Elimination Of Intermediate-Frequency Combustion Instability In The Fastrac Engine Thrust Chamber[a]

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ABSTRACT:

A series of tests were conducted to measure the combustion performance of the Fastrac engine thrust chamber. The thrust chamber exhibited benign, yet marginally unstable combustion. The marginally unstable combustion was characterized by chamber pressure oscillations with large amplitudes and a frequency that was too low to be identified as acoustic or high-frequency combustion instability and too high to be identified as chug or low-frequency combustion instability. The source of the buzz or intermediate-frequency combustion instability was traced to the fuel venturi whose violently noisy cavitation caused resonance in the feedline downstream. Combustion was stabilized by increasing the throat diameter of the fuel venturi such that the cavitation would occur more quietly.

INTRODUCTION:

NASA's Marshall Space Flight Center (MSFC) has been tasked with developing a 60,000 pound (267,670 N) thrust, pump-fed, LOX/RP-1 engine under the Advanced Space Transportation Program(ASTP). This government-led design has been designated the *Fastrac* engine, illustrated in figure-1.

The X-34[b] vehicle, illustrated in figure-2, was to use the Fastrac engine as the main propulsion system. The X-34 was to be a suborbital vehicle developed by the Orbital Sciences Corporation. The X-34 vehicle was to be launched from an L-1011 airliner. After launch, the X-34 vehicle was to be able to climb to altitudes up to 250,000 feet (76,200 m) and reach speeds up to Mach 8, over a mission range of 500 miles (805 Km). The overall length, wingspan, and gross takeoff weight of the X-34 vehicle were to be 58.3 feet (17.8 m), 27.7 feet (8.4 m) and 45,000 pounds (200,752 N), respectively.

This report summarizes the effort of achieving a Fastrac thrust chamber assembly (TCA) mainstage test that was free of intermediate-frequency combustion instabilities. Also summarized is the Fastrac TCA design, the layout of the propellant feed system at MSFC's test stand 116, and the combustion instabilities exhibited by the Fastrac TCA and propellant feed system during testing as was determined from high-frequency fluctuating pressure measurements. Finally, this report summarizes the characterization of the combustion instabilities from the pressure measurements and the steps taken to eliminate the instabilities.

OBJECTIVE:

[a]Approved for public release, distribution is unlimited.
[b]The X-34 project was cancelled by NASA in March, 2001.

One of the objectives of Fastrac TCA testing was to achieve a stable mainstage test that met a criteria for combustion stability as established by JANNAF standards[1]. This criteria was that the amplitude of the chamber pressure oscillations was to be 10% or less of the mean chamber pressure.

Typically, in the context of high-frequency combustion instability, two stardards were to be met. First, the damp time of bomb-induced chamber pressure oscillations was to be 29 milliseconds or less. This damp time was determined from a combustion chamber acoustic frequency for the first-tangential (1T) mode of 1922 Hz. Second, the amplitude of the chamber pressure oscillations was to be 10% or less of the mean chamber pressure after the bomb-induced chamber pressure oscillations damped out. Both of these criteria were met during bomb testing whereby the high-frequency combustion instabilities were eliminated by effective acoustic cavity design[2].

Upon the conclusion of bomb testing, and in the midst of test-19, the mainstage test successfully performed to obtain acoustic cavity temperatures, attention was drawn to high-amplitude chamber oscillations. These chamber pressure oscillations were sustained during the mainstage test, had a frequency of 522 Hz, and a visually average amplitude of about 10% peak-to-peak (2% RMS).

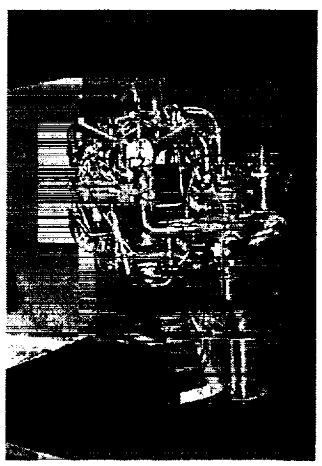

Figure-1: Fastrac Engine.

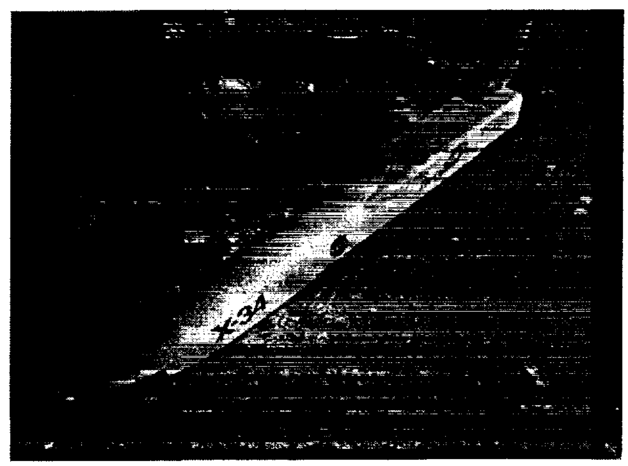

Figure-2: X-34 Vehicle.

TEST ARTICLE DESCRIPTION:

As illustrated in figures 3 and 4, the components of the Fastrac TCA test article are the thrust chamber, nozzle, fuel manifold, LOX dome, injector faceplate, and acoustic cavities. For the TCA operating conditions, the combined LOX/RP-1 flow rate is about 197 lbm/sec (89.56 Kg/sec) at a mixture ratio of 2.34. The chamber pressure is 650 psi (4.495 MPa). Details on the design of the acoustic cavities and the injector faceplate are discussed in related literature[2].

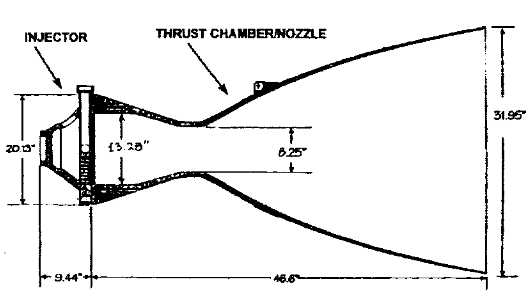

Figure-3: Fastrac Thrust Chamber Assembly.

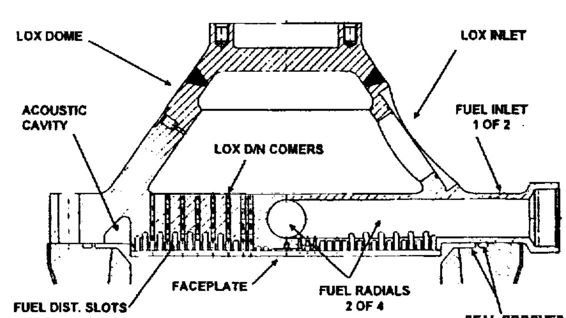

Figure-4: Fastrac Injector.

TEST FACILITY DESCRIPTION:

Testing of the Fastrac engine TCA was performed at MSFC's test stand 116. A typical test of the Fastrac engine TCA at test stand 116 is illustrated in figure-5.

