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J. D. Sterling and E. E. Zukoski, California Institute of Technology, Pasadena, CA

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LONGITUDINAL MODE COMBUSTION INSTABILITIES IN A DUMP COMBUSTOR

J.D. Sterling[*] and E.E. Zukoski[†]
California Institute of Technology
Pasadena, CA

Abstract

The mechanism by which longitudinal modes of a dump combustor are excited has been investigated. The unsteady combustion is a result of the shedding of large scale vortical structures from the flameholder. Driving and damping as determined by Rayleigh's criterion were investigated by using the cross–spectrum and phase of the fluctuating pressure and radiation intensity signals at various locations in the combustor. Thus, the excitation of a particular mode was found to depend on the pressure mode shape and the magnitude and phase of the velocity fluctuation at the flameholder. Fluid mechanical mixing and the chemical reaction rate of the fuel also effect the distribution of heat release and hence the locations of driving and damping. Finally, a mechanism for existence of the limit cycle is discussed.

Introduction

Modern ramjet and afterburner combustion systems often encounter high amplitude pressure oscillations which are referred to as "combustion instabilities." These self-excited oscillations generally occur at frequencies which correspond to circumferential, transverse, or longitudinal acoustic modes of the entire system. The first two "screeching" modes occur at higher frequencies than the longitudinal "rumble" modes and can usually be controlled through the use of baffles or perforated liners. However, the longitudinal modes present a problem because the amplitudes can be large enough to cause structural damage, or failure of the system can result from the inlet shock moving out of the inlet.

These instabilities are closely related to Rijke tube combustion, instabilities of commercial power station combustors, as well as controlled pulsed combustion. Specific research efforts into ramjet instabilities include an analytical investigation by Yang and Culick[1], and experimental investigations by Smith and Zukoski[2] and by Hegde et al[3]. While Smith and Zukoski investigated certain self-excited instabilities in an acoustically complex system, Hegde et al considered an acoustically simpler combustion system driven by acoustic drivers.

The present research has led to a better understanding of the combustion instablilities investigated by Smith[4]. In the instability under study here, acoustic velocity fluctuations cause large vortical structures to be shed from the flameholder. These vortices produce an oscillating heat release which, if in phase with the oscillating pressure, causes driving of that particular acoustic mode. The heat release associated with combustion in a given vortex occurs after a fluid dynamic delay time, associated with the formation of the vortex and mixing between the fuel-air mixture and burnt product, and after a chemical time delay, determined by the fuel type and equivalence ratio. The oscillations reach a limiting value when the driving and damping in the system are of equal magnitude. The growth of the amplitude of the pressure oscillations which results as this system moves from stable combustion in a shear layer to an unstable vortex shedding mode is shown in Figure 1.
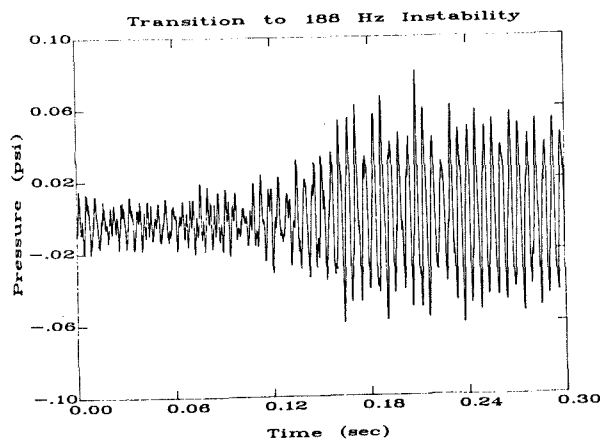

Fig. 1

Experimental Apparatus

Longitudinal mode combustion instabilities were investigated by using a small laboratory combustor in which the flame was stabilized behind either a single rearward–facing step or a double step as shown in Figure 2. The fuels used are methane, a mix of 15% mass

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*Graduate Student, Jet Propulsion Center, Student Member AIAA

† Professor of Jet Propulsion and Mechanical Engineering, Fellow Member AIAA

fraction of hydrogen and 85% methane, and a mix of 30% hydrogen and 70% methane. The fuel and air are premixed and flow from an axisymmetric section to a two-dimensional one 2.54 cm by 7.62 cm as shown in Figure 3. The combustor has quartz side walls and the top and bottom walls are water cooled.
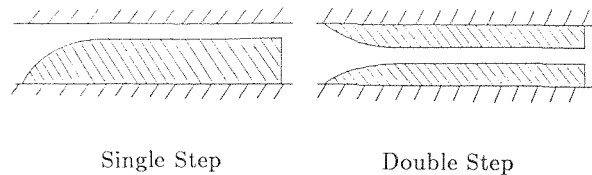

