# FASTRAC GAS GENERATOR TESTING

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## ABSTRACT

A rocket engine gas generator component development test was recently conducted at the Marshall Space Flight Center. This gas generator is intended to power a rocket engine turbopump by the combustion of Lox and RP-1. The testing demonstrated design requirements for start sequence, wall compatibility, performance, and stable combustion. During testing the gas generator injector was modified to improve distribution of outer wall coolant and the igniter boss was modified to investigate the use of a pyrotechnic igniter. Expected chamber pressure oscillations at longitudinal acoustic mode were measured for three different chamber lengths tested. High amplitude discrete oscillations resulted in the chamber-alone configurations when chamber acoustic modes coupled with feed-system acoustics modes. For the full gas generator configuration, which included a turbine inlet manifold, high amplitude oscillations occurred only at off-design very low power levels. This testing led to a successful gas generator design for the Fastrac 60,000 lb thrust engine.

## NOMENCLATURE

| | |
|---|---|
| $D$ | diameter |
| $L$ | length |
| $x$ | axial station downstream of injector |
| $f$ | frequency |
| $P$ | pressure |
| $p'$ | fluctuating pressure |
| O/F | oxidizer to fuel mixture ratio |

SUBSCRIPTS

| | |
|---|---|
| $g$ | turbulence generator |
| $c$ | combustion chamber |

## INTRODUCTION

A gas generator for a 60,000 pound thrust rocket engine was tested at the Marshall Space Flight Center (MSFC) test stand 116 (Figure 1) in 1997 and 1998. This was a Fastrac approach to design and development which required a robust design, success oriented schedule, and minimal testing. The gas generator is a small cylindrical chamber where Lox and RP-1 were injected and burned at a low oxidizer to fuel (O/F) mixture ratio. The gas generator chamber was tested alone and in combination with a turbine inlet manifold (TIM) . In the engine configuration, the hot gas discharges from the gas generator into the turbine inlet manifold which is an annular volume where small nozzles direct the flow into the turbine blade rows to power the Fastrac turbopump. In the initial component test configuration, the hot gas discharges from the gas generator through a small nozzle into ambient atmosphere. In the final component test configuration, the hot gas discharges into a turbine inlet manifold before exiting to the atmosphere.

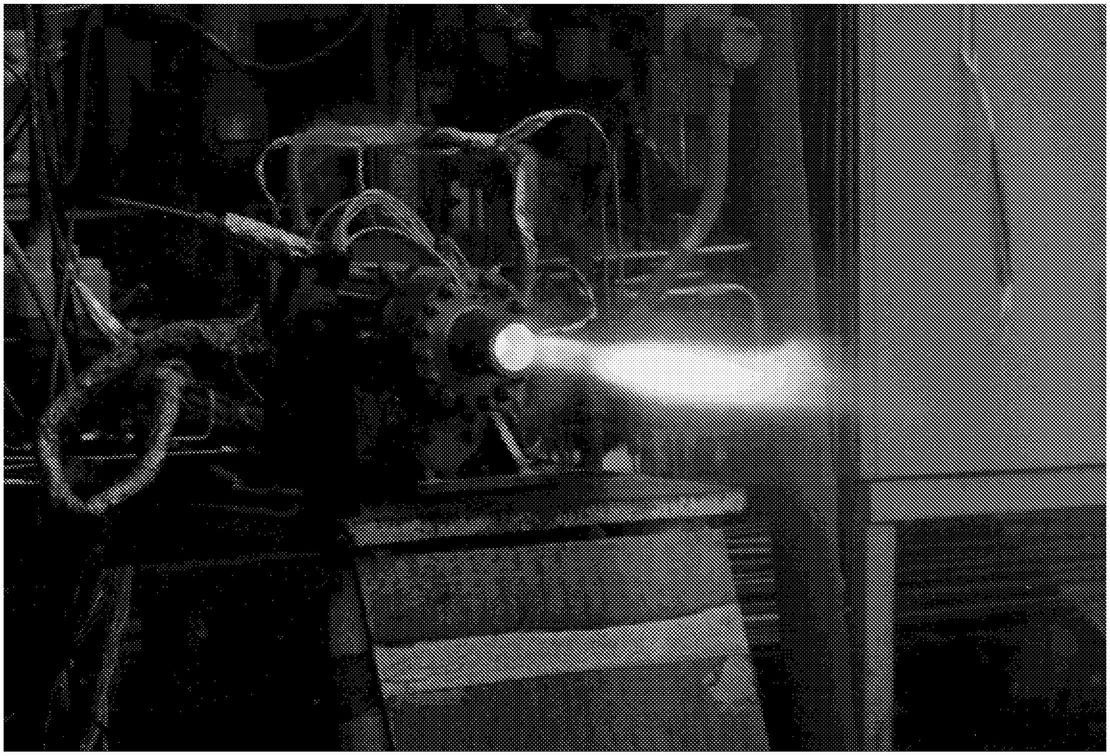

**Figure 1. TS116 GG Component Hotfire**

The objective of the gas generator testing was to develop a design that would operate on the Fastrac engine. This was to be accomplished by defining operational regimes, comparing some chamber and trip ring variations, and verifying wall compatibility. In the course of testing the issues that surfaced were: 1. Accurate properties of Lox/ RP-1 combustion gas, 2. Injector pattern as it related to wall compatibility, 3. Ignition system design, and 4. Internal fluctuating pressure environment and potential effect on the turbine. These issues were all investigated using various configurations of the gas generator test article (Figure 2). The focus of this paper is on the last issue, i.e., the gas generator internal fluctuating pressure environments.