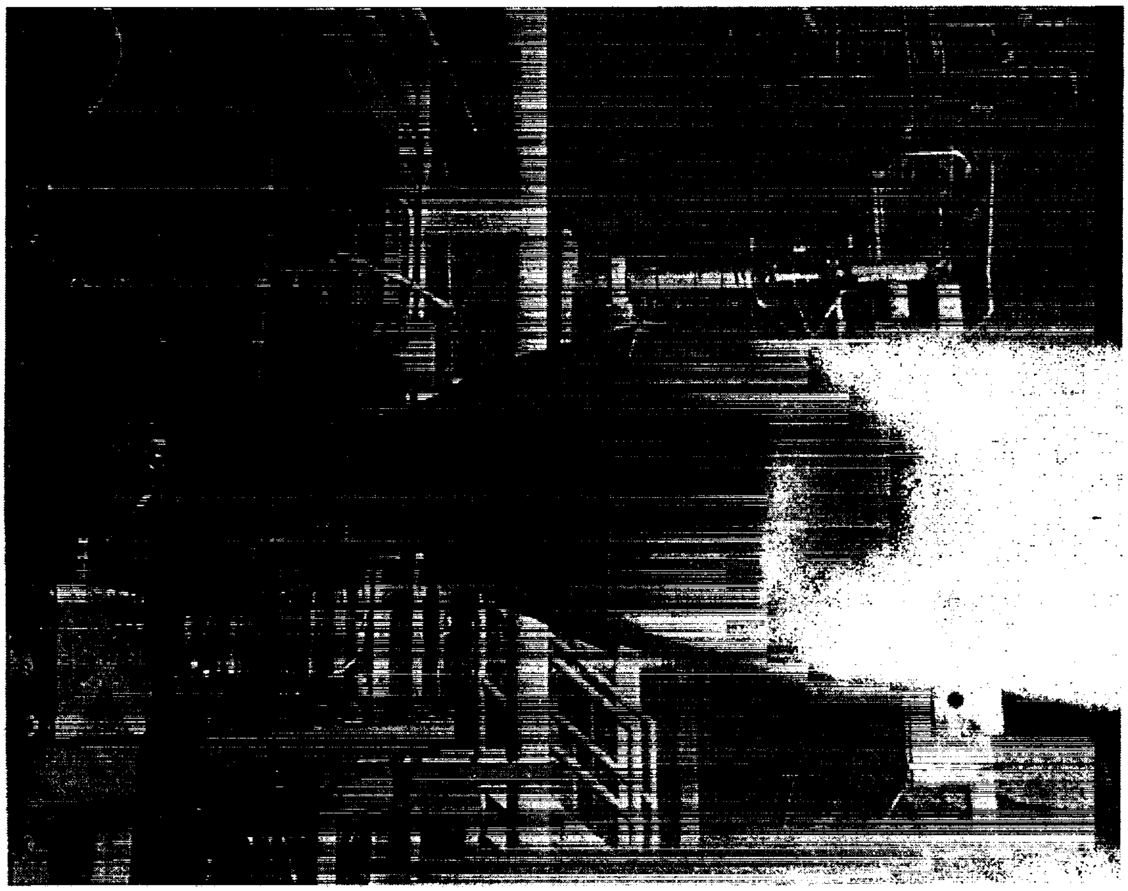

Figure-5: A typical Fastrac TCA hot-fire test at MSFC test stand 116.

The RP-1 feed system is presented in figure-6. The RP-1 feed system consisted of the RP-1 tank, the RP-1 cavitating venturi, the RP-1 valve, the RP-1 injection manifold on the TCA, and 3-inch (7.62 cm) diameter RP-1 feed lines that connect all of these components together. The RP-1 cavitating venturi had a throat diameter of 0.6121 inches (1.555 cm) and a discharge coefficient of 0.96. The RP-1 valve was about 1.792 feet (0.546 m) long. Between the RP-1 cavitating venturi and the RP-1 valve was about 11.25 feet (3.429 m) of RP-1 feed line. Between the RP-1 valve and the RP-1 injection manifold on the TCA was about 8.959 feet (2.731 m) of RP-1 feed line. Not shown in figure-6 were the "steerhorns" that started at about 6.376 feet (1.943 m) downstream of the RP-1 valve. The steerhorns was a split or bifurcation in the RP-1 feed line. The bifurcated feed lines extended about 120° apart to send RP-1 to the two inlets on opposite sides of the RP-1 injection manifold.

The LOX feed system is presented in figure-7. The LOX feed system consisted of the LOX tank, the LOX cavitating venturi, the LOX valve, the LOX injection manifold on the TCA, and 3-inch (7.62 cm) diameter LOX feed lines that connect all of these components together. The LOX cavitating venturi had a throat diameter of 0.9 inches (2.286 cm) and a discharge coefficient of 0.96.

The LOX valve was about 1.67 feet (0.509 m) long. Between the LOX cavitating venturi and the LOX valve was about 8.83 feet (2.691 m) of LOX feed line. Between the LOX valve and the LOX injection manifold on the TCA was about 3 feet (0.914 m) of LOX feed line.

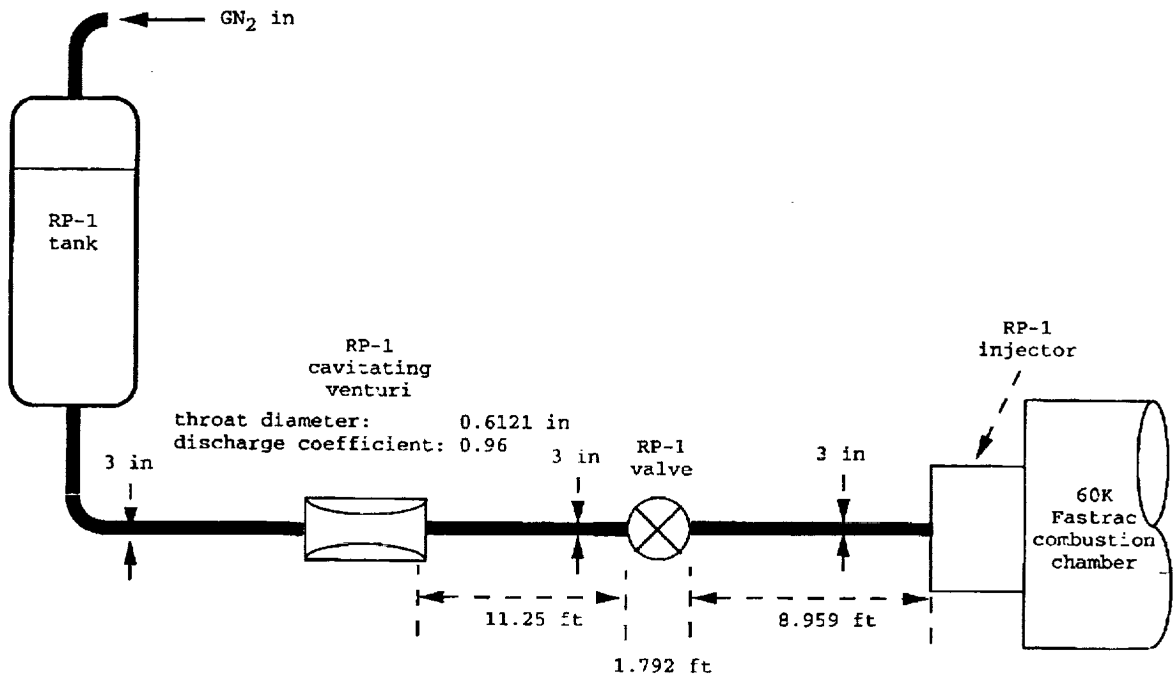

Figure-6: Test stand 116 RP-1 feed system.

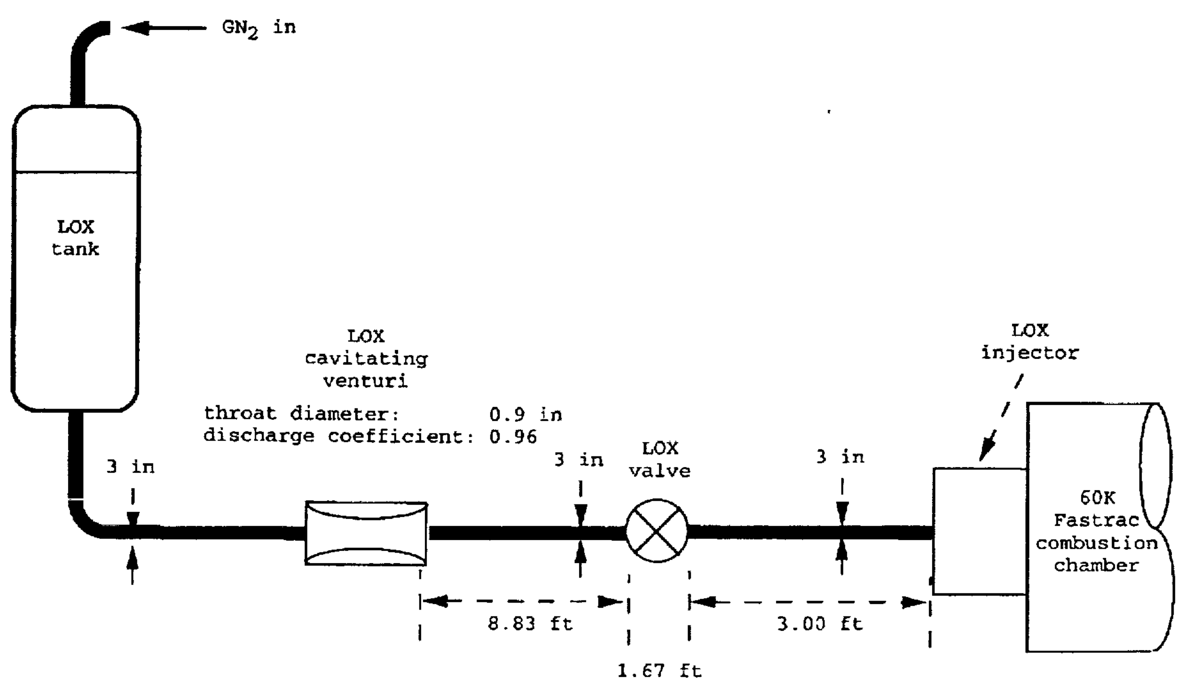

Figure-7 Test stand 116 LOX feed system.

