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COMBUSTION INSTABILITY COUPLING WITH FEED SYSTEM ACOUSTICS

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INTRODUCTION

High frequency combustion instability has recently been observed by Rocketdyne in a 40K thrust methane/LOX combustion chamber. The oscillations had frequencies as high as 14,000 Hz with pressure amplitudes in the LOX dome of 500 psi at a chamber pressures of 2,000 psi. At this frequency the wave length associated with a period of oscillation is 2.3 inches in LOX and 1.4 inches in methane. These distances are comparable to the lengths of the injector elements which requires that acoustic waves be considered in the feed systems rather than using lumped parameters as is normally considered for feed system coupled oscillations.

To expand the capability of existing models, the Feiler and Heidmann (ref. 1) feed system coupled instability model was modified to include acoustic oscillations in the feed system. Similarly the vaporization controlled instability model of Heidmann and Wieber (ref. 2) was modified to include flow oscillations that would be produced by feed system coupling.

The major elements that control oscillations in a rocket combustion chamber are shown in Figure 1. The elements are :

1. Combustion Chamber
2. Oxidizer Feed System
3. Fuel Feed System
4. Combustion of the Oxidizer via atomization and vaporization
5. Combustion of the Fuel via mixing and reaction
6. Nozzle Flow Characteristics
7. Baffles
8. Acoustic Absorbers

All of these elements must be considered together, with the same frequency in each element and interfaces between elements that have the same flow and pressure characteristics on both sides of the interfaces. Instabilities will occur when all of the elements contribute to a wave that will grow in time (system resonance). Stability occurs when "all" organized waves damp.

Only Items 1 through 5 are considered in the analysis reported herein. Items 6 thru 8 (Nozzle, Baffles and Acoustic Absorbers) can be considered as modifying the combustion chamber characteristics. The influence of these parameters have been clearly demonstrated by other studies. Models to include these parameters in the combustion chamber characteristics have been published. Since absorbers and baffles have not been used in the methane/LOX combustion chambers tested by Rocketdyne. A similar engine tested by MSFC did have a small gap at the injector that could act as an absorber and provide additional damping and stability. The nozzles were all the same shape, therefore, these factors were not included in the analysis.

To illustrate the major characteristics of each element they will be discussed separately, along with a brief description of the theory. The first item will be the combustion chamber which determines the general characteristics of the oscillations. This is followed by the LOX and fuel feed systems. These three elements are connected through the combustion process. The major contribution of LOX to the combustion process is through the vaporization process. The fuel influences the combustion process via the gas velocity environment it provides around the LOX and when it mixes and burns with the vaporizing LOX. Each is discussed separately.

To illustrate how the models can be used to analyze and/or predict combustion stability (or instabilities) the Rocketdyne methane/LOX test results are analyzed with the model to show the influence of mixture ratio and fuel temperature on stability limits. These are not to be considered as a complete analysis as "all" possible modes of oscillation were not completely analyzed. The results are then reviewed to indicate the design requirements that provide greater stability.

COMBUSTION CHAMBER

The combustion chamber was analyzed using the theory of Maslen and Moore (ref. 3) for oscillations in a fluid with finite Mach number flow. Only the linear terms (small amplitudes) are included which reduces to the following wave equation:

$$-\phi'_{tt} + \nabla^2\phi' = M^2\frac{\partial^2\phi'}{\partial z^2} + 2M\frac{\partial\phi'_t}{\partial z} \tag{1}$$

$$P' = -\gamma\phi'_t - \gamma M\frac{\partial\phi'}{\partial z} \tag{2}$$

$$\nabla\phi = u \tag{3}$$

where
- ∇ gradient
- M mach number
- P pressure
- t time derivative
- u velocity vector
- z axial derivative

The wave is assumed to be periodic in time and separable in the z, r, and θ coordinates, or

$$\phi' = J_n(mr)e^{in\theta}e^{i\omega t}\left(e^{izB_1} + Ce^{izB_2}\right) \tag{4}$$

where	B_1,B_2	complex coefficients
	i	unit complex
	J_n	Bessel Function of order n
	m	argument of Bessel function
	n	number of pressure nodes in θ direction
	r	radial direction
	t	time
	z	axial direction
	θ	tangential direction

These equations were solved following the procedures described in ref. 4 using the geometry shown in figure 2. A cylindrical chamber is used with radius r and length z. The $z = 0$ plane is at the nozzle end of the combustion chamber and $z = -l$ is at the injector face. Acoustic oscillations can occur in all three directions. Those in the "z" direction are called axial waves. The number of pressure nodes that exist in that direction identifies the mode number. Waves in the angular dimension are called tangential and in the r direction radial. Combinations of modes in all directions are possible.

For modes with radial or tangential components a unique feature is observed with low frequencies as shown in Figure 2. At a frequency below the fundamental the wave amplitude decreases exponentially from the injector face. All modes, except pure longitudinal, exhibit this characteristic. This has a significant impact on potential instabilities as will be shown later.

To solve the wave equation (Eq. 1) the boundary conditions must be specified. For the chamber walls the velocity is set equal to zero (this would not be true with acoustic absorbers). At the nozzle end of the chamber the flow characteristics must also be specified. A complex procedure (ref. 5) can be used to determine this boundary condition. For this analysis it was assumed that the chamber has a simple nozzle where the velocity is constant with time. This results in a flow oscillation that is associated with the adiabatic compression of the gas via the pressure wave.

Following this procedure the flow oscillations required to sustain an oscillation at a given frequency can be determined. For this analysis all flow oscillations are normalized by dividing by the steady state flow and then normalizing for wave amplitude by dividing by the ratio of pressure amplitude to average pressure. This normalized term is called a flow response, or:

$$FLOWRESPONSE = \frac{\frac{OscillatingFlow}{SteadyFlow}}{\frac{OscillatingPressure}{AveragePressure}}$$

Typical amplitudes of the flow responses at the injector end of a combustion chamber similar to that used in the methane/LOX testing is shown in figure 3 as a function of frequency. For the injector end the flow response is called "chamber response". Results are shown for pure longitudinal modes ($n = 0$ and $m = 0$ in Eq. 4) , the first longitudinal($n = 1$ and $m = 1.84$) and 3rd longitudinal ($n = 3$ and $m = 4.2$) modes. The longitudinal mode has minimum amplitudes at 0, 2350, . . . etc. frequencies. These are the frequencies most likely to be observed in an instability as they require the minimum combustion response to drive. The 0 frequency minimum is the pure "chug instability", while the 2,350 Hz minimum is the first longitudinal. Similar characteristics are observed for tangential and radial modes with the exception of the minimum at 0 frequency and a much lower minimum near the first mode which is associated with the exponential decay of amplitude with axial distance as discussed above.

The amplitude of the combustion response that is required to support a wave is only part of the answer provided by the analysis. In addition the phasing between the pressure amplitude and the flow response is also important. This is shown in figure 4 where the combustion response is shown on a complex plane for the 1 T mode. In the complex plane, time is represented by a counter-clockwise rotation. If the combustion, or flow, is in phase with the pressure the chamber response is all positive. If the flow lags the pressure the chamber response has a negative imaginary value.

Ideal resonance is illustrated in figure 4 by the condition where the chamber response curve crosses the real axis. At this point the combustion is in phase with the pressure and the minimum response is required to drive the oscillation. Normally this is referred to as the resonant frequency. Other frequencies can be generated in this chamber if the chamber response is not in phase with the pressure oscillation. If the chamber response lags the pressure the frequencies are lower than the "ideal-resonant" frequency. Higher frequencies are associated with a combustion system that leads the pressure oscillation.

Neutral stability (wave will not change amplitude with time) occurs when the chamber response is on the curves shown in figure 4. With responses that have larger real parts the wave will grow and for smaller real parts of the response the wave will decay. Thus stability is associated with being to the left in figure 4. (See figure 1 of ref. 4 for more detail.)

With transverse or radial modes at frequencies below the lowest "ideal-resonance" the amplitude of the response first decreases and the real part of the response is even negative as shown in figure 4. This is associated with the exponential decay in amplitude with distance from the injector face as mentioned above. Thus it is easier to drive these waves at frequencies "lower" than the "ideal-resonance". The magnitude of this drop in response is inversely related to the Mach number. At very low mach numbers (0.01) the curve is almost a constant value for the real part of the response (see figure 2 of ref. 4).

The complex characteristics of the response function will be directly influenced by changes in the chamber dimensions. For fixed geometries the only factor that influences the chamber response required to sustain oscillations is the mixture ratio which changes the speed of sound and/or Mach number. Changing the mixture ratio from the nominal 3.4 to 2.8 for a first transverse mode is shown in figure 5. The major influence is a slight change (200 Hz) in frequency for the same combustion response.

LOX FEED SYSTEM

A schematic of a typical LOX feed system is shown in figure 6. LOX flows into a dome that feeds all the injector elements. The dome for a 40K methane/LOX engine has a diameter of 6.5 inches and an equivalent (same volume) cylindrical length of 1.12 inches. Each LOX injector element is effectively 3.66 inches long with an inner diameter (ID) of 0.136 inches. At the entrance of each tube is an orifice with an ID of 0.086 inches. This orifice produces a pressure drop of 525 psi with 70 lb/sec of LOX flow.

