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AFOSR ANNUAL TECHNICAL REPORT

INVESTIGATION OF THE FLAME-ACOUSTIC WAVE INTERACTION DURING AXIAL SOLID ROCKET INSTABILITIES

By

Ben T. Zinn
Brady R. Daniel

Prepared for

Air Force Office of Scientific Research
Aerospace Sciences Directorate
Bolling Air Force Base

Under

Grant No. AFOSR-84-0082

March 1987

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
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AFOSR ANNUAL TECHNICAL REPORT

on

INVESTIGATION OF THE FLAME-ACOUSTIC WAVE INTERACTION DURING AXIAL SOLID ROCKET INSTABILITIES

Prepared for

Air Force Office of Scientific Research

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ABSTRACT

The primary objective of this research program is to investigate the mechanisms responsible for the driving/damping of axial instabilities by solid propellant flames. In addition, this research has been investigating whether state-of-the-art flame response models can accurately predict the characteristics of the flame driving/damping mechanisms. To attain the programs's objectives, the response of premixed flat flames, stabilized on the side wall of a duct, to imposed axial acoustic waves has been investigated both experimentally and theoretically. Premixed flames have been chosen for this study because they simulate some important characteristics of solid propellant flames and they are amenable to detailed experimental diagnostics. During the reporting period a previously developed flame response model was used to predict the characteristics of the unsteady heat release rate and velocity components of the experimentally investigated flames. To utilize the developed model, data describing the steady state temperature and heat release rate distributions in the flame region, the acoustic admittance of the burner surface and the global activation energy of the flame were needed as inputs. As described in this report, the needed input data were obtained by a combination of experimental and analytical techniques. Using these data as inputs, the model predicted that the damping or driving of the acoustic field by the investigated flames depends strongly on the acoustic admittance of the burner surface and on the frequency of the acoustic oscillations. Furthermore, the model predicted that the magnitudes of the heat release rate oscillations and the normal velocity oscillations generally decrease as the frequency increases. The experimental efforts during the reporting period used an LDV system to investigate the spatial

dependences of the axial and normal (to the wall) velocities in the flame region. The important phase differences between the oscillating velocities and pressures fields were determined by using the method of "Conditional Sampling". These studies revealed that the premixed flame drives the acoustic oscillation at the investigated frequency of 200 Hz. Finally, comparisons of the measured data with the model predictions showed excellent agreement between the two indicating that state-of-the-art models are capable of predicting the interaction between a premixed gas phase flame and an axial acoustic field. This observation strongly suggests that state-of-the-art models should be able to provide insight into the interaction of actual solid propellant flames with the flow environment in rocket motors experiencing axial instabilities.

INTRODUCTION

This research program is concerned with the determination of the contributions of solid propellant gas phase flames to the driving of axial instabilities in rocket motors. This problem is of much interest because it is well known that the response of the solid propellant combustion process to the flow oscillations is responsible for providing the energy required for the initiation and maintenance of the instability inside the rocket motor. Consequently, acquiring an understanding of the processes which control the interaction of solid propellant combustion processes with the motor flow oscillations may lead to the development of practical solutions for reducing the occurrences of highly detrimental instabilities in solid propellant rocket motors.

At present the mechanisms which control the burn rates of solid propellants in unstable rocket motors are not clearly understood. These mechanisms involve solid and gas phase chemical reactions, complex, multidimensional heat, momentum and mass transfer processes and they generally occur within extremely thin regions (i.e., of the order of tens of microns) next to the solid-gas interface. Because of the small dimensions of the solid propellant flame region, no detailed experimental probing of oscillatory solid propellant flames have been performed to date and all efforts in this area have been confined to the development of theoretical models whose validity has never been confirmed.

To attain an understanding of the phenomena responsible for the occurrence of combustion instabilities in solid propellant rocket motors this research program has been investigating:

1) Gas phase flame mechanisms responsible for the driving/damping of axial instabilities in solid propellant rocket motors.

2) The validity of state-of-the-art solid propellant combustion response models.

Since actual solid propellant flames cannot be used, because of their extremely small dimensions, short burn times and difficulties in handling, in experimental investigations of flame driving/damping of combustion instabilities, other flames which simulate relevant characteristics of solid propellant flames and are amenable to experimental probing must be used in such studies. In the present study the interaction of a premixed flame, stabilized next to the side wall of a duct, with longitudinal acoustic fields has been investigated to determine the mechanisms through which such flames can drive or damp axial acoustic fields. The experimental setup, developed for this study, is presented in Fig. 1. It consists of a long rectangular duct with a flat flame burner on one of its side walls. A reactive air-propane mixture is delivered through a ceramic matrix and ignited to form a flat flame. This flame can be stabilized at various distances away from the burner surface by controlling the mixture flow rate, the air-fuel composition and the location of the wire gauze which is held above the flame. The acoustic drivers at one end of the duct are used to establish a standing acoustic wave of desired frequency and amplitude in the duct and the movable end plate at the other end of the duct is used to "move" the standing acoustic wave relative to the fixed flame position. This, in turn, provides a capability for investigating the flame behavior when it is located at different points on the standing acoustic wave.

A premixed flame has been chosen for this study because it eliminates the complexities arising from the presence of mixing processes and can be stabilized at distances sufficiently far away (e.g., ~ 10 mm) from the side wall of the duct which permits the experimental probing of the flame. The premixed flame also possesses a sharp gas phase temperature rise and its interaction with axial acoustic fields produces an oscillatory velocity component normal to the side wall of the duct. Such large gas phase temperature increases and fluctuating normal velocity components, which are responsible for the driving/damping of acoustic fields, are also expected to occur during the oscillatory combustion of actual solid propellant flames.

RESEARCH ACCOMPLISHMENTS

The dynamic response of a gas phase heat source (e.g., a combustion process) when it is subjected to acoustic oscillations plays an important role in the stability of the system which contains the heat source. The conditions under which an oscillatory heat source would drive or damp acoustic oscillations have been formulated by Rayleigh[1] who showed that this interaction depends upon the phase difference and the amplitudes of the oscillating pressure and heat source. Expressed mathematically, Rayleigh's criterion indicates that the heat source will drive acoustic oscillations within the system when the inequality*,

$$\int_V \int_T p'(x,t)\, Q'(x,t)\, dt\, dV > L \qquad (1)$$

is satisfied. The left hand side of the above equation can be positive or negative depending upon the phase difference between the heat release rate and pressure oscillations. Driving occurs when this phase difference, Φ, satisfies the condition $-90^{\circ} < \Phi < 90^{\circ}$ while for any other value of Φ the heat release rate oscillations damp the acoustic oscillations. It should be also pointed out that the integration in the above equation is performed over the entire volume of interest (or over all regions where $Q' \neq 0$) and that it is quite possible that Q' damps the oscillations in some parts of the system and drives them in other.

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* See nomenclature for explanation of symbols.

During the previous reporting period the amplitude and phase (relative to the pressure oscillations) of the oscillatory radiation, which is a measure of the oscillatory heat release rate[2], of the investigated flames were measured. These data showed that the driving/damping characteristics of the investigated flames are frequency dependent. During the current reporting period the developed flame response model was used to predict the driving/damping characteristics of the investigated flames. The developed model requires the steady state temperature distribution in the flame region (previously measured by the Inclined-slit method), the steady state heat release rate distribution, the global activation energy and the acoustic admittance of the burner surface (previously measured by the classical impedance tube technique) as inputs.

To determine the steady state heat release rate distribution in the combustion zone and the global activation energy for the assumed one step forward reaction, the following non-dimensionalized steady state energy equation derived in Ref. 3,

$$\frac{k}{c_p}\frac{d^2\bar{T}}{dy^2} - \bar{v}_\infty \frac{d\bar{T}}{dy} = - \bar{w}q \tag{2}$$

where,

$$\bar{w}q = S\, c_p \frac{(1 - \bar{T})^2}{\bar{T}^2} e^{-E/\bar{T}} \tag{3}$$

was solved to obtain the values of S and E and the corresponding, theoretical, steady state temperature distribution which provided the "best fit" with the measured temperature distribution. Once these were determined, the steady state heat release distribution was determined using the above relationship for $\bar{w}q$. Typical plots of measured and computed temperature distributions are presented in Fig. 2 whereas a plot of the corresponding steady state heat release rate distribution is presented in Fig. 3.

Utilizing the steady state temperature and heat release distributions presented in Figs. 2 and 3 as inputs for the unsteady flame model the latter was used to predict the behavior of the oscillatory heat release rate of the investigated flames. Specifically, the model was used to predict the unsteady behavior of flames stabilized above the burners having different surface admittances and subjected to axial acoustic oscillations having different frequencies. The phase differences between the oscillating heat release rates and the imposed pressure oscillations were predicted to determine the conditions under which these flames will drive or damp the acoustic waves. Predicted frequency dependences of such phase differences for two different burner surface admittances are presented in Fig. 4. These plots clearly show that the driving/damping characteristics of these flames depend on the frequency of the acoustic oscillation and also on the admittance of the burner surface. For example, when the burner admittance $R = -2.2 + 0.4i$ the flame damps the acoustic field at all the investigated frequencies while when the burner admittance $R = -0.4 - 0.6i$ damping occurs at low frequencies and driving at high frequencies. The predicted frequency dependences of the amplitudes of the heat release rate oscillations for the two cases considered in Fig. 4 are presented in Fig. 5. These predictions indicate that in general the amplitudes of heat release oscillations decrease with increasing frequency, a trend which is consistent with the measured frequency dependence of the oscillatory radiation of the investigated flames. It should be pointed out that the predictions presented in Figs. 4 and 5 were obtained by assuming that burner surface admittances did not vary with frequency. This assumption contradicts, however, the results of earlier studies, conducted under this program, which showed that the acoustic admittance of the burner surface is frequency dependent. The measured frequency dependence of the burner surface admittance has been input into the model and its predictions are presented in Figs. 6 and 7 which show the frequency dependences of the phase differences between heat release rate and pressure oscillations and the amplitudes of the heat release rate oscillations, respectively. These predictions are in good agreement with data measured earlier under this program[4].

The developed flame model was also utilized to predict the behavior of the oscillating velocity components in the flame zone. Of particular interest is the behavior of Real (v'(y)), the normal (to the burner surface) component of the oscillatory velocity. This is the case because the interactions between unsteady solid propellant flames and the local core flow oscillations involve complex fluid mechanical, heat transfer and chemical processes. These interactions occur near the lateral boundaries of the motor cavity and they produce velocity oscillations v'(y) at and near the propellant surface in a direction normal to the direction of the axial oscillations in the core flow. These normal velocity oscillations act as lateral pistons which periodically compress the core flow, thus providing the energy required for initiating and maintaining the core flow oscillations. Specifically, if

$$\int_T p' \, \text{Real } (v'(y)) \, dt > 0 \tag{4}$$

at the edge of the flame or the edge of the boundary layer (if one exists) then these normal velocity oscillations can pump acoustic energy into the core flow oscillations. Thus, processes which increase Real(v') tend to drive acoustic oscillations and processes which decrease Real(v') tend to damp acoustic oscillations. Distributions of Real(v') predicted by the developed model for different acoustic frequencies and different acoustic admittances are presented in Figs. 8 and 9. These predictions show that Real(v') attains a maximum or a minimum at the location of maximum, steady state, heat release rate (i.e., at the flame). Figure 8 indicates, however, that for R = -2.2 + 0.4i Real(v') is always negative indicating that the flame damps the acoustic oscillations for all the investigated frequencies with maximum damping occurring at the flame. This flame damping decreases as the frequency increases from 30 to 400 Hz. In contrast, Fig. 9 shows that for R = -0.4 - 0.6i the flame damps at 10 Hz and it drives the oscillations at higher frequencies. These predictions indicate that the driving/damping characteristics of the investigated flames depend on the frequency of the oscillations and on the acoustic admittance of the burner surface. Finally, the data presented in Figs. 8 and 9 show that the magnitude of Real(v') generally decreases as the frequency increases.

To examine the validity of the reported predictions, some of the experimental efforts during the reporting period investigated the characteristics of the oscillatory velocity component normal to the burner surface in the flame region. A TSI, high power, counter-based, LDV was installed and utilized in this study. The electronic counter was interfaced to an HP1000 A700 minicomputer via a 16-bit parallel I/O for data acquisition and analysis purposes. The measurements of Real(v') required the determination of the magnitude of the velocity oscillation and its phase with respect to the imposed pressure oscillation. To attain these data "Conditional Sampling"[5] and ensemble averaging were used in the data acquisition and reduction procedures. Software capable of performing the required acquisition from the LDV processor and its analysis were developed.

Furthermore, a particle seeding system utilizing Al_2O_3 particles was designed, fabricated and incorporated into the previously developed experimental setup.

A typical, measured time dependence of the normal velocity component at a point in the flame is presented in Fig. 10 while Fig. 11 presents the measured spatial dependence of Real(v') in the flame region of Real(v') when the flame is excited with a 200 Hz acoustic field. Figure 10 shows that the time dependence of the measured velocity is sinusoidal and Fig. 11 shows that Real(v') attains a maximum at the flame location indicating that the flame tends to drive the acoustic wave at this frequency. A comparison of measured and predicted velocity distributions is currently in progress.

In summary, the experimental and theoretical results obtained during the reporting period show that the driving/damping characteristics of the investigated flames depend upon the frequency of the axial acoustic waves and the admittance of the burner surface. These studies also revealed that the driving capabilities of the flames decrease as the frequency increases. Finally, these studies show excellent agreement between the developed flame model predictions and the measured data. The experimental and theoretical results obtained during this study clearly demonstrates the occurrence of oscillatory heat release rates and oscillatory transverse velocities in the combustion zone when axial acoustic oscillations are imposed upon the investigated flames. Such characteristics are undoubtedly exhibited by actual solid propellant flames during axial combustion instabilities and they strongly suggest that the oscillatory heat transfer to the propellant surface that is undoubtedly associated with the observed flame oscillations may be the cause of an unsteady propellant burn rate. This, in turn, would result in an unsteady reactants supply to the gas phase flame which could produce an oscillatory heat release rate is capable of providing the energy required for maintaining the oscillations.

NOMENCLATURE*

c_p	specific heat
E	global activation energy
k	thermal conductivity
L	system acoustic losses
p	pressure
q	heat of combustion per unit mass of fuel
Q	heat release rate
R	admittance of the burner surface
S	constant, see Eq. (3)
t	time
T	period of oscillation; temperature
v	transverse velocity
V	control volume
w	reaction rate of fuel
x	axial coordinate
y	transverse coordinate
Φ	phase difference between radiation and pressure oscillation

Superscript

'	fluctuating quantity
-	steady state quantity

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* All quantities have been non-dimensionalized using the non-dimensionalization scheme described in Ref. 3.

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2. Gaydon, A. G. and Wolfhard, H. G., "Flames: Their Structure, Radiation and Temperature," 4th Edition, John Wiley & Sons, NY, 1979.

3. Hedge, U. G. and Zinn, B. T., "The Acoustic Boundary Layers in Porous Walled Ducts with a Reacting Flow," 21st Int'l Symposium on Combustion, Aug. 3-8, 1986.

4. Sankar, S. V., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Flame Driving of Axial Acoustic Waves: Comparison of Theoretical Predictions and Experimental Observations," AIAA-87-0219.

5. Bell, W. A. and Lepicovsky, J., "Conditional Sampling with a Laser Velocimeter," AIAA-83-0756.

PUBLICATIONS

1. Hedge, U. G. and Zinn, B. T., "The Acoustic Boundary Layer in Porous Walled Ducts with a Reacting Flow," To appear in the Proceedings of the 21st International Symposium on Combustion.

2. Sankar, S. V., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Behavior of Simulated Solid Propellant Flames in Axial Acoustic Fields," Proceedings of the 23rd JANNAF Combustion Meeting, Oct. 20-24, 1986.

3. Sankar, S. V., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Flame Driving of Axial Acoustic Waves: Comparison of Theoretical Predictions and Experimental Observations," AIAA Paper No. 87-0219.

4. Sankar, S. V., Hegde, U. G., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Driving of Axial Acoustic Waves by Simulated Solid Propellant Flames," Submitted for publication, AIAA Journal.

PROFESSIONAL PERSONNEL

The following individuals contributed to the research effort described in this section:

Dr. Ben T. Zinn, Regents' Professor of Aerospace Engineering

Dr. Jechiel I. Jagoda, Associate Professor of Aerospace Engineering

Mr. Brady R. Daniel, Senior Research Engineer

Dr. Uday G. Hegde, Research Engineer II

Mr. Subramanian V. Sankar, Ph.D student

PRESENTATIONS

1. "The Acoustic Boundary Layer in Porous Walled Ducts with a Reacting Flow," Presented at athe 21st International Symposium on Combustion, Munich, West Germany, Aug. 3-8, 1986.

2. "Behavior of Simulated Solid Propellant Flames in Axial Acoustic Fields," Presented at the 23rd JANNAF Combustion Meeting, NASA Langley Research Center, Hampton, Virginia, Oct. 20-24, 1986.

3. "Flame Driving of Axial Acoustic Waves: Comparison of Theoretical Predictions and Experimental Observations," Presented at the AIAA 25th Aerospace Sciences Meeting in Reno, Nevada, Jan. 12-15, 1987.

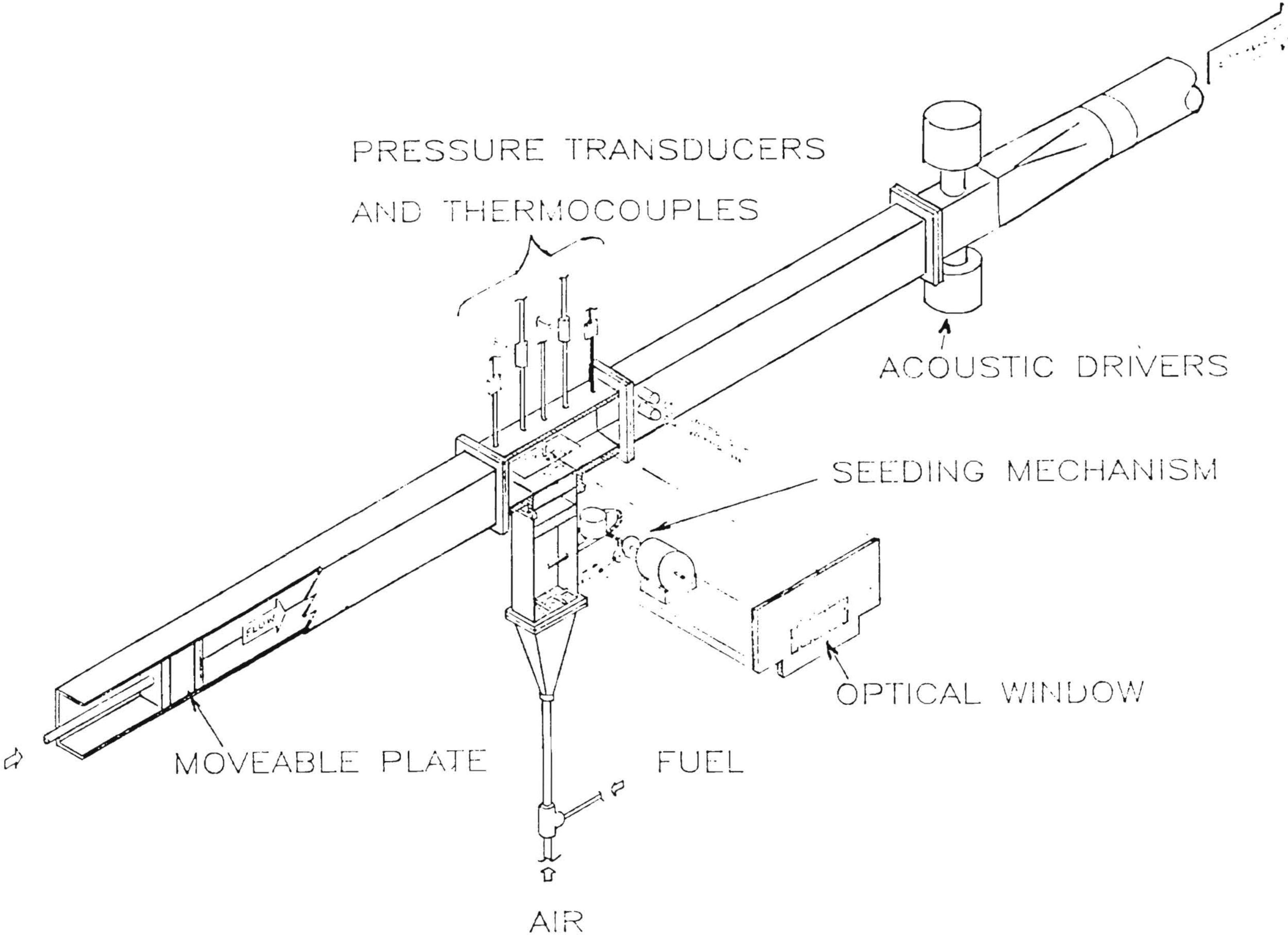


Fig. 1. Schematic of the developed experimental setup.

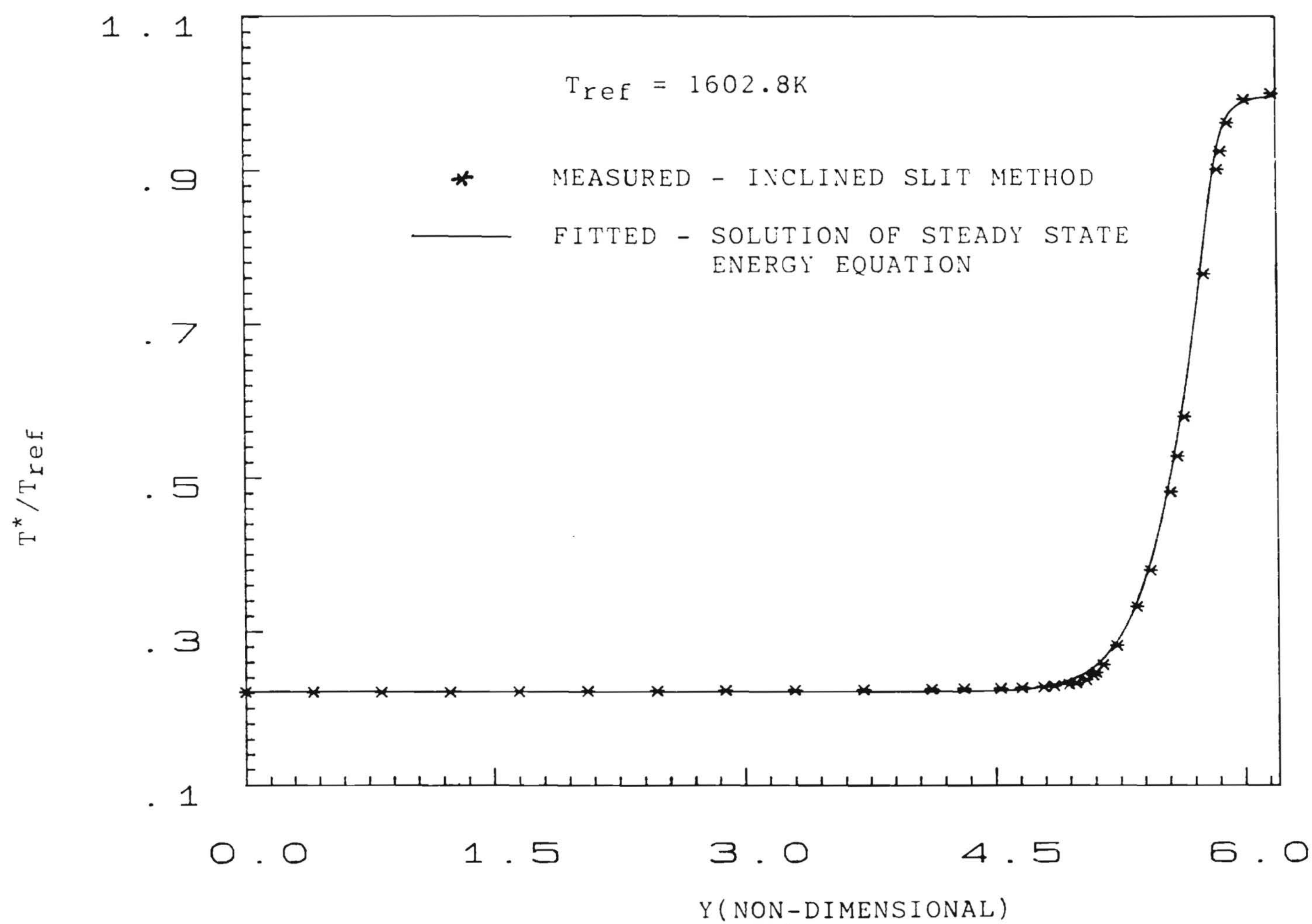


Fig. 2. Typical, measured and "fitted" steady state temperature distributions in the flame region.

