Overview of Combustion Instabilities in Liquid Rocket Engines - Coupling Mechanisms & Control Techniques

Conference Paper · July 2013

DOI: 10.2514/6.2013-4106

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Overview of Combustion Instabilities in Liquid Rocket Engines - Coupling Mechanisms & Control Techniques

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The spontaneous excitation of high frequency combustion instabilities has been a design issue to overcome for liquid rocket engines all throughout their history. This paper provides a critical review of experimental and theoretical combustion instability mitigation techniques that has lead to the design of a new laboratory-scale experiment. Recently, there has been work done to develop new passive instability suppression techniques, some of which are based upon traditional methods (e.g. an asymmetric baffle system and asymmetric fuel injector distribution). Aside from this, various active control techniques (e.g. modulation of the fuel through both actuation valves and acoustic excitation) have shown to effectively dampen instability modes. The results from this review were used to detail a combustion instability study that aims to control the dominant combustion instability mode by strategically applying pressure perturbations within the oxidizer post of an injector.

I. Historical Significance

Perhaps the most notable example of combustion instabilities pertaining to liquid rocket engines (LRE's) occurred during the design of the F-1 engine for the Saturn V in the 1950's & 1960's. During the development of the F-1 engine, the spontaneous excitation of combustion instabilities within its combustor was the main issue that plagued its early design. Starting in 1959, a 17 month testing campaign using the first iteration of the engine was performed, consisting of 44 full-scale tests. Of these tests, high amplitude combustion instabilities occurred in approximately half (20/44 tests). With this critical design issue hindering the success of the engine, Project First was established to solve the instability issue of the F-1 [1].

Under Project First, the combustion instability issues of the F-1 engine were heavily investigated to generate a stable engine design. What began in 1962, the program carried out over 2,000 full scale engine tests with over 100 various injector designs (108 injectors) in an attempt to solve and explain these issues. From these tests, it was determined that certain types of instability (i.e. transverse instabilities) were more detrimental to the engine's operation and overall stability than others (i.e. longitudinal instabilities). These transverse modes were seen as the most severe and had the largest effect on the propellant interaction processes that take place within the combustor (i.e. injection, atomization, vaporization & mixing) and vice-versa. Thus, the focus of solving the instability issue of the F-1 was directed towards developing dampening techniques for the detrimental transverse instability modes [1].

In order to successfully dampen the transverse instability modes to a reasonable level, a passive symmetric baffle system applied to the injector plate was developed. It was found that through a combination of the appropriate injector design and baffle pattern, that the onset of high frequency transverse instabilities could be successfully prevented within the engine [1].

While Project First was successful in delivering a stable F-1, it took many design iterations and full-scale tests to find a workable solution that ended up being tailored specifically to the F-1. Thus, this design experience shows that fundamental understanding behind the phenomenon of combustion instabilities is vital to avoid costly liquid rocket engine development campaigns.

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II. Background

II.A. Thermo-Acoustic Instabilities

During the burning of propellants, periodic oscillations of combustion may occur within the combustion chamber, which are often manifested as periodic oscillations in chamber pressure. When these pressure fluctuations are less than ± 5 % of the mean chamber pressure, operation of the combustor is considered "smooth", while if the periodic oscillations of pressure within the combustor are systemically ordered and exceed that of $p'/p_c \approx 10$ %, combustion instabilities are present and "rough" combustion conditions exist. Typically, rough combustion is more likely to occur at chamber conditions conducive to improved performance, where the rate at which the combustor supplies energy on a per volume basis is high [2, 3].

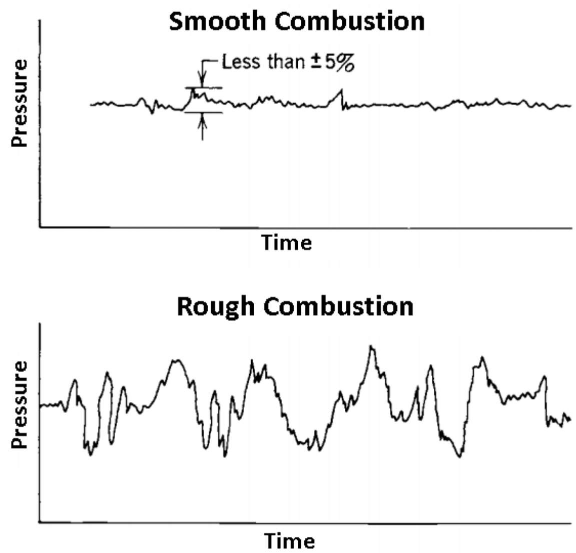

Figure 1: Comparison Between Pressure Oscillation Traces for Smooth & Rough Combustion: Taken and edited from [2]

Generally, flames have naturally occurring instabilities, which produce noise in two forms; the first kind of noise is generated from the presence of instabilities within the turbulent flow of the reaction zone (deemed autonomous noise), while the second type of noise comes from the coupling between the chamber acoustics and the flame front. This coupling noise is the acoustic source of significance in studying the onset of spontaneous combustion instabilities [4].

The unsteady heat release associated with combustion can be thought of as an acoustic source which propagates sound disturbances throughout the combustor. Once these pressure waves traveling away from the source see an acoustic boundary, they reflect back towards the flame; the combination of these reflected waves create acoustic pressure and velocity fluctuations in the vicinity of the injector plate, which alter the incoming propellant stream and cause local perturbations to the unsteady heat release rate. If these acoustic oscillations alter the burning rate with the correct phasing, the intensity of the instabilities within the reaction zone is increased and cause amplified flame oscillations. This in turn causes larger amplitude acoustic disturbances to be generated from the unsteady heat release oscillations, which then drive the instability's growth [3, 4, 5].

The presence of combustion instabilities within the combustion chamber of liquid rocket engines can have detrimental effects to both the operation and lifetime of the engine. The effect of combustion instabilities can range from an increase in acoustic noise to a total failure of the chamber through increased heat transfer to the engine walls or large amplitude structural vibrations. Structural concerns due to enhanced heat transfer have been seen to primarily affect the injector plate and nozzle throat of liquid rocket engines. Knowing the potential consequences due to the presence of combustion instabilities, it is important to understand the physical driving mechanisms behind this phenomenon [3, 7].

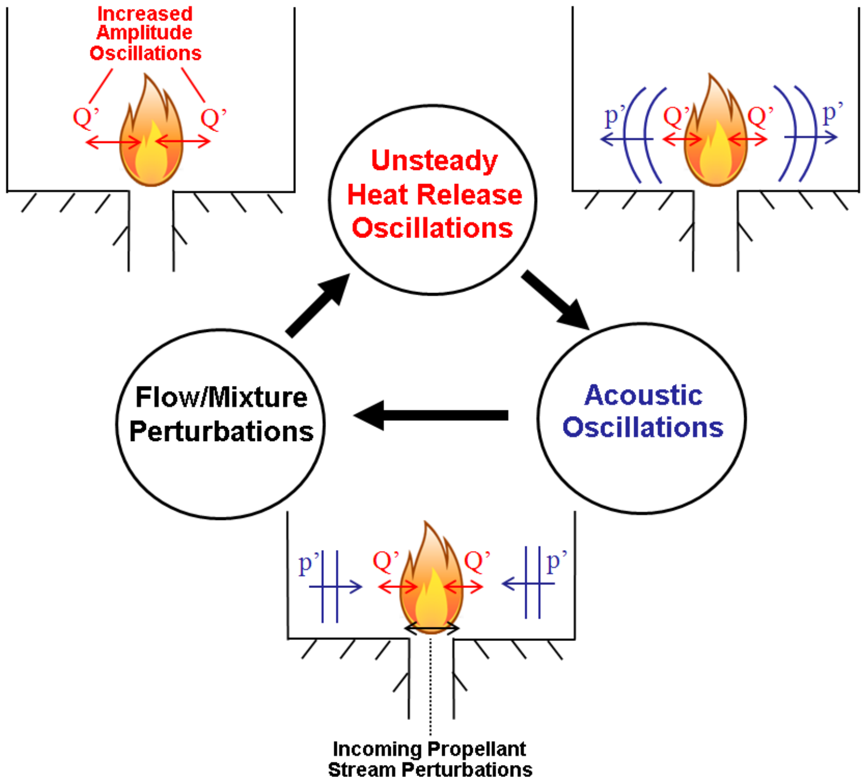

Figure 2: Unsteady Flame/Acoustic Interaction Schematic: Based off a similar diagram presented in [6]

Although the onset of combustion instabilities tend to be specific to each liquid rocket engine design, the physical mechanisms behind the driving and dampening of combustion instabilities within the combustion chamber is applicable to all engine designs. Essentially, combustion instabilities arise when the energy increase from the unsteady heat release acoustic energy is larger than that of the acoustic energy losses to the system; this means that there is a vital energy exchange that takes place with the acoustic energy dispersed throughout the combustor. The way in which this energy is disseminated dictates the propagation of combustion instability modes.

Within the combustor, the chemical energy that is present during the mixing of propellants is transformed into various forms of energy, one of which is acoustic energy. From this, there exists a trade-off that takes place between the acoustic energy generated through unsteady heat release and the acoustic losses dispersed from the unsteady heat source. If this acoustic energy generated is greater than the acoustic losses produced, combustion instabilities can propagate within the combustor. Thus, the more acoustic dampening that exists within the chamber, the less likely combustion instabilities will be generated. This leads combustors tending to be more stable to incorporate walls which have greater acoustic absorption (reduced reflectivity), promoting acoustic energy dissipation through the system boundaries. For typical liquid rocket combustor operating conditions, however, the acoustic losses tend to be less than the acoustic energy present within the system, which creates an environment conducive for the chamber acoustic modes to become excited, as well as spontaneous combustion instabilities. Thus, the acoustic dampening and boundary conditions of the combustion chamber play a large role in the onset of combustion instabilities [7,8].

Formally, the theory has been mathematically represented by Lord Rayleigh in 1878. In his study, Rayleigh came up with a mathematical model that described the exchange of the acoustic energy generated by sound waves and the energy created through unsteady heat release. It should be noted that there are certain assumptions given to his model. Rayleigh's criterion called for the fluid to be inviscid, and as with many acoustic models, only considered linear perturbations (thus neglecting any higher order interactions that may be present within the system). Thus, Rayleigh's criterion states that the amplitude of a sound wave traveling through a medium with the aforementioned assumptions will increase if the following mathematical condition is met [7,8,9]:

$$\int_0^L \frac{(\gamma-1)}{\overline{\rho c^2}}\overline{Q'p'}dx > (p'u'A)_L - (p'u'A)_0 \tag{1}$$

γ – Specific Heat Ratio of the Fluid	p – Pressure
ρ – Density of the Fluid	x – Axial Location
c – Sound Speed through the Fluid	A – Cross-sectional Area
Q – Heat Release per unit Length	L – Length of the Combustor
u – Velocity	

Note: The prime terms are fluctuating quantities
The subscripts 0 & L denote the combustor inlet and exit plane [7]

Two conclusions can be reached from Rayleigh's criterion: (1) Acoustic perturbations are enhanced when the total energy gained through unsteady combustion is larger than the total energy dissipated through the system boundaries (2) Energy of the acoustic perturbations is increased when the rate of unsteady heat release is in phase with the pressure oscillations. Thus, if the unsteady heat release rate is of a large enough amplitude, with the phase offset between the acoustic pressure oscillations and the unsteady heat release rate being approximately zero (at least $|\phi^o| < 90^o$), growth of the instability is promoted. From this, Rayleigh's criterion has proven as a useful method to quantify the onset of combustion instabilities [3, 7, 9].

