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Center # : R6620-0A0 | Center shr #: | OCA file #:
Work type : RES
Contract#: N00019-88-C-0294 | Mod #: | Document : CONT
Prime #: | Contract entity: GTRC

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Does subcontracting plan apply ?: N

Title: CONTROL OF UNSTEADY HEAT RELEASE AND LONGITUDINAL COMBUSTION INSTABILITIES IN ..

PROJECT ADMINISTRATION DATA

OCA contact: E. Faith Gleason 894-4820

Sponsor technical contact	Sponsor issuing office
DALE E. HUTCHINS	REGINALD WALKER, AIR-21523W (202)746-8612
NAVAL AIR SYSTEMS COMMAND AIR-932J WASHINGTIN, D.C. 20361-9320	NAVAL AIR SYSTEMS COMMAND WASHINGTON, D.C. 20361

DEC 1988

Security class (U,C,S,TS) : U | ONR resident rep. is ACO (Y/N): Y
Defense priority rating : DO-A1 | GOVT supplemental sheet
Equipment title vests with: Sponsor X GIT
ITEMS LESS THAN $5,000 VEST WITH GIT UPON ACQUISITION AND WITH PRIOR APPROVAL

Administrative comments -
* INITIATION. CONTINUES WORK BEGUN UNDER E-16-674; ONR CONTRACT. PREAWARD COSTS UP TO $7,000 AND BY 7/1/88 AUTHORIZED VIA MOD P00001.(SEE REV # 1 -TO FOLLOW)

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 02/15/90
Original Closeout Started ********

Project No. E-16-610 Center No. R6620-0A0

Project Director ZINN B T School/Lab AE

Sponsor NAVY/NAVAL AIR SYS CMD - WASH DC

Contract/Grant No. N00019-88-C-0294 Contract Entity GTRC

Prime Contract No.

Title CONTROL OF UNSTEADY HEAT RELEASE AND LONGITUDINAL COMBUSTION INSTABILITIE

Effective Completion Date 890928 (Performance) 890928 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	Y	
Other	N	

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
OCA/CSD	N
Other	N
	N

NOTE: Final Questionnaire sent to PDPI.

E-16-610

INVESTIGATION OF THE MECHANISMS RESPONSIBLE FOR LONGITUDINAL INSTABILITIES IN DUMP COMBUSTORS

Final Report

prepared for

Office of Naval Research

by

Ben T. Zinn, Uday G. Hegde, Dierk Reuter, B. R. Daniel, and Lawrence M. Matta

Georgia Institute of Technology

School of Aerospace Engineering

Atlanta, Ga 30332

Contract No. SFRC #N00019-88-C-0294

January 1990

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ABSTRACT

This report discribes the results of investigations of the mechanisms responsible for the occurrence of longitudinal instabilities in coaxial dump type ramjet combustors. These experimental and theoretical investigations have been performed because an understanding of these mechanisms will guide the development of methods for controlling instabilities. The interaction between a W-shaped flame and the longitudinal acoustic field which is generated by a spontaneous instability in the laboratory combustor has been studied. The primary cause of the instability is the unsteady heat release which results from the periodic modification of the flame structure by large scale coherent vortical structures generated near the flame holders. The effect of low frequency forcing on the instability was investigated experimentally. Studies of jet flows have shown that a process known as vortex pairing can occur when a shear layer is under the influence of pressure oscillations at both its fundimental frequency and a subharmonic of the fundimental. A similar result in the laboratory combustor would result in a large reduction of the amplitude of the pressure oscillation due to the instability. The data shows no evidence that vortex pairing took place in the combustor.

The dependence of the unsteady combustor behavior upon the phase difference between the unsteady heat release and the pressure oscillations was investigated both experimentally and theoretically. Experimentally, the the dependence of the frequency of instability and the amplitude of the pressure oscillation at this frequency were dependent on the phase difference between the heat release and the pressure oscillation. This was shown to be in agreement with Rayleigh's criterion. A theoretical model was developed to predict the frequency of instability, and the predictions of this model are in agreement with measured data.

INTRODUCTION

The principal objective of this research project was to determine the mechanisms which control the driving of low frequency longitudinal combustion instabilities in liquid fueled, single inlet, coaxial dump-type ramjet engines similar to the one shown in Fig. 1. In this type of ramjet combustor, liquid fuel is injected into the air flow in the inlet section, upstream of the dump plane. The liquid fuel droplets evaporate and mix with the air as they both flow towards the combustor. The flow expands over the backward facing step as it enters the combustor, and forms a recirculation zone behind the step which serves as a flameholder. It is expected that the majority of the fuel burns in a flame around a central, jet-like, core flow, which typically extends several inlet diameters downstream from the dump plane.

Development of ramjet engines has been hindered by the occurrence of destructive combustion instabilities[1-5]. These instabilities are often characterized by their frequency. Low frequency rumble is in the 50-500 Hertz range and is characterized by either longitudinal acoustic oscillations in both the inlet and the combustor[6,7], or by longitudinal oscillations in the inlet and a bulk mode oscillation in the combustor[8]. High frequency screech is characterized by transverse acoustic oscillations in the combustor. The low frequency longitudinal instabilities present the more serious problem. The excited high amplitude pressure oscillations may interfere with the inlet shock structure, resulting in inlet unstarting and severe loss of engine performance. This type of instability may also result in excessive vibrational loading on the system that could lead to mechanical failure. Screech type instabilities cause the enhancement of heat transfer to the engine walls, resulting in a loss of performance and reduced lifetime. Transverse-type instabilities may be effectively controlled by the use of acoustic liners, provided that the transverse dimensions of the engine are small enough to result in high frequency transverse acoustic modes. Lower frequencies require increasingly bulky liners.

The longitudinal-type instabilities have the greatest potential for hindering the development of ramjet engines due to the present lack of any effective means for their supression. There is presently no proven model capable of predicting when such an instability will occur. Therefore, the elimination of these instabilities involve costly and time consuming trial and error approaches. The research program discussed in this report addressed the problem of understanding the processes responsible for the occurrence of low frequency ramjet instability so that better methods for the treatment of such instabilities may be developed.

Combustion instabilities have appeared in nearly every type of propulsion system, including liquid[9] and solid[10] rocket motors, air breathing engines[11], and ramjets[12]. The combustion process provides the energy required for the excitation and maintenance of the oscillations in the majority of these cases. The oscillations are damped by energy losses due to viscous dissipation, heat conduction, acoustic energy radiation, and energy convection through the the exhaust nozzle[13]. When the system is unstable, the amplitude of the combustor oscillation grows in time as long as the energy added to the oscillation per cycle is greator than the amount lost through the above mentioned mechanisms. As the amplitude grows, the processes of energy gain and loss become nonlinear and amplitude dependent, and an amplitude is reached at which the energy added to the oscillation per cycle is equal to the energy lost per cycle. When this condition is reached, the fully developed instability continues at a constant amplitude as long as energy added to the oscillations ballances the energy lost.

In order to prevent the occurrence of an instability, either the amount of energy added to the oscillation per cycle must be reduced, or the amount of energy removed from the oscillation per cycle must be increased, or both. In order to apply one of these approaches, an understanding of at least some of the controlling processes is required.

Rayleigh's criterion[14] states that driving of acoustic oscillations by the combustion process occurs when

$$E = \int_V \int_0^T p\, Q\, dt\, dV \quad > \quad 0 \qquad (1)$$

where E, p, Q, t, T, and V are quantities proportional to the total energy added to the waves per cycle, the oscillatory pressure, the oscillatory heat addition by the combustion process, time, the period of the oscillation, and the volume of the combustor, respectively. The integration is performed over the entire combustor volume to account for all possible sources of energy addition. When p and Q are in phase, the above integral is positive and vice versa. Generally, p and Q may be in phase in some portion of V and out of phase in the remainder of V. In such a case, the sign of E depends on the relative magnitudes of the localized volumes of driving and damping in the system. Instability will occur when the integral in Eq. (1) is greator than some quantity L which describes the total energy losses that the system experiences during one cycle.

The interaction of pressure and velocity fluctuations with the combustion process in a ramjet generally determines whether the periodic heat release from the flame will be in phase with the pressure oscillation as required by Rayleigh's criterion for combustion instability to be present. It has been determined in earlier studies under this program[15] that the driving mechanism involves a feedback between acoustic motions, flame instabilities, and unsteady heat release. Specifically, acoustic velocity oscillations reinforce a fluid dynamical instability within the shear layer downstream of the flame holding region. This fluid dynamical instability results in the formation of vortical structures which affect the flame behavior. When the vortex generation is periodic, the unsteady combustion in the vortices results in a periodic heat release rate which oscillates with the frequency of the vortex shedding. If this periodic heat release is in phase with the local pressure oscillation, Eq.(1) indicates that the acoustic oscillation will be amplified. Therefore, in order to reduce or minimize combustion instabilities in ramjets, an understanding of the response of the combustion process to pressure and velocity oscillations is necessary.

CURRENT RESEARCH EFFORT

This research program has been concerned with the understanding of the basic mechanisms of ramjet instability. Previous investigations revealed that a primary cause of combustion instability in ramjets is the unsteady heat release from the core flame region of the combustor which results from the periodic modification of the flame structure by large scale coherent vortical structures. The goal of this research was to gain insight into the cause and behavior of these vortical structures and their interactions with the oscillations. The schematic of the developed experimental apparatus is shown in Fig. 2. One of the flame configurations which was investigated experimentally in the present phase of research is shown schematically in Fig. 3. The wave like flame structure is due to the interaction of the flame with the vortical structures in the flow field. It should be noted that the experimental flame structure is a 2-dimensional simulation of the axisymmetric structure normally found in a ramjet combustor.

One should also note that the vortical structures form symmetrically behind the flameholders. These vortical structures are shed because velocity oscillations at the flame holders generate an unsteady shear layer. The vortical structures are convected downstream at approximately the local flow velocity. These structures modify the shape of the flame, and as a result, the rate of heat release at any position depends on the vortex structure, and is, therefore, time dependent. At any location, the phase of the vortex depends on the time that passed as it was convected from the flameholders to its present location. Therefore, the local phase of the heat release from the combustion in the vortex structures with respect to the pressure and velocity oscillations is related to the convection velocity. The mean convection velocity in the combustor is, in general, small compared to the local speed of sound. This means that the phase of the heat release varies quickly with distance when compared to the phase of the acoustic pressure. The consequence of this is that in some parts of the flame region the pressure and the heat release are in phase, while in other parts they are out of phase. As expected, it has been verified by experiment that when significant pressure oscillations (100 dB or higher) are observed in the set up, the amount of heat added in phase with the pressure exceeds the amount of heat added out of phase with the pressure. It has been confirmed theoretically by Hegde et. al.[15] that the primary cause of the observed acoustic oscillation is the unsteady heat release from the vortical structures.

A complete review of the ramjet instability studies performed at Georgia Tech can be found in the final report of ONR Contract No. N00014-84-K-0470 [16]. The results of the current phase of this project are described in two publications, "Low Frequency Driving of an Unstable Ducted Flame," and "Frequency Control in Unstable and Pulse Combustors," which are provided in Appendices A and B, and briefly summarized below.

"Low Frequency Driving of an Unstable Ducted Flame"

This publication was prepared as a Special Problem in partial completion of the degree of Master of Science for L. M. Matta. It describes an experimental investigation into the possibility of interfering with and controlling the oscillations in a simulated unstable ramjet combustor through low frequency acoustic driving. The experimental setup is shown schematically in Fig. 2. The configuration was spontaneously unstable at approximately 80 Hz., and the experiment involved the driving of acoustic oscillations in the 35 - 125 Hz range. The objective of this study was to determine whether the driven waves reduce the amplitude of the unstable pressure oscillations. A number of recent studies of nonreacting axisymmetric jet flows has shown that a process known as vortex pairing can occur when a shear layer is subjected to pressure oscillations at both the naturally unstable frequency and a subharmonic of this frequency. When vortex pairing occurs, the subharmonic oscillation is amplified and the fundimental is damped. Because of the acoustics of the duct, the combustion process cannot be acoustically unstable at subharmonics of the fundimental frequency of the duct. Therefore, the occurence of vortex pairing would result in stable combustion.

It study showed that the instability was insensitive to driving in this frequency range, and no frequencies of driving could be found at which the amplitude of the pressure oscillation was significantly reduced. It has therefore been concluded that at no driving frequency has vortex pairing occurred in the flowfield.

"Frequency Control in Unstable and Pulse Combustors"

This paper was coauthored by U. G. Hedge, B. T. Zinn, and D. Reuter and was submitted for publication in the Combustion Symposium. It describes a theoretical and experimental investigation of the dependence of the unsteady combustor behavior upon the phase difference between the heat release rate and the pressure oscillations. A mixture of propane and air was burned in a two dimensional combustor, shown schematically in Fig. 4. The flame was stabilized on two cylinderical symmetrically positioned flame holders. In the experiment, the vertical separation distance between the flame holders was varied while maintaining the flame symmetry. This resulted in a variation in the frequency and amplitude of the combustor instability. The dependence of the phase difference between the flame CH radiation and acoustic pressure oscillations upon the flame holder separation distance was determined. According to Rayleigh's criterion, the system is expected to be unstable at the natural acoustic frequency of the unexcited combustor when the heat release (i.e., the CH radiation) is in phase with the pressure oscillation. Furthermore, when the phase of the heat release leads the phase of the acoustic pressure the frequency of instability will be higher than the natural frequency of the unexcited combustor, and vice versa. The measured data confirmed this prediction.

The objective of the theoretical investigation was to develop a model for predicting the the frequency shifts found in the experimental investigation. It is shown that the predictions of the developed model are in general agreement with the experimental observations. The results of this study could guide the development of methods for controlling combustion instabilities.

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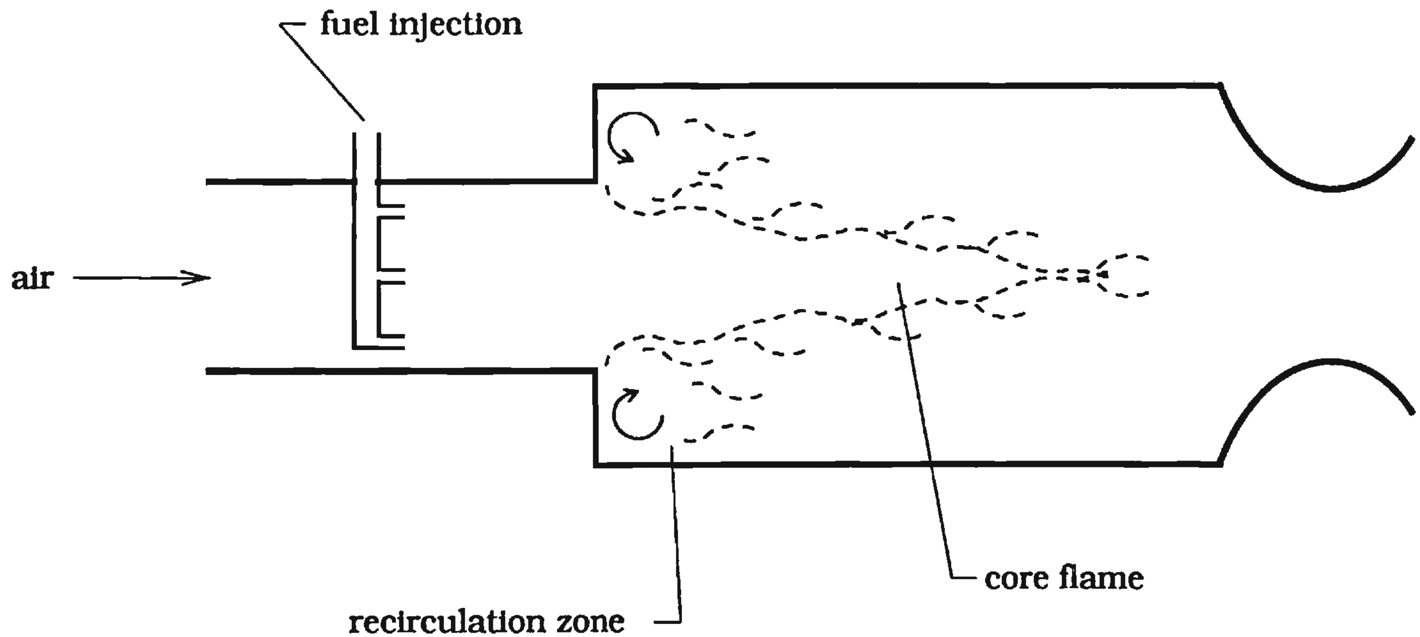

Figure 1. Schematic of a liquid fueled, single inlet, coaxial, dump-type ramjet engine.