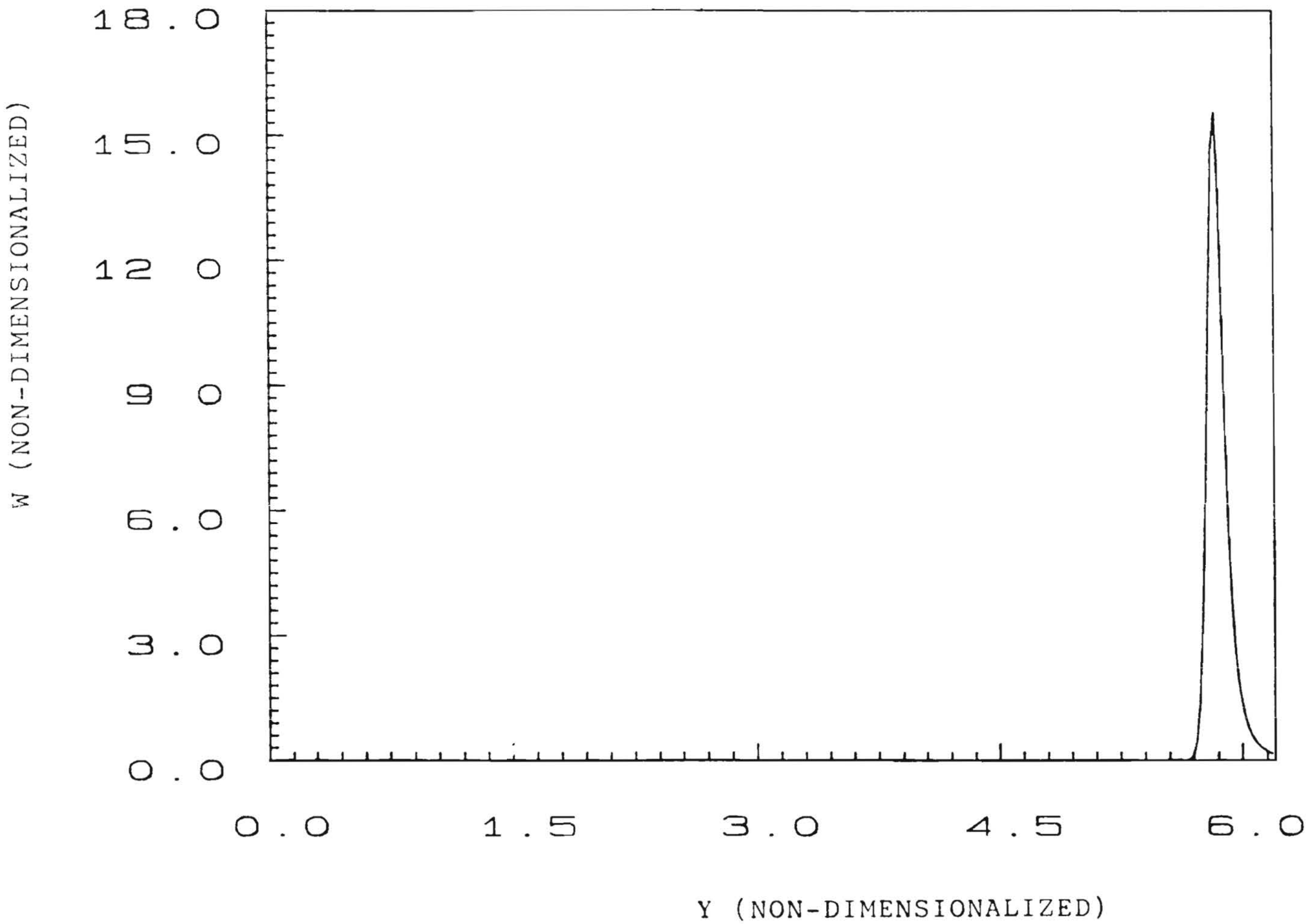


Fig. 3. Computed steady state heat release rate distribution in the flame region.

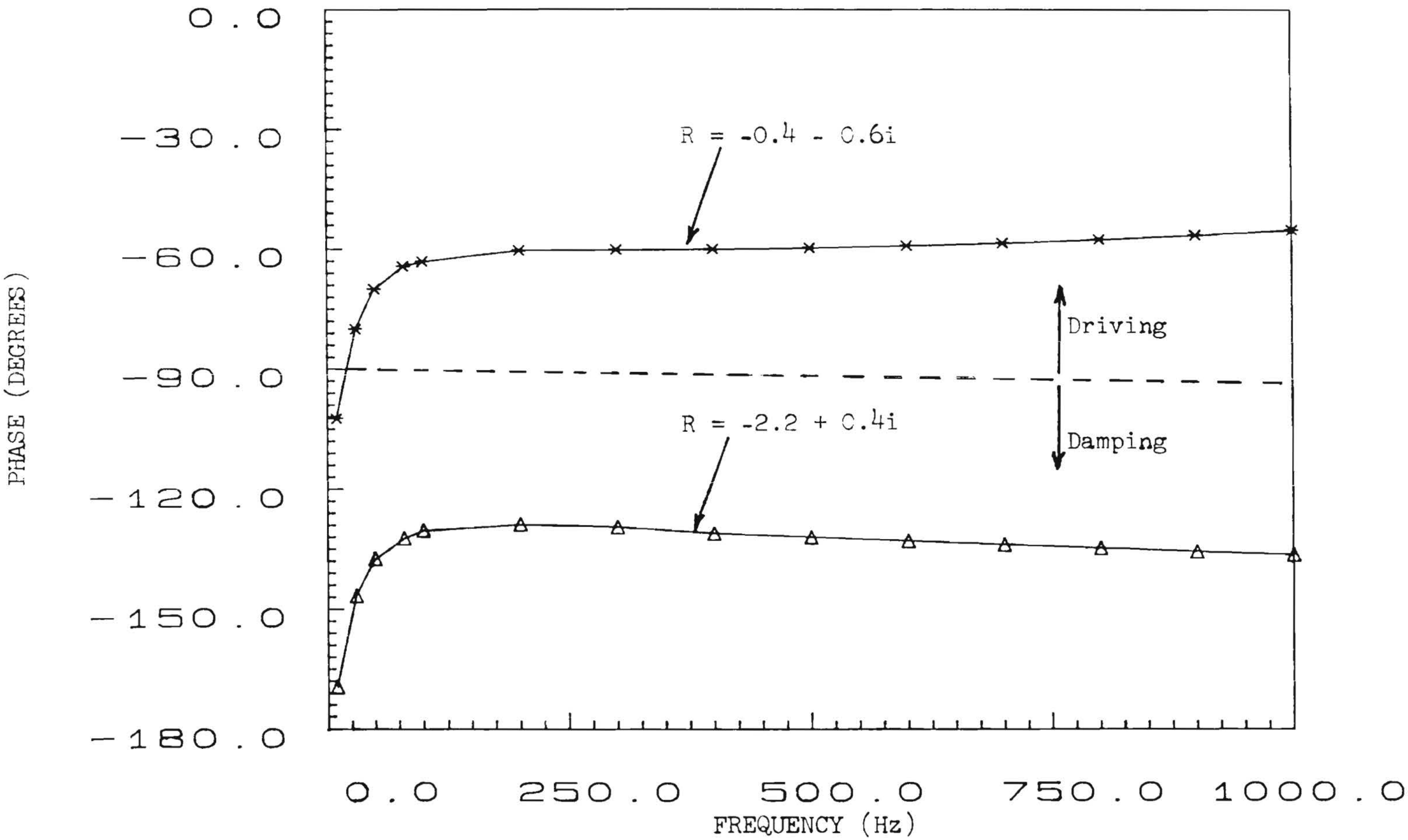


Fig. 4. Predicted frequency dependence of the phase differences between heat release rate oscillations and pressure oscillations for two different burner surface admittances.

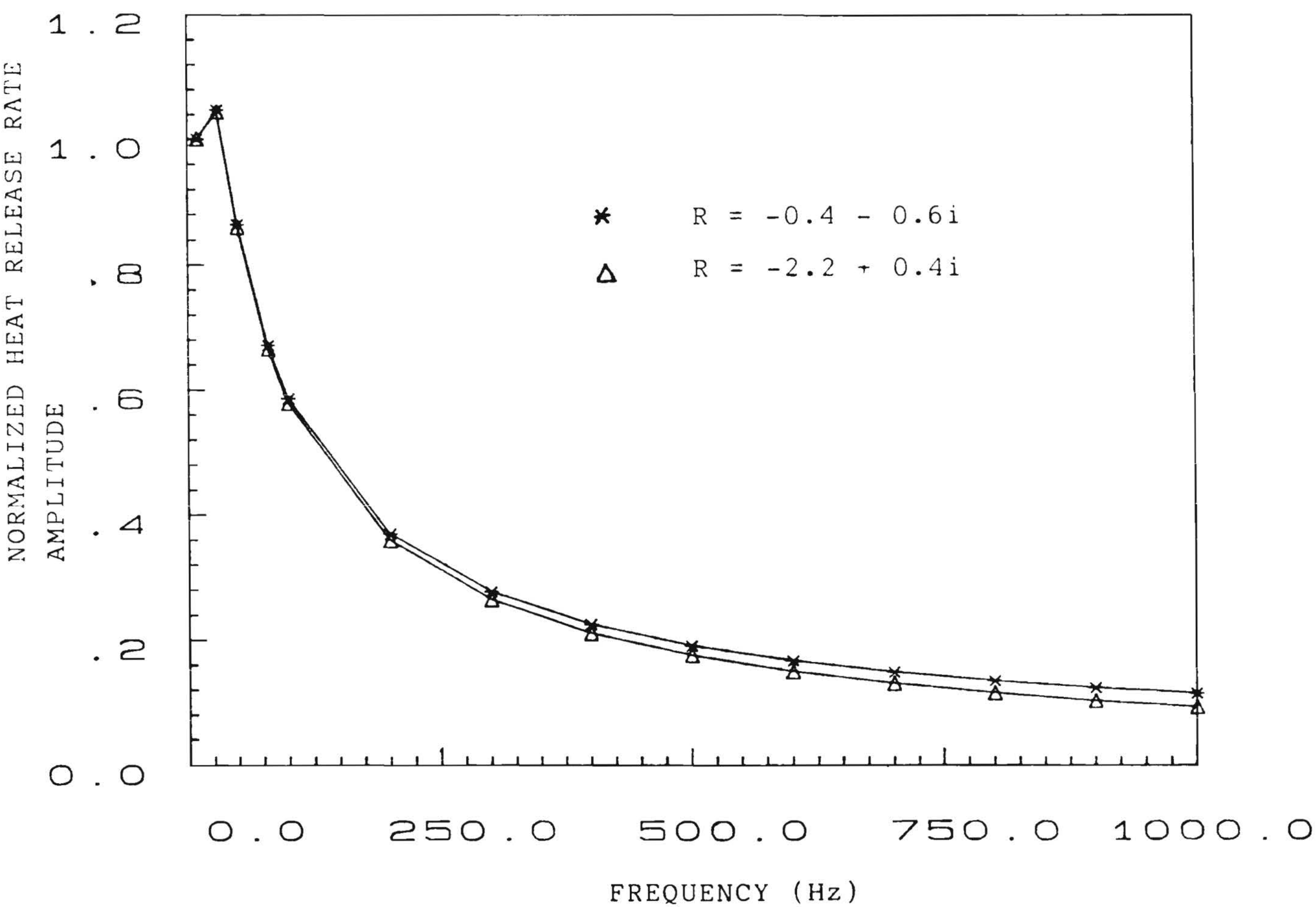


Fig. 5. Predicted frequency dependence of heat release rate amplitude for two different burner surface admittances.

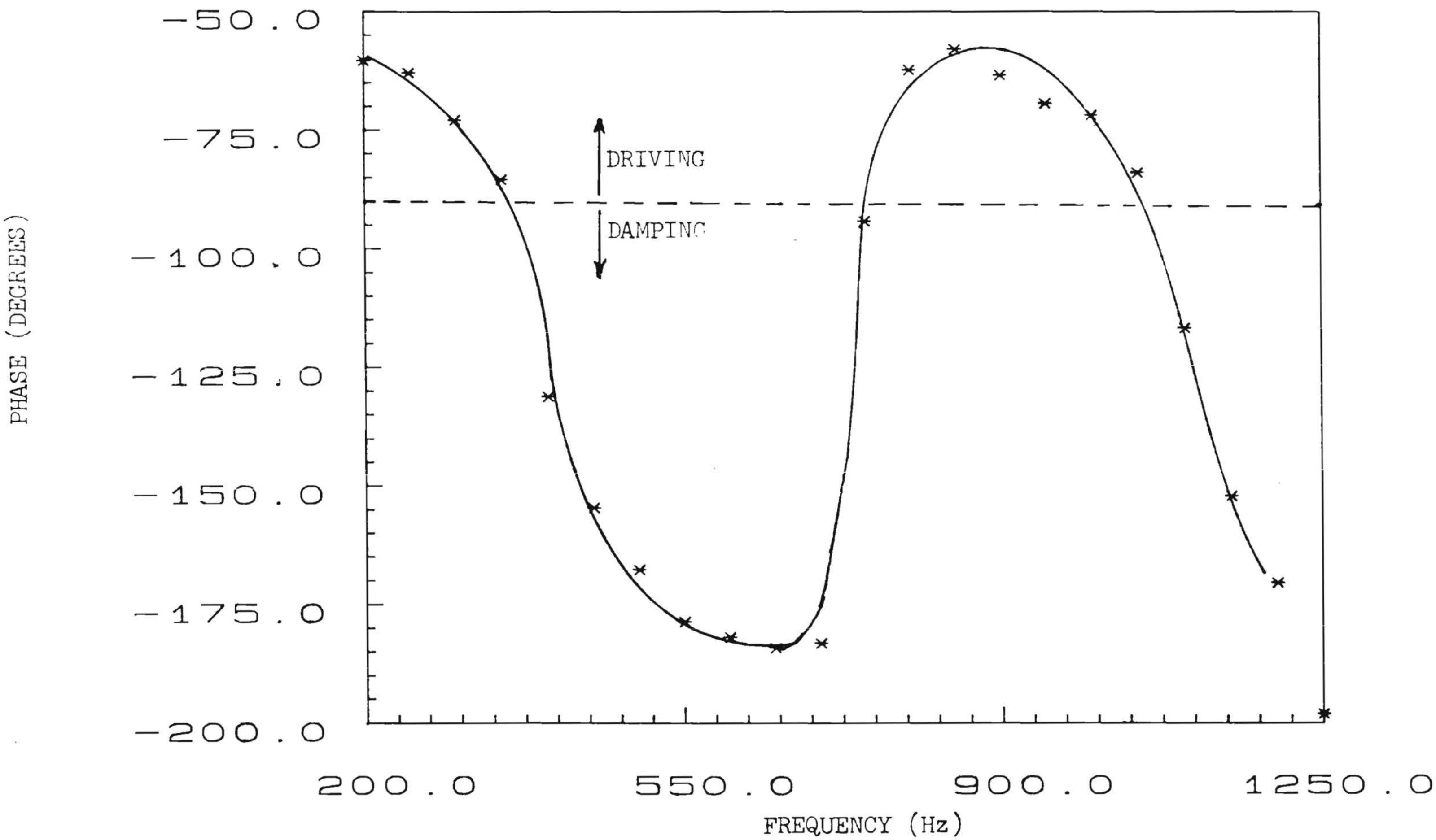


Fig. 6. Predicted frequency dependence of the phase differences between heat release rate oscillations and pressure oscillations - measured, frequency dependent acoustic admittances used as model input.

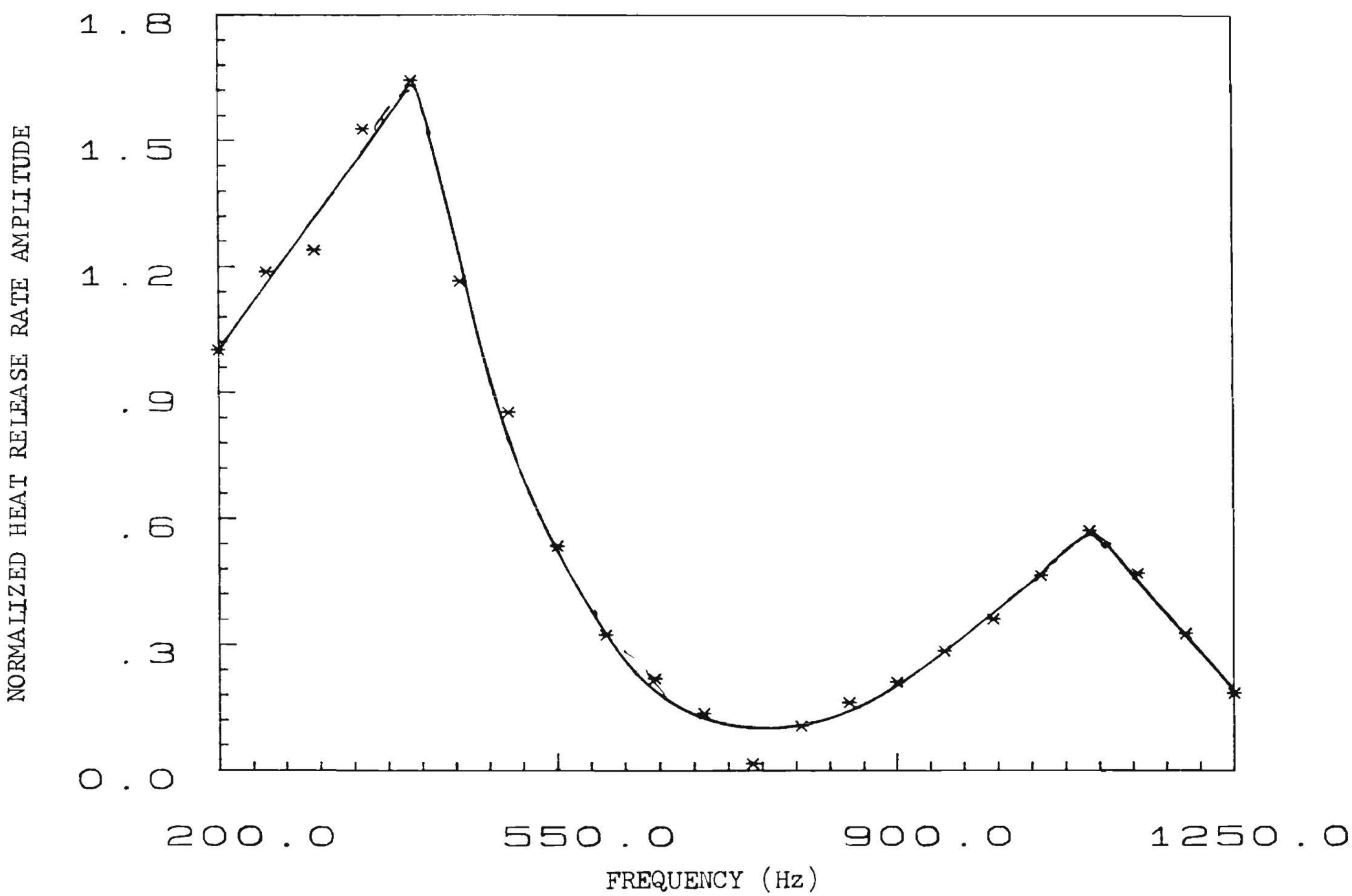


Fig. 7. Predicted frequency dependence of the heat release rate amplitude - measured, frequency dependent acoustic admittances used as model input.

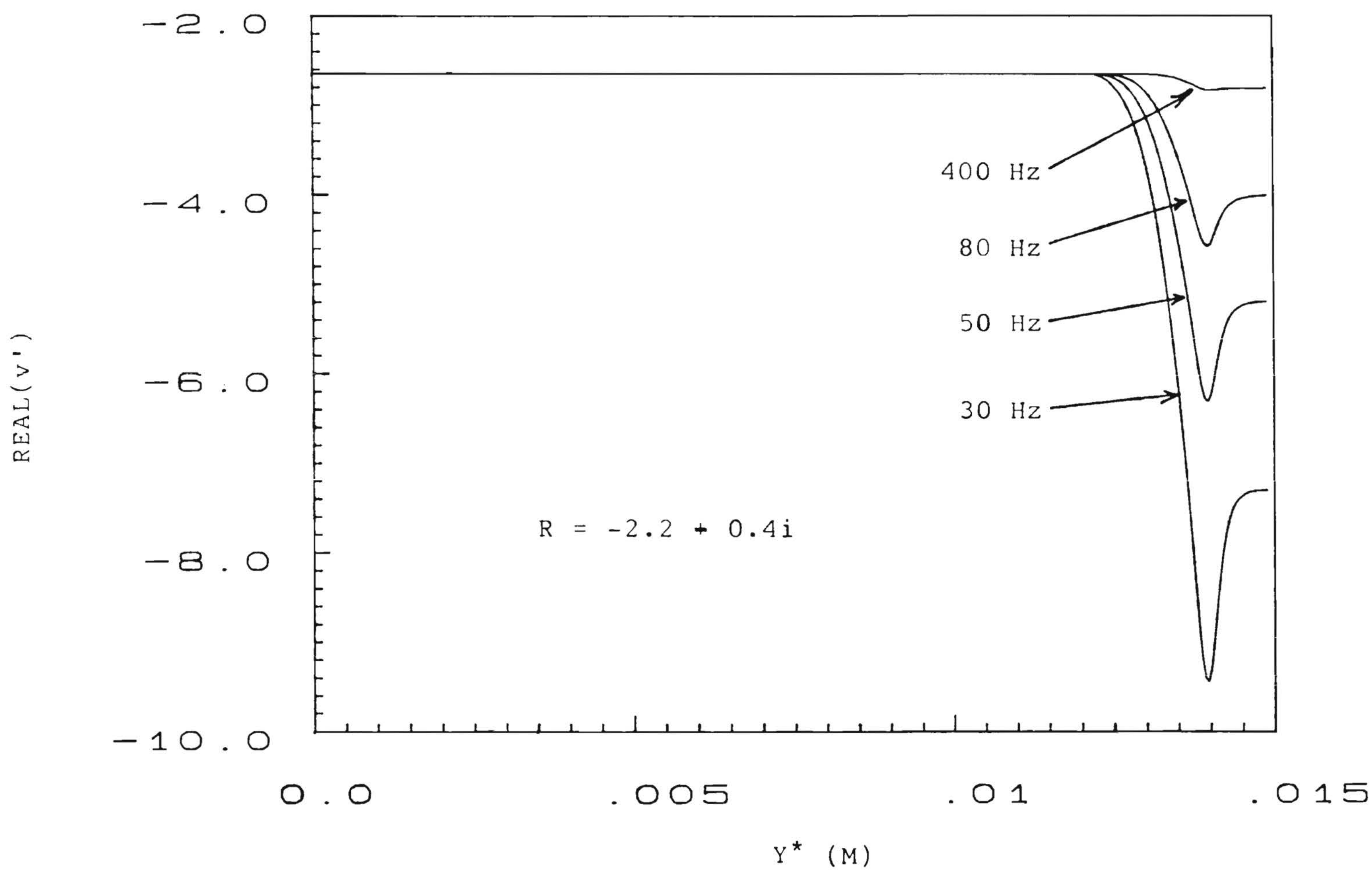


Fig. 8. Predicted Real(v') distributions for different acoustic frequencies - burner surface admittance R = - 2.2 + 0.4i.