The acoustics in the LOX system are determined by solving the same wave equation and procedures as for the combustion chamber. For this analysis it was assumed that the velocity oscillations at the head of the dome were zero. Calculations were also performed with other assumptions, which had a minor influence on the flow oscillations at the end of the LOX tube. However the assumption did influence the pressure profiles in the LOX system. The LOX flow oscillations are only due to velocity oscillations as the change in density with pressure produces a negligible change in flow.

Via this procedure a flow response at the orifice inlet was determined for the same radial-transverse wave modes as assumed in the chamber. This means the dome has the same radial and tangential pressure profiles as existed in the chamber. With the flow response at the inlet to the orifice, calculations were performed to determine the pressure oscillation that would be needed downstream of the orifice to obtain the flow and pressure oscillations calculated upstream. This was accomplished by using the linearized form of the Bernoulli flow equation. With the calculated pressure oscillation downstream, and the same flow rate oscillation, a new flow response is calculated downstream of the orifice.

Only axial acoustic waves were allowed in the small diameter LOX tubes. Thus the wave equation could be solved as discussed above using the flow response downstream of the orifice which is the entrance to the LOX tube. Via this procedure the LOX flow response was calculated at the exit of the tube.

Typical LOX flow response amplitudes are shown in figure 7 for the same wave modes and frequency range used for the combustion chamber in figure 3. Minimums at frequencies of 4400 and 8800 Hz etc., are associated with the resonance in the LOX tube downstream of the orifice. They are close to the "ideal resonant" conditions with no velocity oscillations at both ends of the tube.

Maximum LOX response amplitude is obtained at frequencies where the pressure amplitude is zero at the end of the tube. This is an unreasonable condition as the noise level and other characteristics prevents the pressure oscillations from going to zero. Also it is almost impossible to drive an oscillation (we are driving the LOX system from the chamber pressure oscillations) at a pressure node. LOX flow responses higher than twenty would be difficult to drive.

The phasing of the LOX flow response for a first transverse mode in the chamber and LOX dome is shown in figure 8. All of the responses are in the second and third quadrants as the orifice requires that flow be high when the chamber pressure is low. Comparing figure 8 with figure 4 points out the need for a phase shift between the LOX flow and combustion. Generally the flow is 180° out of phase with that required to sustain the oscillations in the chamber. The two lobes in figure 8 are associated with resonances occurring in the LOX dome.

For a given geometry the LOX flow response curves are only dependent on LOX velocity or flow rate. The flow rate changes slightly if the mixture ratio is changed. The response at different mixtures is shown in figure 9. The response is only slightly shifted to lower negative responses at lower mixture ratio due to the higher flow velocity in the tube. To show the influence of velocity on LOX response, results are also shown for a higher velocity. At higher LOX velocities the response is greatly decreased which is a very stabilizing feature.

FUEL SYSTEM

A schematic of a typical methane fuel system is shown in figure 10. It is similar to the LOX system with a dome being supplied by a feed line. For the typical 40K methane/LOX engine the dome is 6 inches in diameter and has an equivalent thickness of 2.225 inches. Flow enters the injector element through an annulus around the 0.25 inch LOX tube outer diameter (OD). The radial distance of this gap is 0.060 inches. The annulus length is 0.73 inches.

An equivalent orifice with a gap of 0.013 inches controls the fuel flow. With 20.59 lb/sec of methane at a density of 8.5 lb/ft^3 this orifice produces a pressure drop of 804 psi. Downstream of the orifice is an annulus with a radial gap of 0.010 inches that is 0.40 inches long.

Calculations of acoustic oscillations in the fuel system follows the same procedures as used in the LOX except that the flow rate oscillations are influenced by the change in density with pressure as methane is compressible at these conditions. Flow response at the entrance to the first annulus is equated to the response calculated for the dome. Only axial oscillations are used in the first annulus to calculate a response at the entrance of the orifice. The change in flow response across the orifice and the flow response at the end of the fuel tube follows the procedures used in the LOX system.

Fuel flow responses for the same frequency range and chamber modes as used for the combustion chamber are shown in figure 11. Minimum amplitudes correspond to the conditions where the velocity oscillations are minimum at the chamber and the orifice exit. Maximum amplitudes occur when the pressure is minimum at the chamber.

The complex characteristics of the fuel system for a third transverse oscillation are shown in figure 12. All of the responses are in the first and fourth quadrants of the graph indicating that part of the flow is always in phase with the pressure. This is due to the compressibility of the fuel, in contrast to the out of phase characteristics of the incompressible LOX. The profile of the fuel response is represented by circles that keep increasing in size with frequency and which precess around the imaginary axis.

The influence of fuel temperature and velocity on fuel response is shown in figure 13. Decreasing fuel temperature (which is accompanied by a decrease in velocity) increases the response. The influence of changing only the velocity (as would be produced by decreasing the fuel annulus) is indicated by the curve for a velocity of 639 ft/sec. With the increased velocity the response is much less which is a very stabilizing influence.

LOX COMBUSTION

Calculated results shown above for the LOX system clearly indicates that chamber pressure oscillations can produce flow oscillations much larger than required by the combustion system to be unstable. However to be effective in driving the combustion system the LOX must go through the combustion process to produce the hot gas required for driving. In methane/LOX combustion the slowest step is the vaporization of LOX. While other parts of the combustion process (atomization, mixing and chemical reaction) can influence the overall combustion process, the ability to drive pressure oscillations is controlled by the slowest process.

Previously the ability of the vaporization process to drive pressure oscillations was studied by Heidmann and Wieber (ref. 2). They calculated the rate of vaporization of an array of repetitively injected drops into a combustion chamber which had traveling transverse oscillations. While the study was mainly conducted for n-Heptane, calculations were also performed for LOX. The maximum response calculated for LOX was 0.82 (at a frequency of 1500 Hz for 50 μm drops) with a decrease at higher frequency. This could only drive a combustion chamber oscillation at the unique conditions associated with the exponential pressure decay with length that occurs with tangential waves at frequencies slightly below the fundamental mode.

Since LOX flow oscillations can influence the response of the LOX vaporization process the Heidmann and Wieber analysis was extended to include the effect of flow oscillations. This was accomplished as shown in figure 14. LOX leaves the tube at various velocities and travels through the recess of the element. This is shown schematically as a varying thickness of the LOX stream. LOX is being atomized by the surrounding high velocity methane. Eventually at the effective "atomization plane" the LOX stream is completely atomized and begins to vaporize. For the standard methane/LOX engine the atomization plane is estimated at 0.228 inches downstream of the effective end of the LOX tube. (Effective end of the LOX tube for oscillations is .026 upstream from the end of the LOX tube, $\frac{1}{2}$ of the chamfer section minus one tube diameter). This places the atomization plane 0.002 inches downstream of the injector face.

Drops are formed at varying rates as represented by the number of drops in figure 14. As the drops travel down the chamber they are vaporizing. For the standard methane/LOX engine it is estimated that 50% is vaporized and burned at a distance of 0.185 inches, with 98% vaporized and burned in 1.85 inches.

The flow of drops into the vaporization zone (at the atomization plane) will depend on the amplitude of the flow oscillations at the exit of the LOX tube, phasing of the flow oscillation with pressure and the additional phase shift associated with the time to travel from the end of the LOX tube to the atomization plane. Therefore the Heidmann and Wieber vaporization model was modified to include a flow response with a given amplitude and phase shift between the flow and pressure. The amplitude and phasing is calculated by the procedure described above for the LOX system. The phase shift was determined by the time to travel from the LOX tube to the atomization plane.

The LOX combustion response for the vaporization limited model with flow oscillations is mainly dependent on the amplitude of the flow oscillation and the burn time to wave time ratio. This is shown in figure 15 where the amplitude of the LOX combustion response for individual drops of LOX is given for different LOX flow responses as a function of time to burn 50% of the mass compared to the wave time. At very short burn times (less than .05 of the wave time) the combustion response is equal to the LOX flow response. For these short burn times the drops burn immediately (relatively to the wave period) and the instantaneous burning rate is equal to the flow rate.

For large burn times (greater than 5) the combustion response converges to the value for no flow oscillations (0.85 in this analysis). At these conditions every drop sees many cycles of oscillations and at any instant the total number of drops and size in the combustion chamber is equal to the average or steady flow values. Unstable combustion would be associated with short burn times and large flow response values. Stable combustion would be achieved by having larger times to burn and low flow response values.

Complex characteristics of single drop LOX combustion response and influence of delay angle on the response are shown in figure 16 for a burn time to wave time of 1.0 and LOX flow response of 5.0. With no delay angle the combustion response lags the pressure oscillation about 60°. As the delay angle increases the lag increases and forms an ellipse with the center at the combustion response associated with no flow (0.85). Increasing the delay angle will therefore first reduce the amplitude of the combustion response and then increase the amplitude. Delay angle will be very important in matching the combustion response with the chamber response at a given frequency.

