Nonlinear Dynamics of an Unstable Swirl Combustor: Frequency Locking and Open Loop Control

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Introduction

This paper describes an ongoing investigation into the nonlinear interactions between natural acoustic modes and driven oscillations in a lean, premixed swirl stabilized combustor. This work is motivated by the fact that combustion instabilities continue to hinder gas turbine combustor development and operation[1-5]. These instabilities occur when the unsteady combustion process couples with one or more of the combustor's acoustic modes, resulting in self-excited oscillations. The objective of this work is to improve the understanding of the nonlinear dynamics associated with these oscillations. Improved understanding of the nonlinear combustion process is needed to further development of methods to predict limit cycle amplitudes.

In addition to improved understanding of nonlinear combustor dynamics, this work also has implications on active instability control[6]. In many cases, active control is implemented by closed loop control of fuel flow oscillations that are out of phase with the instability. However, the use of open loop, non-resonant frequency, forcing has also been demonstrated by many researchers[7-11]. The present study provides some insight into the underlying combustor processes which impact the effectiveness of these open loop control strategies.

This work is motivated by a previous study focusing on the nonlinear flame transfer function between driven pressure oscillations and heat release fluctuations in a high-pressure, gas turbine combustor simulator[12]. During these tests, nonlinear interactions between a natural combustor mode and those due to acoustic forcing were observed. Specifically, the amplitude of the unstable mode monotonically decreased, before it disappeared completely, with increases in amplitude of the driven mode. This behavior was attributed to frequency-locking, a well-known nonlinear oscillator phenomenon. Frequency locking is due to nonlinear interactions between oscillations that are closely spaced in frequency. It is manifested as a decrease in amplitude of the self-excited or natural mode oscillations as the amplitude of the driven oscillations increases.

Lieuwen & Neumeier[12] performed a limited investigation of the effect of forcing frequency upon this frequency locking phenomenon by considering two forcing frequencies. Their data did not indicate a significant change in the entrainment amplitude at the two driving frequencies. This was contrary to expectation, however, as we had anticipated the entrainment amplitude to be proportional to the frequency spacing between the forced and self-excited frequency. These considerations motivated this study, which more systematically investigates these frequency spacing effects on entrainment amplitude.

Experimental Setup

Experiments were performed on a 100 KW swirl stabilized burner, illustrated in Figure 1. Natural gas and air are supplied from building facilities, whose flow rates are measured with flowmeters. In order to ensure that acoustic oscillations do not affect fuel/air mixing processes, the air and fuel are introduced upstream of a choke point. Thus, the equivalence ratio of the reactive mixture entering the flame is essentially constant. This was done because of the sensitivity of the flame chemiluminescence levels to both heat release rate and equivalence ratio.