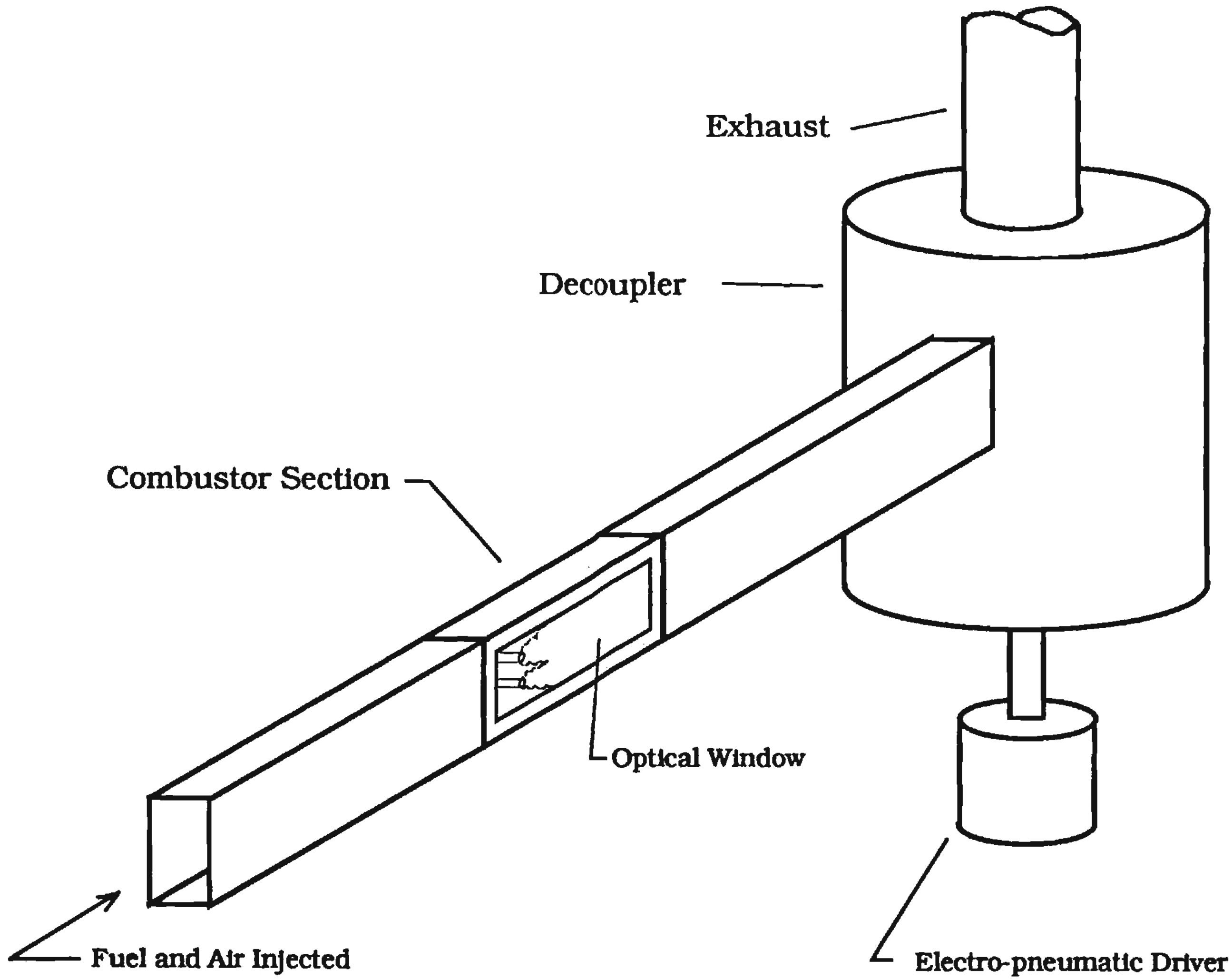

Figure 2. A schematic of the experimental set-up.

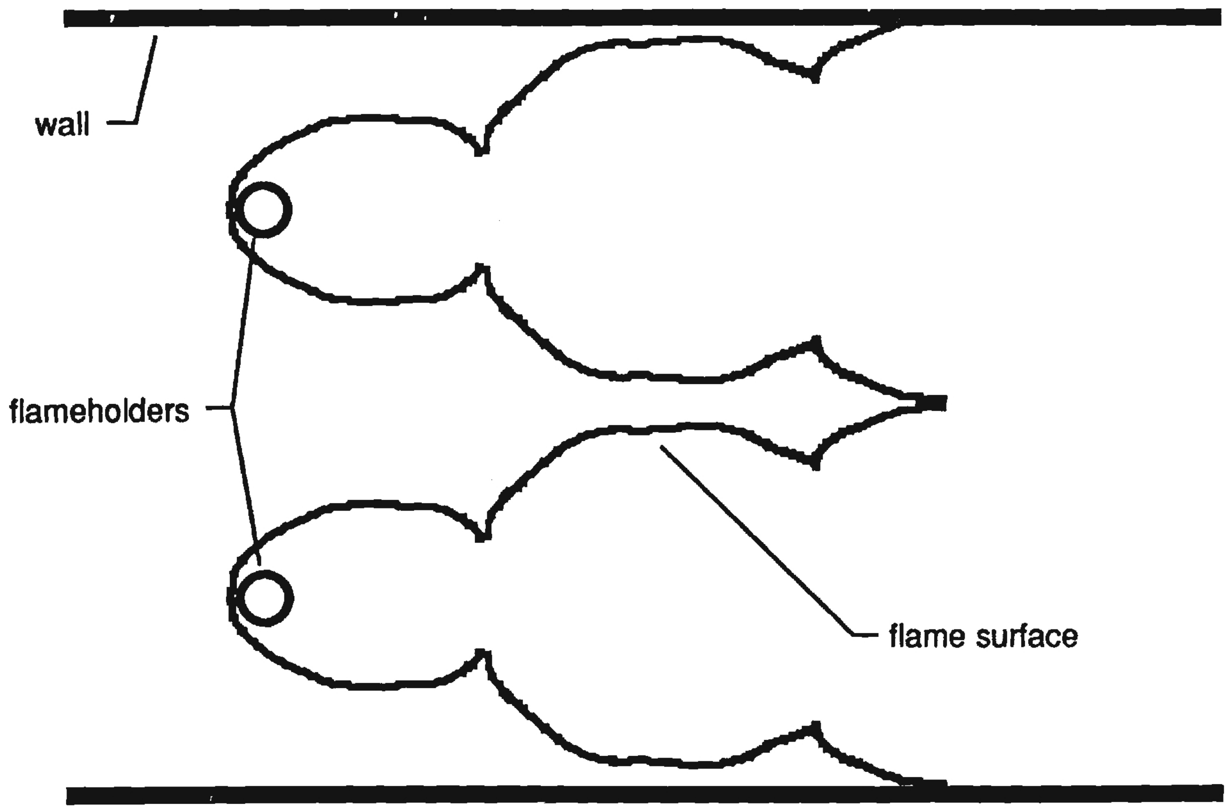

Figure 3. Schematic of the flame structure showing convolutions due to vortical structures.

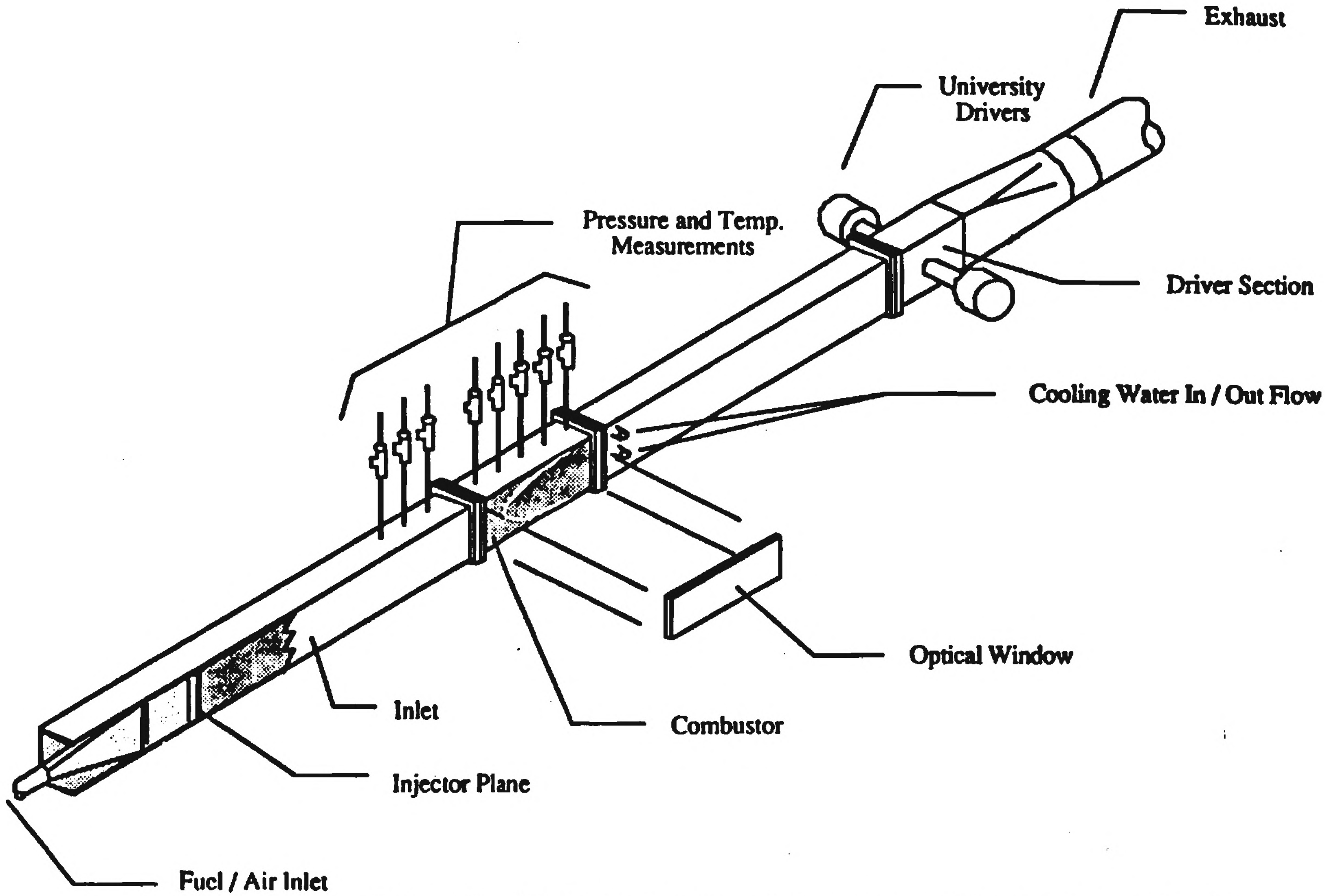

Figure 4. Experimental configuration used in the determination of the dependence of the frequency and amplitude of the unstable oscillations upon the vertical separation distance between the flame holders.

APPENDIX A.

LOW FREQUENCY DRIVING OF AN UNSTABLE DUCTED FLAME

L. M. Matta[1] and B. T. Zinn[2]

Georgia Institute of Technology
Atlanta, Georgia 30332

ABSTRACT

The objective of this experimental investigation was to enhance the current understanding of the nature of combustion driven, longitudinal mode, acoustic instabilities in ramjets. These longitudinal acoustic instabilities have been shown to result from a complex mechanism involving vortex shedding from the flame holders, convection of these vortices, distortion of the flame geometry by these vortices, acoustical driving by unsteady heat release, and the geometry of the duct. A laboratory ramjet combustor was developed to test the possibility that low frequency driving may affect the processes that generate large scale vortical structures in the combustion region, and promote the shedding of these structures from the flame holders at a frequency at which no acoustical instability was observed. This theory is based primarily on the observation of vortex merging in experiments conducted in non-reacting jet flows acoustically driven near subharmonics of their natural vortex shedding frequencies. Though some control over the frequency of instability was achieved through forcing at low frequency, no means of significantly reducing the overall sound pressure level of the system was discovered in this investigation.

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[1] Graduate Research Assistant

[2] Regent's Professor

Introduction

This paper is the result of a study into the effects of low frequency driving on longitudinal instabilities in single inlet, liquid fueled ramjet combustors. A ramjet is a simple air-breathing propulsion system characterized by the absence of moving parts. This type of engine relies on dynamic compression, and is therefore only useful at supersonic speeds. Flow enters the ramjet and is decelerated in the inlet diffuser section. A shock wave just downstream of the diffuser throat reduces the flow velocity of the air to subsonic. Fuel is injected and mixes with the air as it is convected downstream. The fuel and air mixture then enters the combustion chamber. The geometry of the combustor must provide a region of low velocity where the flame can stabilize. This is accomplished by the use of flameholders or a dump plane characterized by a backward facing step. The hot exhaust gases are then accelerated through a nozzle to produce thrust.

The combustion process in ramjets often becomes unstable. Combustion instabilities are a consequence of the sensitivity of the combustion process to fluctuations in pressure and velocity. If attenuation of these oscillations is weak, the unsteady motions in the flowfield may reach sufficient strength to interfere with the proper operation of the engine.

In ramjets, instabilities generally fall into two categories; high frequency screech in the 1000 - 3000 Hz range, and low frequency buzz in the 50 - 500 Hz range. High frequency screech involves excitation of one or more of the tangential acoustic modes of the combustor. Screech may enhance heat transfer to the engine walls, resulting in loss of performance and shorter engine life. Reduction of these instabilities may be effected through the use of acoustic liners. Low frequency buzz, on the other hand, seems to be much more troublesome to ramjet operation. Low frequency buzz involves the excitation of the longitudinal mode of the combustor. Instabilities in this range can interact with the inlet shock structure, reducing the efficiency of the system. In extreme cases, the shock is displaced from the diffuser, resulting in unacceptable loss of performance. Acoustic liners are not a practical solution to the problem of low frequency buzz, and so other methods of control must be developed.

