Survey of Liquid Rocket Engine Acoustic Combustion Instability

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This paper presents an overview of liquid bipropellant rocket engine combustion instability for high frequency instabilities pertaining to acoustic effects. These effects can be the result of combustion chamber geometry, injector shapes, or feed instabilities for supplying propellant into the engine. This paper will address some of the most significant studies in liquid rocket engine instability, and the modern techniques used to predict, model, and analyze acoustic instabilities. An introduction to this topic is provided to illustrate the necessity to understand and diagnose acoustic instabilities as well as background covering theory in acoustic effects for rocket engines. Recent studies are summarized and how developing technology is addressing modern engines and the acoustic issues that can still arise. Finally, future and on-going research is discussed for predicting what additional areas of research exist for this topic.

I. Nomenclature

a	=	speed of sound of gas
A	=	cross-sectional area
f	=	frequency
l	=	length
p	=	pressure
r	=	radius
R	=	gas-specific gas constant
Re	=	Reynolds number
t	=	time
u	=	velocity
V	=	volume
γ	=	ratio of specific heats
λ	=	amplification factor
ω	=	angular frequency

II. Introduction

Liquid rocket engines convert chemical energy stored in liquid propellants into kinetic energy to produce thrust. Their functionality is greatly dependent upon proper injection, atomization, and combustion of the liquid constituents, and is rarely a smooth operation. Instabilities can occur due to the pumped-in propellants, interactions with the combustion chamber geometry, or even the injector ports that spray the propellant into the chamber. An instability is observed as a variation in temperature and pressure within the combustion zone and can make steady operation difficult or lead to an engine shutdown or rapid unscheduled disassembly of the engine altogether. Instabilities can be low frequency, such as pogoing effects within the entire rocket (10-400Hz), or high frequency, over 1000Hz that can rapidly alter an engine's performance or destroy it altogether.

This paper will focus on the high frequency instabilities that are aligned with acoustics effects from the propellant feed system, injection, or chamber resonance properties. These instabilities can be the hardest to diagnose from the rapid response effects that can result and the inability to shut down an engine in time before the pressure and temperature fluctuations destroy the hardware itself as shown below in Figure 1.

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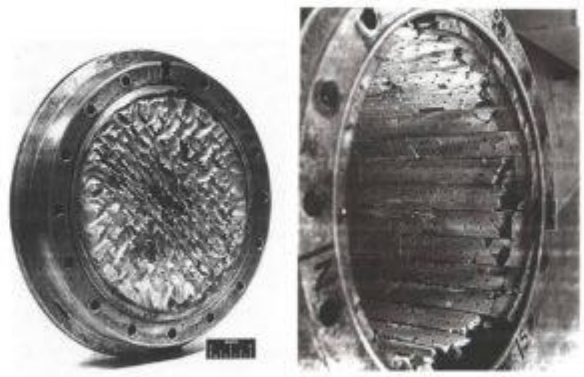


Figure 1: Damaged injector and thrust chamber due to combustion instability [1]

By combining summaries of the most important and significant findings on acoustic instabilities, a general trend may be observed for future rocket propulsion groups to anticipate design considerations, development issues, or testing schedules that could arise from solving high frequency instabilities. Not only would this save time and money for government groups, space startup companies, or even university teams, but safety is also increased, as are the long-term odds of a successful liquid rocket engine leaving the test stand and seeing the launchpad.

III. Background

A combustion instability is considered a pressure fluctuation ±5% of the average chamber pressure. Instabilities can be categorized into 3 ranges of low, medium, and high frequencies. Low frequency instabilities range from 10-400Hz and result from pressure interactions of the propellant feed system with the rocket engine or even the whole rocket. Intermediate frequencies range between 400 and 1000Hz and are due to mechanical vibrations of the propulsion structure and fluctuations in the fuel to oxidizer mixing ratio. High frequencies are called screaming, screeching, or squealing and correspond to frequencies above 1000Hz. These are linked to combustion pressure forces and chamber acoustical resonance properties [2], occurring at frequencies close to that of the acoustic modes of the combustion chamber.

High frequency instabilities can occur in 2 primary acoustic modes: longitudinal and transverse. The longitudinal mode extends the length of the combustion chamber and nozzle and can be reflected against the injector and converging nozzle section. Transverse modes can be split into radial and tangential modes perpendicular to the longitudinal chamber axis. Tangential vibrations can form standing waves or spinning/traveling waves that amplify pressure fluctuations for the fixed and rotating directions, respectively. The tangential mode is also the most damaging, increasing heat transfer 4-10 times, leading to melting walls of the combustion chamber or burning through it altogether [2]. The pressures can also fluctuate to twice the steady state operation values for these acoustic instabilities. These are shown schematically below in Figure 2.

