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ANALYSIS OF 5 KHz COMBUSTION INSTABILITIES IN 40K METHANE / LOX COMBUSTION CHAMBERS

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ABSTRACT

In 40K methane / LOX 5 KHz engine tests, (first transverse mode) combustion instabilities observed by Rocketdyne are analyzed using Heidmann and Wieber's vaporization model modified to include LOX flow oscillations. The LOX flow oscillations are determined by including acoustic waves in the feed system analysis. The major parameter controlling stability is the distance (or time delay) associated with atomizing the LOX stream in the coaxial injection system. Results of the analysis to show the influence of mixture ratio, oxidizer and fuel injection velocities, burning time and combustion chamber/injector dimensions on stability are used to explain the existing data. Calculated results to predict the influence of design changes being made for the next set of experiments are also presented.

INTRODUCTION

The use of a LOX/hydrocarbon propellant combination appears advantageous for the next generation launch vehicle booster engine. Due to its high bulk density and relatively high performance characteristics, the LOX/methane propellant combination has emerged as a strong candidate for the Space Transportation Booster Engine. Historically, the development of stable, high performance LOX/hydrogen engines has been a more predictable and cost effective process than the development of LOX/hydrocarbon engines such as the F-1. It would, therefore,be desirable if the stability rating techniques used for LOX/hydrogen engines were applicable to LOX/ methane engine development. The LOX/Hydrocarbon Combustion Instability Investigation Program (NAS3 - 24612) was instituted to determine the degree of applicability of stability rating techniques such as fuel temperature ramping and bombing to the LOX/methane propellant combination. The goal of this program is to demonstrate an instability threshold as a function of fuel temperature and other related parameters so that comparisons can be made with existing LOX/hydrogen instability data . To date, the program has identified spontaneous and temperature ramping induced instability regimes for the 5.66 in. diameter, 82 - coaxial element hardware.[1,2] The oscillations associated with these instabilities had frequencies as high as 14,000 Hz. The wavelengths associated with these instabilities are comparable to the lengths of the injection elements. This suggests that feed system coupling may play a dominant role in the occurance of these instabilities.

To expand the capability of existing models, the Feiler and Heidmann[3] feed system coupled instability model was modified to include acoustic oscillations in the feed system. Similarly, the

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vaporization controlled instability model of Heidmann and Wieber[4] was modified to include flow oscillations that would be produced by feed system coupling. These models as well as a model of the combustion chamber based on the theory of Maslen and Moore[5] were combined into a single computer program to analyze LOX injection system coupling. These models were used previously to provide a credible explanation of the instabilities encountered with the 5.66 in. diameter, LOX/methane LeRC hardware. Additional detail on the computer model, the engine design, and the operating conditions are given in a previous paper.[6] This paper focuses on the LOX system only, identifies deficiencies of the current code, and suggests how they will be remedied in a computer program under development by the second author.

COMBUSTION CHAMBER

The combustion chamber was analyzed using the theory of Maslen and Moore 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 coordinate

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 coordinate
- t time
- z axial coordinate
- θ azimuthal coordinate

To solve the wave equation (Eq. 4) in the combustor, the boundary conditions must be specified. At the chamber walls, the velocity is set equal to zero (this would not be true with acoustic absorbers). For the nozzle boundary condition, a simple nozzle where the velocity is constant with time was assumed. 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 the steady state flow and by wave amplitude (the ratio of pressure amplitude to average pressure). This normalized term is called a flow response, or:

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

LOX FEED SYSTEM

The acoustics in the LOX dome 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. The LOX flow oscillations are due to velocity oscillations only as the change in density with pressure produces a negligible change in flow. It was assumed that the dome has the same radial and tangential modes as the chamber.

With these assumptions and using the same procedure as was used for the combustion chamber, the flow response at the orifice inlet was determined. Using 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, a new flow response is calculated downstream of the orifice. In the small diameter LOX tubes, axial acoustic waves only were permitted. 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.