II.B. Low Frequency Combustion Instabilities

Within the combustion chamber, there can be multiple combustion instability mode types that can be excited during operation. Largely, these are categorized as either low frequency (LF) or high frequency (HF) instabilities. Low frequency instabilities are primarily due to coupling of the injector or propellant feed system to the unsteady heat release from combustion. This type, referred to as "chugging" instability, is normally on the order of f ≈ 100 Hz or lower and typically has a linear growth rate from low to high amplitudes. When the feed system couples with combustion at these frequencies, unsteady heat release is onset by fluctuations present within the propellant injection system, which then couple with the acoustic modes of the chamber, generating the feedback necessary to sustain instability growth [10].

Within the combustion chamber, very low frequency instability modes can also be excited (on the order of f ≈ 1 − 100 Hz). These instabilities, denoted as "POGO" instabilities, are attributed to the oscillation of the propellant flow rate, which arise from gravitational force loading on the liquid propellant storage tanks. The driving mechanism behind POGO instabilities is the coupling of chamber thrust oscillations to the structural mode of the rocket. While this type of instability is related to the engine of the rocket, it does not interact with the combustion of propellants primarily, as this instability type acts at such low frequencies (with extremely long time periods) that it cannot alter the mechanisms for combustion; it is for this reason that POGO is generally not classified as a primary type of combustion instability. Noted in Table 1 is a historical example of the Titan II, 1st Stage Engine, which experienced a low frequency POGO instability during its development [10, 11].

Table 1: A Historical Example of a Liquid Rocket Motor that Experienced a Low Frequency "POGO" Instability: Taken and edited from [11]

PROJECT	MOTOR	ORGANIZATION CONTRACTOR	PROPELLANTS	THRUST (lbf)	PERFORMANCE (%)	CHAMBER PRESSURE (psia)	INSTABILITY ENCOUNTERED	STABILIZATION DERIVES	INJECTOR TYPE
Gemini	Titan II 1st Stage	USAF/NASA Aerojet	50% N_2H_4 50% UDMH } A50 N_2O_4	236,400	97.2	783.0	POGO Mode ±2.5g	Standpipe inserted into N_2O_4 feedlines	Like doublet

II.C. High Frequency Combustion Instabilities

High frequency instabilities, which are sometimes referred to as "screech" modes, tend to be on the order of f ≈ 1,000 Hz – 10,000 Hz and are the most damaging of instability types. These instabilities are believed to be the most dangerous because they are characterized by very large acoustic pressure and velocity fluctuations at high frequencies, which are highly localized throughout the combustor; these acoustic fluctuations lead to an increase in localized heat release rates through faster mixing of the propellants, and if the localized heat release rate becomes too large, it can ultimately cause harm to the combustor [7].

Longitudinal Instabilities

High frequency instabilities can be classified as either longitudinal, transverse, or a combination of the two. High frequency longitudinal modes have oscillations that fluctuate along the axial direction within the combustor. Longitudinal mode shapes are typically independent of the combustor cross sectional shape, but rather are dictated by the longitudinal boundary conditions of the combustor. In liquid rocket engines, however, there exists some natural damping of these instabilities due to the nozzle and axial spatial distribution of combustion, making this instability type generally less harmful than transverse modes. Seen in Table 2 is a historical example of the Titan II, 2nd Stage Engine, which experienced a high frequency longitudinal instability during its development [10, 11].

Table 2: A Historical Example of a Liquid Rocket Motor that Experienced a High Frequency Longitudinal Instability: Taken and edited from [11]

PROJECT	MOTOR	ORGANIZATION CONTRACTOR	PROPELLANTS	THRUST (lbf)	PERFORMANCE (%)	CHAMBER PRESSURE (psia)	INSTABILITY ENCOUNTERED	STABILIZATION DERIVES	INJECTOR TYPE
Gemini	Titan II 2nd Stage	USAF/NASA Aerojet	50% N_2H_4 50% UDMH } A50 N_2O_4	100,000	97.4	827.0	Longitudinal mode	7 compartment copper baffles	Quadlet

Transverse Instabilities

Transverse instability modes have oscillations that propagate perpendicularly to the injector surface. As opposed to longitudinal modes, transverse mode shapes are affected by both the cross sectional shape of the combustor and the combustor wall boundary conditions. For typical cylindrical combustors, transverse modes are manifested as one of the following: (1) Purely Tangential, (2) Purely Radial or (3) Combined Tangential-Radial Modes. Also, combinations of longitudinal and transverse modes are possible, but generally unlikely due to natural damping of longitudinal modes. As such, purely transverse modes tend to be the most dangerous type of high frequency instability. A schematic of some purely tangential and radial modes can be seen in Figure 3 [10, 11]:

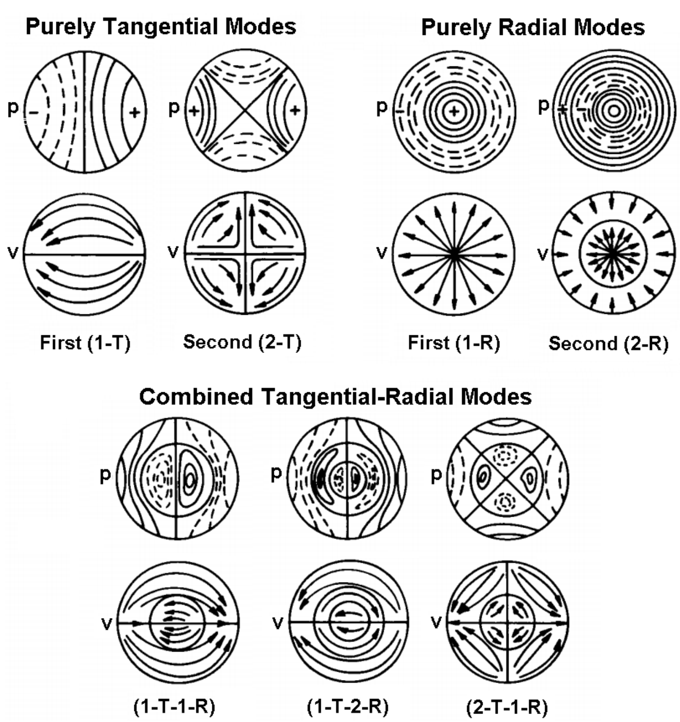

Figure 3: Schematic Diagrams for Common Transverse Instability Modes [10]

Tangential modes have pressure node lines which split the combustor in the circumferential direction. These instabilities are either one of two variations: (1) Spinning or (2) Standing. Spinning tangential modes occur when the instability node lines spin tangentially around the chamber at a rate equal to the instability frequency in a clockwise/counter-clockwise fashion (*Note: The spinning direction is arbitrary*). Standing tangential modes, on the other hand, occur when the instability nodes have a fixed orientation in the combustor. While these two mode variations are independent of one another, it has been seen that spinning tangential modes are able to be transformed into standing modes spontaneously and standing tangential modes can also shift node positions during operation. Thus, a hybrid of these mode variations is possible in liquid rocket engine combustors [10, 12].

Radial modes have circular pressure node lines oriented orthogonal to the radial axis of the combustor. Due to the orientation of the circular node lines for radial modes, there does not exist multiple variations of this mode type. The final type of high frequency transverse instabilities are combined tangential-radial modes. As the name suggests, combined modes have both a tangential and radial component, which have node lines that split the chamber in both the circumferential and radial directions. As this mode type has a tangential component, both spinning and standing variations of this type are possible [10].

First Tangential Mode Instability

Upon considering all of the high frequency instabilities, historically, the first tangential (1-T) mode has proven to be the most harmful. The most harmful instability modes are those which have the highest energy content associated with its pressure oscillation and the first tangential mode is most often this mode that is excited within liquid rocket engines [13].

As with all tangential instabilities, the first tangential mode can have either spinning or standing variations. Essentially, the first spinning tangential mode is characterized by a high heat intensity pocket of combustion products moving tangentially around the inside of the combustor, close to the inner wall. In other words, when the spinning 1-T mode is active, combustion products spin unabated around the combustor. The first standing tangential mode, on the other hand, is typified by a high heat pocket of combustion products which travels back and forth across the combustor, perpendicular to its node line. Cycle images for the two variations of the first tangential mode can be seen in Figures 4 & 5 [12].

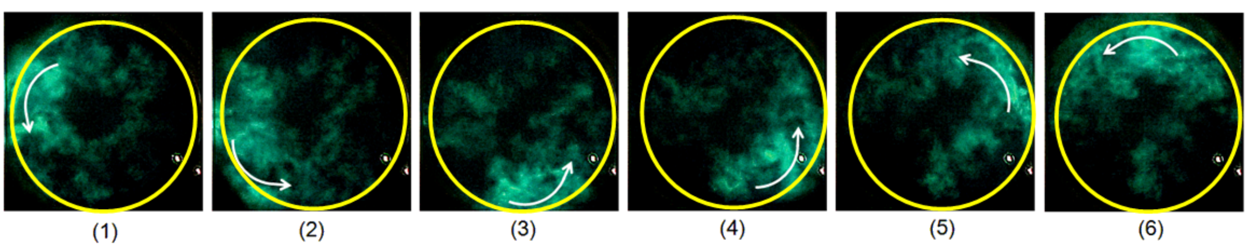

Figure 4: Images Documenting One Cycle of the Spinning First Tangential Mode [12]
Note: For this model LRE, the frequency of this instability was approximately $f \approx 5{,}000$ Hz.

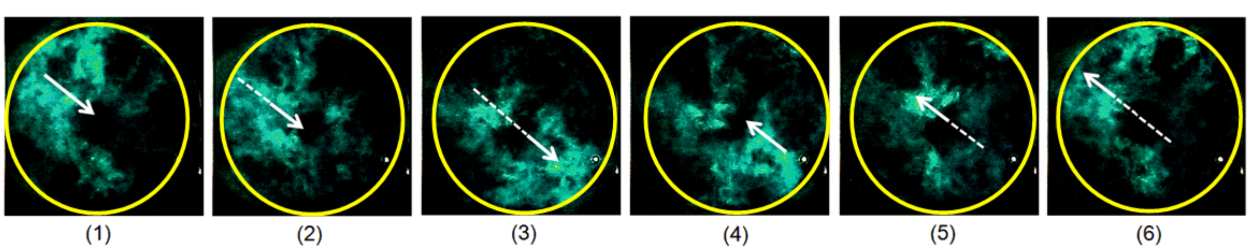

Figure 5: Images Documenting One Cycle of the Standing First Tangential Mode [12]
Note: For this model LRE, the frequency of this instability was approximately $f \approx 5{,}000$ Hz.

While both of these mode variations (or a combination of the two) are possible, the first spinning tangential mode has shown to be the most fierce and harmful transverse mode. This can be primarily attributed to the increased heat transfer to the combustor walls. Spinning modes are the most efficient at perturbing hot combustion products towards the combustor walls, while also increasing combustor performance through enhanced chemical mixing. Combined, these two effects cause spinning transverse modes to be associated with the greatest increase of heat transfer upon their excitation. As seen in Table 3, the first tangential mode (excited at f = 1,800 Hz & f = 500 Hz) was the primary combustion instability seen during the development of the F-1 and J-2 engines for the Saturn V, respectively [11].

