



Combustion Dynamics Characteristics and Fuel Pressure Modulation Responses of a Three-Cup Third-Generation Swirl-Venturi Lean Direct Injection Combustion Concept

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Abstract

This paper presents the combustion dynamic data and fuel modulation response of a three-cup Lean Direct Injection (LDI) combustor developed by Woodward FST Inc. The test was conducted at the NASA Glenn Research Center CE-5 flame tube test facility. The facility provided inlet air up to 922 K and pressure up to 19.0 bar. At the low-power configuration, the combustion noise was quiet. Large combustion pressure oscillations were observed with the high-power configuration at an off design condition, with low inlet air temperature and pressure conditions and a high equivalence ratio (about $T_3 = 600$ K, $P_3 = 800$ kPa, and $\phi = 0.46$). The noise amplitude was as high as 1.5 psi at around 220 Hz. As inlet air pressure and temperature increased, this combustion instability decreased. Fuel modulated signals were produced with the WASK fuel modulator located in the fuel line upstream of the center cup pilot fuel-air mixer. The amplitudes of the modulated signals detected in the combustor were low. Only less than 0.13 percent (0.06 psi) of the input energy was detected, and the signal amplitudes decreased as the modulated frequencies increased. Interaction between the modulated signals and the combustion noise varied with operating conditions. At a condition with low combustion noise around 150 Hz, modulating a signal at around the same frequency would increase the combustion noise from 0.2 psi to as high as 0.6 psi, whereas at a condition with a high combustion instability around 250 Hz, the modulated signal did not seem to have much effect on the combustion noise.

Introduction

NASA's Advanced Air Transport Technology (AATT) project is focused on developing a 22,800 lbf thrust engine at rolling takeoff conditions with an overall pressure ratio (OPR) of 55 and small core size of 3.0. This engine is expected to enter into service between the 2030 to 2040 time frame. The engine combustor design is required to have the Landing and Take-off (LTO) NO_x emissions with 80 percent reduction (relative to the ICAO CAEP 6 levels) with good combustion efficiency (> 99.0 percent) at any LTO cycle conditions. To reach the emissions goal, NASA has collaborated with United Technologies Research Center (UTRC) and Woodward FST Inc., to develop a new combustor concept. The combustor concept developed by Woodward FST Inc. is a three-cup, Lean Direct Injection (LDI) concept that consists of 19 individual fuel-air mixers. This design integrates the complex fuel lines into one fuel stem for each combustor cup. The gas emission characteristics of this injector concept were experimentally evaluated and showed emissions reduction between 85 to 89 percent, relative to the ICAO CAEP 6 levels (Ref. 1).

Combustion instability is a concern for combustors, particularly lean-burn combustors such as LDI. The LDI concepts utilize multiple fuel injection points, and promote rapid and uniform fuel-air mixing to minimize local near-stoichiometric regions that produce high NO_x emissions. Uniform fuel-air mixing regions are typically more susceptible to combustion dynamics. Previous studies with a 9-point LDI combustor under choked outlet boundary conditions exhibited interactions between the fuel-air mixers, combustion thermal expansion, and air density changes that would alter the combustion dynamics (Ref. 2). Other studies have also reported on the combustion dynamics for LDI concepts. Among these are a single-mixer LDI injector study that found instability increased with fuel air ratio, which might prevent full-engine power operation (Ref. 3). Another study reported dynamic data for a second-generation Woodward LDI (Ref. 4). This study found that combustion pressure fluctuations were low (< 0.5 psi peak to peak) for most conditions, but at one low-power condition when the fuel air ratio was more than double of the correct value for the cycle point, the peak-to-peak dynamic pressure fluctuation was greater than 1.5 psi.

In addition to the gas emissions data, combustion dynamic data of the Woodward three-cup, 19 fuel-air mixers combustor was also collected. A fuel modulator developed by WASK Engineering, Inc., through a NASA Small Business Innovation Research (SBIR) contract, was also tested in open loop where the modulating pressure signals were varied from 50 to 1000 Hz. In this paper, combustion dynamic characteristics and responses to the fuel modulating signals of the Woodward third-generation LDI concept are presented.