TEST PROCEDURE:

A typical mainstage test was initiated by slightly opening the LOX valve to allow a small amount of LOX flow to chill the LOX feedline downstream and LOX injector prior to ignition. During pre-chill, this small amount of LOX flow vaporized upon injection into the chamber and was discharged out through the nozzle. Ignition was performed by injecting TEA/TEB into the chamber while maintaining this small amount of LOX flow. After ignition, fuel-rich "level-1" combustion was initiated by completely opening the RP-1 valve to allow the full amount of RP-1 flow to be injected into the chamber. Simultaneously, the TEA/TEB flow was terminated and the small amount of LOX flow was maintained. After level-1 combustion was briefly established, oxidizer-rich "level-2" combustion was initiated by completely opening the LOX valve to allow the full amount of LOX flow to be injected into the chamber. Level-2 combustion constituted mainstage operation of the Fastrac TCA.

Chamber pressures for level-1 and level-2 combustion were 450 psi (3.06 MPa) and 650 psi (4.42 MPa), respectively.

Those feed systems inactive during pre-chill, ignition, level-1, and level-2 operations were purge with nitrogen gas to prevent backflow into the injector.

SUMMARY OF MAINSTAGE TESTS:

The results of the mainstage tests, where the large amplitude, 500 Hz chamber pressure oscillations were exhibited and eliminated are presented in table-1. The amplitudes presented were determined by visual averaging and are not RMS values, which will be lower. Out of the 15 successful mainstage tests, 10 of these tests had amplitudes of at least 8%, and 6 of these tests had amplitudes of at least 10%.

Table-1: Fastrac TCA Mainstage Test Results

Test #	Type	Duration (sec)	Frequency (Hz)	Pc (psi/MPa)	δPc/Pc (%)
1	ignition	n/a	n/a	n/a	n/a
2	ignition	n/a	n/a	n/a	n/a
3	level-1	5	410	450/3.06	11.8
4	level-2	7	513	644/4.38	5.1
5	level-2	25	508	625/4.25	11.1
6	not successful	n/a	n/a	n/a	n/a
7	level-2	25	522	643/4.37	8.1
8	level-2	53	522	650/4.42	10.2
16	level-2	8	527	641/4.36	9.2
17	level-2	27	527	631/4.29	10.5
19	level-2	130	522	640/4.35	11.9
20	level-2	17	508	645/4.39	8.5
21	level-2	17	503	641/4.36	8.9
22	level-2	17	493	635/4.32	12.9
23	level-2	150	498*	656/4.46	3.0
24	level-2	150	515*	664/4.52	3.9
25	level-2	6	142	649/4.41	6.8
26	level-2	150	*	664/4.52	2.9

Tests 1 and 2 were ignition tests. Test-3 was a level-1 test that exhibited large amplitude chamber pressure oscillations at 410 Hz. Test-6 was unsuccessful. Tests 9-15, and 18 were not included in table-1 since these were bomb-tests[2]. Tests 16, 17, and 19 were level-2 tests conducted to obtain acoustic cavity temperatures. Tests 23 and 24 were level-2 tests that not only had the 500 Hz oscillation, but had oscillations at 60 Hz and its harmonics indicated by the asterisk in the frequency column.Test-25 was the first level-2 test where the 500 Hz oscillation was eliminated, leaving behind what could be interpreted as low-amplitude chug. Test-26 was the second level-2 test where the 500 Hz oscillation was eliminated leaving only low-amplitude oscillations at 60 Hz and its harmonics indicated by the asterisk in the frequency column. Tests 27-31 also were not included in table-1 since these were additional bomb tests.

CHARACTERIZATION OF CHAMBER PRESSURE OSCILLATIONS:

Presented in table-2 are the natural frequencies of the combustion chamber acoustic modes. These frequencies were based on a chamber diameter of 13.28 inches (33.73 cm) and a chamber speed of sound of 3628.8 ft/sec (1106.1 m/sec). The 500 Hz, large-amplitude, chamber pressure oscillation was too low in frequency to be characterized as an acoustic mode.

Table-2: Fastrac TCA Chamber Acoustic Frequencies

Tangential modes		Radial modes		Mixed modes	
1T	1922 Hz	1R	4000 Hz	1T-1R	5565 Hz
2T	3188 Hz	2R	7322 Hz	1T-2R	8900 Hz
3T	4385 Hz	3R	10,618 Hz	2T-1R	7000 Hz
4T	5550 Hz				

The 500 Hz oscillation was too high in frequency to be characterized as low-frequency combustion instability. This was because the injector pressure drops were 19% and 20% on the RP-1 and LOX sides, respectively. Using this pressure drops, a linear analysis[3] was conducted to determine the low-frequency combustion stability characteristics of the TCA combined with the RP-1 and LOX feed systems downstream of the venturies. The results of this analysis were that pressure oscillations would occur in the TCA and RP-1 and LOX feed systems at a frequency of 65 Hz and would be damped to 1% of their initial amplitude in about 7 milliseconds.

The large-amplitude, 500 Hz chamber pressure oscillation was too low in frequency to be identified as high-frequency combustion instability. Also, the 500 Hz oscillation was too high in frequency to be identified as low-frequency combustion instability. Therefore, this oscillation was identified as intermediate-frequency combustion instability or "buzz".

In the literature, buzz was identified in the above manner[4]. Also, buzz was described as pressure oscillations in the combustion chamber at a frequency that did not correspond to an acoustic mode of the combustion chamber, but to that of a propellant feedline. Finally, buzz was described as being benign provided that the amplitudes are sufficiently low so that damage was not sustained. There was no incident of the 500 Hz oscillation in chamber pressure causing any damage in the combustion chamber.

This explanation of buzz suggested that a feedline acoustic mode was being driven to resonance by a noise source in the feed system. To investigate this explanation, the chamber pressure and the feed system pressures from test-19 were reviewed. Test-19 was the first full-duration, mainstage test. The chamber pressure, the LOX injection pressure, and the LOX valve upstream pressure from the initial portion of test-19 is presented in figure-8. The chamber pressure, the RP-1 injection pressure, and the RP-1 valve upstream pressure from the initial portion of test-19 is presented in figure-9. There was no significant increase in the amplitude of pressure oscillations as one proceeded upstream from the combustion chamber into the LOX feed system. However, there was a significant increase in the amplitude of pressure oscillations as one proceeded upstream from the combustion chamber into the RP-1 feed system.

The conclusion that the 500 Hz large-amplitude, chamber pressure oscillation was due to a RP-1 feedline acoustic mode driven to resonance by noise from the RP-1 cavitating venturi was based on five pieces of evidence.

The first piece of evidence was the increase in pressure amplitude as one proceeded upstream into the RP-1 feed system, as illustrated in figure-9.