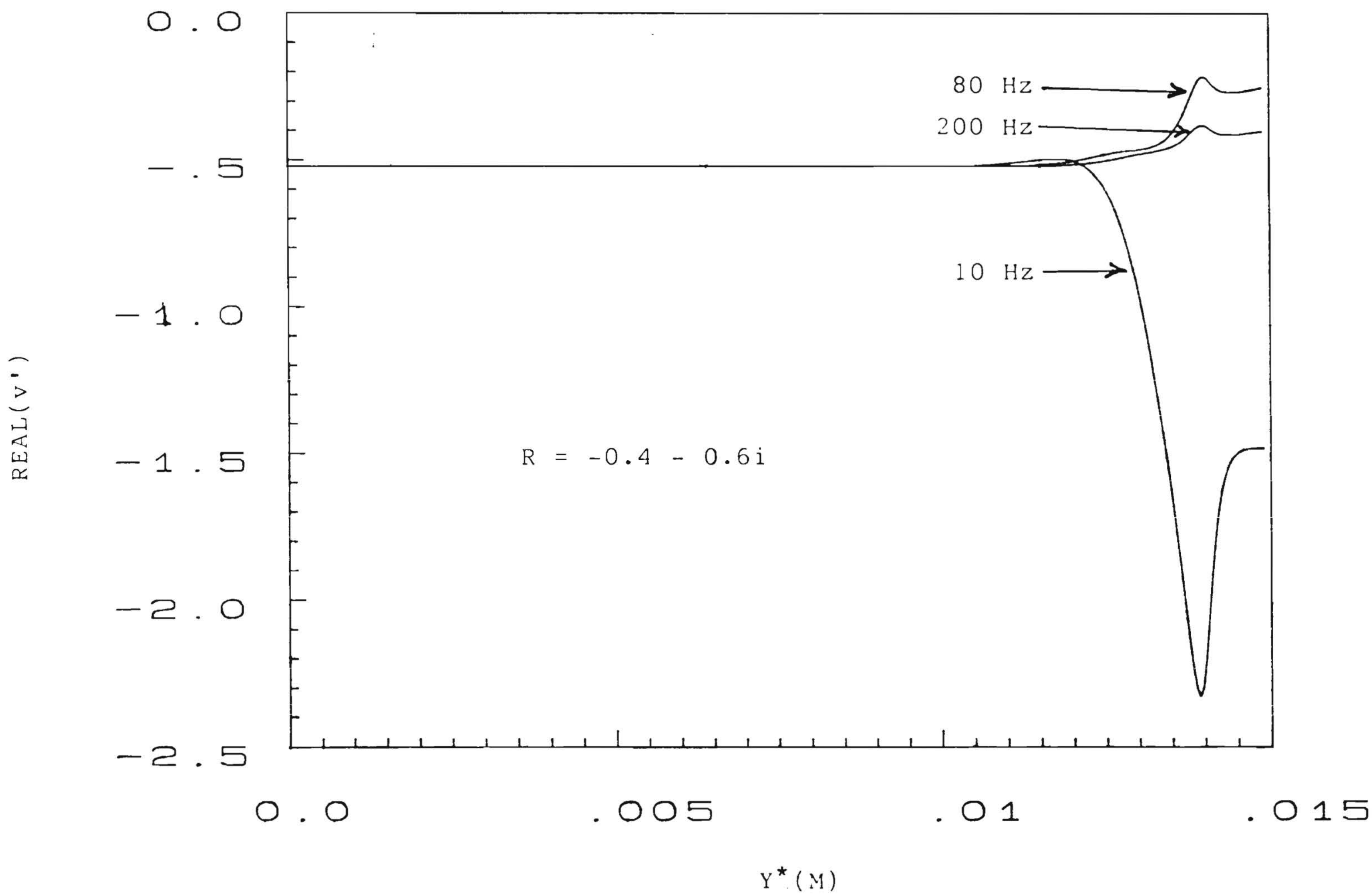


Fig. 9. Predicted Real(v') distributions for different acoustic frequencies - burner surface admittance R = - 0.4 - 0.6i.

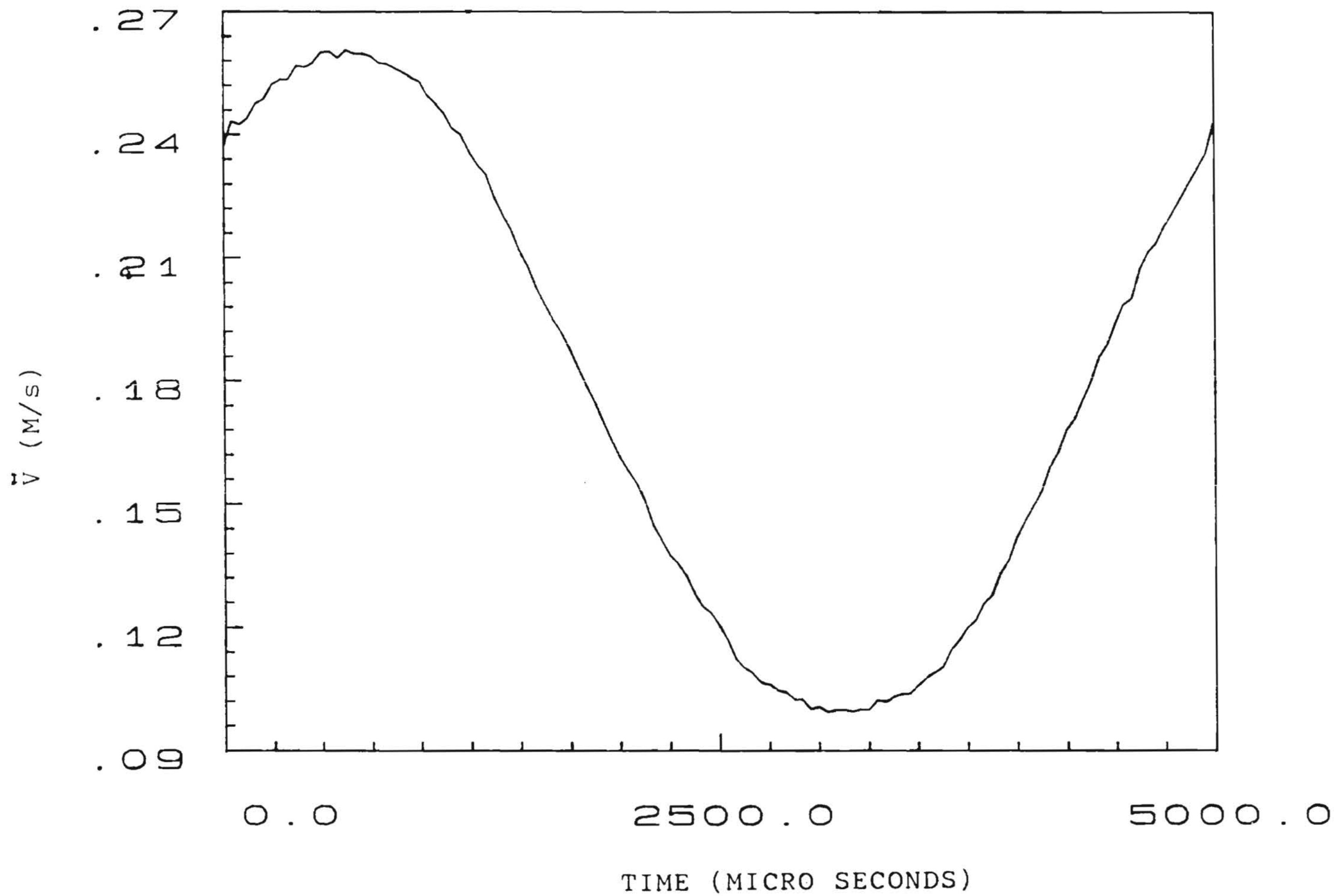


Fig. 10. A typical, measured time dependence of the normal velocity component at a point in the flame.

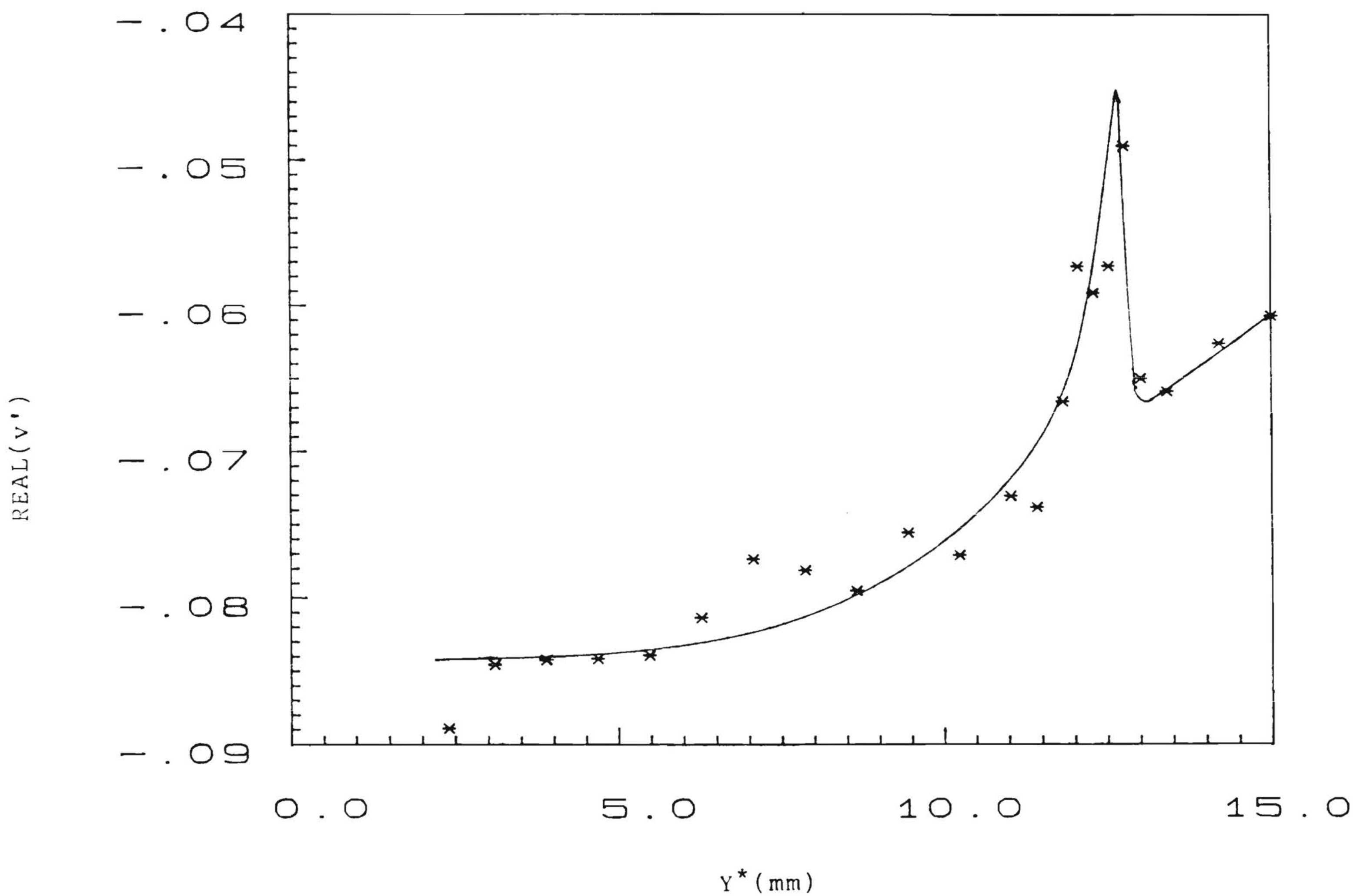


Fig. 11. Measured spatial dependence of Real(v′) in the flame region - flame excited with a 200 Hz acoustic field.

E16630/DR. ZINN

ANNUAL TECHNICAL REPORT FOR 2/29/88

PROGRESS TO DATE

This section briefly describes the results obtained during the first phase of this research program and the conclusions which may be drawn from it. As noted earlier, this program is concerned with the elucidation of solid propellant gas phase flame processes which contribute to the driving of axial instabilities in solid propellant rocket motors. Since the extremely small dimensions of actual solid propellant flames[1] and limitations of available diagnostics techniques currently prevent experimental probing of these flames, this study has investigated both theoretically and experimentally a related problem; that is, the interaction between a premixed flame stabilized next to the sidewall of a duct and a standing, longitudinal acoustic wave (see Fig. 1). As discussed earlier, this simulated flame-acoustic wave interaction problem has important similarities with the interaction occurring during combustion instabilities in solid propellant rocket motors. For example, the temperature of both flames increase sharply with distance from the wall or propellant surface and similar theoretical approaches can be used to model both flames. However, the investigated premixed flame can be stabilized sufficiently away from the wall to allow performing the required measurements.[13-17]

This research program had the following objectives:

1. To determine whether state of the art models of unsteady solid propellant flames(when suitably modified) are capable of predicting the characteristics of the investigated premixed flames under conditions simulating those encountered in unstable solid propellant rocket motors, and

2. to determine those features of the flame which exert the greatest influence upon the flame driving/damping of the core flow acoustics.

The developed experimental set up[18] (see Fig. 3) consists of a long rectangular tube having a flat flame burner on one of its side walls, an axially movable injector plate at the inlet end and two acoustic drivers at the exhaust end. During an experiment, a combustible mixture of propane and air is fed into the side wall burner and a flat flame is stabilized a short distance (i.e., 5-15 mm) away from the burner surface (see also Fig. 4). Next, the acoustic drivers are turned on to excite a standing longitudinal acoustic wave of desired frequency and amplitude in the tube. The position of the flame relative to the standing acoustic wave (i.e., next to a pressure node or pressure antinode) can be varied by moving the injector plate axially.

As the results obtained during this investigation are best described in terms of comparisons of experimentally measured data with theoretical predictions, the theoretical model (described in detail in Ref. 10) will be briefly outlined. The flow variables including temperature, pressure, velocity, fuel mass fraction and so on are split into steady and unsteady components. A set of nonlinear differential equations is obtained for the steady state components and a set of linear differential equations for the unsteady components. The analysis for the unsteady components is two dimensional and depends both upon the axial location (x) and the normal distance (y) from the burner surface. The equations for the unsteady components contain coefficients which depend upon the steady state solutions and are subject to boundary conditions at the burner surface ($y = 0$) and at the downstream edge of the flame ($y = y_f$). Thus, the steady state solutions

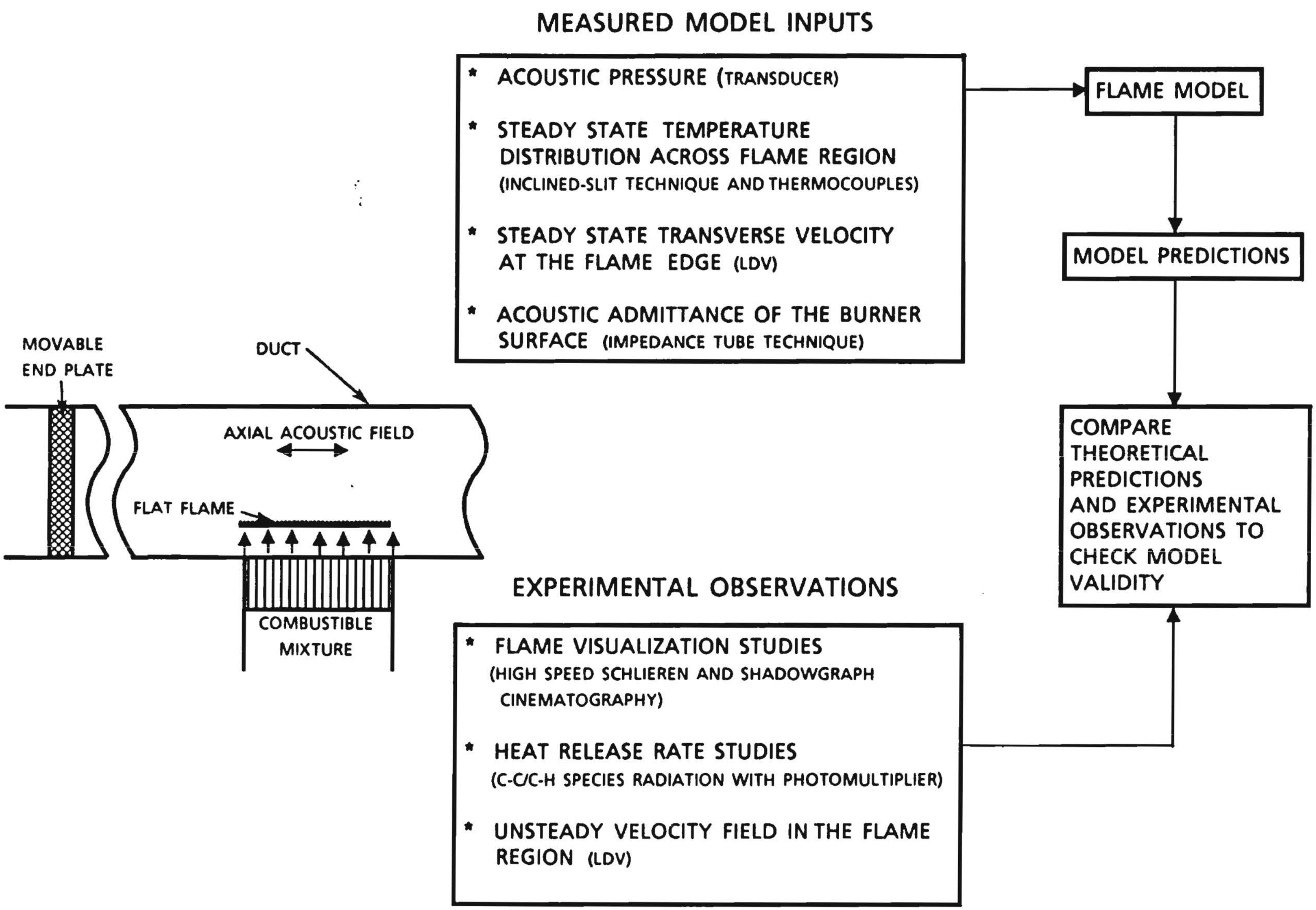


Fig. 4. Summary of the Research Program on the Interaction between Premixed Flat Flames and Longitudinal Acoustical Waves.

need to be determined either theoretically or experimentally or by some combination of the two. In addition, some of the boundary conditions, in particular the value of the normal component of the velocity fluctuation, v', at the burner surface need to be input from experimental measurements.

The acoustic driving/damping characteristics of the investigated flames may be determined in two ways. First, the acoustic energy input (or extracted) by the flame from the core flow oscillations is given by the time average of the product p'v' of the acoustic pressure p' and the normal component of the velocity fluctuation v'. In this connection it should be pointed out that a normal component of the fluctuating velocity v' is formed in the flame region as a result of the periodic characteristics of the flame. If the product p'v' is positive, then energy is fed into the acoustic oscillations and vice versa. If all phases are referred to that of the acoustic pressure (as was done in the experiments) then the pressure oscillations may be taken to be purely real. In such a case, the energy input of the flame is given by $< p' \text{ Real } (v') >$ which is the time average of the product of p' and the real part of v' generated by the flame. This yields a quantitative measure of the flame driving/damping characteristics. Secondly, a qualitative measure of the driving characteristics of the flame may be obtained using Rayleigh's criterion[19] which states that if the unsteady heat release from the flame is in phase with the local pressure oscillations, then acoustic driving by the flame results (and vice versa). Both of these criteria were utilized in the conducted studies.

Comparisons Between Theory and Experiment

The model for the unsteady flame behavior requires the following input:

(i) steady state spatial distributions of the temperature, velocities and heat release rate.

(ii) the value of the normal velocity fluctuation v' at the burner surface $y = 0$.

In accordance with the statements made earlier about the driving/damping characteristics of the flame, attention will be focussed herein on the following predictions of the model:

(i) the distribution of the real part of the normal velocity fluctuation, Real (v') and

(ii) the distribution of the heat release rate fluctuation, q'.

The required steady state temperature and velocity distributions were obtained experimentally. The steady state temperature distribution was determined using the inclined slit method[8,20] while the velocities were measured using LDV. The steady state reaction rate ($\bar{w}$) is related to the steady state temperature, $\bar{T}$, by the following Arrhenius type relation

$$\bar{w} = A \frac{(1 - \bar{T})^2}{\bar{T}^2} e^{-E/\bar{T}}$$

where E is the (normalized) activation energy and A is the steric factor. As these quantities depend upon the overall reaction characteristics of the flame and are not readily available, the theoretical model was used, in the inverse mode, to determine these quantities; that is, instead of solving for

$\bar{T}$ using knowledge of A and E, A and E were determined from the steady energy equation using the experimentally determined distribution of $\bar{T}$.

A typical measured temperature profile and a corresponding steady state solution obtained theoretically are shown in Fig. 5. The temperature is plotted as a function of the normal distance y from the burner surface. Two factors are of interest; the flame standoff distance is of the order of 1 cm thus enabling experimental probing and the steady state temperature gradient is very small in the neighborhood of y = 0. This means that heat transfer (by conduction) to the burner surface is not an important factor in the experiments. It should however be noted that this is not true for actual solid propellant flames for which the stand off distance is of the order of 50 microns. The implication of this will be discussed shortly. One should also note the sharp temperature rise in the flame or reaction zone. The corresponding steady state reaction rate profile is shown in Fig. 6.

The value of v' at y = 0 was obtained in terms of the acoustic admittance R (i.e., R = v'/p' at y = 0) of the side wall burner surface. This admittance was obtained experimentally using the impedance tube technique. The obtained admittance[20,21] is plotted as a function of frequency in Fig. 7 and is seen to depend strongly upon it.

To determine the flame driving characteristics, consider first the comparisons of predicted Real (v') distributions with values obtained experimentally using LDV techniques. As noted earlier this gives a quantitative measure of the driving/damping by the flame. In Fig. 8, Real (v') is plotted as a function of y at a frequency of 200 Hz (the driving frequency). At y = 0, it is given by the sidewall admittance and is negative indicating that the sidewall acts as an acoustic damper. It varies slowly between the burner surface (y = 0) and the flame region where the strongest

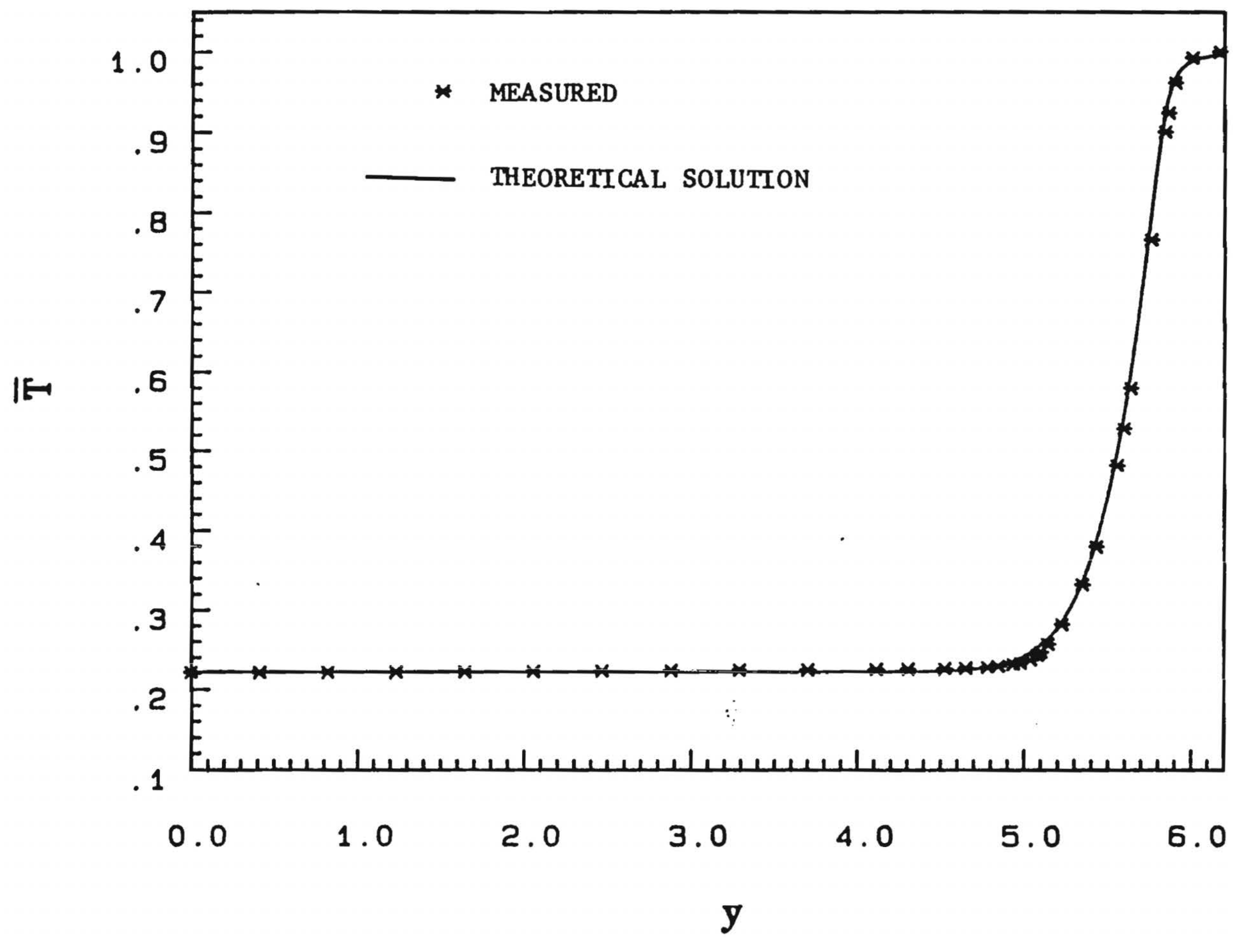


Fig. 5. Typical Temperature Distribution as a Function of the Normal Distance, y (Non-Dimensional), from the Burner Surface.