To date, a small number of experimental studies of the coupling between the combustion process and acoustic instabilities in a ramjet combustor environment have been conducted. These include studies by Davis [1] and Heitor et al [2]. Davis identified two modes of low frequency instability in dump type combustors using high speed photography. The first mode was characterized by a cyclic oscillation of the entire combustion zone, while in the second mode, regular shedding of hot spots from the recirculation zone at the dump plane was observed. Heitor et al measured the frequency and strength of oscillations induced by premixed methane air flames stabilized on baffles located on the axis of a closed-open duct. They found that instability involving the quarter wave mode occurred for a wide range of fuel to air ratios. Smith and Zukoski [3] studied combustion instability involving a flame stabilized in the recirculation zone of a rearward facing step. It was reported that when the combustion was acoustically unstable, large vortical structures were formed downstream of the step at an acoustically resonant frequency. These structures were convected down stream from the step and the resulting unsteady combustion was found to feed energy to the acoustic oscillations. Keller et al. [4], in a study involving the mechanisms responsible for flashback, identified three modes of instability. This phenomenon was attributed to the action of vortices in the recirculation zone behind the step. These studies indicate that the fluid mechanics of the flame stabilization region plays an important role in combustion instability. Previous studies in this facility have suggested that low frequency instabilities are driven by unsteady combustion in vortical structures shed at the flame holders [5],[6]. Instability in the shear layer formed in the wake of flame holders was observed to interact with the acoustic oscillation at the frequency of instabilty which gave rise to the vortex shedding process [7]. It was found that these vortices periodically distort the flame front, causing oscillatory changes in the rate of heat released by the combustion [8]. Recent studies of axisymmetric jet flows have shown that shear layer instabilities may be influenced by low frequency driving. It has been shown by a number of researchers including Ho and Huang [9], Monkewitz [10], and Mankbadi [11] that a shear layer influenced by pressure oscillations at both the naturally unstable frequency and a subharmonic of this frequency greatly amplifies the subharmonic oscillation in a process known as vortex pairing. According to Monkbadi, vortex pairing occurs when the subharmonic absorbs energy from the fundimental oscillation to become the dominant instability component.

In the present experimental effort, a ramjet-type combustor will be acoustically forced at frequencies near the natural frequence of instability. Pairing of the vortices shed from flame holders could influence the ability of the unsteady combustion process in a ramjet to drive a pressure oscillation at the normally unstable frequency. It is also possible that by forcing an oscillation at a frequency at which the shear layer is less stable than at the natural frequency of the entire system, that the vortices shed from the flame holders may no longer be capible of driving the acoustic instability.

The **W**-shaped flame geometry used in this experiment is shown in figure 1. The character of this flame structure is quite complex in nature. The flame is stabilized in the low velocity region in the vicinity of the flame holders, and the flame sheet locates itself in the flow field where the flame speed is equal to the freestream velocity component normal to the flame surface. Due to the unsteady velocity component, vortices are periodically shed from the flame holders which distort the flame surface. These distortions in the flame surface are convected downstream, where they impinge upon either a wall or an opposing flame branch. This causes the total flame area to change periodically. The result of the change in total flame area is periodic heat addition to the flow field. If the heat release is in phase with the acoustic pressure of the combustor, the acoustic pressure will increase in amplitude. This will result in an increase in acoustic velocity, which in turn will cause the strength of the vortices shed from the flame holders to increase.

The boundary layer of the flame holders during combustion appears to be unstable over a range of frequencies which include the natural frequency of the combustor. This instability results in periodic shedding of vortex pairs from the flame holders. This shedding is not alternating, as in the classic Von Karmen vortex shedding from a cylinder, but instead two vortices are shed simultaneously. These vortex pairs are shed when the time dependent component of the velocity is at a maximum in the downstream direction. These vortices then proceed to roll up into coherent structures, affecting the flame sheet as shown in figure 2.

As these coherent structures convect downstream, they impinge upon either a wall or an opposing flame branch. As the vortical structures impinge, pockets of reactants are consumed in such a way that the flame lengthens and shortens over time, resulting in a periodic variation of flame area. Assuming that the propagation speed of the flame remains constant in a premixed gas undergoing only small pressure variations, the total reaction rate, and therefore the heat release rate, is a function of the flame area. The heat release rate may or may not be in phase with the acoustic pressure, because the phase of the heat release is dependent on the time needed to convect the vortex pairs from the flameholders to the impingement region.

The periodic heat release may add or remove energy from the acoustic signal in the system, depending on the phase difference between the acoustic pressure and the periodic heat release. This may be understood by Rayleigh's criterion. Figure 3, taken from Wood [12], shows that if the pressure signal and the heat release are in phase, driving will occur. If they are of opposite phase, damping will occur. If they are exactly 90° out of phase, no influence on the amplitude will be seen, although there may be some effect on the frequency of the pressure oscillation.

Experimental Efforts

A schematic of the set-up is shown in figure 4. It was developed to simulate the combustion process in the core flame of an operational ramjet combustor. The set-up contains 4 basic elements: the combustor, the electro-pneumatic driver, the decoupler, and the exhaust duct. The combustor section consists of an injection and cold flow zone, a combustion zone, and a hot flow zone. The injector is moveable, providing a maximum possible length from the injector surface to the exit of the combustor duct of 3 meters. This length determines the low frequency limit of the fundimental mode of the combustor. A mixture of air and propane flows in through the sintered stainless steel plate of the injector. The mixture flows downstream in the 5.0 x 7.6 cm^2 duct through a fine wire mesh grid to dissipate turbulence.

A flame is stabilized in the combustion zone on two horizontal, cylinderical flame holders, each with a diameter of 6.3 mm. This generates a **W**-shaped flame structure. The hot combustion products then procede downstream and exit the combustor section duct into the decoupler.

Acoustic driving is provided by a Ling electro-pneumatic transducer model EPT-94B, which can generate an acoustic output of 4000 watts in a range of 10 - 500 Hz. The output of the driver is directed into the decoupler, tangent to the axis of the combustor duct. The exhaust section exits the decoupler opposite the driver, and is kept at a pressure slightly below ambient, so that backflow into the combustor can be minimized.

For this experiment, the flameholders were set symmetrically, so that all vortical impingement phenomena occurred in phase. This means that the flameholders were situated in the duct at $^1/_4$ and $^3/_4$ the duct height and at the same axial location, so that the the 4 branches of the **W**-shaped flame inpinged upon either a wall or an opposing flame branch at the same axial distance downstream of the flame holders. With this geometry, the unsteady heat release from each flame branch is in phase, because the covection time from the flame holders to the impingement region is the same for each branch. This produces a high level of instability. The fuel/air ratio was adjusted to 0.024. This ratio was maintained throughout in an attempt to provide a constant level of instability. Measurements of the pressure oscillation and the global C-H radical radiation were taken for various driving frequencies. As the natural mode of the system was found to be near 90 Hz, measurements were taken at 5 Hz increments from 50 Hz to 120 Hz. At each frequency, measurements were taken without driving, as a reference, and then at various amplitudes of driving. Pressure measurements were taken using Kistler model 211B-5 piezotron pressure transducers amplified with Kistler model 504E amplifiers. These transducers were routinely calibrated using a Breul and Kjaer type 4221 high pressure microphone calibrator. Temperature readings were taken using a type-K, Chromel-Alumel, thermocouple and a NEFF DC amplifier. The C-H radical radiation was collected through an optical filter at 513.5 nm and captured in a Hamamatsu R-374 photomultiplier.

Results

The auto-spectrum data show a very strong correlation between the radiation output and the pressure signal in the neighborhood of the instability. Figures 5, 6, and 7 show the pressure and normalized radiation spectra for runs with no driving, weak driving at 70 Hz, and strong driving at 70 Hz as typical examples. The radiation measurement allows only a relative magnitude of the heat release, because the constant of proportionality between the photomultiplier output and the heat release rate is unknown. However, this relative magnitude is enough to indicate the relationship between the heat release rate and the pressure. Therefore, the normalized radiation signal is auto-spectrum of the output voltage from the potomultiplier, which is proportional to the rate of heat release. In figure 5, the auto-spectrum of the pressure oscillation follows very closely the trends of the normalized radiation spectrum, especially between 80 and 100 Hz. The maximum amplitude of the pressure oscillation, which is the unstable frequency, occurred at approximately 92 Hz. in this test. This shows that for the studied range of frequencies there is definitely a direct correlation between the pressure oscillations and the unsteady combustion. Notice, however, that in both figures 6 and 7, where driving is at 70 Hz, that there is very little correlation between the radiation signal and the pressure signal in the neighborhood of the driving frequency. It is evident that forcing at this frequency does not have a direct effect on the unsteady combustion. This is in contrast to the case of driving at 60 Hz, which is shown in figure 8, where the 2 curves are seen to have similar tendencies over the entire spectrum including the forcing frequency. The phase difference as a function of driving frequency is shown in figure 9. The line shown on the figure represents a least squares fit of the phase data for strong and weak driving. This data shows a linear phase relationship that depends on the frequency and not the amplitude of driving. The phase difference between the radiation and pressure signals at the same frequencies but without driving is shown for comparison. The linear nature of this curve suggests that the phase of the heat release at a particular frequency is a function of the the convection velocity between flameholders and the impingement zone. This has previously been established for the frequency of the instability in previous studies.

A characterization of the processes involved in this experiment can be developed following the obtained results. This involves a characterization of the feedback loop mechanisms through which the instability is generated.

Vorticity is generated at the flame holders through a shear-layer instability. The strength this vorticity is a function of the unsteady component of velocity seen by the flame holders. The vortices roll up into coherent structures, and are then convected downstream at roughly the local mean velocity. The majority of the unsteady heat release occurs where the vortices impinge upon either a wall or a vortex structure from an opposing flame branch. This is exemplified by the fact that when the system is unforced, the greatest amplitude of instability occurs when the vortex impingement of all the flame branches occur in phase. The unsteady heat release occurs because the flame sheet is involved in these structures.

When driven, the system contains 2 signals; the naturally unstable oscillation and the forced oscillation. The shear layer of the flame holders is unstable for some range of frequencies. When driven below the range of frequencies for which the shear-layer is unstable, the forced pressure oscillation modifies the magnitude of the vorticity, while the vortices are shed at the natural frequency. Thus, the unsteady heat release occurs at the natural frequency while its amplitude varies at the forcing frequency. The system is still strongly driven at the frequency of instability. Some reduction is noticable in the pressure level of this mode, however. This is because the amplitude of the pressure oscillation due to the instability is limited by damping effects in the system. This damping is a non-linear, and the amount of damping increases with the amplitude of the pressure oscillation. The effect of this non-linearity is that when the system is driven in this range of frequencies, slightly more of the energy added to the acoustic oscillation by the unsteady combustion is removed by attenuation processes. For driving in this range, the forced oscillation may be reinforced or damped by the unsteady heat release. This is entirely dependent on the phase difference between the heat release and the pressure oscillation, which for a particular system depends only on the mean convection velocity between the flame holders and the impingement zone. Whether the forced oscillation is reinforced of damped by the unsteady heat release does not seem to influence the oscillations due to the instability.

Forcing an oscillation with a frequency within a range near the naturally unstable frequency causes a large reduction in the amplitude of the oscillation at the naturally unstable frequency. However, it also results in a greater amplitude of pressure oscillation at the forced frequency. Figure 10 shows the results of driving the system at 85 Hz. Here, the pressure signal of the natural instability is shown to be greatly reduced, and the system is now dominated by the strong signal at the driving frequency. Under these 'near frequency' driving conditions, the vortices are shed from the flameholders at the forcing frequency. This occurs only above a certain threshold amplitude, where the forced ocillations begin to dominate the natural oscillations. The necessity of this domination makes this an impractical method for controlling the instability. The range of frequencies for which may be considered 'near frequencies' is not clearly defined, as the change in behavior of the system is gradual. For this set-up with the given conditions, the range extends from slightly below 80 Hz to about 105 Hz.

Conclusions

An experimental study has been made to assertain the effect of low frequency forcing on the low frequency instability in a ramjet combustor. The process of acoustic driving by the combustion process is predominantly determined by a feedback loop involving the generation of vortical structures in the vicinity of the flame holders, the downstream convection of these vortices, the impingement of the flame branches upon other flame branches or walls, and the generation of pressure disturbances by unsteady heat release. Low frequency driving has not shown in this investigation to be a means by which these processes may be controlled. Low frequency driving does, however, offer some insight into the details of the feedback process. At the present time, the feedback process is not fully understood, and so no analytical methods can be developed to predict the behavior of the system. However, a detailed investigation involving visualization techniques to reveal the details of the combustion process under near frequency forcing may make possible a modeling technique that may then be generalized for use with other systems.

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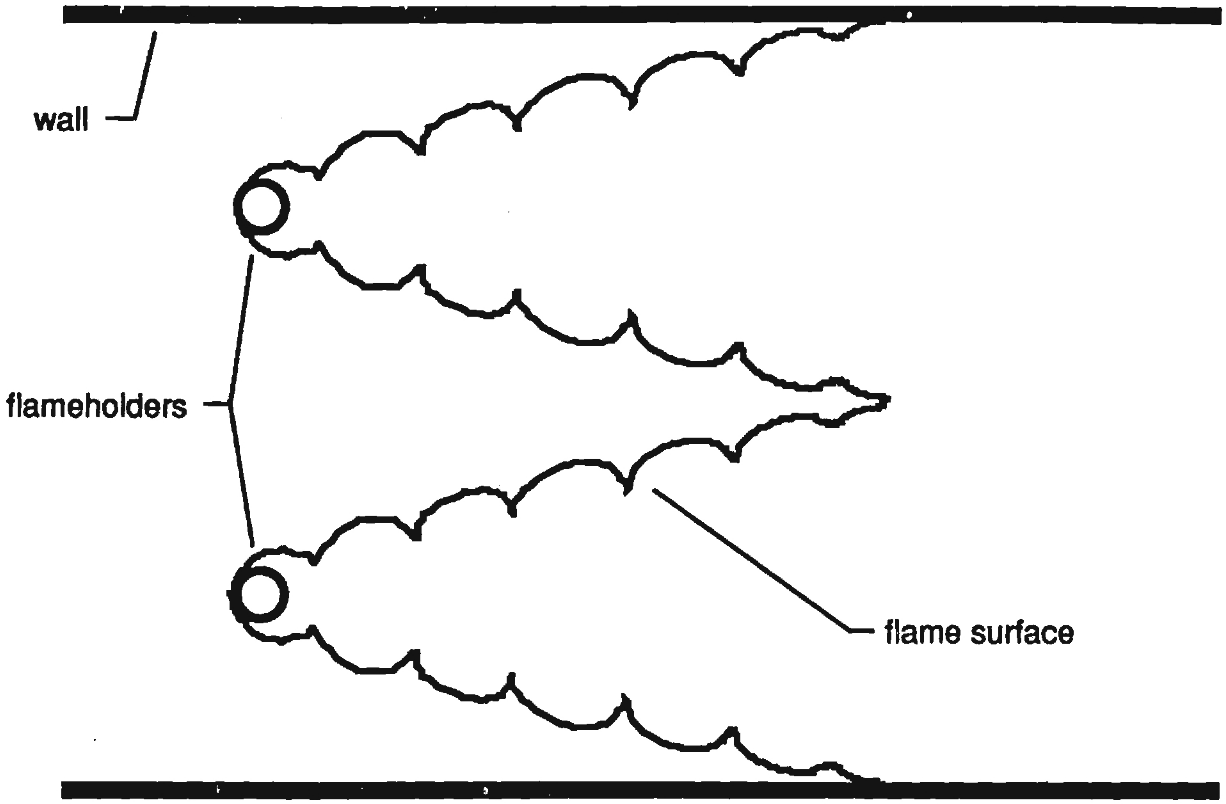


Figure 1. Schematic of the W-shaped flame.