For sprays of varying size drops the response of the individual drops would be averaged on the basis of the mass associated with each size. Each size would also have a different time to burn. Therefore the smallest drops would have the largest influence on the LOX combustion response because they have the shortest time to burn.

FUEL COMBUSTION

The role of the fuel in the combustion process with methane/LOX as indicated in figure 1 is to influence the flow field in which the LOX burns and finally mix and react with the LOX. Since the methane is considered to be a gas and fills the chamber as soon as it is injected, excess methane is available for combustion at all times. methane flow oscillations will therefore influence the combustion response by changing the instantaneous environment around the LOX drops.

A schematic of the combustion process with fuel flow oscillations is shown in figure 17. Fuel flow oscillations are shown radiating spherically from a sphere at the end of the LOX tube. The amplitude of this oscillation decays with the square of the diameter of the sphere. The center of the sphere is 15 LOX tube diameters upstream of the end of the LOX tube. Since a standing wave is produced in the fuel annulus (rather than a traveling wave) a standing wave is also used in the spherical radiation. Hence the phase of the oscillation at any distance is the same as that which is calculated for the fuel flow oscillation.

The spherical radiating waves therefore are constantly modifying the velocity environment around the drops. Since the vaporization rate is directly related to the velocity difference between the drops and the surrounding gas the burning rate will be constantly changing due to flow oscillations. This can be calculated by using a time varying gas field in the calculations performed for LOX vaporization.

In addition to changing the vaporization process the oscillating fuel flow would also change the atomization rate and drop size as a function of time. Both of these processes are also related to the velocity difference between the LOX and the surrounding gas. Variations in atomization rate would produce a flow variation of drops entering the atomization plane as was used above. Varying the drop size would change the burning time as a function of time. Both of these factors could be included in the LOX vaporization model.

Since most flow oscillations in the fuel system (especially with the methane/LOX system) are associated with high frequency (14,000 Hz) the time to burn compared to wave time would be very high. As shown in figure 15, with times to burn to wave times that are greater than 2, the contribution of LOX flow oscillations to the LOX combustion response is minimum. Therefore, in this analysis, the influence of the fuel flow oscillations on LOX atomization rate and drop size has been ignored.

Results of calculating the fuel combustion response with fuel oscillations (using the vaporization model modified to include a spherical radiation field) is shown in figure 18. Amplitude of the fuel combustion response is shown as a function of the fuel flow response amplitude for different phase angles between the flow oscillation and chamber pressure oscillation. The atomization distance and time to vaporize are those associated with the standard methane/LOX engine.

With no phase angle the combustion response is almost linear with flow response. Combustion response is always in phase with pressure and has a zero value when the flow oscillation is -1. Increasing the flow response increases the combustion response. At -1 flow oscillation the influence of chamber pressure on vaporization rate is canceled by the negative influence of the flow oscillation being out of phase with pressure.

The influence of changing the flow oscillation delay angle on the combustion response is also shown in figure 18. A positive or negative change in angle results in the same change in amplitude of the combustion response. However if the flow leads the pressure the resultant combustion response lead the pressure and if the flow lags, the combustion lags. With a phase angle the combustion response amplitude never goes through zero. This is a result of adding two vectors that are not in phase.

Calculations for the influence of fuel flow oscillations on LOX combustion response shows that the amplitude of the fuel response has a strong effect. High fuel flow response values would be associated with instability. Lowering fuel flow response should improve stability. Phase angle between the fuel flow response and pressure is important in matching the LOX combustion response with the response required to drive the combustion chamber.

Complex characteristics of the combustion response as well as the influence of frequency on the fuel combustion response with fuel oscillations, for the standard methane/LOX engine, is shown in figure 19. As frequency changes the fuel response amplitude and phase changes as indicated by the large circle. These flow oscillations produce the combustion response as specified by the smaller crescent. Realize that the large fuel response values are associated with minimum pressures occurring at the exit of the fuel annulus which can not be sustained. Therefore the regions of high response are not considered valid conditions for driving an instability. The combustion response in figure 19 moves counter-clockwise with frequency while for the combustion chamber the response moved clockwise as shown in figure 4.

METHANE-LOX ENGINE

The combustion stability characteristics of the methane-LOX engine tested by Rocketdyne were analyzed using the procedures described above. The basic characteristics of this engine (designated the NASA-Lewis, or LeRC, design) are:

DESIGN FEATURES OF NASA-LeRC METHANE/LOX ENGINE		
Chamber Diameter	5.66	inches
Nozzle Diameter	3.31	inches
Chamber Equivalent Cylindrical Length	11.38	inches
LOX Tube Exit Diameter	0.136	inches
LOX Tube Length	3.66	inches
LOX Orifice Diameter	0.086	inches
LOX Dome Diameter	6.5	inches
LOX Dome Equivalent Length	1.12	inches
Fuel Annulus ID	0.202	inches
Fuel Exit Annulus OD	0.224	inches
Fuel Exit Annulus Length	0.400	inches
Fuel Orifice Annulus OD	0.215	inches
Fuel Entrance Annulus OD	0.323	inches
Fuel Entrance Annulus Length	0.730	inches
Fuel Dome Diameter	6.0	inches
Fuel Dome Equivalent Length	2.225	inches
Element Recess	0.2	inches

OPERATING CONDITIONS

	O/F = 3.4	O/F = 2.8	
Nominal Chamber Pressure	1,971	1,971	psia
Combustion Gas Speed Sound	4443	4633	ft/sec
$\frac{C_p}{C_v}$ of Combustion Gas	1.205	1.196	
Nominal LOX flow	70.00	65.92	lb/sec
Nominal Fuel Flow	20.59	23.54	lb/sec
Exit Velocity of fuel	467.2	534.2	ft/sec
Exit Velocity of Lox	114.1	107.4	ft/sec
LOX Density	65.3	65.3	lb/ft^3
LOX Speed of Sound	2684	2684	ft/sec
$\frac{C_p}{C_v}$ of LOX	2.094	2.094	
Fuel Temperature	25	25	deg F
Fuel Density	8.49	8.49	lb/ft^3
Fuel Speed of Sound	1617	1617	ft/sec
Fuel $\frac{C_p}{C_v}$	2.161	2.161	
Atomization Distance	0.284	0.220	inches
Distance to Vaporize 50 %	0.185	0.126	inches
Distance to Vaporize 98 %	1.85	1.26	inches

The difference in atomization plane distance and distance to vaporize was calculated on the basis of the Rocketdyne CICM model (ref. 6). This model calculates an atomization rate and a drop size based on the velocity difference between the surrounding gas and the liquid and gas density. The stripping rate was proportional to the $\frac{4}{3}$ power of the velocity difference and $\frac{2}{3}$ power of the density. Therefore the atomization distance is inversely proportional to the $\frac{4}{3}$ power of velocity difference and $\frac{2}{3}$ power of density. Similarly the drop size was inversely proportional to the $\frac{4}{3}$ power of velocity difference and $\frac{2}{3}$ power of density. Since vaporization distance is proportional to the the $\frac{3}{2}$ power of drop size the vaporization distance was considered to be inversely proportional to the square of velocity difference and first power of density.

With the LeRC engine design, Rocketdyne observed a 5,000 Hz first tangential mode instability at a mixture ratio of 2.8. The analysis described above, using the design and operating conditions described above for the 2.8 mixture ratio, was performed to determine the predicted stability characteristics. These results are shown in figure 20 for a frequency range of 4,500 Hz to 5,500 Hz. The LOX flow oscillations are in the third quadrant.

A phase lag of 260° is introduced (at 5,000 Hz) by the time to travel from the end of the LOX tube to the atomization plane (0.126 inches). This moves the flow oscillations entering the vaporization zone into the first quadrant (flow from the previous cycle now lags the pressure slightly). Using the vaporization model with oscillating flow rate with a time to burn to wave time of 0.676 (at 5,000Hz) adds another 90° phase lag and reduces the amplitude of the response. The LOX combustion response is now almost 90° behind the pressure oscillation. The flow enters the vaporization zone more than a cycle after the pressure oscillation that produced the flow oscillation.

The chamber response is also shown on figure 20 as a function of frequency. The chamber response crosses the LOX combustion response at 5,000 Hz indicating an instability is expected at this frequency. The chamber and LOX combustion responses move in opposite direction with frequency. Thus only the 5,000 Hz condition satisfies the requirement that the two responses must be equal at the same frequency. At frequencies between 4,000 Hz and 5,000 Hz the LOX combustion response is in the unstable portion of the chamber response curve. However the frequencies do not match at the same response numbers. This indicates a metastable system where a oscillation could try to grow but can not sustain itself. Oscillations in the 4,000 to 5,000 Hz range were observed in the engine.

Obviously the perfect match for LOX combustion and chamber response shown in figure 20 is not fortuitous. In establishing the atomization distance and burning distance for the LeRC engine these parameters were varied slightly to determine the exact numbers that would be consistent with the 5,000 Hz instability condition. These numbers were within the range of expected values. A detailed analysis of the steady state combustion process using a complete steady state combustion model was not made.