LOX COMBUSTION

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 limiting 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 slow vaporization process.

Previously the ability of the vaporization process to drive pressure oscillations was studied by Heidmann and Wieber.[4] 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) and the response decreased with higher frequency. This could only drive a combustion chamber oscillation at the unique conditions associated with the exponential pressure decay as a function of 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 these effects (this was accomplished as shown in Figure 1.). 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 LeRC methane/LOX engine the atomization plane is estimated at .579 cm (0.228 in.) downstream of the effective end of the LOX tube (effective end of the LOX tube for oscillations is .066 cm (.026 in.) upstream from the end of the LOX tube, $\frac{1}{2}$ of the chamfer section minus one tube diameter). This places the atomization plane .0051 cm (0.002 in.) downstream of the injector face.

Drops are formed at varying rates as represented by the number of drops in Figure 1. As the drops travel down the chamber they are vaporizing. For the standard methane/LOX engine, it is estimated that (based on the stability characteristics) 50% is vaporized and burned at a distance of .47 cm (0.185 in.) with 98% vaporized and burned in 4.7 cm (1.85 in.).

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 LOX flow and pressure as 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 at the average LOX velocity.

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 2 where the amplitude of the LOX combustion response for individual drops 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 5% of the wave time) the combustion response is equal to the LOX flow response. For these short burn times the drops burn immediately (relative 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.

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.

The effects of varying mixture ratio, temperature ramping, and a proposed geometry change on the occurance of a 1T instability were analyzed. Changing the mixture ratio, ramping down in temperature, and increasing the fuel annulus gap all alter the vaporization and atomization distances. The difference in atomization plane distance and distance to vaporize was calculated on the basis of the Rocketdyne CICM model[7]. 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 and drop size were 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 $\frac{3}{2}$ power of drop size, it was considered to be inversely proportional to the square of velocity difference and first power of density.

DISCUSSION AND RESULTS

The results of calculations for some of the test conditions and geometries of interest to the LOX / Hydrocarbon Combustion Investigation Program are presented below. At a given frequency, stability is associated with the real combustion response being to the left and above the combustor response curve (that is, the first, second, and top half of the third quadrant in Figure 3) for equal imaginary responses.

Increasing the mixture ratio while keeping the total mass flowrate of propellants constant significantly decreases the exit velocity of the fuel and marginally increases the exit velocity of the LOX. This then increases the atomization and vaporization distances. The effect of increasing the mixture ratio from 2.8 to 4 is to detune and stabilize the LOX combustion from the 5000 KHz instability that occurs at a mixture ratio of 2.8 . This is shown in Figure 3 as a clockwise rotation of the combustion response curve about the origin (greater stability being associated with moving to the left and upward from the combustor response curve).

During temperature ramping at a mixture ratio of 4 the decrease in methane density increases the atomization and vaporization distances. The effect of decreasing methane temperature is a clockwise rotation of the combustion response curve as shown in Figure 4. Figure 4 indicates that a 1T mode instability is possible during temperature ramping tests, a phenomena not seen during previous tests.

The effect of increasing the fuel annulus gap on stability was investigated. The gap was increased from .011" to .015". At a mixture ratio of 3.4 (previously stable), the lower methane velocity produces a decidedly destabilizing influence as shown in Figure 5.

In a previous paper[6], calculations with the current computer model were largely concentrated at modes and frequency ranges of known instabilities. Recently, calculations were performed with the same model for a larger range of frequencies (2000 - 14000 Hz) and for the first through fourth tangential modes. A condensed list of the stability conditions where the imaginary part of combustor and combustion responses are equal at the same frequency is provided in Table 1.