Table 3: Historical Examples of Liquid Rocket Motors that Experienced the First Tangential Mode Instability: Taken and edited from [11]

PROJECT	MOTOR	ORGANIZATION CONTRACTOR	PROPELLANTS	THRUST (lbf)	PERFORMANCE (%)	CHAMBER PRESSURE (psia)	INSTABILITY ENCOUNTERED	STABILIZATION DERIVES	INJECTOR TYPE
Apollo Saturn IB S-IVB Saturn V S-II, IVB	J-2	NASA/ Rocketdyne	LH_2 LOX	230,000	98.6	686.0	1800 Hz First Tangential Mode	3 compartment aluminum baffles	Coaxial
Apollo Saturn V S-1C	F-1	NASA/ Rocketdyne	RP-1 LOX	1,552,000	93.8	1128.0	500 Hz First Tangential Mode	13 compartment copper baffles	Like doublet

First Radial Mode Instability

While it is typically not as harmful as the first tangential mode, the first radial mode instability has also been found to appear during engine development. The first radial mode perturbs the hot combustion products and incoming propellants in a manner in which combustion efficiency is enhanced, albeit typically less than that of the first tangential mode. Similarly to the first tangential mode, if the chemical mixing is augmented in such a way that the combustion temperature is raised beyond a threshold, this instability mode can be detrimental to the operation of the engine. As seen in Table 4, the first radial mode (excited at f $\approx$ 3,500 Hz) was one instability that was seen during the development of the lunar module ascent engine for the Apollo Lunar Lander [11,14].

Table 4: A Historical Example of a Liquid Rocket Motor that Experienced the First Radial Mode Instability: Taken and edited from [11]

PROJECT	MOTOR	ORGANIZATION CONTRACTOR	PROPELLANTS	THRUST (lbf)	PERFORMANCE (%)	CHAMBER PRESSURE (psia)	INSTABILITY ENCOUNTERED	STABILIZATION DERIVES	INJECTOR TYPE
Apollo/ Lunar module ascent	LMAE	NASA Bell	50% N_2H_4 50% UDMH } A50 N_2O_4	3,500	97.1	120.0	First Radial Third Tangential modes	3 compartment baffles	Unlike doublet

III. Coupling Mechanisms

In order to better understand the onset of combustion instabilities through Rayleigh's criterion, it is important to quantify the mechanisms behind unsteady heat release. Generally, unsteady heat release is said to be directly related to the processes that occur during propellant interaction within the chamber. A variation in one of these mechanisms can directly affect the burning rate oscillation's phase and amplitude, while altering the spatial distribution of combustion. These alterations to the unsteady heat release play a direct role in driving the instability, and thus it is necessary to fundamentally understand how these combustion mechanisms interact with the acoustic pressure and velocity oscillations in the chamber [3,15].

Characteristic times of the processes for combustion have a direct effect on the onset of combustion instabilities. Inherently, there exists a time delay, referred to as "time lag", that is associated with the propellant interaction that takes place in the combustor. It has been suggested that combustion instabilities are more likely to become excited at frequencies in which the characteristic time for combustion is of the same order of magnitude as that of the time period for acoustic oscillations (e.g. for f $\approx$ 1,000 Hz, $\tau_{\text{comb}} \approx \tau_{\text{acous}} \approx 1$ ms). This characteristic time for combustion is dictated by the rate controlling mechanism (i.e. the process with the longest time scale), in which all other processes during propellant interaction appear to happen instantaneously in relation to the longest step. If the rate controlling process modifies the unsteady heat release in such a way that its amplitude and phase are adequate to overcome the damping forces (as per Rayleigh's criterion), this mechanism will play a large role in the excitation of combustion instability modes [3].

Generally, when the characteristic time of a process is much greater than the time period for acoustic oscillation, the process does not directly interact with acoustic pressure and velocity oscillations. In this case, the time it takes for the mechanism to occur is too long for it to be drastically modified by the oscillation. However, if the characteristic time of the process is shorter than the time period of oscillation, the process and oscillation typically are able to interact with one another, albeit most likely in a quasi-steady fashion. While these types of processes can interact with the oscillation, they are not rate controlling, and thus do not play as large a role as that of the rate controlling process [3].

Although a propellant interaction process may not have a time scale on the order of that of the acoustic pressure and velocity oscillations, the mechanism can still affect the driving of combustion instabilities. While the characteristic time dictates whether or not a mechanism is likely to directly interact with acoustic oscillations, an instability response can be achieved if that process affects the characteristic time of another combustion process that is rate controlling. Aside from this, mechanisms can have an indirect effect on the driving of combustion instability modes if there is an alteration of the spatial distribution of heat release within the combustor, rather than modifying the unsteady heat release rate. Thus, if a combustion process falls within one of these categories, it should be considered as a potential mechanism that attributes to the driving of the instability [3].

III.A. Injection

The main propellant interaction processes that take place within the combustor directly depend on whether the incoming propellants are either subcritical or supercritical in nature. Subcritical injection takes place when the temperature and pressure of the incoming propellants do not exceed that of their respective critical temperature and pressure (T_{cr} & P_{cr}). Under these conditions, the state of the propellants can exist in a distinct liquid, vapour or gaseous phase. Under supercritical conditions, however, the temperature and pressure of the incoming propellants do exceed that of their respective critical values and a supercritical fluid exists within the combustor. Under supercritical conditions, there is not a distinguishable difference between the gaseous and liquid phases of the flow. Both subcritical and supercritical conditions can be seen in combustors for liquid rocket engines, and as such, both need to be considered.

For subcritical injection, the main propellant interaction processes that take place within the combustor are the following: (1) Injection (2) Atomization (3) Vaporization (4) Mixing & (5) Combustion. Typically, the injection of the propellants in liquid rocket engines occur through feed systems in which the characteristic pipe dimensions (e.g. length and volume) are sufficiently large to yield characteristic times of injection much greater than 1 ms. While propellant injection tends to not have a characteristic time that permits direct interaction with high frequency acoustic oscillations, the manner in which the propellants are injected play a large role in affecting atomization, vaporization and mixing. For example, how the propellant is injected controls the original size of propellant droplets for atomization, which in turn can alter the vaporization and mixing processes. Thus, propellant injection can be a large factor in indirectly altering the growth of combustion instabilities [3].

III.B. Atomization

Propellant atomization tends to not be a rate controlling process, as its characteristic time typically ranges from τ_{atom} = 10 ns (10^{-8} s) – 10 μs (10^{-5} s). With atomization not being rate controlling, it is not the primary mechanism attributed to directly affecting the unsteady heat release rate. Rather, it is similar to propellant injection, as atomization can have an indirect effect on the oscillation through the droplet size. It has been seen that during atomization, acoustic pressure and velocity oscillations can vary the initial droplet size, which in turn, modifies the vaporization and mixing processes [3, 16].

III.C. Vaporization

In subcritical injection, vaporization is said to typically be the rate controlling process for combustion. As vaporization occurs through both of the concurrent processes of droplet boiling and evaporation, it is important to understand which of these processes is rate limiting. Boiling primarily involves droplet liquid heating, while evaporation involves heating of the droplet boundary-layer; the characteristic time associated with heating of the droplet liquid is generally longer than that of boundary-layer heating, causing boiling to be the limiting process for vaporization. Aside from this, it has been seen that the characteristic time for droplet boiling is of the same order of magnitude of the droplet lifetime (e.g. kerosene derived fuels) or larger (e.g. LO_X), making the process of liquid heating rate-controlling. Generally, the characteristic time for droplet boiling is on the order of $\tau_{\text{vap}} = 1$ ms (10^{-3} s), permitting the mechanism to directly interact with the acoustic oscillations and thus most likely to be the primary coupling mechanism responsible for driving high frequency combustion instabilities in subcritical environments [3, 16].

III.D. Mixing

Turbulent chemical mixing in liquid rocket engines generally has a characteristic time that can range from $\tau_{\text{mix}} = 10$ μs (10^{-5} s) – 1 ms (10^{-3} s), and is typically shorter than 1 ms. With chemical mixing tending to occur more rapidly than vaporization, chemical mixing is not the rate controlling process, and is often not considered in subcritical injection as the primary mechanism which directly affects the burning rate. However, chemical mixing can have an effect (albeit slight) on the spatial distribution of heat release within the combustor; the degree as to which this effect has on driving the instability is said to be much smaller than that of vaporization for subcritical injection [3].

During supercritical injection, there are no appreciable atomization or vaporization processes which occur. Thus, the primary mechanisms which cause unsteady heat release at frequencies on the order of the acoustic oscillations within the chamber become more complicated. Now that vaporization, in the nature it exists during subcritical injection, no longer occurs, but rather the dissolving and turbulent mixing of threadlike structures in the jet core are pertinent during supercritical injection, the rate-controlling process for combustion is modified. It is expected that for supercritical injection, the driving of combustion instability modes is primarily attributed to the dispersion and turbulent mixing of threadlike structures from the jet core; it is this process which is rate limiting and occurs on a time period similar to that of the acoustic oscillations within the chamber. Thus, a coupling between this mechanism and the acoustic oscillations is anticipated, however, the particulars of this coupling are not entirely identified. However, it is this coupling which is the primary source of interest in understanding combustion instabilities in supercritical propellant injection [3, 17].

III.E. Combustion

Once the propellants are sufficiently chemically mixed, chemical reactions for combustion occur. Chemical times for combustion are proportional to the chemical kinetic rates of reaction and are dictated by the longest steps in the chemical mechanism. Chemical kinetic rates are highly dependent on pressure and temperature, and at conditions typical for liquid rocket engines (i.e. high pressure and high temperature), these chemical times will be short. Typically, characteristic chemical times are on the order of $\tau_{\text{chem}} = 100$ μs (10^{-4} s) – 1 cs (10^{-2} s), and for subcritical injection, chemical reactions for combustion are not rate controlling as they generally are an order of magnitude smaller than the characteristic time for vaporization. However, during fuel rich combustion (similar to those seen during ignition of liquid rocket engines), chemical times become on the order of $\tau_{\text{chem}} \approx 1$ ms (10^{-3} s), which permits the process to directly interact with acoustic oscillations. Thus, depending on the conditions within the chamber, chemical kinetics may be a contributing factor in driving combustion instabilities [3, 16].

IV. Combustion Instability Control Techniques

In order to design stable and reliable combustors for liquid rocket engines, mitigation techniques preventing the onset of instabilities have been developed. Depending on the type of instability, the suppression technique employed differs and is often tailored to remove a specific instability.

Over the course of history for liquid rocket engine design, there have been numerous methods employed to suppress high frequency instabilities. Compared to low frequency modes, high frequency combustion instabilities are more difficult to prevent and the reasons behind the effectiveness of their suppression techniques are not entirely known. Control techniques for high frequency combustion instability are employed to either provide enough damping to take away the energy for instability driving or break the coupling between the unsteady heat release of combustion and the acoustic pressure oscillations of the chamber. Thus, these suppression methods are aimed at either dampening the acoustic modes of the chamber or altering the energy release process for combustion (either temporally or spatially), or a combination of the two.