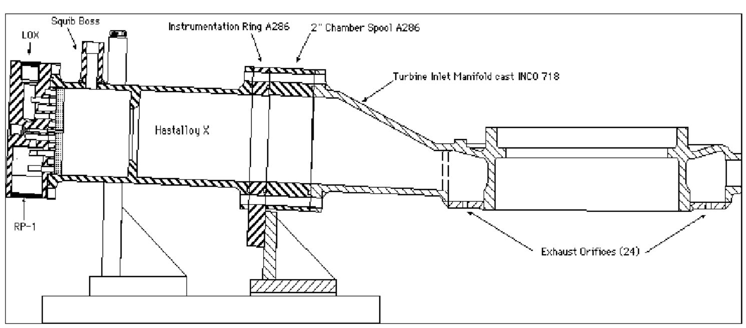


**Figure 2. GG Test Article**

TEST ARTICLE

The gas generator hardware consists of an injector, combustion chamber, turbulence ring, instrumentation ring, chamber spools, and turbine simulator. The gas generator component tests were conducted with several variations to the test article hardware. The combustion chamber diameter, $D$, remained constant and the turbulence generator diameter, $D_g$, at 0.6 $D$ through all the testing. However the injector pattern, length of the chamber ($L$), position of the turbulence generator ($x_g$), and turbine simulator were all varied at some point in the testing.

The basic gas generator test article (Figure 3) is a cylindrical enclosure with an injector at the head end, a flow restrictive trip ring near the head end, and a concentric hole discharge. The injector elements were paired, self-impinging RP-1 orifices enshrouding a single oxidizer showerhead orifice (F-O-F triplet). An igniter boss is located near the injector face. The flow restrictive trip ring is a turbulence generator and was configured at either $x_g = 0.57$ $D$ or $x_g = 0.85$ $D$ downstream of the injector. This version of the test article differs from the engine configuration which has a gradually tapering discharge and an annular manifold. The test article chamber also had spools inserts to vary chamber length. An instrumentation ring was located at $x_g = 2.32$ $D$ down the chamber.

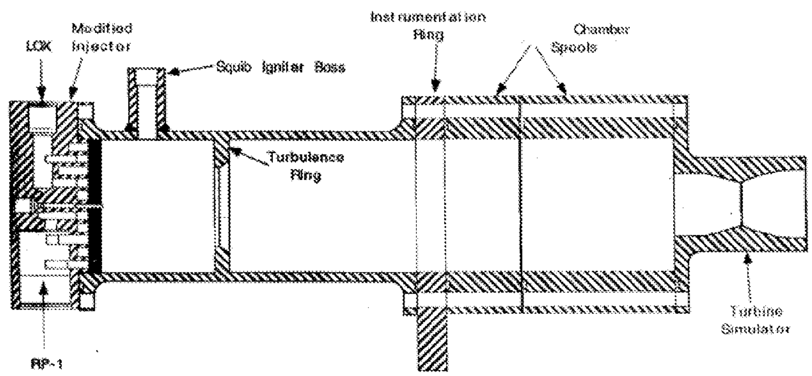


**Figure 3. Cross-section of Basic GG Test Article**

During testing the injector was modified to improve distribution of outer wall coolant and the igniter boss was also modified to investigate the use of a pyrotechnic igniter. After cooling, ignition, and combustion issues were resolved subsequent tests were conducted with a tapered gas generator discharge (Figure 4) and a turbine inlet manifold (Figure 5).

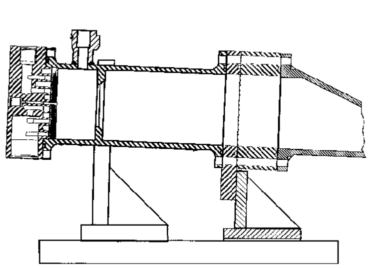

**Figure 4. GG with Tapered Discharge**

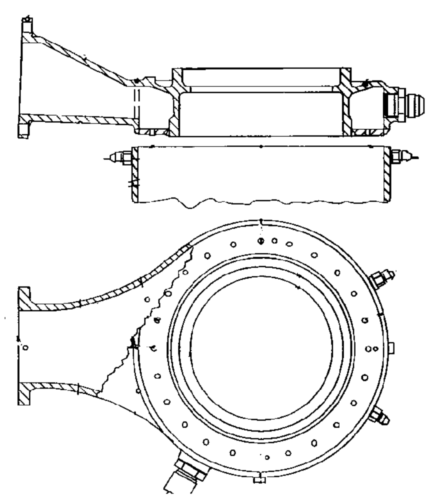

**Figure 5. Tapered Discharge and Turbine Inlet Manifold**

INSTRUMENTATION

The gas generator test article was designed with a ring that could be inserted into the chamber body with a full array of instrumentation. The instrumentation ring contained a high frequency pressure transducer and several thermocouples. Five thermocouples were inserted into the chamber through the instrumentation ring with varying depths of penetration.

Selected gas generator measurements were recorded on the test stand 116 high sample data system (Table 1). Typically from 11 to 14 of these measurements were recorded on any one test. The high sample test data were lowpass filtered at 10,000 Hz and then sampled at 40,000 samples per second. One dynamic pressure transducer was close-mounted to the chamber inner wall but the other pressure measurements were susceptible to senseline resonance with limited usefulness for evaluating fluctuating pressure amplitudes.