Calculations to indicate why decreasing the mixture ratio would produce an instability were also made and the results shown in figure 21 for a mixture ratio of 3.4. Changing the mixture ratio had a small impact on the LOX flow response due to a small change in LOX velocity as was shown in figure 13. The biggest influence was the effect of velocity difference on the atomization distance and vaporization time or distance. At 3.4 mixture ratio the methane velocity is much lower and this results in much longer atomization and vaporization distances. Consequently the phase shift due to atomization is much larger at 3.4 mixture ratio. This results in the LOX combustion response being in the first and second quadrant, or stable zone. Other modes were not examined in detail due to the lack of available time.

The LeRC methane/LOX engine was originally built with a chamfer angle on the LOX tube ID of 15° in contrast to the standard design of 6° (obtained by reaming the LOX tubes). With a 15° angle the length of the effective LOX tube is increased by 0.061 inches. This changes the LOX flow response slightly. However the increased effective length decreases the distance from the effective end of the LOX tube to the atomization plane by 0.061 inches. As a result the phase shift due to atomization is decreased. Calculations were performed for a 15° LOX chamfer at MR = 3.4. For this configuration, at frequencies between 4,000 and 5,000 Hz, the combustion response moved into the third and fourth quadrants and is unstable as observed in the tests.

With the modified 15° chamfer angle, engine stability was lost by decreasing the delay time associated with the atomization process. Similarly with the LeRC engine stability was lost when mixture ratio was decreased due to the decrease in delay time associated with the atomization process.

Another 40K methane/LOX engine has been built and tested by MSFC over a wide range of mixture ratio and chamber pressure without observations of an instability. The two designs are considered by some to be identical. However they do have some major differences as noted below:

COMPARISON OF NASA LeRC and MSFC METHANE-LOX ENGINE DESIGNS MR. = 2.8			
	LeRC	MSFC	
LOX Tube ID	0.202	0.202	inches
LOX Tube Length	3.61	4.68	inches
Fuel Exit Annulus Gap	0.020	0.020	inches
Fuel Exit Annulus Length	0.40	0.63	inches
Fuel Flow/element	23.54	21.19	lb/sec
Fuel Velocity	534.2	480.8	ft/sec
Velocity Difference	426.7	373.4	ft/sec
Atomization Distance	0.22	0.263	inches
Vaporization Distance	0.126	0.165	inches
LOX Flow Response @ 5,000 Hz	6.05	62.2	
LOX Combustion Response @ 5,000 Hz	-0.17	-2.54	Real
	-1.74	+3.28	Imaginary

From this table it is obvious that the two engine designs are not identical when considered from an instability point of view. The major impact is the increased length of the LOX tube which increased the LOX flow response and the increased atomization distance due to the lower methane velocity. The 4.68 LOX tube length corresponds very closely to a quarter wave of the 5,000 Hz oscillation. This places a pressure anti-node at the exit of the LOX tube which means the high LOX flow oscillations have to be driven by very low pressure oscillations. This is unrealistic and very difficult to drive, hence the LOX flow can not oscillate with this design. Also the shorter LOX tube introduces a much larger phase lag in the LOX flow response.

The reduced fuel velocity (due to part of the fuel being used to cool the regimesh face) results in longer atomization and vaporization distances. Stability is improved by the combination of increasing the phase shift in both the atomization process (via increased atomization length) and the increased phase angle in the flow response as noted above. These two increases in phase lag result in the combustion response being shifted into another quadrant (second quadrant) where the system is very stable. However the major stabilizing factor in the MSFC design is operating the LOX system at the $\frac{1}{4}$ wave length. It is not unusual for small differences in an engine design to have a large impact on the stability characteristics. The analysis described above permits calculating the influence of these small design changes.

The objective of the Rocketdyne program to test the NASA LeRC design was to determine if methane temperature could be used to rate a methane/LOX engine. This was accomplished by testing the engine with continually decreasing methane temperature until a 14,000 Hz oscillation was observed at a fuel temperature of $-50°$F.

Calculations using the procedures described above were also performed to aid in understanding the 14,000 Hz oscillation. At 14,000 Hz the time to burn to wave time has increased to 2 which is in the region where LOX flow oscillations have a minor influence on combustion response (see figure 15). Therefore considering LOX flow oscillations would not result in a influence on 14,000 Hz instabilities. The analysis therefore concentrated on the influence of the fuel on stability.

The fuel velocity impacts the LOX vaporization by changing the velocity environment surrounding the vaporizing drops. Therefore the fuel combustion model discussed above was used to analyze the 14,000 Hz oscillations. The influence of fuel temperature on the various parameters that influence stability is shown below:

INFLUENCE OF FUEL TEMPERATURE ON STABILITY CHARACTERISTICS LeRC Engine at MR. = 3.4 and 14,000 Hz Oscillations			
Fuel Temperature	+25	-50	$^\circ F$
Fuel Velocity	467	320	ft/sec
LOX Velocity	107	107	ft/sec
Velocity Difference	360	213	ft/Sec
Fuel Density	8.49	12.41	lb/ft^3
Atomization Distance	0.284	1.18	inches
Vaporization Distance	0.185	1.58	inches
Fuel Flow Response	2.15	2.95	
Fuel Combustion Response	0.884	0.943	Real
Combustion Chamber Response	0.934	0.934	Real

The main impact of decreasing fuel temperature is to decrease the fuel velocity (and density). The reduced velocity produces a longer atomization distance and vaporization distance as shown above. Decreasing the fuel temperature increases the fuel flow response due to the lower velocity from 2.15 to 2.95 at −50°F. The fuel combustion response increases from .884 at 25°F to .943 at a temperature of −50°F. The chamber response at this frequency is .934, thus it would be predicted that an instability would occur around −50°F.

The major factor in decreasing fuel temperature to achieve an instability is the decrease in velocity around the drops vaporizing near the injector. With a lower velocity the fuel flow oscillation has a larger influence on vaporization and results in an increased fuel combustion response. The increase in atomization and vaporization distances due to lower velocity is a stabilizing influence. The decrease in velocity around the drops near the injector with lower fuel temperature is the major factor in determining stability with the standard engine.

The stability of the MSFC design with methane temperature was also analyzed. It has a different fuel annulus system along with the reduced fuel flow and velocity through the elements due to an estimated 10% of the fuel flowing through the regimesh face plate. Comparison of the calculated stability characteristics of the LeRC and MSFC engines to 14,000 Hz oscillations are:

STABILITY CHARACTERISTICS OF LeRC and MSFC DESIGNS MR. = 3.4, 25°F Fuel Temperature and 14,000 Hz Oscillations			
	LeRC	MSFC	
Fuel Velocity	467	420	ft/sec
Fuel Annulus Length	0.40	0.67	inches
Atomization Distance	0.284	0.342	inches
Vaporization Distance (50%)	0.185	0.245	inches
Fuel Flow Response	2.15	2.33	Real
Fuel Combustion Response	0.884	0.881	Real
Combustion Chamber Response	0.934	0.934	Real

The calculations show that both combustors have about the same stability margin at 25°F fuel temperature (0.884 and 0.881 fuel combustion response). The lower fuel velocity resulted in a higher fuel flow response for the MSFC design. The increased atomization and fuel distances with the MSFC compensated for the higher flow response to produce the same stability. These results indicate the importance of performing a complete analysis rather than assuming that the lower velocity and higher flow oscillations with the MSFC design would produce a more unstable engine.

SUMMARY OF RESULTS

A model to predict combustion instabilities associated with feed system coupling and vaporization limited combustion was developed that included acoustic waves in the feed system and flow oscillations into the vaporization zone. Calculations showed that stability is improved by:

1. Increasing the LOX velocity to decrease flow oscillations improves stability.
2. For LOX coupled oscillations decreasing the fuel velocity improves stability.
3. For fuel coupled oscillations increasing the fuel velocity improves stability.
4. Increasing the time to vaporize to wave time improves stability.
5. Changes in atomization distance can tune the system to either improve or decrease stability.

Performing calculations to determine the stability characteristics of the methane/LOX engines tested by Rocketdyne and MSFC has shown:

1. Low frequency (5,000 Hz) oscillations were predicted for the standard engine at a mixture ratio of 2.8. Decreasing mixture ratio decreases stability because at lower mixture ratio the higher methane velocity decreases atomization distance which "tunes" the system.

2. Changing the chamfer angle of the LOX tube from 15° to 6° stabilized the engine as it increased the atomization distance which results in a lower mixture ratio before the system "retunes".

3. The MSFC engine has improved stability because the longer LOX tubes and lower methane velocity (due to regimesh cooling) "detunes" the vaporization process even though the LOX oscillation amplitude is larger with the MSFC engine.

4. Reducing the fuel temperature reduces stability due to the lower methane velocity which reduces the velocity surrounding the vaporizing drops near the injector face. A 14,000 Hz instability associated with fuel flow oscillations coupling with the vaporization process was predicted at −50°F.

5. The MSFC engine had about the same stability margin for a 14,000 Hz oscillation even though it had larger flow oscillations due to the change in atomization and vaporization distances.

6. Preliminary analysis of the methane/LOX engine instability data indicates that it is behaving like the hydrogen/oxygen system and is amenable to design changes that can be analyzed to show definite stability margins.