Experimental Facilities and Hardware

Experimental data used in this study were collected on Stand-1 of the CE-5 flame-tube test facility at the NASA Glenn Research Center (Ref. 5). Figure 1 shows a cartoon cutaway drawing of the combustion rig test section. Nonvitiated air was pre-heated to a maximum inlet air temperature of 922 K and a pressure of 19 bar. Jet-A aviation fuel was used. Fuel flow rates were measured by Coriolis flow meters, and the air flow rate was measured by a venturi meter. The fuel-air mixture was injected into a flame-tube

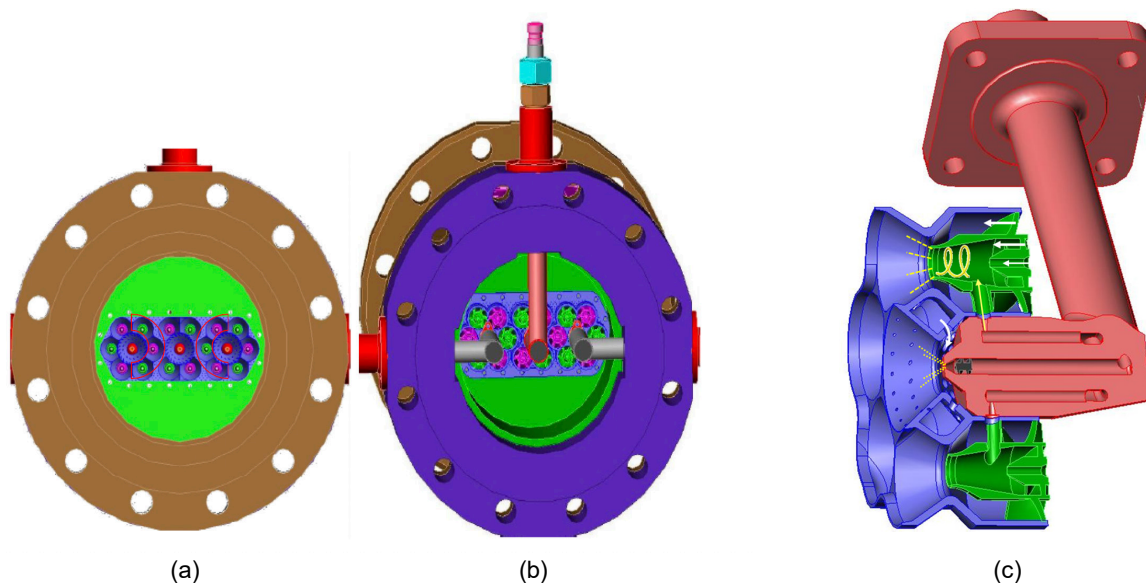


Figure 1.—Woodward three-cup third-generation LDI hardware. (a) front end view. (b) back end view. (c) flow schematics of a 7-point cup.

with a cast ceramic liner. A gas probe was placed 20 cm downstream of the injector dome face to collect combustion products for analysis. The combustion products were cooled down to 500 K by mixing with sprayed water before exiting to an altitude exhaust system.

The LDI module described here contains 19 fuel-air mixers in a three-cup setting as shown in Figure 1. The center cup contained 5 fuel-air mixers (5-point cup), while the two adjacent cups contained 7 fuel-air mixers (7-point cup). The center fuel-air mixer in each cup was used as the pilot fuel-air mixer whereas the other surrounding fuel-air mixers were considered as the main fuel-air mixers.

These were two fuel-flow schemes with using three fuel circuits. The first fuel-flow scheme was used mainly for gas emissions assessments. One fuel circuit controlled fuel flow through the 3 pilot fuel-air mixers (the center fuel/air mixer in each of the three cups) for low engine power operation (7 percent engine power). The second fuel circuit used to control the fuel flow through the main fuel-air mixers in the center injector cup. The third fuel circuit controlled the fuel flow through the main fuel-air mixers in both 7-point cups on either side of the 5-point cup. For 30 percent engine power operation, only the 3 inner fuel-air mixers within each of the 7-point cups were used for fuel injection (a total of 6 fuel-air mixers, circled in red in Figure 1). For higher engine power operation, all 12 fuel-air mixers in the 7-point cups were used. When testing with the WASK modulator, the fuel control scheme was different than described above. The fuel modulator was placed in the fuel line about 60 cm upstream of the center cup pilot fuel-air mixer in the first fuel circuit. The second fuel circuit controlled the pilot fuel-air mixers in the other two 7-point cups. The third first circuit controlled all the main fuel-air mixers.