Single Step   Double Step
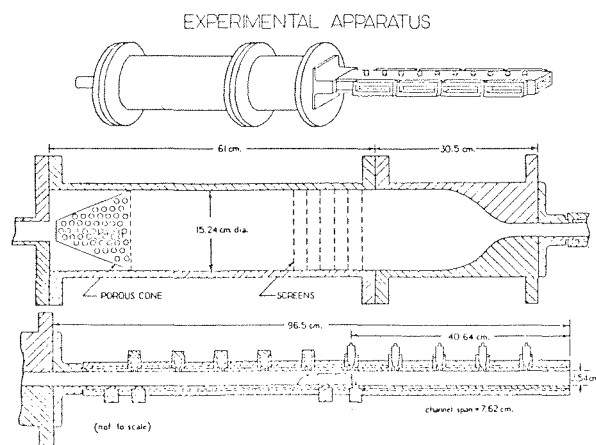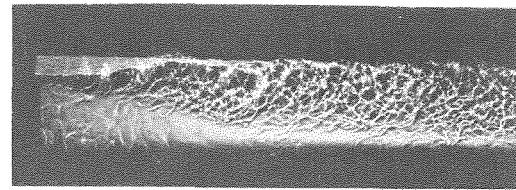
Fig. 2 Flameholder Classification

Fig. 3 Laboratory Combustor Design

Spark shadowgraphy is used to take polaroid pictures of the flow of the combusting gases. Also, a Hy-cam high–speed motion picture camera is used at over 6000 frames per second for further flow visualization. Pressure transducers used to measure the oscillating pressure field are located at various locations in the entire system and the velocity above the flameholder is measured using hot-wire anemometry. The radiation intensity from the flame is measured by a moveable photomultiplier tube which is restricted to view only a small vertical slice of the flame zone. Data were recorded using a multi-channel analog tape recorder and were analyzed using a SD360 spectrum analyzer.
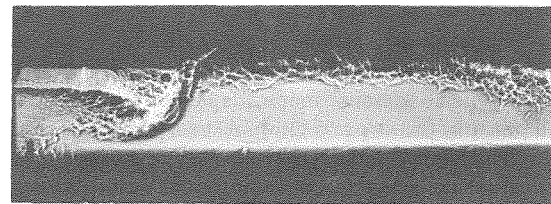
Results

Unstable combustion has been investigated for various mixtures of methane and hydrogen and with two different flameholders. The most prominent feature of the unstable combustion investigated here is the existence of large vortical structures which are shed from

the flameholder at one of the frequencies at which large pressure oscillations occur. Figure 4 shows the striking difference in the flow fields of stable and unstable combustion. The growth and motion of these vortices for a few operating points was described in detail by Smith[4].

Stable Flow

Unstable Flow

Fig. 4 Flow Field Classification

Changes in step height, mean flow velocity, fuel type, and equivalence ratio result in different pressure and radiation intensity spectra. Figure 5 shows the dominant vortex shedding frequencies for a fixed geometry and fuel type. These frequencies are generally very close to resonant acoustic modes that are predicted by linearized acoustic theory. In Figure 5, the symbol at a particular equivalence ratio and mean flow velocity represents the frequency of the acoustic mode which is closest to the frequency of the largest peak in the radiation intensity spectra. The radiation was measured at 7.62 cm downstream of the flameholder lip and ensemble averages of 16 spectra were used to determine the dominant shedding frequency. The cross-hatched region shows conditions of stable combustion. Hysteresis effects are present so that an instability may remain even after the operating point is changed to new conditions, for example, within the cross-hatched region. The symbols shown result from radiation spectra upon ignition at the conditions represented. Hence, Figure 5 does not reflect hysteresis boundaries.

