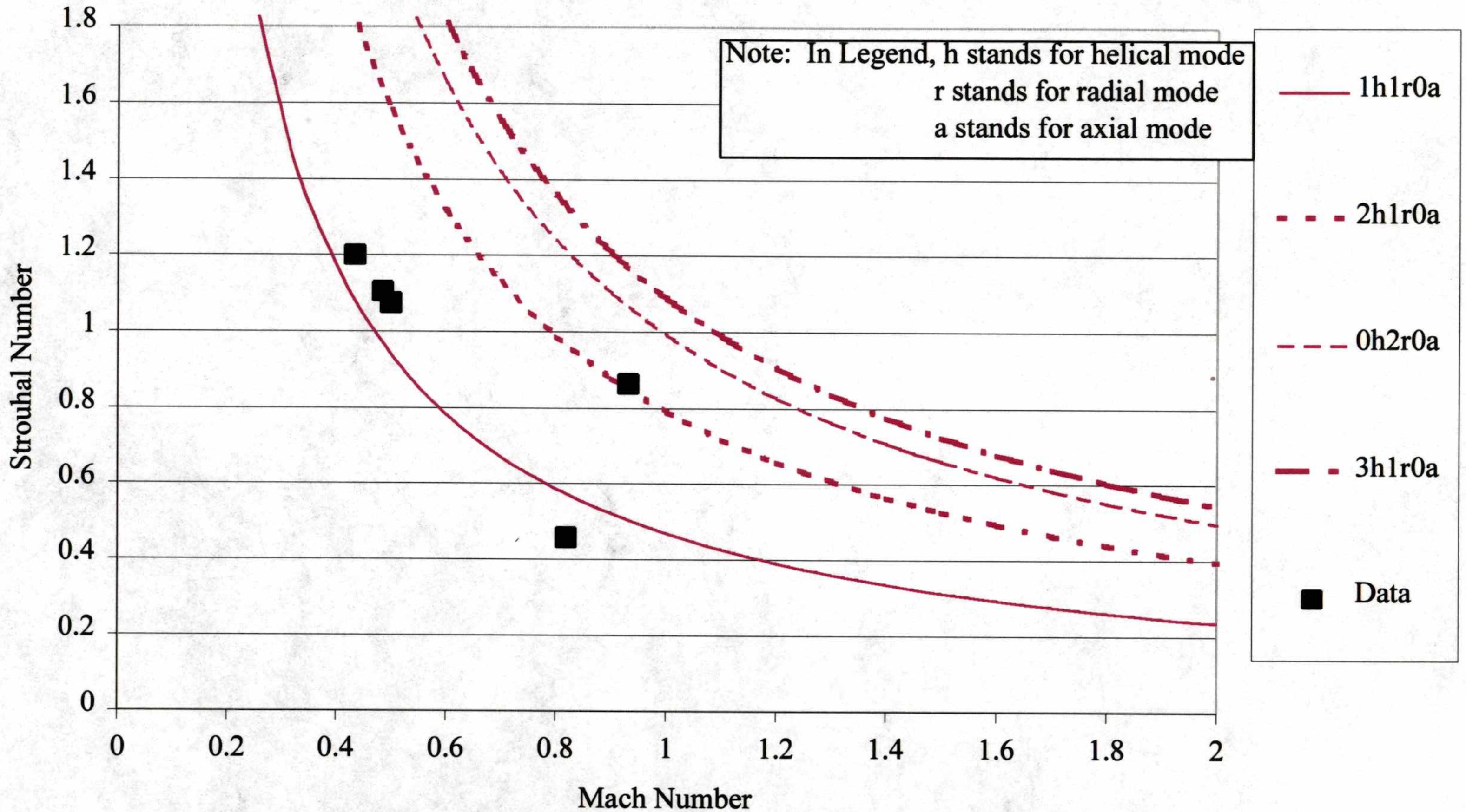


Figure 4-9 Comparison of Cavity Acoustic Modes with Cavity Resonance Data L/D = 1.63

