

# INVESTIGATION OF LIQUID ROCKET INJECTOR ELEMENT STABILITY MARGINS\*

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## ABSTRACT

Due to the prohibitive costs of full-scale liquid rocket engine (LRE) injector combustion stability testing, single element screening is an attractive alternative. A carefully designed single element experiment will yield valuable data on the stability characteristics of a particular injector type and also allow for multiple designs to be more readily assessed. An analysis methodology has been formulated to evaluate the stability margins of a LRE injector element. A system of transfer functions, set in terms of fluctuating flowrates and pressures, is used to describe the key processes in an injector. All feedback couplings associated with the injector are included in a complete block diagram that provides insight into the dynamic characteristics of the particular element.

An experimental approach to quantify all the representative transfer functions is also proposed. The experimental device may allow for impulsive and oscillatory disturbances to be imposed on the injected propellants and combustion gases, while the longitudinal acoustics of the combustor will be varied via a variable length combustion chamber. In this approach the element is tested at its design flowrates and pressure to reduce scaling uncertainties and ensure its applicability to the full-scale engine. The activities performed to date are described and a review of previous driven combustion stability experimental approaches is also presented.

## INTRODUCTION

Characterization of combustion stability through subscale testing has long been a goal of the rocket engine community. An instance of combustion instability at a full-scale component- or engine-level test is disastrous, ruining expensive hardware, jeopardizing valuable test facilities, and putting the development program at risk of failure due to technical and programmatic concerns. Subscale test results could help eliminate these risks if they were used to rank injector designs prior to committing to the expensive build and test of the full-scale engine, and to evaluate design fixes to full-scale designs that are demonstrated to be unstable. Recent work at Purdue University has focused on developing a method to examine the stability characteristics of single element combustors.

Subscale test devices that have been used in the past include two-dimensional combustors and T-burners that provide similar transverse mode acoustics to the full-scale chamber.<sup>1</sup> The clear and simple evidence of their lack of success is that, although these subscale tests have been attempted for decades, they are not generally used in development programs in the US. Trying to match the transverse acoustics and other important flow characteristics in a subscale chamber is extremely difficult; two-dimensional chambers are highly damped, and reduced-flow cylindrical chambers with the matched diametrical dimension do not come close to reproducing the mean flow characteristics. The ultimate subscale approach, however, would be to determine injector stability characteristics using a single element injector and subsequently use these results for full-scale engine design.

In a typical combustion chamber that employs coaxial propellant injection, the injector consists of dozens to hundreds of individual flow elements. Each element may be subtly different than its neighboring element. Fuel-side and oxidizer-side orifice sizes may be varied to adjust the local flowrate and mixture ratio in the element, while the length of the injector post may be varied to "tune" the acoustic response of a compressible propellant flow away from potentially harmful chamber acoustic resonances. The use of different elements across the injector face enables the combustor designer some measure of

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control over the transverse energy release profiles in the chamber. Implications are that near-wall elements can be sized at off-nominal mixture ratio in order to alleviate film-cooling requirements, while local mixture ratios, flowrates, and injection dynamic responses could be distributed across the injector face in such a manner as to break up any coherence between fluctuating energy release and the transverse acoustic modes of the combustion chamber. In fact, the Russian RD-170 main combustion chamber employs all of these tactics in its design.<sup>2</sup> U.S. designs, such as the SSME, have incorporated injector post length variation across the chamber diameter to circumvent high-frequency injector-coupled instabilities.<sup>3</sup>

It is clear that combustion stability characterization of single element injectors provides an attractive alternative in designing a stable, full-scale engine—even if the aforementioned strategies at instability suppression were not regularly employed. Single element testing may even be sufficient to characterize full-scale chamber stability limits of particular injectors. For instance, Russian injector designs for large, high pressure combustors take special care to ensure that elements operate independently with a substantial amount of intra-element propellant mixing occurring in a recessed “mixing cup.” The initial mixing zone is thus sheltered from transverse velocity oscillations in the combustion chamber. This design philosophy permits significant confidence to be gained from single element tests and reduces risk for instabilities to appear during larger scale testing. With this potential benefit in mind, an analytical and experimental approach to characterize the stability of a single element combustor to the greatest extent possible has been formulated.

The single element characterization approach will be summarized in this paper. A model of the dynamics of a coaxial injector is described to gain insight into the method of analysis. Experimental pulsating devices that have been used in the past will also be reviewed. An initial single element combustor experiment has been designed to aid in verifying the modeling approach as well as to gain test experience with pulsator hardware. A summary of the work performed to date is also presented.

## **SINGLE ELEMENT APPROACH**

An effective experimental and analytical approach must be taken to quantify the stability of a single element injector. The experimental approach adopted at Purdue is one that decreases the uncertainties in analysis. Each injector element will be designed to its full-scale physical dimensions and tested at its nominal operating conditions (i.e. flowrates and pressures). Thus, there will be no need to extrapolate single element tests to full-scale chamber conditions. This is an important consideration, especially for high-pressure engine designs. At lower pressures, stability characteristics are difficult to match as concurrent examination of such influential parameters as momentum ratio, velocity ratio, and mixture ratio, is difficult to achieve. Furthermore, in engines that operate well above the supercritical pressures of their injected liquid propellants, the atomization and vaporization processes may proceed differently.<sup>4-5</sup>

Along with maintaining nominal operating conditions, the single element combustor will be designed to replicate the axial flow and energy release profiles in the full-scale chamber. The chamber diameter is set by the injector mass flux to match a nominal “stream-tube” of the full-scale chamber, while the throat diameter is sized for full-scale chamber Mach number matching. The length of the single element combustor is near the size of the full-scale chamber to complete axial similitude.

With some of the typical scaling problems alleviated by design of the single element experiment, a detailed model of the combustor is still required to gain the desired stability information. The dynamics of the injector element are analyzed using a “controls systems”-based analogy in which various mechanisms provide a frequency-dependent “gain” in a block diagram representation of the engine. This approach has seen considerable attention and advancement by the Russian industry and is detailed in the literature.<sup>6,7</sup> The model may be as complex as required to adequately describe all of the mechanisms that effect combustion dynamics. Experimental measurement requirements are driven by the analytical model.