From this figure it can be seen that the equivalence ratio has a very strong effect on the frequency of instability. For a given velocity, the flame can be stabilized
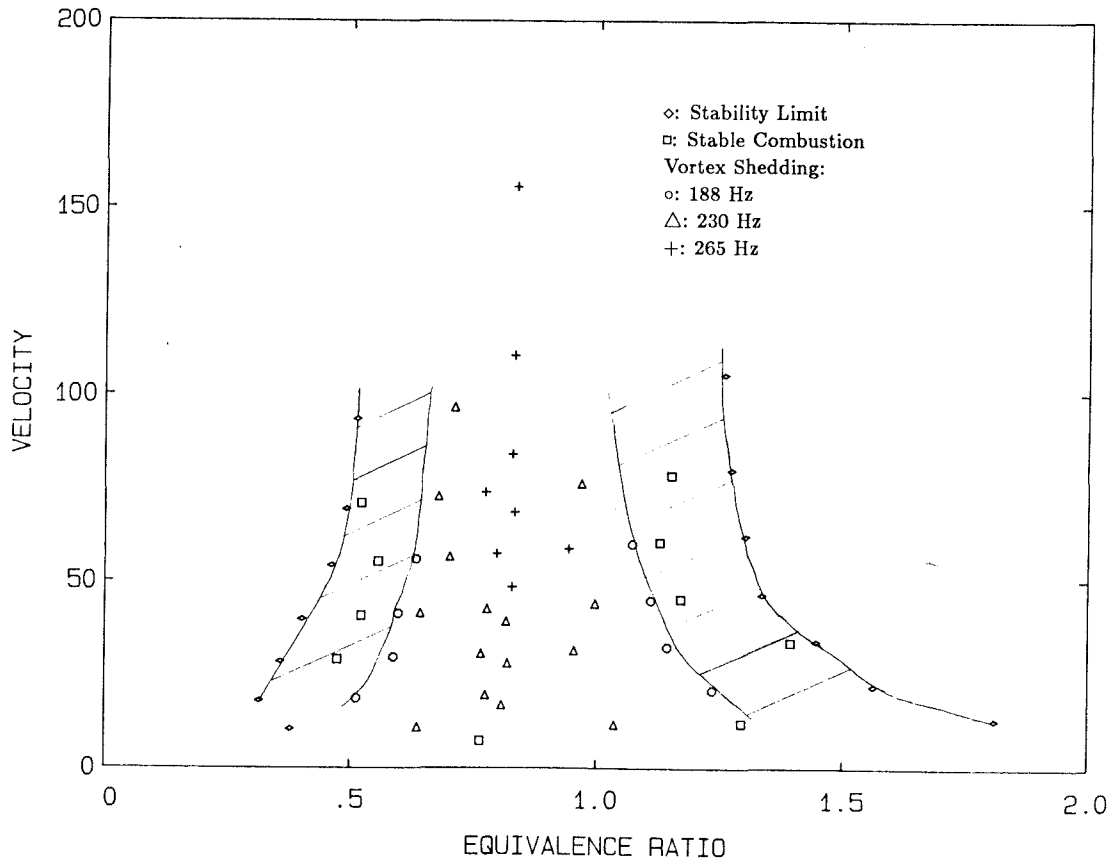
Fig. 5 Dominant Vortex Shedding Frequencies

with no large vortex shedding, or shedding can occur predominately at one of the three different frequencies depending on the equivalence ratio. The dependence on the mean flow velocity is not as strong; however, a shift in the dominant shedding frequency can occur solely due to changes in the mean flow velocity.

Other experimental results show that for fixed fuel conditions, a change in the flameholder from the single to the double step can result in a change of the instability frequency to a higher mode. Also, a change in fuels alone can result in a shift of the instability frequency.

Discussion

Acoustic Analysis

A linearized, one-dimensional acoustic model is used to predict the pressure and velocity fluctuations. This model includes a volume source at the flameholder as the driving mechanism and includes damping in the form of inlet and exit impedances. The amplitude and phase of the pressure response at the flameholder to an arbitrary unit driving is given in Figure 6, and the velocity response is given in Figure 7.

Under various operating conditions, the experimental pressure spectra reveal peaks at 188, 231, 377, 457, and 530 Hertz which correspond quite well with the resonant frequencies predicted by the model. Near a stoichiometric equivalence ratio Figure 5 reveals shedding at 230 Hz at low mean flow velocities and shedding at 530 Hz at high velocities. In between there exists a region where shedding occurs at intermediate values and appears to lock-in to shedding at 265 Hz which is the subharmonic of 530 Hz.