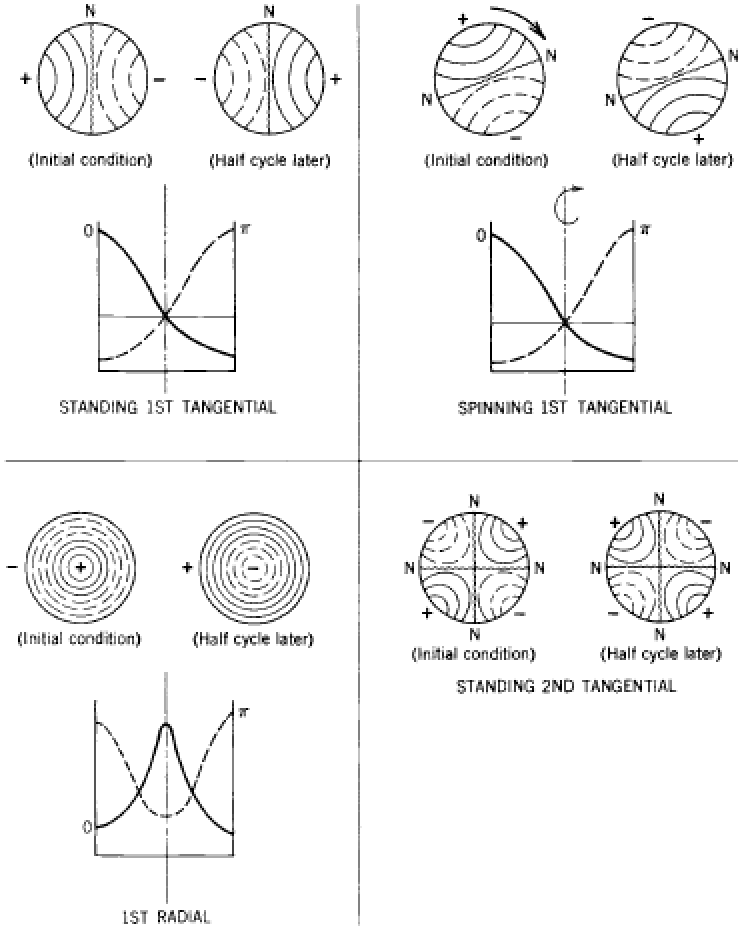


Figure 2: Examples of transverse acoustic modes [2]

The energy that drives high-frequency acoustic instabilities are due to acoustically-stimulated variations in droplet vaporization and acoustic changes in combustion rates. This means that if a certain acoustic condition is met, the high frequency nature of the instability can quickly lead to destructive failure of the engine.

Some instabilities are amplified if they coincide with the natural frequency of combustion chamber vibrations, The natural frequency can be calculated with Eq. 1 below where l is the wavelength and a is the acoustic velocity in the chamber. The wavelength depends on the type of acoustic mode being studied. A takeaway from this relation is that smaller chambers result in higher natural frequencies.

$$f = \frac{a}{l} = \frac{\sqrt{\gamma RT}}{l} \tag{1}$$

Controlling instabilities is most often accomplished by means of acoustical damping techniques inside the combustion chamber. These include injector face baffles, acoustic absorption cavities, acoustic liners inside the chamber, or even injector design changes. Injector baffles were very common in the 1960s and are an empirical solution, sometimes requiring trial and error to damp transverse modes. The Rocketdyne F-1 engine (Figure 3) is a classic example of this. It was subject to more than 3200 full-scale tests to arrive at a successful injector design using baffles to control instability excitation [3]. Baffles are suitable for acoustic instabilities below 4000Hz, as above this threshold, damage from instabilities is rare.

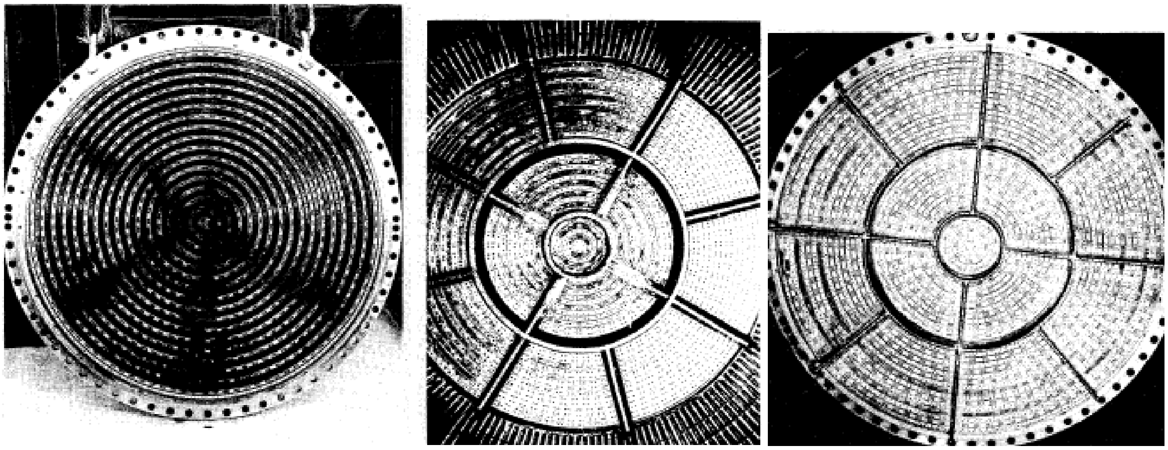


Figure 3: Evolution of F-1 engine baffles on the injector face [3]

While some damping occurs from the combustion products, it is not enough to absorb the pressure fluctuations induced by the instabilities themselves. Thus, acoustical absorbers are necessary and are designed as Helmholtz resonators. These are devices that can be designed as absorption cavities and placed near the injection face to absorb acoustic energy and unwanted pressure fluctuations that contribute to instabilities. The resonance frequency of a Helmholtz resonator is calculated with Eq 2.

$$f = \frac{a}{2\pi}\sqrt{\frac{A}{VL}} \tag{2}$$

These provide broadband damping in two ways: damping due to viscous drag and heat transfer at the cavity walls, and damping due to the formation of vortices at the cavity exit [4]. Their effectiveness is improved with increasing velocity at the cavity entrance and greater amplitude of oscillation encountered. They can be designed such that the resonance frequency of the cavity aligns with certain predicted or observed acoustic instability present in an engine, thereby extracting energy from the instability, or preventing excitation of the instability altogether. The analysis of Helmholtz resonators is not so simple however, as the high pressure, temperature and sound levels complicate using these as acoustic absorbers.

IV. Current Research

Recent studies and present knowledge of high frequency combustion instabilities include control mechanisms that actively mitigate instability excitation, modeling of combustion flows to predict instabilities and their acoustic modal interactions with the injector and chamber, and finally, testing of hardware (subscale or full-scale) prior to hotfire testing.

A. Control Mechanisms

Culick and Yang conducted a survey overview of combustion instabilities and provided an introductory discussion of instability control techniques [5]. These techniques fall into two categories: passive and active control. Passive control techniques generally involve hardware components with optimized geometry to act as resonators, damp oscillations by means of baffles, or lining the chamber with an acoustic absorber. The primary downside to these include limited frequency response and may only perform for a limited range of oscillation frequencies. Advantages however are ease of testing at room temperature and historical data on passive devices used in other engines previously. One must be mindful of extrapolating room temperature data to the combustion environment.