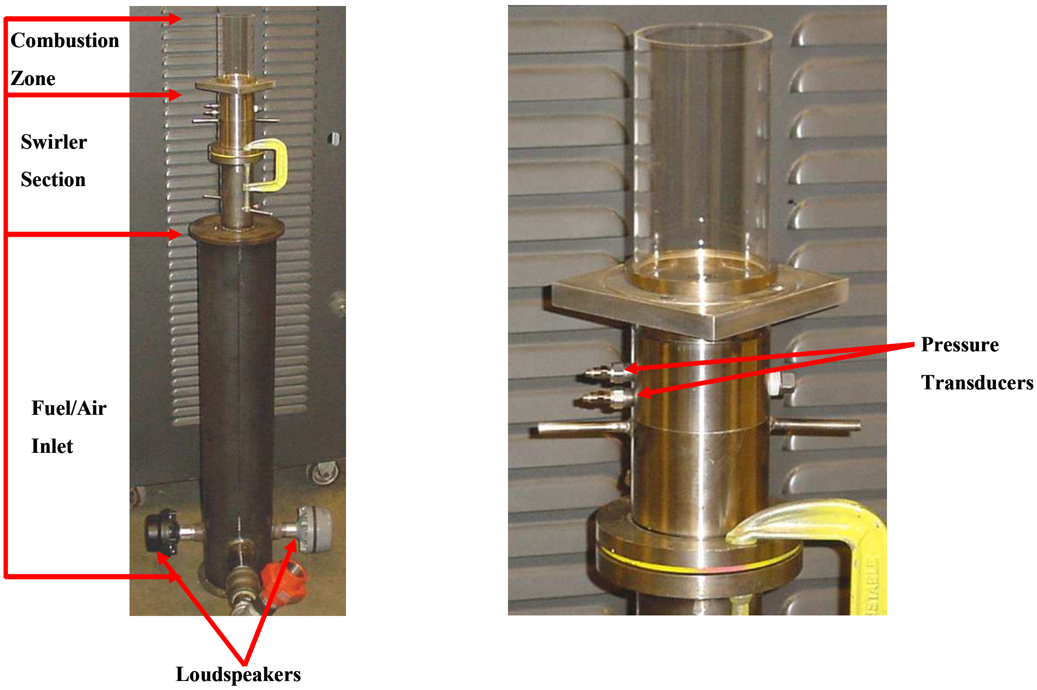


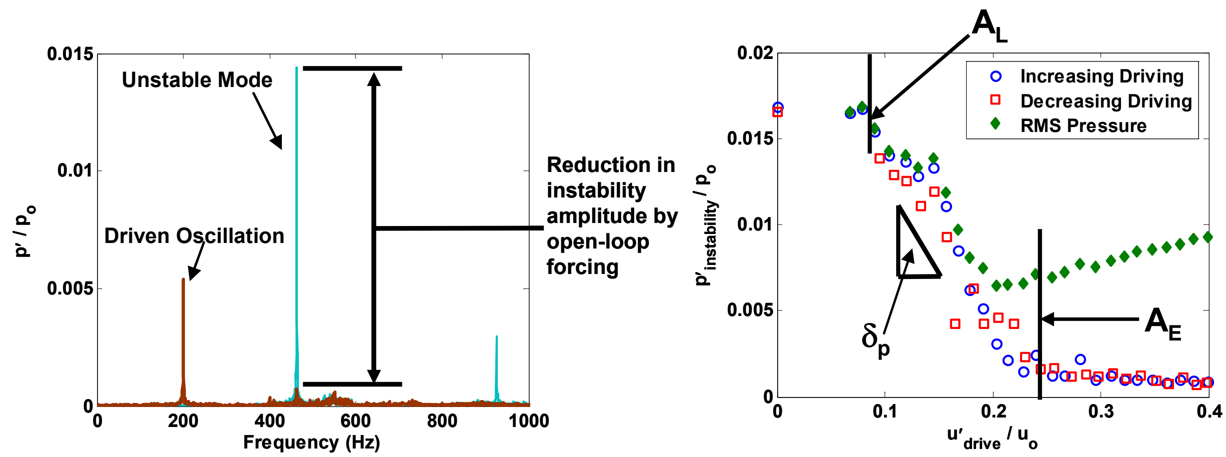
Figure 1: Photograph of burner setup (left); Photograph of swirler section and combustion zone (right)

Pressure oscillations are measured with Model 211B5 Kistler pressure transducers mounted downstream of the swirl vanes, 5.85cm and 7cm upstream of the rapid expansion. Velocity oscillations are calculated using the two microphone method outlined in e.g. Ref. [13]. The relative magnitude of the combustion heat release oscillations are obtained by measuring the global CH* and OH* chemiluminescence with a photomultiplier fitted with a 10 nm bandwidth filter centered at 430 nm and 310 nm, respectively. The fiber optic is installed downstream of the flame zone at an angle such that it can view the entire combustion zone. Oscillations are driven in the combustor by two loudspeakers mounted into the inlet section; see Figure 1.

Results

The reported tests were performed at a nominally unstable condition, with an instability frequency of 461 Hz. The forcing frequencies investigated ranged from 150 to 430 Hz and for all cases, the overall acoustic power was substantially reduced by the presence of acoustic forcing.

A typical result is shown in Figure 2. The nominal amplitude of the 461 Hz instability is about 1.5-2% of the mean pressure in the combustor. In this particular case, forced oscillations are excited at 200 Hz over a range of amplitudes. As shown in Figure 2, increased forcing levels cause the 461 Hz mode amplitude to monotonically decrease, and to nearly disappear when the driving amplitude reaches approximately 25% of the mean velocity. Thus, the entrainment amplitude for this case is $u'/u_o=0.25$. It is also seen that the harmonic associated with the instability at 922 Hz disappears. Also shown in the figure is the overall RMS amplitude in the 0-1000 Hz range, which has a minimum near the entrainment amplitude and then begins to rise with increased forcing levels, due to the growing amplitude of the imposed oscillations. The acoustic power in the spectra between 0 and 1000 Hz is reduced by 90% for this case.



(a) (b)

Figure 2: (a) Spectrum of combustor pressure at two driving amplitudes showing decrease in combustor instability mode as driving amplitude is increased (instability frequency = 461 Hz, driving frequency = 200 Hz). (b) Dependence of instability amplitude on driving velocity amplitude at 200 Hz driving frequency.