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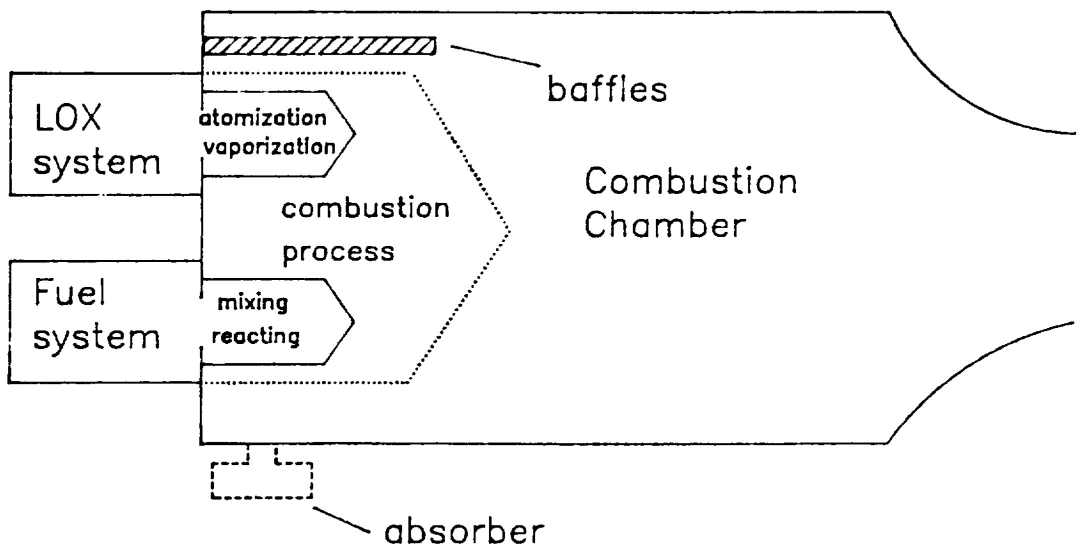