The single element combustor must be perturbed from its steady operating conditions in order to measure its dynamic response. To accomplish this, a pulsating device must be incorporated in the experimental design that can generate controlled, repeatable perturbations of the combustor. The combustion response to longitudinal oscillations is investigated by imposing either impulsive or continuous pulsations on any combination of locations including the propellant manifolds and combustion chamber. In conjunction with pulsing, a variable length combustion chamber allows for alteration of the natural longitudinal acoustic modes that couple with high-frequency combustion instabilities. Analytically, the disturbances and chamber length variation amount to forcing functions of selected response frequencies. High-frequency pressure measurements will be correlated with the model and the relative stability of different injectors may be ascertained from perturbation tests.

### ANALYTICAL MODEL

Each of the individual combustor processes (such as injection, atomization, vaporization, etc.) is described with a transfer function relating some input disturbance to an output response. These transfer functions are related to each other and cast in the form of a controls-system model. The model may be as complex as required to adequately describe all of the mechanisms that effect combustion dynamics. This methodology has great advantages in that it is generic and can in principle be applied to any engine and propellant system. Another advantage of the methodology is that it forces a rigorous approach to evaluate response functions for all pertinent processes in the feed, injection, and combustion path. If done successfully, maximum insight into combustion instability phenomenon will be gained.

The gas-centered, liquid-swirled, coaxial injector is selected as a model element. These particular injectors have recently seen interest for main chamber application in oxidizer-rich, staged combustion (ORSC) engines.<sup>8,9,10,11,12</sup> Several investigations of this injector are ongoing at Purdue that will provide data to develop and eventually validate the present model.<sup>8,13,14</sup> Moreover, the design features of these particular injectors allow for a suitable examination of the effects of longitudinal pressure oscillations. These injectors are designed with a limited sensitivity to transverse velocity perturbations, thereby making "pressure-coupling" effects more important to resolve. The block diagram model of such an injector, in its most simple form, is shown in Figure 1.

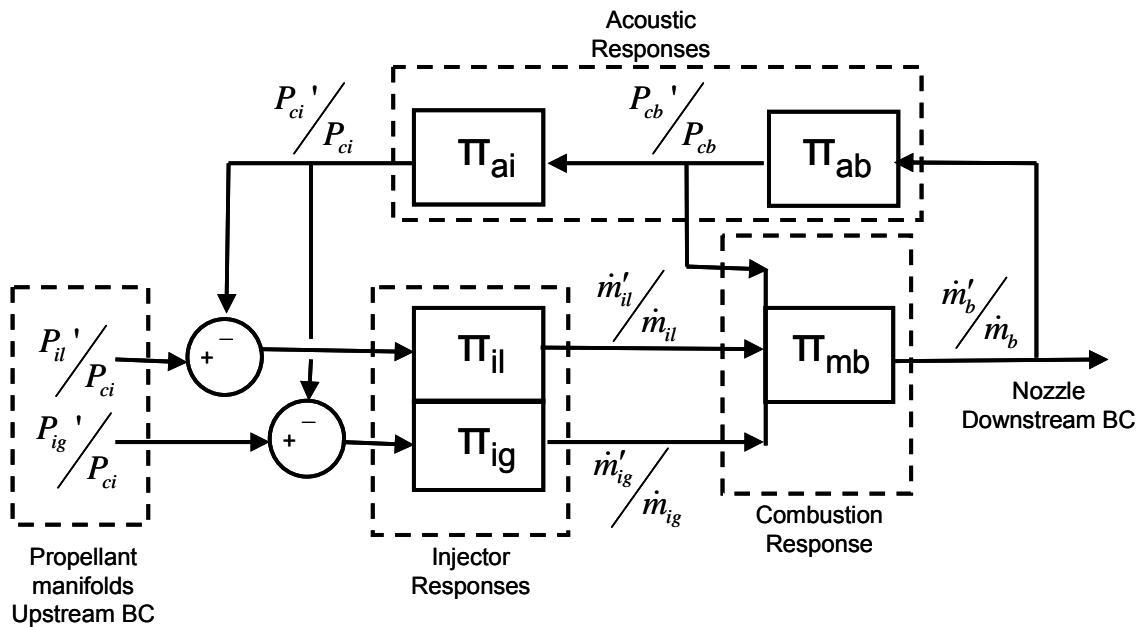


Figure 1: Block Diagram of Coaxial Injector/Combustor

The primed variables shown in Figure 1 denote the fluctuating component of a given variable. All signals are non-dimensionalized by their mean values as determined by steady-state analysis. The mean flowrates through the gas and liquid sides,  $\dot{m}_{ig}$  and  $\dot{m}_{il}$ , are induced by the pressure differences across the injector. These pressure differentials are the mean injector manifold pressures,  $P_{ig}$  and  $P_{il}$ , minus the mean pressure realized downstream of the injector,  $P_{ci}$ . Two different feedback signals,  $P_{ci}$  and  $P_{cb}$ , are considered for this particular injector to allow for a shift in the acoustic response through the “mixing and burning” zone. Due to rapid entrainment of liquid into the central gas core flow, the acoustic speed is considerably reduced from that of the combustion zone. The  $P_{ci}$  signal corresponds to feedback influencing the injection responses, while the  $P_{cb}$  feedback effects the mixing and burning response. To complete the description of the mean properties, it is noted that  $\dot{m}_b$  is the sum of gas and liquid mean flow rates, or the total combustor flow.

$$\dot{m}_b = \dot{m}_{ig} + \dot{m}_{il} \quad (1)$$

Due to natural unsteadiness introduced by the combustion process the flow parameters will fluctuate from their average values. The injector will alter the phase and amplitude characteristics of these unsteady pulsations. Oscillatory injector flows respond to the variations in pressure drops on the gas and liquid sides,  $\Delta P'_{ig}$  and  $\Delta P'_{il}$ , respectively. These pressure drop perturbations are defined as the vector difference between the manifold and downstream ( $P_{ci}$ ) oscillations:

$$\Delta P'_{ig} = P'_{ig} - P'_{ci} \quad (2)$$

$$\Delta P'_{il} = P'_{il} - P'_{ci} \quad (3)$$

The pressure drop oscillations in the injector will lead to massflow pulsations,  $\dot{m}'_{ig}$  and  $\dot{m}'_{il}$ , at the injector exit plane. Transfer functions are defined for both gas and liquid sides of the injector:

$$\Pi_{ig} = \frac{\dot{m}'_{ig} / \dot{m}_{ig}}{\Delta P'_{ig} / \Delta P_{ig}} \quad (4)$$

$$\Pi_{il} = \frac{\dot{m}'_{il} / \dot{m}_{il}}{\Delta P'_{il} / \Delta P_{il}} \quad (5)$$