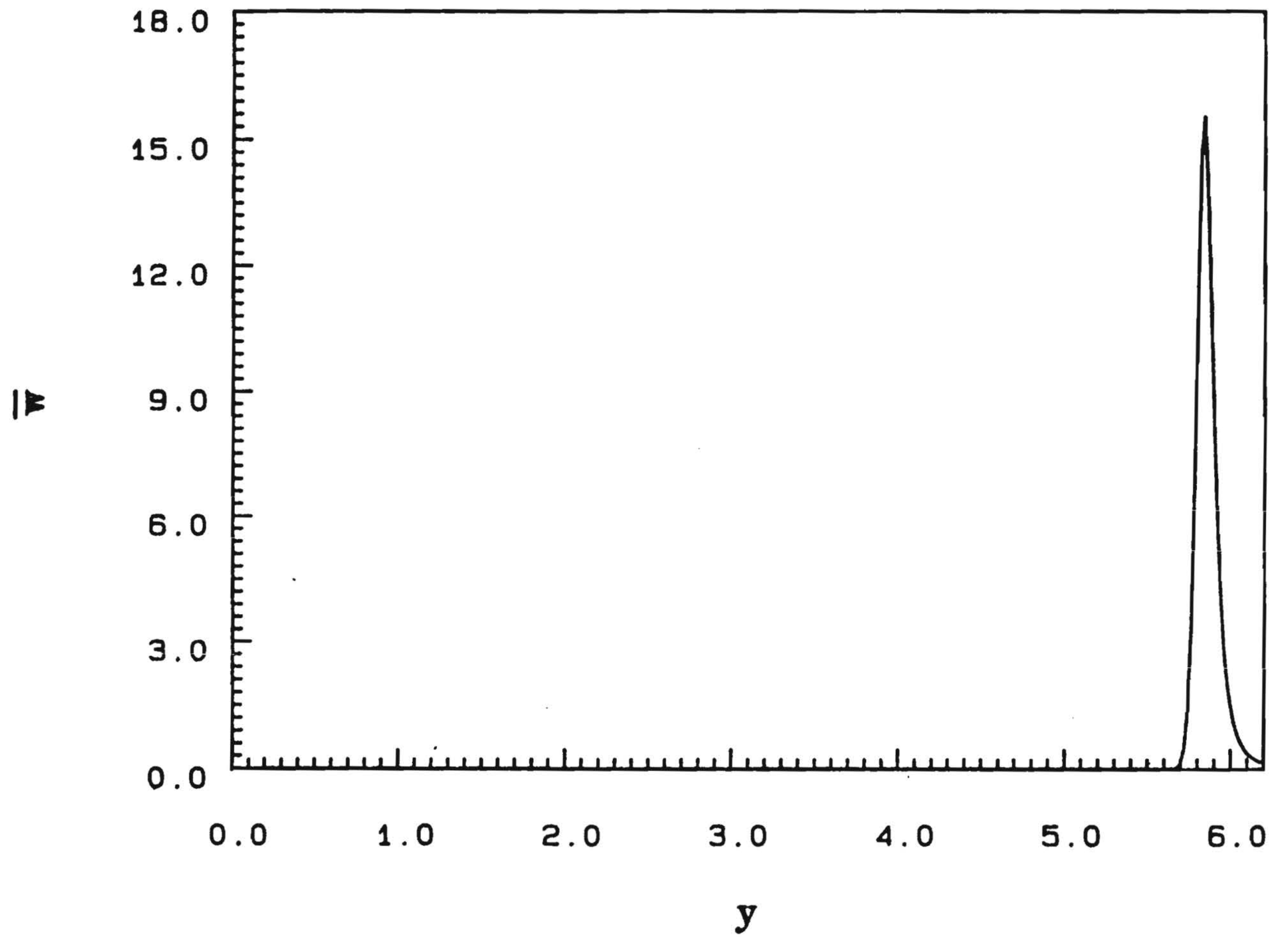


Fig. 6. Steady State Reaction Rate Profile.

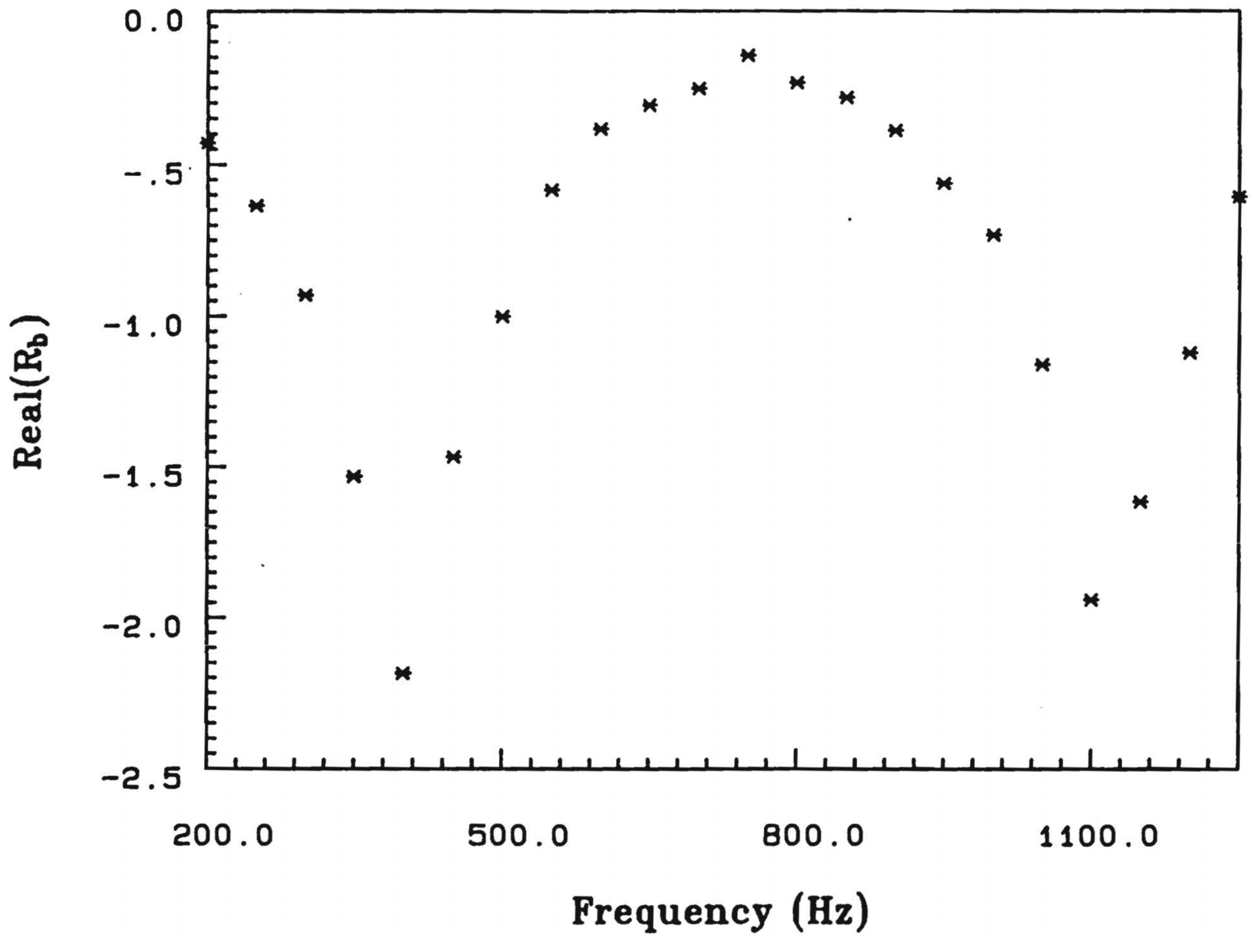


Fig. 7. Measured Real Part of the Burner Surface Admittance as a Function of Frequency.

temperature rise occurs (compare with Fig.5). In this flame region Real (v') becomes sharply less negative(or equivalently more positive and more in phase with the pressure oscillations). This means that at 200 Hz, the flame inputs energy into the core flow oscillations. Note also that the prediction of the model (the solid line) agrees extremely well with the measurements. It is also important to note that although the flame inputs energy into the acoustic field (by decreasing the "negativeness" of Real (v')), it is not able to overcome the strong damping effect of the sidewall burner surface. This implies that in a solid rocket motor situation, the admittance at the propellant surface is an important parameter relating to axial instabilities.

Consider next a case where the driving was at 400 Hz (Fig. 9). In this case Real (v') becomes even more negative in the flame region which indicates damping by the flame. What is important here is that the model agrees with the measurements and therefore demonstrates its capability to distinguish between situations where the flame drives and damps.

From the Rayleigh criterion point of view, the phase of the unsteady heat release needs to be compared with that of the pressure. The heat release fluctuations have a component in phase with the pressure oscillations if the phase difference between the two is less than $\pm 90^{o}$. The predictions of the model are compared with experimentally measured values of the phase in Fig. 10. These were obtained by measurements of overall CC radiation emission from the flame. As noted in earlier reports,[8,9,20] these emissions are indicative of the heat release rates from the flame. Note that at 200 Hz, p' and q' are in phase (indicating flame driving of the acoustics) while at 400 Hz they are out of phase (indicating flame damping of the acoustics). These predictions are in agreement with the trends exhibited by Real (v') in Figures 8 and 9.

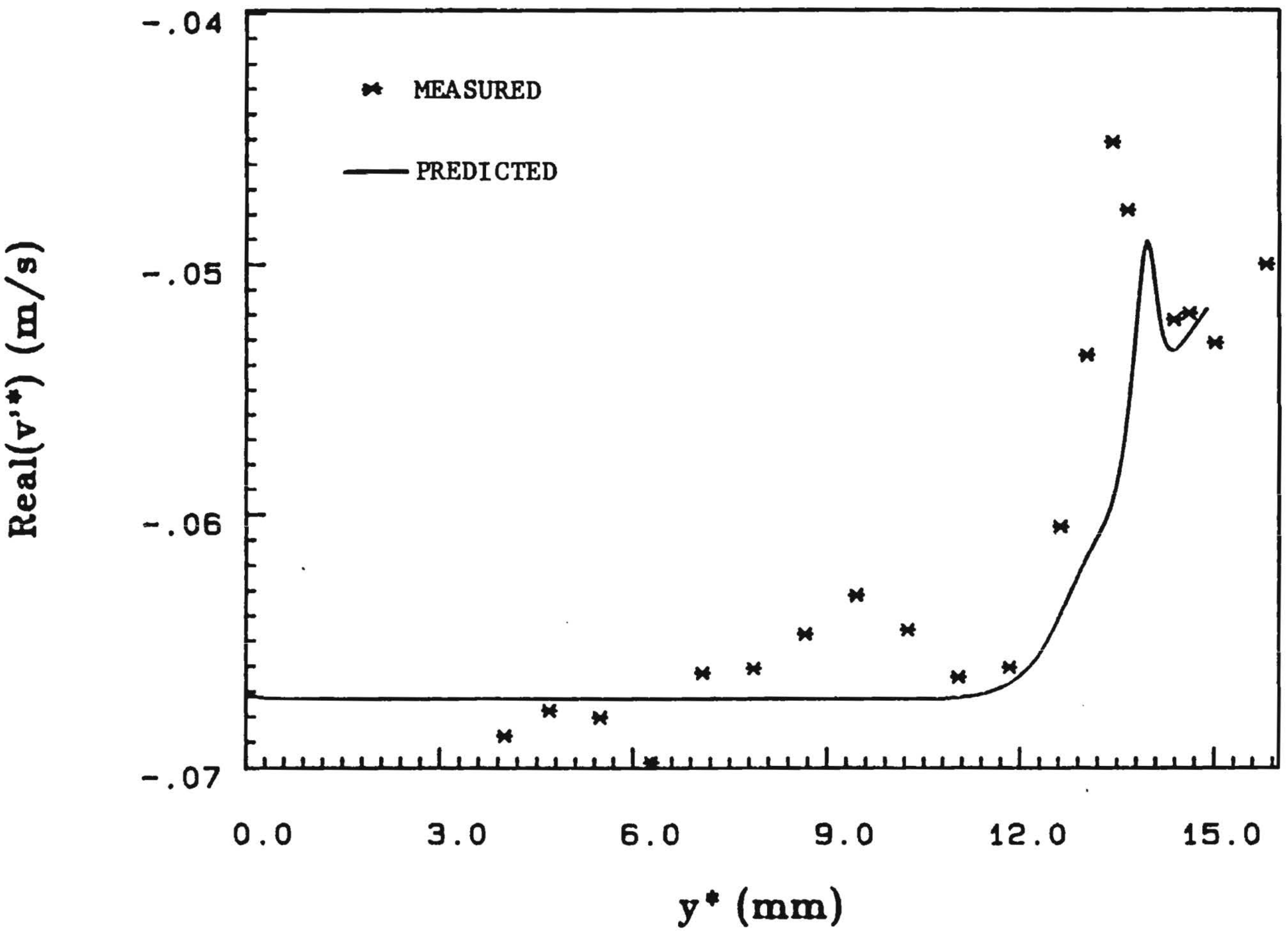


Fig. 8. Measured and Predicted Values of Real (v′) as a Function of the Normal Distance from the Burner Surface at 200 Hz.

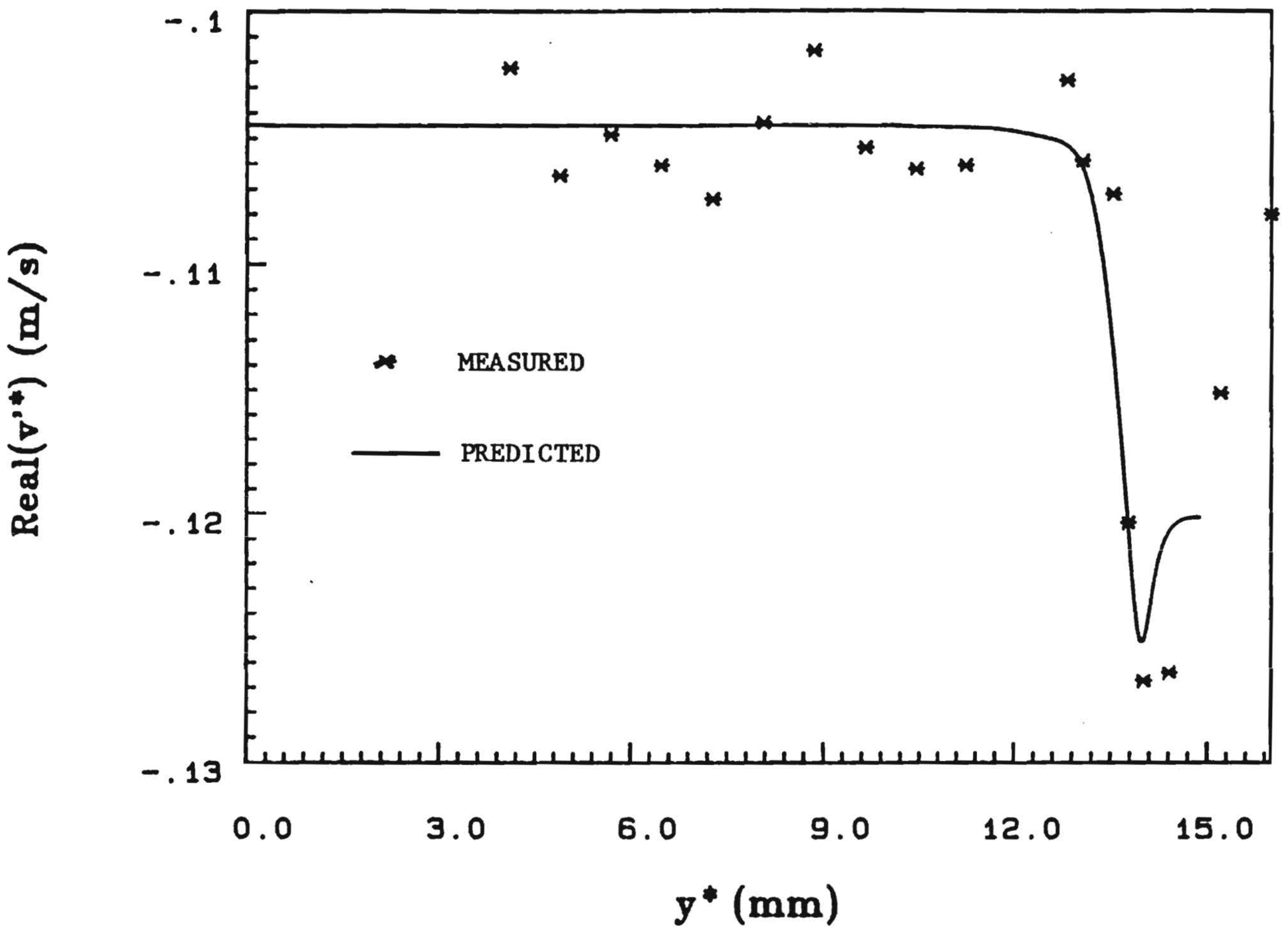


Fig. 9. Measured and Predicted Values of Real (v′) as a Function of the Normal Distance from the Burner Surface at 400 Hz.

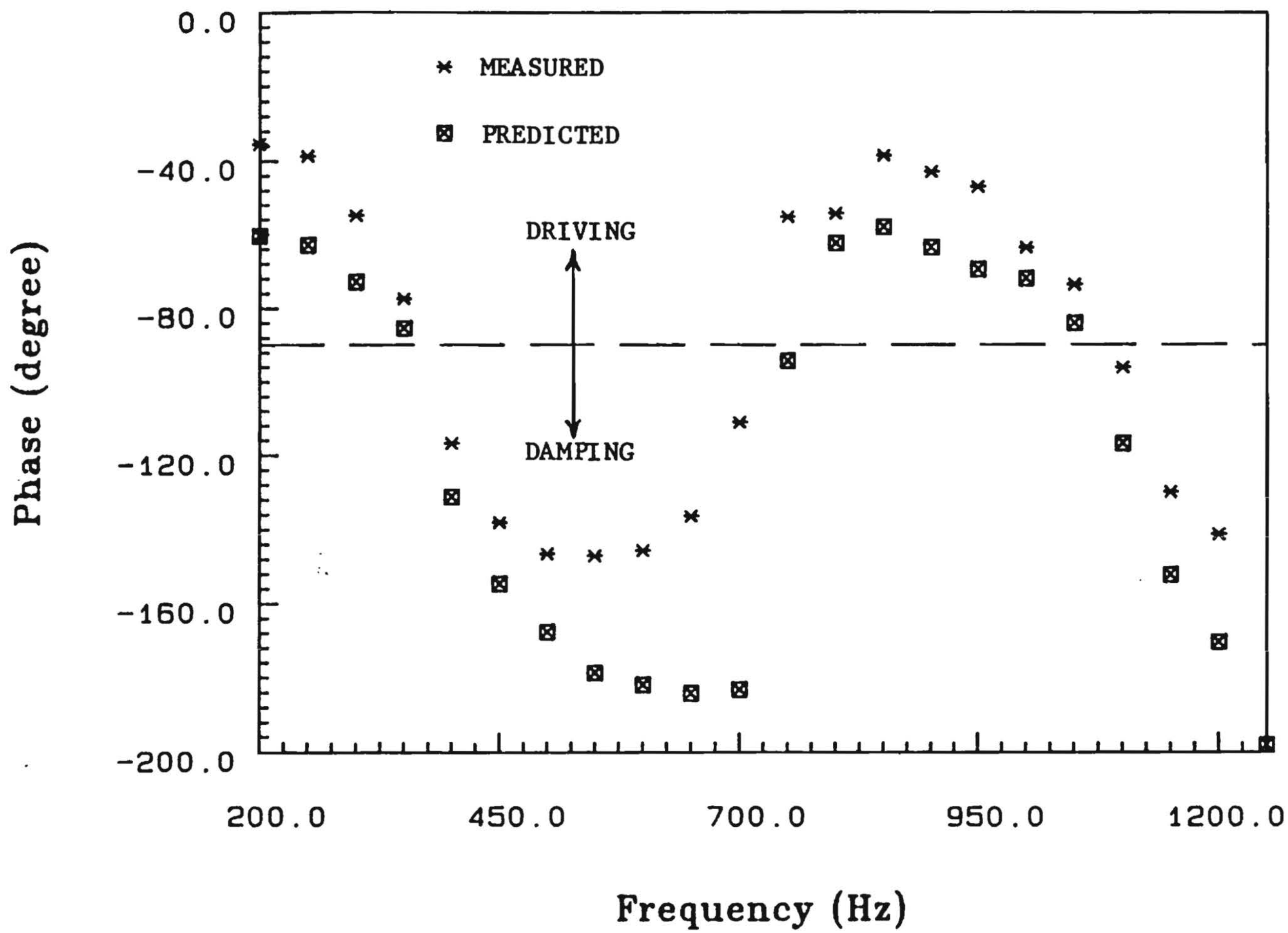


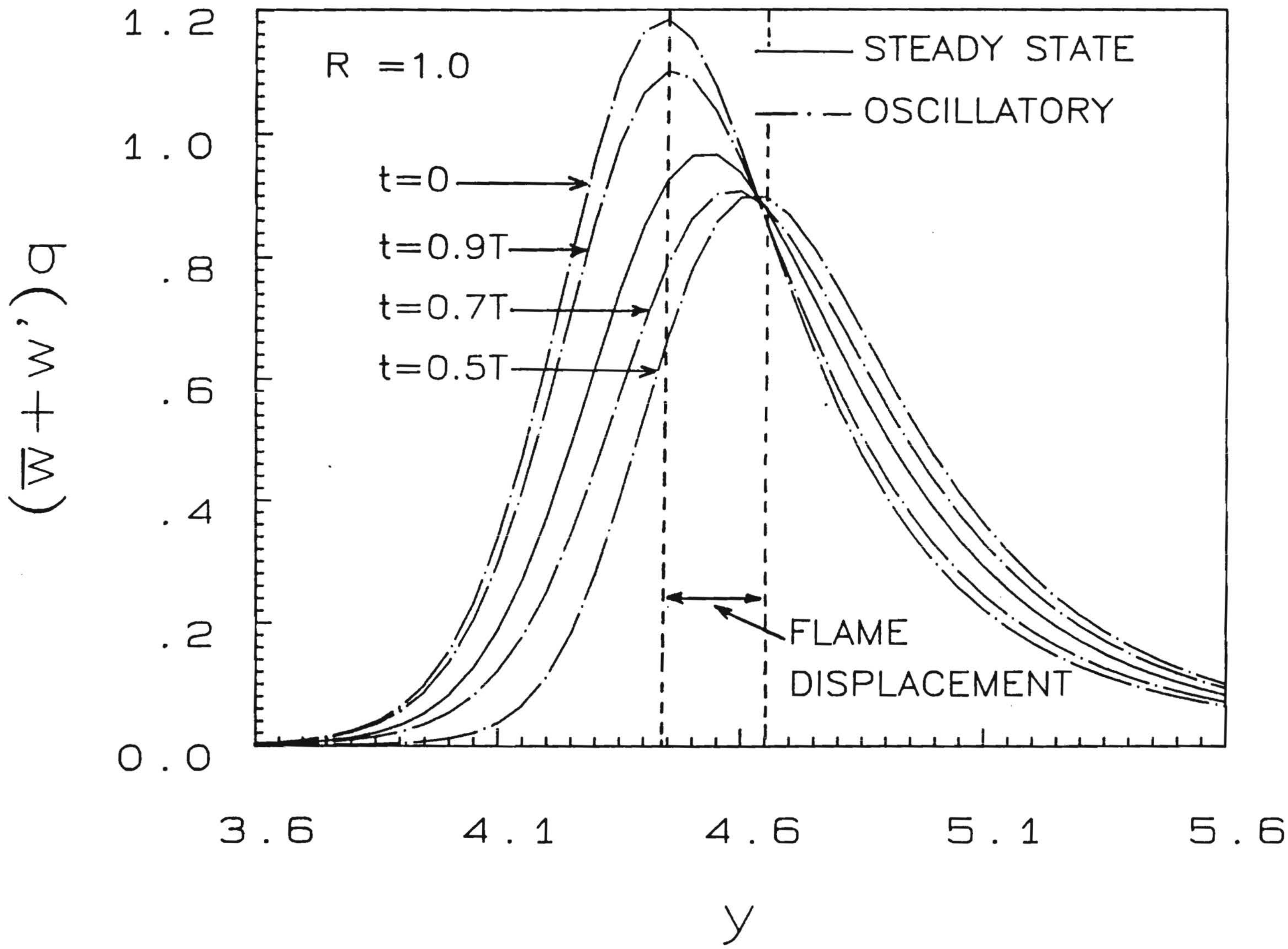
Fig. 10. Measured and Predicted Phase of the Unsteady Heat Release (Radiation) with Respect to the Imposed Pressure Oscillations.