IV.A. Historic Transverse Instability Mode Control

High frequency transverse combustion instabilities tend to be more difficult to remove than high frequency longitudinal instabilities (which can be eliminated through alterations to the combustor length). As such, there exists many different mitigation techniques developed for high frequency transverse instabilities. These mitigation techniques can be classified as either passive or active systems. As their names suggest, passive systems aim to dampen combustion instability modes in a non-responsive fashion, while active systems are able to alter the instability response dynamically in real time. Both control types have their advantages and disadvantages, with passive systems historically being implemented in liquid rocket engines due to their inclusion of non-movable parts. Thus, the following high frequency transverse instability mitigation techniques have been incorporated in flight rated combustors, and as such, will be covered in greater detail: (1) Symmetric Injector Plate Baffle (Passive) (2) Symmetric Fuel Injector Distribution (Passive) & (3) Resonance Absorbers (Passive).

Symmetric Injector Plate Baffle

In order to prevent the onset of high frequency instabilities (primarily transverse modes), symmetric plate baffle systems have become the standard method employed for liquid rocket engines developed in the United States. This type of suppression technique has been utilized from the development of the Atlas HA-5 (Project Mercury) through to the F-1 (Apollo) and the more recent Space Shuttle Main Engine (Space Shuttle). Symmetric plate baffle systems are comprised of metal barriers attached to the face of the injector plate, which segment the injection plate in both the tangential and radial directions. Axially, these baffle systems penetrate the combustor at lengths long enough to provide adequate acoustic damping, while not permitting unwanted heat transfer or performance loss of the engine. The symmetric injector system developed for the F-1 engine can be seen in Figure 6 [11].

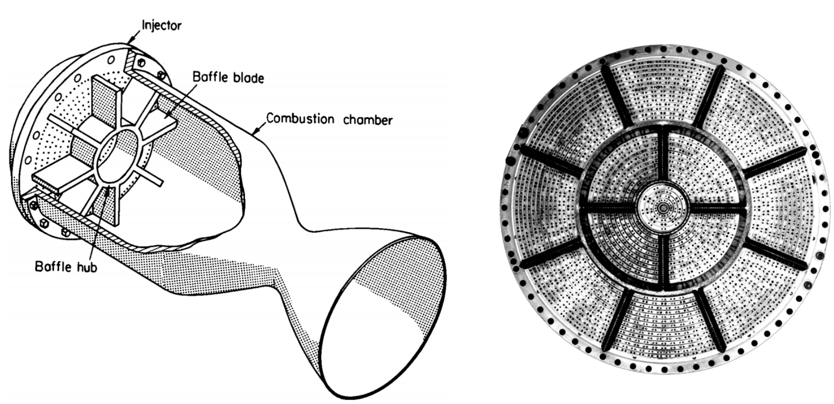

Figure 6: Schematic of a Symmetric Injector Plate Baffle System (Left) & Baffle Design for the F-1 Engine (Right): Taken and edited from [10, 18]

Complete understanding as to why this suppression technique is effective in preventing the onset of transverse combustion instabilities is still not known. However, certain effects pertaining to the addition of the baffle system have been identified as possible reasons behind the successful prevention of these instabilities. Firstly, the addition of the baffle system modifies the acoustic resonance properties of the combustion chamber. Figure 7 details the effects an injector plate baffle system has on the acoustic resonant frequencies of a liquid rocket engine combustor.

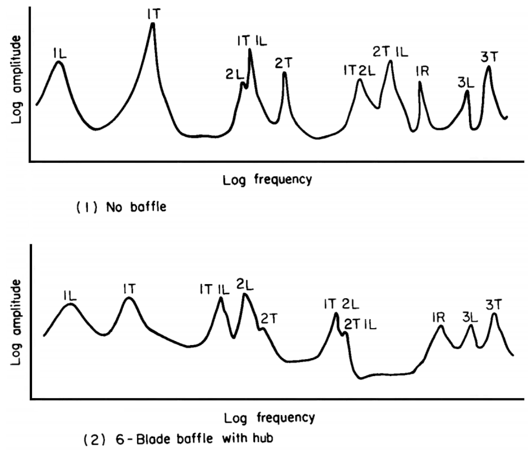

Figure 7: Comparison of Acoustic Resonance Characteristics between a Liquid Rocket Engine Combustion Chamber with and without an Injector Plate Baffle System [10]

As can be seen in Figure 7, the addition of a baffle has a dual effect on the acoustic resonance. Both the frequencies of the lower-order transverse modes (specifically the 1-T mode) are drastically reduced, and the amplitudes of all the resonant frequencies are decreased. With an evident decrease in resonant frequency amplitude, this is an indication that the dampening rates of these modes are increased (i.e. making the Rayleigh criterion for sustained combustion instability growth more difficult to be achieved). Thus, the baffle system aides the dampening of acoustic energy by providing more boundaries for acoustic losses [10].

In addition to altering the chamber acoustic modes, a positive effect attributed to the injector face baffle system is its modification of the oscillatory flow over the injection plate. Due to the physical boundaries baffle blades place on the combustor, it is more difficult for the transverse acoustic velocity oscillations to propagate across the injector plate, limiting the unsteady oscillations between baffle compartments. Also, there is an acoustic velocity node created at each baffle boundary, which greatly reduces the amplitude of velocity oscillations that may be present. By reducing the ability for velocity oscillations to move throughout the combustion chamber, the baffle system essentially makes unsteady heat release less likely to be onset by transverse acoustic velocity oscillations [10, 11].

Injector plate baffle systems have also been shown to provide energy damping of oscillations within the combustion chamber. The existence of baffle blades on the injector plate allow the shedding of vortices and flow separation to occur, along with viscous dissipation being enhanced within the chamber; these effects combined contribute to the energy dissipation of oscillations within the chamber. In order to successfully dampen out the instability, this energy dissipation effect can either be large enough to directly reduce the instability amplitude to a non-sustaining level or to provide adequate energy removal to prohibit adequate instability driving between the acoustic and heat release oscillations [11].

With regards to the axial lengths of baffle systems, it has been found that increasing the baffle length generally increases the dampening effect on the system. However, after a certain amount of dampening has been reached, the losses will never be less than the acoustic energy gained from unsteady heat release and thus, the baffle will not have any greater effect past this desired length. This, compounded with the potential for unwanted heat release and performance loss with a baffle system penetrating too far into the combustor, dictates the desired baffle length [10, 11].

While generally effective, symmetric injector plate baffles have a couple of drawbacks. Firstly, their designs have been developed largely through trial and error processes. For instance, during the baffle development for the F-1 engine, no stringent baffle design criteria detailing the optimal blade number and baffle pattern was ever determined. This is partially because the addition of baffle components can alter the oscillation patterns within the combustion chamber in an unpredictable manner, while certain baffle designs can also produce new acoustic modes within the chamber at frequencies in which instabilities can be sustained. Finally, all of the traditional injector plate baffle systems incorporate a passive design, meaning their characteristics cannot be altered during operation of the engine. Passive baffle systems are not as versatile as active systems, as they cannot make real time alterations to help prevent combustion instabilities. Thus, traditional symmetric baffle systems and their development can be improved to optimize the prevention of combustion instability modes [8, 19].

Symmetric Fuel Injector Distribution

Aside from employing baffle systems to mitigate the onset of high frequency transverse instabilities, Russian built liquid rocket engines have utilized symmetric fuel injector distributions, which entail strategically positioned fuel injectors with modified sprays to simulate baffle conditions through spray characteristics. A schematic of a typical symmetric fuel injector distribution can be seen in Figure 8 [19].

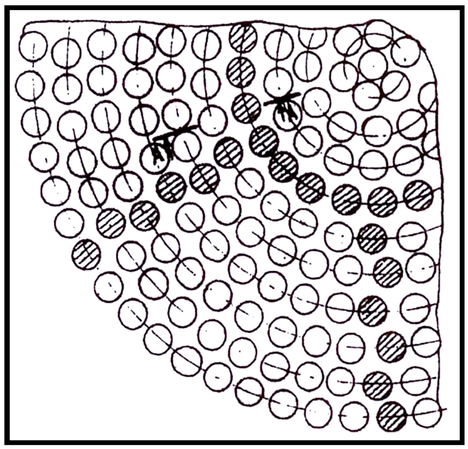

Figure 8: Schematic of a Symmetric Fuel Injector Distribution [19]

In combustors which utilize this type of instability control, certain fuel injectors have spray conditions that differ from the rest (e.g. axial spray instead of radial spray). To simulate baffle conditions, a certain number of patterned fuel injectors operate under modified spray conditions, which segment the combustor similar to a physical baffle [19].

The ideology behind utilizing this mitigation technique over traditional baffle systems revolves around the thought that the reliability of liquid rocket engines with altered fuel injector sprays is greater than that of liquid rocket engines with baffle systems; the presence of baffle systems can reduce reliability due to the baffle being directly exposed to the high heat of combustion products [19].

Since the modified fuel injector distribution essentially reproduces baffle conditions within the combustor using injectors' sprays, the mechanisms behind how this instability suppression method works are similar to that of a physical injector plate baffle, with the primary being attributed to the positive modification of the oscillatory flow over the injection plate, rather than acoustic mode dampening. By causing the transverse acoustic velocity oscillations to be perturbed by regions of modified spray, it becomes more difficult for unsteady oscillations to travel between combustor segments, while also depleting some energy of these oscillations as they travel through regions of modified spray. These two flow effects compounded make it more difficult for the growth of combustion instability modes to be promoted within the chamber [19].

Resonance Absorbers

Acoustic resonance absorbers are another passive mitigation technique utilized to prevent the onset of combustion instabilities through solely removing the acoustic energy available for potential instability growth. Acoustic resonators are acoustic side lobe chambers attached to the combustor that are geometrically tailored to dampen out the resonant frequency of the dominant instability mode. Acoustically, these side lobes act as Helmholtz Resonators which take the acoustic energy out of a specific resonance; the frequencies at which these absorbers resonate depend on the volume of the side lobe and are independent of geometry. Thus, typical resonance absorbers, such as the one seen in Figure 9, have simple geometric shapes [19].

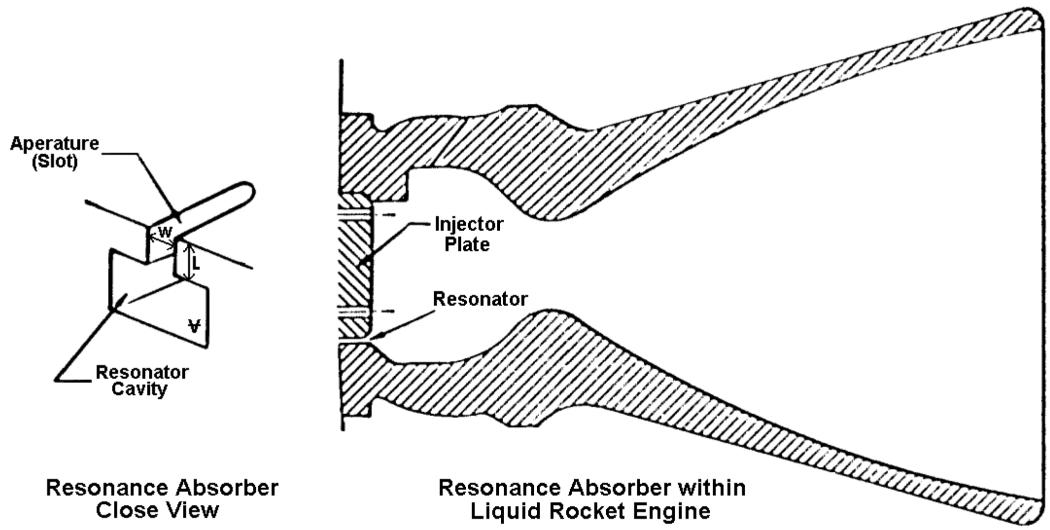

Figure 9: Schematic of an Acoustic Resonance Absorber for Liquid Rocket Engines: Taken and edited from [20]

In order to maximize the dampening effect of resonance absorbers, these acoustic side lobes are located at an acoustic pressure anti-node of the instability. Thus, due to the acoustic hard wall boundary conditions found at the injector plate and walls of the combustor, there exists zero acoustic velocity at these locations and correspondingly, a pressure anti-node for all modes. Thus, resonance absorbers are generally installed at the injector plate, near the combustor walls. This can be seen on the right of Figure 9 [19, 21].