**Table 1. High Sample Data Instrumentation**

| MSID | NOMENCLATURE | UNITS |
|---|---|---|
| P3001 | GG Pc dynamic pressure | PSI |
| P3004 | GG Pc pressure #1 | PSI |
| P3005 | GG Pc pressure #2 | PSI |
| P8307 | GG Pc upstream turb ring | PSI |
| A3001 | Axial accel injector | G PK |
| A3002 | Radial accel | G PK |
| A3003 | Injector inlet | G PK |
| P2305 | GG Lox injection | PSI |
| P4304 | GG TEA injection pressure | PSI |
| P7350 | Turbine inlet manifold simulator | PSI |
| P8306 | Fuel manifold pressure #1 | PSI |
| P8307 | Fuel manifold pressure #2 | PSI |
| P8308 | GG fuel inlet at RP1 filter | PSI |
| DP8309 | Fuel injection $\Delta P$ | PSI |
| T7301 | ℄ GG temp. at instr. ring | mV |
| TC7302 | ¼ dia. GG temp. at instr. ring | mV |

**TEST RESULTS**

Four series of gas generator hotfire tests were conducted at test stand 116. Thirty seven component hotfire tests in all were completed during the gas generator development. Series 1 consisted of tests 1 through 8 which were conducted in summer of 1997. These tests featured the modified triplet element injector with film coolant holes and the baseline gas generator combustion chamber. The eight tests were conducted with chamber pressures, at the injector end, ranging from 505 to 705 psia and oxidizer-to-fuel mixture ratios ranging from 0.25 to 0.36. The gas generator chamber was exhausted through a 1.1" diameter nozzle. Test duration varied from 64 seconds to 154 seconds (flight duration).

Series 2 consisted of tests 9 through 24 conducted in fall 1997. Tests 9 through 12 had the gas generator exhausting through outer nozzles, and tests 13 through 15 went back to the first nozzle configuration. Power spectral density analysis (PSD) showed an anomalous 1600 - 1870 Hz frequency in the chamber fluctuating pressure and accelerometers . This frequency appears to coincide with a broader acoustic mode frequency early on in test 13, the end of test 21, and throughout test 22. The oscillation showed up at a discrete 1660 Hz, with harmonics, on test 23 (Figure 6). The pressure oscillations produced vibrations of around 26 G rms (Figure 7).

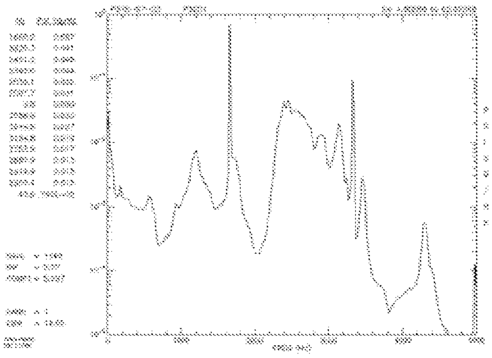

**Figure 6. Chamber Pressure PSD**

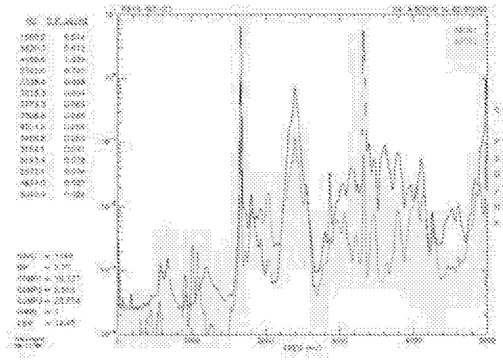

**Figure 7. Accelerometer PSD's**

The gas generator was inspected after series 1 and again after the first few series 2 tests. Some bluing of the chamber plus erosion damage to the turbulence generator was noted. The damage is a result of the pressure drop in the fuel manifold (from top to bottom). The external thermocouples also showed there is an asymmetry, with a temperature of 1500° F measured at the top and 800° at the bottom. The bluing problem was eliminated by two changes to the gas generator. The first change was to increase the diameter of the RP-1 line into the fuel manifold from ¾" to 1" to create a more uniform flow into the manifold and subsequently the ΔP across the injector. The second change was to drill outer wall coolant holes in the injector on the side where high temperatures were a problem.

Series 3 consisted of Tests 25 through 30 conducted in early 1998. The objectives of these tests were to develop a pyrotechnic igniter start sequence and demonstrate acceptable operation of the flight configuration hardware. The hardware was configured with a pyrotechnic igniter, barrel chamber, gradually tapering exhaust duct, and fuel turbine inlet manifold. This is flight configuration hardware with the exception of drilled holes in the turbine inlet manifold instead of nozzles. The series 3 tests show that the high amplitude discrete 1870 Hz frequency is no longer present (Figure 8). A low amplitude resonant condition does occur at the start of some of these tests however.