As can be seen from this table, quite a few "false instabilities" occur. These "false instabilities" are points where the current model indicates that the combustion response is sufficient to drive an instability where no instability is observed or is not the major frequency observed. A comparison of Table 1 with the pressure isoplots from the previous test series indicates that the "false instabilities" are at frequencies where significant pressure fluctuations have occurred (Figure 6 is a pressure isoplot from a spontaneously unstable case). Although the current model does not correctly predict the occurance of instabilities, it does seem to correctly identify those frequencies where problems are likely to occur.

The major limitations of the current computer model are its simple treatment of the vaporization process via a Reynolds number function only in the combustion response model and its inviscid treatment of LOX flow oscillations. Damping due to viscous shear in the LOX tube would reduce flow oscillations at higher frequencies and eliminate the antinode resonances. Numerically solving the one-dimensional viscous flow equations in the tube should capture these phenomena. For the higher frequencies, the vaporization time is large compared with the cycle time. The mean drop temperature rises from its injection value to the equilibrium temperature with only a small oscillatory component and the response should decrease with higher frequencies faster than the current model predicts.[3,4] A computer model under development will have a much more thorough treatment of the spray vaporization process than the current program. Random noise in the chamber can become a significant fraction of the lower amplitude oscillations associated with the higher frequencies. This noise would act to reduce both the LOX flow oscillations and the combustion response at the higher frequencies. The effects of this noise can be assessed by imposing a random noise distribution on the calculated (noise free) pressure field and using the resultant pressure field to calculate the combustion and LOX flow responses.

SUMMARY

A model for injection coupled (LOX side) instabilities was outlined. This model was utilized to show the destabilizing effects of increasing the fuel annulus gap on the LeRC 40K methane / LOX engine. The possibility of 1T mode instabilities occurring during temperature ramping tests was also shown. Defficiencies in the current model were identified and remedies for these deficiencies proposed.

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Table 1. Stability Boundaries at Higher Frequency Modes.

MR = 2.8

Mode	Freq (Hz)	Imag	Flow Amp	Real Combustion	Real Combustor	Margin	Status
1T,1R,0L	5000	−1.7	6.1	−.15	−.20	−.05	Unstable
1T,1R,1L	8890	−.19	2.4	1.20	.94	−.26	Unstable
2T,1R,0L	9250	−.4	4.8	.03	1.73	−1.7	Unstable
3T,1R,0L	10580	−2.3	36.	−.79	−.36	−.43	Antinode
3T,1R,0L	11720	−1.5	19.	−.94	−.15	−.79	Antinode

MR = 3.4

Mode	Freq (Hz)	Imag	Flow Amp	Real Combustion	Real Combustor	Margin	Status
1T,1R,.5L	7320	1.9	18.	1.2	.934	−.27	Antinode
1T,1R,1L	8590	−.01	2.3	1.20	.94	−.26	Unstable
1T,1R,2L	10770	.01	52.	1.91	1.06	−.85	Antinode
1T,1R,3L	12430	.22	6.5	1.67	.94	−.73	Unstable
2T,1R,0L	9000	.03	2.7	.38	.21	−.17	Unstable
2T,1R,0L	9540	.015	7.2	−.37	2.03	1.66	Stable
2T,1R,1L	12650	.101	4.5	1.41	.94	−.47	Unstable
3T,1R,0L	12410	.286	6.7	1.68	.47	−1.21	Unstable
3T,1R,0L	12710	.013	4.	1.34	1.01	−.33	Unstable