It should be noted that resonance absorbers have a couple of drawbacks. While the existence of resonance absorbers within a liquid rocket engine typically does not have a drastic change on the oscillatory flow within the chamber, the acoustic characteristics of the chamber are significantly affected. As seen with baffle systems, the addition of resonance absorbers can successfully dampen out one resonant frequency only to have another resonance appear. Specifically, frequency bifurcation, a phenomenon in which the main resonant frequency is dampened while two acoustic resonances appear in its place (typically one at a frequency lower and one higher than the original resonance), has been seen in combustors which employ resonance absorbers. Thus, with the acoustic pressure distribution potentially being altered in an unpredictable fashion with the addition of resonance absorbers, tailoring these absorbers can be a challenging process [10, 19].

IV.B. Novel Combustion Instability Control Techniques

More recently, there has been research into designing more versatile combustion instability mitigation systems. Some of these instability control techniques aim to improve upon the historically utilized methods, while others (mainly the active control techniques) are focused on dynamically controlling the dominant instability through various means. To date, many advancements have been made in both of these areas. The following novel mitigation techniques have shown to efficiently control high frequency transverse instability modes, and as such, will be covered in greater detail: (1) Asymmetric Injector Plate Baffle (Passive) (2) Asymmetric Fuel Injector Distribution (Passive) & (3) Fuel Line Flow Modulation (Active).

Asymmetric Injector Plate Baffle

For this research investigation, a replica model liquid rocket engine (seen in Figure 10) was equipped with six propellant injectors and a single baffle blade able to traverse the entire length of the combustor. Using this configuration, numerous studies were performed to ascertain the effectiveness of this baffle system at controlling the first spinning tangential mode, specifically. From these tests, the unstable/stable regimes of the combustor corresponding to baffle insertion length were able to be determined [22].

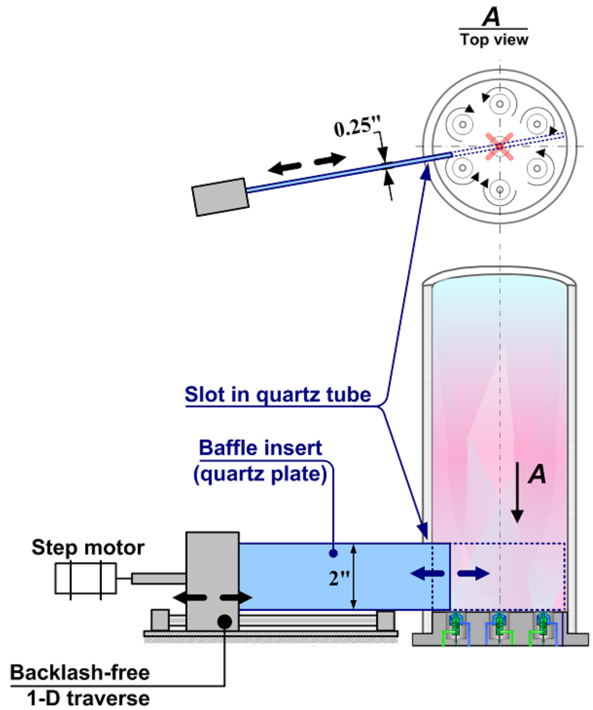

Figure 10: Asymmetric Baffle System for the Model Liquid Rocket Engine [22]

During these tests, the combustor was purposefully operated under unstable conditions, with the first spinning tangential instability mode being excited within the chamber at f ≈ 5,000 Hz. Under these conditions, the baffle blade was inserted into the combustor. Beginning with 0 % baffle insertion, the blade was incrementally traversed all the way to 100 % combustor diameter baffle insertion. During the test, it was found that when the baffle was ≈ 10 − 30 % inserted into the combustor, the 1-T spinning tangential mode was fully damped, leading to stable conditions within the combustor. At this baffle insertion length, the suppression of the 1-T spinning tangential mode was said to be due to enhanced acoustic dampening of the system, similarly to that of a traditional baffle system. Once the baffle was inserted past 40 % of the combustor's diameter, another instability mode, the first standing tangential mode, became excited within the combustion chamber [22].

With the first standing mode excited within the combustion chamber at 40 % baffle insertion, the magnitude of the instability's pressure oscillations increased until the baffle was inserted to 70 % of the combustor diameter. When the baffle was inserted past this point, the amplitude of instability began to decrease again until the baffle was inserted 100 % into the combustor. Thus, this laboratory experiment showed that depending on the baffle blade configuration (i.e. the amount of baffle insertion), the acoustics can be altered to the point where another mode in the combustor was excited (as also found with some symmetric plate baffle configurations). The pressure amplitude and frequency of oscillation corresponding to the baffle insertion length in both an inward and outward traversing manner can be seen in Figure 11 [22].

Aside from the oscillation amplitude trend discussed previously, Figure 11 shows that the frequency of oscillation linearly decreases from f ≈ 5,000 Hz to f ≈ 3,000 Hz across the baffle insertion range; the linear frequency dependence on baffle insertion was said to be attributed to an acoustic characteristic change, rather than an adjustment in the reaction zone location (i.e. the flame moving away from the injector plate). Hence, this investigation proved that this mitigation technique is able to successfully dampen the amplitude and reduce the frequency of the first spinning tangential instability mode in a controllable fashion within the model liquid rocket engine [22].

Thus, an asymmetric baffle method could be employed as an engine design approach in liquid rockets employing baffle systems, in which the shape of the baffle sections could be finely tuned to develop baffle systems in a more efficient manner.

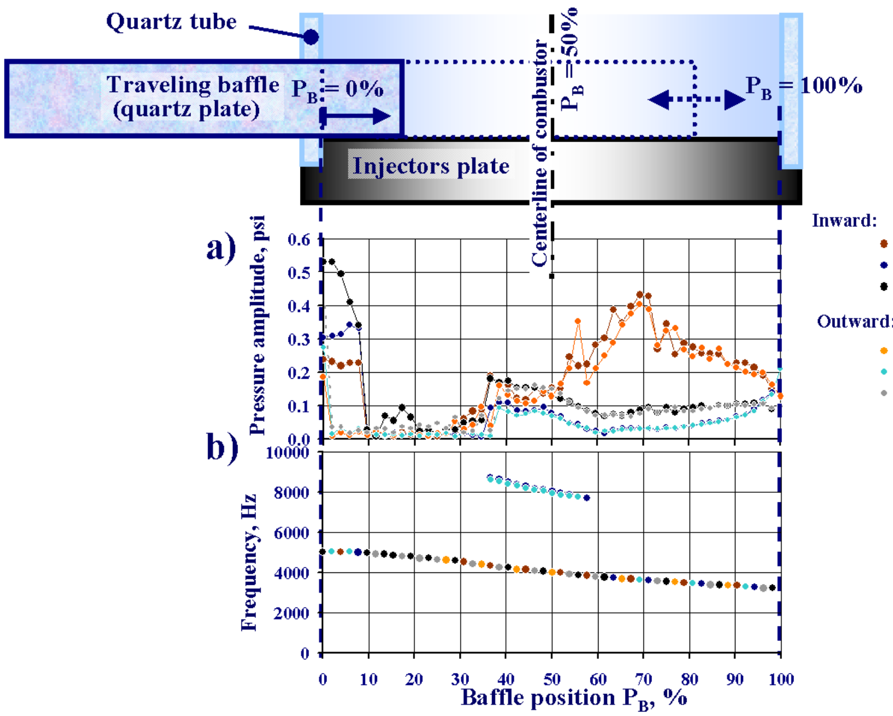

Figure 11: Instability Pressure Amplitude & Frequency Corresponding to Baffle Insertion Length [22]

Asymmetric Fuel Injector Distribution

Drawing from both the symmetric fuel injector distribution system and the asymmetry aspect of the asymmetric baffle study, this mitigation technique incorporated an asymmetric fuel injector distribution to control high frequency transverse instabilities. For this research study, a replica model liquid rocket engine was equipped with six "smart" co-axial injectors that permitted the injectors' sprays to be changed from radial to axial spray through altering the injectors' air-split ratio, $K = p_{in}/p_{out}$ (the ratio of the inner to outer pressure of the injectors' passages). In order to achieve asymmetry with the injectors' sprays, a single fuel injector has been made able to change its spray characteristics independent of the other five injectors. Using this configuration (shown in Figure 12), numerous studies were able to be performed to determine the effectiveness of the asymmetric fuel injector distribution at controlling the first spinning tangential mode, specifically. From these tests, the unstable/stable regimes of the combustor corresponding to the spray shape of the single injector were able to be resolved [12].

In order to demonstrate instability control, the combustor was purposefully operated under unstable conditions during testing, with the first spinning tangential instability mode being excited at $f \approx 5{,}000$ Hz and $p'/p_c \approx 10$ %. In order to achieve these unstable conditions, all six injectors were set to have radial spray ($K \approx 25/75$). With the 1-T spinning mode active, the spray of the single injector was changed from radial to axial spray independently of the rest of the injectors (which continued to hold radial spray conditions). During the test, when the air-split ratio of the single injector increased from $K_1 = 27/73 - 55/45$, there was a drastic reduction in oscillation amplitude, with the minimum amplitude being reached at $K_1 = 54/46$, at which point the 1-T spinning mode was fully dampened within the combustor [12].