The mode shapes of the pressure oscillations are also predicted quite accurately by the model. For example, using methane and the single rearward-facing step and a flow velocity of 22 m/sec, the pressure measured at the step results in the spectrum of Figure 8. By using the amplitude of the 188 Hz peaks from the spectra measured at many locations in the system, the
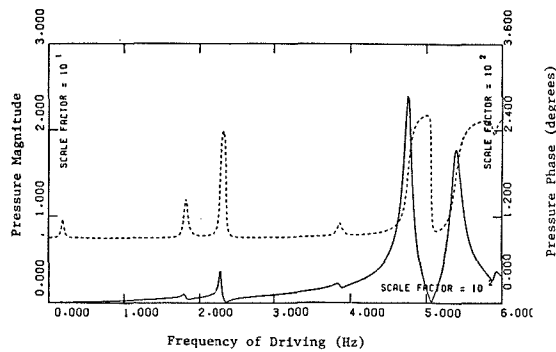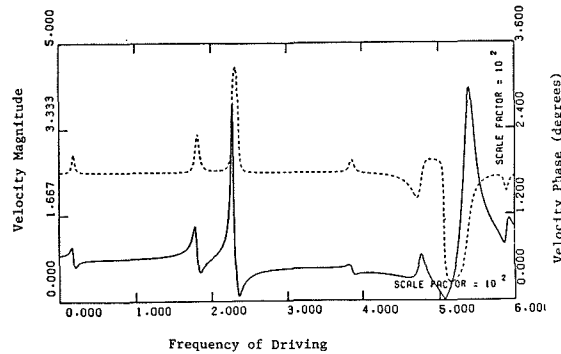
Fig. 6 Pressure Response to Unit Driving

Fig. 7 Velocity Response to Unit Driving

mode shape was determined and matched at the flame-holder to the predicted shape as shown in Figure 9. The mode shapes of other frequencies and the phase data also tend to verify the accuracy of the acoustic model. Even for pressure oscillations as large as 8% of am-bient, where nonlinear effects would be expected, the mode shapes predicted by linearized acoustics are still quite accurate.
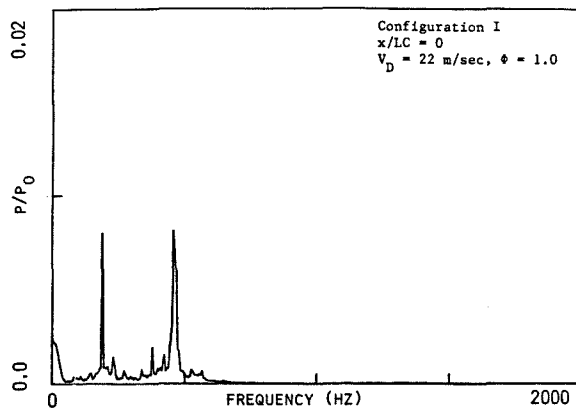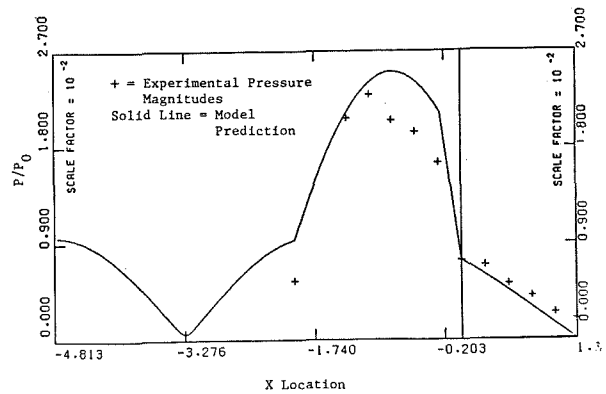