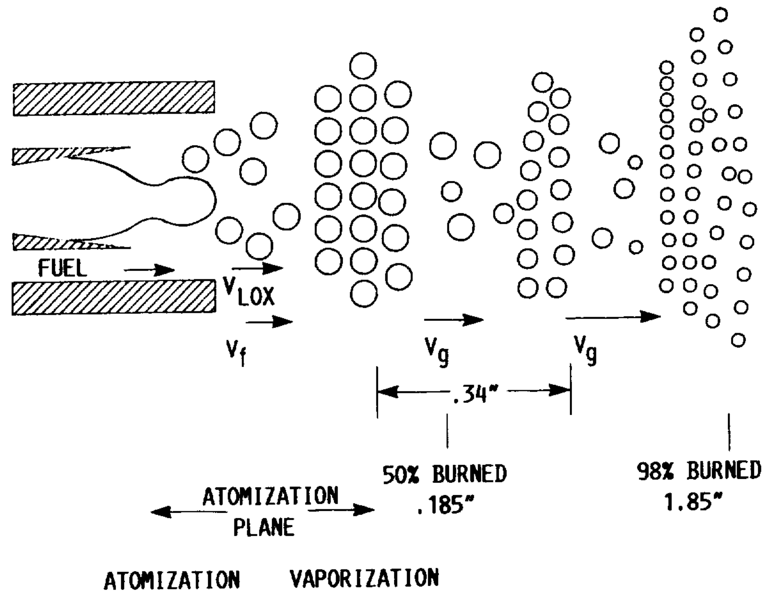

FIGURE 1. - SCHEMATIC OF ATOMIZATION AND VAPORIZATION PROCESS.

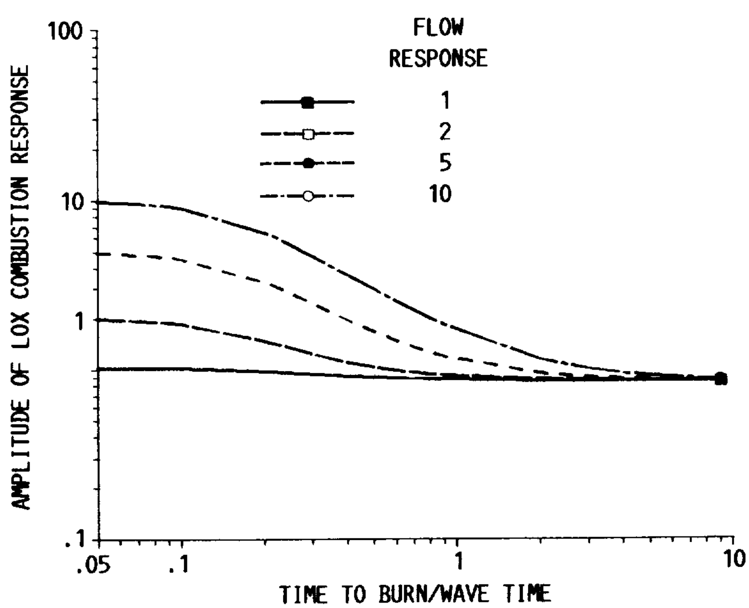

FIGURE 2. - INFLUENCE OF LOX FLOW OSCILLATIONS ON COMBUSTION RESPOSNE.