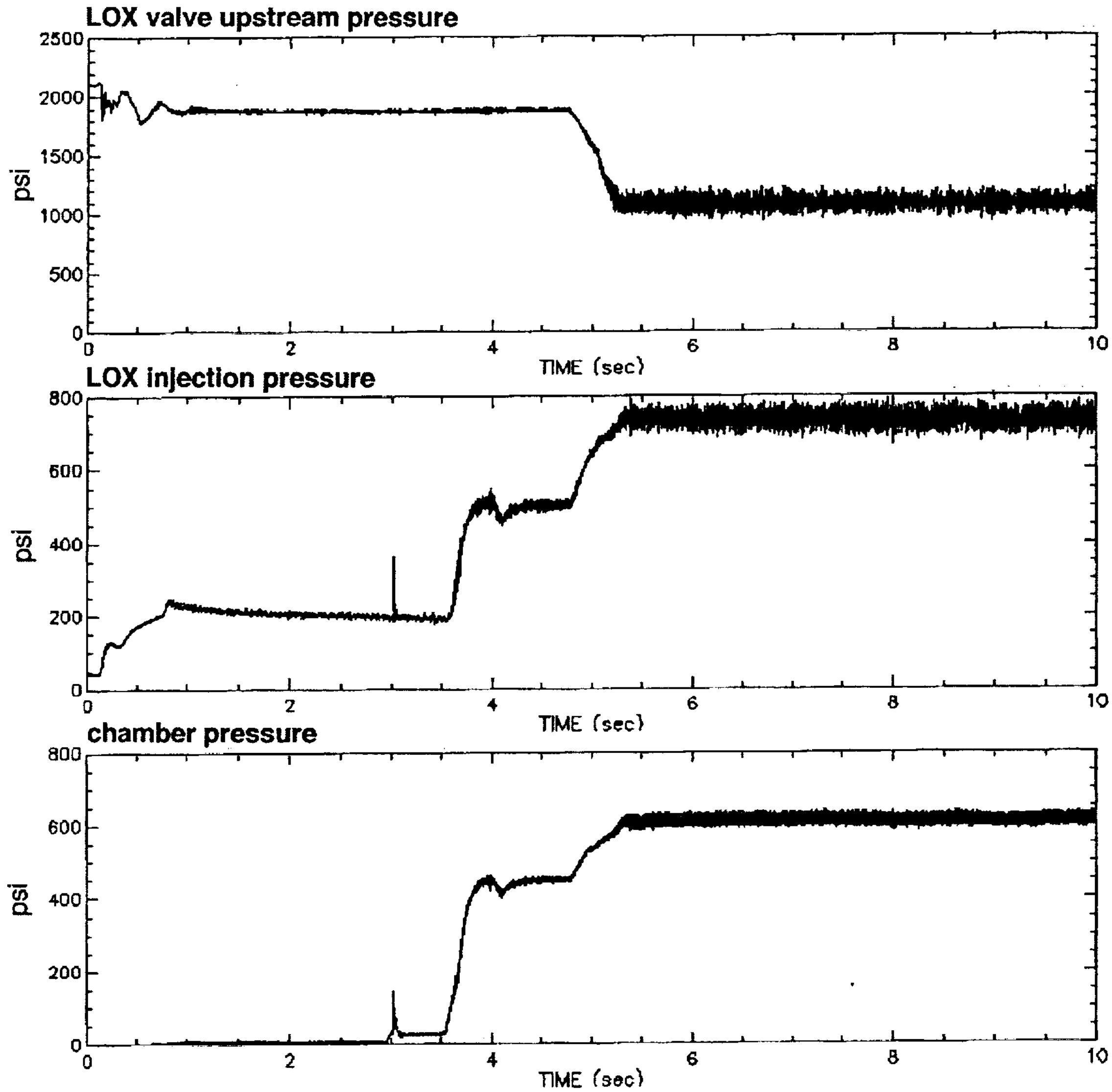

Figure-8: Pressures in the combustion chamber and the LOX feed system during test-19.

The second piece of evidence that suggested that the source of noise in the RP-1 feed system was the RP-1 cavitating venturi was the spectrum of pressure oscillations. In figures 10, 11, and 12, the test-19 pressures and their spectra are presented for the combustion chamber, the RP-1 injection manifold, and the RP-1 venturi discharge, respectively. These spectra of the pressure oscillations showed that the spectral intensity had peaks at 522 Hz of 4.1 psi/Hz (0.028 Mpa/Hz), 113.8 psi/Hz (0.774 Mpa/Hz), and 77.4 psi/Hz (0.527 Mpa/Hz) in the combustion chamber, RP-1 injection manifold, and upstream of the RP-1 venturi, respectively. Therefore, other than the 283 Hz oscillation downstream of the venturi, the 522 Hz pressure oscillations in the RP-1 feed system appear to be dominant.

In figures 13 and 14, the test-19 pressures and their spectra are presented for the LOX injection manifold, and the LOX venturi, respectively. Along with figure-10, these spectra of the pressure oscillations showed that the spectral intensity had peaks at 522 Hz of 4.1 psi/Hz (0.028 MPa/Hz), 3.0 psi/Hz (0.020 MPa/Hz), and 2.0 psi/Hz (0.014 MPa/Hz) in the combustion chamber, LOX injection manifold, and upstream of the LOX venturi, respectively. Therefore, the 522 Hz pressures oscillations in the LOX feed system appear to be nearly non-existent.

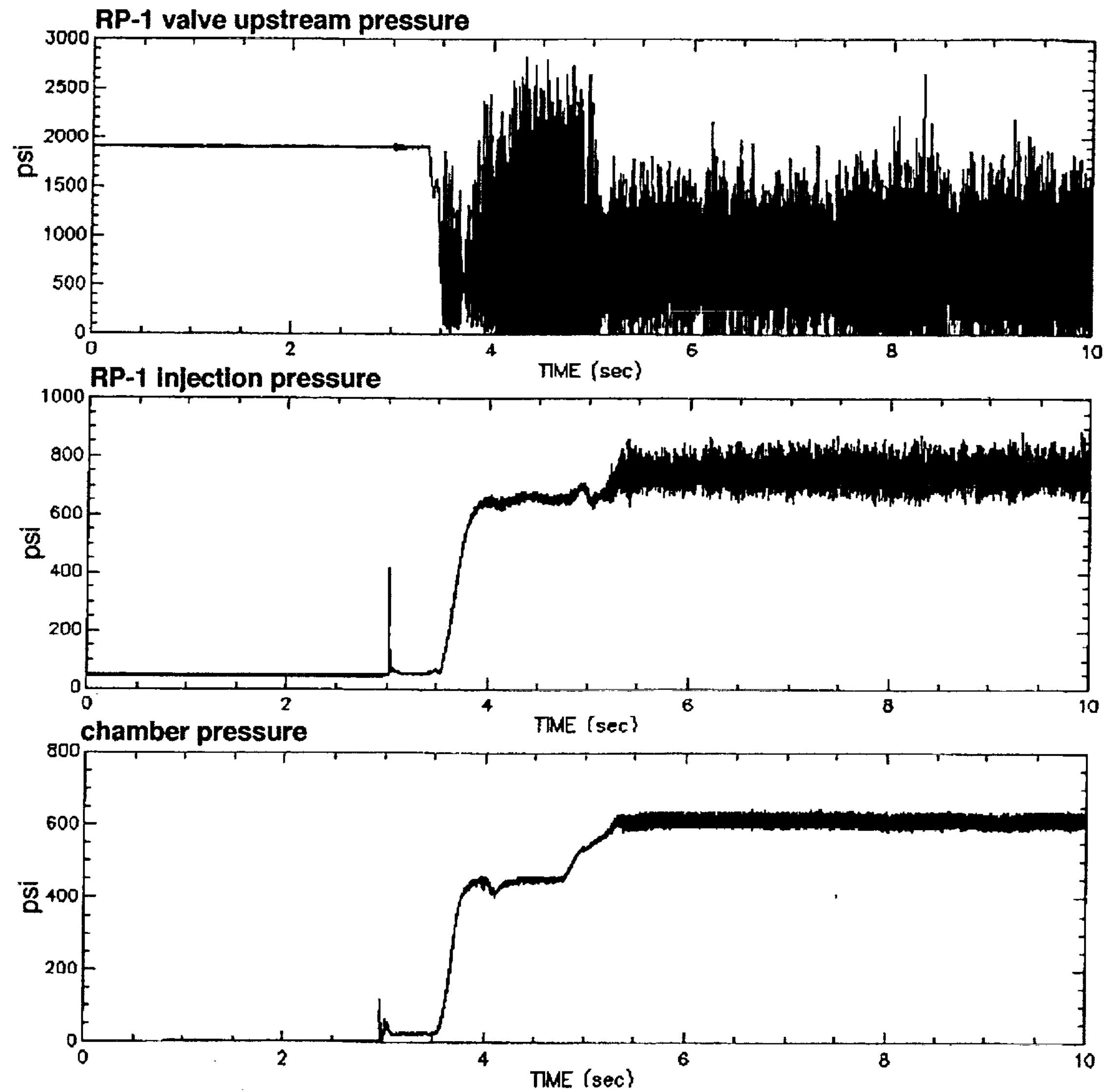

Figure-9: Pressures in the combustion chamber and the RP-1 feed system during test-19.