Modulation of the fuel was accomplished with the use of an actual fuel modulation device. The fuel modulator used was a device developed by WASK Engineering, Inc. through a NASA SBIR contract. Picture and dimensions of the WASK modulator are shown in Figure 2, and design specifications are listed in Table I. Cold flow characterization of the modulator was documented by Saus (Ref. 6). During this testing, the fuel modulation signals were within the ranges of 10 to 1000 Hz.

Dynamic pressure was measured at three different locations with PCB dynamic sensors (Model 112A22). One sensor was placed upstream of the combustor (P3 location). The other two sensors were placed in the combustor, at 7.6 cm in and 20 cm downstream (axially) of the dome face of the combustor. Due to the temperature limitation of the sensors, sampling tubes (ID = 0.635 cm) were inserted into the combustor rig instead. The sensor was placed at about 0.9 m away from the tube inlet, each with a 30 m tail to damp out the dynamic signals. A slow nitrogen purge flow at the end of the tail provided positive flow to keep the sensors from the hot combustor gas.

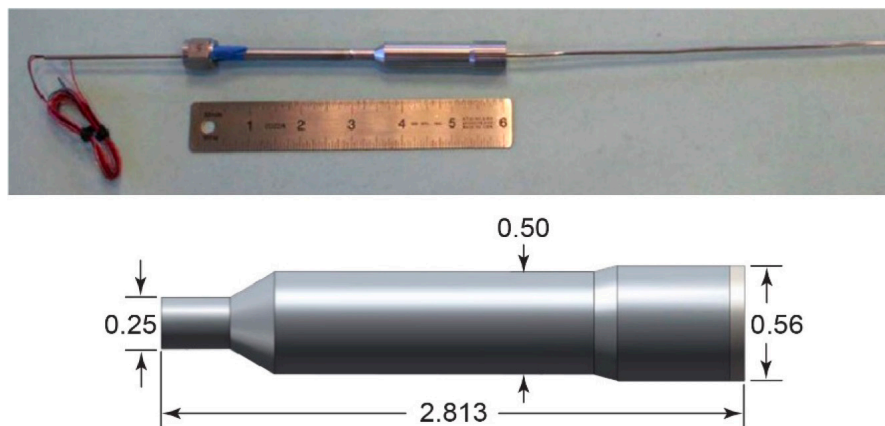


Figure 2.—Picture and drawing of the WASK fuel modulator.

TABLE I.—DESIGN SPECIFICATIONS OF THE
WASK FUEL MODULATOR

Maximum mean flow rate	56.7 kg/hr
Flow number range	1 to 5
Inlet pressure range	0 to 6.9 MPa
Desired modulation	±40 percent of mean mass flow
Minimum outlet pressure	1.7 MPa
Minimum bandwidth	1000 Hz
Flow media	water, JP-8 Jet fuel
Maximum fuel inlet temperature	305 K
Maximum operating temperature	978 K

Data acquisition used a Dewetron acquisition system at a rate of 30 kHz or 50 kHz for a period of 60 sec. Dynamic pressure signals were patched to a Precision Filters system, where frequencies higher than 10 kHz were filtered out before reaching the Dewe 43A. For post processing, each recording was split into segments of 2^{15} points. The signals were converted to the frequency domain using the Fast Fourier Transform (FFT) function and Spectrogram function in MATLAB® (The MathWorks, Inc.). No line loss correction was added to account for viscous dissipation occurring in the sampling tube. The line loss increases as frequency goes higher. For the set up of this experiment, the line loss was about 20 and 12 percent for a 2000 Hz signal at 690 and 1723 kPa, respectively (Ref. 4).

Results and Discussions

Combustion Dynamic Characteristics

Multipoint LDI promotes rapid fuel-air mixing by replacing one traditionally-sized fuel-air mixer with several smaller fuel-air mixers. In addition, fuel staging is required for combustion stability during the LTO cycle.