The typical dependence of the natural instability amplitude on the driving amplitude is shown in Figure 2(b). At the highest driving amplitudes, the instability has essentially disappeared at the cost of the increase in amplitude of the driven pressure. There are several basic features of the instability amplitude dependence upon driving amplitude that can be discerned from Figure 2(b). First, the instability amplitude is independent of the forcing amplitude for some amplitude range before decreasing; we have referred to the driving amplitude at which this decrease begins as A_L. Second, the instability amplitude decreases with some slope, δ_p, for further driving amplitude increases. Third, the instability amplitude essentially goes to zero, or to near zero values above some driving amplitude, referred to here as the entrainment amplitude, A_e. For example, in Figure 2(b) the entrainment amplitude is ~25% of the mean velocity at the premixer exit. Finally, the dependence of the unstable mode amplitude upon the driving amplitude exhibits some hysteresis. Because of space limitations, we will not consider this further, but simply note that typical hysteresis levels are on the order of u'/u_o = 0.03.

These characteristics depend significantly upon driving frequency. We consider first the entrainment amplitude dependence upon driving frequency, which is plotted in Figure 3. The entrainment amplitude, A_E, grows as the forcing frequency is moved away from the instability frequency of 461 Hz, except very close to the instability (f_{drive} = 400-430 Hz). The trend in Figure 3 was expected although we do not have any specific theory our intuition was based upon. Figure 3 also reinforces the fact that the velocity oscillation amplitude in unstable combustors is a major controlling factor which affects the nonlinear combustion process. It should be noted that a different trend is observed if the perturbation pressure*, rather than velocity were used to quantify the forcing amplitude. This is due to the frequency dependence of the pressure-velocity relation. This result explains the confusion over this issue raised in our prior study, which used the perturbation pressure as a measure of disturbance amplitude.

* In this combustor, the entrainment pressure amplitude increases monotonically with decreasing frequency up to about 230 Hz. It then decreases for lower frequencies.

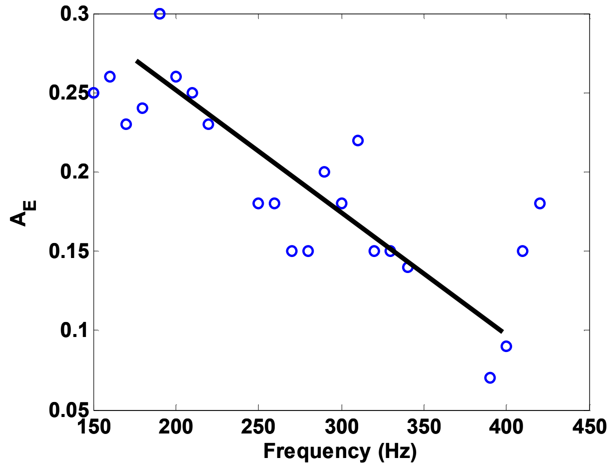


Figure 3: Dependence of velocity entrainment amplitude, A_E upon driving frequency (instability frequency = 461 Hz).

We next consider the slope of the instability amplitude rolloff, δ_p, shown in Figure 4. In contrast to the entrainment amplitude, the instability rolloff has a complex dependence on frequency which is not understood. The highest slopes, and therefore the most rapid rolloff of the instability amplitude, occur at 250 and 400 Hz. Local minima are seen at 160 Hz and 310 Hz. Similarly, the parameter A_L's frequency dependence is shown in Figure 5 . In general, A_L is found to be largest at frequencies which are far away from the instability and smallest at frequencies closer to the instability. The values of A_L range from u'/u_o= 0.02-0.10. At 240 Hz, this value decreases linearly from it maximum value, near where the instability rolloff hits its maximum, and flattens out after 310 Hz, where the instability rolloff hits a minimum. In general, the parameter A_L is seen to change values near local minima and maxima in the instability rolloff value.

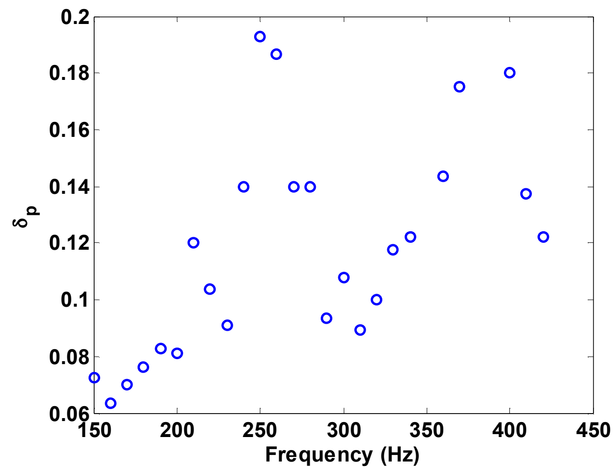


Figure 4: Dependence of instability rolloff, δ_p on driving frequency (instability frequency = 461 Hz)