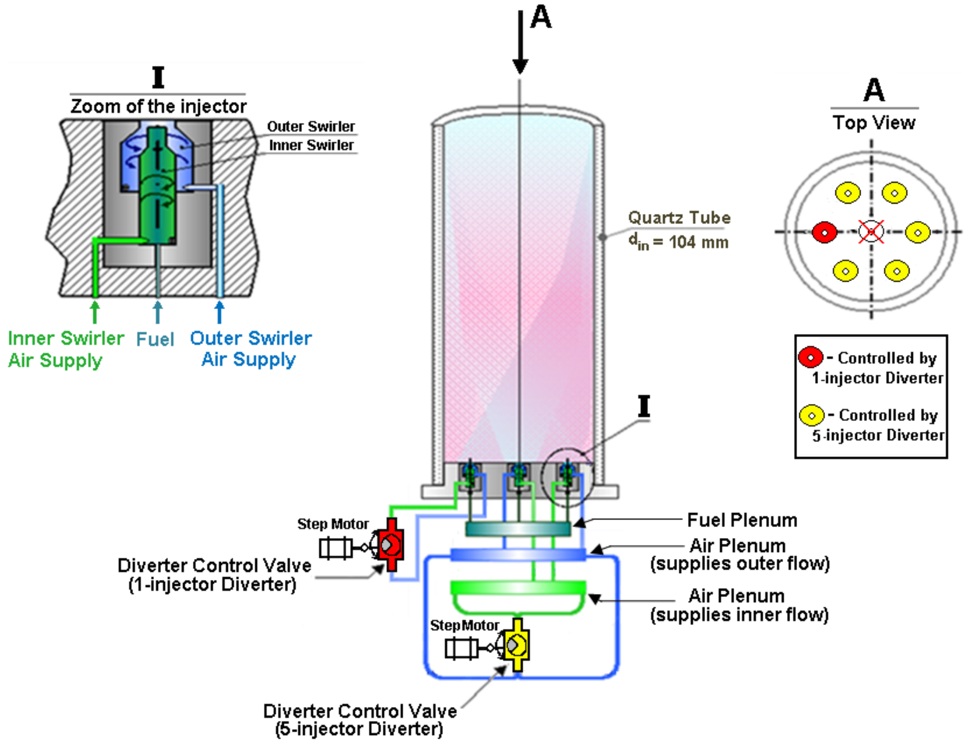

Figure 12: Asymmetric Fuel Injector Distribution System for the Model Liquid Rocket Engine [12]

By increasing the air-split ratio of the single injector further to $K_1 = 64/36$ (i.e. mostly axial spray), the first tangential spinning mode was transformed into the first tangential standing mode at f $\approx$ 5,000 Hz, however, at appreciably low amplitudes ($\approx$ 6X smaller than that for the undamped 1-T spinning mode). Thus, for this single injector spray condition, there exists stable conditions within the combustor. The oscillation's pressure amplitude and frequency spectra corresponding to the air-split ratio of the single injector can be seen in Figure 13 [12].

Aside from the oscillation amplitude trend discussed previously, Figure 13 shows the frequency spectra from one of the pressure transducers at various points during the experiment to help further characterize the instability. From the first and third frequency spectra plots, it can be seen that both the large amplitude 1-T spinning mode and low amplitude 1-T standing mode exist at f $\approx$ 5,000 Hz. During the mode transition (corresponding to the second frequency spectra), a doubling in oscillation frequency is present; this can be attributed to the mode nodal plane passing over the pressure transducer port at this instant, rather than a physical doubling of instability frequency. Since this mitigation process dampens the 1-T spinning tangential mode instability without reducing the frequency of oscillation, it is said that the asymmetric fuel injector distribution does not have a direct effect on the acoustic modes of the combustor as does a physical baffle, but rather that breaking the symmetry of the reaction zone interrupts the media path through which the acoustic wave propagates to an extent that a significant depletion of oscillation energy occurs [12].

From this study, this asymmetric modified fuel injector distribution proved to be successful at controlling the first spinning tangential mode instability in a model liquid rocket engine combustor. Thus, this instability control technique could be employed as an engine design approach in liquid rocket engines which seek to employ adjustable spray injectors and could be utilized to finely tailor the injector spray pattern to develop a modified fuel injector distribution in a more efficient manner.

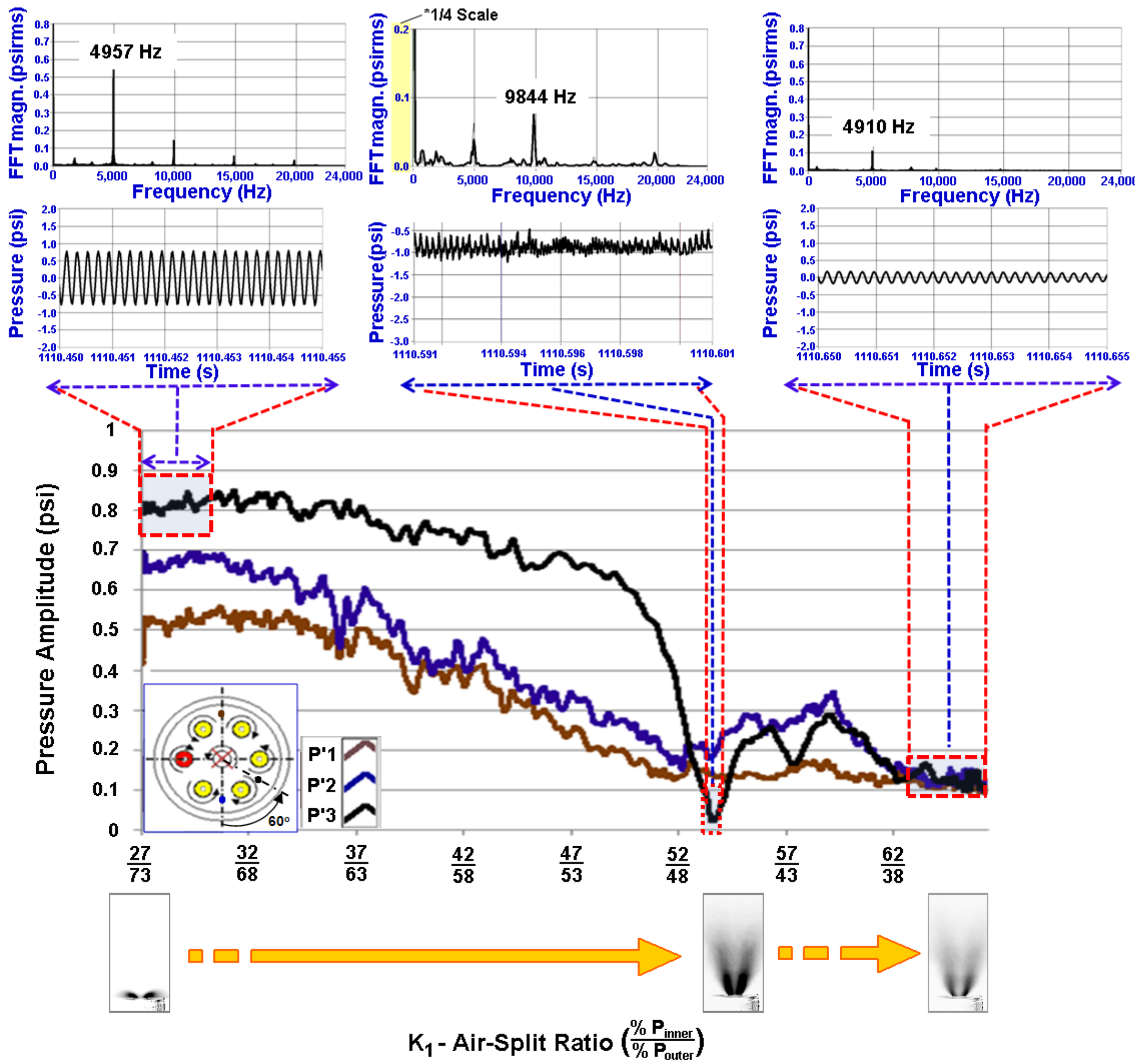

Figure 13: Pressure Amplitude vs. Air-Split Ratio (K_1) Plot [12]

Note: The Frequency Spectra & Time Histories for P'3 at various air-split ratios are also shown.

Fuel Line Flow Modulation

An instability mitigation technique utilized in active control systems is flow modulation of the fuel into the combustion chamber. Dampening of combustion instabilities has shown to be possible through pulsing the flow rate of the fuel in a way that causes the feedback between the unsteady heat release of combustion and acoustic pressure to be broken. Generally, the frequency of propellant flow pulsation is on the order of that of the instability, to permit direct interaction with both the rate limiting mechanism of combustion and the acoustic pressure oscillations. However, modulation of the incoming propellant at frequencies off that of the dominant instability also has shown to be effective [15, 23, 24].

Pulsing propellant flow rates at frequencies on the order of the instability has been a control technique developed mainly for turbine engine applications through the use of fast response actuating valves. This is done to decouple the feedback of the acoustic oscillation and heat release through two means. The first is that pulsing the flow rate increases the acoustic energy losses at the injector plate. By increasing the acoustic energy losses at the injector plate, this mitigation technique works in some ways similar to that as acoustic resonators and baffle systems. Aside from the acoustic effect, pulsing the propellant flow has also been said to perturb propellant injection in a manner that promotes damping of the instability driving burn rate [25].

One study which utilized harmonic fuel modulation with an actuation valve showed a significant dampening of a f $\approx$ 400 Hz, 1-L longitudinal instability was possible when the valve was forced at a specific frequency other than that of the dominant instability mode. To test the theory, the harmonic forcing of the valve ranged from f = 50 Hz - 500 Hz in a laboratory scaled turbine combustor operating at $p_c \approx$ 100 - 150 psi [24].

Prior to the actuation frequency sweep tests, a series of $0^o - 360^o$ phase sweep tests were performed for an actuation frequency which matched the 1-L instability frequency. It was found that a 2X amplitude decrease of the dominant instability was achieved with the optimal phase applied (with respect to the phase associated with the largest instability amplitude) [24].

For each actuation frequency sweep test, the phase of the actuation signal was not varied. With this, the actuation signal was swept from f = 500 Hz - 50 Hz at a rate of 0.5 Hz/sec. For this set of tests, both the frequency and amplitude of the dominant instability were tracked. As can be seen in Figures 14 & 15, both the instability frequency and amplitude were drastically affected by the characteristics of the actuation signal. When the actuation frequency is altered across the frequency range of f $\approx$ 300 Hz - 400 Hz, a noticeable frequency shift of the dominant instability mode is present (i.e. shifting in the direction of the actuation frequency). However, when the actuation signal is out of this frequency range, the instability frequency response does not directly follow that of the modulation signal. Thus, the frequency of the instability is more prone to oscillation from the fuel flow modulation within this frequency range [24].

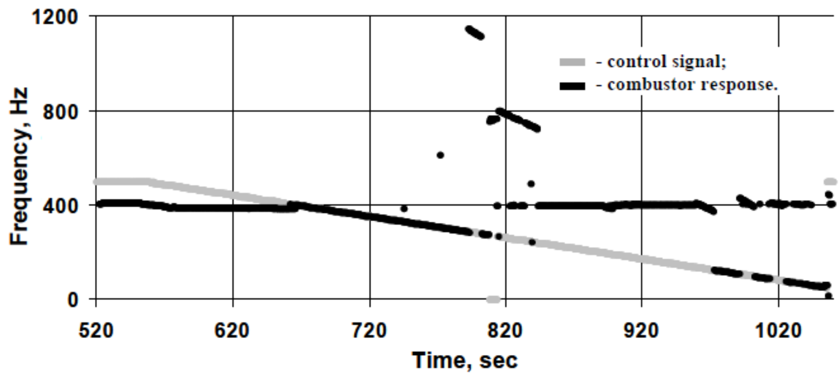

Figure 14: Combustion Instability Frequency Response due to the Alteration in Fuel Flow Rate Actuation Frequency [24]

Non-coherent fuel flow modulation also has a significant effect on the amplitude of the dominant combustion instability mode. As can be seen in Figure 15, the instability amplitude is reduced 10X that of the maximum instability amplitude at the following frequency ranges: (1) f $\approx$ 50 Hz, (2) f $\approx$ 120 Hz - 130 Hz & (3) f $\approx$ 250 Hz - 330 Hz. However, it also should be noted that when the fuel flow is modulated at frequencies close to that of the dominant instability (i.e. f $\approx$ 400 Hz), with an arbitrary actuation signal phase, there exists large amplitude instability oscillations [24].