Combustion instabilities, which manifest as noise, may be experienced by any combustor design, and fuel staging may impact to onset and behavior of these instabilities. Figure 3 shows the combustion dynamic response of the Woodward LDI combustor at the 7 percent engine power condition. During this power condition only the three pilot fuel air mixers were used for fuel injection. The dynamic response (in terms of pressure oscillation magnitude) is less than 0.04 psi across the frequency spectrum, which is low compared to the pressure drop across the combustor. When the dynamic pressure oscillation is higher than the pressure drop across the combustor, the flame may flashback or push out of the combustor and cause damage. The pressure drop across the combustor is about 4 percent of the combustor inlet pressure. At the 7 percent power condition, combustor pressure drop is 3 to 4 psi.

The 30 percent engine power condition used the three pilot fuel-air mixers and ten other main fuel-air mixers for fuel injection. For this condition the combustion dynamics were relatively higher relative to the low power condition (as one might expect), yet the observed pressure amplitudes were considered acceptable. Depending on the fuel distribution among these fuel air mixers, various small amplitude broadband noises occurred in the range of 200 to 600 Hz, as shown in Figure 4(a). The use of main fuel-air mixers in the two outer 7-point injector cups might produce a noise band around 300 Hz. As shown in Figure 4(b), a 300 Hz noise band was not observed when fuel was not injected through the main fuel air mixers in the two outer 7-point cups.

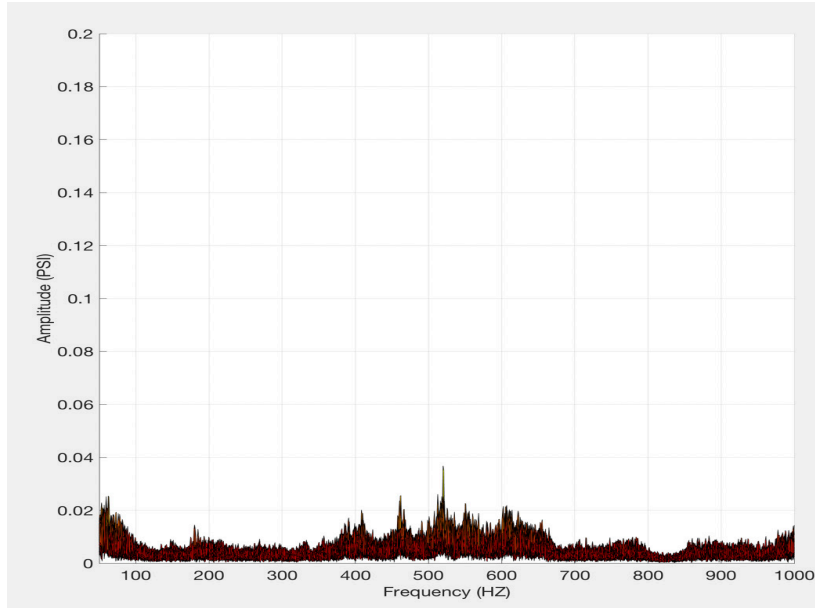
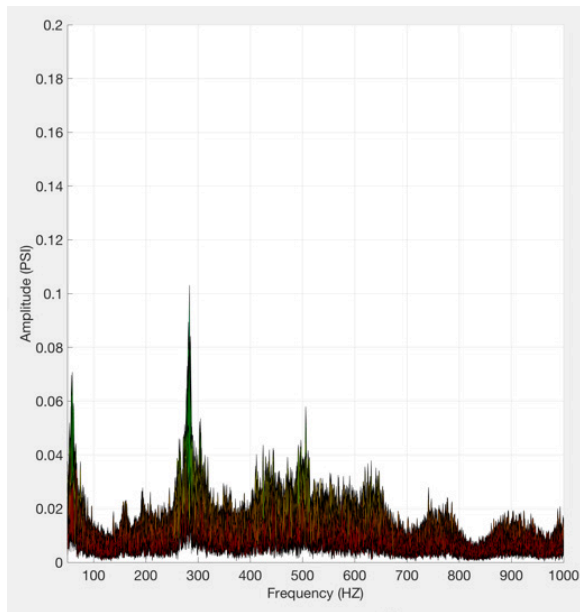
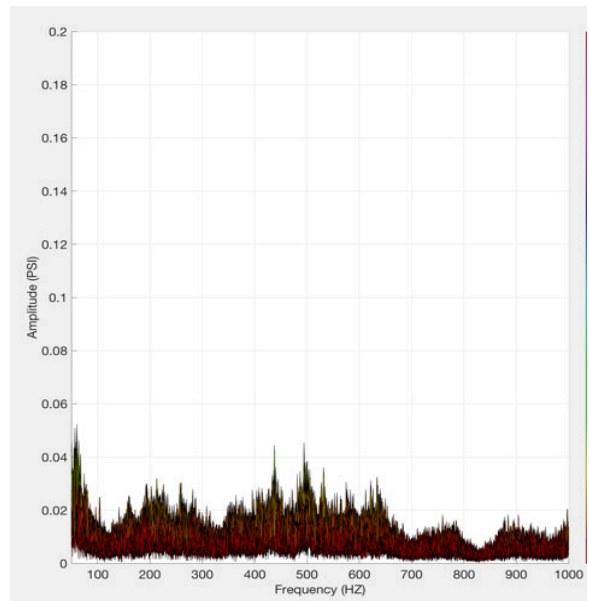