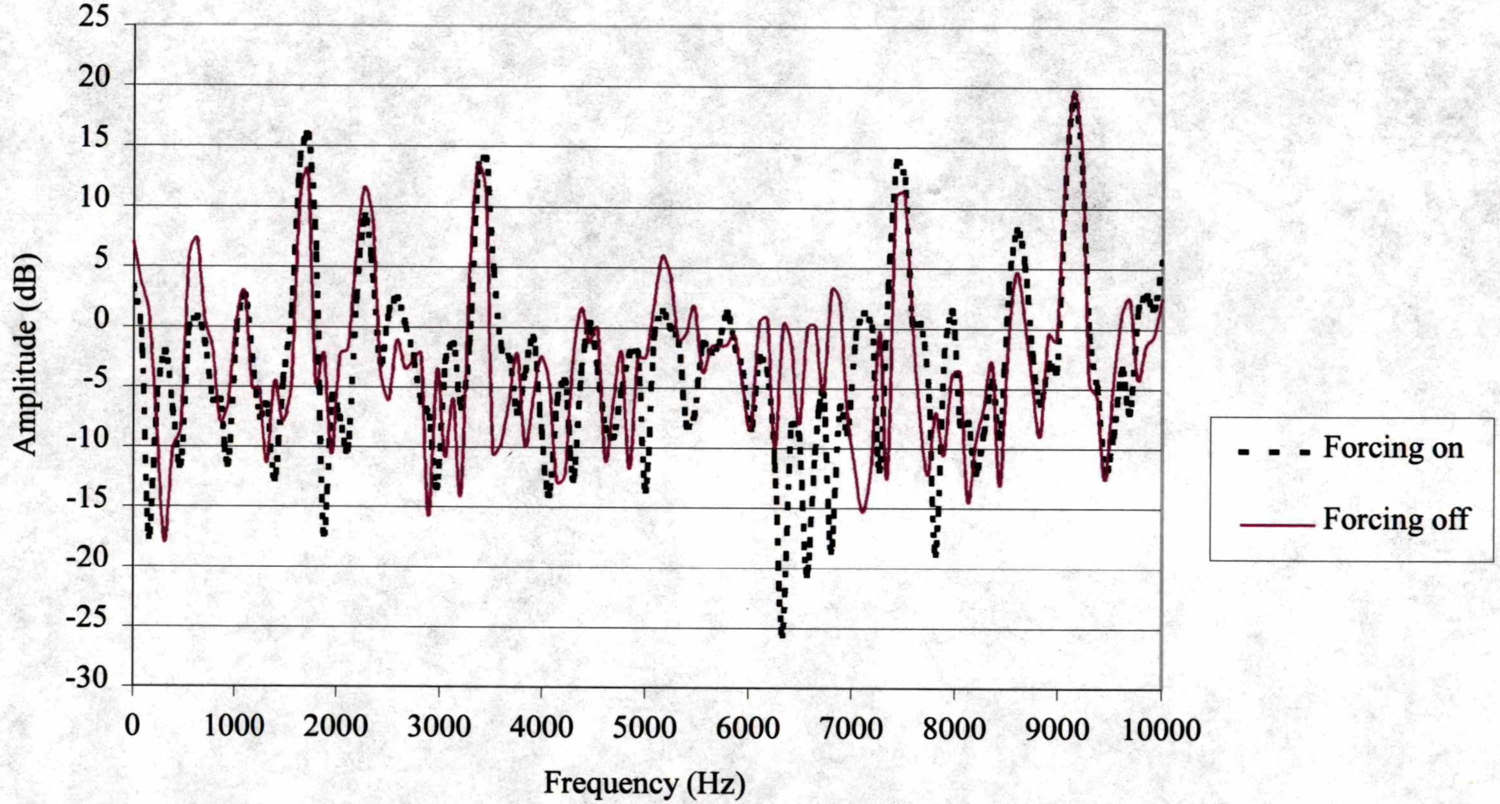


Figure 4-10 Cavity Resonances at Mach 1.20 With and Without Frequency Forcing at 8520 Hz

Although the frequency spike produced by the speaker output was seen to move as the input forcing frequency was changed, the amplitudes of the resident resonance peaks did not change during the frequency sweep.

There are a number of possible explanations as to why these results were obtained. These are:

a. The expected results were based on the assumption that the impingement of the vortices caused the acoustic feedback. By increasing the growth rate of the vortices, larger amplitude acoustic waves would be generated which would increase the amplitude of the oscillations. However as discussed earlier the models of Heller and Bliss as well as Tam and Block stated that the sinusoidal fluctuation of the shear layer was the primary means of creating the acoustic feedback. If this were the case, additional forcing of the shear layer would have little effect on the amplitude of the oscillations.

b. The method of forcing used in this experiment was similar to that of Crow and Champagne and Chan, referred to by Ho and Heurre as collective interaction. In this situation, large forcing amplitudes (ratio of the perturbation velocity to the jet velocity in the order of 10^{-2}) are necessary to force the shear layer successfully into this regime. In this experiment, the amplitude of the forcing may not have been enough to force the shear layer into collective interaction.

c. As stated earlier, one of the important parameters when considering forced shear layers is the relative phase of the forcing and the natural frequency of the shear layer. Depending on the relative phase the shear layer growth can be enhanced or retarded. In this investigation, the phase of the forcing frequency and the natural frequency of oscillation of the cavity was not measured nor could it be varied. If the phase of the forcing frequency and the natural frequency of oscillation of the cavity were not in the proper phase, no enhancement would occur.

d. Gauthier and Tam and Block both indicate that the responsiveness of the shear layer decreases as the initial momentum thickness of the shear layer increases The initial thickness of the shear layer was not known in this investigation. A thick shear layer would reduce the shear layer responsiveness, which would inhibit the effect of enhancement.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The frequency properties of enclosed cavities with L/D ranging from .813 to 1.63 with jet speeds ranging from 0.4 Mach to 1.4 Mach were investigated. Additionally the effects of forcing using an external acoustic source on the amplitude of the oscillations produced in a cavity L/D of 1.26 were also investigated.

As a result of this study, the following conclusions were drawn:

a. Oscillations were observed in the enclosed cavities that had significantly higher frequencies than the calculated Helmholtz frequency of the cavity;

b. The Rossiter equation is not a complete model to use in describing the oscillation characteristics of the cavity. The oscillations produced by the jet are complex and may involve coupling with both the cavity acoustic modes as well as viscous interaction of the shear layer with the cavity;

c. A significant increase in oscillation amplitude was not observed when a forcing frequency was applied. This may have been due to inadequate control.

With regards to the investigation of cavity oscillations, it is recommended that further studies be conducted. Such studies should include measuring the phases and identifying the modes of oscillations.

With regards to the enhancement of oscillation amplitude through active frequency forcing, it is recommended that further studies be conducted. Such studies should include:

a. Performing flow visualization studies to further investigate the behavior of the shear layer inside the cavity,

b. Quantitatively investigate the growth of the shear layer inside the cavity;

c. Quantitatively investigate the effect of increased amplitude of forcing.

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VITA

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