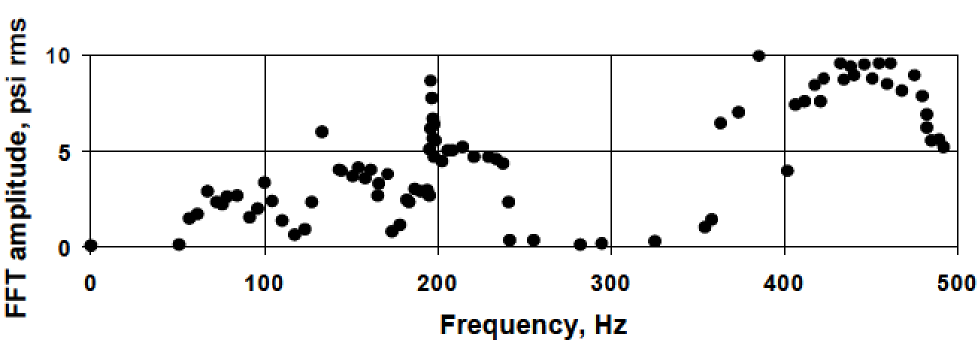

Figure 15: Combustion Instability Amplitude Response due to the Alteration in Fuel Flow Rate Actuation Frequency [24]

Thus, when the fuel flow is modulation at frequencies away from that of the active instability, the dominant mechanism which is responsible for driving combustion instability growth is augmented in such a way that the unsteady heat release oscillations are out of phase with that of the pressure oscillations (thus resulting in instability dampening as dictated by Rayleigh's criterion). When the fuel is modulated at frequencies similar to that of the active instability mode, the phase of the actuation signal plays a large role in whether the instability is dampened or amplified. From this, it has been suggested that modulating the fuel at frequencies off that of the dominant instability frequency can be a successful method to dampen out the dominant instability mode, regardless of phase.

Other than pulsing the flow rate of the propellants utilizing a fast response actuating valve, there has been some work done with providing fuel flow rate modulation through acoustic driving. To test this concept, a model dump combustor with acoustic speakers was utilized to modulate the fuel flow rate into the mixing region of the co-axial injector. A pressure transducer downstream of the injector was employed to measure the acoustic pressure fluctuations within the chamber, which was then filtered and phase-shifted to be utilized as the acoustic driver signal. A schematic of the experiment configuration can be seen on the left of Figure 16 [26].

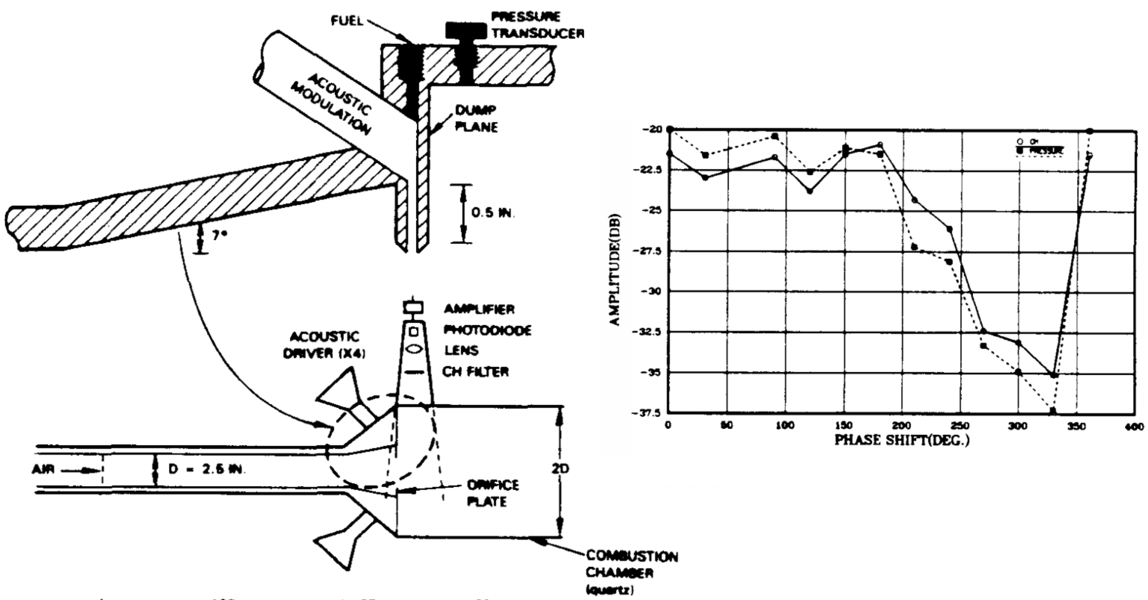

Figure 16: Experiment Configuration of Fuel Flow Modulation (Left) & Instability Suppression Plot Utilizing Acoustic Forcing (Right) [26]

Utilizing this set-up, the pressure amplitude of the primary instability at f $\approx$ 300 Hz was significantly reduced by approximately 13 dB, with the proper phasing of acoustic driving (seen on the right of Figure 16). It was conjectured that at this phasing, the acoustic driving caused the burning rate oscillations to be significantly reduced through diminishing the coherence of large scale vortical structures within the propellant jet shear layer, while also providing acoustic dampening at the inlet of the combustor. Thus, this mitigation technique is capable of reducing the amplitudes of the acoustic oscillations and unsteady heat release to the point in which combustion instability feedback can no longer be sustained within the combustor, making it a viable combustion instability suppression method for liquid rocket engines [25, 26].

IV.C. Novel Flame-Acoustic Interaction Research

Recently, there has been work done on studying flame-acoustic interaction under the influence of controlled acoustic excitation. The experiment configuration used for this research consisted of a rectangular combustor with a single coaxial injector (burning GH_2/GO_2 or $GH_2 - GCH_4/GO_2$) and an acoustic compression driver located at the wall of the combustor. This set up (shown in Figure 17) permitted transverse acoustic waves to be applied at specified frequencies, in order to investigate the flame-acoustic interaction within the model combustor [27, 28].

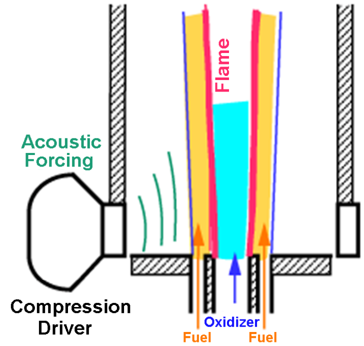

Figure 17: Experiment Configuration of Single Injector with Acoustic Forcing. Taken and edited from [27]

For this investigation, the applied frequency (f $\approx$ 1,150 Hz) from the compression driver was selected because it was directly between the first two dominant resonant (standing wave) modes of the chamber and thus, would not excite a standing wave acoustic mode. This was done to isolate the interaction between the flame and traveling acoustic waves. When the compression driver was forced at this frequency, the portion of the flame close to the speaker experienced significant flame distortion, while the side of the flame opposite of the compression driver did not. This phenomena was shown to be more prevalent when the density ratio between the oxidizer and fuel ($\rho_{\text{ox}}/\rho_{\text{fuel}}$) was large [28].

When acoustic waves interact with the propellant interface, it can result in the production of local vorticity, which can ultimately affect the stability of the flame. Seen below is the vorticity equation, which describes how vorticity of a fluid particle progresses as it travels with the flow:

$$\frac{D\vec{\omega}}{Dt} = \frac{\nabla\rho \times \nabla p}{\rho^2} + (\vec{\omega} \cdot \nabla)\vec{u} - \vec{\omega}(\nabla \cdot \vec{u}) + \nu \nabla^2 \vec{\omega} + (\nabla\nu) \times \nabla^2 \vec{u} \tag{2}$$

$\vec{\omega}$ – Vorticity
ρ – Density of the Fluid
P – Pressure of the Fluid
$\vec{u}$ – Velocity
ν – Kinematic Viscosity

As can be seen from the above equation, vorticity can be generated through multiple ways and the term of interest that describes vorticity generated through the interaction between acoustic waves and the propellant interface is the $\frac{\nabla\rho \times \nabla p}{\rho^2}$ term, which represents baroclinic torque. Thus, vorticity is generated through baroclinic torque if the gradients of pressure and density are significantly large and misaligned with one another. Schematics demonstrating both stable and unstable interaction between compression waves and the fuel-oxidizer interface can be seen in Figure 18.

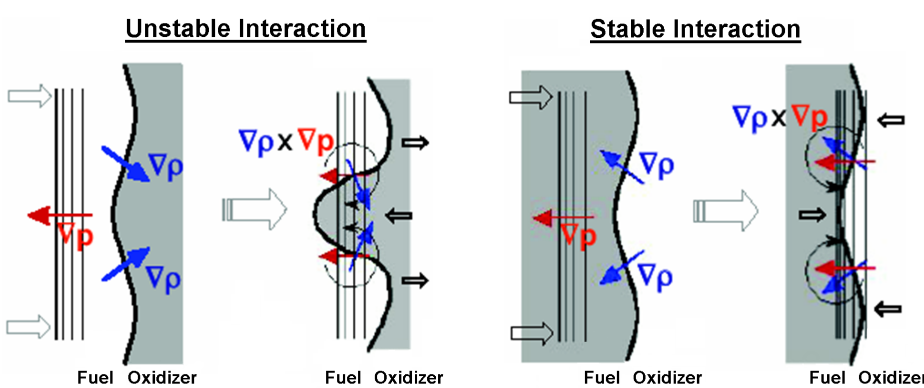

Figure 18: Perturbation Growth/Decay at the Fuel-Oxidizer Interface Due to the Alignment of ∇p & $\nabla\rho$ [27]

As can be seen in Figure 18, the alignment of the pressure and density gradients is key in whether a stable or unstable interaction occurs. When the pressure and density gradients are in the same direction, as is the case on the left side of Figure 18, the torque generated is in a fashion in which a reduction of flame wrinkling occurs. However, when the pressure and density gradients are misaligned with one another, as is the case on the right side of Figure 18, the torque generated is in a manner in which an amplification of flame wrinkling takes place. Thus, under these conditions, baroclinic torque plays a large effect in flame stability, specifically when the density ratio between the oxidizer and fuel is particularly large [27].