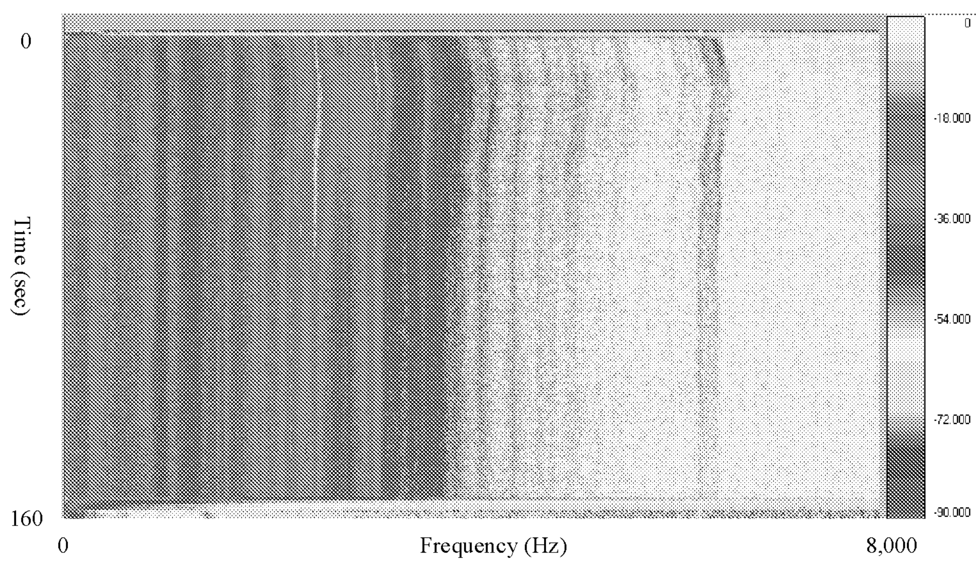


**Figure 8. Dynamic Chamber Pressure Spectragram of Test 30**

Series 4 consisted of tests 31 through 37 in fall of 1998. This series completed the planned gas generator component development test program. The primary objectives of this series of tests were to repeatedly demonstrate proper ignition of the gas generator using a new pyrotechnic igniter and operation at 40-50% power level. Additional objectives were to gather thermal environment data on the cast turbine inlet manifold and demonstrate good ignition with a helium atmosphere in the gas generator. All test objectives were met and the new igniters performed well. On these tests, however, the gas generator exhibits significant chamber pressure oscillations at chamber pressures below 260 psia (47% of nominal). An interesting example of this occurred on test 34 where a “jump” to higher oscillation levels (Figure 9) was coincident with a “shift” in chamber hot gas temperature (Figure 10) and some chamber oscillation frequencies changed from narrow band random peaks (Figure 11) to high amplitude discrete peaks (Figure 12).