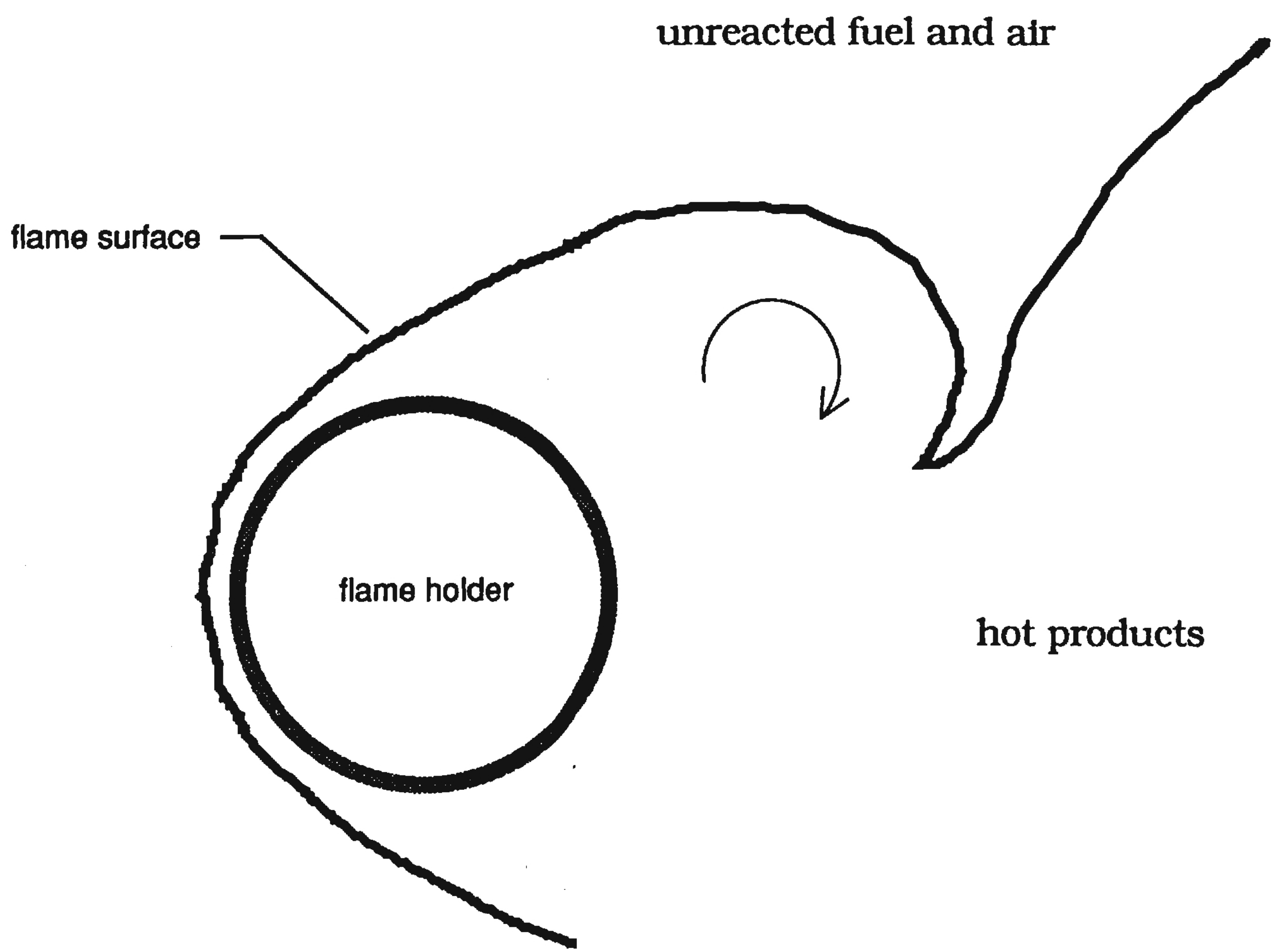
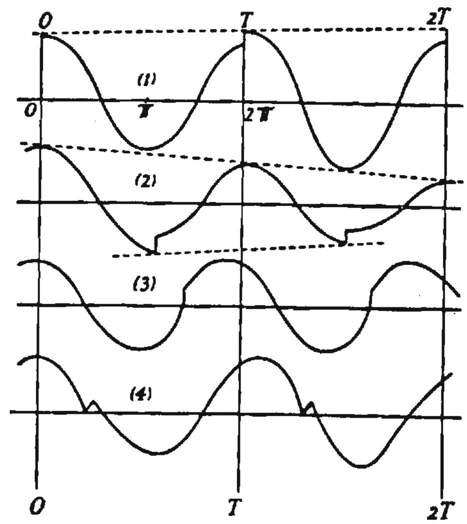


Figure 2. Schematic showing the deformation of the flame surface by the vortex structures.



Wave form of resultant vibrations.

Phase of heat addition relative to the phase of pressure.	Effect on:	
	Amplitude	Frequency
(1) In phase	increasing	none
(2) Opposite phase	decreasing	none
(3) Leading 1/4 period	none	increasing
(4) Lagging 1/4 period	none	decreasing

Figure 3. The effect of the phase difference between heat addition and pressure on an acoustic oscillation.

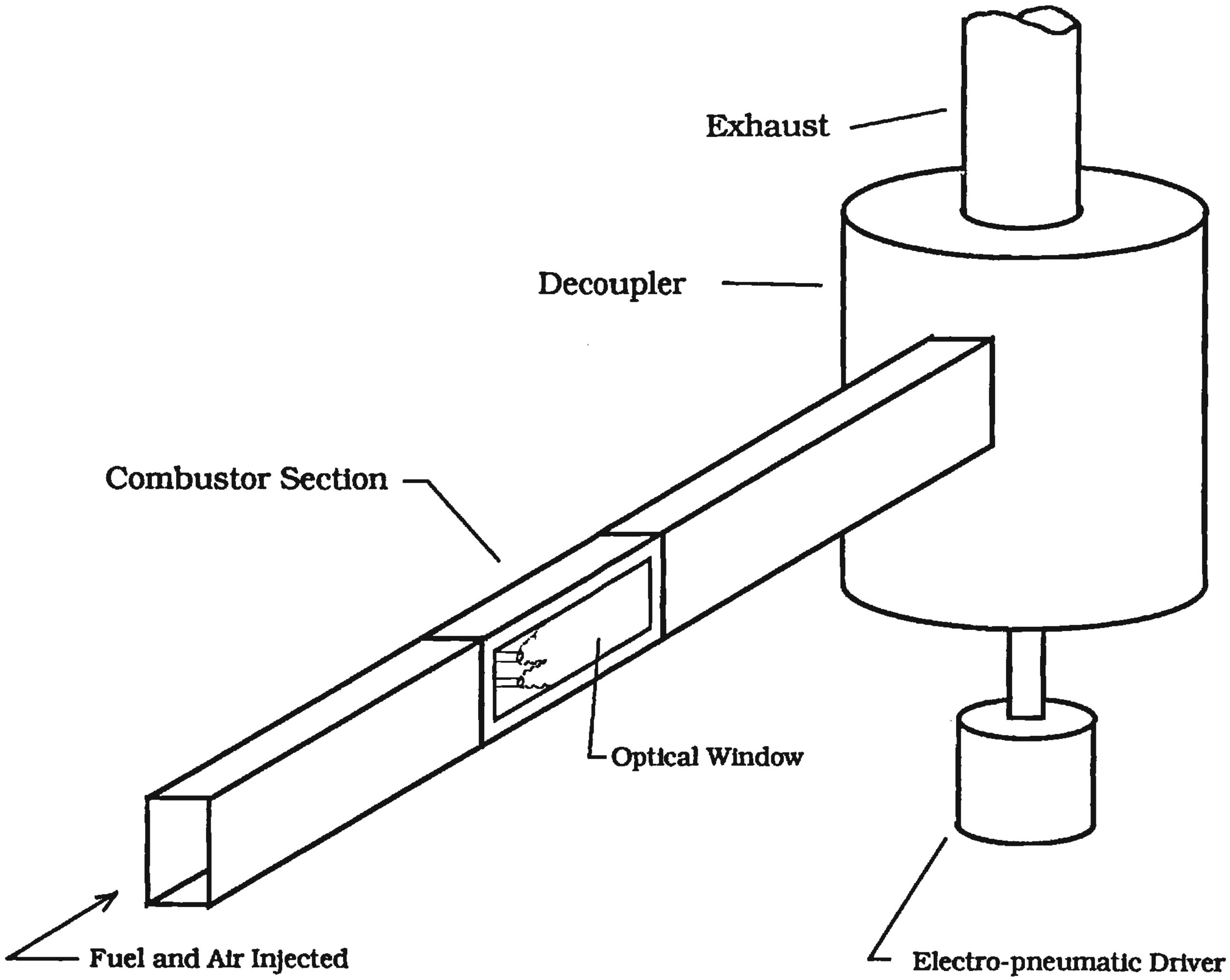


Figure 4. A schematic of the experimental set-up.

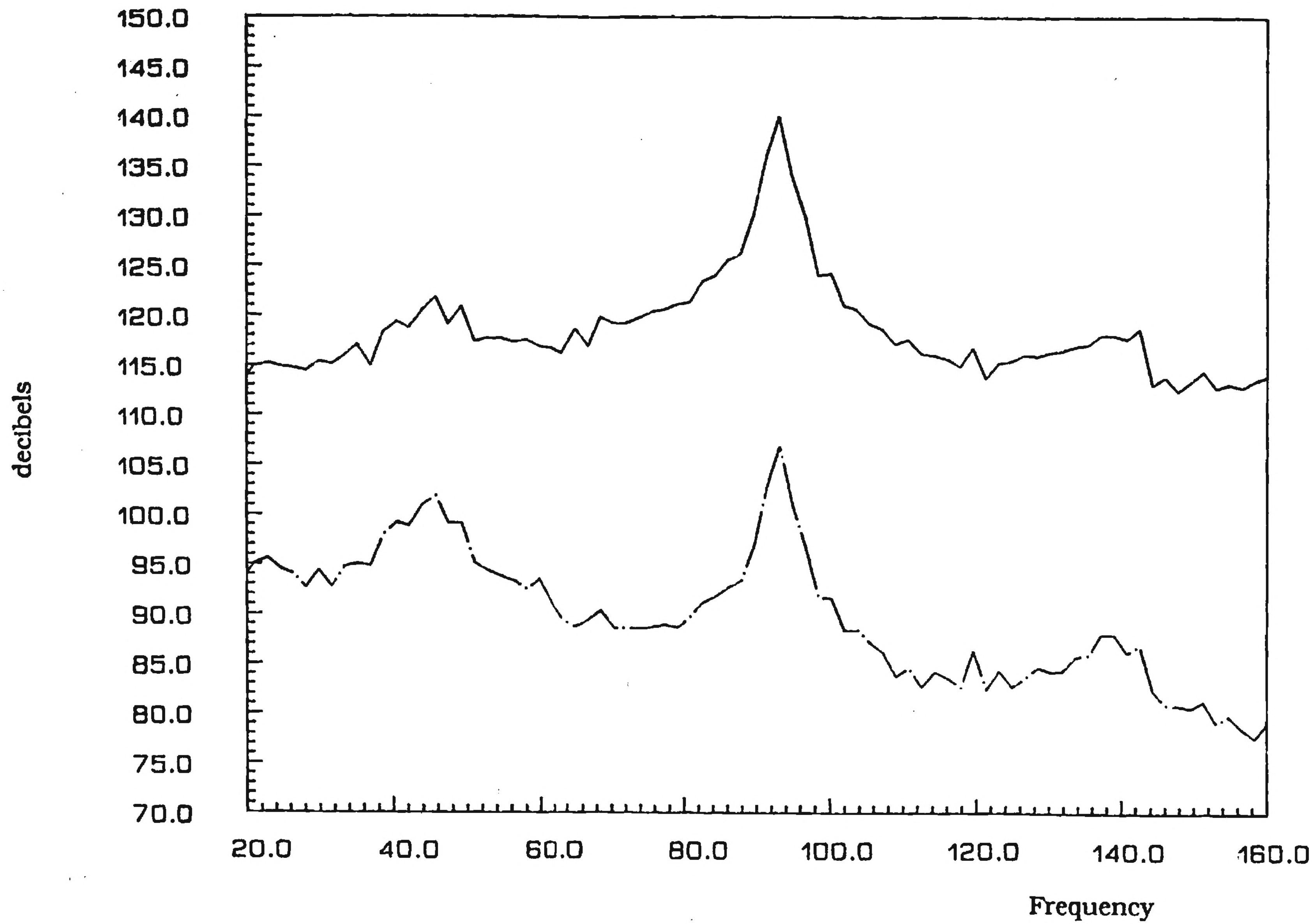


Figure 5. The pressure spectrum measured at the injector surface (solid line) and the normalized radiation spectrum of the entire flame (broken line) with no driving.

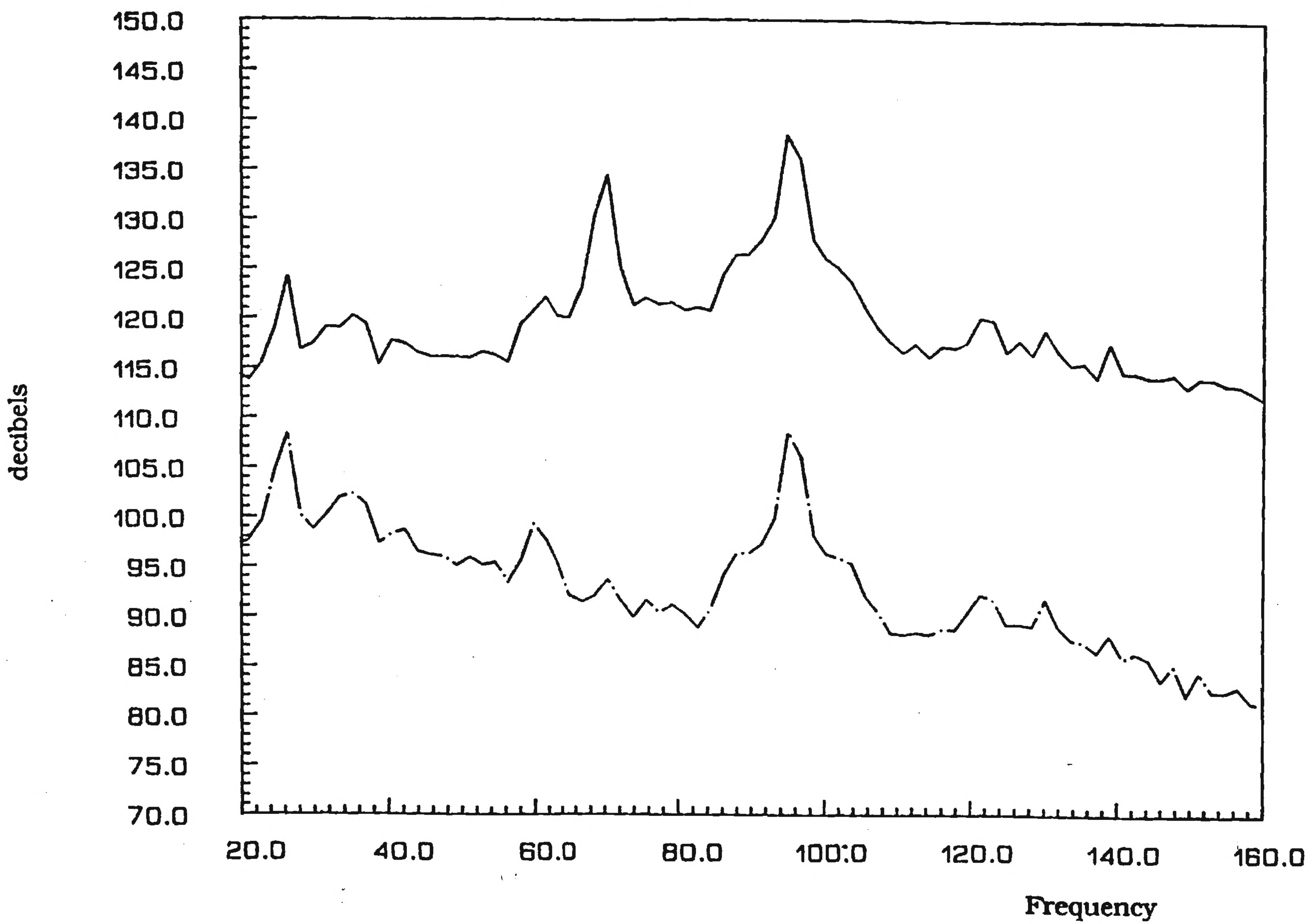


Figure 6. The pressure spectrum measured at the injector surface (solid line) and the normalized radiation spectrum of the entire flame (broken line) with weak driving at 70 Hz.