FIGURE 1. - SCHEMATIC OF COMPONENETS THAT INFLUENCE COMBUSTION CHAMBER OSCILLATIONS

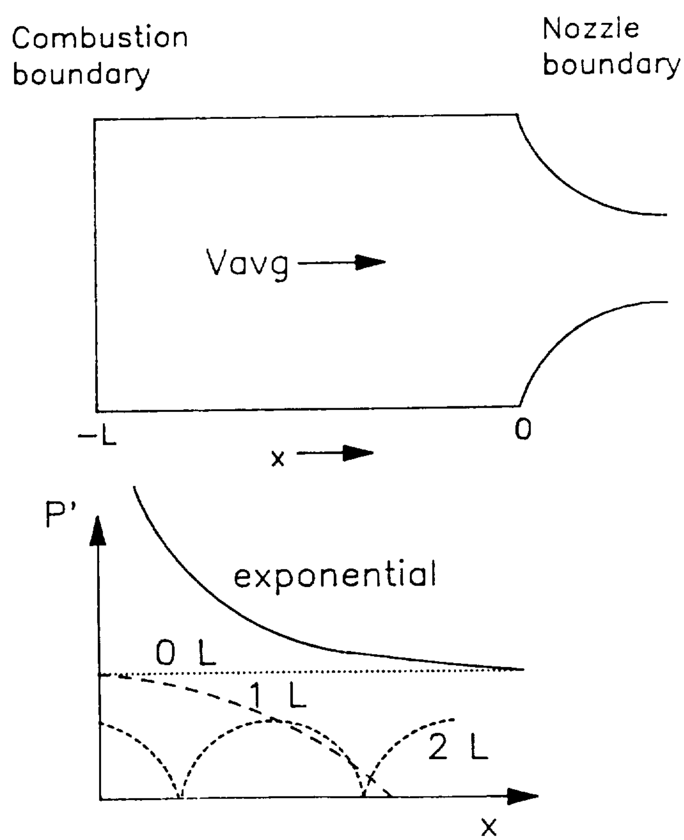

FIGURE 2. - COMBUSTION CHAMBER OSCILLATIONS

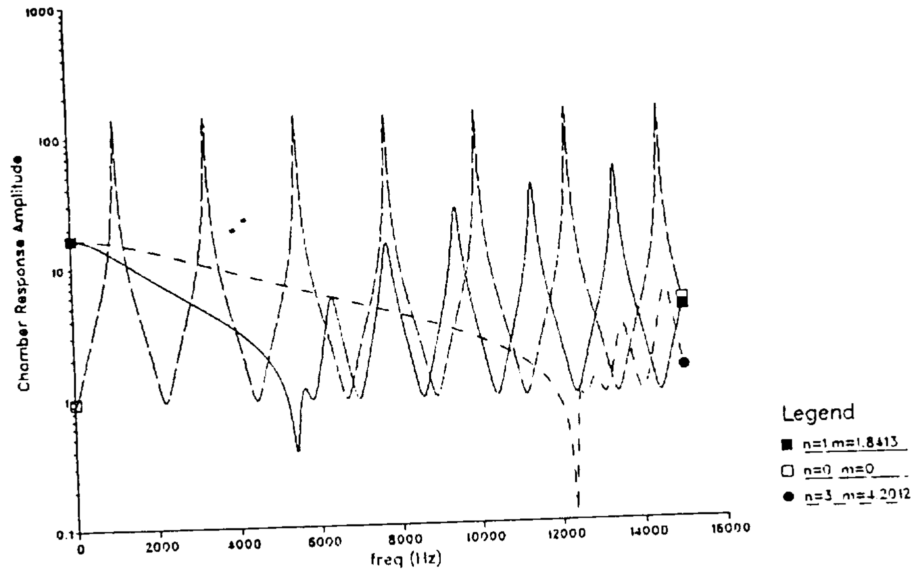

FIGURE 3. - CHARACTERISTICS OF COMBUSTION CHAMBER OSCILLATIONS MR = 3.4

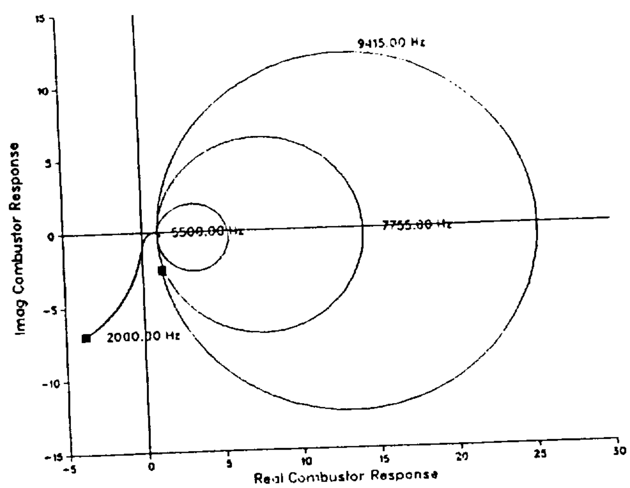

FIGURE 4. - COMPLEX CHARACTERISTICS OF COMBUSTION CHAMBER OSCILLATIONS WITH 1T MODE MR = 3.4

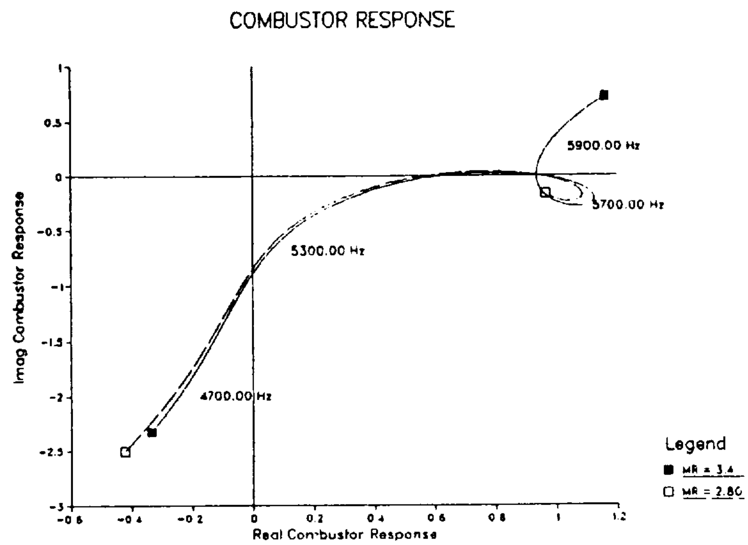

FIGURE 5. - INFLUENCE OF MIXTURE RATIO ON CHAMBER OSCILLATIONS WITH 1T MODE

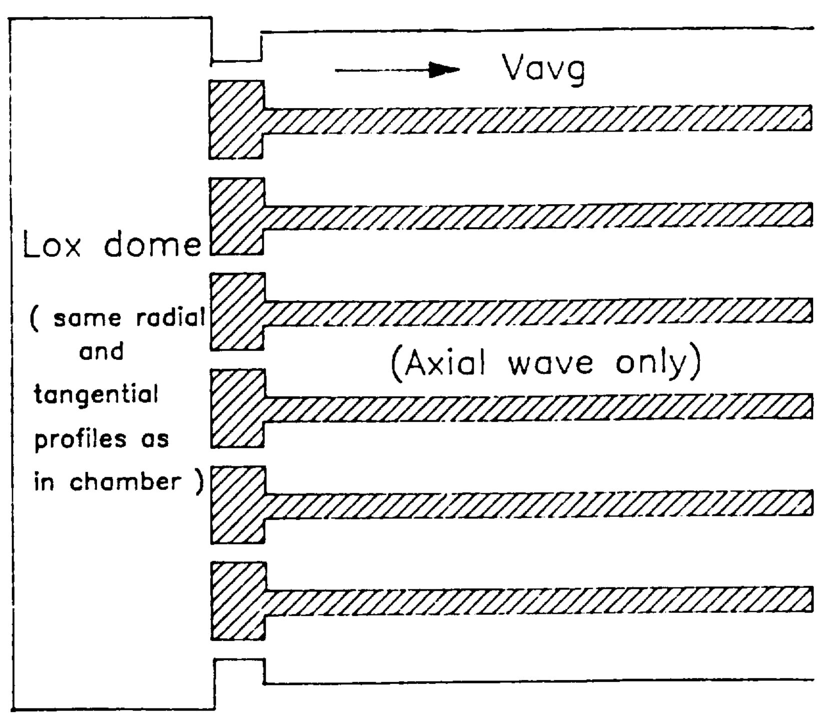

FIGURE 6. - LOX SYSTEM SCHEMATIC

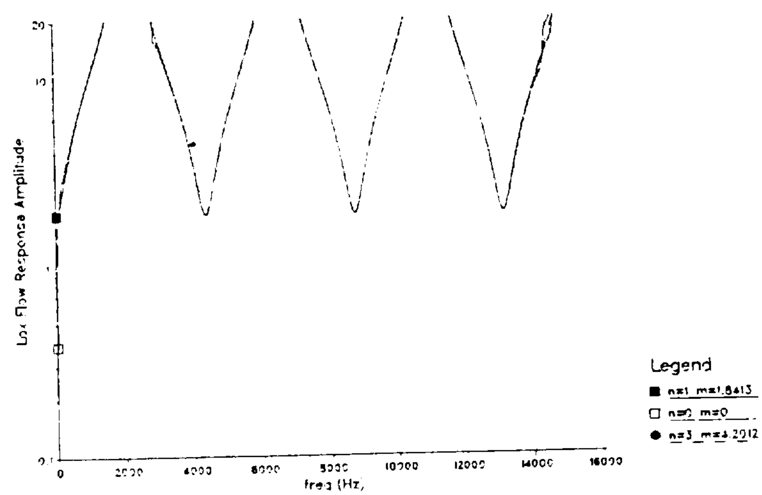

FIGURE 7. - CHARACTERISTICS OF LOX FLOW OSCILLATIONS

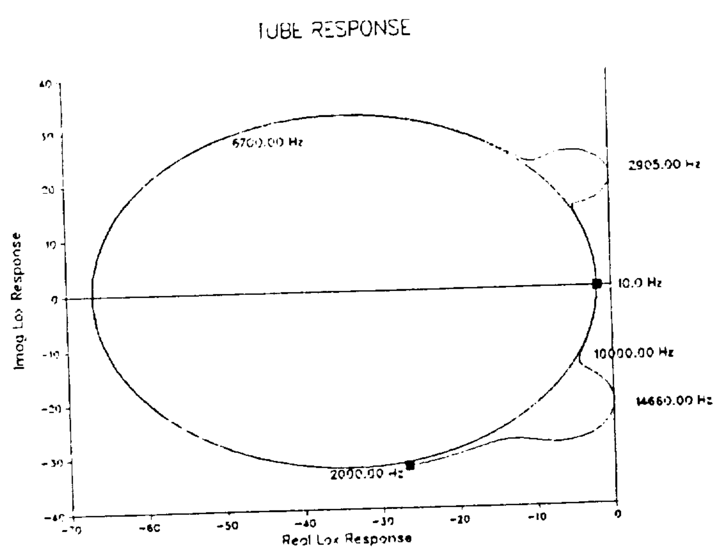