Figure 3.—Low power configuration combustion dynamic frequency spectrum ($T_3 = 588$ K, $P_3 = 735$ kPa, and $\phi = 0.13$).



(a) With using outer cups 6 fuel-air mixers $\phi = 0.26$



(b) Without using outer cups 6 fuel-air mixers $\phi = 0.21$

Figure 4.—Frequency spectrum for 30 percent engine power configuration with or without using outer cups fuel-air mixers ($T_3 = 660$ K, $P_3 = 1380$ kPa).

The high power configuration used all 19 fuel-air mixers for fuel injection. At an off-design condition with low inlet air temperature and pressure but high fuel-air ratio ($T_3 = 600 \text{ K}$, $P_3 = 800 \text{ kPa}$), high amplitude combustion instability was observed around 220 Hz. The fundamental and higher-order harmonic frequencies (up to 4th) were observed at 220, 440, 660, and 880 Hz with amplitudes as high as 1.5 psi, as shown in Figure 5(a). By increasing the fuel-air equivalence ratio from 0.46 to 0.50, the noise amplitude was significantly decreased to 0.1 psi along with a reduction in the number of harmonic frequencies present (Figure 5(b)). At high inlet air temperature ($>800 \text{ K}$), the 220 Hz noise band was reduced, and three other noise bands were observed at approximately 300, 500, and 650 Hz, with amplitudes lower than 0.16 psi (Figure 6).