The injector transfer functions may be obtained by several means. Linear perturbation methods such as those described in References 6 and 15 may be used to calculate the liquid and gas injector responses, respectively. Special consideration must be taken into effect for the element under consideration, as the gas and liquid flows are in communication with each other while still inside the injector. A computational effort at determining the “total” injector transfer functions is ongoing at Purdue. The injector also serves as a mixer and the net flow produced will be assumed to be a vector sum of the gas and liquid massflow pulsations produced at the exit plane. These pulsations will be responsible for mixture ratio variations that will ultimately lead to unsteadiness in the burning in the combustion zone and attendant variations in gas evolution and chamber pressure.

The chamber transfer function relates fluctuations in mass burning rate to the fluctuating chamber pressure.

$$\Pi_{ab} = \frac{P'_{cb} / P_{cb}}{\dot{m}'_b / \dot{m}_b} \quad (6)$$

The chamber transfer function may be obtained by analytical methods such as those described in Reference 16. The additional acoustic response accounts for a possible phase shift through the mixing and burning zone as previously mentioned.

$$\Pi_{ai} = \frac{P'_{ci} / P_{ci}}{P'_{cb} / P_{cb}} \quad (7)$$

A single mixing and burning response function is used to represent the complex combustion process.

$$\Pi_{mb} = \text{fn} \left( \frac{\dot{m}'_{il}}{\dot{m}_{il}}, \frac{\dot{m}'_{ig}}{\dot{m}_{ig}}, \frac{P'_{cb}}{P_{cb}} \right) \quad (8)$$

The mixing and burning response function will presumably relate mixture ratio and massflow variations in the injector along with fluctuations of the local pressure in the mixing and burning zone. The  $\Pi_{mb}$  transfer function will be measured by experiment.

The model is anchored on the “upstream” end to a controlled input or boundary condition. In general, this controlled input results from a propellant tank, manifold, or cavitating venturi whose pressure or flowrate is isolated from downstream pressure oscillations generated by combustion feedback. Alternatively, the input could be non-zero as a result of forced oscillations being imposed on the feed system. The combustion chamber sonic nozzle provides the “downstream” boundary condition. This boundary condition may also be non-zero as a result of perturbations to the combustion chamber or modulation of the nozzle throat area. Experimental perturbation techniques are discussed in the next section.

By casting the combustor dynamics in such a detailed model, accurate phase-gain relationships must be developed for all of the inter-related processes. A closed-loop solution of the combustor transfer function model provides information on stability margins, or what type and magnitude of perturbation drives the system unstable. This is in contrast to a “response factor” approach where the open-loop response of a single limiting process, such as atomization or vaporization, is treated as the controlling stability mechanism.<sup>17</sup>

## REVIEW OF EXPERIMENTAL DEVICES

A comprehensive review of experimental techniques in examining combustion instability was included in NASA Special Publication 194, *Liquid Propellant Rocket Combustion Instability*.<sup>18</sup> Though written over thirty years ago, the techniques described in SP-194 still describe the state-of-the-art in U.S. rocket engine stability testing. The more recent review conducted by Dexter et al. provides an excellent summary on the scaling of performance and stability characteristics between full-scale and sub-scale hardware, as well as an interesting glance at Russian stability rating methodology.

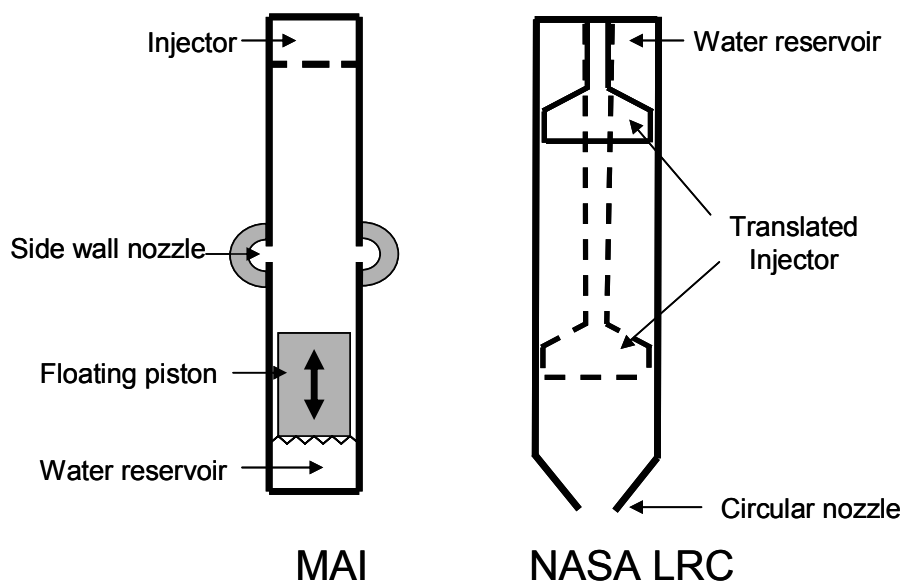
Combustion stability experiments in which there was active pulsing or chamber length variation were reviewed for possible use with the single element application. A wide range of pulsator devices were examined for their effectiveness and design qualities. The review aided in the design of the pulsator devices used on the initial combustion experiment.

### Variable Length Combustors

The length of the combustion chamber must be varied in order alter the natural acoustic frequencies of the chamber. By varying the chamber length, a range of frequencies covering the most prevalent unstable full-scale chamber modes is examined. Length variation is accomplished with either a continuous or discrete method.