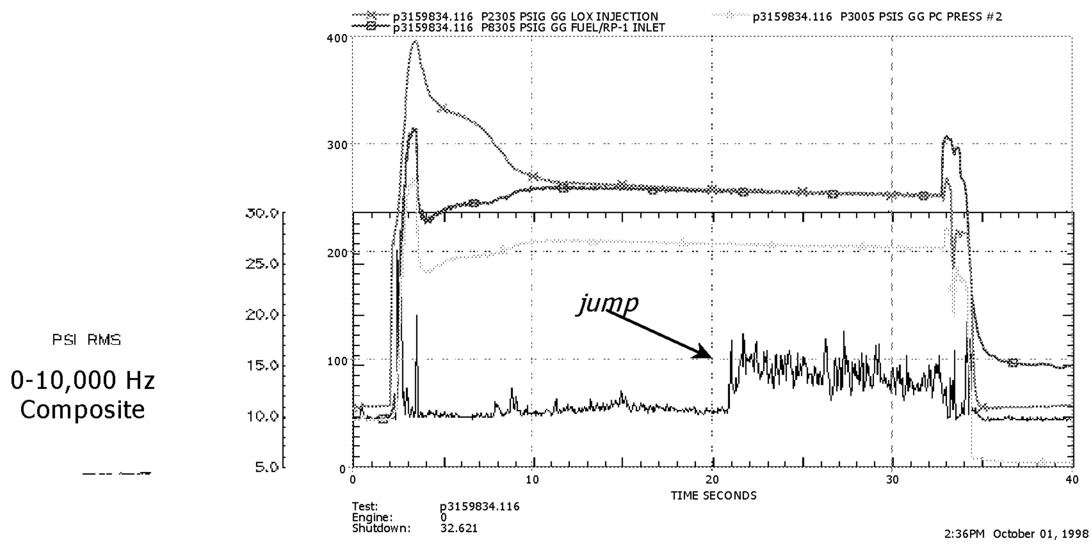


**Figure 9. Low Pc Test "Jump" in Oscillation Amplitude**

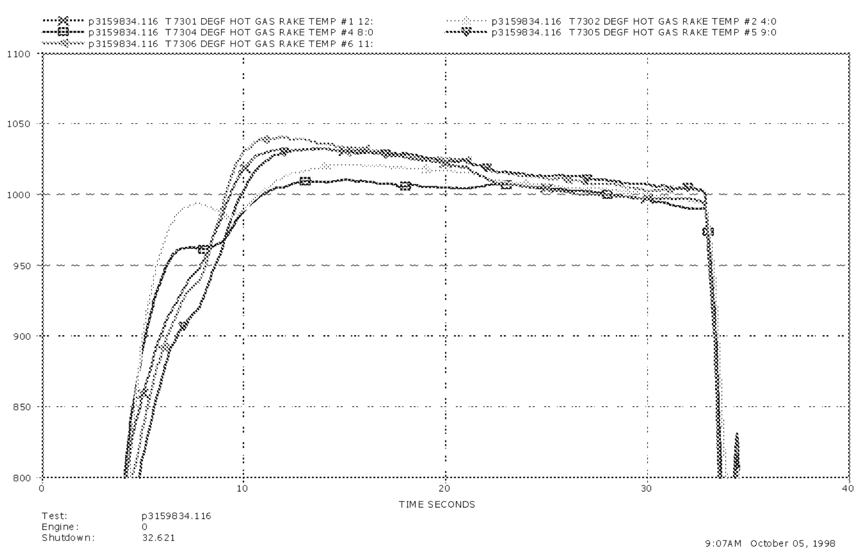


**Figure 10. Low Pc Test "Shift" in Hot Gas Temperatures**

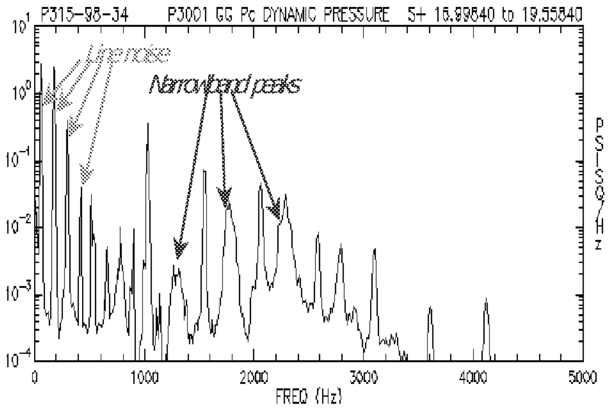


**Figure 11. Low Pc Test "Before-Jump" PSD**

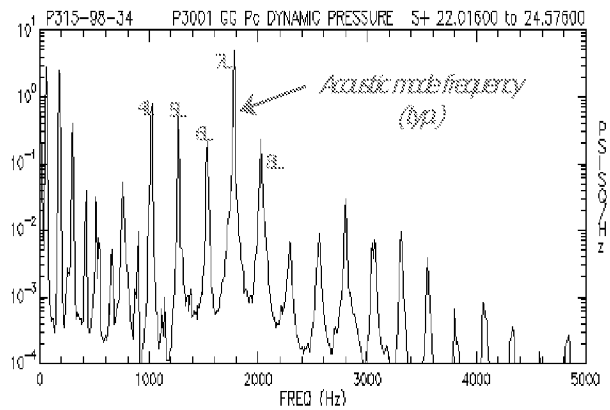


**Figure 12. Low Pc Test "After-Jump" PSD**

GENERAL RESULTS

Based on the general characteristics of gas generator chamber oscillations several oscillation mechanisms were postulated. Acoustic waveguides of the fluid systems were postulated as the resonators and fluid mechanisms as exciters. The acoustic modes of the gas generator were of prime importance. The chamber axial dimensions and oxidizer to fuel mixture ratio (O/F) were two of the key parameters affecting acoustics that were varied during Fastrac gas generator component testing. Three different gas generator chamber lengths, *L*, were tested. The range of test mixture ratios varied from a low O/F = 0.18 to a high O/F = 0.37. Table 2 shows the gas generator test numbers in a matrix of chamber length versus mixture ratio. The outlined test numbers in Table 2 indicate the use of turbulence ring at $x_g = 0.85\ D$ downstream of the injector instead of $x_g = 0.57\ D$.

**Table 2. Test Matrix**

| | Test Numbers | | |
|---|---|---|---|
| (O/F) | *L* = 11” | *L* = 15” | GG + TIM |
| Low MR (.18 - .26) | 10, 11, 12, | 13, 15, 16, 17, 18, | 28, 29 |
| Nominal MR (.27 - .32) | 3, 4, 5, | 6, 7, 8, 9, 19, 21, 23 | 26, 27, 30, 31, 34 |
| High MR (.33 - .37) | | 14, 20, 22, 24 | 25, 32, 33, 35, 36, 37 |

ACOUSTIC ANALYSIS

The properties of the Lox / RP-1 hot gas at mixture ratios of around 0.3 are difficult to determine. The best source of this information is a set of data and curve fits resulting from an Aerojet study.[1] Estimates of sound speed using equilibrium equations were higher than measured in the Aerojet study. An empirical analysis combining both sound speed estimations and measured hot gas temperature and pressure led to a nominal average chamber sound speed of 1441 ft/s. Furthermore, computational fluid dynamic analysis[2] showed sound speed varying from around 700 ft/s near the injector to 1000 ft/s at the turbulence generator and increasing towards the nozzle. The nominal fluid properties for the oxidizer and fuel are shown in Table 3 along with the hot gas properties at three different mixture ratios.

**Table 3. Fluid Properties**

| Component | Fluid | Flow rate ($lb_m/s$) | Temp (°R) | Press (psia) | Density ($lb/ft^3$) |
|---|---|---|---|---|---|
| GG chamber | O/F=0.25 | 8.1 | 1,470 | 551 | 1.350 |
| | O/F=0.31 | 7.2 | 1,616 | 542 | 0.970 |
| | O/F=0.36 | 6.4 | 1,706 | 532 | 0.717 |
| Oxidizer Inlet | Lox | 1.7 | 211 | 686 | 63.03 |
| Fuel Inlet | RP-1 | 5.46 | 523 | 630 | 49.5 |

Since the gas generator is a long cylinder, standing acoustic waves were expected as in an organ pipe. Even with the turbine inlet manifold ring attached a variety of standing wave pressure patterns can be envisioned (Figure 13). For acoustic waves in the chamber, the injector will provide a near rigid termination as will the nozzle end for the gas generator alone configurations. The turbulence ring will serve to block some axial gas oscillation and will also generate downstream shear layer oscillations. The acoustic modal patterns can be checked for consistency with measured relative phase from available high frequency measurements.