Recently, more attention has been devoted to active control mechanisms. Early concepts for this targeted low-frequency instabilities (chugging) by varying propellant supply as shown in Figure 4, but research remains to be done in actively controlled acoustic instabilities. The basis for this area stemmed from noise control and using antisound for destructive interference and cancelling out unwanted instabilities.

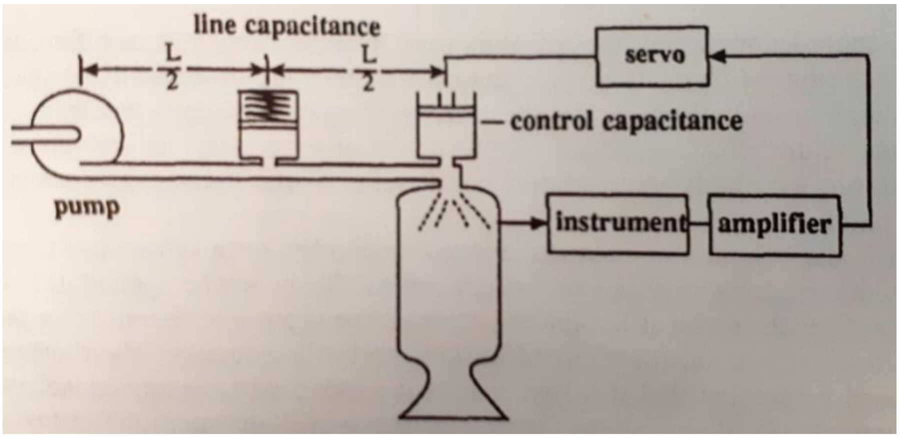


Figure 4: Active control mechanisms for chugging stability [5]

The need for control/stabilization devices can vary for different propellant types. In their survey of liquid hydrogen and oxygen (hydrolox) engines, Hulka and Hutt indicate that control mechanisms for this propellant combination are largely unnecessary because stability configurations were identified early on in hydrolox engine development [6]. However, the J-2 engine utilized an acoustic wall liner of axial-array Helmholtz resonators that solved an instability configuration when the liner was absent [7]. A liner of Helmholtz resonators was not shown to be impactful on the SSME [8], so this propellant combination certainly can create variance in the degree of instabilities that exist.

Another common propellant combination is the kerosene-liquid oxygen (kerolox) engine. Muss identified that the most common injector element for these engines is the like doublet or like-on-like (LOL) [9]. For this design, each liquid propellant is atomized prior to mixing with one another and were used on the Atlas, Thor, and H-1 engines. However, it was found that maximum stability occurred when unlike propellant sprays combined. A figment of this injector type is that unlike propellant mixing resulted in low combustion efficiency between 90 and 95% [10]. From the studies presented by Hulka and Hutt and Muss, injector design is partly established for a given propellant combination. This could lead to a strong starting point for future engine designs that use these propellants. Figure 5 indicates a stability criterion for several kerolox engines in various configurations for injector diameter D_j and injected velocity of kerosene, V_j.

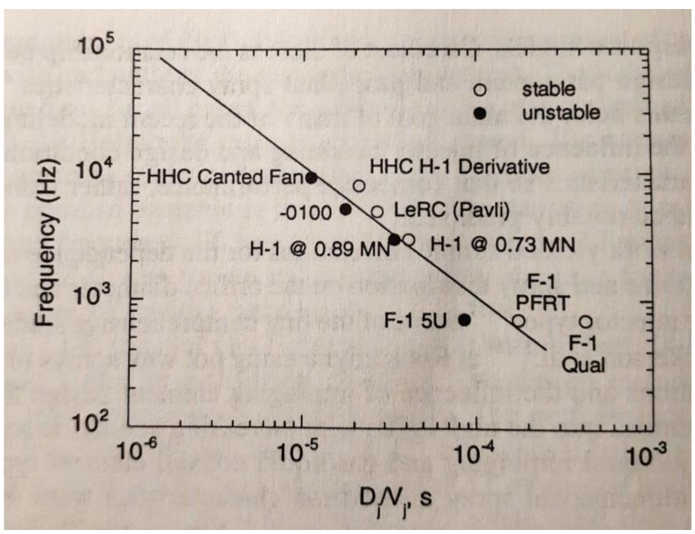


Figure 5: Empirical correlation for stability of several kerolox engines using like-doublet injectors [9]

Combustion instabilities are also unique for Earth-storable bipropellant combustion. Hurlbert, Sun, and Zhang studied instabilities for hydrazine-based engines including the Apollo Service Propulsion System Engine, Lunar Excursion Module Descent Engine, Apollo Lunar Module Ascent Engine, Space Shuttle Primary RCS Thruster, and Space Shuttle Orbital Maneuvering Engine [11]. These engines were not as plagued with instability issues like some booster-stage engines, but isolation of component testing was occasionally necessary. The Apollo Lunar Module

Ascent Engine utilized baffles in an injector redesign, but ultimately what achieved high-frequency dynamic stability was an ablative chamber. Early development of the Space Shuttle Primary RCS Thruster used acoustic cavities totaling 4% of the injector area, but as a result would go unstable in the first tangential mode. Ultimately, stability resulted when the cavity area was increased to 8% of that of the injector. These solutions were unique to various engines, despite using common propellants. The instabilities were from the differing thrust magnitude and application.