In the discrete approach, the chamber length is adjusted by adding or removing sections of the combustion chamber assembly. The amount of variability in chamber length is limited to a finite number of values corresponding to all of the possible combinations of chamber assemblies. This is the major disadvantage associated with the discrete variation approach since the actual chamber resonances cannot be exactly determined a priori. The major advantage of discrete variation is the simplicity in its design—to change the chamber length; another section is either bolted up to the chamber assembly or removed. Most of the previous work in variable length combustors has been performed with a discrete examination of combustor length where the combustion chamber was simply built up in axial sections between tests.<sup>19</sup>

Continuous variation of the combustion chamber length has an advantage over discrete variation in that it is not limited to a finite number of chamber lengths. Linking a translating drive mechanism to the chamber and sealing hot gas on sliding surfaces add complexity to the variable length design. Two different experiments in which chamber length was continuously varied are shown schematically in Figure 2.



**Figure 2: Designs for Continuously Varying Combustion Chamber Length**

Bazarov tested injectors at the Moscow Aviation Institute (MAI) in an apparatus where chamber length was varied during a test. This was achieved by draining water from behind a piston that comprised the end opposite of the injector. Combustion gas was vented radially out of ports in the cylindrical side walls and collected in an exhaust manifold. Due to the manner in which the gases were exhausted, the

chamber acoustics may not be entirely representative of those in a traditional combustion chamber with a circular throat at the end opposite of the injector; however the sidewall T-shaped nozzle was said to exhibit low acoustic losses.

Stability testing of a 10 Klbf, 300 psia hydrogen/oxygen engine with a variable length chamber was conducted at NASA Lewis Research Center in the late '60's and early 70's.<sup>20</sup> The Lewis design was mechanically similar to that of MAI's in that a draining water reservoir was used to vary the chamber length. The chamber was continuously varied by a hydraulic ram that was located behind the injector. The 10.8" diameter chamber was translated at a rate of approximately 20 in/sec with a maximum stroke length of 24.7". With a single test, Lewis researchers were able to identify minimum and maximum critical lengths at which unstable combustion occurred.

### Pulsating Devices

The pulsator devices considered are classified into two categories describing the type of perturbation they impose. Impulsive disturbances are generally high amplitude perturbations which are designed to excite all frequencies equally by being enacted over a very short duration. Oscillatory disturbances are generally lower in amplitude so as to be considered "linear" perturbations and are imposed continuously at a specific driven frequency.

Bombing the combustion chamber is one of the more popular stability rating methods. Bombing involves detonating an explosive charge inside the chamber causing a rapid increase in chamber pressure. The time required to damp the oscillations generated by the bomb gives a measure of the stability of the combustor. The intensity of the initial pressure spike may be tailored by varying the amount of explosive charge contained within the bomb casing. The bomb itself is relatively simple in design consisting of a casing, explosive, and fitting. The explosive material is detonated either electrically by an input current or thermally by the heat of combustion. Care must be taken in the design in order to prevent shrapnel damage to the chamber and injector.

Pulse guns function similarly to bombs. Both devices introduce detonation waves into the combustion chamber. Pulse guns are mounted on the outside of the chamber and direct gases through a shock tube and into the chamber transverse to the injector. A pulse gun allows the chamber to be pulsed "directionally". The gun is pointed radially or tangentially into the chamber in an effort to trigger a standing or spinning tangential modes. Again, the single pulse gun is rather straightforward in its design. The amount of shrapnel introduced into the chamber is reduced as a high-pressure burst diaphragm is used to contain the charge until it overpressures. Multiple pulse guns have been fashioned from machine guns that are able to pulse the chamber at low frequencies.

Directed gas flows into the chamber have also been used to examine the stability of a combustor. Gas expansion into the chamber is more controllable, but slower, than the release of detonation products. An inert gas flow may be ramped or pulsed and may also be oriented directionally into the chamber as with the pulse guns. Gas flow into the chamber causes more of a steady velocity perturbation on the combustion process than bombing and pulse gun techniques. The duration of the velocity perturbation on bomb and pulse tests is believed to be relatively short.<sup>19</sup>

In order to maximize the effect of the oscillatory pulsator devices, oscillations are driven at the natural (1L) or harmonic (2L, 3L, etc.) frequencies of the combustion chamber. The driving frequency range of interest is typically between 1-6 kHz corresponding to the first few longitudinal and transverse modes of a booster-class or orbital transfer engine. Since the chamber length will be variable, the chamber pulsator must also be capable of varying the driving frequency to match the acoustic mode of interest. If the chamber is built up discretely, the pulsator frequency will only need to be varied over a few discrete values. The driving frequency may be reset prior to each test. If the chamber length is varied continuously, the driver must be varied in-run and will probably require a feedback controller to hold the desired length/frequency relationship throughout the stroke of the chamber.

Brown et al. used a rotating valve to create longitudinal pressure-velocity oscillations in a solid grain combustor.<sup>21</sup> On this apparatus, a rotating valve was used in conjunction with another separate fixed-area nozzle at the exhaust end of the motor. The valve consisted of 20 holes drilled in a rotating cylinder which would alternately allow gases to vent out the rotating valve port, effectively varying the throat area of the combustion chamber. Hot fire tests were driven at frequencies up to 800 Hz with this device.

Micci et al. have used a rotating geared wheel to modulate the throat area of a solid rocket motor.<sup>22</sup> This device operates on the same principle of flow area variation. The outer edge of the geared wheel was set just outside of the combustor exit and created an effective throat area variation as the teeth of the gear passed over the throat. Pressure oscillations of 1-5% of mean chamber pressure were driven at frequencies up to 2300 Hz with this apparatus. The spinning wheel could also be slowed by a braking mechanism allowing a range of frequencies to be examined in one test.

Researchers at ONERA also applied the rotating gear modulator concept to solid and liquid motors.<sup>23,24,25,26</sup> In this experiment, a rotating wheel was placed in a plane perpendicular to the combustion gas flow. A set of three teeth on a small sector of the 14" wheel were used to modulate the throat area at frequencies up to 10 kHz on each revolution. After the third tooth passed over the throat, the combustor was allowed to naturally damp for the remaining portion of the revolution. While operating at 6 kHz and completely obstructing the throat during each pass of a gear tooth, this device was able to generate a 10% peak-to-peak chamber pressure variation. Although not truly a continuous pulsator, this method could be used to drive selected frequencies throughout the duration of a test if desired and numerous pulses could be enacted in a single test.