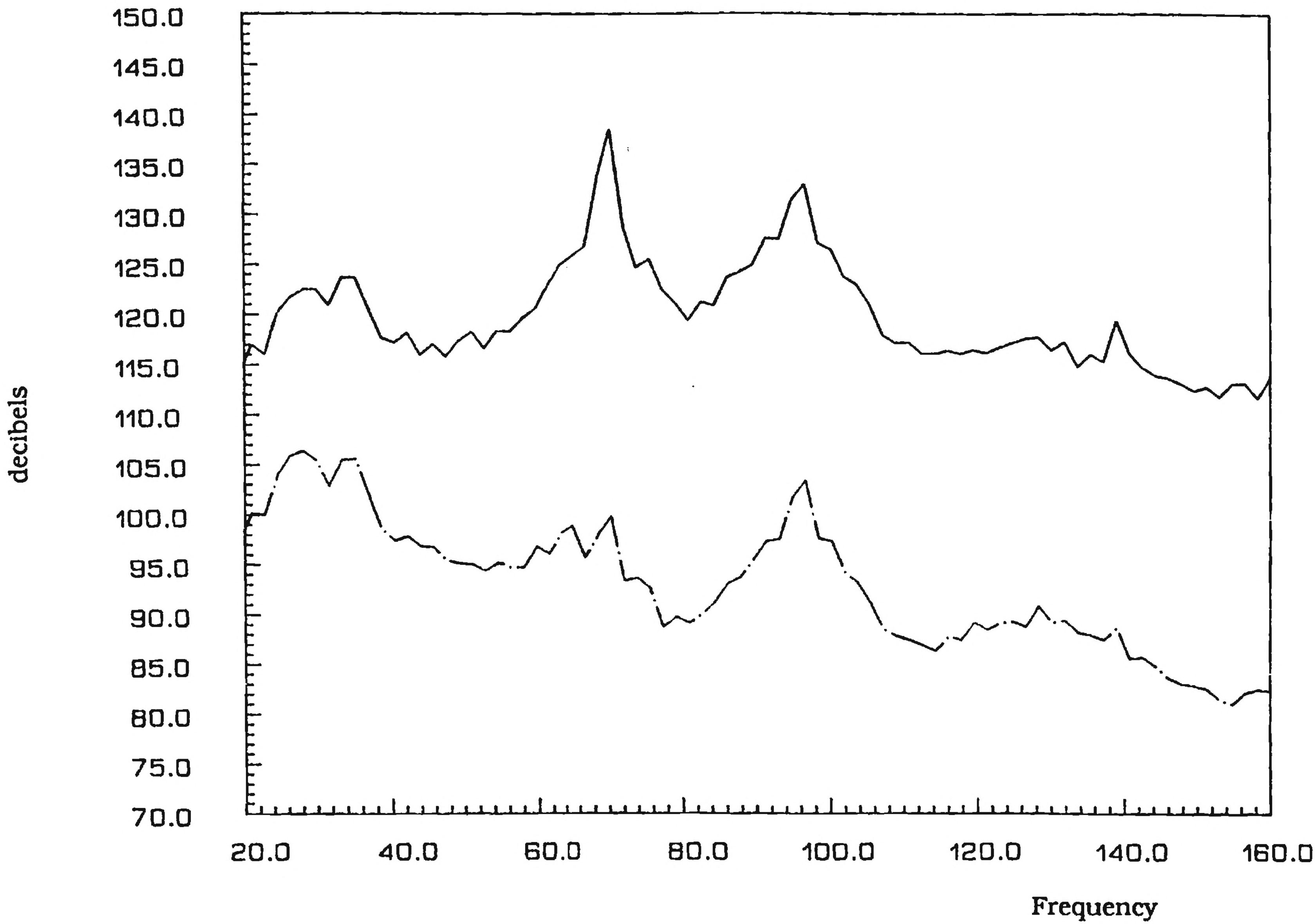


Figure 7. The pressure spectrum measured at the injector surface (solid line) and the normalized radiation spectrum of the entire flame (broken line) with strong driving at 70 Hz.

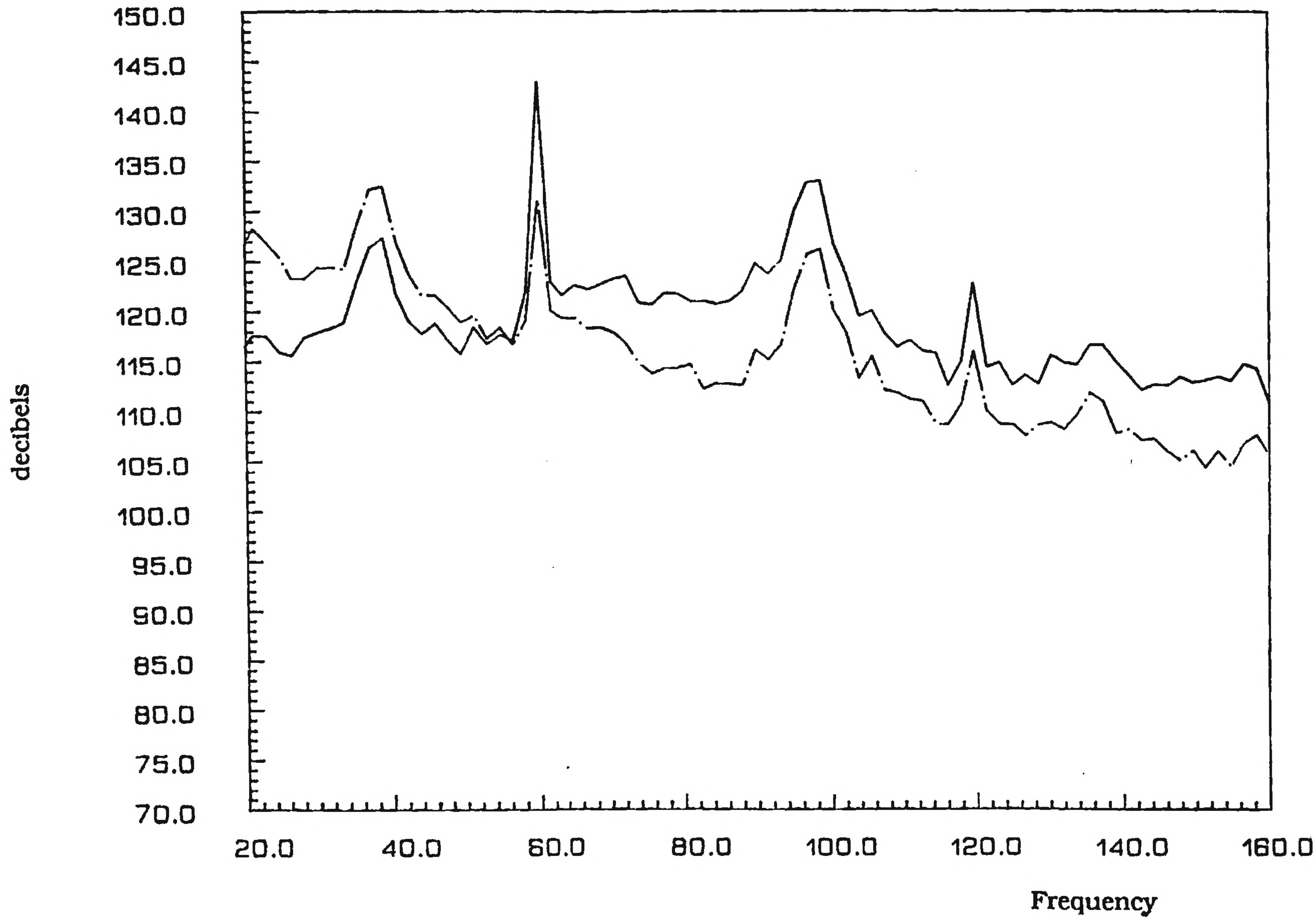


Figure 8. The pressure spectrum measured at the injector surface (solid line) and the normalized radiation spectrum of the entire flame (broken line) with strong driving at 60 Hz.

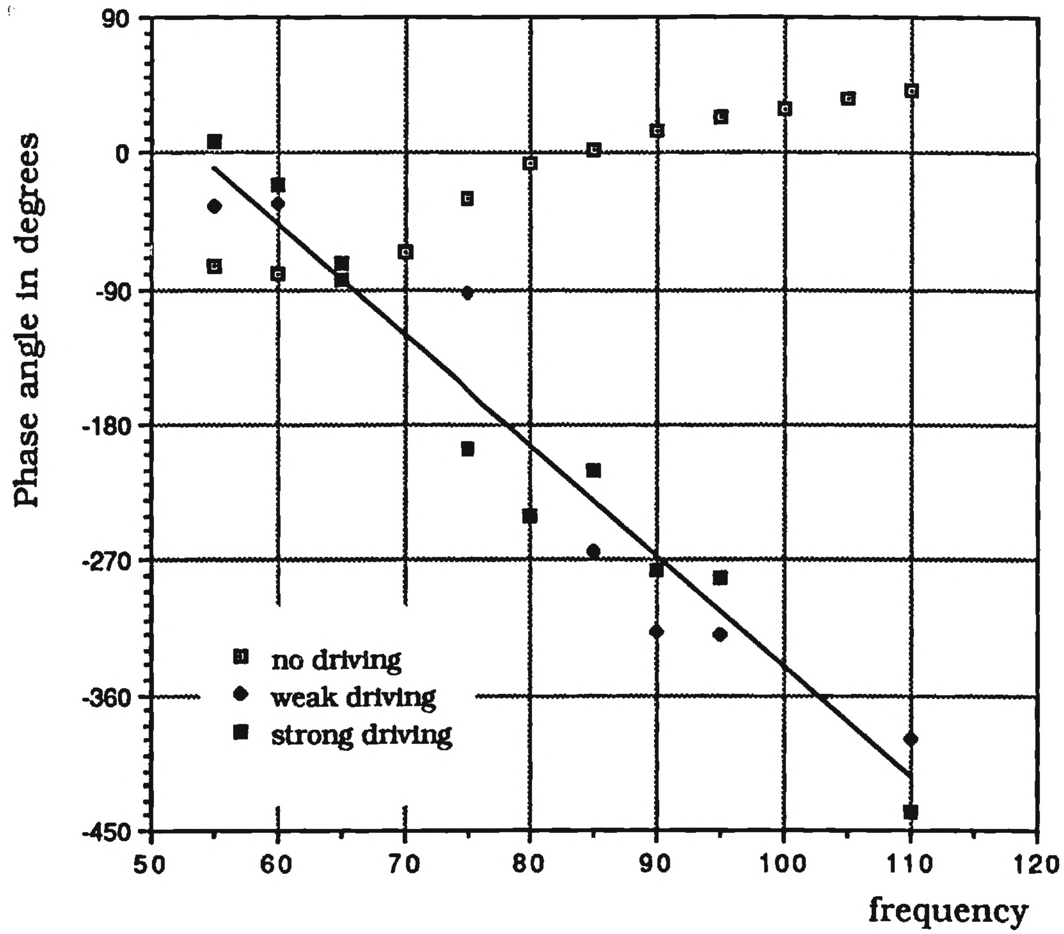


Figure 9. The phase difference between the heat release and the pressure oscillation at the driving frequency.

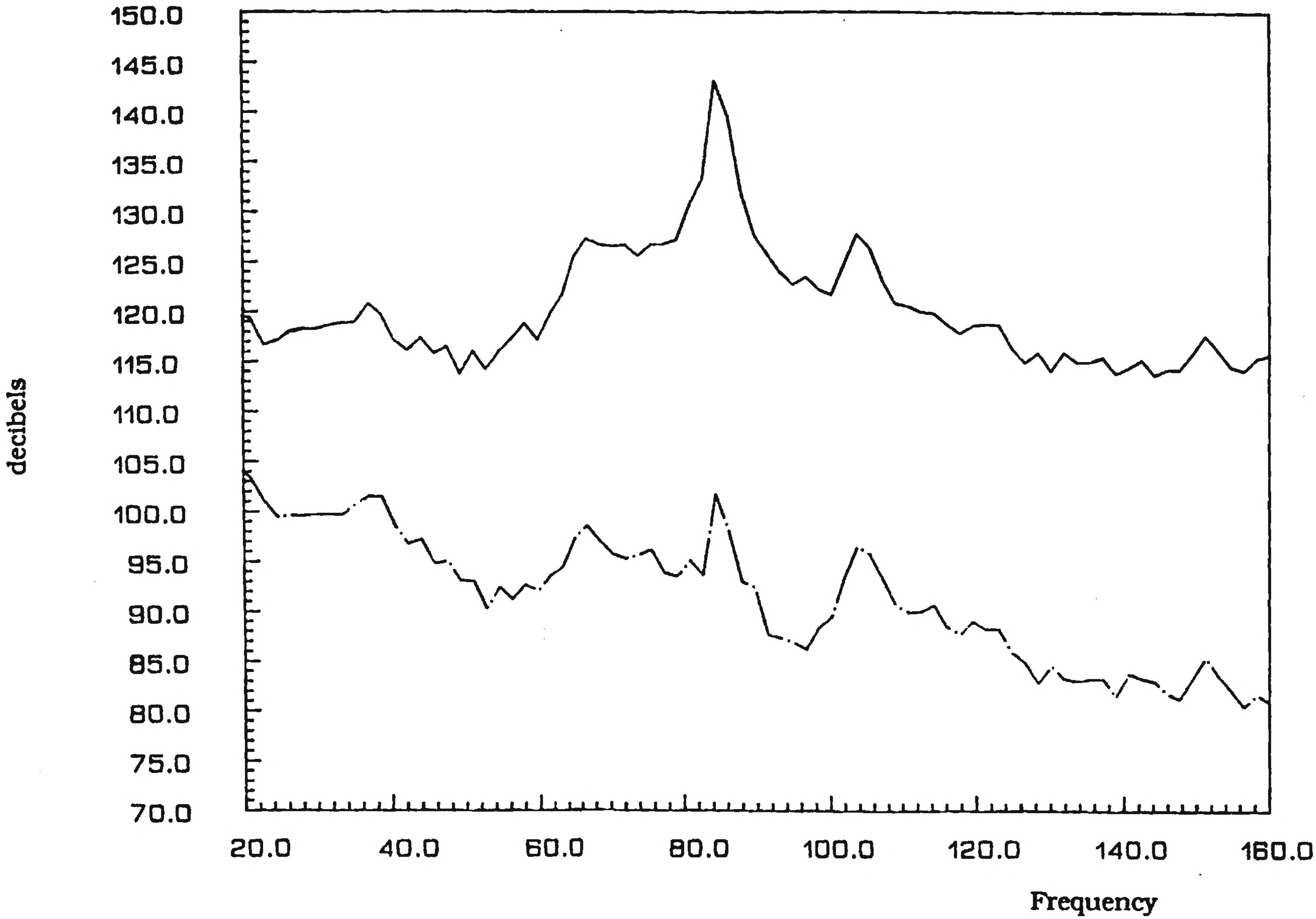


Figure 10. The pressure spectrum measured at the injector surface (solid line) and the normalized radiation spectrum of the entire flame (broken line) with strong driving at 85 Hz.