For the third piece of evidence, the acoustic frequency of the sixth longitudinal mode of the RP-1 feedline was determined to be about 526 Hz. This frequency was based on a venturi to injector feedline length of 22 feet (6.7 m), a RP-1 speed of sound of 4205 ft/sec (1282 m/sec), and "closed-open" boundary conditions. Additionally, the acoustic frequency of the fifth longitudinal mode was determined to be about 430 Hz. The frequency of pressure oscillations in the RP-1 feedline downstream of the venturi were observed to be 522 Hz and 410 Hz for level-2 and level-1 operation, respectively, according to Table-1.

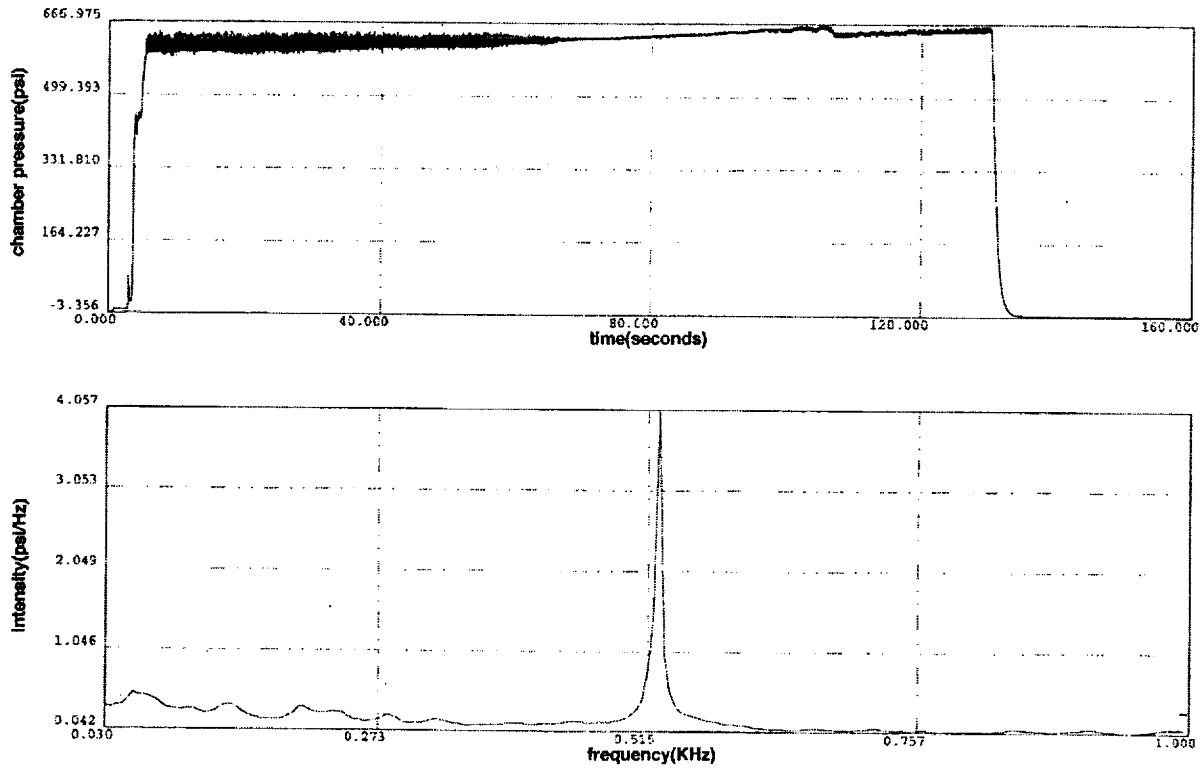

Figure-10: time trace and frequency spectrum of the combustion chamber pressure during test-19.

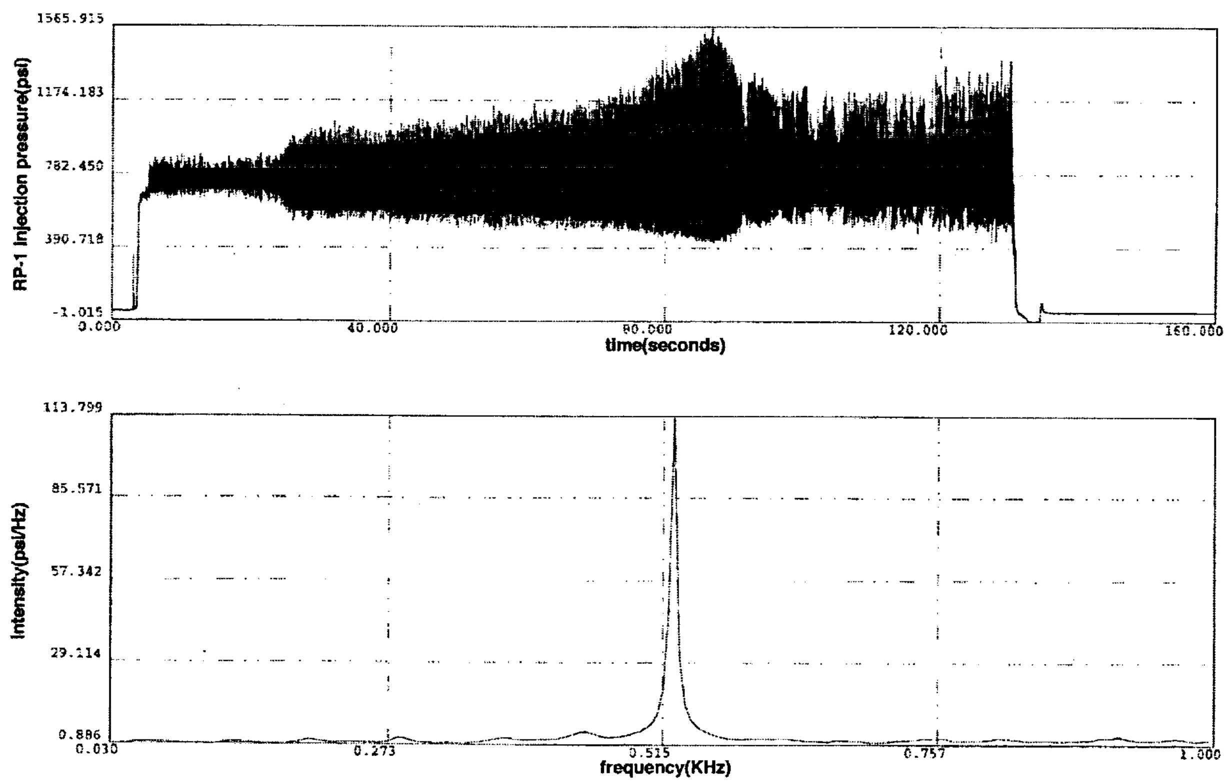

Figure-11: time trace and frequency spectrum of the RP-1 injection pressure during test-19.