Liquid lines have typically been pulsed by way of a "hammer" mechanism. The hammer is loaded by a detonation or gas pressure until it shears off its restraining pins. The hammer travels a short distance before striking a piston which transmits the hammer's momentum into the fluid in a short duration pulse (on the order of 100  $\mu$ sec) before it is stopped by a retainer. The amplitude of the pulse can be varied by adjusting the hammer momentum, restraining pin strength, and/or stroke of the piston/anvil piece.

Continuous feedline oscillations have been driven by means of a bleed-off siren apparatus installed in the feedline. The device, as described in Reference 19, was used to vary the flow in a full-scale engine. Flow was modulated by the periodic opening and closing of a bleed line. The drive shaft, operating at 600 RPM, was designed to open and close at a frequency of 200 Hz. The siren was effective at modulating the flow, but experienced damaging vibrations at high frequencies. The experimental set-up at MAI also incorporated a feedline pulsator of the bleed-off siren type. This pulsator was able to generate a chamber pressure modulation of 175 psia at frequencies up to 3000 Hz.<sup>7, 27</sup>

Early experimental work at Princeton focused on developing the time-lag theory also incorporated a feedline flow modulation unit.<sup>28</sup> A short-stroke piston imposed a sinusoidal disturbance on the propellant flow. The piston was located downstream of a cavitating venturi to achieve the desired mean flowrate. Driving frequencies were relatively low, on the order of 100 Hz.

A high frequency actuator located on the fuel manifold might be used to impose flow oscillations. Magnetostrictive actuators have been used successfully to modulate injector flow in a lab-scale combustor using a small pintle injector.<sup>29</sup> In these experiments, liquid fuel at a steady flowrate of approximately 0.5-0.6 g/sec was modulated at frequencies up to 5 kHz using a 1 mm in diameter pintle head. The supply pressure to the pintle injector was 1200 psia and the back pressure (during cold flow tests) ranged from 0-150 psia. Scaling such pintle-type injectors up to higher flowrates and pressures of a practical injector element may require a prohibitive pressure drop across such a pintle.

Instead of using the actuator to cause a variable restriction in a flow passage, it might be used as a small piston to compress the liquid inside an injector manifold. This approach has been used successfully in a low-flow, lab-scale combustor to modulate propellant atomization and drive combustor pressure oscillations at frequencies up to 8000 Hz.<sup>30</sup>

## CURRENT EXPERIMENTAL WORK

An ongoing combustion experiment is aimed at developing the single element stability characterization approach. The designed experiment includes the use of an external pulsating device to perturb the combustion process and a discretely variable length combustion chamber to alter the natural longitudinal frequencies. Stability margins will be determined from the measured dynamic pressure response to the input pulses. Hot-fire and “cold”-flow tests performed with this test apparatus will provide the initial data used in the development and validation of the individual transfer functions that compose the aforementioned analytical model. Testing is being carried out at Purdue University’s High Pressure Combustion Laboratory.

### Combustor Design

For simplicity, the injector was designed for use with storable propellants and operation at moderate pressure. Hydrogen peroxide (90% by weight) decomposed to superheated water and oxygen vapor is used to oxidize a kerosene fuel. A chamber pressure of 400-psia was selected to meet several design requirements. A chamber contraction ratio of 5 and equivalence ratio of 1.5 were selected to give sufficient margin for propellant auto-ignition based on considerable test experience with a hydrogen peroxide/kerosene dump combustor.<sup>31</sup> Combustor parameters are summarized in Table 1.

Fuel flowrate, lb/sec	0.2
Oxidizer flowrate, lb/sec	1.067
Chamber pressure, psia	400
Mixture Ratio	5.33
Equivalence Ratio	1.5
Chamber Mach number	0.12
Oxidizer post Mach number	0.24
Oxidizer injector $\Delta P$ , psia	120
Fuel injector $\Delta P$ , psia	48
Film thickness, in	0.0128
Injector diameter, in	0.908
Number of tangential channels	8
Diameter of tang. channels, in	0.035
Chamber diameter, in	1.83
Throat diameter, in	0.82
Combustion chamber length, in	20.94
Ox post length, in	6.28

**Table 1: Injector/Combustor Parameters**

An assembly of the injector/combustor assembly is shown in Figure 3. The combustor is tested in a horizontal orientation with the square ox injector block mounting to a thrust stand on the face opposite the ox injector. A catalyst bed attaches directly to the top flat face of the block. Decomposed peroxide flows from the catalyst bed into a manifold within the ox injector block where it is then introduced into the oxidizer injector post through ten radial orifices. The ox injector post consists of two parts—one is inserted into the ox manifold and the other into the fuel manifold. Inserts with different lengths and locations of inlet ports may be tested to examine their influence on combustion dynamics.

The heat sink combustion chamber consists of a single 5” long OFHC copper section bolted to the fuel manifold housing and a number of steel flanged chamber sections. The copper section is ported for a PCB water-cooled, helium-bleed, high-frequency pressure transducer, as well as static pressure measurements. The chamber sections are used to extend the chamber length and allow for a range of

natural longitudinal frequencies to be examined. Along with the high-frequency pressure measurement near the head-end of the combustion chamber, dynamic pressures are simultaneously recorded at three other locations on the combustor. One measurement is taken in each of the two propellant manifolds, while another transducer port is located at the closed end of the ox injector post as shown in Figure 4.