Also, the theoretically predicted trends are in good agreement with the experimental measurements.

These comparisons were made with the flat flame stabilized at a pressure antinode of the excited standing waves. Similar results were obtained with the flame stabilized at other locations of the standing wave as long as this location was not at a pressure node. At a pressure node, depending upon the excitation levels, the flame surface would get distorted by the appearance of spikes or wavelets and in extreme cases the flame would break up and be extinguished. This feature has been described in earlier reports in detail.[9,20] Only at very low levels of excitation could a stable flame be maintained. However, under these conditions measurements could not be made with any degree of precision and hence efforts have been concentrated on understanding the flame behavior away from a pressure node.

Important discoveries have been made by considering the time dependent motion of the flame. By means of high speed cinematography (described in References 9 and 20), it was determined that under the influence of a sound field flames located away from a pressure node exhibit an up and down motion relative to their steady state location at the frequency of the excited wave. At the phase of maximum pressure, the flame would be located closest to the sidewall and at the phase of minimum pressure it would be located farthest from the sidewall. A prediction of the flame motion obtained using the developed theoretical model is presented in Fig. 11. It plots the instantaneous heat release rate at different times during a cycle of oscillation as a function of the normal distance y from the sidewall. At any given time, the location of maximum heat release rate may be identified as the flame location. As the pressure was taken to vary as $\cos 2\pi t/T$, where T is the period of excitation and t is the time, $t = 0$ represents the phase of

Fig. 11. Predicted Time Dependent Heat Rates (Normalized). The Location of the Maximum Heat Release Rate at a Given Time, t, Determines the Instantaneous Flame Location.



maximum pressure. As is seen from the figure, at this time the flame is closest to the side wall. One half period later it is farthest away from the wall. Thus, in this respect too, the predictions of the model are in complete agreement with the experimental observations.

Much more can be learned, however, from a closer inspection of Fig. 11. Note that when the flame is closest to the wall, the instantaneous heat release rate is also the highest during the cycle and when it is farthest the instantaneous heat release rate is the lowest. Similar results were obtained experimentally also (see Ref. 9) in complete agreement with the theoretical model. It was noted earlier that in the experiments, heat transfer from the flame to the sidewall was not an important factor due to the flame standoff distance being of the order of 1 cm which resulted in a very low steady state temperature gradient at the wall. In an actual solid propellant flame standoff distances are, however, of the order of 50-100 microns so that heat transfer to the surface of the propellant is an important issue. If the heat release rate is highest when the flame approaches the propellant surface, as is the case with the premixed flame, a mechanism is available to sustain a non steady burn rate of the propellant in tandem with the pressure oscillations which may lead to strong instabilities.

The Flame Driving Mechanism

Up to this point the discussion has centered upon the excellent agreement between the developed model and the experimental data which indicates that state of the art models of unsteady solid propellant flames may indeed be capable of capturing the salient features of the flame behavior. Now attention is focused on the driving characteristics (i.e., consideration of the flame as an acoustic source) of the investigated premixed flames. It is well known that the most fundamental acoustic source is a monopole[22] which may be envisioned as a periodically expanding and contracting balloon. Other acoustic sources are obtained by suitable combination of monopole sources; that is, two closely spaced monopoles of equal strength operating 180^{o} out of phase constitute a dipole[22] and two closely spaced dipoles of equal strength operating 180^{o} out of phase with each other constitute a quadrupole.

The sharp changes in Real (v') in the flame region (see Figures 8 and 9) indicate a monopole type of acoustic source. The periodic expansion of the gases as they move through the flame under the influence of an acoustic field is similar to, in notion, to that of a periodically expanding and contracting balloon. If this periodic expansion and contraction of the gases is in phase with the pressure oscillations then the resulting pumping action feeds energy into the acoustic oscillations. If the periodic expansion and contraction is out of phase with the acoustic oscillations energy is lost from the acoustic motions.

However, from considerations of the spatial distribution of the heat release rate fluctuations it was found that this picture was not complete. Experimentally, the heat release rate fluctuations may be obtained in terms of emitted CH or CC radiation from the flame (see Ref. 9). These radiation emissions were measured as a function of y by capturing the radiation from narrow(2 mm wide) slits aligned perpendicular to the normal coordinate y by means of a photomultiplier arrangement. As expected, close to the sidewall, the measurements captured only the shot noise from the photomultiplier indicating no significant heat release rates in this region.

The interesting discoveries were made in the vicinity of the steady flame location. Just upstream of this location, a large peak in the magnitude of the unsteady heat release rate was obtained. At the location of the steady flame hardly any unsteady radiation could be detected which at first glance may seem surprising but is not so as will be explained shortly. Just downstream of this location, however, the radiation levels peaked again although the peak was smaller than the first observed just upstream of the steady flame location. This behavior was found to occur at frequencies up to 1000 Hz. When the theoretical model was applied to obtain the magnitude of the unsteady heat release rates as a function of y, it showed identical results. An example is shown in Fig. 12, which plots the theoretical radiation levels (normalized) as a function of y for an arbitrary driving frequency. The corresponding experimental result is shown in Fig. 13.

In addition, the model predicted that for all frequencies the heat release rate fluctuations upstream and downstream of the steady flame location differed in phase by 180^{o} (Fig. 14). According to Rayleigh's criterion the heat release rates may be considered as the acoustic source of the flame. These peaks on either side of the steady flame location are, according to the model, 180^{o} out of phase with each other. If the magnitude of the upstream peak be thought of as the sum of two parts, one of magnitude equal to the downstream peak and the other accounting for the remainder, then theoretically the flame may be viewed as a combination of an acoustic dipole and a monopole. This result is entirely new and to the best of the investigators knowledge, not found in the literature. This split is important from the point of view of the directionality of the emitted sound by the flame. While a monopole source is non directional in nature, a dipole source shows a strong preference for channeling the emitted sound waves along its axis(determined by joining the centers of the two monopoles constituting the dipole). Thus, for a ducted flame, the monopole source will exhibit a

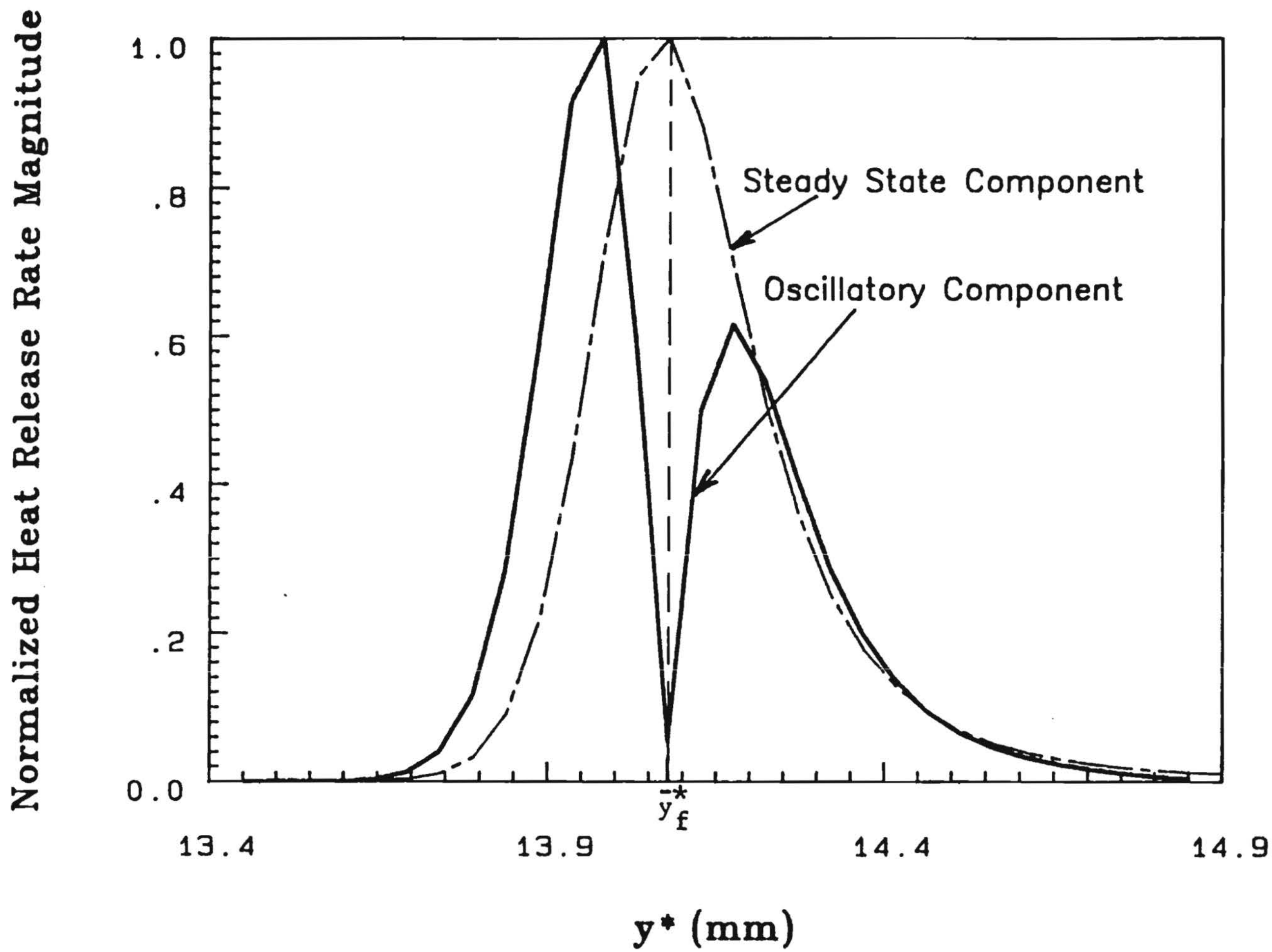


Fig. 12. Predicted Steady State and Oscillatory Heat Release Rate Magnitudes. Note the Sharp Peaks of the Oscillatory Component Upstream and Downstream of the Steady State Flame Location ($\bar{y}_f^*$).

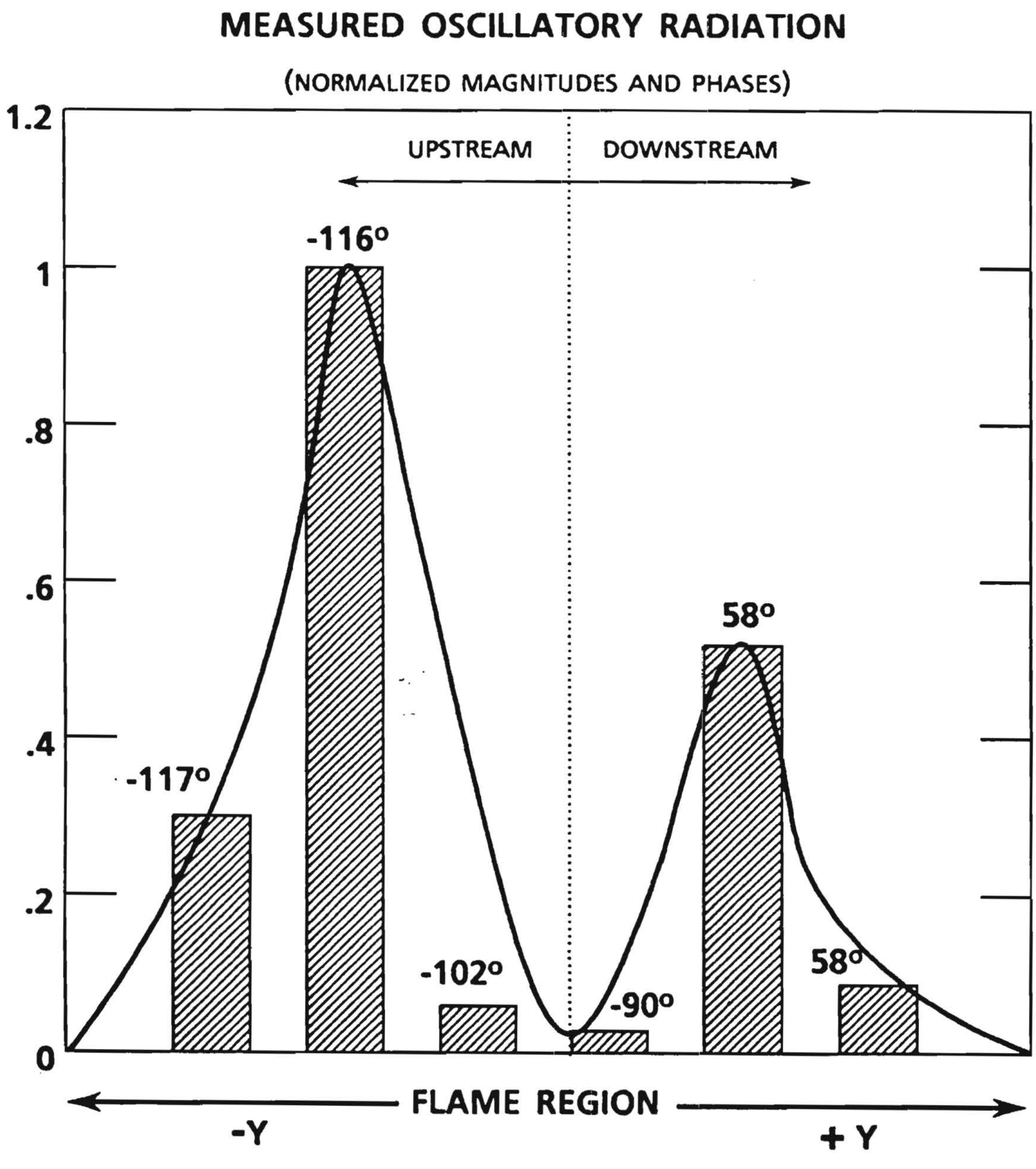


Fig. 13. Measured Oscillatory Radiation (Heat Release Rate) in the Flame Region.

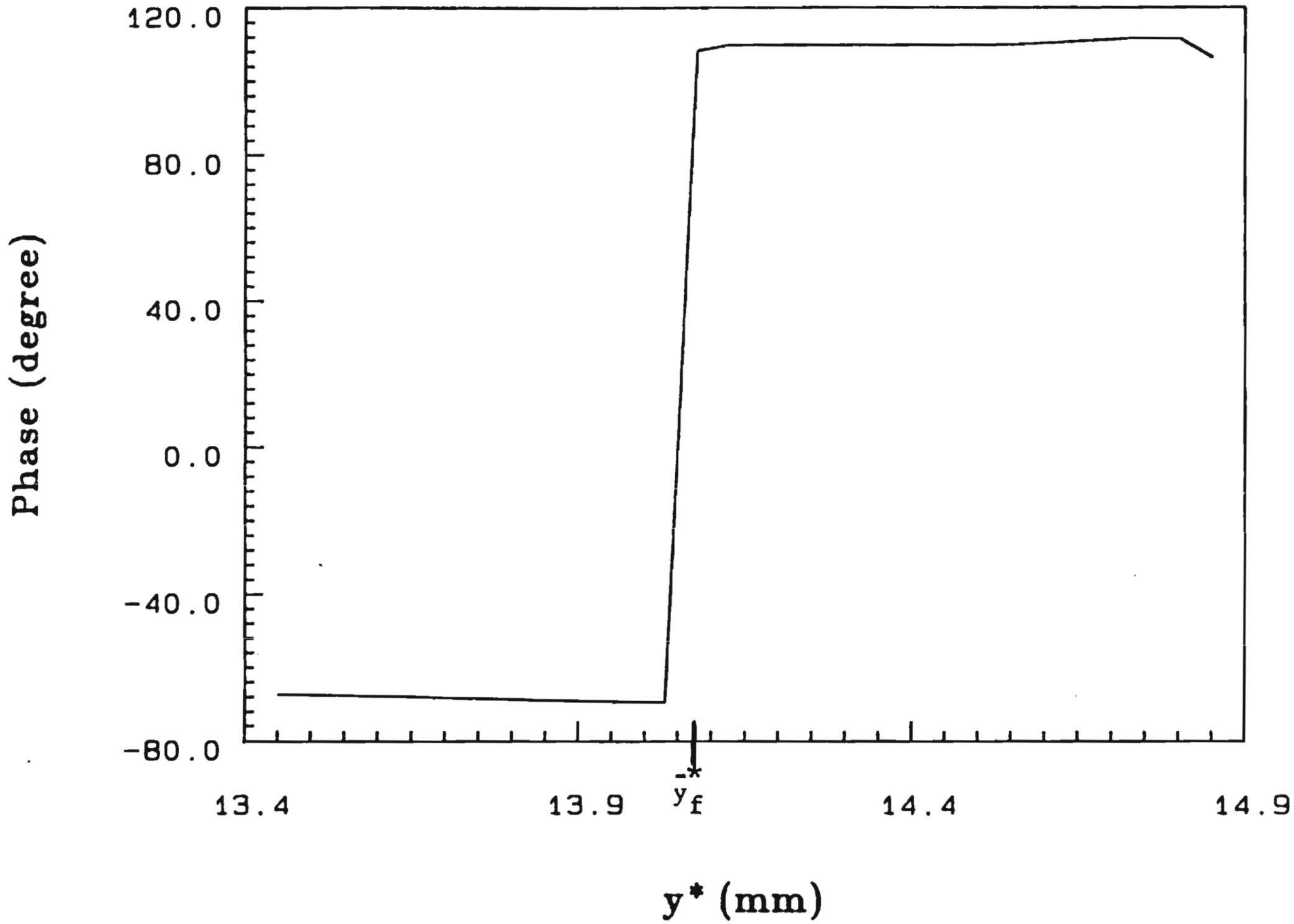


Fig. 14. Predicted Values of the Phase of the Unsteady Heat Release Rate (Radiation) with Respect to the Imposed Pressure Oscillation.

directional preference purely due to wave guide effects created by the confining effects of the duct walls[22] while the dipole source introduces additional directionality of its own. This may become important if transverse acoustic modes are considered.

The only discrepancy between the theoretical model and the experimental measurements was found in the phase difference between the radiation (heat release rate fluctuation) peaks upstream and downstream of the flame. Experimentally, it was found that the phase difference was not always 180^{o} but varied between 130^{o} to $180.^{o}$ This may not, however, be entirely the model's fault as the spatial resolution of the radiation measurements was limited by data acquisition constraints. A set of experimentally obtained phase values is also presented in Fig. 13.

The reason why the radiation fluctuations at the steady state flame location are small in comparison to the sharp peaks obtained upstream and downstream (Figures 12 and 13) remains to be discussed. This may be understood by considering Fig. 11. At any location y, the magnitude of the radiation fluctuations is equal to the difference in the values of the levels at t = 0 and t = 0.5T. Upstream and downstream of the steady flame location (situated in the flame displacement zone) this difference is seen to be high with the upstream levels being of greater magnitude. This corresponds to the two peaks noted earlier. However, in the region close to the steady state flame location, the curves of the instantaneous heat release rates at all times during a cycle of oscillation intersect. This indicates very weak fluctuations in the reaction rate at this location and explains the low radiation fluctuation levels obtained here.

Summary

Keeping in mind the previously stated objectives of this phase of the research program the following conclusions may be drawn:

(i) The close agreement between theory and experiment indicates that state of the art models of unsteady solid propellant flames are indeed capable of predicting the flame acoustic interactions during axial instabilities with the caveat that the effect of diffusion flame processes is still an open question.

(ii) The effect of the flame driving or damping characteristics is manifested in sharp changes in the normal velocity fluctuations in the flame region. This pumping action results in the interchange of energy between the core flow oscillations and the unsteady flame processes.

(iii) Unsteady heat transfer from the flame to the propellant surface may provide a mechanism for the locking in of the propellant burn rate with the acoustic oscillations and aid in sustaining axial instabilities.

(iv) The acoustic admittance at the propellant surface may exert considerable influence in the overall driving/damping characteristics.

(v) The flame may be considered as a combination of an acoustic monopole and an acoustic dipole. The dipole nature may become important in studies of transverse wave mode oscillations.

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AFOSR ANNUAL TECHNICAL REPORT

on

INVESTIGATION OF THE FLAME-ACOUSTIC WAVE INTERACTION DURING AXIAL SOLID ROCKET INSTABILITIES

Prepared for

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ABSTRACT

This research program is concerned with the determination of (1) the processes which control the driving of axial instabilities by solid propellant flames and (2) whether state of the art theoretical models can accurately predict the characteristics of oscillatory solid propellant flames. In the first phase of the program, completed during the reporting period, the characteristics of the driving provided by premixed, flat flames stabilized in the acoustic boundary layer next to a side wall of a long duct were investigated in a specially developed experimental set up. Premixed flames were chosen for the first phase of the investigation because they simulate many important characteristics of solid propellant flames without the complicating effects of diffusion processes which are being studied in the second phase of the program. During the reporting period, it was shown that the investigated premixed flame oscillates at the frequency of the duct acoustic wave and that it possesses a spatial structure which exhibits a large and a small reaction rate peaks upstream and downstream of the mean flat flame location, respectively. The flame driving was shown to be equivalent to that provided by a combination of a monopole and a dipole acoustic sources. This behavior is caused by the oscillation of the flame front with respect to the duct side wall due to interaction with the acoustic field. Predictions of the developed theoretical model are in good agreement with these findings. This newly uncovered mechanism is believed to play an important role in solid rocket instabilities where flame oscillations relative to the propellant surface will produce an oscillatory heat transfer to the propellant. This, in turn, will result in an oscillatory surface regression rate capable of driving the instability. During the reporting period, the second phase of the research program aimed at determining the

effects of diffusion processes in solid rocket flame driving/damping was also initiated. To this end, a theoretical model of a diffusion flame exposed to axial acoustic fluctuations was formulated. A computer program incorporating this model is under development and testing. On the experimental side, a diffusion flame burner simulating many important features of actual solid propellant flames was designed, fabricated and installed in the previously developed acoustic duct simulating the rocket motor cavity. High speed shadowgraphy and measurements of the oscillatory heat release rates from the developed diffusion flames were carried out for several acoustic excitation conditions. Detailed analysis of these experiments is currently in progress.

INTRODUCTION

This research program is concerned with the determination of the contributions of solid propellant gas phase flames to the driving of axial instabilities in rocket motors. This problem is of much interest because the response of the solid propellant combustion process to the flow oscillations is responsible for providing the energy required for the initiation and maintenance of the instability inside the rocket motor. Consequently, acquiring an understanding of the processes which control the interaction of solid propellant combustion phenomena with the motor flow oscillations may lead to the development of practical solutions for reducing the occurrences of highly detrimental instabilities in solid propellant rocket motors.