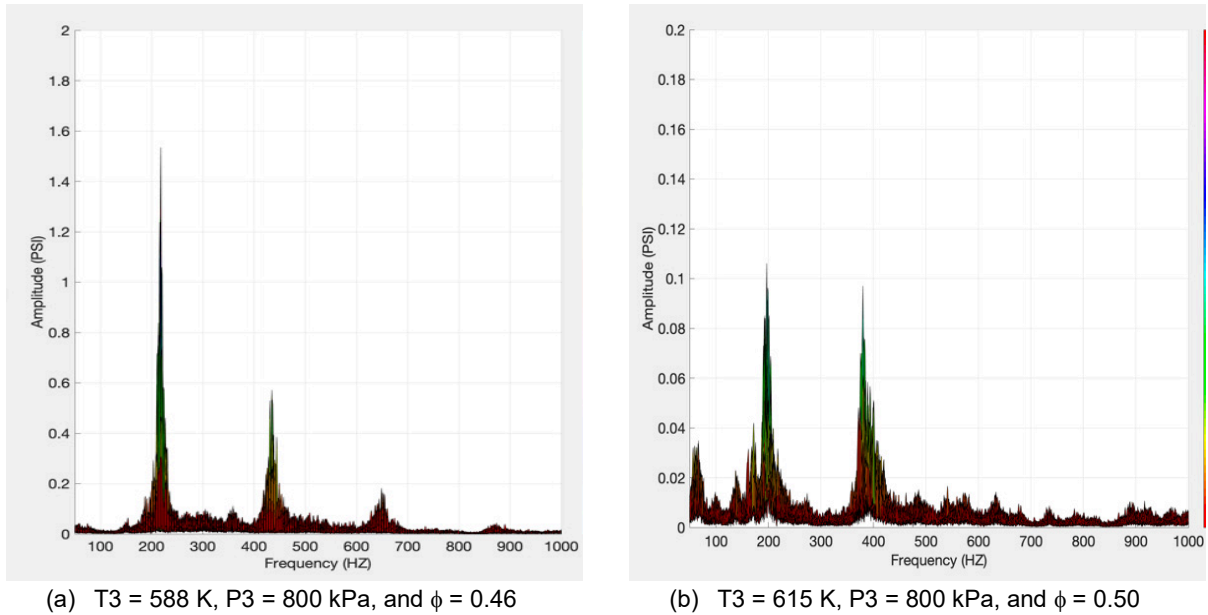


Figure 5.—High amplitude combustion noise at around 200 Hz.

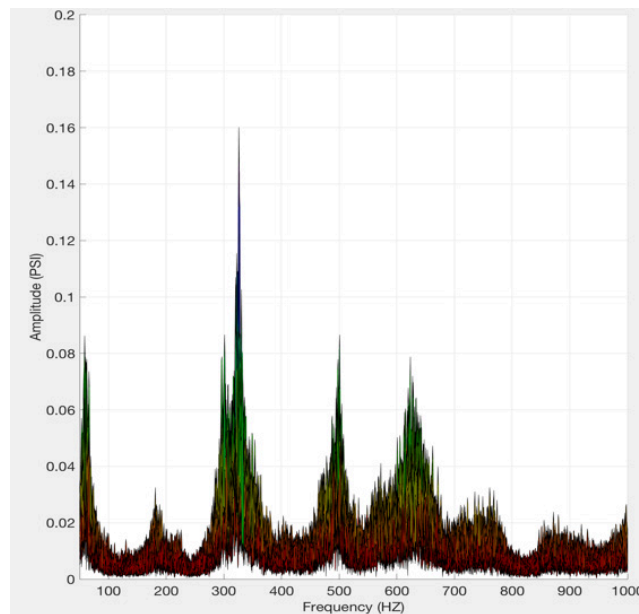


Figure 6.—Frequency spectrum of high power configuration at stable operating conditions ($T_3 = 860 \text{ K}$, $P_3 = 1110 \text{ kPa}$, and $\phi = 0.44$).

Fuel Modulation

The purpose of fuel modulation testing, or in this case pilot-fuel modulation, is to influence the combustor's heat release near or at the frequency of a detected instability so as to produce a dynamic pressure signal with sufficient authority to attempt closed-loop control that suppresses combustor instabilities. For the data reported in this study, fuel modulation occurred only through the pilot fuel injector of the 5-point center-cup fuel-air mixer. The input energy to the fuel modulator was about 8 V (p-p), which caused up to about 40 psi in dynamic pressure amplitude at the output of the WASK modulator or at the PCB sensor. Significant reduction of this pressure wave was expected at the fuel injector due to long line lengths and flow area changes along the way. Figure 7 shows the combustor pressure time-response spectrum due to this fuel modulation at a low engine-power configuration (with only the pilot of each cup fueled). The fuel modulator was subjected to a logarithmic frequency sweep from 50 to 1000 Hz over a period of 1 min. As was previously stated, the combustion dynamic response was weak for the low-power configuration. Modulated signals were clearly detected in the combustor. The detected signals were small, only as high as 0.13 percent (0.05 psi). As frequency increased, the detected modulated signals decreased. As a result, the majority of the modulated signal was, in all likelihood, damped in the fuel line before reaching the combustor.

Figure 8 shows the combustor dynamic response coupled with the modulated signals at around 150 Hz. The combustor dynamic response at around 150 Hz was less than 0.2 psi, and the fuel-modulated signal that was detected in the combustor was less than 0.06 psi. When the combustor dynamic response coupled with the modulated signals at around 150 Hz, the coupling dynamic amplitude increased to as high as 0.55 psi. This is significant as this test indicates response and entrainment of the instability energy in the neighborhood of 150 Hz, which shows some modulation authority that could be suitable for active combustion control.