B. Analytical Modeling

The most basic approach to analyzing high-frequency combustion instability begins by approximating acoustic motions using the homogenized wave equation. Heister et al. discuss the basic approach to this method [4]. This initial approximation assumes low Mach numbers in the chamber (as the exhaust gases have not yet entered the converging-diverging nozzle by this point), a choked nozzle, and incident waves are efficiently reflected against the combustion chamber's metal walls. Pressure fluctuation, p, is described by Eq. 5 where $\bar{p}$ is the average pressure, Re is Reynolds number, p' is the complex pressure fluctuation, s is a complex eigenvalue defined in Eq. 4, and t is time.

$$p = \bar{p} + Re(p' e^{st}) \tag{3}$$

In Eq. 4, λ is the amplification factor and ω is angular frequency.

$$s = \lambda + \mathrm{i}\omega \tag{4}$$

By using conservation equations, Eq. 3, linearizing, and neglecting higher order terms, results in the zeroth-order wave equation in Eq. 5. Pure longitudinal motion is given by Eq. 6 and 7 where u_0 is the velocity at both ends of the combustion chamber and is zero for this analysis.

$$s_0^2 p_0 + \nabla^2 p_0 \tag{5}$$

$$\frac{s_0 p_0}{\gamma} + \frac{du_0}{dx} = 0 \tag{6}$$

$$s_0 u_0 + \frac{d}{dx}\left(\frac{p_0}{\gamma}\right) = 0 \tag{7}$$

As s_0 is the eigenvalue, it is always imaginary. By combining Eq. 8 with Eq. **Error! Reference source not found.**, the frequency of oscillation, f, is determined in Eq. 9 where j is the integer of the longitudinal mode pressure node location, $\bar{a}_c$ is the speed of sound, and L is the combustion chamber length (distance between system inlet and exit).

$$s_0 = i\omega_0 = ij\left(\frac{\pi}{L}\right) \tag{8}$$

$$f = \frac{j\overline{a_c}}{2L} \tag{9}$$

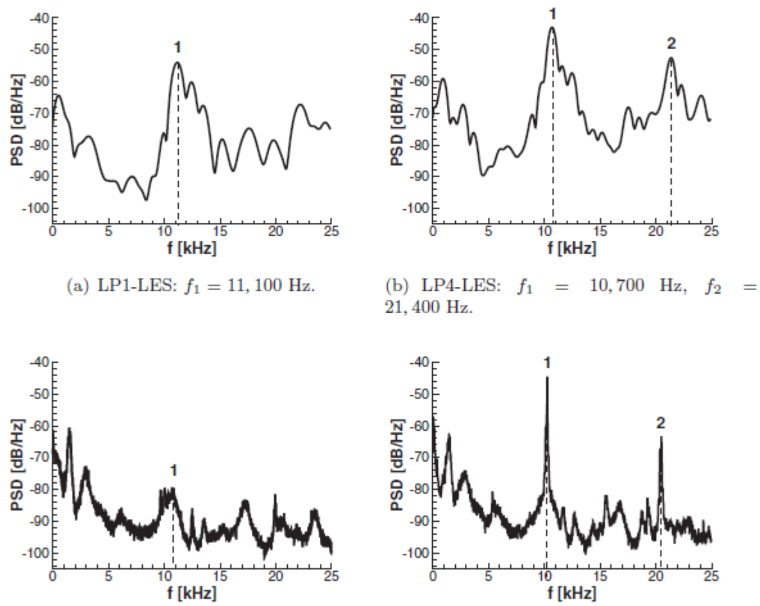
Finally, by altering the zeroth-order equations for cylindrical transverse motions, transverse mode frequencies can be calculated with Eq. 10 where $s_{v\eta}$ is a value between 1.8413 and 8.5263 depending upon the transverse mode character, and r_c is the combustion chamber radius.

$$f = \frac{s_{v\eta}\overline{a_c}}{2\pi r_c} \tag{10}$$

These wave equation-based approximations are the first step in estimating combustion instabilities. The most common step for more advanced analysis is by utilizing numerical simulations. This refers to governing equations of motion, conservation equations, and modelling all physical processes present in the combustion chamber. This results in two types of inaccuracies: computational errors and errors from the fundamental approximations. Culick and Yang state that numerical simulations are challenged by a lack of computing power and the difficulty in modeling a *range of parameters* [5]. The authors of this study provided a discussion of the basis of most analytical models that stems from equations for unsteady motions for liquid and gas phases of the combustion process. This applies most accurately for linear oscillations and serve as the foundation for nonlinear oscillations. Rayleigh's Criterion is a contributing factor that indicates heat transfer into the oscillating fluid helps drive acoustic waves if added in phase and at the oscillation's point of greatest amplitude.

An early study in using computational fluid dynamics (CFD) for modelling instabilities was conducted by Grenda, Venkateswaran, and Merkle [12] in 1995. It is the author's recommendation that CFD be used as a testbed for evaluating how certain parameters affect instability processes. Rather than model the entire combustion reaction, a given injector shape or chamber geometry could be modified to understand that parameter's effect on the engine's stability performance. The authors stress the importance of validating CFD to experimental data and for a future study of theirs, they recommend a model that accounts for unsteady atomization effects and more accurate dynamic models of droplet vaporization.

As challenging as modeling combustion instabilities may be, a breakthrough was made recently in 2016 by Urbano et al. in which the authors used Large Eddy Simulations (LES) to predict occurrence of transverse high-frequency instabilities at separate operating conditions that feature differing levels of acoustic activity [13]. This was a unique study because it was one of the first that used CFD to analyze combustion instability of a full-scale engine, not just isolated components or scaled analogs. It did require the use of an IBM BlueGene Q supercomputer, but this was a beneficial first step towards full-scale CFD studies. The authors observed favorable comparison of experimental data to the analytical model, including data shown below in Figure 6 which plots analytical data on the top column and experimental data below when the chamber is subject to 1 and 2 perturbations.



(a) LP1-LES: $f_1 = 11,100$ Hz.