Fig. 8 Pressure Spectrum at the Flameholder

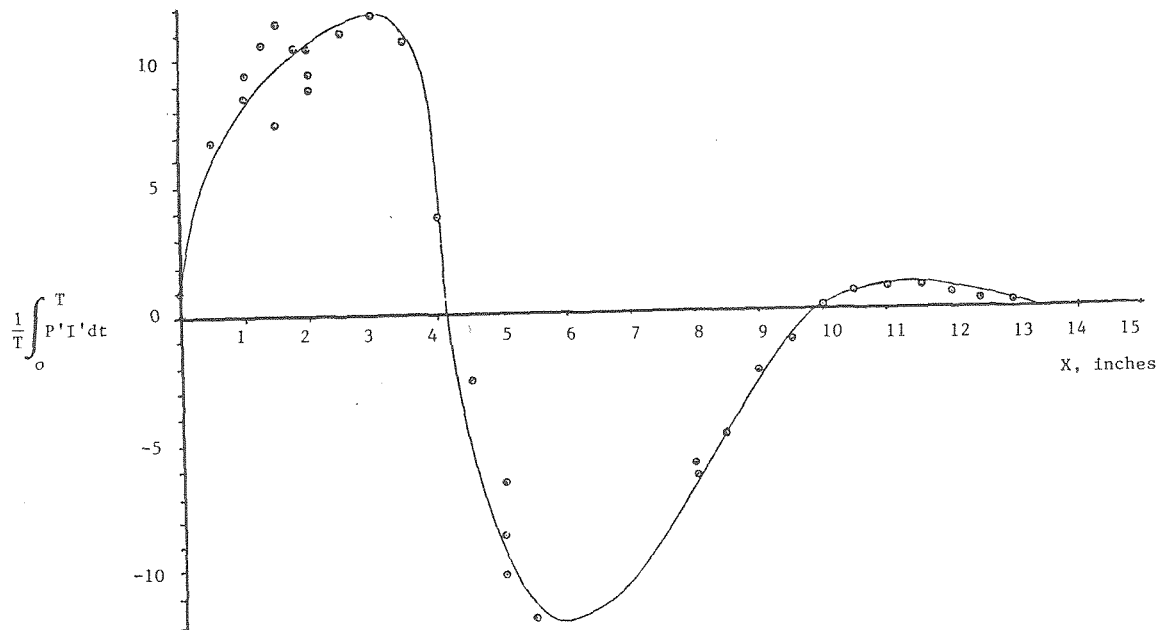Fig. 9 188 Hz Pressure Mode Shape

Driving Mechanism

Detailed investigation into the driving mechanism as satisfied by Rayleigh's criterion has been performed for the single step flameholder using methane at a stoi-chiometric ratio with air and at a velocity of 22 m/sec. The criterion states that driving occurs when the os-cillating pressure and heat release are in phase[5]. By taking the cross-spectrum and phase of the pressure and radiation intensity at a given location in the com-bustion chamber, the relative magnitude of the driving at that location can be determined. This assumes that oscillatory heat release varies linearly with the emitted radiation from the flame[2].

The results of this approach are given in Figure 10 for the shedding frequency that results from the above conditions. The driving occurs primarily in the first four inches of the combustion chamber because the phases of the heat release and the pressure are pos-itively correlated and the magnitudes of the pressure (see Fig. 9) and radiation intensity (not shown) are largest in that segment. Damping of this mode actu-ally occurs in the region between five and ten inches. The net value of the integral of the curve is slightly pos-itive and this is the expected result since the data were obtained when the pressure oscillations had reached fi-nite limiting amplitudes and the driving was balanced by the damping.

Both the fluid dynamic mixing time and the chem-ical reaction time govern the oscillatory heat release. The chemical delay time depends on the fuel type and the equivalence ratio of the premixed supply. The ob-served shedding frequency can change as this chemical time is varied as reported in the above results. How-ever, shifts in the shedding frequency also occur for changes in the fluid mechanical mixing time.

Fig. 10 Rayleigh's Criterion for 188 Hz Instability

$$\frac{1}{T}\int_{0}^{T} P'I' \, dt$$

For given operating conditions, the mixing time is a strong function of the magnitude of the velocity fluctuations at the flameholder. Hendricks[6], has investigated the evolution of a vortex, created as a shock wave passes over a rearward-facing step, using a numerical Euler code. It was demonstrated that as the magnitude of the velocity fluctuation at the flameholder is increased, mixing is enhanced as the resulting vortex grows and impinges against the lower combustor wall.

Consequently, as energy is fed into an acoustic mode, the amplitude of the pressure and velocity fluctuations increases and a decrease in the fluid mechanical mixing time occurs. This gives a new distribution of driving and damping in the system . Thus, sustenance of an acoustic mode may require a particular value of the pressure amplitude, resulting in the limit cycle observed experimentally in Figure 1. As a result, it would be expected that higher frequency modes would require quicker energy addition and hence, larger pressure amplitudes. This analytic result is in good agreement with our experimental observations that the amplitude of the pressure oscillations increases as the frequency of the excited mode increases.

Conclusion

This investigation has shed light on the mechanism of the internal feedback necessary to excite low frequency pressure oscillations in ramjet-type combustion chambers. Longitudinal modes for which the fluctuating velocity at the flameholder is sensitive to driving are determined primarily by the system geometry. An oscillating flow results in large vortex structures being shed at the flameholder. Their subsequent development and the associated heat release depends on step height, mean velocity, fuel type, and equivalence ratio. The distributed combustion then drives the instability in areas of the combustor where its oscillatory component is in phase with the pressure.

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