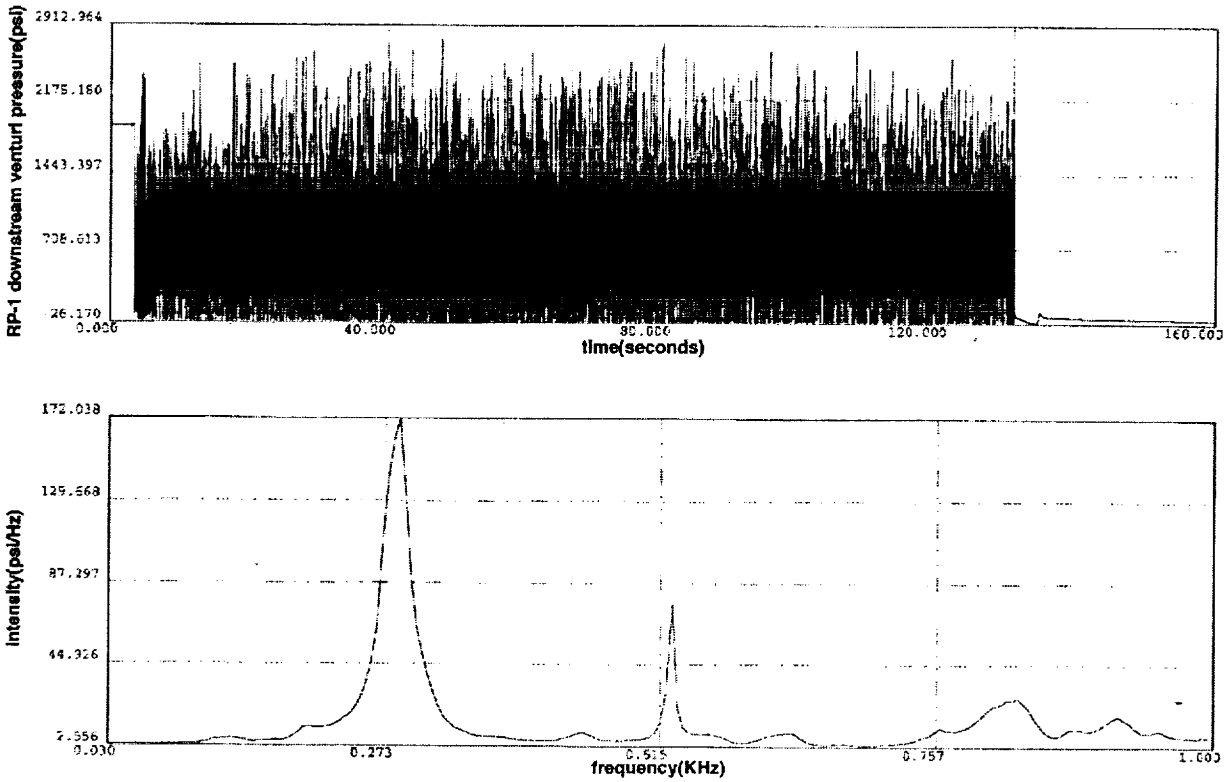

Figure-12: time trace and frequency spectrum of the RP-1 downstream venturi pressure during test-19.

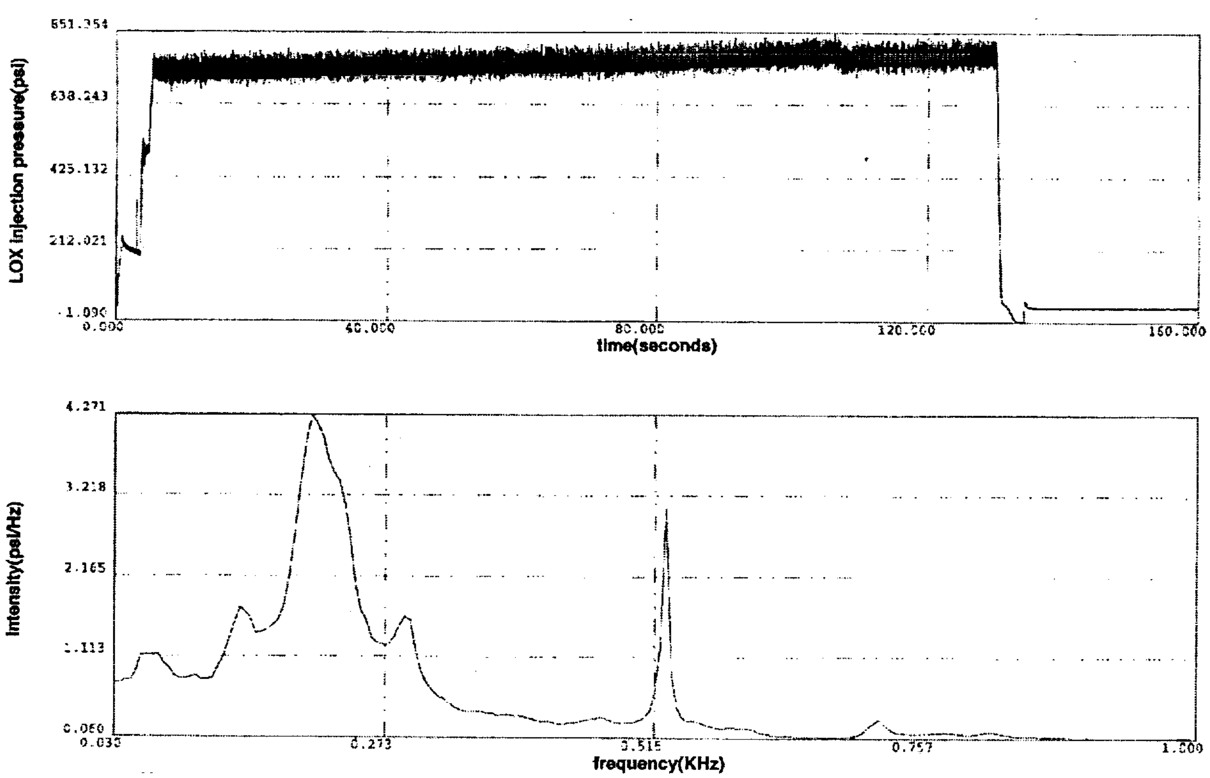

Figure-13: time trace and frequency spectrum of the LOX injection pressure during test-19.

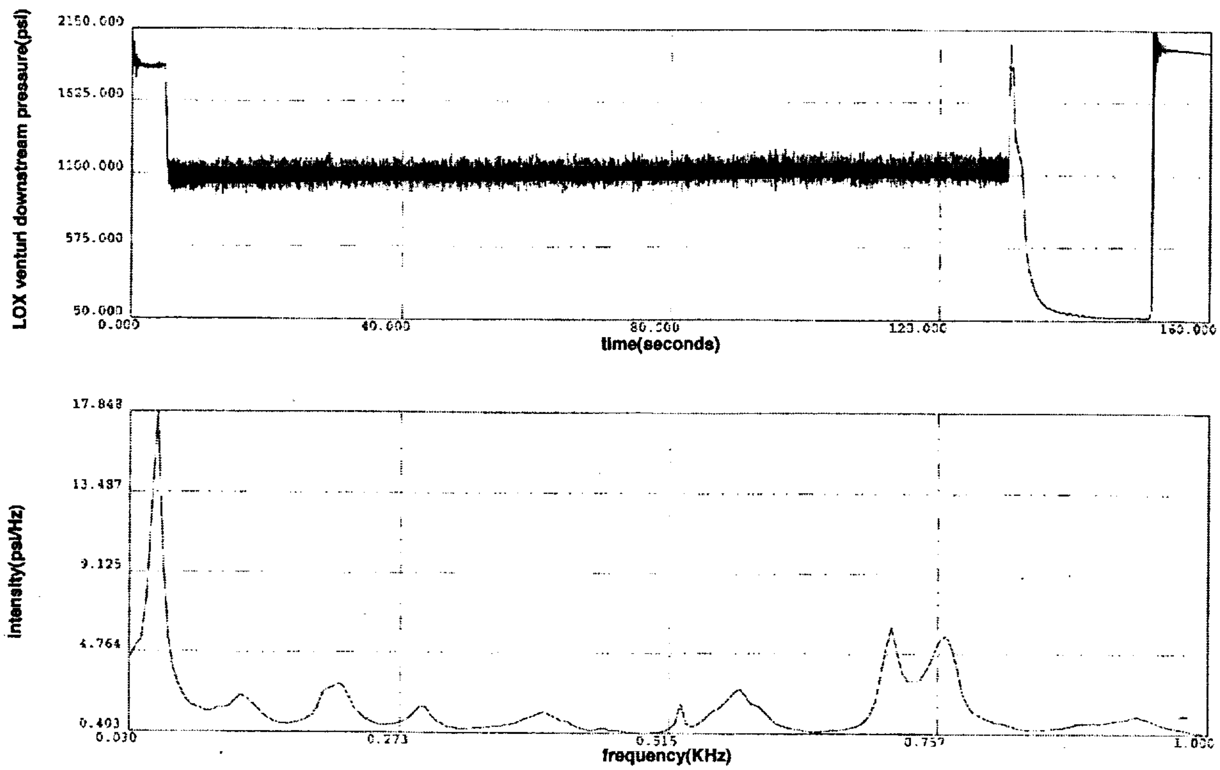

Figure-14: time trace and frequency spectrum of the LOX downstream venturi pressure during test-19.