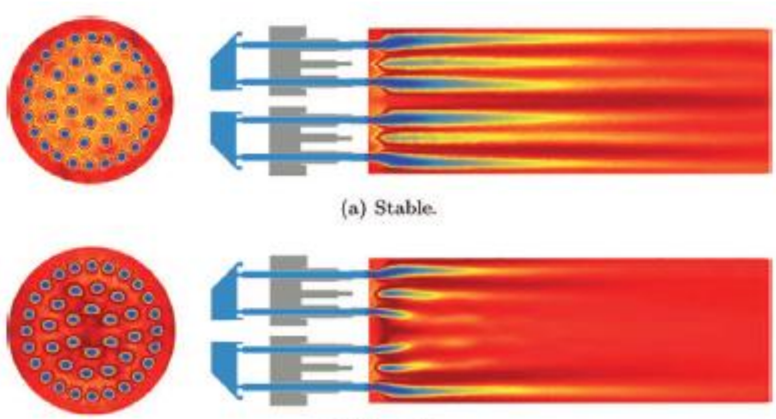
(b) LP4-LES: $f_1 = 10,700$ Hz, $f_2 = 21,400$ Hz.

(c) LP1-experiment: $f_1 = 10,800$ Hz.

(d) LP4-experiment: $f_1 = 10,260$ Hz, $f_2 = 20,500$ Hz.

Figure 6: Power spectral density (PSD) vs frequency for 1 and 2 perturbations [13]

Furthermore, indications of injector and corresponding flame geometry resulted from the author's CFD. Below in Figure 7a, stable combustion occurs, but in Figure 7b, the short flames at the centerline of the injector plate are indicative of instability in the transverse mode. This study will likely become the foundation for future analytical models in predicting and studying instabilities within future rocket engines.



(a) Stable.

(b) Unstable.

Figure 7: Speed of sound within the engine blue (239m/s) to red (1997m/s) [13]

C. Component-Level Testing

Pirk et al. [14] performed an acoustic characterization of a thrust chamber for a 75kN liquid rocket engine developed by the Institute of Aeronautics and Space in Brazil. This was done prior to any hotfire testing in which they placed microphones (Figure 8) within several thrust chamber configurations of varying lengths and nozzle shapes. Their findings of the chamber's natural frequency aligned reasonably well, generally less than 10% difference from the theoretical calculations. This data helps to predict the natural frequencies that could be expected during engine operation. However, they recommend that more extensive analytical methods such as Finite Element Method (FEM) or Boundary Element Method (BEM) be used to confirm their findings before further development take place. This study is indicative that although experimental data can be valuable, there remains a need for robust computations to determine mode shapes.

Figure 8: Combustion chamber acoustic testing conducted by Pirk et al. [14]

Vingert et al. [15] also studied engine hardware without combustion testing. This study sought to characterize the spray behavior of coaxial injectors used in the Vulcain engine, and it was observed that experimental data wasn't consistent when compared to other similar studies. This further indicates that experimental data can be obtained, but it isn't necessarily representative of actual chamber conditions, and further analyses are needed.

Instability phenomena can often vary and behavior be unique to propellant combinations. Hulka and Hutt analyzed instabilities for liquid hydrogen and liquid oxygen (hydrolox) engines [6] from a variety of manufacturers and missions. The authors cite a commonality between these engines including the Space Shuttle Main Engine (SSME or RS-25), RL10, and J-2 that feature the concentric or coaxial (shear coax) orifice injector type. This injector design, shown schematically below in Figure 9 was key to achieving combustion stability for hydrolox engines.

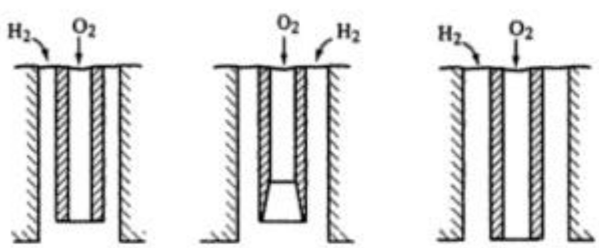


Figure 9: Parallel fuel shear coax injector schematic [6]

Testing with shear coax injectors was done on the J-2 and included varying hydrogen injection temperature to improve stability, and further testing at Pratt and Whitney showed higher hydrogen temperature and velocity ratio relative to the injected oxygen velocity. A plot of stability ratings is shown below in Figure 10. As indicated by the star symbol for stable operation, the sweet spot occurs mostly near an oxidizer-fuel ratio (O/F) between 5 and 6 for the range of injection velocity ratios. The most stable fuel-oxidizer (F/O) ratios are between 8 and 16, so variance is permitted as a result of this injector type.

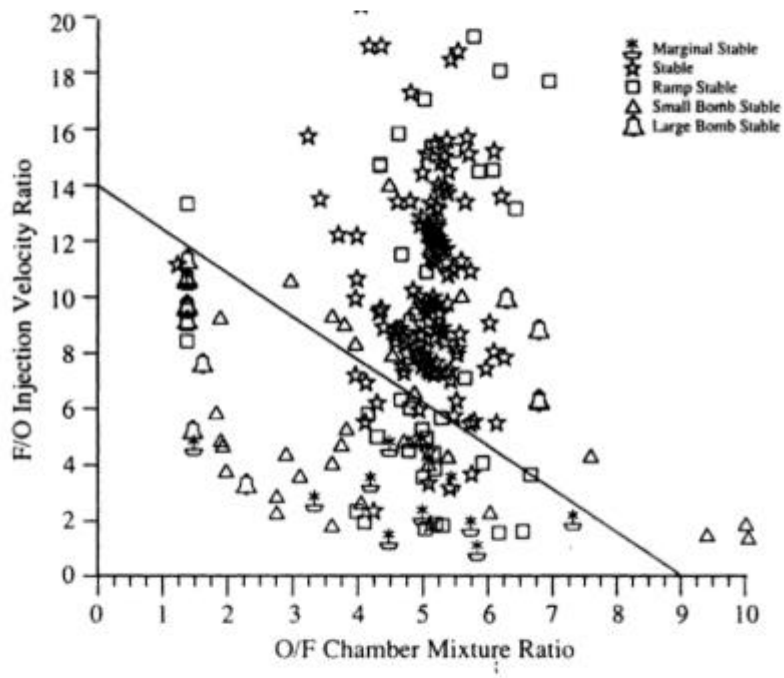


Figure 10: Stability criteria for a range of mixture and injection velocity ratios [6]

Additional testing of shear coaxial injectors was conducted by Hutt and Rocker at NASA's Marshall Space Flight Center (MSFC) to determine the injector geometry's influence on instability, as coax injectors are especially prone to high-frequency instabilities because the resonant frequencies of the injector often matches that of the chamber [16]. A plot of the responsive band around the natural acoustic mode of the chamber is shown below in Figure 11. This plot is particularly useful as the chamber resonant frequencies are the parabolic dashed lines coming down from the top of the plot, while the observed combustion frequency response is the solid line below. Instabilities can theoretically only occur where the two lines overlap. This kind of testing can help predict instability behavior for a given chamber size and combustion behavior that could result during hotfire operation.