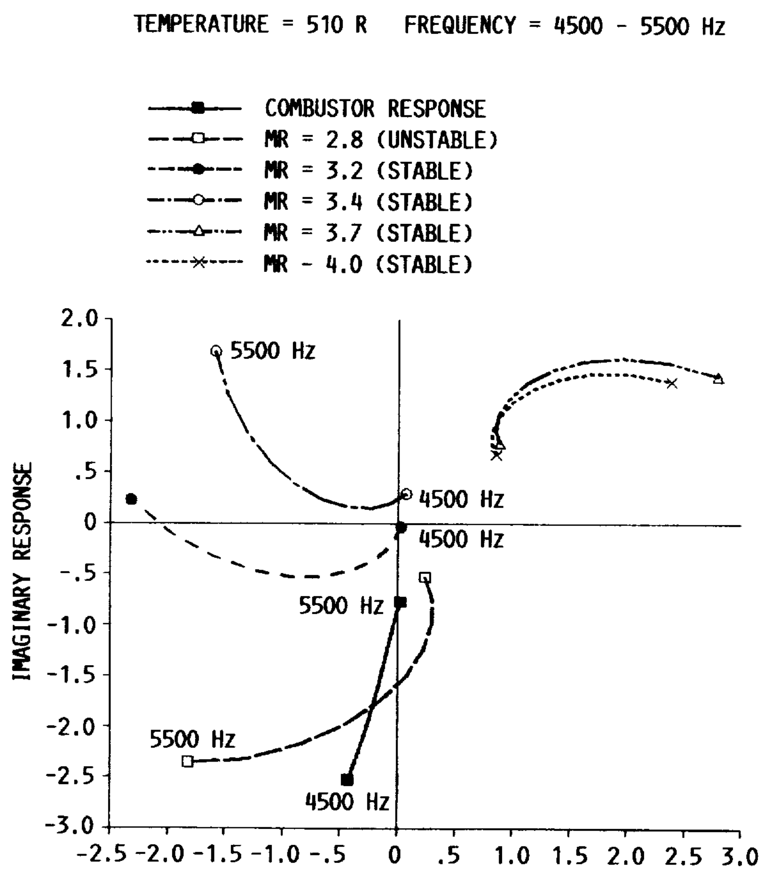

FIGURE 3. - STABILIZING INFLUENCE OF INCREASING MIXTURE RATIO.

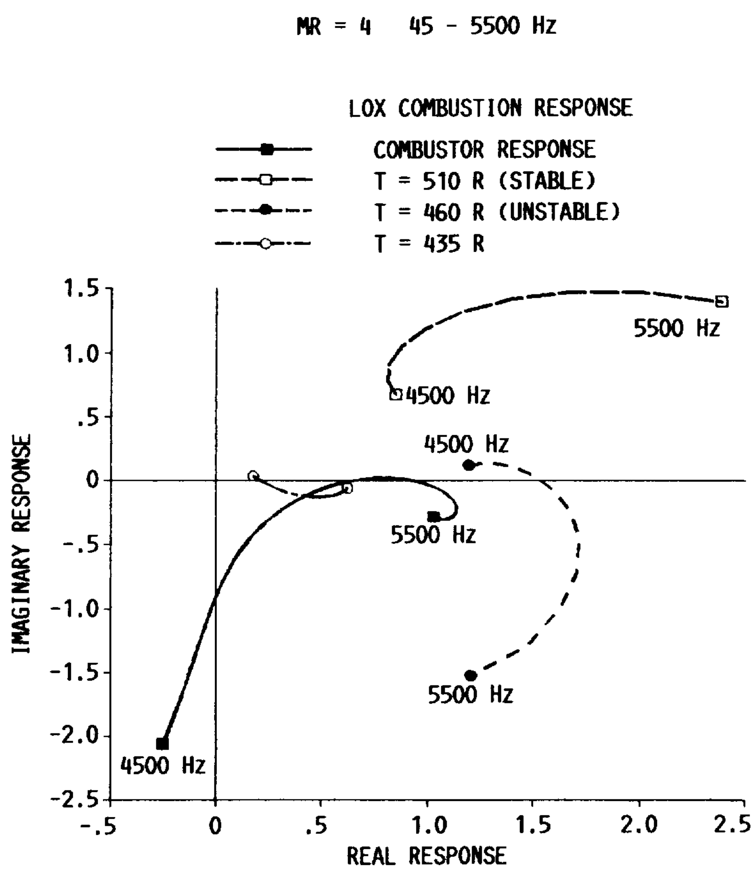

FIGURE 4. - DESTABILIZING INFLUENCE OF A RAMP DOWN IN METHANE TEMPERTURE.