The fourth piece of evidence was the potential for severe cavitation. This severity was measured by the ratio of the downstream venturi pressure to the vapor pressure of the propellant. For example, from figure-14, the pressure downstream of the LOX venturi was about 1100 psi (7.48 MPa). This vapor pressure for LOX at 200°R (111°K) is about 85 psi (0.58 MPa). This would give a LOX cavitation severity of about 13. However, from figure-12, the pressure downstream of the RP-1 venturi was about 950 psi (6.46 MPa). The vapor pressure for RP-1 at 530°R (294°K) is about 0.02 psi (0.14 KPa) This would give a RP-1 cavitation severity of about 47,500!

The fifth and final piece of evidence was the result of a numerical simulation of the unsteady fluid dynamics in the RP-1 feedline[5]. The amplitude of the noise that represented venturi cavitation was 10% peak-to-peak. The frequencies of the noise were 450 Hz, 510 Hz, and 530 Hz. The result was that as the frequency of the noise at the venturi end of the feedline upstream approached the feedline acoustic frequency of 530 Hz, the amplitude of pressure oscillations immediately upstream of the RP-1 valve diverged as a result of resonance.

Therefore, it was determined that the buzz in the combustion chamber was caused by the resonating RP-1 feedline downstream of the venturi. The RP-1 feedline was driven to resonance by the noisy cavitation in the venturi.

The original cavitating venturi for the fuel is presented in figure-15. The noise was measured by a pressure transducer about 135 inches (342.9 cm) downstream of the venturi, immediately upstream of the valve. The buzz was eliminated by slightly enlarging the venturi throat diameter from 0.612 inches (1.55 cm) to 0.708 inches (1.80 cm) to quiet the cavitation.

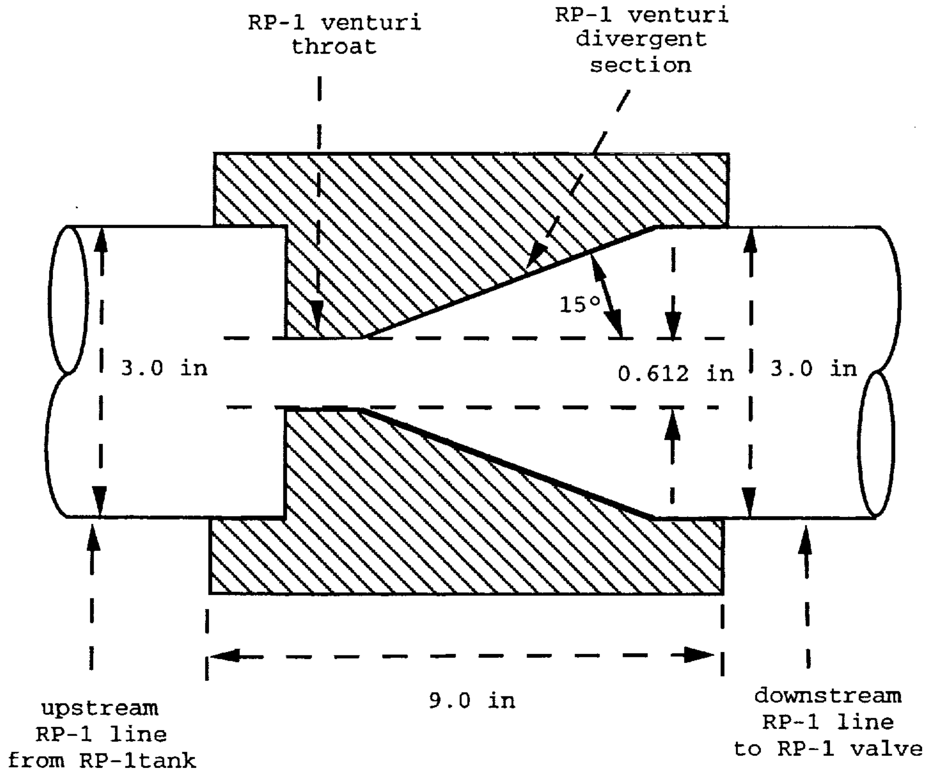

Figure-15: RP-1 cavitating venturi used in the Fastrac TCA hot-fire tests at test stand-116 at NASA/MSFC.

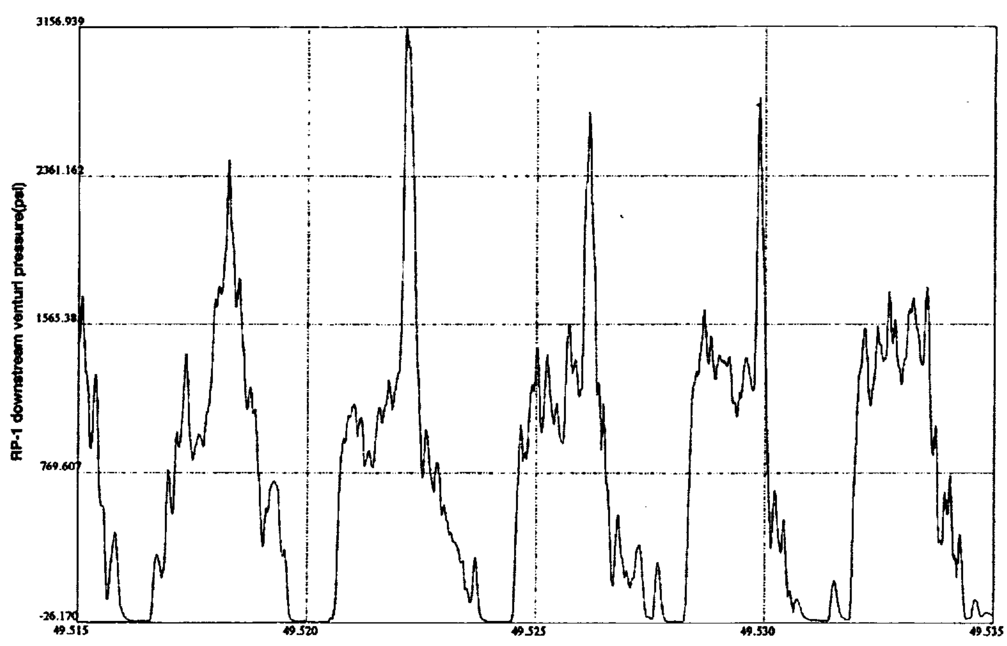

Figure-16: 20 milliseconds of RP-1 downstream venturi pressure test data from test-19 with the cavitating venturi before enlargement.