APPENDIX B.

FREQUENCY CONTROL IN UNSTABLE AND PULSE COMBUSTORS

U. G. Hegde*, D. M. Reuter and B. T. Zinn
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332, U. S. A.

ABSTRACT

The main objective of the experimental and theoretical investigations reported in this paper has been to develop capabilities for controlling the behavior of unstable and pulse combustors. In pursuit of this objective, the dependence of an unsteady combustor behavior upon the phase difference between the heat release rate and pressure oscillations has been investigated. Propane-air mixtures were burned in a two dimensional combustor and the phase of the heat release rate oscillations was varied by changing the relative positions of two circular flame holders which stabilized the combustion process. The combustor performance was determined from CH radiation and acoustic pressure measurements. Simultaneously, a theoretical model of the investigated combustor has been developed and used to predict the dependence of the excited combustor pressure oscillations upon the unsteady heat release rate. The predictions of the model are shown to be in good agreement with the measured data. The results of this study suggest approaches for controlling the oscillations in unstable and pulse combustors.

Subject matter: Instability, Modeling and Simulation, Other

Corresponding author:

Dr. B. T. Zinn
Regents' Professor
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
U. S. A.
Tel: (404) 894-3033

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*Current address: Sverdrup Technology, Inc., Lewis Research Center Group, Cleveland, Ohio 44135, U.S.A.

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INTRODUCTION

This paper presents results of theoretical and experimental investigations of the effect of the phase of the unsteady heat release rate oscillations upon the acoustic behavior of a laboratory ramjet combustor. Interactions between various unsteady combustion processes and combustor acoustic motions are of considerable scientific and practical interest. For example, these interactions control the occurrence and characteristics of detrimental combustion instabilities in various propulsion devices[1]. Furthermore, these interactions control the operation of pulse combustors which utilize the pulsations to increase the combustion efficiency, reduce pollutant formation, and increase the productivities and thermal efficiencies of heating and industrial processes which utilize the pulse combustor[2].

The amplitude and frequency of combustion driven acoustic oscillations strongly depend upon the phase difference between the acoustic pressure and the unsteady heat release rate oscillations. According to Rayleigh's criterion[3], an oscillatory heat source will tend to drive acoustic oscillations within a system if the inequality

$$\int_V \int_t p'(\underset{\rightarrow}{x},t)\, Q'(\underset{\rightarrow}{x},t)\, dt\, dV > o \qquad (1)$$

is satisfied. Specifically, the heat source Q' will tend to drive acoustic oscillations when the phase difference, ϕ, between Q' and p' satisfies the condition $-90° < \phi < 90°$, while for other values of ϕ the oscillatory heat source damps the acoustic motions. Furthermore, Rayleigh's criterion states that if there is a component of Q' which leads or lags p' by 90° then the added heat increases or decreases the frequency of the oscillations, respectively.

It is useful to consider the latter statement from the point of view of the stability[4] of acoustic motions in duct type combustors. In general, a linearized acoustic wave equation can be constructed for the combustor which has a known time averaged flow field. In the absence of an acoustic source in the combustor (termed herein as an unexcited combustor), the wave equation yields a set of real eigenvalues which represent the natural acoustic mode frequencies of the unexcited combustor. However, when an acoustic source is present in the combustor (e.g., an oscillatory heat source) then the eigenvalues of the wave equation are, in general, complex. The imaginary part of the complex eigenvalue represents the growth rate of the acoustic oscillations while the real part represents the "natural" frequency of oscillation of the excited combustor. The natural frequency of oscillation of the excited combustor is generally different from that of the unexcited combustor and depends upon the characteristics of the acoustic source. Hence, Rayleigh's criterion may be interpreted as meaning that when a component of Q' leads p' by 90° then the natural acoustic mode frequency of the excited combustor is greater than that of the unexcited combustor and vice versa. A corollary of Rayleigh's criterion is that the natural frequencies of unexcited and excited combustors coincide when the phase difference between Q' and p' is either 0° or 180°.

Acoustic wave driving by combustion processes has been studied by several investigators[5,6,7]. For example, Strahle[5] has derived a general theory of sound generation by unenclosed flames which has been confirmed by Sivashankara[6] et al. The corresponding problem for ducted flames has been worked out by Hegde[8] et al. These studies verified that flame driving of acoustic waves requires that a component of the heat release rate oscillation be in phase with the pressure oscillation.

Several investigations of frequency shifts caused by the phase difference between the unsteady heat release rate and pressure oscillations have been conducted to date. Zinn[2] has derived an expression for the frequency shift caused by a localized unsteady heat source in a constant temperature combustor. The analysis is carried out in terms of the normal modes of the combustor and it determines the frequency shift relative to the natural acoustic mode frequencies of the unexcited combustor. Culick[9] has also used the normal mode decomposition technique to predict frequency shifts. Kailasanath[10] et al. have determined numerically the frequency shifts of reacting flows downstream of backward facing steps. Finally, Keller[11,12] et al. have demonstrated experimentally and numerically that the frequency of a pulse combustor can be changed by changing various characteristic mixing and chemical times which affect the phase difference between the pressure and heat release oscillations. While some of these studies[11,12] showed qualitative agreement between their data and Rayleigh's criterion, none provides a direct experimental verification of theoretical predictions of the combustor behavior.

In this paper, the dependence of the frequency of the pressure oscillations excited in a laboratory ramjet combustor simulator upon the phase difference between the heat release rate and pressure oscillations is investigated both experimentally and theoretically. The phase of the heat release is varied by changing the geometry of the flame zone. Frequency shifts from the fundamental natural frequency of the unexcited combustor are measured. A theory which predicts these frequency shifts is developed and its predictions are compared with the experimental observations. These comparisons serve to verify Rayleigh's criterion regarding frequency shifts and are useful in computing the frequencies of unstable and pulse combustors.

A second practical benefit of the findings of this paper is their application to the control of combustion instabilities. Specifically, it can be shown that for a given magnitude of heat release rate oscillations and combustor acoustic properties, the amplitude of the instability maximizes at the natural acoustic mode frequencies of the unexcited combustor. In many cases, these maxima are very sharp, particularly if the combustor acoustic losses are small. Thus, even small frequency shifts away from the unexcited natural frequencies of the combustor can result in substantial reduction in the amplitude of the instability. Such trends have been observed by the authors in previous studies of combustion instability control in ramjets[13]. The present paper provides an approach for predicting these frequency shifts from known heat release rates.

EXPERIMENTAL INVESTIGATIONS

The utilized experimental set up (see Fig. 1) has been described in detail in earlier publications[8,13]. It consists of a 3 m long, 7.5 x 5 cm^2, rectangular duct consisting of an inlet, combustor and exhaust sections. A combustible mixture of propane and air is introduced into the set up through a porous, sintered steel, injection plate located at the upstream end of the inlet section. After ignition, a W shaped flame is stabilized in the combustor section on two, 5 mm diameter, cylindrical flame holders (see Fig. 2). These flame holders can be moved both axially and vertically, in the x and y directions, relative to each other. Wall mounted pressure transducers and thermocouples are used to measure the pressure oscillations and temperature rise across the flame. The combustor section side walls are made of quartz to permit flame and flow visualization, and optical diagnostics. The diagnostics included LDV measurements of the velocity field in the flame region[13] and space and time resolved CH radiation measurements from the flame[14]. The latter are indicative of the distributions of reaction and heat release rates.

Spontaneously induced combustion instabilities, whose amplitudes depend upon the fuel mass fraction, have been observed in the experimental set up. Usually, the instability excites the first natural acoustic mode of the combustor although certain combinations of relative flame holder locations have excited the second natural acoustic mode. The reason and significance of this behavior have been described elsewhere[13]. In this paper, the effect of the phase difference between the heat release rate and pressure oscillations on the frequency of the first natural mode instability are considered. As noted earlier, the phase of the heat release rate oscillations can be varied by changing the relative displacements of the flameholders.

In the reported experiments, the flame holders were moved vertically in the y direction while maintaining symmetry. The length of the flame zone in all cases was of the order of 20 cm. The instability frequencies were of the order of 90 Hz yielding an acoustic length scale (i.e., wavelength) of the order of 5 m. Since the acoustic length scale is an order of magnitude greater than the flame length (i.e., which is also the length scale of the acoustic source), the flame may be assumed to be acoustically compact[8]. Hence, it is appropriate to consider the phase of the integrated CH radiation (which is proportional to the heat release rate) oscillations from the entire flame when evaluating the frequency shifts. Furthermore, since the flame is acoustically compact, the acoustic pressure measured at the axial location of the flameholders is representative of the oscillations in the flame region. Therefore, the flame response to changing flameholders geometry has been monitored by measuring (i) the net oscillatory CH radiation from the entire flame, and (ii) the acoustic pressures at the flameholders axial location and at the injector.

Figures 3 through 6 illustrate the response of the combustor to the variation in the flame holders separation and, thus, the flame geometry. Figure 3 describes the dependence of the acoustic pressure amplitude at the dominant frequency of oscillation (i.e., the instability frequency) at the injector location upon the normalized separation distance of the flame holders. The zero separation point represents the configuration where the two flame holders are placed on top of each other in the center of the combustor and the flame is reduced to a single V shaped configuration. The corresponding variation of the frequency of instability is plotted in Fig. 4.

The dependence of the phase difference between the flame CH radiation and the acoustic pressure oscillations at the frequency of instability upon the separation distance between the flameholders is shown in Fig. 5. The same phase data as a function of the frequency of instability are presented in Fig. 6. Since, according to Rayleigh's criterion, the system is expected to oscillate at the natural acoustic frequency of the unexcited combustor when the heat release (i.e., CH radiation) oscillations occur in phase with the local pressure oscillations, the data presented in Fig. 6 suggest that the unexcited natural acoustic frequency is about 90 Hz. Furthermore, the data in Fig. 6 indicate that the frequencies of the instabilities are higher than the frequency of the acoustic mode of the unexcited combustor when Q' leads p', and vice versa, in agreement with Rayleigh's criterion.

THEORETICAL INVESTIGATIONS

The objective of the theoretical investigations is to develop a model for predicting the frequency shifts observed in Fig. 6. Use is made of the results of a previous paper[8] in which the authors have formulated a theory for sound generation by acoustically compact ducted flames. A combustor of length L is considered. Since the flame is acoustically compact, it may be assumed, for the purposes of acoustic analysis, to be concentrated at a fixed axial station $x = L_1$. In the present analyses, L_1 is taken to be the axial location of the flame holders. The time averaged temperatures upstream and downstream of the flame location are taken to be $\bar{T}_1$ and $\bar{T}_2$, respectively. Furthermore, the unknowns are assumed to possess an harmonic time dependence of the form $e^{i\omega t}$. The starting point here is the following expression for the pressure p_ω developed in Ref. 8

$$p_\omega(x) = \frac{i\omega\, Q_\omega(L_1)\, G(x;\, L_1)}{2\, C_p} \tag{2}$$

where $G(x;L_1)$ is the relevant Green's function for the combustor which describes the manner in which the oscillatory heat release $Q_\omega(L_1)$ at $x = L_1$ drives acoustic motions within the duct. Substituting the following definition of $\hat{R}_\omega(x;L_1)$, which describes the "combustor process response" to the acoustic pressure oscillations,

$$\frac{Q_\omega(L_1)}{2C_p} = \hat{R}_\omega(x;\, L_1) p_\omega(x) \tag{3}$$

into Eq. (2) and letting $x = L_1$ results in the following relationship:

$$i\omega\, \hat{R}_\omega(L_1;L_1)\, G(L_1;L_1) = 1 \tag{4}$$

The expression for the Green's function $G(x,L_1)$ is given in Ref. 8. It is a function of the frequency, and the acoustic and geometric properties of the combustor. The utilized experimental apparatus closely approximates a rigid walled duct with the inlet and exhaust ends acting as acoustically closed and open terminations, respectively. Neglecting the acoustic losses in the setup, the Green's function developed in Ref. 8 provides the following expression for $G(L_1,L_1)$ which is applicable to the investigated setup and sufficient for obtaining a solution for the frequency shift:

$$G(L_1;\, L_1) = \frac{-\sin\beta\cos\alpha}{k_1\bar{T}_1\sin\alpha\ \sin\beta - k_2\bar{T}_2\cos\alpha\cos\beta} \tag{5}$$

where $k_1 = \frac{\omega}{c_1}$, $k_2 = \frac{\omega}{c_2}$, $\alpha = k_1 L_1$ and $\beta = k_2 (L-L_1)$

It should be noted, however, that the above expression for $G(L_1;L_1)$ cannot be used to obtain the combustion process response $\hat{R}_\omega(L_1;L_1)$ in the vicinity of a natural acoustic mode (defined by Eq. (7) below) by use of Eq. (4). The reason is that for a lossless combustor any negligibly small amplitude driving at a natural acoustic mode frequency results in unbounded amplitudes of the acoustic oscillations. This is manifested mathematically as an infinite value of the Green's function at the natural mode frequencies. A proper accounting of acoustic losses (which creates finite bounds for the Green's function) is essential if Eq. (4) is to be used to determine $\hat{R}_\omega(L_1;L_1)$ at a natural frequency of the combustor. However, since the present study is primarily concerned with the determination of the frequency shift, no difficulty arises in using Eq. (5) for this purpose.

Substituting Eq. (5) into Eq. (4), using the perfect gas equation, assuming constant specific heats, and rearranging the resulting expression yields the following equation:

$$B \sin \alpha \sin A\alpha - \cos \alpha \cos A\alpha = -i\, R_\omega(L_1;L_1) \sin A\alpha \cos \alpha \qquad (6)$$

where $A = \left(\frac{\bar{T}_1}{\bar{T}_2}\right)^{0.5} \left(\frac{L-L_1}{L_1}\right)$; $B = \left(\frac{\bar{T}_1}{\bar{T}_2}\right)^{0.5}$ and

$$R_\omega (L_1;L_1) = B \left(\frac{\gamma R_g}{\bar{T}_1}\right)^{0.5} \hat{R}_\omega (L_1;L_1)$$

It is evident from Eq. (3) that in the absence of unsteady heat release (i.e., an acoustic source) $R_\omega (L_1;L_1) = 0$ and Eq. (6) reduces to

$$B \sin \alpha_n \sin A\, \alpha_n - \cos \alpha_n \cos A\alpha_n = 0 \qquad (7)$$

where the subscript n refers to the nth natural acoustic mode of the unexcited system. Consequently, Eq. (7) can be used to determine the natural acoustic mode frequencies of the unexcited combustor.