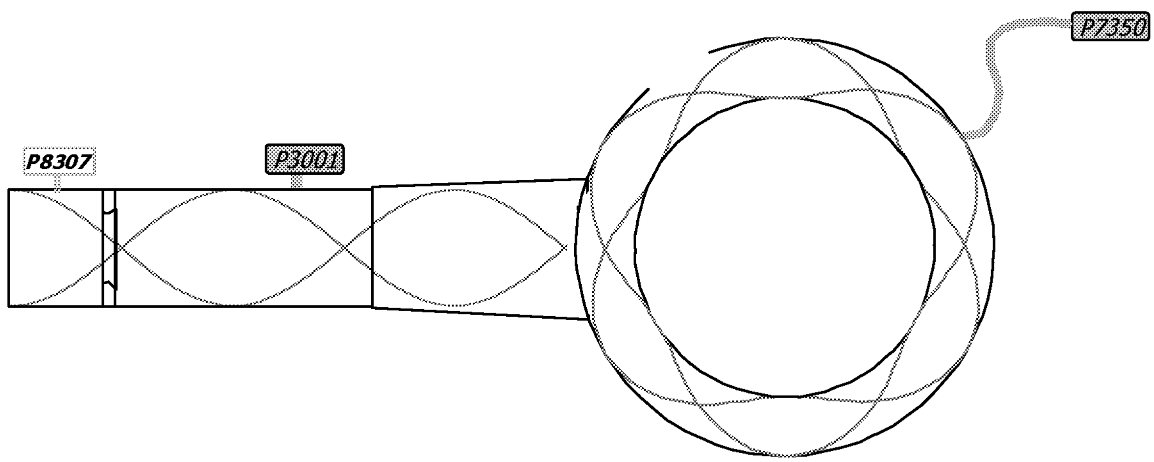


**Figure 13. GG+TIM Acoustic Mode (typical)**

Estimates were made of the gas generator test article acoustic mode frequencies where a constant sound speed of 1440 ft/s was assumed and the gas generator combustion chamber was modeled as a closed-closed pipe element. The GG + TIM frequencies were estimated determining the stem and top resonance frequencies of a T-tube pipe element.[3] The physical system was approximated by assuming static (no flow) hot gas within a T-tube having all pipe radii equal. Various top and stem standing wave combinations were determined.

The major peaks from measured gas generator chamber dynamic pressure spectra were compiled for most tests. The spectral peaks occur in integer multiples as would be expected from longitudinal acoustic modes of the gas generator chamber. The measured peak frequency divided by integer multiple was plotted versus sound speed (Figure 14). This plot shows the data divides into three distinct linear trends based on the chamber length.

**Table 4. Acoustic Mode Frequencies (Hz)**

| Mode | GG 11 | GG 15 | GG + TIM |
|---|---|---|---|
| 1 T | 2,952 | 2,952 | 2,952 |
| 2 T | 4,897 | 4,897 | 4,897 |
| 1 R | 5970 | 5970 | 5970 |
| 1 L | 786 | 576 | 252 |
| 2 L | 1,572 | 1,153 | 511 |
| 3 L | 2,358 | 1,729 | 758 |
| 4 L | 3,144 | 2,306 | 1023 |
| TIM 1T | -- | -- | 765 |
| TIM 2T | -- | -- | 1275 |

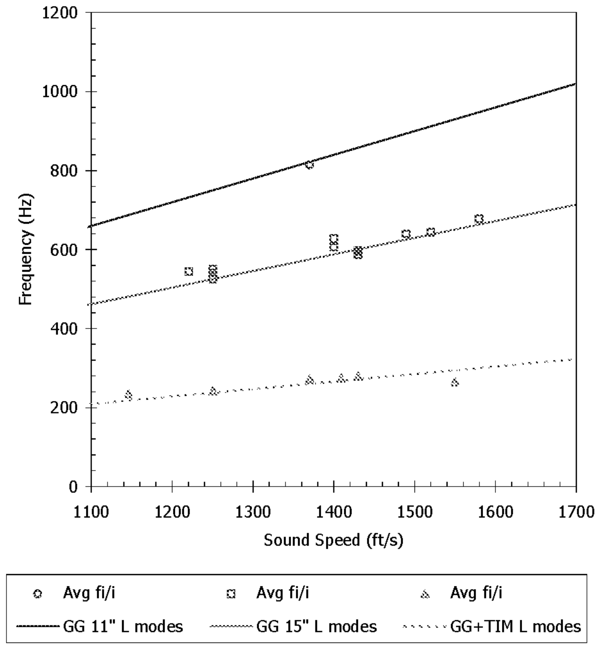


**Figure 14. Measured GG Oscillation Frequencies**

The instrumentation ring was well situated for measuring chamber pressure fluctuations, however, it would not be available on the gas generator used in turbopump and engine testing. For those tests the chamber pressure was measured at a boss located in the chamber wall between the injector and the turbulence ring. Some of the last gas generator component tests were conducted with dynamic pressure transducers located in the new location and in the instrumentation ring. The new transducer was able to detect most of the discrete spectral peaks from the chamber acoustic modes, however, the magnitudes were significantly lower than measured at the instrumentation ring (Figure 15).