FIGURE 8. - COMPLEX CHARACTERISTICS OF LOX FLOW OSCILLATIONS WITH 1T MODE

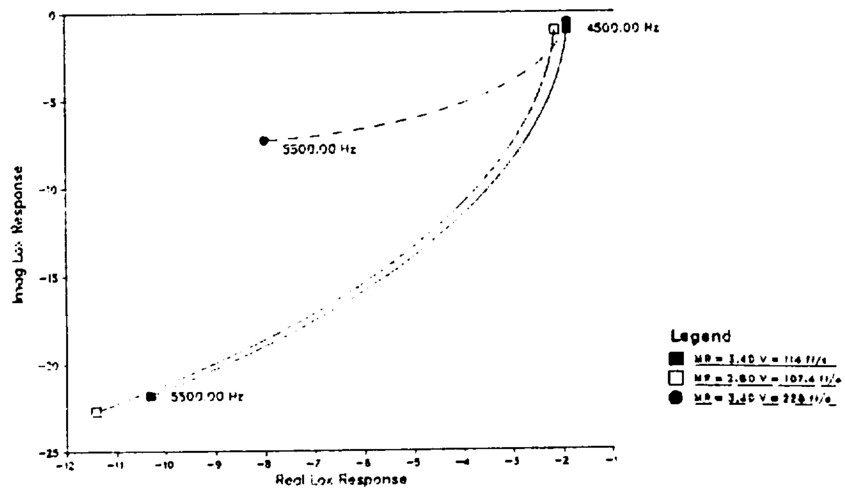

FIGURE 9. - INFLUENCE OF MIXTURE RATIO AND VELOCITY ON LOX FLOW OSCILLATIONS

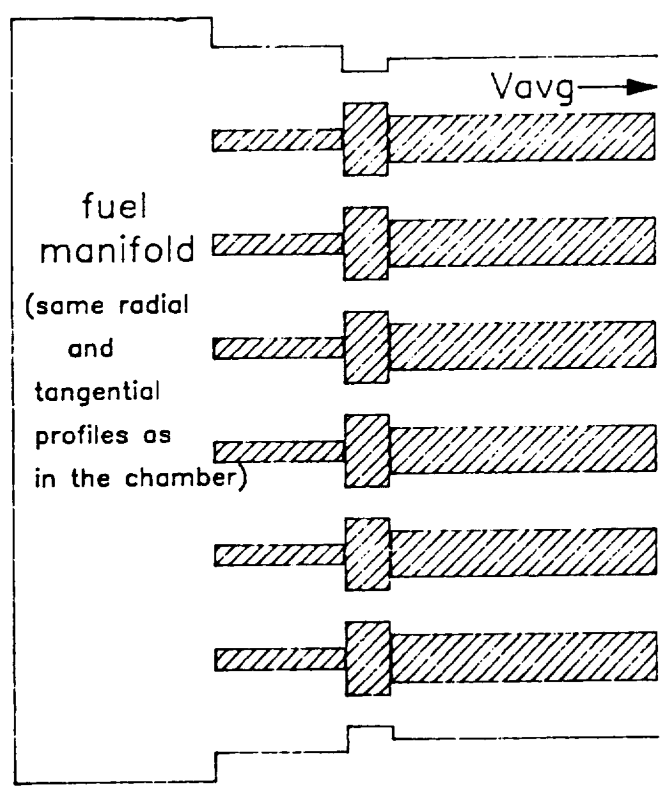

FIGURE 10. - FUEL SYSTEM SCHEMATIC

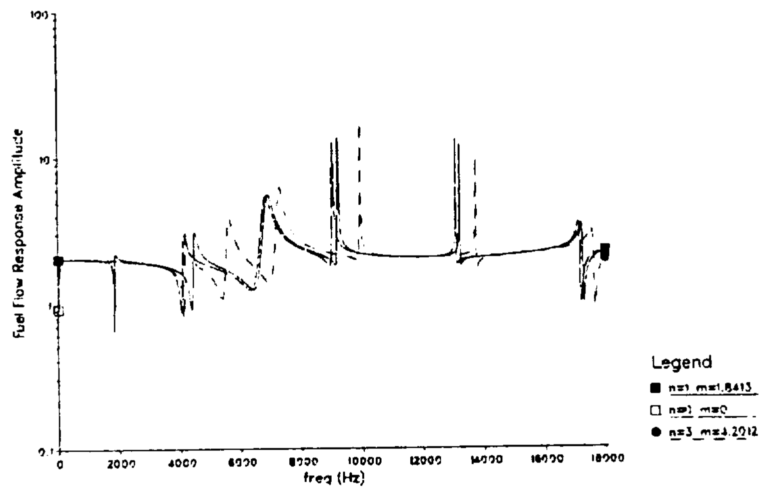

FIGURE 11. - CHARACTERISTICS OF FUEL FLOW OSCILLATIONS

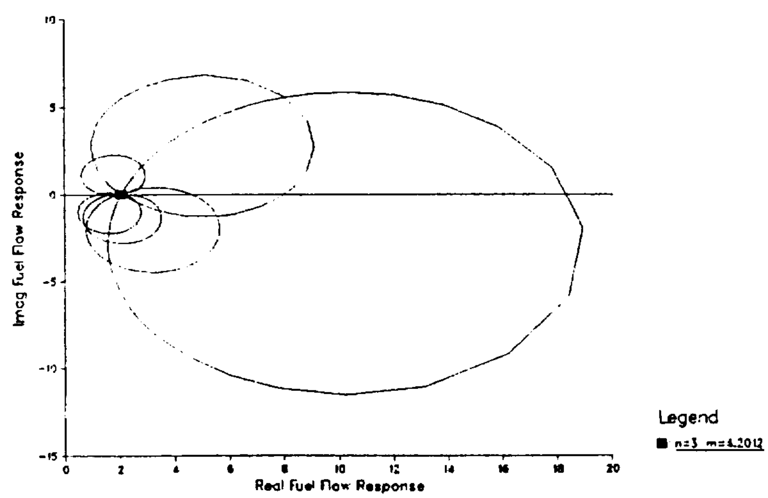

FIGURE 12. - COMPLEX CHARACTERISTICS OF FUEL FLOW OSCILLATIONS

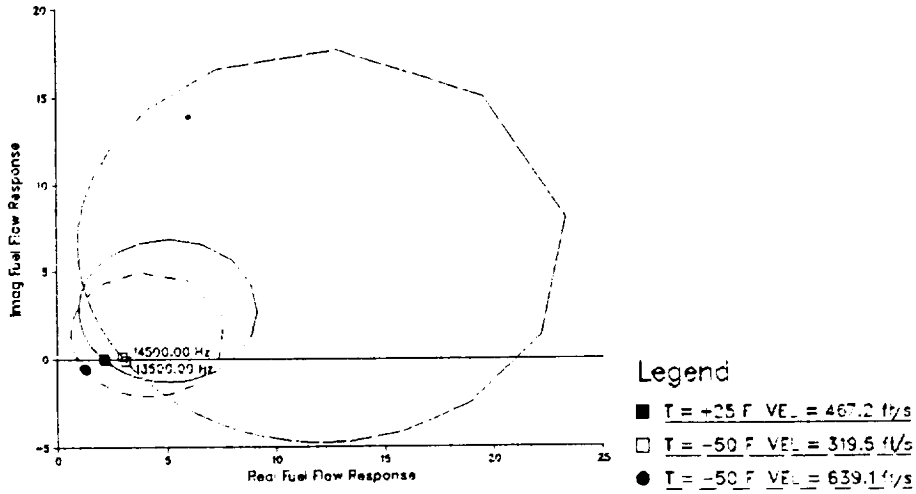

FIGURE 13. - INFLUENCE OF FUEL TEMPERATURE AND VELOCITY ON FUEL FLOW OSCILLATIONS

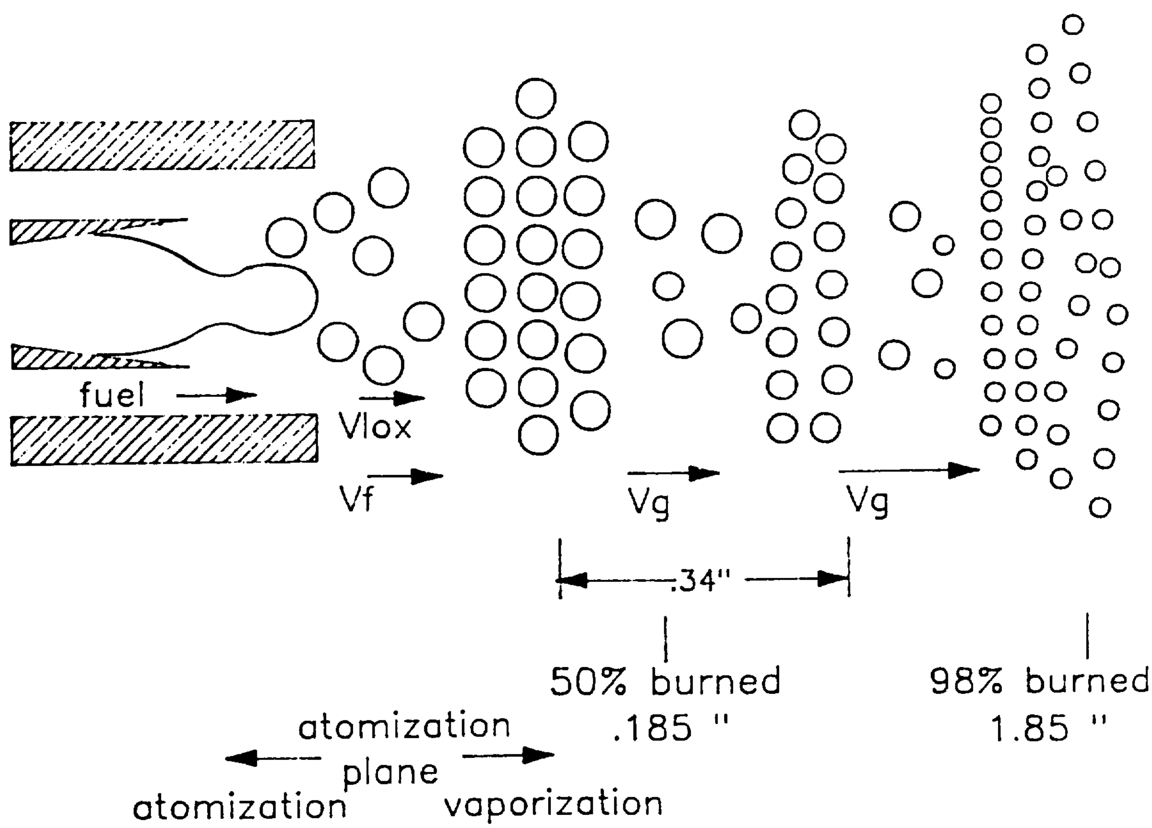

FIGURE 14. - SCHEMATIC OF ATOMIZATION AND VAPORIZATION PROCESS

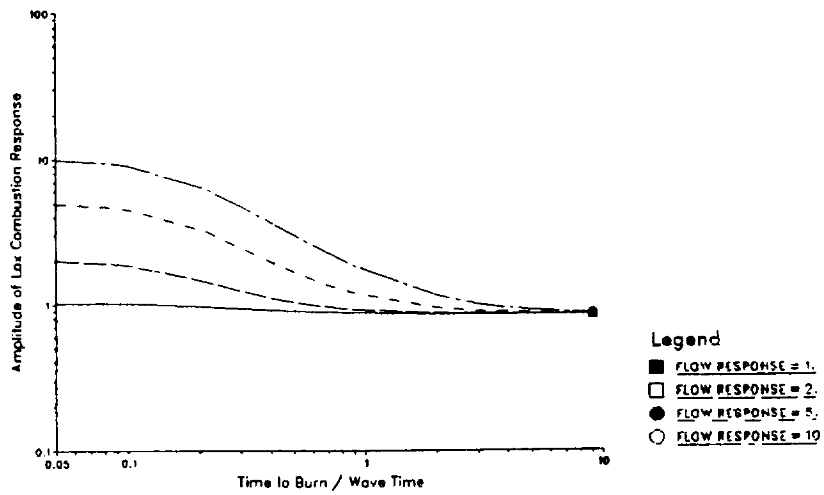