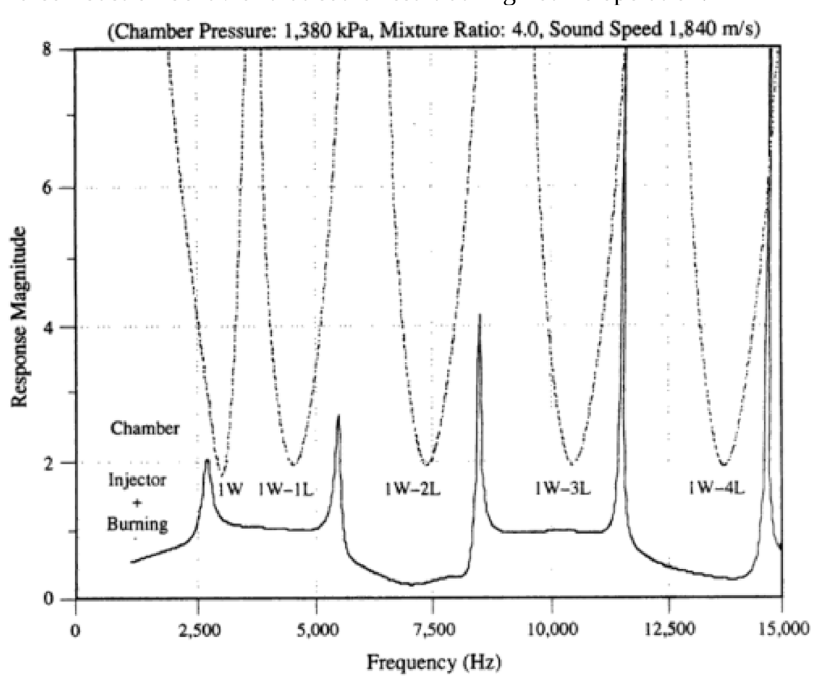
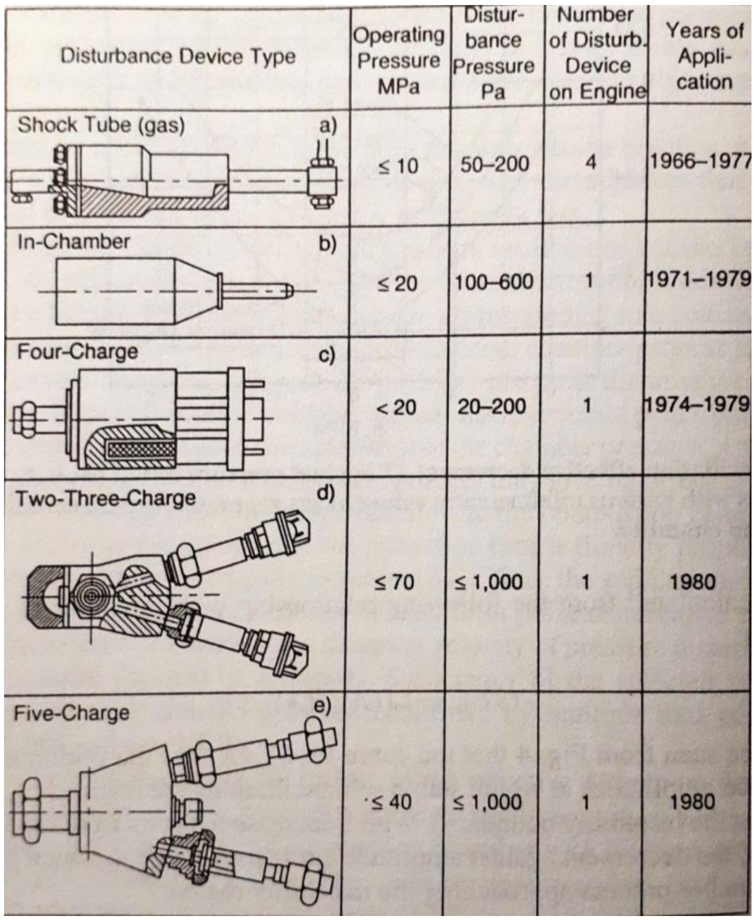


Figure 11: 2D stability research combustor response plot [16]

Disturbance devices are a means to test a chamber stability by supplying an instantaneous excitation. Agarkov et al. [17] describe disturbance devices as those that create an artificial pulse equivalent to most pressure disturbances normally present in the engine, applied at a controlled time, and the disturbance created should be well characterized in form and duration. Types of these charges are shown below in Figure 12.



Disturbance Device Type	Operating Pressure MPa	Disturbance Pressure Pa	Number of Disturb. Device on Engine	Years of Application
Shock Tube (gas) a)	≤ 10	50–200	4	1966–1977
In-Chamber b)	≤ 20	100–600	1	1971–1979
Four-Charge c)	< 20	20–200	1	1974–1979
Two-Three-Charge d)	≤ 70	≤ 1,000	1	1980
Five-Charge e)	≤ 40	≤ 1,000	1	1980

Figure 12: List of disturbance devices with their induced pressure and operating pressure [17]

These charges usually consist of a small detonation reaction through a burst diaphragm resulting from a mixture of ignited methane and oxygen. Their use in a combustion chamber pressure plot is shown below in Figure 13. The disturbance charge detonates at τ=006, induces a pressure fluctuation and exhibits recovery thereafter. Disturbance devices allow for tuning an engine at specific pressures and frequencies to determine instability behavior after a fluctuation is induced.