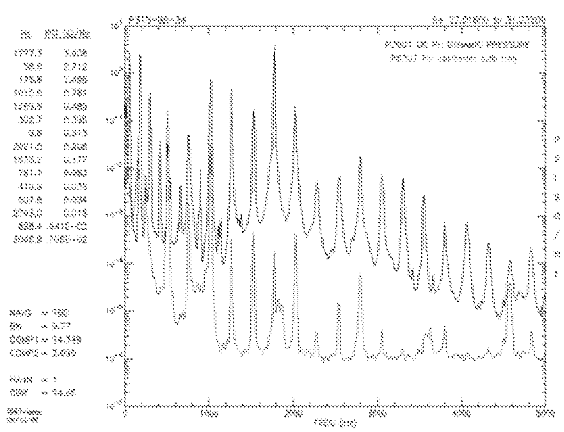

**Figure 15. Measurement Location Change**

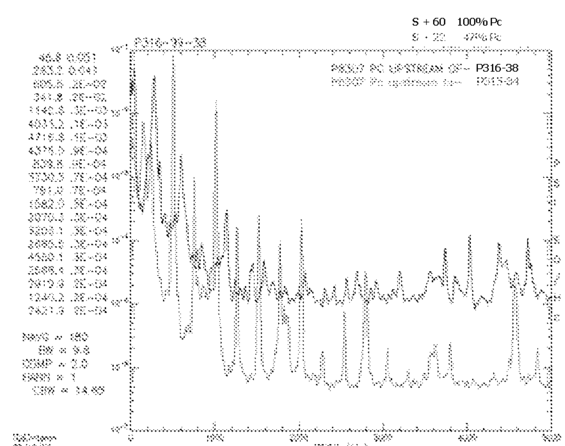


**Figure 16. TPA and GG Pc Log PSD's**

The turbopump assembly (TPA) was tested several times with a gas generator to power the turbine. On these tests the gas generator chamber fluctuations were measured at the boss between the injector and the turbulence generator. A comparison of the chamber fluctuations from the gas generator on the turbopump assembly to the gas generator component test (Figure 16) shows that in the former the acoustic modes are not excited.

Furthermore, the fluctuations that do occur have been identified as related to a 1.2 times synchronous frequency that is a rotating cavitation signature from the Lox pump. The pump related oscillations are of significantly lower amplitude than the acoustic resonance peaks from the gas generator test article as observed in the chamber pressure fluctuations (Figure 17) and injector accelerometers (Figure 18).

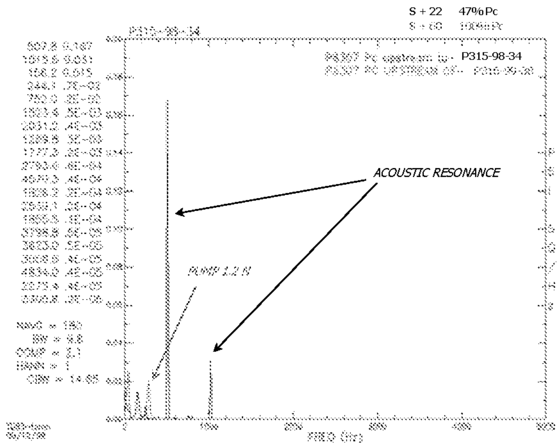


Figure 17. GG and TPA Pc Linear PSD's

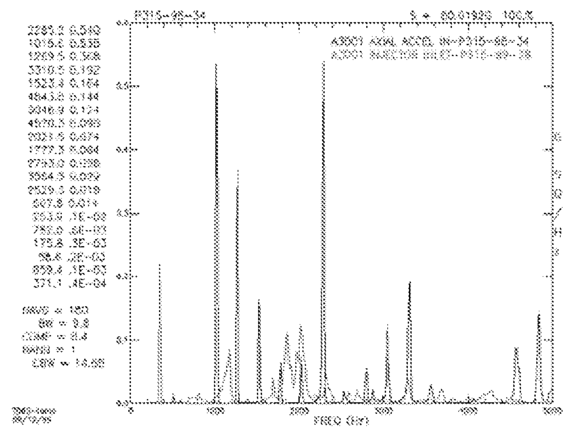

Figure 18. GG to TPA Accel Linear PSD's

EXCITATION ANALYSIS

High amplitude oscillations in the gas generator require excitation of the acoustic resonators. The potential flow exciters considered were broadband flow noise, discrete shear layer oscillation (self-excited), and vortex shedding. Another potential excitation considered was coincidence with feedsystem acoustics. The validity of each of these phenomena as the excitation mechanism for the high amplitude oscillation was assessed based on interpretation of the dynamic data.

The first flow excitation mechanism considered was broadband flow noise. The source of this noise would be the injector flow impingement, breakup, and mixing plus the secondary mixing from turbulence and diffusion. The response would be in the form of broad spectral peaks at the gas generator longitudinal acoustic mode frequencies. Since the high amplitude oscillation spectra display narrow (discrete) peaks, this mechanism was rejected.

The second flow excitation considered was a discrete shear layer oscillation. The source of this mechanism would be shearing flow at the turbulence generator ring. This would become a self-excited oscillation if the shearing flow impinges on the downstream nozzle with feedback to the flow separation point. The mechanism would be characterized by discrete spectral peaks, frequency variation with flow rate, and "lock-in" with acoustic modes. The measured oscillations fit this mechanism with nondimensional frequencies (Strouhal numbers) matching empirically estimated upper stage modes. High amplitude oscillations were observed with the GG+TIM configuration however, which did not have a downstream impingement point. For this reason this mechanism was rejected.

The third flow excitation mechanism is vortex shedding. The instrumentation ring thermocouple probes protruding into the hot gas flow were the only possible source of vortex shedding oscillations. The vortex shedding frequency would be expected to vary with flow rate. The estimated frequencies from this mechanism did not match the high amplitude oscillation frequencies, therefore this mechanism was rejected.