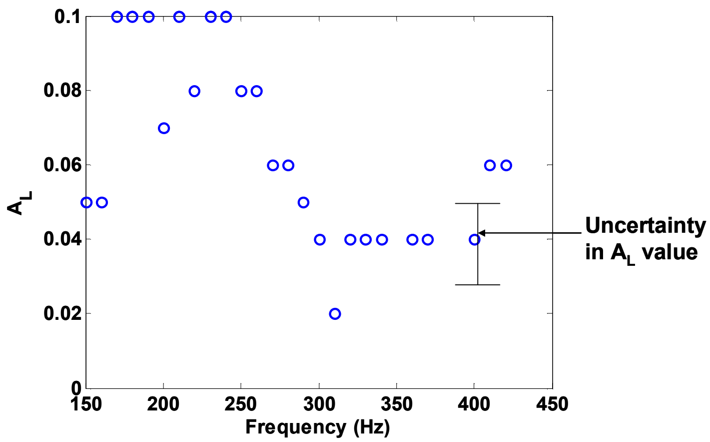


Figure 5: Dependence of A_L parameter (velocity oscillation amplitude range which is independent of forcing) on driving frequency (instability frequency = 461 Hz)

As these results have direct implication on open loop forcing as an active control methodology, it is of interest to analyze the total acoustic power reduction in the 0-1000 Hz range where power is defined as:

$$Power = \int \left| p' \right|^2 df \qquad (1)$$

Figure 6 plots the frequency dependence of the maximum reduction in acoustic power due to open-loop forcing observed at each frequency over the whole forcing amplitude range. We have found that we can reduce the acoustic power by at least 70% of its original value at optimized driving amplitudes at this operating condition. The best results occur at frequencies where the entrainment *pressure* amplitude is smallest and the worst results are where the entrainment pressure amplitude is highest, as may be expected. For larger entrainment amplitudes, more acoustic power is being added into the system at the point of entrainment. Therefore, the reduction in instability amplitude comes at the cost of larger driven amplitudes.

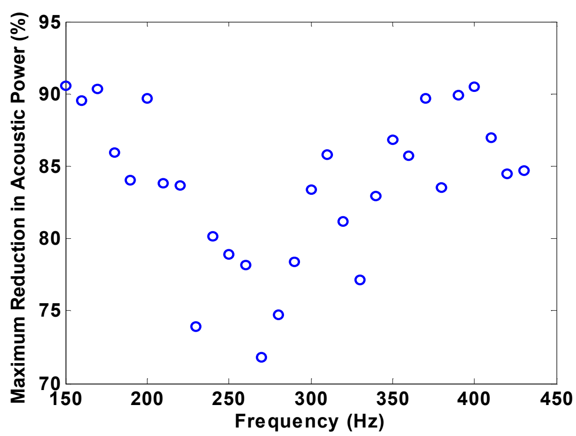


Figure 6: Dependence of maximum acoustic power reduction on driving frequency (instability frequency = 461 Hz).

Conclusions

This study clarifies a number of issues related to the nonlinear interactions between driven and natural unstable combustor modes but also raises new questions. It has been shown that the entrainment velocity amplitude monotonically grows with driving-instability frequency separation. We have found that the instability rolloff and velocity oscillation range which is independent of forcing amplitude both have complex dependencies on driving frequency. Changes in the parameter, A_L, are seen to accompany local minima and maxima in instability rolloff. Further work is being performed to analyze the effect on these parameters of driving frequencies greater than the instability frequency.

In addition, open loop forcing of the combustor, at frequencies different from the instability frequency, was found to significantly reduce the acoustic power in the 0-1000 Hz range by as much as 90%. The performance of this open loop control scheme is dependent on the entrainment amplitude. The best results were obtained for frequencies which had the lowest entrainment pressure amplitudes, as might be expected.

The generality of this methodology is an open question, however, as we found some operating conditions where entrainment did not occur in the same fashion and the instability amplitude is marginally reduced. For example, in one situation, the addition of forcing caused a shift in instability frequency to a value 40 Hz higher than its unforced value (from 510 Hz to 550 Hz). For driving frequencies whose harmonics do not fall around this new frequency, this value is relatively constant. The acoustic power in the 0-1000 Hz range is only slight reduced (~20%) before increasing rapidly, unlike the conditions presented in this paper. An investigation on this behavior is also ongoing.

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