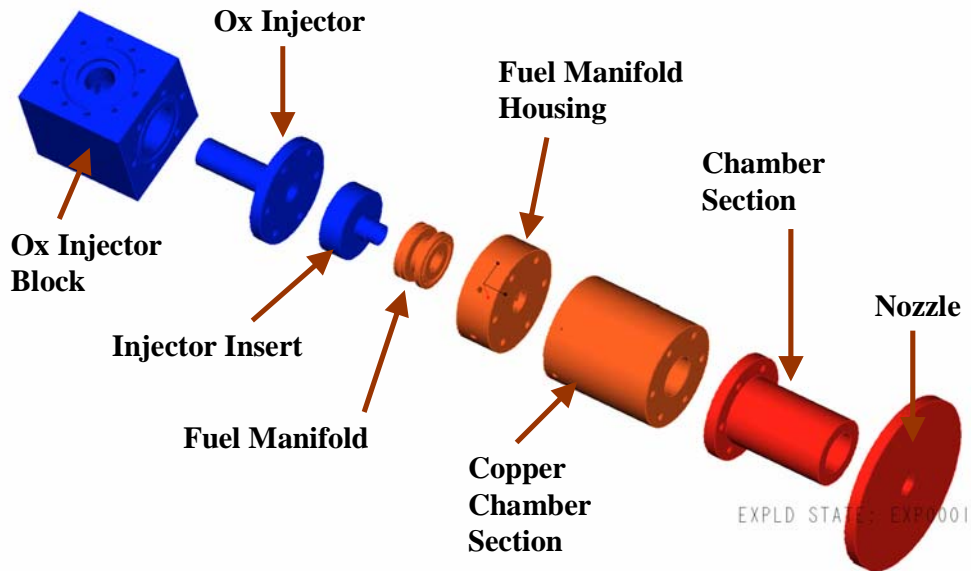


Figure 3: Injector/Combustor assembly

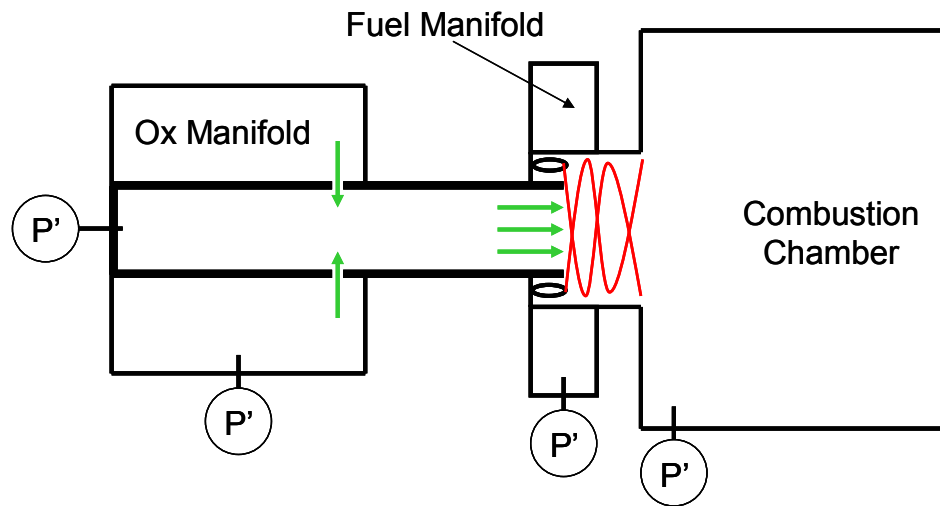
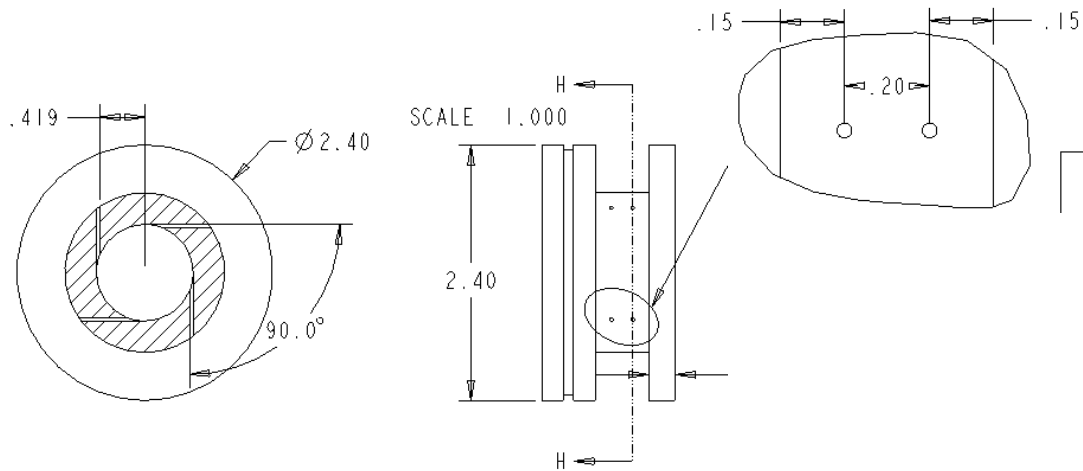


Figure 4: Combustor Dynamic Pressure Measurements

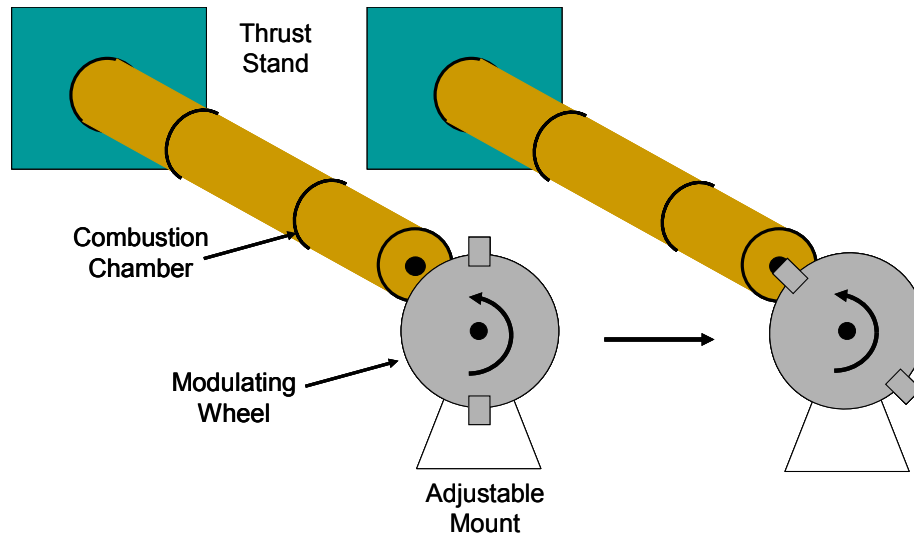
The fuel swirl injector, shown in Figure 5, consists of two rows of four inlet ports that inject the fuel tangent to the injector wall. The ox injector insert extends past the fuel inlet ports thereby initially sheltering the liquid sheet from the gas core. As shown schematically in Figure 4, the swirling liquid sheet is exposed to the high velocity gas flow while still inside of the injector. This leads to rapid liquid atomization and propellant mixing inside the injector.