Solid propellant flames are extremely complex and involve solid and gas phase chemical reactions and multi-dimensional heat, momentum and mass transfer processes. To compound the problem further, these processes occur within an extremely thin region (of the order of tens of microns) next to the solid-gas interface. Probing such thin zones experimentally with physical probes, or even available optical probes, is not feasible. Hence to date, most efforts in this area have been confined to the development of theoretical models whose validity has never been confirmed.

The present research program was initiated in order to deal with this problem and to attain an understanding of the phenomena responsible for the occurrence of axial combustion instabilities in solid propellant rocket motors. This research program has two phases. In the first phase of investigation, completed during the current year, the response of premixed flames in longitudinal, standing acoustic waves (which simulate the behavior of the oscillations in solid propellant rockets experiencing axial instabilities) was studied. A premixed flame was chosen for this first phase as it eliminated the need to deal with difficulties arising from diffusion processes in the flame (these are currently being studied in the second phase of the program) while providing many similarities with actual solid propellant flames. For example, it possesses the sharp temperature rise between the propellant surface and the flame edge, it interacts with temperature and velocity acoustic boundary layers which also exist next to burning solid propellant surfaces and it provides a situation in which an oscillatory, multidimensional flame region interacts with one dimensional core flow oscillations.

The experimental set up used during the first phase of this research program is shown schematically in Fig. 1. The investigated premixed, flat flame is stabilized above a porous plate burner on the lower wall which simulates a solid propellant surface. The thickness of the premixed flame can be controlled experimentally, thus enabling one to perform the needed measurements. Acoustic drivers at one end of the apparatus are used to establish a standing acoustic wave of desired amplitude, frequency and pressure and velocity relationship in the vicinity of the flame. The behavior of the flame has been investigated both theoretically and experimentally in order to determine the nature of its interaction with the adjacent oscillatory flow.

The first phase of the investigation specifically addressed the following two questions:

1. Are state of the art models of unsteady solid propellant flames capable of predicting the characteristics of the developed premixed flame under conditions simulating those encountered in unstable rocket motors?
2. What features of the flame (e.g., maximum flame temperature, heat transfer to the propellant surface, spatial and temporal distributions

of the flame heat release rate and so on) exert the greatest influence upon the flame driving/damping of the core flow axial oscillations? In the second phase of the program started during the current year, the earlier investigations have been extended with a view to answering the following additional questions:

3. How does the presence of diffusion processes in the flame region affect the driving/damping characteristics of the flame?
4. Can diffusion processes be incorporated properly into theoretical models of unsteady solid propellant flames?

To answer these questions, the experimental set up has been modified during the current year by replacing the side wall porous plug burner (see Fig. 1) by a row of parallel, alternating fuel and oxidizer inlet ports simulating, for example, a sandwich type of propellant in which the oxidizer and binder portions alternate (see Fig. 2). Details of the development of this burner are provided in the next section. It should be noted that as with the premixed flame set up, this configuration possesses many of the features of actual solid propellant flames. It simulates the sharp temperature rise between the solid propellant surface and the flame edge, it interacts with the temperature and velocity acoustic boundary layers which also exist next to the burning solid propellant surface and so on. In addition, the important effects of diffusion processes in the flame region are included.

As with the premixed flame investigations, the diffusion flame studies also include a close coupling between the experimental and theoretical aspects of the program. To this end, during the current year, a theoretical model describing the interactions between the wall stabilized diffusion flames with axial acoustic oscillations has been developed. This model is also described in the next section.

RESEARCH ACCOMPLISHMENTS

During the current year the investigations of the acoustic driving/ damping mechanisms of the premixed flame were completed and studies of the interactions of the developed diffusion flames with acoustic waves were initiated. The accomplishments of these studies are described below.

(a) Acoustic Driving Mechanisms of the Premixed Flame:

The conditions under which an oscillatory heat source will tend to drive acoustic oscillations within a system is given by Rayleigh's criterion[1] which states that the heat source will drive the oscillations when the following inequality is satisfied

$$\int_{cycle} \int_{volume} |p' \, Q'| \, \mathrm{Cos}\, \phi \, dV \, dt > 0 \qquad (1)$$

Specifically, the heat source will tend to drive the acoustic oscillations when the phase difference, ϕ, between Q' and p' satisfies the condition $-90^{o} < \phi < 90^{o}$, while for other values of ϕ the oscillatory heat source will tend to damp the acoustic oscillations. Furthermore, the magnitude of the driving/damping also depends on the magnitude of the oscillatory heat release rate oscillations. Thus, the acoustic driving mechanisms of the flame may be understood by focussing on the interactions between the oscillatory heat release rates and the local pressure fluctuation in the flame.

The time dependence of the heat release rate was determined from C-C, C-H and O-H radiation intensity measurements which are known[2] to provide a measure of the reaction rate and, thus, the heat release rate. The radiation emission from the oscillatory flame was collected by the setup shown in Fig. 3. Appropriate bandpass filters were placed between the collecting lens and the photomultiplier to permit analysis of only the wavelength of interest (i.e., 515.5 nm for C-C, 431 nm for C-H and 307 nm for O-H). It was found, however, that all three species yielded similar oscillatory radiation signals and, therefore, no attempt is made herein to distinguish among the three. The local pressure oscillations were measured with a transducer mounted on the wall above the flame.

To investigate the driving characteristics of the flame in detail, spatial distributions of the heat release rate fluctuations were measured. The spatially resolved radiation emissions were measured as a function of the height y above the burner surface by collecting the radiation from a narrow, 10 mm x 1.5 mm, horizontal slit which was placed at different y positions.

As expected, close to the burner surface the measurements captured only the shot noise from the photomultiplier indicating no significant heat release rates in this region. Oscillatory radiation, in detectable amounts, was present only in the vicinity of the steady state, blue, flame location. Just upstream of this location (near the wall) a large peak in the magnitude of the oscillatory radiation was measured. Moving upward towards the location of the steady state flame the magnitude of the oscillatory radiation decreased to nearly zero. Moving downstream of this location, the radiation levels peaked again, although the second peak was smaller than the first peak. This behavior occurred at all of the investigated frequencies. An example is shown in Fig. 4 for a driving frequency of 800 Hz.

The developed flame model predicted qualitatively similar behavior of the magnitude of the oscillatory heat release rate distribution, see Fig. 5. Unfortunately, the 1.5mm width of the measuring slit (in the y-direction) was not thin enough to spatially resolve the steady state heat release zone which was less than 1mm thick. Attempts to improve the spatial resolution by reducing the width of the slit resulted in a strong decrease in the signal to noise ratio and they were not pursued. Thus, quantitative comparisons between the measured and predicted data in the steady state reaction zone were not possible. It should be noted, however, that both the theoretical and experimental results show the magnitude of the peak in the downstream location to be approximately about 0.6 times that in the upstream location.

In addition, the model predicted that for all frequencies a phase difference of 180^0 exists between the heat release rate fluctuations upstream and downstream of the steady flame, see Fig. 6, indicating that the radiation peaks on either side of the steady flame location are 180^0 out of phase with each other. According to Rayleigh's criterion (see Eq. 1) the space and time variations of the heat release rate Q'(x,t) describe the acoustic driving characteristics of the flame. Therefore, if the upstream peak is considered as the sum of two parts, one of magnitude equal to that of the downstream peak and the other equal to the difference between the two peaks, then, acoustically, the flame may be viewed as a combination of an acoustic dipole and an acoustic monopole[3]. The acoustic dipole consists of the two equal magnitude upstream and downstream radiation peaks which oscillate out of phase and the monopole consists of the difference between the magnitudes of the two radiation peaks as described above. This result is entirely new and to the best of the investigators' knowledge not found in the literature. Understanding the "acoustic structure" of the flame is important for understanding the directionality of the sound emitted by the flame. While a monopole source is non directional in nature, a dipole source shows a strong preference for channeling the emitted sound waves along its axis (determined by joining the centers of the two monopoles constituting the dipole). Thus, for a ducted flame, the monopole source will exhibit directional preference purely due to wave guide effects created by the confining effects of the duct walls while the dipole source introduces additional directionality of its own. This may become important if transverse acoustic modes are considered.

The only discrepancy between the model prediction and the experimental data was found in the phase difference between the radiation peaks upstream and downstream of the steady state flame. The experimental data showed that the phase difference was not always 180^{o} (as predicted by the model) but varied between 175^{o} and 60^{o} depending upon the investigated acoustic frequency. For example, the set of experimentally obtained phase values for 800 Hz, shown in Fig. 4, indicate a jump of 174^{o} in the measured phase. A possible explanation for this discrepancy may be provided by considering Figures 7 and 8 which present predicted and measured normalized magnitudes and phases of the oscillatory radiation upstream of the steady state flame, respectively. Note that a pronounced discrepancy in the phases (Fig. 8) occurs mainly at frequencies in the neighborhood of 700 Hz. In this frequency range, the magnitude of the oscillatory radiation is very small (see Fig. 7) so that the accuracy of the radiation measurements at these frequencies may be suspect. At other frequencies, where strong radiation signals exist, the agreement between the predictions and measurements is very good. Also, Figure 8 indicates that the investigated flames drive acoustic waves in certain frequency ranges (where the magnitudes of the phases are smaller than 90^{o}) and they damp them in others, according to Rayleigh's criterion (i.e., see Eq. 1).

The reasons for the existence of upstream and downstream radiation peaks with a minimum in between (see Figs. 4 and 5) can be explained using the developed flame model. Consider the predictions of heat release rate distributions throughout the flame at different instants during a cycle, as shown in Fig. 9. For these predictions, the existence of a hypothetical steady state, flat flame having a heat release zone thicker than the experimental flame (which had a very thin reaction region) has been assumed. The sole purpose for doing this was to elucidate the unsteady processes which occur within the reaction zone. In spite of the differences in flame thickness, this "theoretical" flame was qualitatively similar to the experimental flame.

At any given time, the location of maximum heat release rate may be identified as the flame location. As the pressure was assumed to vary as $\cos(2\pi t/T)$, $t = 0$ represents the phase of maximum pressure. At any location y, the amplitude of the radiation fluctuations is proportional to the difference in the values of the reaction rate levels at $t = 0$ and $t = 0.5T$ (which is the phase of minimum pressure). Upstream and downstream of the steady flame location (situated at the location of maximum steady state heat release) this difference is seen to be high with the upstream levels being of greater magnitude. These differences correspond to the two radiation peaks, see Figs. 4 and 5. On the other hand, in the region close to the steady flame location, the curves of the instantaneous heat release rates at all times during a cycle of oscillation nearly intersect. Consequently, very small amplitude reaction rate oscillations occur at this location, resulting in the minimum in the magnitude of the radiation fluctuation in this region, see Figs. 4 and 5.

Figure 9 also shows that the flame position oscillates with time. Also, when the flame is closest to the wall the instantaneous heat release is the highest during the cycle and when it is farthest the instantaneous heat release is the lowest. Similar results were obtained experimentally[4]. While in the present experiments heat transfer from the flame to the sidewall was not an important factor due to the large flame standoff distance (being of the order of 1 cm), in an actual solid propellant flame standoff distances are considerably smaller (of the order of 50-100 microns) and heat transfer from the flame to the surface of the propellant is an important factor. Thus, the findings of this study strongly suggest that during actual instabilities the solid propellant flame will oscillate relative to the propellant surface. This, in turn, will result in an oscillatory heat transfer to the propellant surface which will produce an oscillatory propellant burn rate capable of driving the instability.

b) Diffusion Flame Studies:

While the premixed flame investigations have provided important insights into mechanisms which are likely responsible for the driving/damping of acoustic waves by solid propellant flames, the effect of diffusion processes on this driving/damping is not accounted for. In order to overcome this deficiency the studies have been extended in the current year to considerations of the driving mechanisms of side wall stabilized diffusion flames. As noted earlier, the configuration considered (see Fig. 2) possesses many of the features of actual solid propellant flames and the driving mechanisms in the two cases are believed to be closely related.

This phase of the investigations, as with the premixed flame studies, consists of theoretical and experimental aspects. The accomplishments during the current year of this research program in these two aspects are described below.

(i) Theoretical Accomplishments:

A major objective of the diffusion flame studies is the development of a theoretical model of oscillatory diffusion flames stabilized in longitudinal sound fields simulating those found in unstable solid propellant rocket motors. During the current year, such a model has been developed based upon the Schvab-Zeldovich coupling function formalism[5]. This approach was adopted as it is known to be capable of predicting the behavior of diffusion flames under steady conditions. Moreover, it captures the effects of diffusion processes which are the focus of this phase of the investigation.

The Schvab-Zeldovich approach is most applicable to those cases in which the diffusion rates of fuel and oxidizer towards each other control the overall reaction rates; that is, in those cases where the time taken for chemical reaction is very small compared to the time it takes for the reactants to diffuse towards each other. In such cases, the actual flame region may be taken to lie on a surface or sheet. Moreover, by appropriate definitions of temperature and species coupling functions[5], β_T and β, respectively, the chemical reaction rates may be eliminated from consideration.

The theoretical model considers the configuration shown in Fig. 10. A number of diffusion flames are established on the side wall of a duct by means of alternate fuel and oxidizer slots. These flames are exposed to known axial acoustic pressure and velocity oscillations. Of interest is the response of these flames to the imposed oscillations. It is sufficient to consider a single flame as the response of any one of the flames is largely governed by the conditions existing locally. Thus, the model considers a single diffusion flame as in Fig. 10. The influence of the other flames is accommodated by prescribing the flow variables along the boundary of the domain of interest as shown in Fig. 10.

The model considers three unknowns, namely:

(1) the normal velocity fluctuation, v'

(2) the fluctuations in the temperature coupling function, β_T', and

(3) the fluctuations in the species coupling function, β'

These unknowns are related to the applied acoustic field described in terms of known pressure fluctuations, p', and axial velocity fluctuations, u', by making use of the conservation equations for mass, momentum and energy along with the equation of state. A matrix equation of the following form emerges

$$A_{ij} \nabla^2 X_i + B_{ij} \nabla \cdot X_i + C_{ij} X_i = F_i \qquad (2)$$

where

$$X_i = \begin{bmatrix} v' \\ \beta_T' \\ \beta' \end{bmatrix}$$

A_{ij}, B_{ij} and C_{ij} are 3 x 3 coefficient matrices which depend upon the steady state solutions. These have to be obtained experimentally or, as with the premixed flame model, by a combination of theory and experiment. F_i depends upon p' and u' and may be regarded as a forcing function for the unknowns X_i. Conditions on the velocity, temperature and species fractions (i.e., on v', $\beta_T'$and β') have to be prescribed on the boundary as depicted in Fig. 10. These boundary conditions have to be obtained experimentally for a general case.

A computer program to solve the above equation numerically is currently being developed and tested.

(ii) Experimental Accomplishments:

During the current year, the design, fabrication and installation of the side wall diffusion flame burner has been completed. In addition, some preliminary high speed flame shadowgraphy visualizations and radiation measurements have been carried out.

(1) Burner Design:

The major requirement that the burner had to satisfy was that the flame size (in particular, the flame height) be as small as possible in order to simulate solid propellant flames but be large enough in order to allow experimental probing of the flame structure. This requirement made it necessary that the injection velocities of fuel (propane) and oxidizer (air) in the burner slots (Fig. 2) as well as the slot widths be carefully specified. Hence, considerable time and effort was spent in designing and fabricating the burner.

In order to simulate the pyrolysis of a solid propellant, the fuel and oxidizer injection velocities were determined from the condition that the Reynolds number of the flow through the slots be of the same order of magnitude as that estimated for a real flame inside a rocket motor. The Reynolds number of the fuel flow is given by

$$R = \frac{vb}{\nu}$$

where v, b and ν are the injection velocity, slot width and kinematic viscosity, respectively. Calculations of the flow inside typical rocket motors yielded the following estimate for R

$$R \sim O(10)$$

Thus, the flow velocity v could be determined as a function of the slot width b.

For each set of v and b obtained, the flame height was estimated by a steady state Burke-Schumann type[5] analysis of the flame. The requirement imposed on the flame height was that it be smaller than the half height of the duct but remain large enough to enable experimental measurements. This condition resulted in a selection of a narrow range of slot widths. Finally, the widths of the oxidizer and fuel slots to be used in the experiment were chosen by requiring that the flame heights obtained be in the range noted above for the widest possible range of injection velocities.

The final burner configuration is shown in Fig. 11. Ceramic matrices of high porosity were inserted into both the fuel and oxidizer slots as this arrangement was found to yield two dimensional steady state diffusion flames which were extremely stable with respect to environmental disturbances. Finally, when the developed burner was installed in the duct, it was found that a fine wire mesh above the established diffusion flames further helped in stabilizing the flames with respect to inadvertent disturbances.

(2) Preliminary Experimental Studies:

The experimental investigations initiated on the diffusion flame set up during the current year included flame visualization by high speed shadowgraphy and measurements of the C-H radiation emitted by the flame under different oscillatory conditions.

High speed shadowgraph films (5000 frames/sec) have been taken with the flame excited at different frequencies in the range of 250 to 1000 Hz by means of the acoustic drivers (Fig. 12). The axially movable end plate made it possible to place the diffusion flame burner on different locations of the established standing wave, that is at a pressure maximum, minimum or in between. Preliminary observations of the films indicate that under the influence of an acoustic field, the flame oscillates axially and the frequency of oscillation coincides with the frequency of the excited acoustic wave.

A frame by frame analysis of the high speed films is currently underway. The objectives of this analysis are twofold. First, the differences (if any) in the behavior of the flame when it is placed on different locations of the standing wave will be determined. Second, the phase difference between the flame position oscillations and the excited pressure oscillations will be determined. These studies will yield important qualitative insights into the unsteady acoustic wave - diffusion flame processes.

Measurements of the C-H radiation emitted by the diffusion flames have also been carried out for different frequencies and flame locations as noted above. These measurements are indicative of the heat release rates of the flames[2]. A detailed analysis of these measurements is in progress. Specifically, the phase difference between the pressure and radiation aoscillations is being evaluated for different flame conditions. An example is shown in Fig. 13 which plots the measured phase difference between the flame radiation and acoustic pressure oscillations at a pressure maximum for different frequencies in the range between 250 to 1000 Hz. As noted earlier (see Eq. (1)) when the phase difference between the two is within $\pm 90^{\circ}$ flame driving of the acoustics takes place. Thus, it may be noted that depending upon the frequency, the flame may either drive or damp the acoustics.

Similar measurements for other flame locations on the established standing wave are being carried out. Along with the determination of the pressure and radiation intensities, this will enable the calculation of the Rayleigh integral (Eq. (1)). This will yield a quantitative estimate of the driving/damping capabilities of the established diffusion flames under different conditions.

SUMMARY

In summary, during the reporting period, the investigations into the driving/damping mechanisms of the premixed flame were completed and studies of the interactions between the oscillatory combustion and axial acoustic waves in the newly developed diffusion flame apparatus were initiated.

It was shown that the premixed flame drives or damps acoustic waves by an acoustic monopole-dipole type of mechanism. This newly uncovered mechanism is caused by the oscillation of the flame front relative to the duct side wall due to its interaction with the acoustic field. These findings were in agreement with the developed theoretical flame model predictions. This mechanism is also believed to play an important role in solid propellant rocket instabilities where the flame oscillations will produce an oscillatory heat transfer to the propellant surface. This, in turn, will result in an oscillatory surface regression rate capable of driving the instability inside the rocket motor.

The second phase of the research program aimed at determining the effects of diffusion processes on solid propellant flame driving/damping was initiated. A theoretical model of the diffusion processes - acoustic interactions was developed. A computer program incorporating this model is being developed and tested. A diffusion flame burner simulating actual solid propellant flames in many important respects was designed, fabricated and installed in the previously developed acoustic duct simulating the rocket motor cavity. Experimental studies of the interactions of the developed diffusion flames with axial acoustic waves were begun. These studies have, to date, included visualization studies by means of high speed shadowgraphy and determination of the oscillatory heat release rates by measurements of C-H radiation emission. Detailed analysis of these experiments are currently in progress.

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PROFESSIONAL INTERACTIONS

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Mr. Brady R. Daniel, Senior Research Engineer

Dr. Uday G. Hegde, Research Engineer

Mr. Subramanian V. Sankar, Ph. D. Student

Mr. Tzengyuan Chen, Graduate Student

B. Degrees Awarded:

Mr. Subramanian V. Sankar, Ph. D., September 1987.

Mr. Tzengyuan Chen, M. S., December 1987.

C. Publications:

1. Narayanaswami, L. L., Daniel, B. R. and Zinn, B. T., "Experimental Investigation of the Characteristics of Solid - Propellant, Velocity - Coupled Response Functions", AIAA Journal, Vol. 25, No. 4, pp. 584-591, April, 1987.

2. Sankar, S. V., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Driving of Axial Acoustic Fields by Side Wall Stabilized Premixed Flames", Proceedings of the 24th JANNAF Combustion Meeting, Monterey, CA, Oct. 5-9, 1987.

3. Sankar, S. V., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Measured and Predicted Characteristics of Premixed Flames Stabilized in Axial Acoustic Fields", AIAA Paper No. 88-0541, Jan. 1988.

4. Sankar, S. V., Hegde, U. G., Jagoda, J. I. and Zinn, B. T., "Driving of Axial Acoustic Waves by Side Wall Stabilized Premixed

Flames", Submitted to the 22nd Symposium (International) on Combustion to be held at Seattle, WA, August 1988.

D. Presentations:

1. "Driving of Axial Acoustic Fields by Side Wall Stabilized Premixed Flames", Presented at the 24th JANNAF Combustion Meeting, Monterey, CA, Oct. 5-9, 1987.

2. "Measured and Predicted Characteristics of Premixed Flames Stabilized in Axial Acoustic Fields", Presented at the AIAA 26th Aerospace Sciences Meeting, Reno, NV, Jan. 11-14, 1988.