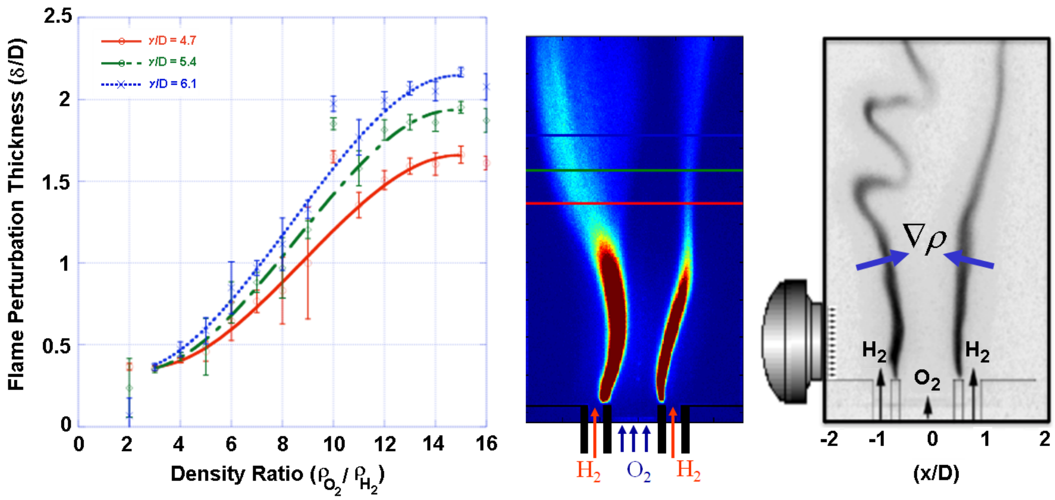

Figure 19: Flame Perturbation Thickness vs. Density Ratio Plot & OH* Chemiluminescence Images with Acoustic Forcing: Taken and edited from [27]

This baroclinic torque effect is presented in Figure 19. The plot on the left of the diagram shows normalized flame perturbation thickness (taken at three spatial planes downstream of the injection plane) vs. the propellant density ratio. For each of the three spatial planes, the flame perturbation thickness increases fairly linearly over almost the entire range of density ratio's, until a density ratio of $\rho_{\text{ox}}/\rho_{\text{fuel}} \approx 14$, where the flame perturbation thickness begins to asymptote. This research investigation shows how phenomena such as vorticity play a vital role in flame-acoustic interaction under certain conditions, and this, in turn, drastically affects the propagation of combustion instability modes in the presence of acoustic excitation.

V. Application of High Frequency Pressure Disturbances within the Oxidizer Post of an Injector to Control Combustion Instabilities

Drawing from these combustion instability suppression techniques and flame-acoustic interaction research, it has been proposed that applying pressure disturbances within a propellant injector can be used to control combustion instability modes. A schematic displaying this concept can be seen in Figure 20. For this control technique, a piezoelectric speaker (JBL 2447H Compression Driver) will be located at the injector base in a fashion to generate longitudinal pressure disturbances within the injector's oxidizer post. The piezoelectric speaker will be connected to a function generator and amplifier capable of producing high frequency pressure disturbances at amplitudes large enough to modulate the propellant flow, through altering the injector acoustics.

For one research investigation, the applied acoustic signal will be set to the frequency of the dominant instability mode with an adjustable time offset (provided through a TOA D-1103 Digital Signal Delay). This digital signal delay will permit the phase of the speaker's input signal to be altered in real time. Through altering the phase offset of the applied pressure disturbances, an effect on the output parameters within the combustor, p' & Q', will be achieved, causing a suppression of the dominant instability at the correct phase offset. Based upon the Rayleigh criterion (R.C.), a suppression of the dominant instability mode can occur through one of the following ways: (1) Reducing the amplitude of pressure oscillations and/or unsteady heat release oscillations within the chamber (2) Causing the absolute value of the phase offset between the pressure oscillations and unsteady heat release to exceed 90°, or (3) A combination of the previous two. Thus, this research investigation will determine the necessary phase offset for the applied acoustic signal that will lead to the maximum instability suppression, while using measurements of p' & Q' within the chamber to discern which effect can be attributed to the suppression.

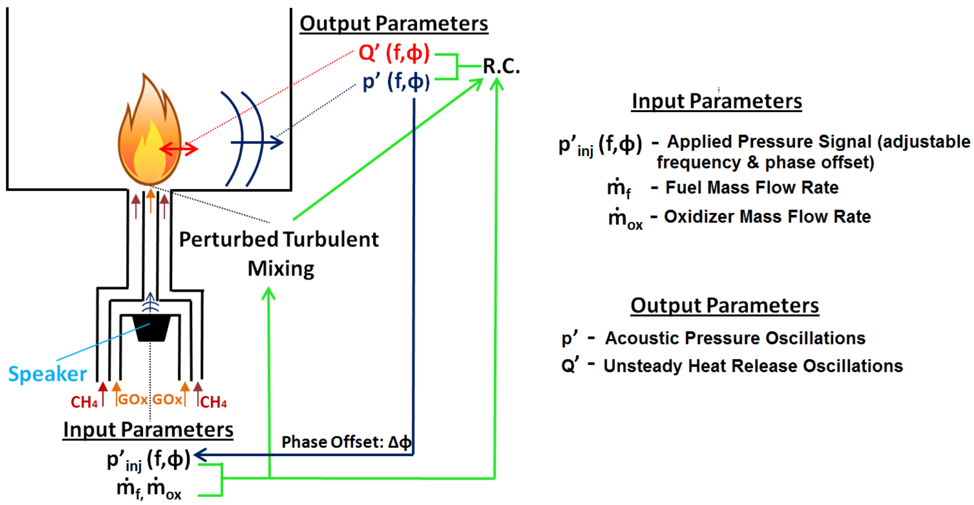

Figure 20: Experiment Configuration Schematic with Acoustic Modulation

To provide a more detailed explanation of this instability control concept, a schematic showing how combustion instability development is altered can be seen in Figure 21. On the left of this diagram shows an instability growth cycle without any applied pressure disturbances within the injector. The cycle begins with an acoustic pressure oscillation at the flame which travels back to the injector, causing acoustic velocity oscillations at the injector and thus fluctuations of the propellant mass flow rate entering the combustor. For the instability to grow, the unsteady heat release oscillation generated from these mass flow rate fluctuations is in phase (at least $|\phi^o| < 90^o$) with the acoustic pressure oscillations at the flame.

On the right hand side of the diagram is the representation of the combustion instability feedback cycle where pressure disturbances from the piezoelectric speaker are applied within the injector to reduce the active instability mode. Again, the instability feedback cycle begins with an acoustic pressure oscillation at the flame which travels to the injector, causing velocity oscillations at the injector and mass flow rate fluctuations of the propellant. However, pressure oscillations within the oxidizer post of the injector are applied to provide a counter acoustic oscillation (180° out of phase) at the injector. This then corresponds to a significant reduction in the oscillation of the propellant mass flow rate at the injector and therefore a reduction in unsteady heat release oscillation.

Aside from the signal phase offset testing, another series of tests will involve applying pressure disturbances at frequencies off that of the dominant instability mode. This will be done in a similar fashion to the active control study using a fast actuation valve (see Section IV.B). As such, a range of frequencies will be applied, regardless of phase. Once the individual frequencies that provide the largest dampening are found, band limited white noise encompassing these frequencies will be applied to see if a larger amount of instability suppression is possible. The option of applying band limited white noise is an advantage of modulating the propellant flow through acoustic means rather than fast actuation valves (which can only be pulsed at a single frequency). Thus, through these tests, the most effective acoustic suppression strategy will be ascertained.

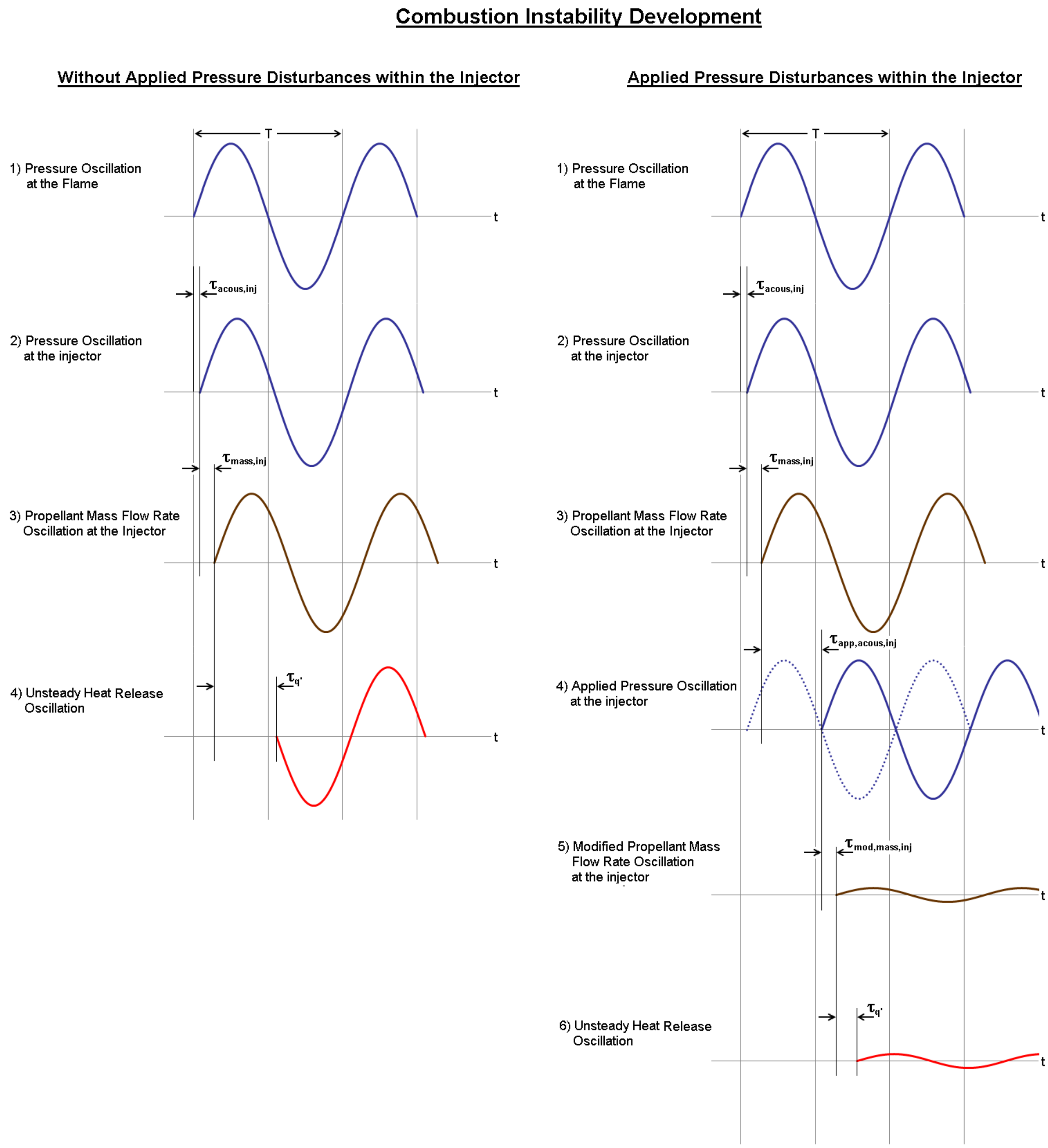

Figure 21: Combustion Instability Feedback Cycle both without (Left) and with (Right) High Frequency Pressure Disturbances Applied

VI. Conclusion

The onset of combustion instabilities continue to be a prevalent concern while designing liquid rocket engines. Although much is known about the various coupling mechanisms contributing to the onset of instabilities within these combustors, historically, their design processes have shown to incorporate a large amount of empiricism. This is why research which aims to perfect stable combustor designs using reliable combustion instability control techniques is still ongoing. From advancements on historical techniques to new active control methods, there is a plethora of different instability control ideologies that have been investigated. Based upon some of these ideas, a novel control method, which implements applied pressure disturbances within a propellant injector to dampen combustion instability modes, has been proposed. It is the goal of this research to find the optimal acoustic pressure signal to successfully dampen the dominant high frequency instability, demonstrating this control technique as a robust instability suppression method for use in future liquid rocket engines.

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