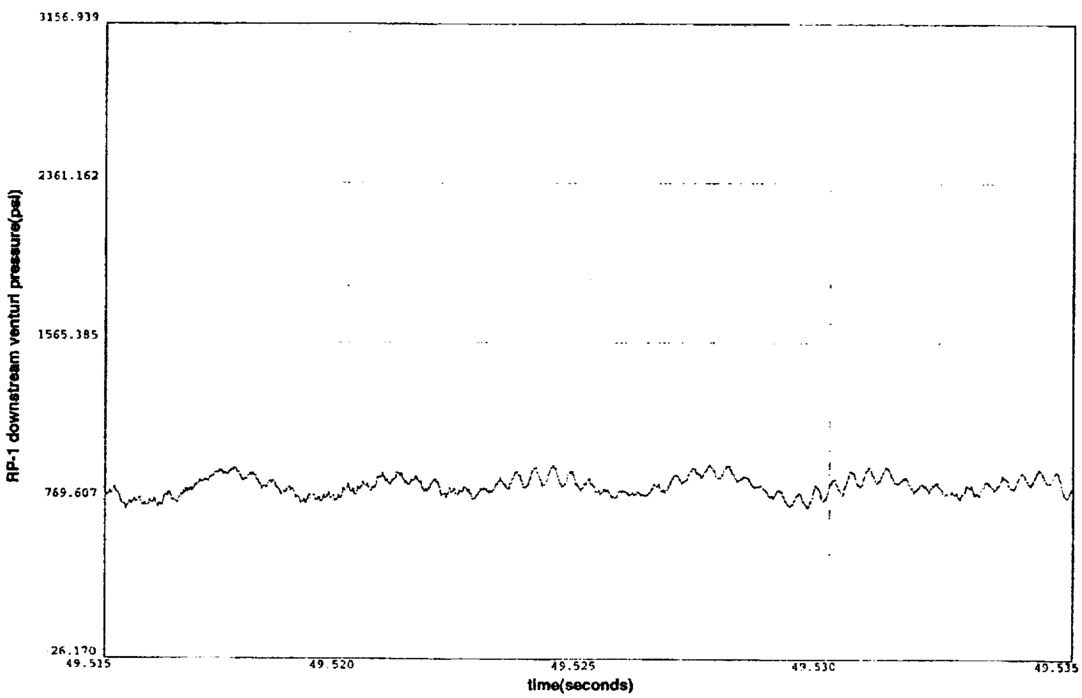

Figure-17: 20 milliseconds of RP-1 downstream venturi pressure test data from test-26 with cavitating venturi after enlargement.

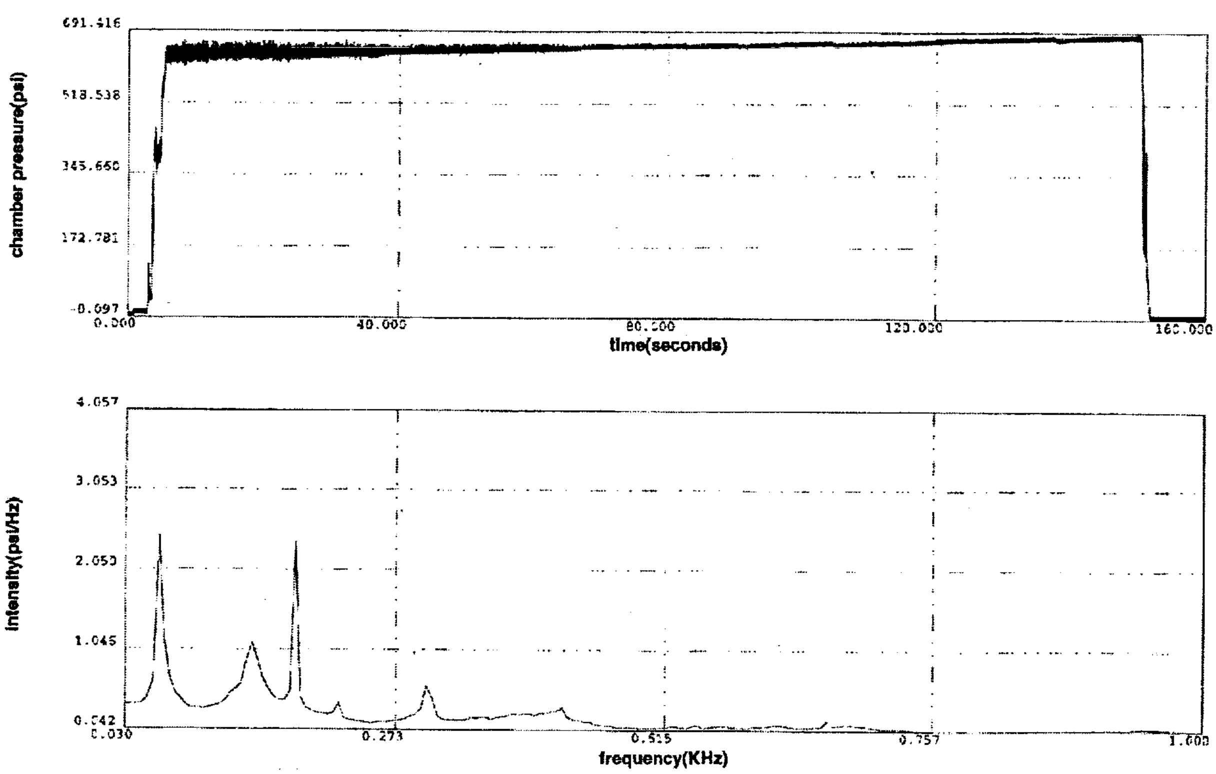

Figure-18: time trace and frequency spectrum of the combustion chamber pressure during test-26.

The effect of venturi throat enlargement on the pressure oscillations downstream of the RP-1 venturi is presented in figures-16 and 17. In these figures, 20 milliseconds of pressure oscillations are presented. In figure-16 is 20 milliseconds of test data from test-19. In figure-17 is 20 milliseconds of test data from test-26. As a result of the venturi throat enlargement, the amplitude of pressure oscillations downstream of the venturi in test-26 is about one-tenth of the amplitude from test-19. Additionally, from table-1, the amplitude of chamber pressure oscillations were reduced from 11.9% in test-19 to 2.9% in test-26. Finally, in figure-18, the spectrum of the test-26 chamber pressure indicated that oscillations at 522 Hz with an intensity of 4.1 psi/Hz (0.028 MPa/Hz) has been eliminated. In it's place were peaks at 60 Hz and 180 Hz with intensities or 2.5 psi/Hz (0.017 MPa/Hz) and 2.4 psi/Hz (0.016 MPa/Hz), respectively.

SUMMARY

A series of 15 successful mainstage tests were conducted to measure the combustion performance of the Fastrac engine thrust chamber. The thrust chamber exhibited benign, yet marginally unstable combustion in that no damage to the thrust chamber assembly was ever sustained. Out of the 15 successful mainstage tests, 10 of these tests had amplitudes of at least 8%, 6 of these tests had amplitudes of at least 10%, and 12 of these tests had chamber pressure oscillations with a frequency on the order of 500 Hz. This frequency was too low to be identified as acoustic or high-frequency combustion instability and too high to be identified as chug or low-frequency combustion instability.

The source of the buzz or intermediate-frequency combustion instability was traced to the RP-1 venturi whose violently noisy cavitation caused resonance in the feedline downstream. This cause was determined from five pieces of evidence. The first piece of evidence was that the pressure amplitudes increased as one proceeded upstream into the RP-1 feed system. The second piece of evidence was the peak in spectral intensity at about 500 Hz increased as one proceeded upstream into the RP-1 feed system. The third piece of evidence was that the frequency of the sixth longitudinal mode of the RP-1 feedline was determined to be about 526 Hz. The fourth piece of evidence was the RP-1 cavitation severity, the ratio of feedline pressure over the vapor pressure was about 47,500! The LOX cavitation severity was about 12. Finally, the fifth piece of evidence was the result of a numerical simulation of the unsteady fluid dynamics of the RP-1 feedline. The results indicated that the amplitude of pressure oscillations at the valve inlet became large and subsequently diverged as the frequency of noise at the venturi end of the feedline approached 530 Hz.

Combustion was stabilized by increasing the throat diameter of the fuel venturi such that the cavitation would occur more quietly. Therefore, the marginally unstable combustion was related to the facilities and not to the thrust chamber itself.

ACKNOWLEDGMENTS:

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REFERENCES:

1) "Guidelines For Combustion Stability Specifications And Verification Procedures For Liquid Propellant Rocket Engines", CPIA Publication-247, page-4, 1973.

2) "Elimination of High-Frequency Combustion Instability in the Fastrac Engine Thrust Chamber", M. Rocker and T.E. Nesman, presented at the 1999 JANNAF Joint Meeting of the Combustion, Airbreathing Propulsion, and Propulsion System Hazards Subcommittees in Cocoa Beach, Florida, 1999.

3) "Characterization of Low-Frequency Combustion Stability of the Fastrac Engine", M. Rocker, to be published, 2001.

4) "Liquid Propellant Rocket Combustion Instability", NASA SP-194, editors: D. T. Harrje and F. H. Reardon, page 19, 1972.

5) "Transient Simulation of Pressure Oscillations in the Fuel Feedline of the Fastrac Engine Thrust Chamber", B. Bullard, from the proceedings of the Tenth Annual Symposium of the Penn State University Propulsion Engineering Research Center, pages 24-29, 1998.