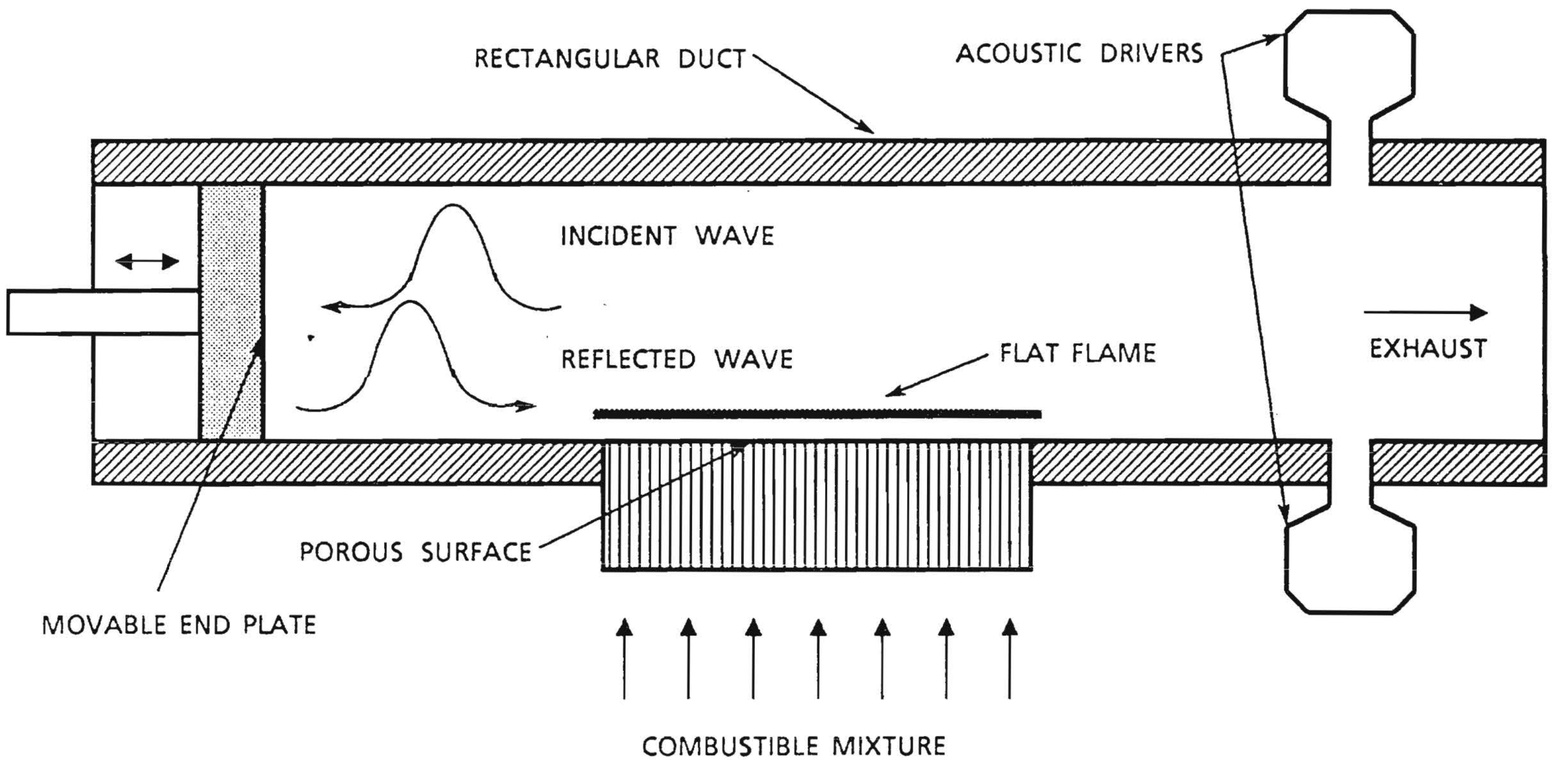

Figure 1. Schematic of the Premixed Flame Experimental Set Up

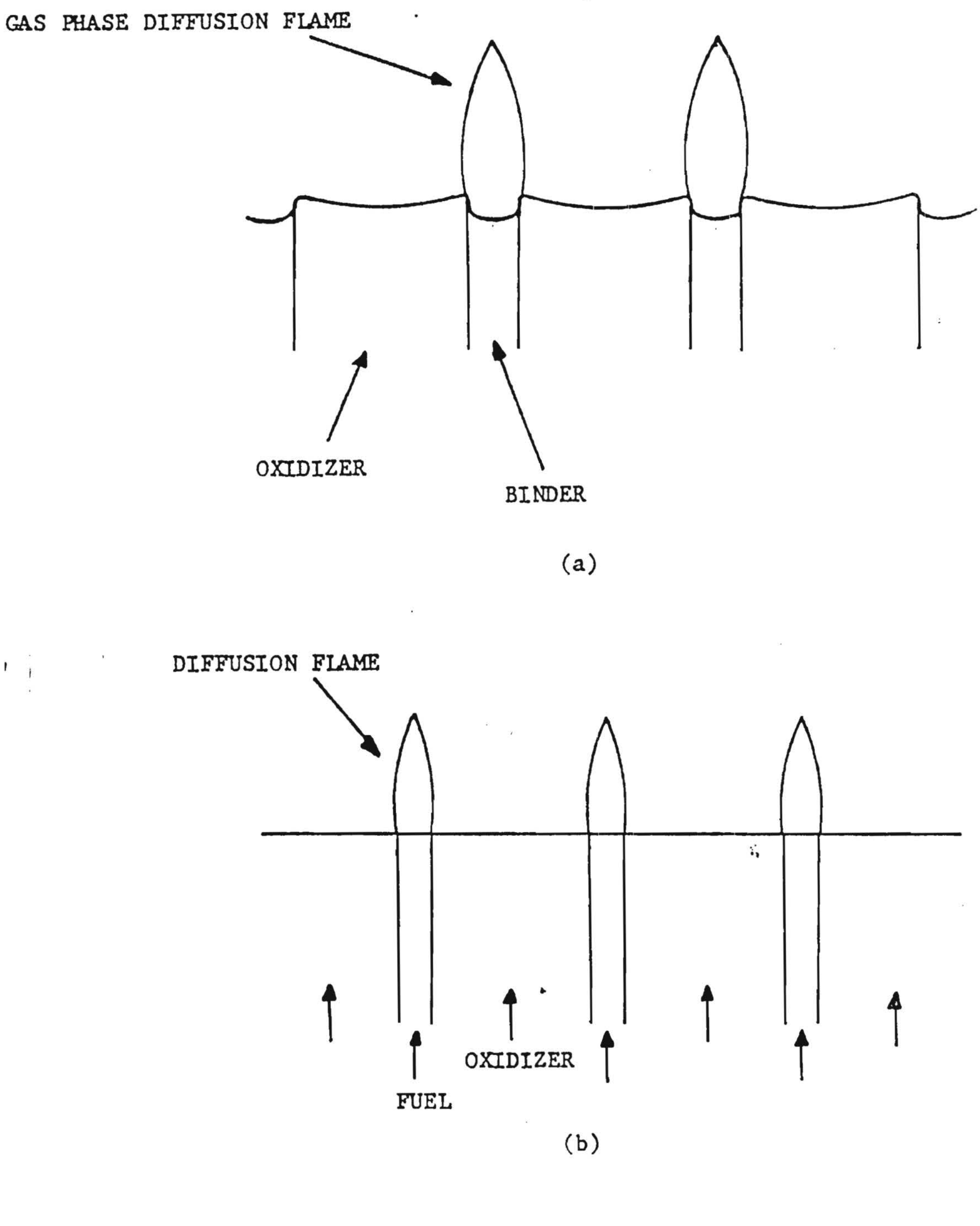

Fig. 2. (a) Sandwich Propellant with Established Gas Phase Diffusion Flames and (b) Simulation by Gaseous Diffusion Flames.

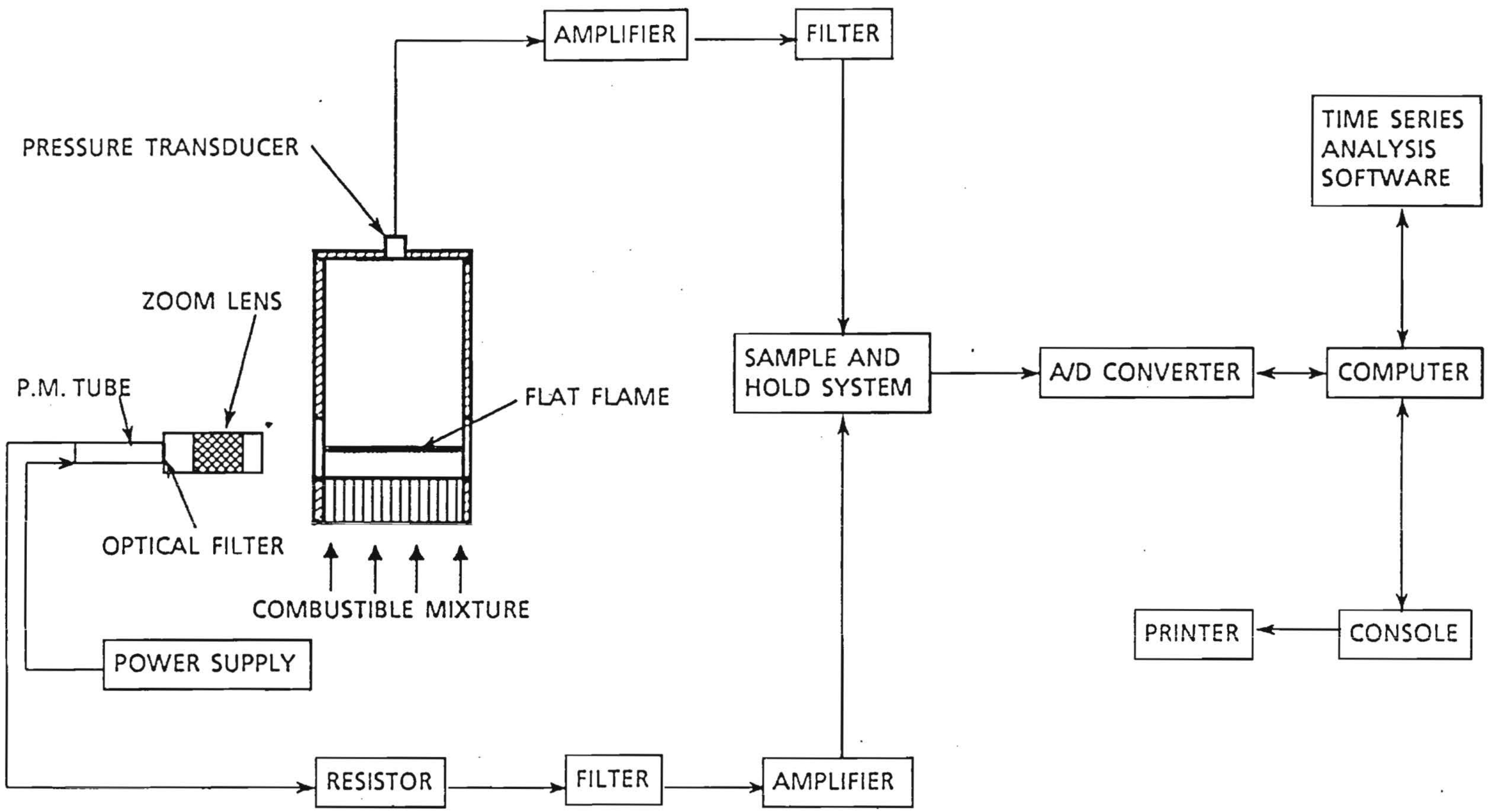

Figure 3. A Schematic of the Radiation and Acoustic Pressure Measurement Systems.

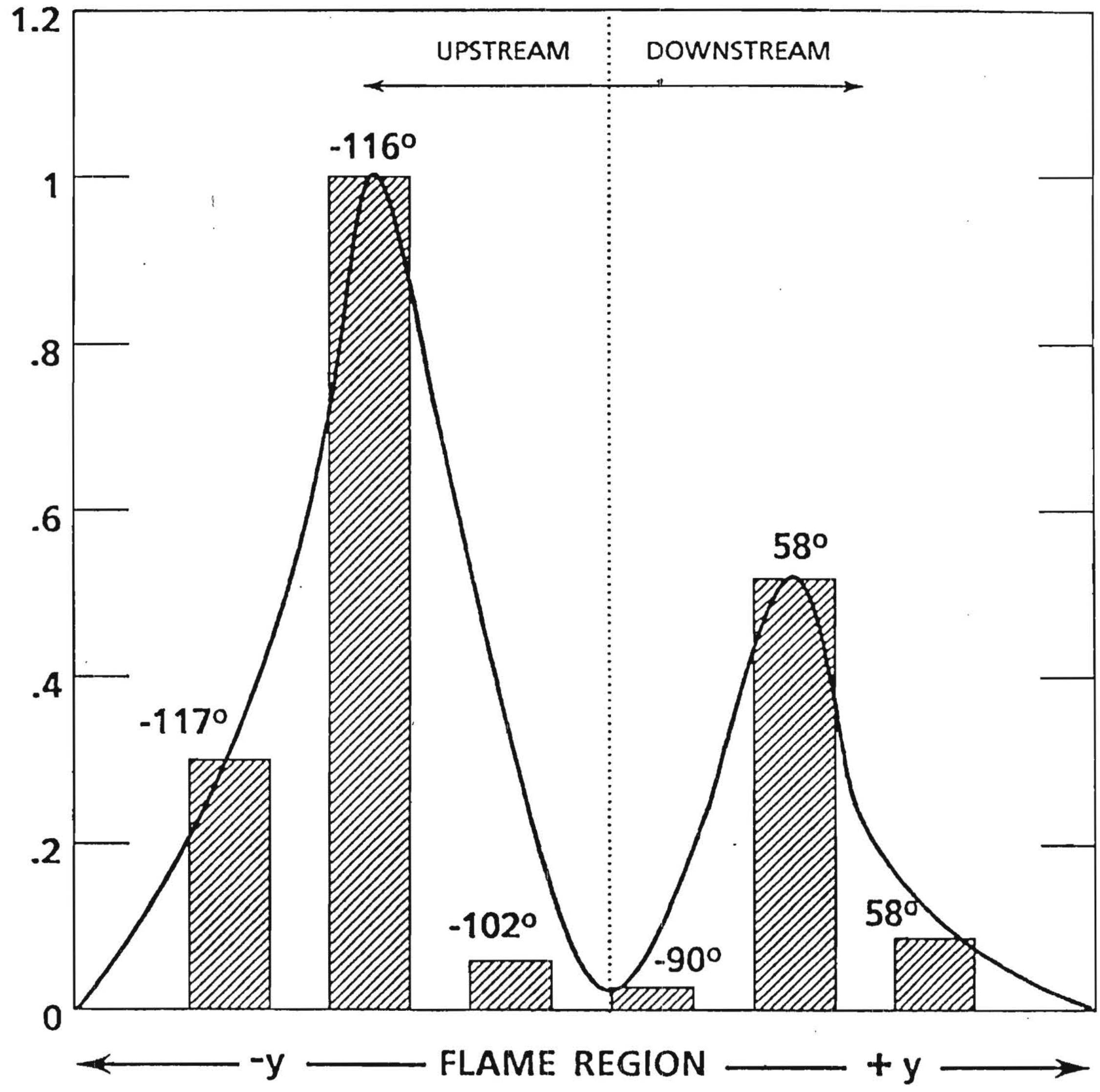

Figure 4. Measured Distributions of the Magnitude and Phase of the Oscillatory Radiation Upstream and Downstream of the Investigated (2.9% Propane Content) Steady Flame Location when subjected to an 800 Hz Acoustic Oscillation.

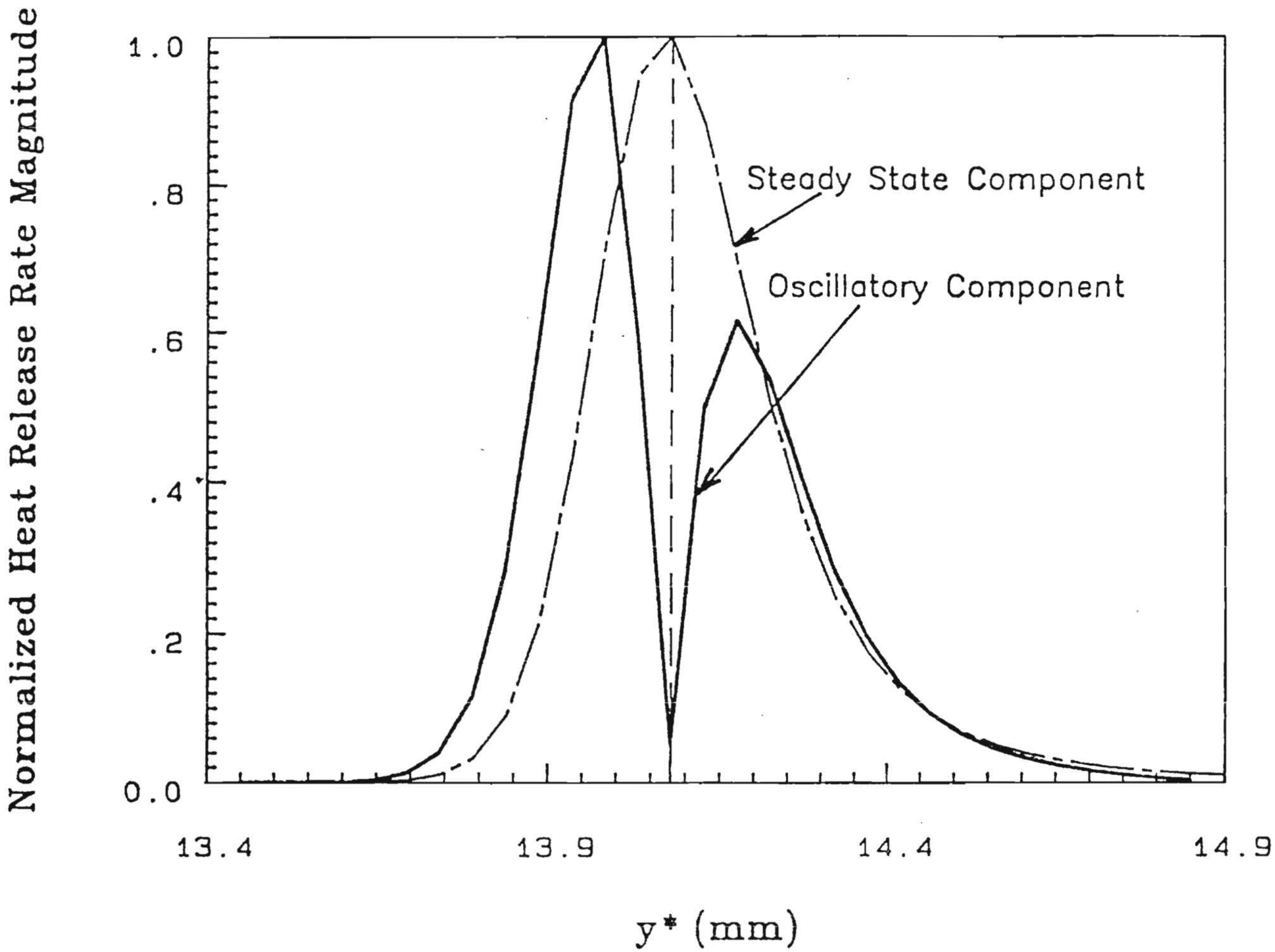

Figure 5. Predicted Spatial Distribution of the Magnitude of the Oscillations Heat Release Rate in the Investigated Flame (2.9% Propane Content) for an 800 Hz Acoustic Oscillation.

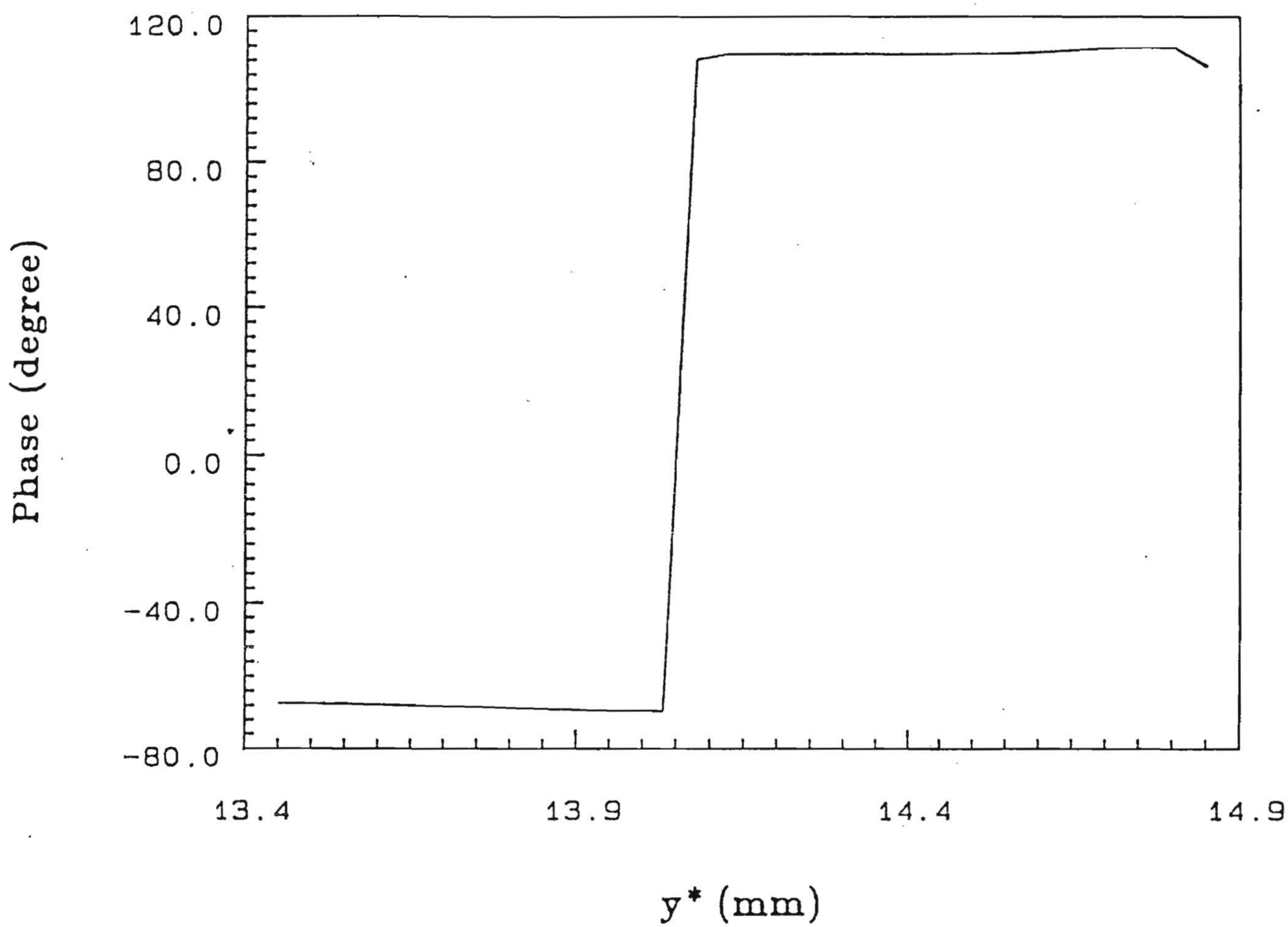

Figure 6. Predicted Spatial Dependence of the Phase of the Oscillatory Heat Release Rate in the Investigated Flame (2.9% Propane Content) for an 800 Hz Acoustic Oscillation.

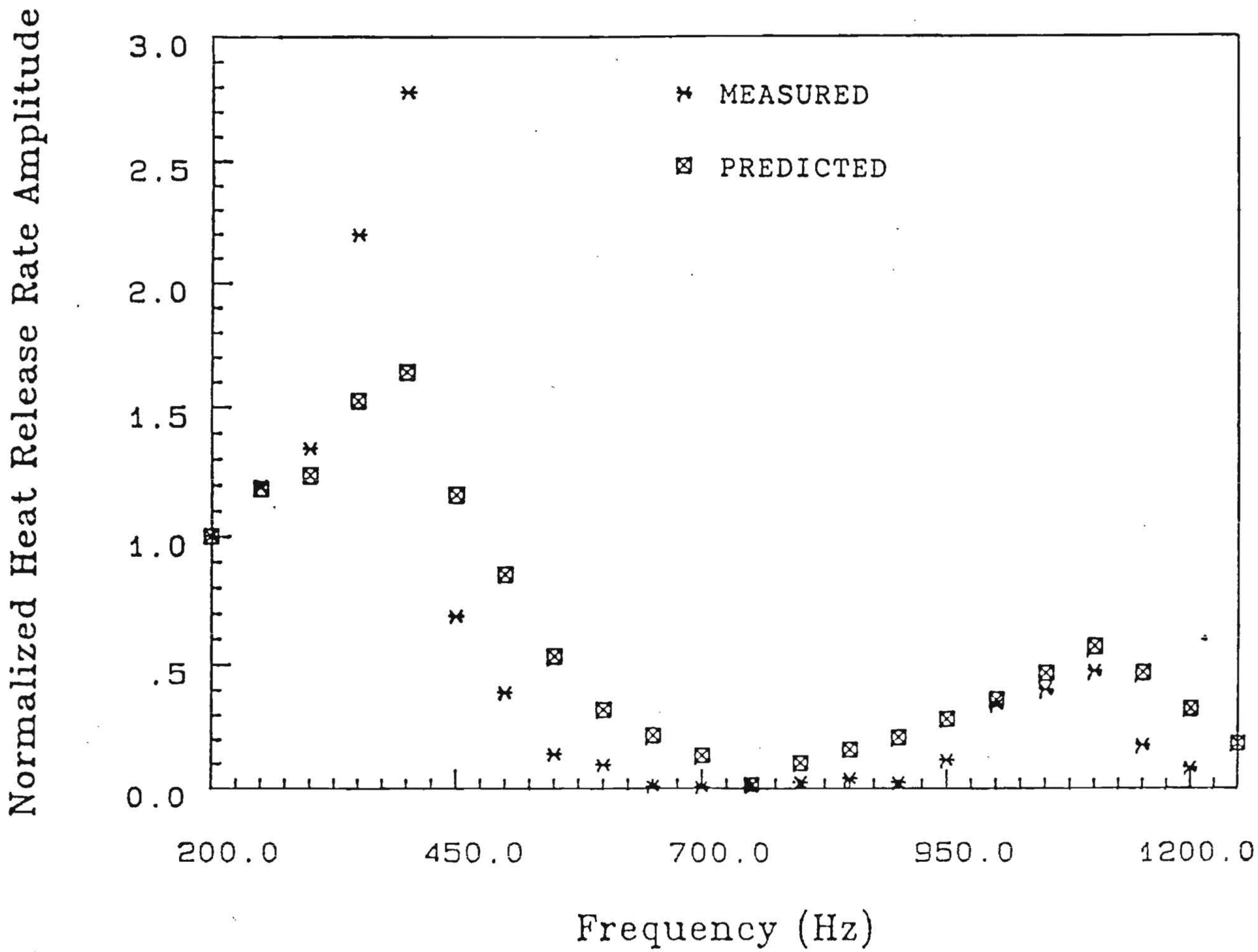

Figure 7. A Comparison of the Frequency Dependences of the Normalized Predicted and Measured Magnitudes of the Radiation/Heat Release Rate Oscillations in the Upstream Region of the investigated Flame (2.9% Propane Content).