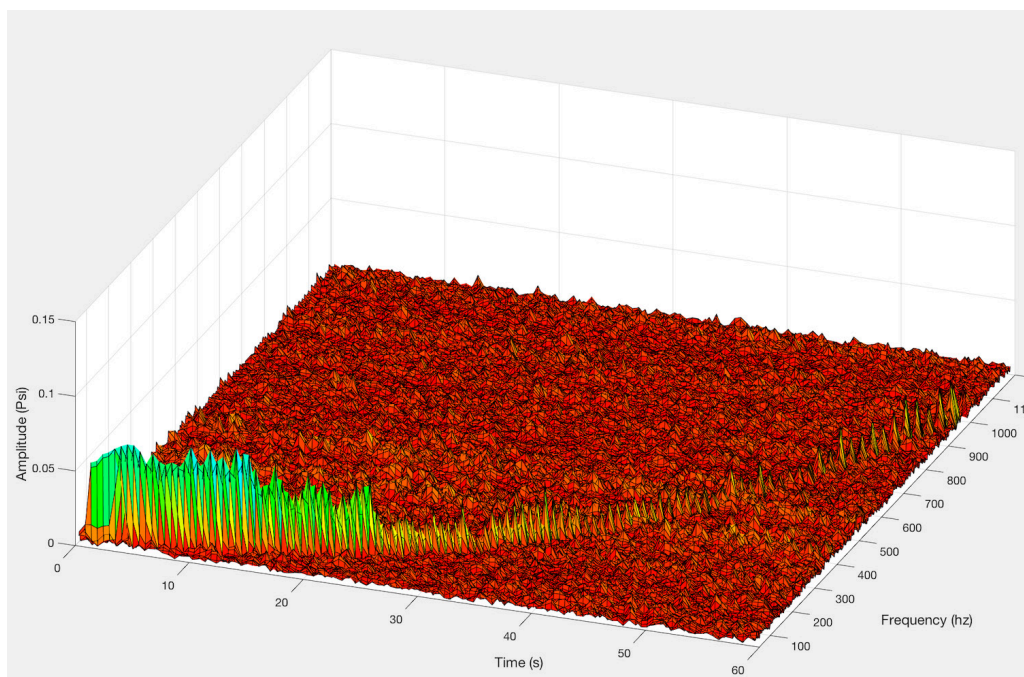
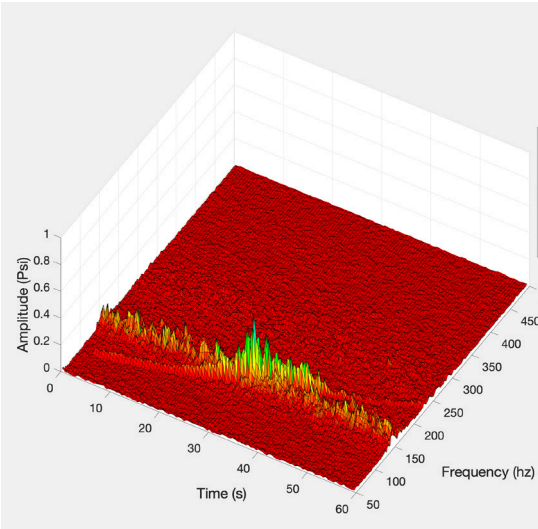
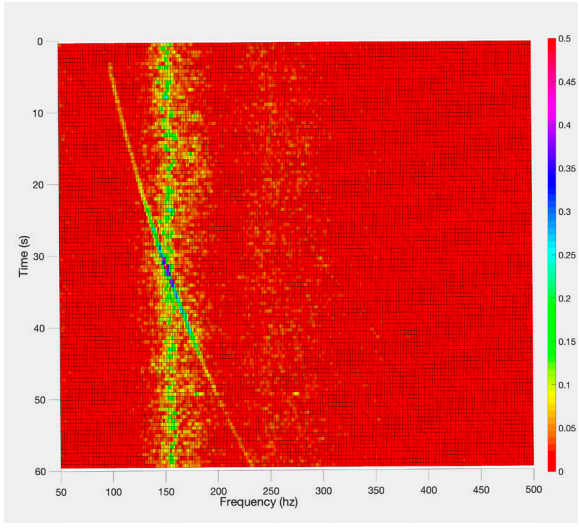


Figure 7.—Fuel modulator response to a frequency sweep from 50 to 1000 Hz over a period of 1 min in the combustor ($T_3 = 555$ K, $P_3 = 700$ kPa, and $\phi = 0.17$).