FIGURE 15. - INFLUENCE OF LOX FLOW OSCILLATIONS ON COMBUSTION RESPONSE

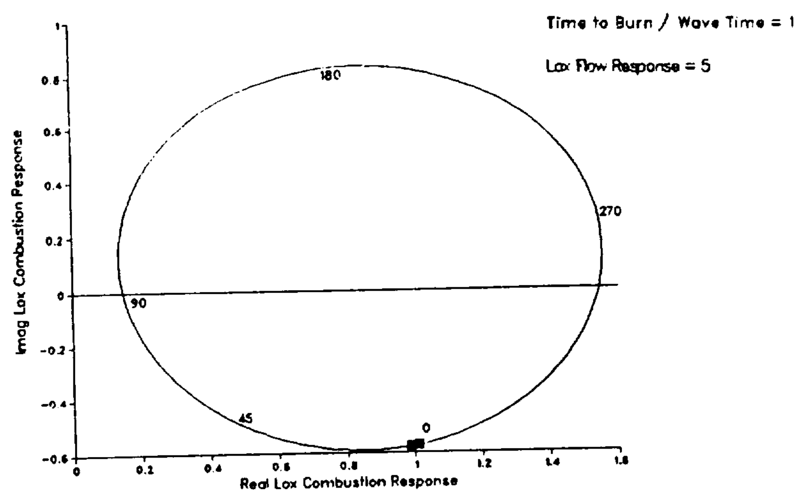

FIGURE 16. - INFLUENCE OF DELAY ANGLE ON SINGLE DROP MODEL OF LOX COMBUSTION RESPONSE

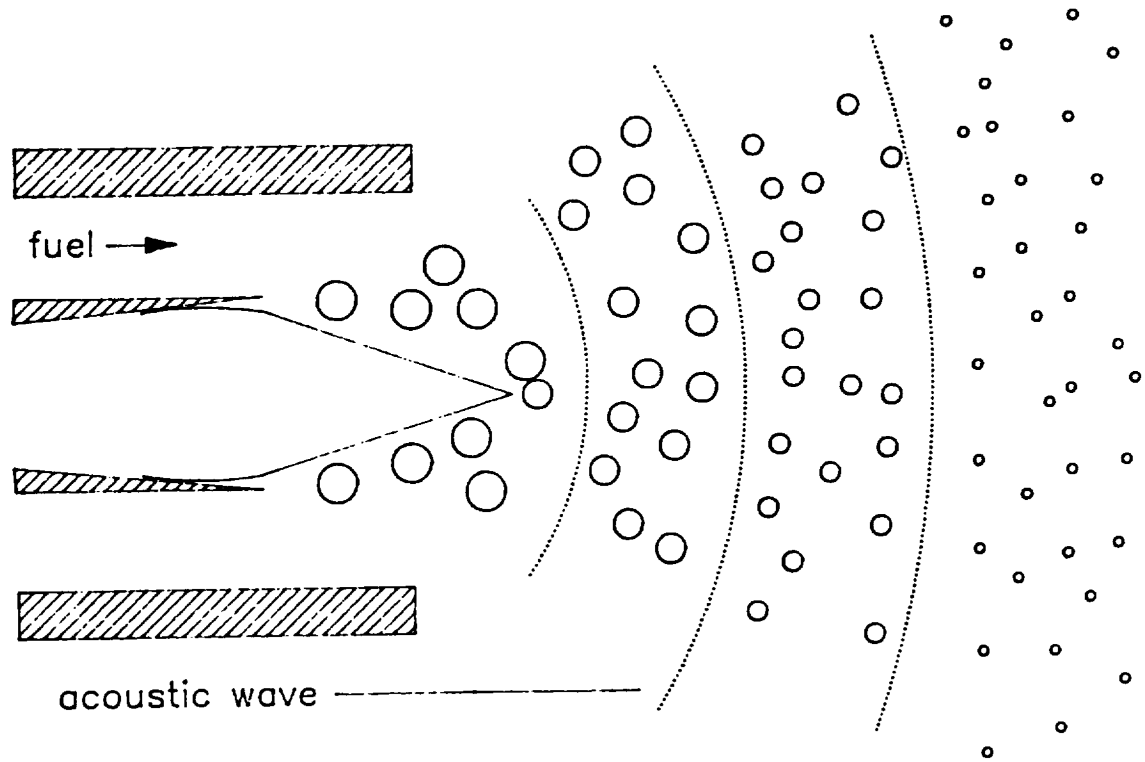

FIGURE 17. - COAXIAL INJECTOR SCHEMATIC

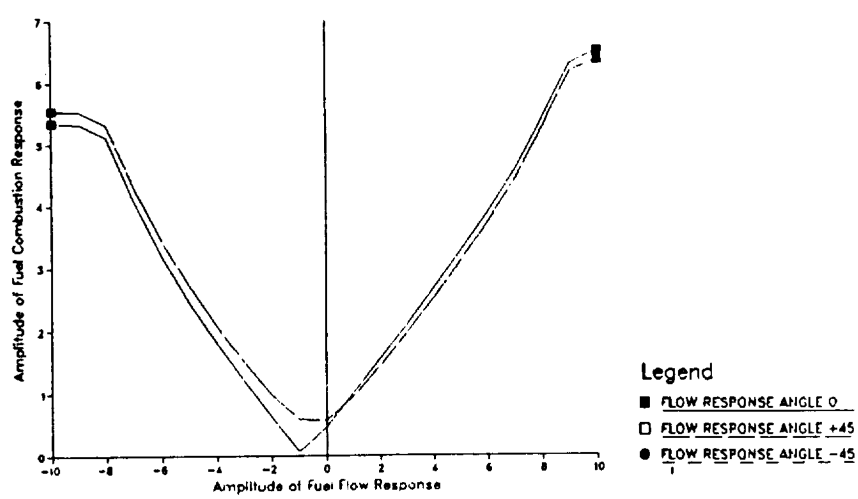

FIGURE 18. - INFLUENCE OF FUEL FLOW OSCILLATIONS ON COMBUSTION RESPONSE

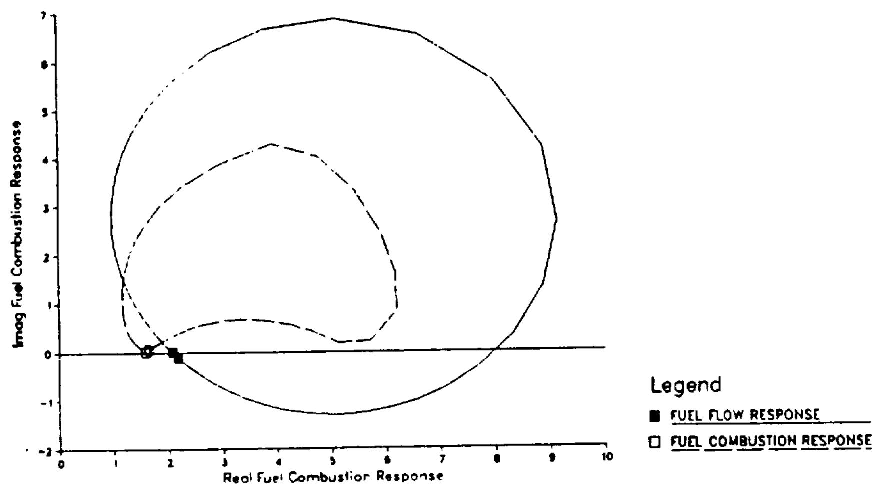

FIGURE 19. - TYPICAL FUEL COMBUSTION RESPONSE vs. FREQUENCY WITH FUEL FLOW OSCILLATIONS

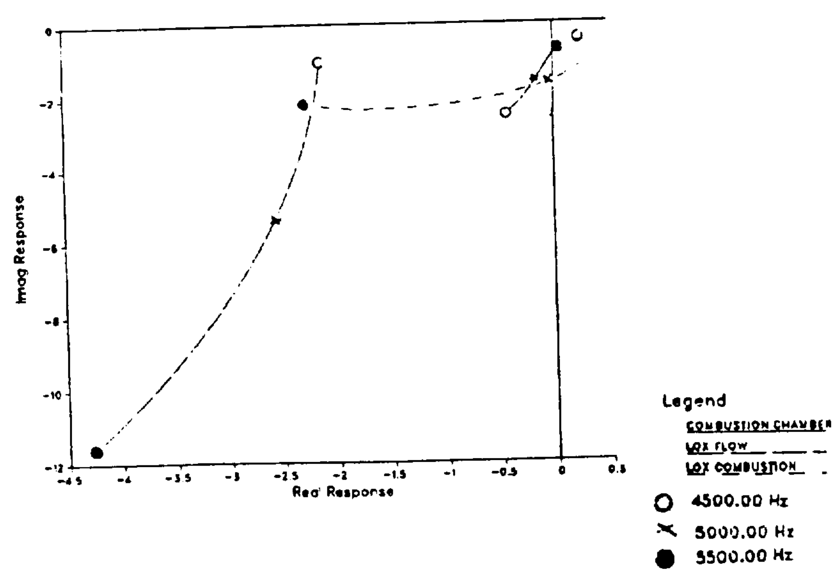

FIGURE 20. - STABILITY CHARACTERISTICS OF LeRC ENGINE AT MR = 2.8

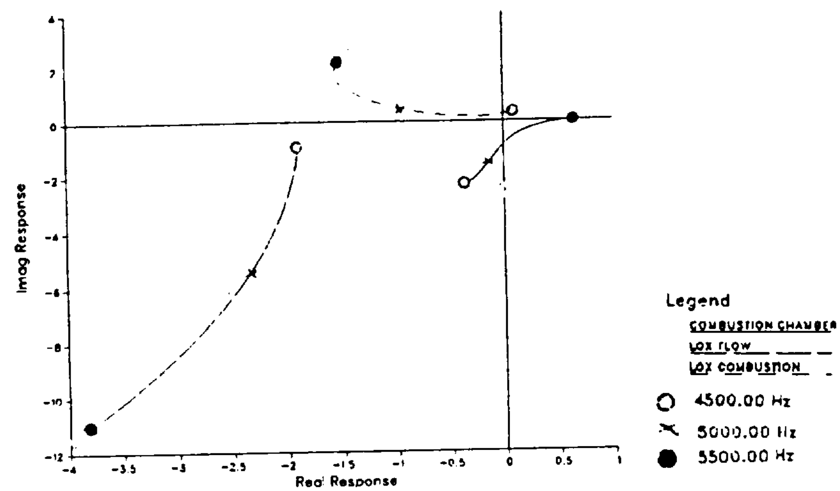

FIGURE 21. - STABILITY CHARACTERISTICS OF LeRC ENGINE AT MR = 3.4