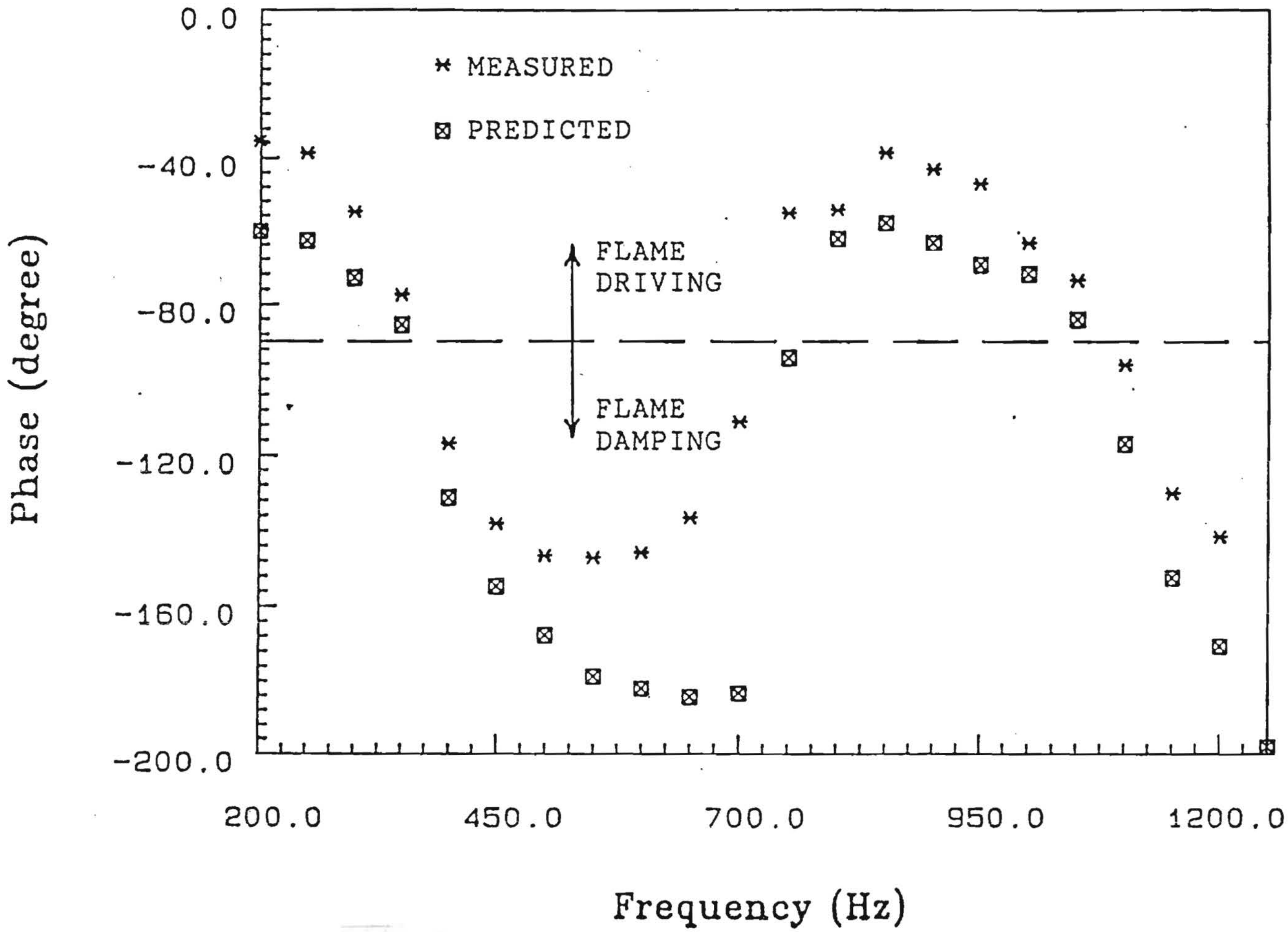

Figure 8. A comparison of the Frequency Dependences of the Predicted and Measured Phase Differences between Radiation/Heat Release and Pressure Oscillations in the Upstream Region of the Investigated Flame (2.9% Propane Content).

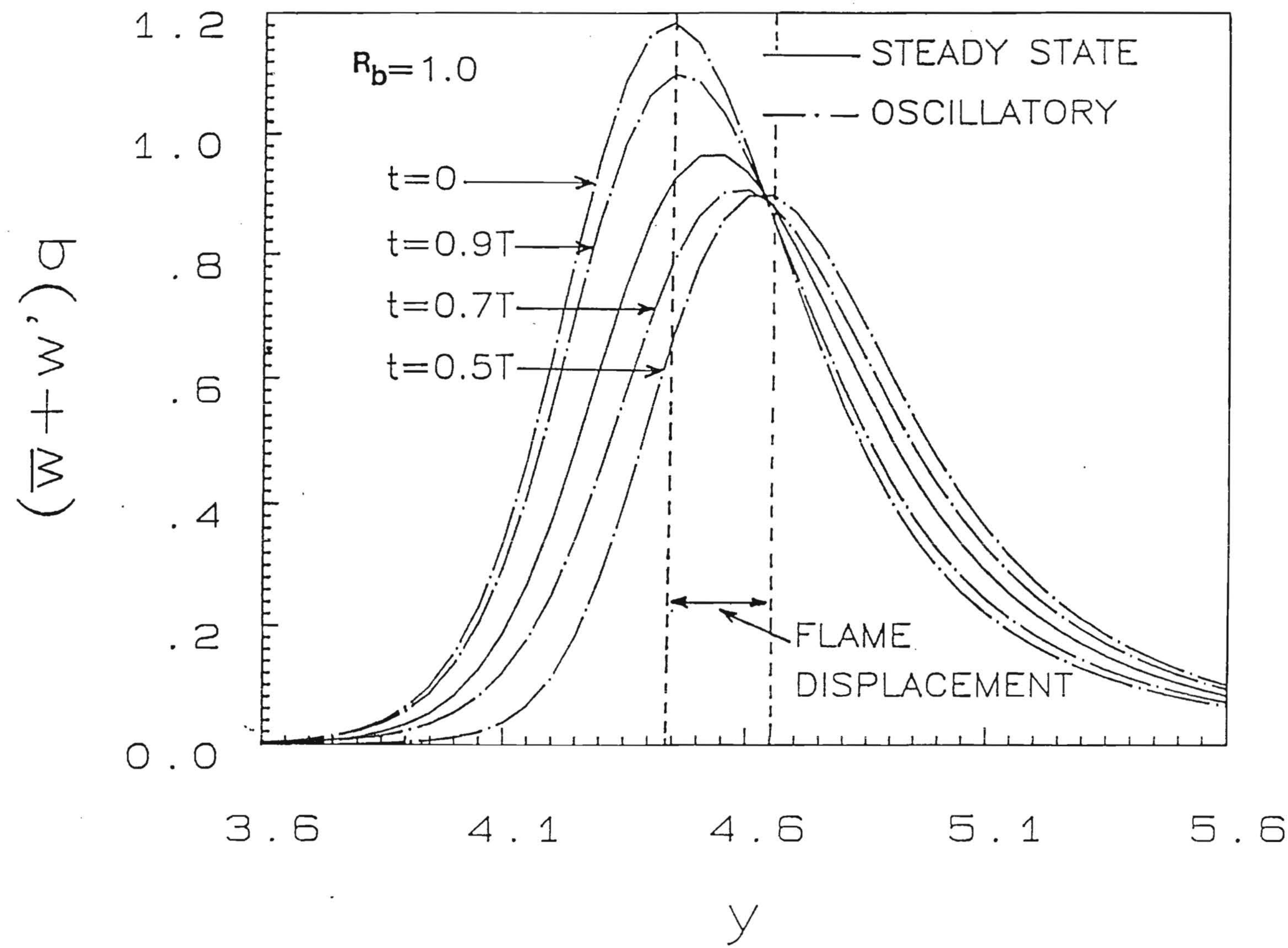

Figure 9. Predicted Instantaneous Heat Release Rate Distributions in the Vicinity of the Flame Region for Different Instances During One Cycle of Pressure Oscillation obtained with Assumed Input Data.

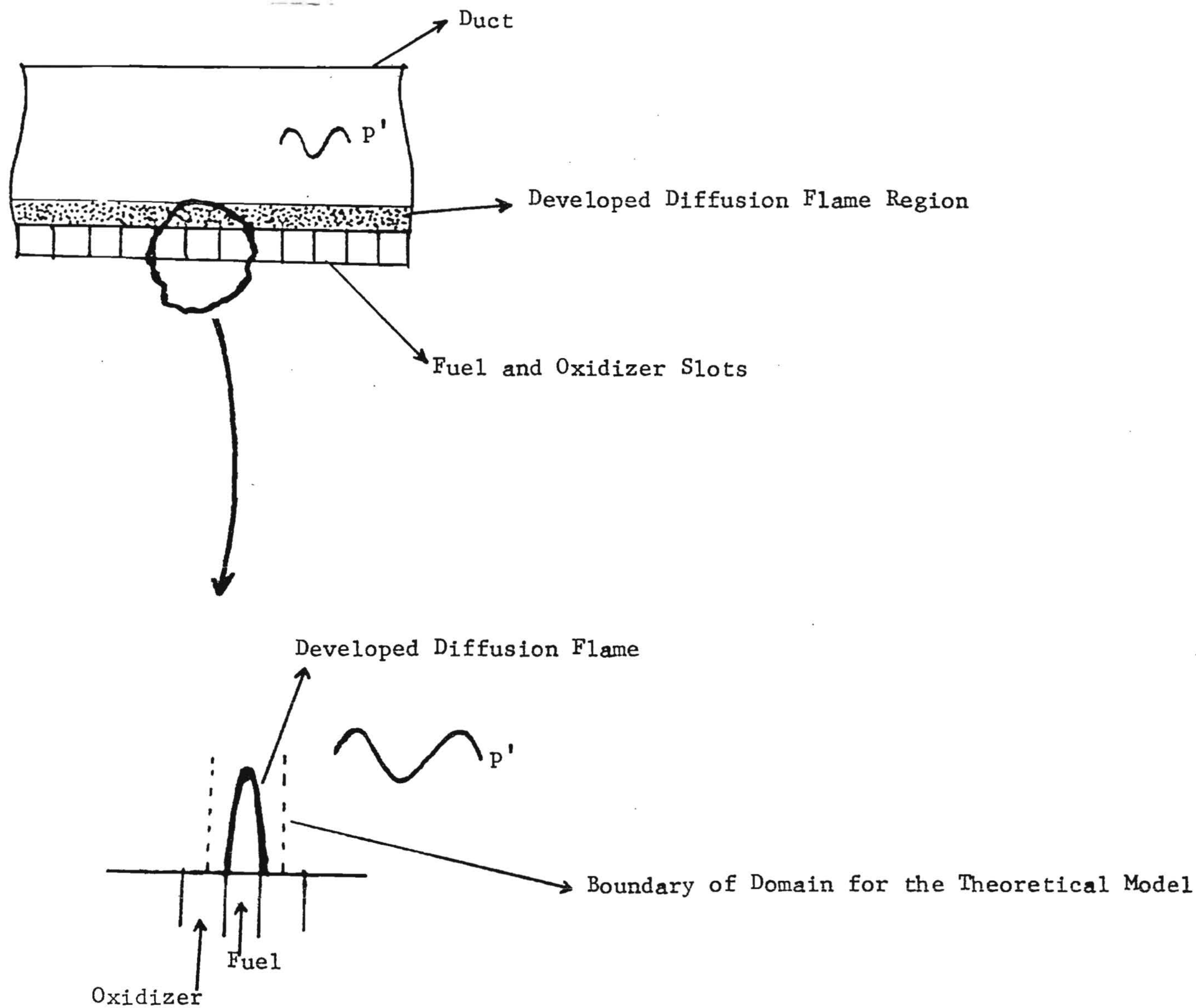

Figure 10. Configuration For the Theoretical Model of the Diffusion Flame-Acoustic Interactions.

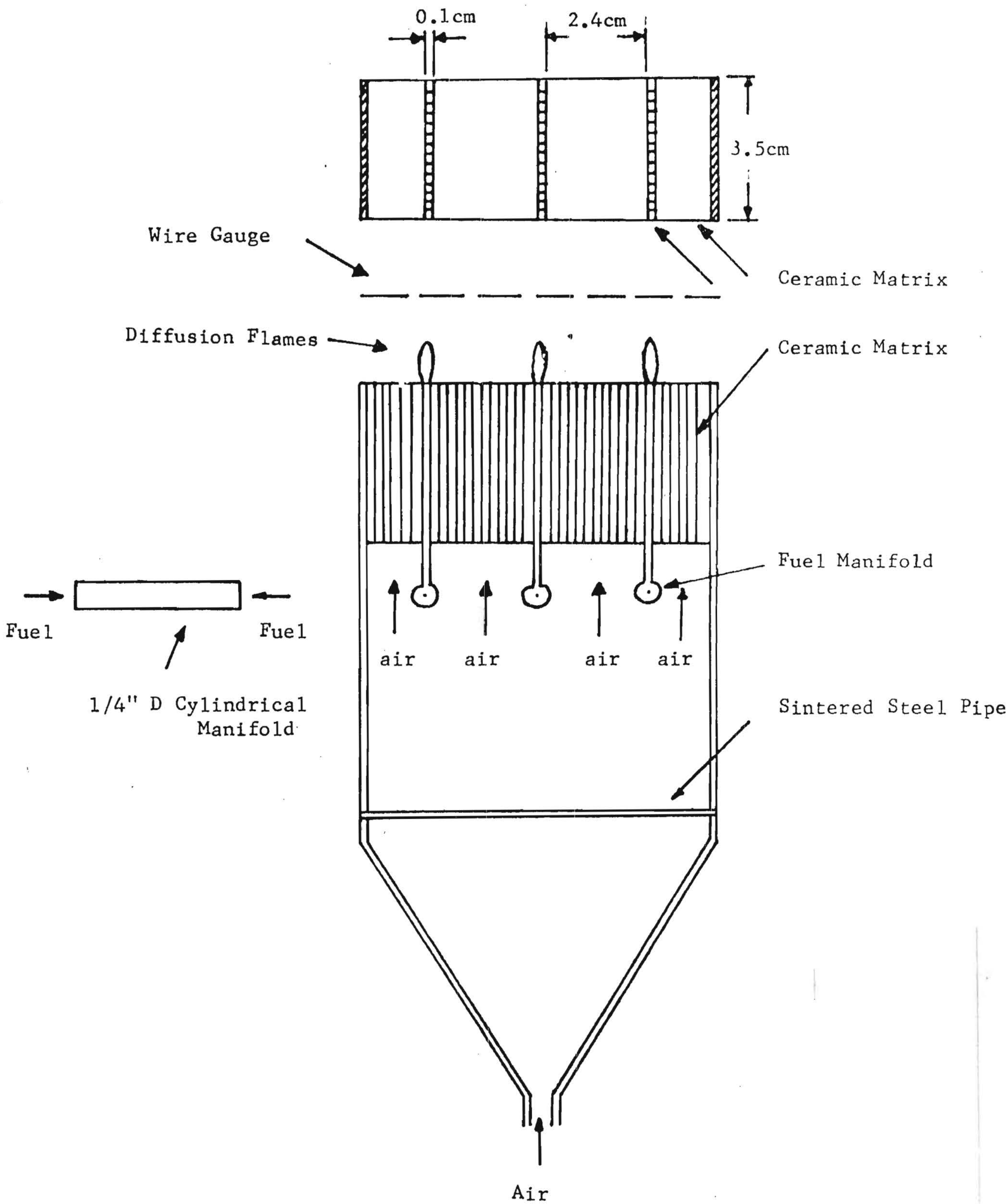

Figure 11. Developed Diffusion Flame Burner.

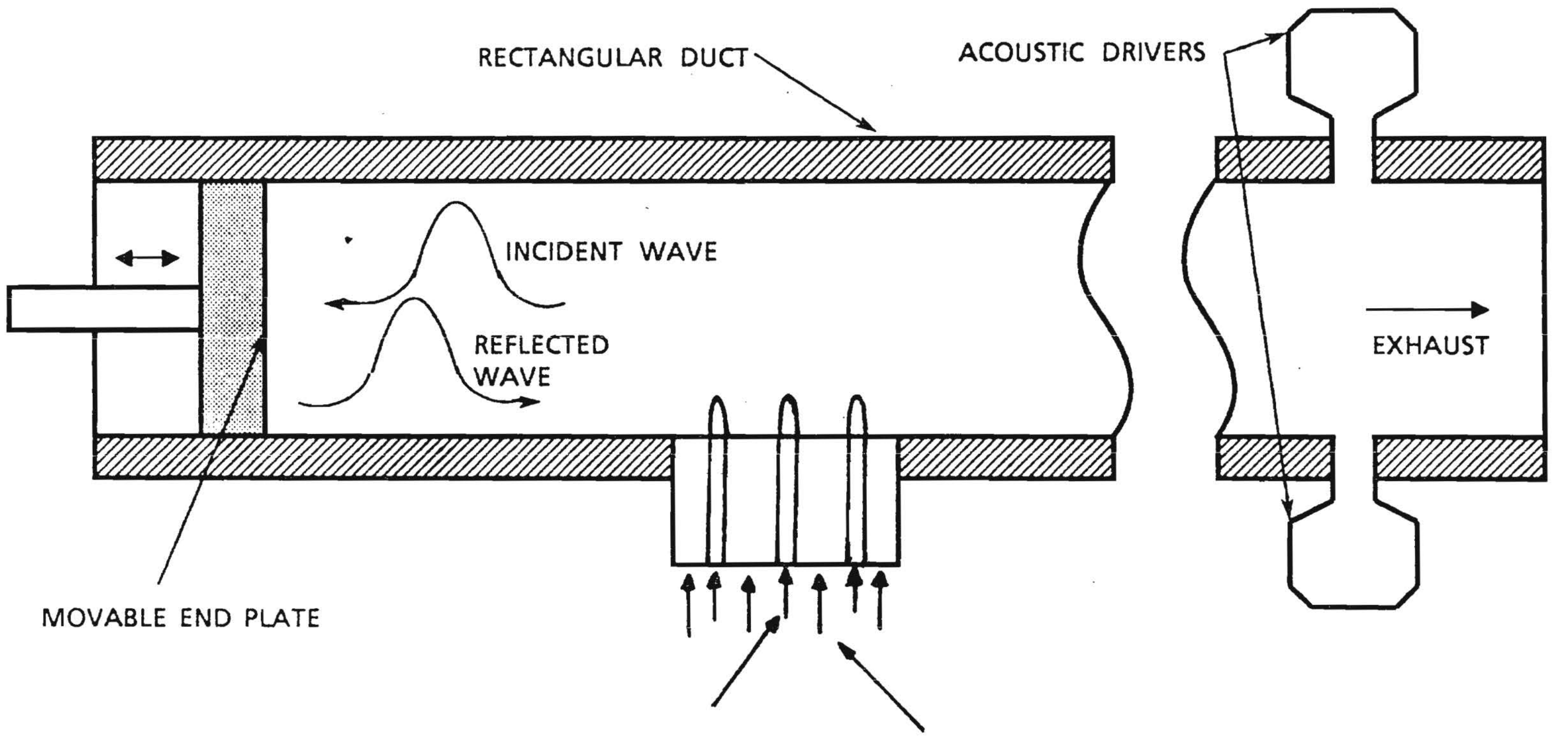

Figure 12. Schematic of the Experimental Set Up to Investigate the Interactions between Gas Phase Diffusion Flames and Longitudinal Acoustic Fields.

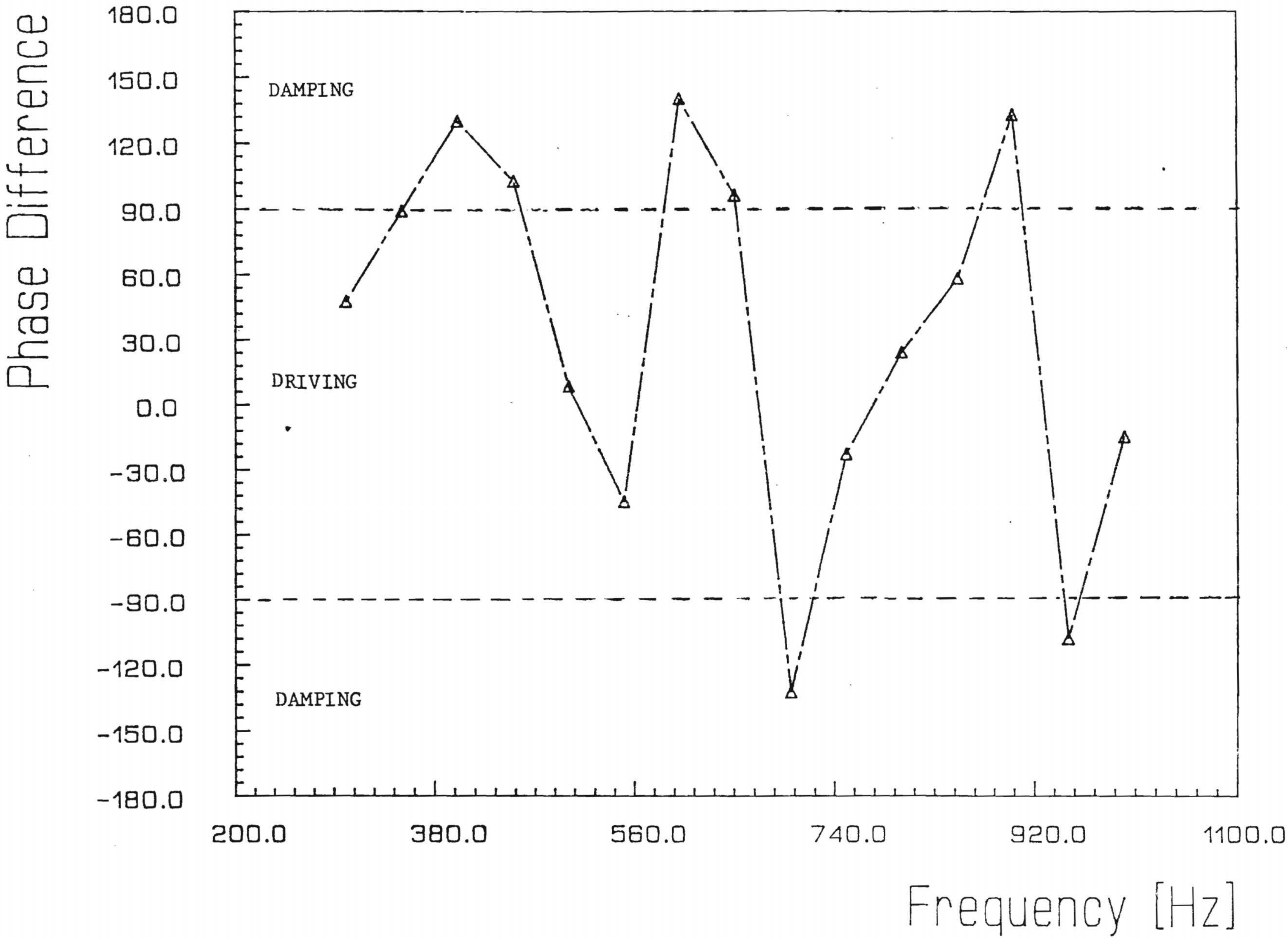

Figure 13. Frequency Dependence of the Phase Difference Between the Flame Radiation and Acoustic Pressure Oscillations Measured with the Flame at a Pressure Maximum.