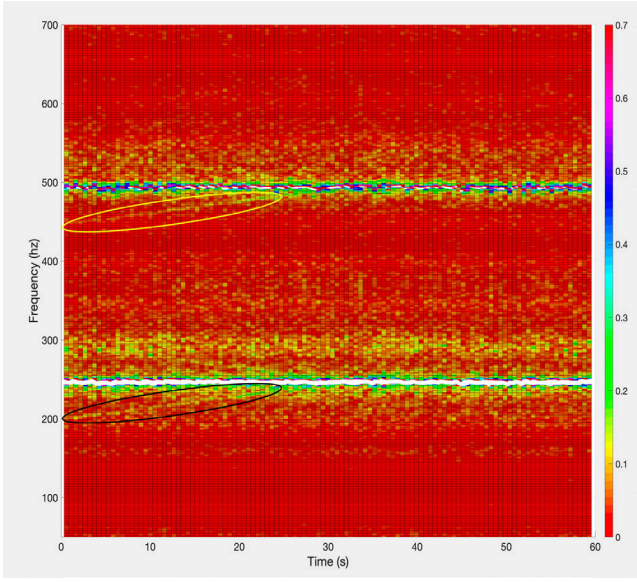


(a)

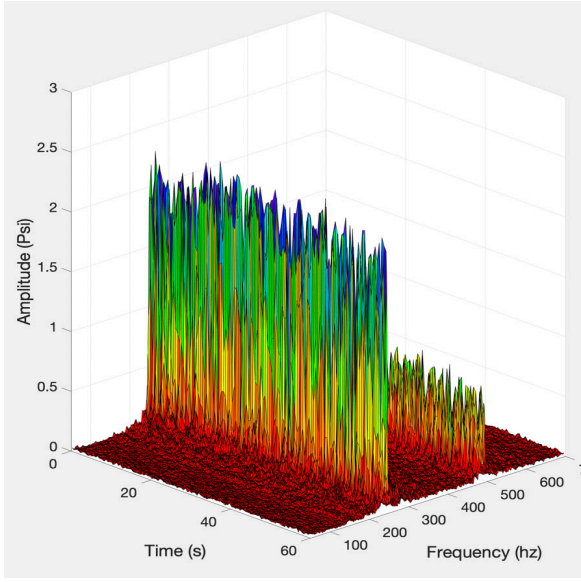


(b)

Figure 8.—Fuel modulator response to a frequency sweep from 100 to 230 Hz over a period of 1 min in the combustor ($T_3 = 635$ K, $P_3 = 790$ kPa, and $\phi = 0.40$).



(a)



(b)

Figure 9.—Fuel modulator response to a frequency sweep from 200 to 300 Hz over a period of 1 min in the combustor ($T_3 = 635$ K, $P_3 = 850$ kPa, and $\phi = 0.51$).

At the high combustion instability condition, the modulated signal was still detectable. As shown in Figure 9, high combustion instability was observed near 250 Hz and its second harmonic frequency was around 500 Hz. The fuel modulator was subjected to a frequency sweep of 200 to 300 Hz over a period of 1 min. As circled in black in Figure 9(a), the result of the fuel modulation was observed in the combustor with an amplitude lower than 0.1 psi between 200 to 250 Hz. Additionally, a low-amplitude noise line was also seen (circled in yellow) between 450 to 500 Hz. This could be a second harmonic of the beat frequency for the 250 Hz instability, which indicates that the modulated signal was interacting with the combustion noise. Nevertheless, the modulated signal did not seem to have much effect on the 250 Hz instability as its amplitude had little or no change, as shown in Figure 9(b).

Conclusions

Combustion dynamic characteristics and fuel modulation responses of a three-cup LDI combustor are reported in this study. Combustion broadband noises were actively observed between 200 to 650 Hz and were dependent on the fuel distribution among the 19 fuel-air mixers and the inlet air conditions. The 300 Hz noise band could be caused by the use of the main fuel air mixers in the two 7-point cups of the combustor. High-amplitude combustion instabilities occurred in the high power configuration at off-design conditions using low inlet air temperature and pressure. The fuel-modulation signals were detected in the combustor, but compared to the input energy, the amount of modulated energy detected in the combustor was small. Interaction between the modulated signal and the combustion noise varied from case to case.

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