Next, the changes in the acoustic modes resulting from the introduction of an oscillatory heat source are considered. Since the small amplitude source is expected to produce small deviations from the acoustic solutions for the unexcited combustor, one can set $\alpha = \alpha_n + \alpha'$ where $\left|\frac{\alpha'}{\alpha_n}\right| \ll 1$. Furthermore, $R_\omega(L_1;L_1)$ is expanded in a Taylor series about ω_n to yield

$$R_\omega\ (L_1;L_1) = R_n\ (L_1;L_1) + \left(\frac{\partial R_\omega}{\partial \omega}\right)_n \omega'$$

where $\omega' = \omega - \omega_n$ and $R_n(L_1;L_1)$ refers to the value of $R_\omega(L_1;L_1)$ at ω_n.

Differentiating Eq. (4) with respect to ω and noting the definition of $R_\omega(L_1;L_1)$ it follows that

$$R_\omega G + \omega G\ \frac{\partial R_\omega}{\partial \omega} + \omega\ R_\omega\ \frac{\partial G}{\partial \omega} = 0$$

Dividing by G and taking the limit as ω tends to ω_n (so that G becomes unbounded) one obtains

$$\left(\frac{\partial R_\omega}{\partial \omega}\right)_n = \frac{-R_\omega}{\omega_n}$$

and Eq. (6) may be written as

$$B \tan\ (\alpha_n + \alpha') - \cot A\ (\alpha_n + \alpha') = -iR_n(L_1;L_1)\left[1 - \frac{\alpha'}{\alpha_n}\right] \qquad (8)$$

Using standard trigonometric identities, taking advantage of the smallness of α', using Eq. (7) and the relationship $\alpha' = \omega' L_1/c_1$ one obtains to first order in ω'

$$\omega' = \omega_r' + i\omega_i' = \frac{-ic_1 R_n\ (L_1;L_1)}{L_1[B \sec^2\alpha_n + A \operatorname{cosec}^2 A\ \alpha_n]} \qquad (9)$$

It will be now shown that the expression for ω', Eq. (9), is consistent with Rayleigh's criterion. This will be demonstrated by considering the following special cases:

Case (1): Q' is in phase with p'. In this case $R_n(L_1;L_1)$ is a positive real number and it follows from Eq. (9) that

$$\omega_r' = 0 \quad \text{and} \quad \omega_i' < 0$$

which indicates that the heat source excites acoustic motions which oscillate with the frequencies of the natural modes of the unexcited combustor.

Case (2): $Q'$is out of phase with p'. In this case $R_n(L_1;L_1)$ is a negative real number and it follows from Eq. (9) that

$$\omega_r' = 0 \quad \text{and} \quad \omega_i' > 0$$

which indicates the heat source damps the acoustic motions which oscillate with frequencies of the natural modes of the unexcited combustor.

Case (3): Q' leads p' by 90°. In this case, $R_n(L_1;L_1)$ can be written in the form iS^2 where S is a real number and it follows from Eq. (9) that

$$\omega_r' > 0 \quad \text{and} \quad \omega_i' = 0$$

Therefore, no energy is added by the heat source and the frequency of the oscillation is higher than the frequency of the related acoustic mode in the unexcited combustor.

Case (4): Q' lags p' by 90°. In this case, $R_n(L_1;L_1)$ can be expressed in the form $-iS^2$ where S is a real number and it follows from Eq. (9) that

$$\omega_r' < 0 \quad \text{and} \quad \omega_i' = 0$$

Therefore, no energy is added by the heat source and the frequency of the oscillation is lower than the frequency of the related acoustic mode in the unexcited combustor.

In order to compare the theoretically predicted frequency shifts with the experimentally measured shifts, the quantity $R_n(L_1;L_1)$ has to be determined at the fundamental mode frequency of the unexcited combustor. If the acoustic losses of the combustor are known, a Green's function which accounts for these losses can be derived, substituted into Eq. (4) and the resulting expression could be used to determine $R_n(L_1;L_1)$. However, because of the presence of a flame, it is difficult to measure the combustor losses and determine the needed Green's function. Consequently, $R_n(L_1;L_1)$ has been determined experimentally by constructing the crosspectrum between the pressure and heat release rate oscillations. This was accomplished by letting $x = L_1$ in Eq. (3), multiplying the resulting expression by $p_\omega{}^*$ and ensemble averaging to obtain

$$R_n(L_1;L_1) = \frac{B}{2C_p}\left(\frac{\gamma R_g}{\bar{T}_1}\right)^{0.5}\left(\frac{S_{qp}}{S_{pp}}\right)_n$$

where the pressure autospectrum S_{pp} is given by

$$S_{pp} = \overline{p_\omega\, p_\omega{}^*}$$

and the crosspectrum between the heat release rate and pressure oscillations is given by

$$S_{qp} = \overline{Q_\omega\, p_\omega{}^*}$$

Since in the present study the heat release oscillations are determined from measured CH radiation oscillations, one must first obtain a relationship between the radiation and heat release rate oscillations. This was accomplished using a straightforward technique, described in Ref. 8, which converts the CH radiation-pressure oscillation crosspectrum to the heat release rate-pressure oscillation crosspectrum.

A comparison between predicted and measured frequency shifts is presented in Fig. 7. This plot demonstrates that the developed theory can predict small shifts (i.e., less than 10 Hz) from the natural mode frequencies of the unexcited combustor. For larger frequency shifts, the tendency is to underpredict the magnitude of the frequency shift. To the authors knowledge, this is the first time that observed natural mode frequency changes caused by an unsteady combustion process have been directly correlated with theory.

CONCLUSIONS

A combined experimental and theoretical investigation of the changes in natural acoustic modes frequencies of a combustor caused by an unsteady combustion process has been carried out. Experimentally, the unsteady heat addition was supplied by a premixed flame stabilized on two moveable, cylindrical, flame holders. The results are in agreement with Rayleigh's criterion; that is, the frequency increases and decreases when the heat addition oscillation leads or lags the pressure oscillation, respectively. Predictions of the developed theoretical model are in agreement with the experimental observations. The results of this study could be used in the development of methodologies for controlling (i.e., preventing) combustion instabilities in propulsive devices such as ramjets.

ACKNOWLEDGEMENT

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NOMENCLATURE

A, B	quantities defined in Eq.(6)
c	speed of sound
C_p	specific heat at constant pressure
G	Green's function for the combustor acoustics
H	duct height
k	wave number
L	combustor length
L_1	axial location of flame in the compact limit
p	pressure
Q	heat release rate
$\hat{R}_\omega$	defined in eq.(3)
R_ω	modified form of $\hat{R}_\omega$
R_g	gas constant
S_{pp}	autospectrum of pressure oscillations
S_{qp}	crosspectrum of pressure and heat release rate oscillations
t	time
T	temperature
V	volume of a system
x	axial coordinate
y	normal coordinate
α,β	quantities defined in Eq.(5)
γ	ratio of specific heats
ω	frequency
ϕ	phase difference between pressure and heat release rate oscillations

Superscripts

'	perturbation
-	time average or ensemble average
*	complex conjugate

Subscripts

1	location upstream of flame
2	location downstream of flame

i	imaginary part of a complex quantity
n	quantity evaluated at nth natural mode frequency
r	real part of a complex quantity
ω	Fourier component at frequency ω
$\rightarrow$	vector quantity

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LIST OF FIGURES

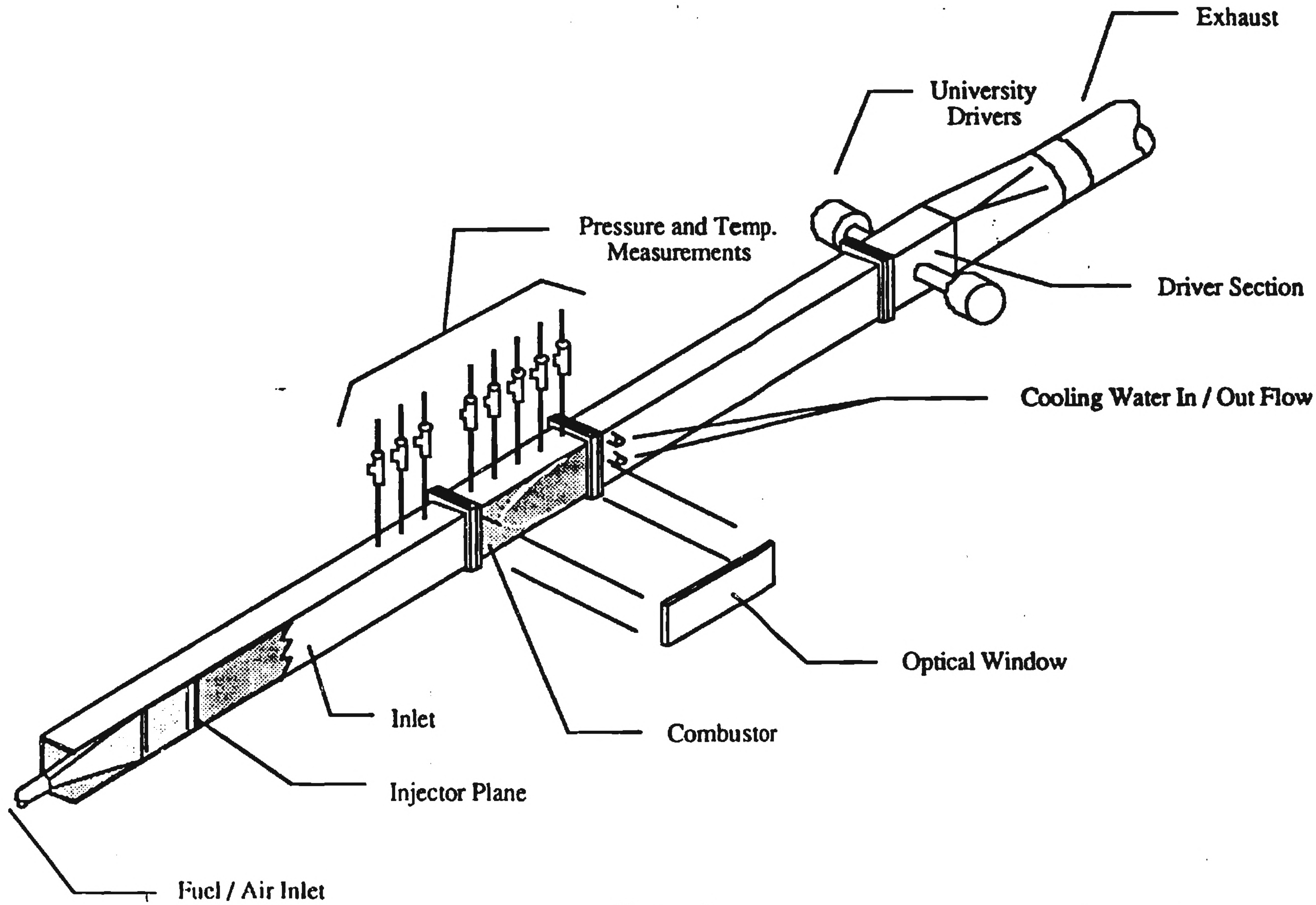

Exhaust
University Drivers
Pressure and Temp. Measurements
Driver Section
Cooling Water In / Out Flow
Optical Window
Inlet
Combustor
Injector Plane
Fuel / Air Inlet