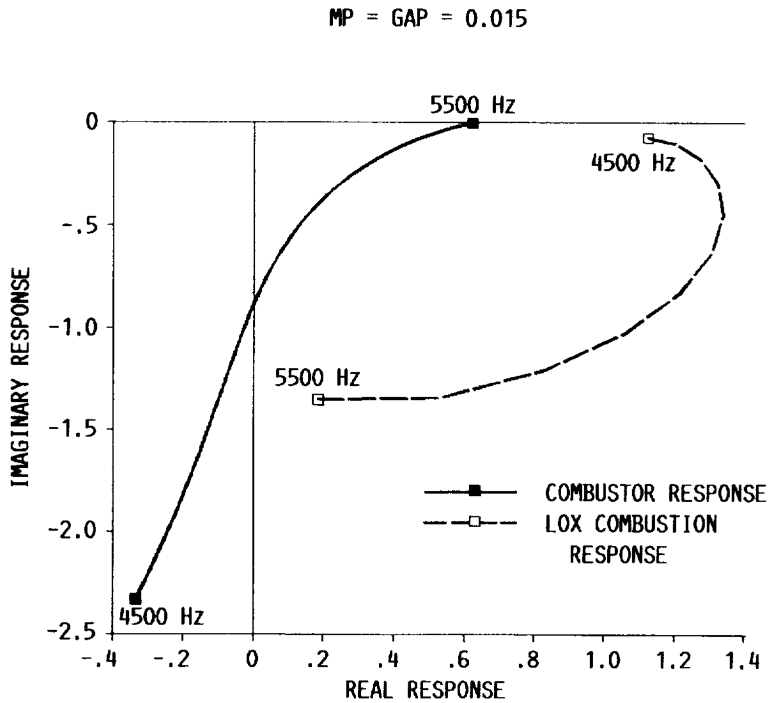

FIGURE 5. - DESTABILIZING INFLUENCE OF INCREASED FUEL ANNULUS GAP.

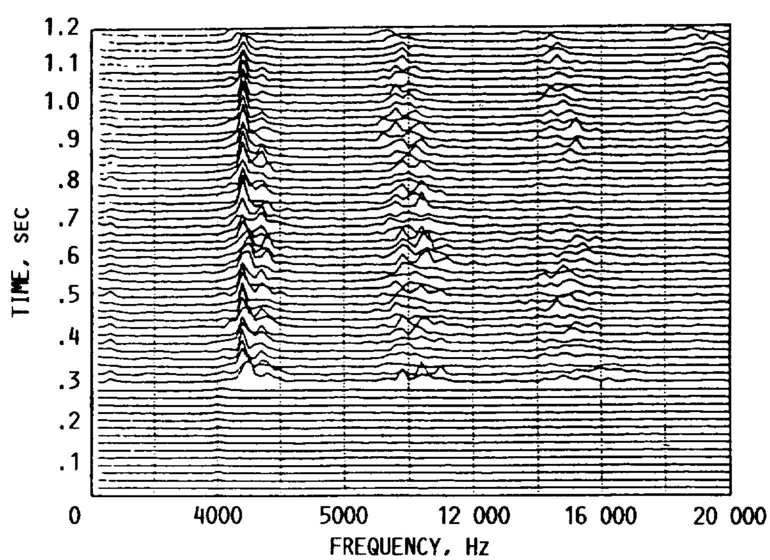

FIGURE 6. - HIGH FREQUENCY CHAMBER PRESSURE ISOPLOT FOR A FIRST TANGENTIAL INSTABILITY.

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16. Abstract

In 40K methane/LOX 5 KHz engine tests, (first transverse mode) combustion instabilities observed by Rocketdyne are analyzed using Heidmann and Wieber's vaporization model modified to include LOX flow oscillations. The LOX flow oscillations are determined by including acoustic waves in the feed system analysis. The major parameter controlling stability is the distance (or time delay) associated with atomizing the LOX stream in the coaxial injection system. Results of the analysis that show the influence of mixture ratio, oxidizer and fuel injection velocities, burning time and combustion chamber/injector dimensions on stability are used to explain the existing data. Calculated results to predict the influence of design changes being made for the next set of experiments are also presented.

17. Key Words (Suggested by Author(s))

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