**Figure 5: Fuel Injector Design**

In this first examination, an attempt was made at designing the combustor to be unstable. Different known instability mechanisms were exploited in order to make the combustor sensitive to high-frequency chamber oscillations. In particular, the chamber and ox post lengths were sized to encourage a longitudinal or “organ-pipe” type instability. The nominal ox post length, generally much shorter than the length of the combustion chamber, was “lengthened” somewhat so that its first longitudinal frequency (2200 Hz) matched the second harmonic of the combustion chamber. From a simple acoustical view, this configuration supports longitudinal pressure oscillations occurring at the even longitudinal modes (2L, 4L, etc) of the combustion chamber. The oxidizer post was designed for minimum damping of these pressure oscillations. A closed-end acts as a reflecting surface for waves that propagate down the ox tube. Radial injection ports are placed at the midpoint of the ox tube—the location corresponding with the pressure node for the ox post 1L mode—to yield minimum damping of the resonant frequency. Additionally, the fuel injector ports were oriented to provide maximum sensitivity to a fluctuating pressure differential across the ports. The two rows of inlet ports were spaced in an attempt that the downstream ports would amplify the massflow pulsations of the upstream row.

A pulsating device has been designed to impose a number of impulsive disturbances on the combustor during a single test. A rotating wheel with two diametrically opposed “teeth” periodically modulates the throat area of the combustor. This device is similar to the one tested by ONERA.<sup>23-6</sup> The pulse amplitude is adjusted by varying the area and duration that the teeth block the throat. The wheel and motor are affixed to a rigid mount that may be adjusted relative to the combustor which is attached to the thrust stand. A schematic diagram of the pulsator is shown in Figure 6.



**Figure 6: Combustion Chamber Pulsator Wheel**

### Test Approach

The major objective of the current test program is to initiate the single element characterization approach by beginning to acquire the data necessary to determine the individual transfer functions in the analytical model. In general, these transfer functions may be quite complex and, in the case of the mixing and burning ( $\Pi_{mb}$ ) and injector ( $\Pi_{il}$  and  $\Pi_{ig}$ ) functions, highly non-linear. Validation of all the individual transfer functions is beyond the scope and capability of the present experiment. However, the acoustic response transfer functions,  $\Pi_{ai}$  and  $\Pi_{ab}$ , do lend themselves to experimental verification through cold-flow tests and, in the limit of “linear” or small oscillations, linear perturbation methods may be used to analytically derive injector responses,  $\Pi_{il}$  and  $\Pi_{ig}$ . The form of the remaining function,  $\Pi_{mb}$ , is deduced from hot-fire test measurements.

“Cold”-flow tests are conducted to provide experimental verification of the acoustic response transfer functions,  $\Pi_{ai}$  and  $\Pi_{ab}$ . In these tests, decomposed peroxide or hot air will be flowed through the ox injector while a gaseous or liquid inert is flowed through the fuel injector. Dynamic pressure measurements taken during pulsed tests will yield the phase and gain relationships between the chamber and ox post transducers enabling the “open-loop” (no combustion feedback) acoustic response transfer functions to be verified.

Hot-fire combustion tests provide the complete or “closed-loop” response of the combustor model to the input pulse generated by the modulator wheel. For a given injector design, parametric studies will be conducted by varying flowrates and pressures to analyze the form of the mixing and burning response,  $\Pi_{mb}$ . Examination of injector design subtleties may also be carried out to determine their effect on the overall sensitivity of the combustion process to driven pulses.

### **FUTURE WORK**

Injector characterization testing is intended to be performed at nominal operating pressures and flowrates in order to alleviate uncertainties associated with scaling. Further development of the single element approach may utilize the capabilities of Purdue University’s High Pressure Combustion Laboratory, which can test high-pressure booster-class or orbital transfer engine full-scale injector

elements at their nominal conditions. The experiment may also be developed to include impulsive or continuous perturbations at different locations on the combustor.

## SUMMARY

Purdue University is currently conducting an investigation of the combustion stability margins of a single element injector. A gas-centered, liquid swirl injector was selected for the initial test series. The adopted analytical approach characterizes the combustion process by using a “controls-systems” based model consisting of a set of inter-related transfer functions to describe the dynamics of combustion. Initial experimental work will focus on measuring the combustion response to impulsive disturbances imposed by rapid throat area modulation. Testing the combustor with discrete chamber lengths will examine the effect of varying the natural acoustic frequencies. Relative stability margins will be determined between different injector design parameters. Further development of the single element approach will be advanced by experience gained from the present experiment.