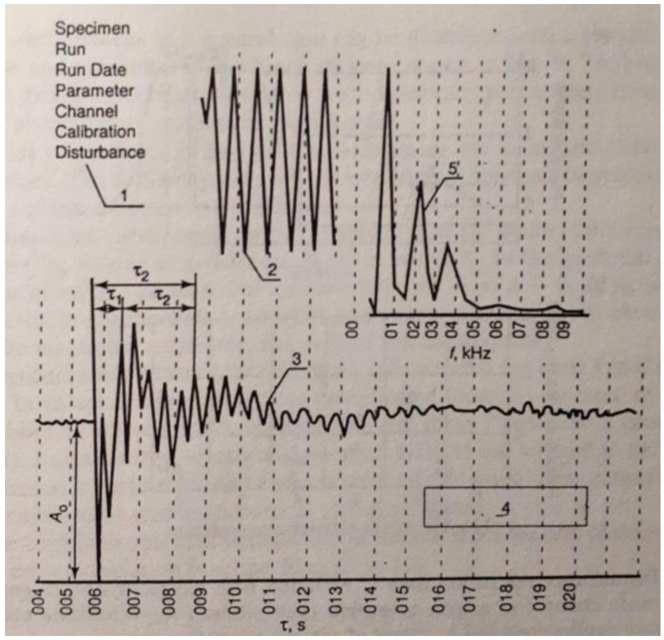


Figure 13: Pressure disturbance recovery following disturbance device charge [17]

Densisov et al. [18] discuss component-level testing of liquid rocket engines citing the importance of pressure pulsation measurements *upstream* of the injector, instead of just chamber pressure downstream of the injector. The authors cite two primary reasons for this: 1) pulsations and vibrations upstream of the injector are sensitive to vibrations past the injector and can be indicative of stability characteristics occurring downstream, and 2) engine safety as a result of mitigating adding holes to the combustion chamber for instrumentation. The study went on to examine reproducibility in multiple engine tests and evaluating pressure pulsations and the resulting variance between these tests. Their reproducibility plot is shown below in Figure 14. The primary takeaway from this is that reproducibility of stability characteristics is higher for repeated tests of the same specimen rather than multiple tests of different specimens. This means that each engine and test article will be unique and may necessitate its own testing individually to adequately characterize stability characteristics.

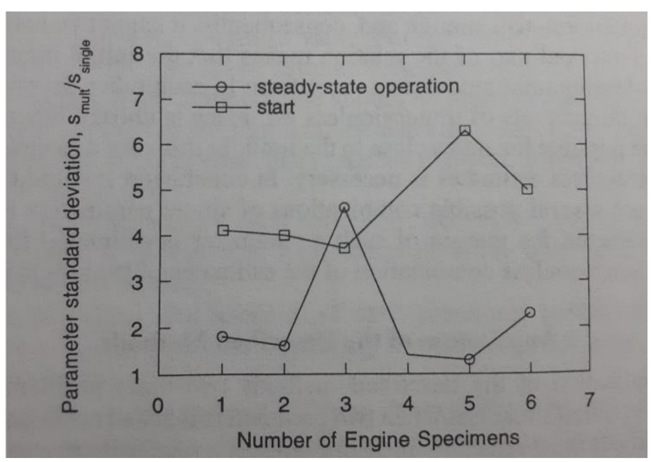


Figure 14: Reproducibility of complex parameter stability estimates

Finally, Fisher et al. [19] conducted a study of scaling techniques for stability testing. This is a key step before achieving a full-scale engine test that can be costly, time-consuming, and complex at early stages of engine development. To make subscale tests meaningful, design features often result in tradeoffs between stability, performance, and heat flux characteristics. This can yield changes to the injector pattern, combustion chamber and nozzle geometry, and even cooling techniques used. It may even be desirable to have modular components that can be swapped out for other parts to test different individual elements. Often if instabilities occur at a smaller scale, the same instabilities could be expected at the larger scale. Transverse modes, in particular, are observable in subscale hardware but not representative of the behavior seen at the full-scale. The goal of subscale testing is to create a database of anchored stability and performance models to provide confidence in the full-scale system. Examples of the types of subscale test combustors that can exist are explained in greater detail below.

Single-element combustors (labscale devices) are the simplest and most affordable testbeds but also yield the least amount of data in terms of stability and performance. Often one or few injector elements are used, and the objective is to characterize flow behavior of the individual injector of injector pattern. Disturbance devices can be implemented at this stage as well. One of the gaps that will exist for testing at this level is the lack of accurate representation of tangential acoustic modes at the large scale, as the tangential modes will be higher than the full-scale baffle compartments. An example of a tabletop setup of a single-element combustor is shown below in Figure 15 for a turbine drive combustor.

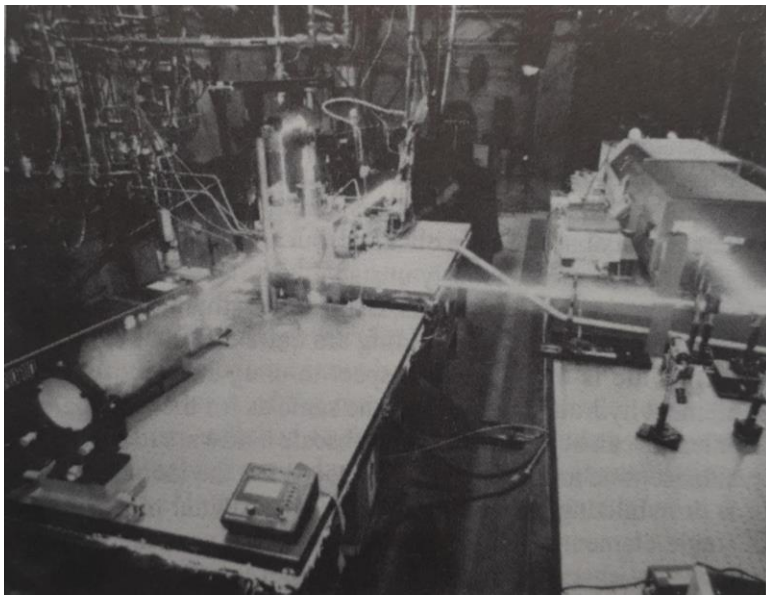


Figure 15: Single-element combustor with Raman and schlieren instrumentation [19]