Figure 1

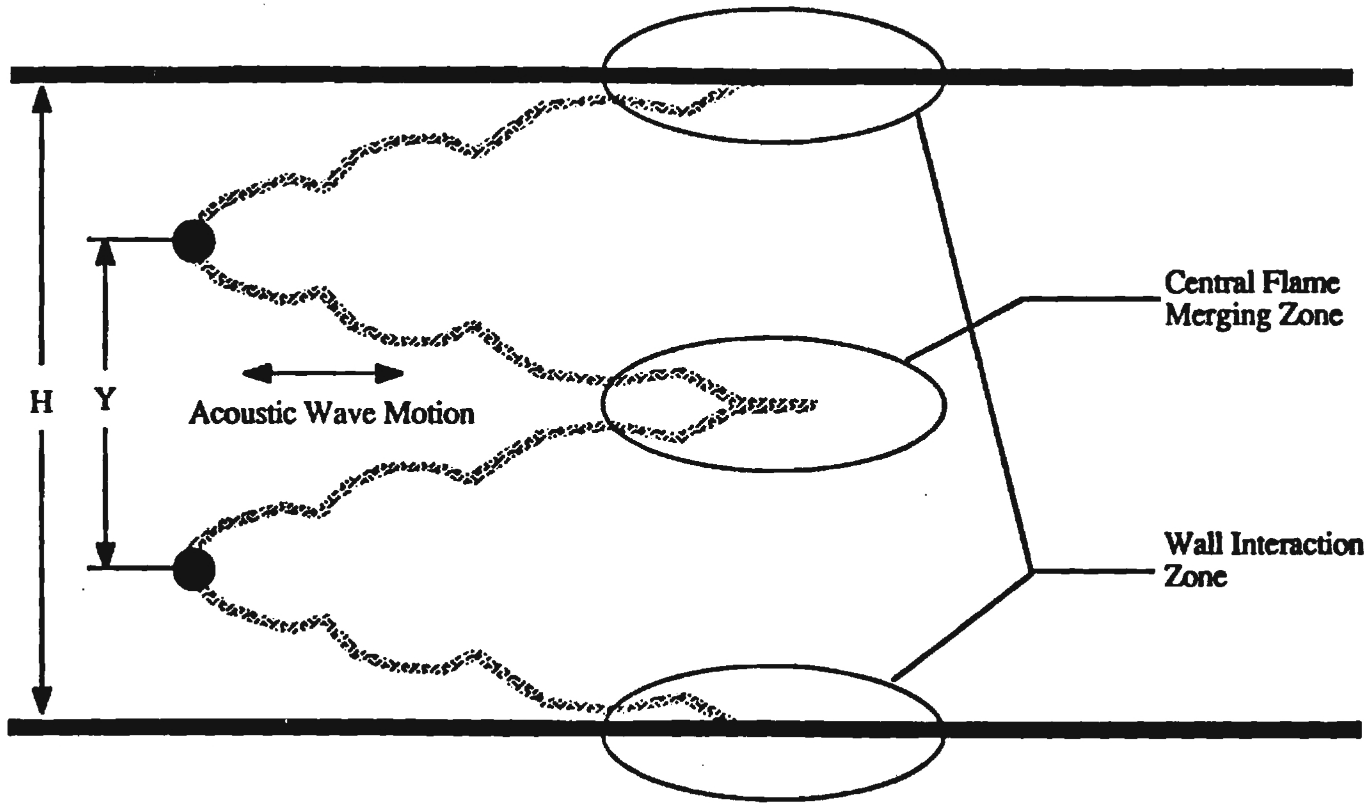

H
Y
Acoustic Wave Motion
Central Flame
Merging Zone
Wall Interaction
Zone

Figure 2

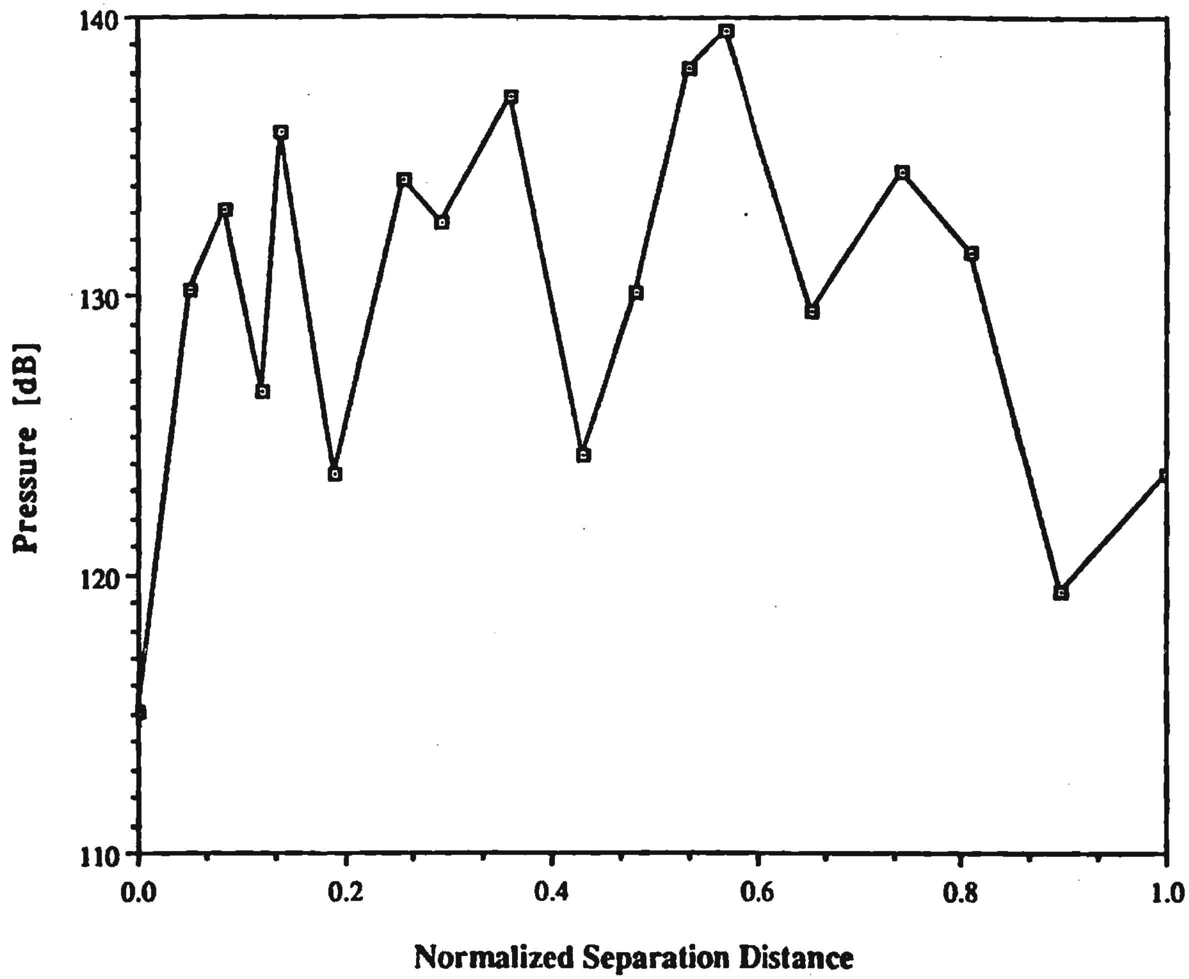

Pressure [dB]
140
130
120
110
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Separation Distance

Figure 3

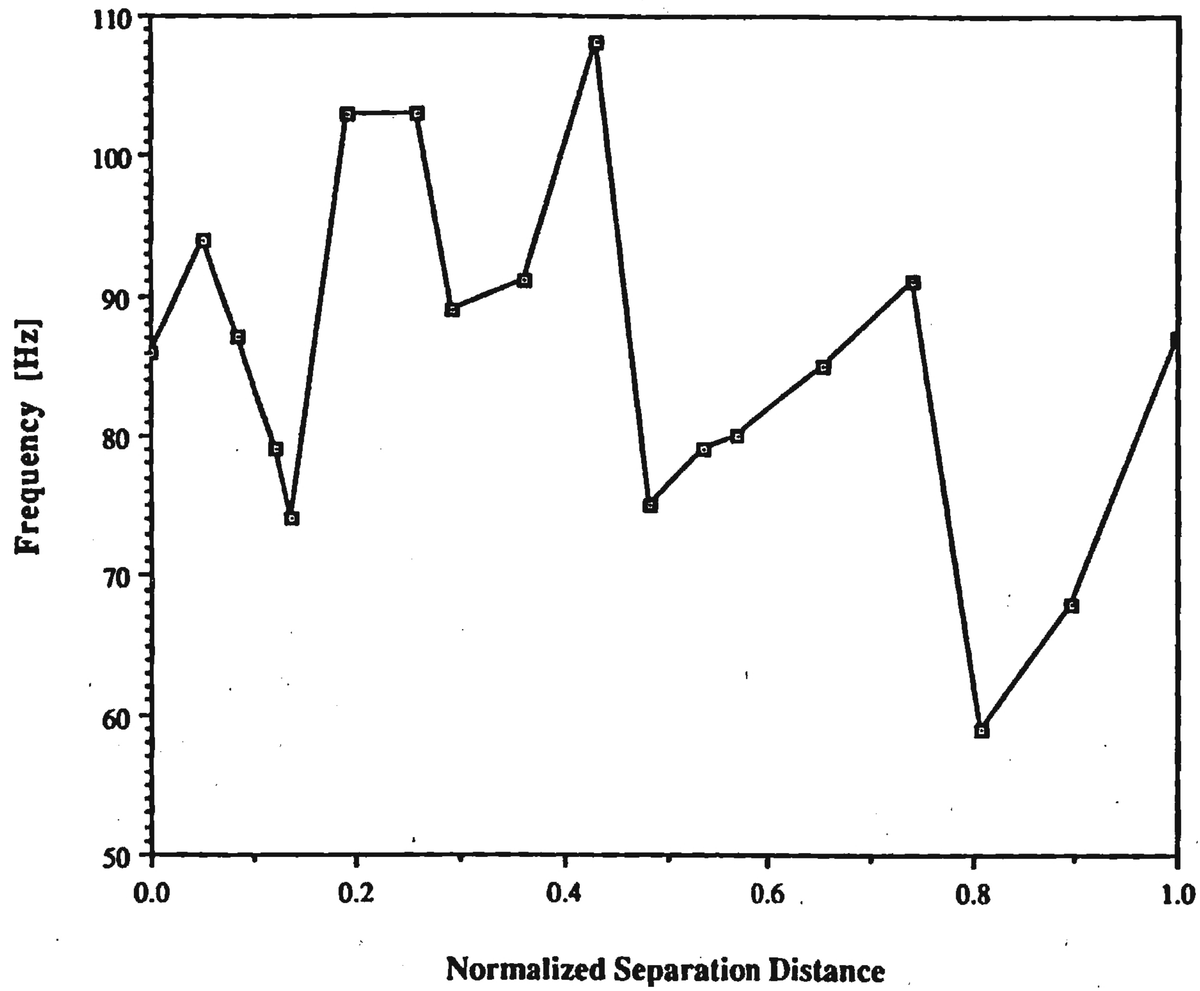

110
100
90
80
70
60
50
Frequency [Hz]
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Separation Distance

Figure 4

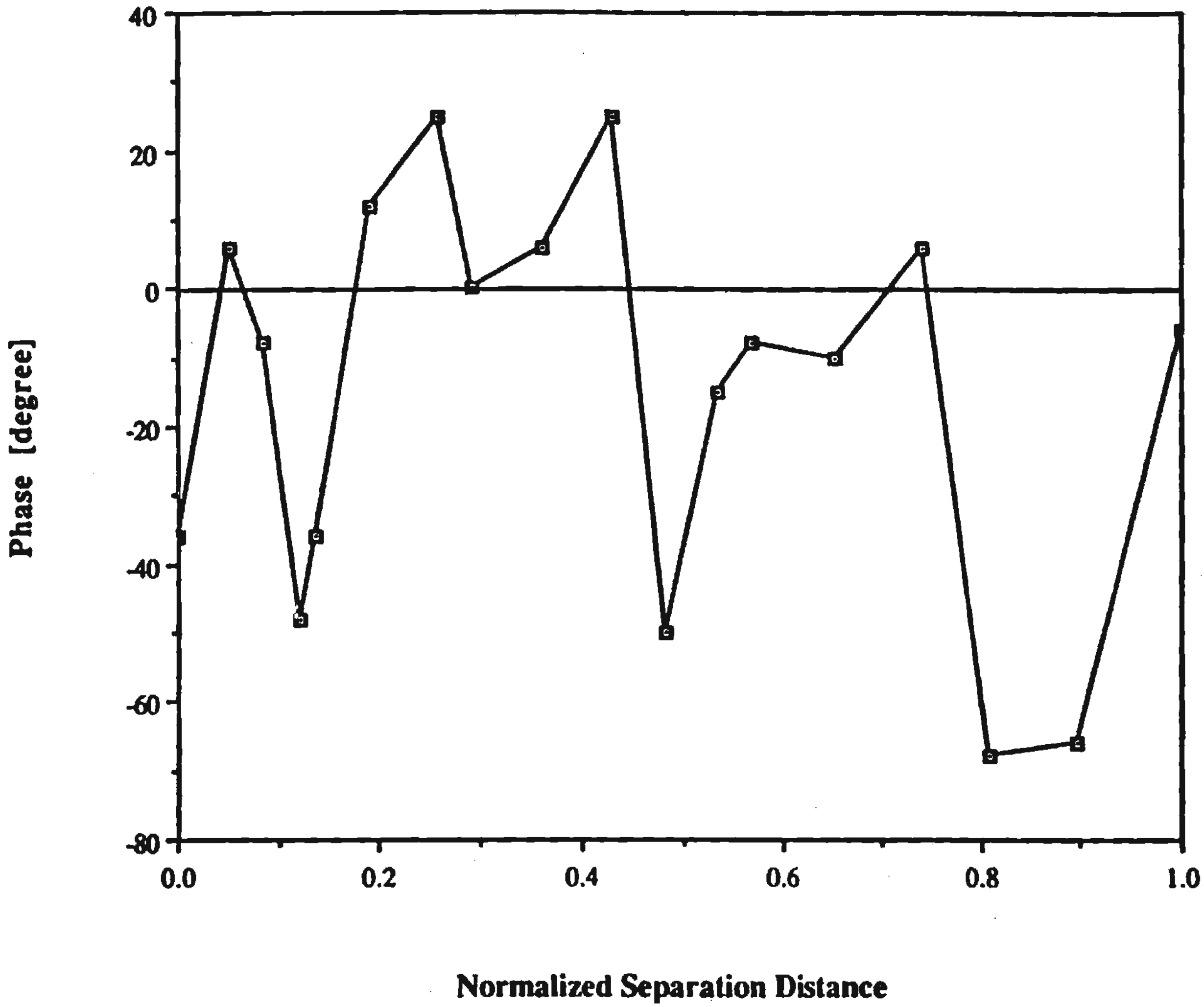
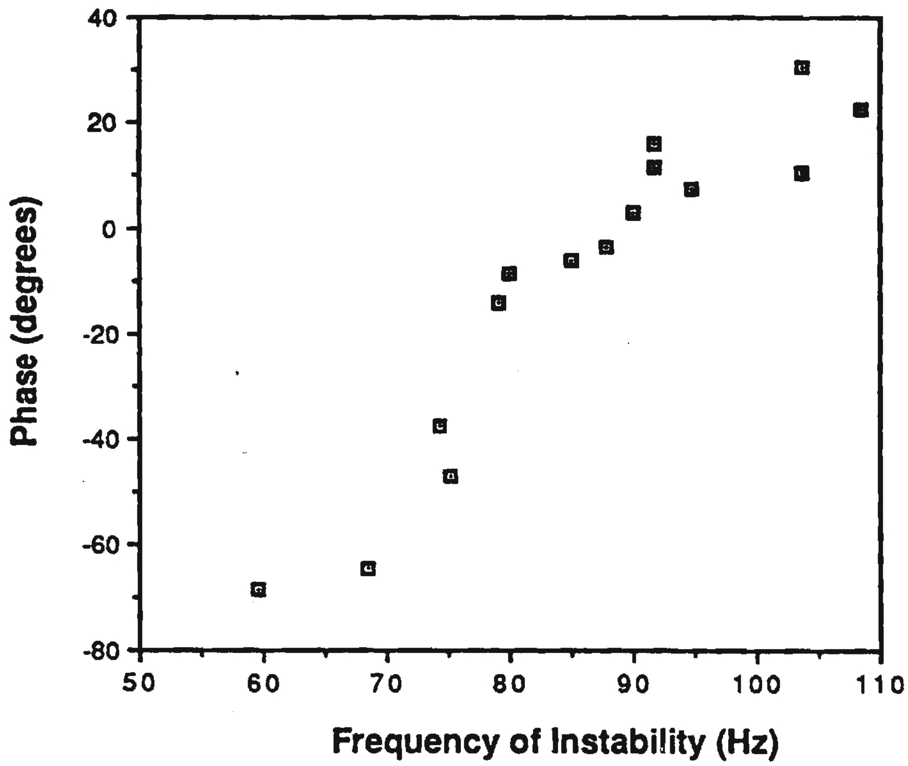
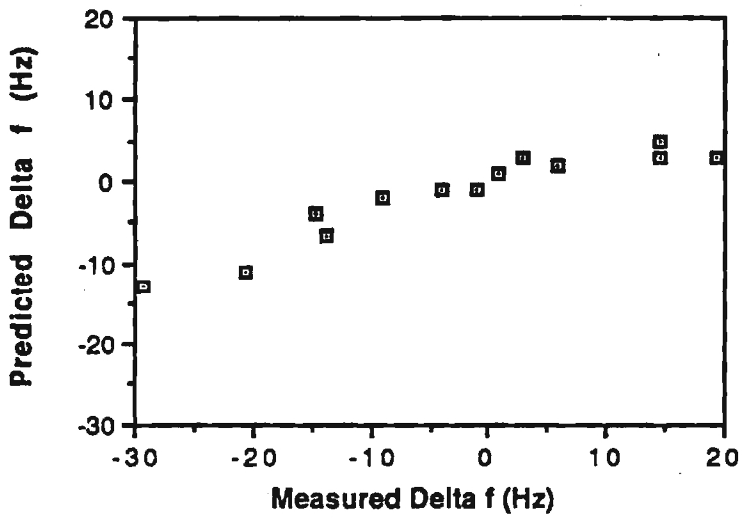

40
20
0
-20
-40
-60
-80
0.0
0.2
0.4
0.6
0.8
1.0
Phase [degree]
Normalized Separation Distance

Figure 5



40
20
0
-20
-40
-60
-80
Phase (degrees)
50
60
70
80
90
100
110
Frequency of Instability (Hz)

Figure 6



20
10
0
-10
-20
-30
-30
-20
-10
0
10
20
Predicted Delta f (Hz)
Measured Delta f (Hz)

Figure 7