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## REFERENCES

1. Dexter, C. E., Fisher, M. F., Hulka, J. R., Denisov, K. P., Shibanov, A. A., and Agarkov, A. F., “Chapter 16: Scaling Techniques for Design, Development, and Test,” in Habiballah, M., Popp, M., and Yang, V., *Liquid Rocket Combustion Devices – Aspects of Modeling, Analysis, and Design, Proceedings of the Second International Symposium on Liquid Rocket Propulsion*, Chatillon, France, 1995.
2. Vasin, A., et al., United States Patent, US 6,244,041 B1, Jun. 12, 2001.
3. Hutt, J. J., and Hulka, J. R., “Chapter 2: Instability Phenomena in Liquid Oxygen/Hydrogen Propellant Rocket Engines,” in Yang, V., and Anderson, W.E., *Liquid Rocket Engine Combustion Instability*, AIAA, Washington, D.C., 1995.
4. Mayer, W. O. H., Schik, A. H. A., Vielle, B., Chauveau, C., Gokalp, I., Talley, D. G., and R. D. Woodward, “Atomization and breakup of cryogenic propellants under high-pressure subcritical and supercritical conditions.” *Journal of Propulsion and Power*, Vol. 14, No. 5, Sep.-Oct. 1998, pp. 835-842.
5. Delplanque, J.-P. and W. A. Sirignano, “Transcritical vaporization of liquid fuels and propellants,” *Journal of Propulsion and Power*, Vol. 15, No. 6, Nov-Dec. 1999, pp. 896-902.
6. Bazarov, V. and Yang, V., “Liquid Propellant Rocket Injector Dynamics,” *Journal of Propulsion and Power*, Vol. 14, No. 5, Sep-Oct 1998, pp. 797-806.
7. Bazarov, V., “Influence of Stationary and Dynamic Parameters on High Frequency Combustion Stability,” AIAA Paper 96-3119.
8. Long, M. R., Bazarov, V. G., Anderson, W. E., “Main Chamber Injectors for Advanced Hydrocarbon Booster Engines,” AIAA Paper 2003-4599.
9. Cheng, G. C., Davis, R. R., Johnson, C. W., Muss, J. A., Greisen, D. A., and Cohn, R. K., “Development of GOX/Kerosene Swirl-Coaxial Injector Technology,” AIAA Paper 2003-4751.
10. Cohn, R. K., Strakey, P. A., Bates, R. W., Talley, D. G., Muss, J. A., and Johnson, C. W. “Swirl Coaxial Injector Development,” AIAA Paper 2003-0124.
11. Muss, J. A., Johnson, C. W., Cohn, R. K., Strakey, P. A., Bates, R. W., Talley, D. G., “Swirl Coaxial Injector Development Part I — Test and Results,” 38th JANNAF Combustion Subcommittee Meetings, Destin, FL, April 8-12, 2002.
12. Cheng, G., Johnson, C. W., and Muss, J. A., “Swirl Coaxial Injector Development Part II — CFD Modeling,” 38th JANNAF Combustion Subcommittee Meetings, Destin, FL, April 8-12, 2002.

- 
13. Canino, J. V., Heister, S. D., and Garrison, L., "Hydrodynamics Modeling of Oxidizer-Rich Staged Combustion Injector Flow," 52<sup>nd</sup> JANNAF Propulsion Meeting, Las Vegas, NV, May 10-13, 2004.
  14. Merkle, C. L., Sankaran, V, and Ellis, M., "Computational Simulation of Acoustic Modes in Rocket Combustors," 52<sup>nd</sup> JANNAF Propulsion Meeting, Las Vegas, NV, May 10-13, 2004.
  15. Hutt, J. J., and Rocker, M., "Chapter 12: High-Frequency Injection-Coupled Combustion Instability," in Yang, V, and Anderson, W.E., *Liquid Rocket Engine Combustion Instability*, AIAA, Washington, D.C., 1995.
  16. Strahle, W. C., et al., "Chapter 3: Dynamics of Combustion and Flow Processes," in Harrje, D. T., and Reardon, F. H, *Liquid Propellant Rocket Combustion Instability*, NASA SP-194, Washington, D.C., 1972.
  17. Sirignano, W. A., et al., "Chapter 4: Analytical Models of High Frequency Combustion Instability," in Harrje, D. T., and Reardon, F. H, *Liquid Propellant Rocket Combustion Instability*, NASA SP-194, Washington, D.C., 1972.
  18. Harrje, D. T., and Reardon, F. H, *Liquid Propellant Rocket Combustion Instability*, NASA SP-194, Washington, D.C., 1972.
  19. Combs, L. P., et al. "Chapter 10: Stability Rating," in Harrje, D. T., and Reardon, F. H, *Liquid Propellant Rocket Combustion Instability*, NASA SP-194, Washington, D.C., 1972.
  20. Morgan, C. J., and Sokolowski, D. E., "Longitudinal Instability Limits with a Variable Length Hydrogen-Oxygen Combustor," NASA TN-D-6328, Washington, D.C., April 1972.
  21. Brown, R. S., Erickson, J. E., and Babcock, W. R., "Combustion Response Function by the Rotating Valve Method." *AIAA Journal*, Vol. 12, No. 11, 1974. pp. 1502-1510.
  22. Micci, M. M., Caveny, L. H., and Summerfield, M., "Solid Propellant Rocket Motor Responses Evaluated by Means of Forced Longitudinal Waves." AIAA Paper 77-974.
  23. LeCourt, R., and Foucaud, R., "Experiments on Stability of Liquid Propellant Rocket Motors." AIAA Paper 87-1772.
  24. Vuillot, F., and Kuentzmann, P., "Flow Turning and Admittance Correction: An Experimental Comparison," AIAA Paper 85-1484.
  25. Barrere, M., Nadaud, L., and Lhuillier, J. N., "ONERA and SNPE Recent Work on Solid Propellant Combustion Instability," *Journal of Spacecraft*, Vol. 11, No. 1, Jan. 1974, pp. 33-40.
  26. LeCourt, R., Foucaud, R., Kuentzmann, P., "Etude experimentale de la sensibilit e acoustique d'injecteurs de moteurs fusees a ergols liquids," *La Recherche Aerospatiale*, no. 5, pp. 325-336, 1986.
  27. Bazarov, V. G., personal patent list.
  28. Crocco, L., Grey, J., and Matthews, G. B., "Preliminary Measurements of the Combustion Time Lag in a Monopropellant Rocket Motor," *5th Symposium (Int'l) on Combustion*, Reinhold, 1965.
  29. Neumeier, Y, Lubarsky, E., Heising, R., Israeli, O., Neumaier, M., and Zinn, B.T.. "Liquid Injector Actuator for Control of Combustion Processes." AIAA Paper 98-3540.
  30. Anderson, W. E., Miller, K. L., Ryan, H. M., Pal, S., Santoro, R. J., and Dressler, J. L., "Effects of Periodic Atomization on Combustion Instability in Liquid-Fueled Propulsion Systems." *Journal of Propulsion and Power*, vol. 14, no. 5, pp. 818-825.
  31. Sisco, J., Mok, J, Austin, B, and Anderson, W, "Auto-ignition of Kerosene by Decomposed Peroxide in a Dump Combustor Configuration", AIAA Paper 2003-4921.