Three-dimensional cylindrical subscale chambers are a step above single-element combustors with more injector patterns, but still operate at smaller chamber diameters and lower flowrates. A key finding from this scale of combustors is the "response of the combustion process to high-amplitude steep-fronted waves." The J-2, F-1, and SSME engines all used this rating technique. However, lower frequency transverse modes are still not representative of the full-scale engine and may require larger length-to-diameter ratios so as to preserve combustion residence time and achieve complete droplet vaporization. While still not as complex as the completed engine, instrumentation can be extensive as shown below in Figure 16. Another type of subscale combustor also exists in two dimensions.

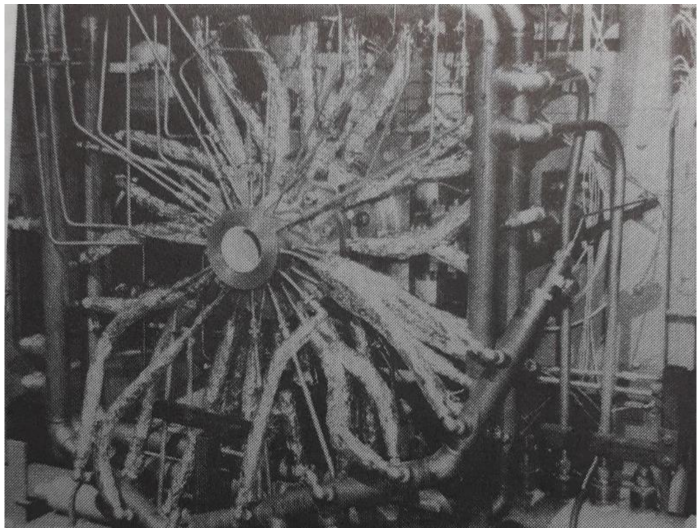


Figure 16: Santa Susana test facility 82-element methane-liquid oxygen subscale hardware

Two-dimensional slab combustors are possibly the most representative of full-scale acoustic stability. These are made so that the first width mode of the 2D combustor matches the first tangential mode of the full-scale engine. Recall that tangential modes were the most difficult to accurately represent with subscale hardware discussed previously. Injector elements also match the full scale for such a test arrangement. The chambers can even be made transparent for combustion visualization; this was done with the J-2S engine during testing. An example of a modular system of this type is shown in Figure 17 for the stability research combustor (SRC) at NASA MSFC.

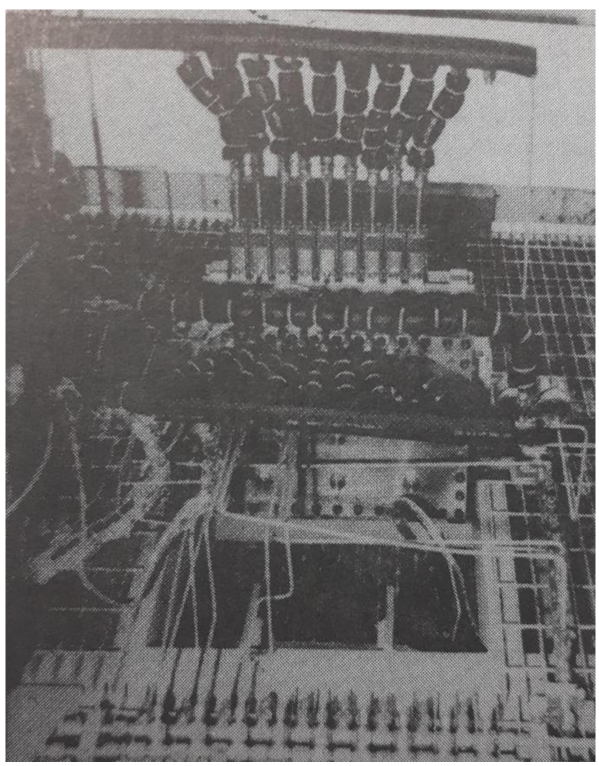


Figure 17: Stability research combustor at MSFC

Lastly, other subscale hardware can include barrel, annular, and wedge chambers, designed to isolate individual engine components and target certain acoustic modes or test passive control mechanisms such as baffles. Wedge chambers are particularly useful for the latter.

V. Conclusions and Future Work

In this paper, an introduction to high-frequency combustion instability was presented and analysis methods summarized. Control mechanisms were described and how propellant combinations can influence certain acoustic behaviors. The fundamental equations (stemming from the acoustic wave equation) of instability analytical models were presented as well as component-level testing that has occurred and can be done before hotfiring a full-scale rocket engine to determine acoustic instabilities.

Combustion stability research is one of the most studied areas still to this day in chemical rocket propulsion. As more spaceflight operations shift from government and military institutions to commercial ventures, a renewed interest in eliminating combustion instabilities without compromising expensive test hardware is on the horizon. In addition to mitigating costs, there are time and test location constraints and that will have new rocket engine designers accounting for the risks that combustion instability pose from the onset of engine development.

Additionally, one propellant combination that is recently hitting test stands more often is the liquid oxygen-liquid methane bipropellant system. SpaceX and Blue Origin are pursuing these propellants as a more sustainable and higher-performing alternative to kerolox, while avoiding the low densities and complexities of hydrolox engines. No methalox studies were discussed in this paper as the instability research is being done currently and still in development as this private companies certify their methalox engines for flight. This could very well introduce new areas of research into methalox combustion instabilities for low, medium, and high frequency acoustic instabilities. Future rocket engine designers should acknowledge the gaps in this area and prepare to be on the forefront of methalox instability research as they develop such systems. It was the goal of this paper to make such designers aware of research areas that have been examined previously and prepare for such research during engine development.

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