One final excitation considered was feedsystem coupling. In this type of oscillation, one of the feedlines would be in resonance with combustion chamber acoustics and the other feedline would be passive. Though flush mounted feedline pressure measurements were not available to identify feedline acoustic mode frequencies, some hint of these frequencies was detected in the existing pressure measurements despite the senseline effects.

In addition, frequency response functions showed some correlation between feedline measurements and chamber measurements during high amplitude oscillations. On test 34, for example, based on coherence (Figure 19) it appears that the lox feedline is a passive element in the high amplitude oscillation resonance. On this same test however, the fuel feedsystem (Figure 20) and the turbine inlet manifold (Figure 21) appear to participate in the acoustic resonance of the chamber.

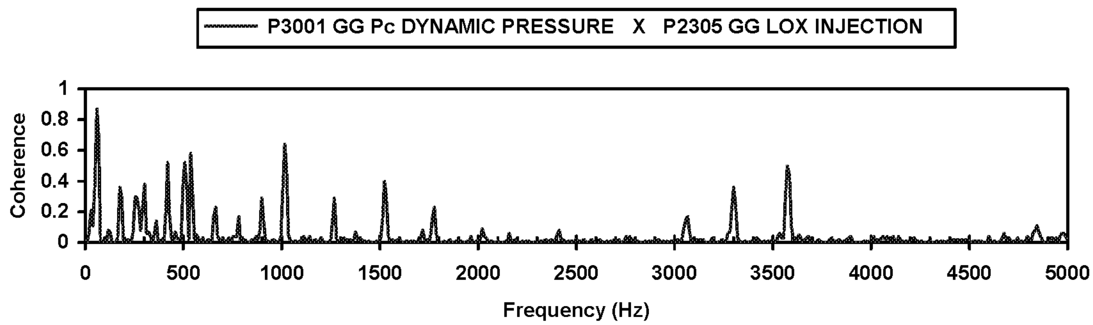


**Figure 19. Lox Feedline to Chamber Coherence**

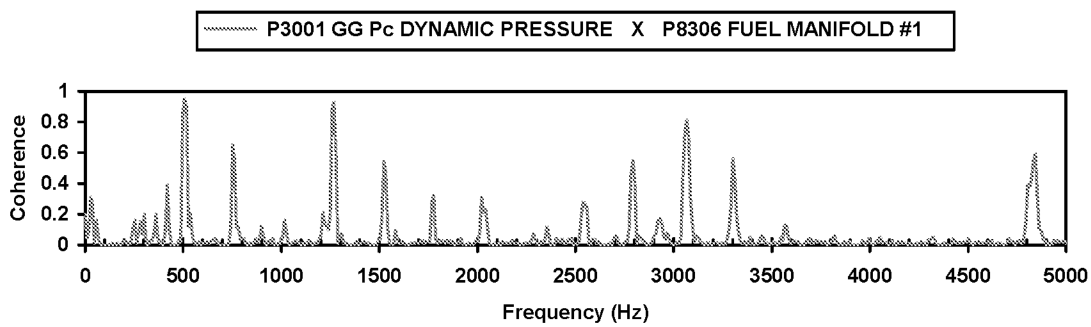


**Figure 20. Fuel Feedline to Chamber Coherence**

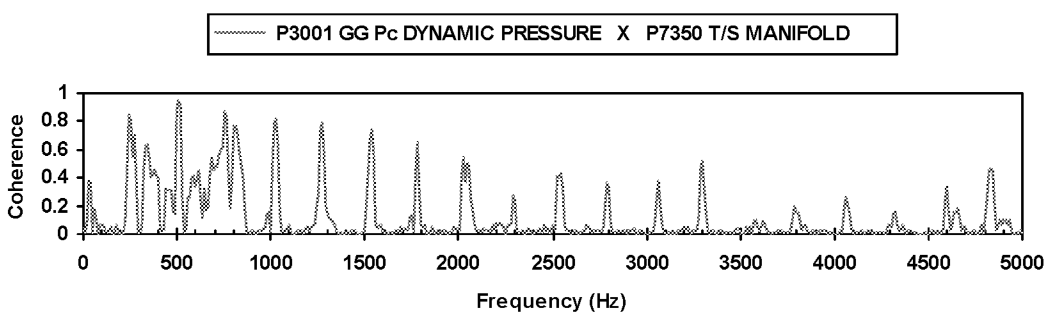


**Figure 21. TIM to Chamber Coherence**

## CONCLUSIONS

Component testing was performed at MSFC to develop a gas generator design that would operate on the Fastrac engine. This was accomplished by performing 37 tests to address several design issues that surfaced. The gas generator internal fluctuating pressure environment was one of these issues. In early testing, it was observed that Fastrac gas generator chamber pressure oscillations occurred at or near longitudinal acoustic mode frequencies. The gas generator oscillations were shown to be dependent on gas generator length and hot gas sound speed, consistent with longitudinal acoustic modes of the gas generator. Three different Fastrac gas generator lengths were tested and with each configuration high amplitude chamber acoustic mode oscillations were observed under certain operating conditions. Elimination of the gas generator component test feedsystem, i.e., turbopump component testing, eliminated the high amplitude oscillations. Because of this last observation, and because of the high coherence between feedline and chamber pressures, the high amplitude oscillations observed in testing were attributed to acoustic modes of the gas generator in resonance with the acoustic modes of the feedsystem .

## ACKNOWLEDGEMENTS

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