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ASRM COMBUSTION INSTABILITY STUDIES

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ABSTRACT

Combustion response measurements predict that the pressure-coupled response characteristics of the RSRM and ASRM formulation propellants should be very similar. For the fundamental longitudinal acoustic mode of the ASRM, it is recommended that the response function real component be set equal to the zero frequency intercept value -- the burning rate pressure exponent, n.

The pressure-coupled response results for the ASRM Igniter Propellant were normal in amplitude, typical of propellants of this type. The results yielded a bimodal distribution with frequency for the real component. At the 2,000 psia pressure burning rate, the peak responses are predicted to occur at frequencies of approximately 2800 and 8400 Hz.

ABBREVIATIONS AND ACRONYMS

AO 2246	trade name for 2,2'-methylenebis (4-methyl-6-tertiarybutyl phenol)
AP	ammonium perchlorate
ASRM	Advanced Solid Rocket Motor
DOA	2-ethyl hexyl adipate (dioctyl adipate)
HX-752	trade name for a mixture of 2-methylaziridine (1%), 1,1'-(1,3-phenylenedicarbonyl) bis [2-methylaziridine] (97%), and toluene (2%)
IPDI	isophorone diisocyanate
IR	infrared
JPL	Jet Propulsion Laboratory
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
RSRM	Redesigned Solid Rocket Motor
R-45 M	hydroxyl-terminated polybutadiene
SRM	solid rocket motor

NOMENCLATURE

e	base of natural logarithm
f	cyclic frequency
i	$\sqrt{-1}$
m	mass burning rate per unit area of propellant surface
n	burning rate equation pressure exponent
p	pressure
q	heat flux
r	propellant regression rate
R_p	pressure-coupled response function
R_q	heat flux-coupled response function
TF	transfer function
α	propellant thermal diffusivity
θ	phase relationship between r' and q'
ρ	propellant density
Ω	nondimensionalized frequency

<u>Superscripts</u>

(r)	real component
$-$	mean or time-averaged value
'	oscillating component

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OBJECTIVES

The objectives of this task were to measure and compare the combustion response characteristics of the selected propellant formulation for the Space Shuttle Advanced Solid Rocket Motor (ASRM) with those of the current Redesigned Solid Rocket Motor (RSRM) formulation. Tests were also carried out to characterize the combustion response of the selected propellant formulation for the ASRM igniter motor.

BACKGROUND

An important parameter in characterizing the combustion stability of solid propellants is the pressure-coupled response function -- the oscillatory mass regression rate response to an oscillation in pressure -- each normalized by its mean value

$$R_p = \frac{m'/\overline{m}}{p'/\overline{p}} = \frac{r'/\overline{r}}{p'/\overline{p}} \qquad (1)$$

where mass evolution rate is related directly to the regression rate of the propellant-gaseous zone interface by the expressions $m' = \rho r'$ and $\overline{m} = \rho\overline{r}$.

The pressure-coupled response function, R_p, is a complex parameter with real and imaginary components:

$$R_p = |R_p|e^{i\Theta} \qquad (2)$$

The pre-exponential term of Equation (2) is the amplitude (absolute value) of the response function; the exponential term is the argument of the response function -- the phase relationship, Θ, between r' and p'. The real (in-phase) component of the response function $R_p^{(r)} = |R_p|\cos\theta$, as a function of frequency, is used as one of the major acoustic driver inputs in analytically predicting the stability characteristics of any SRM design.

A system was previously developed at JPL for measuring a propellant's pressure-coupled response function in a direct manner using a microwave Doppler velocimeter technique.[1,2] A propellant sample, enclosed in a burner, is exposed to externally driven pressure oscillations. A microwave signal propagates through the propellant sample and is reflected from the propellant burning surface/gas-phase interface, Figure 1. The phase angle between the incident and reflected signals is shifted by the regressing burning surface, and the rate of regression (burning rate) is directly proportional to the rate of change of this phase shift.

Generating pressure oscillations of sufficient amplitude to ensure adequate signal-to-noise of the measured signal (transient flow effects cause the amplitude of the pressure oscillations in the test burner to fall off with increasing frequency), and isolating the burner-microwave system from the vibration of the pulsating pressure source have been the limiting factors in the experimental technique. Together, they have limited the upper frequency range of the test technique to below 1 HKz.[3]

To overcome this signal strength problem, a new test system has been developed, using the microwave Doppler velocimeter technique to measure the propellant combustion response to an incident, oscillating thermal radiation source (CO_2 laser), Figure 2, rather than oscillating pressure.[4] The laser output can be modulated sinusoidally at heat flux amplitudes from 0 to 100% of full power

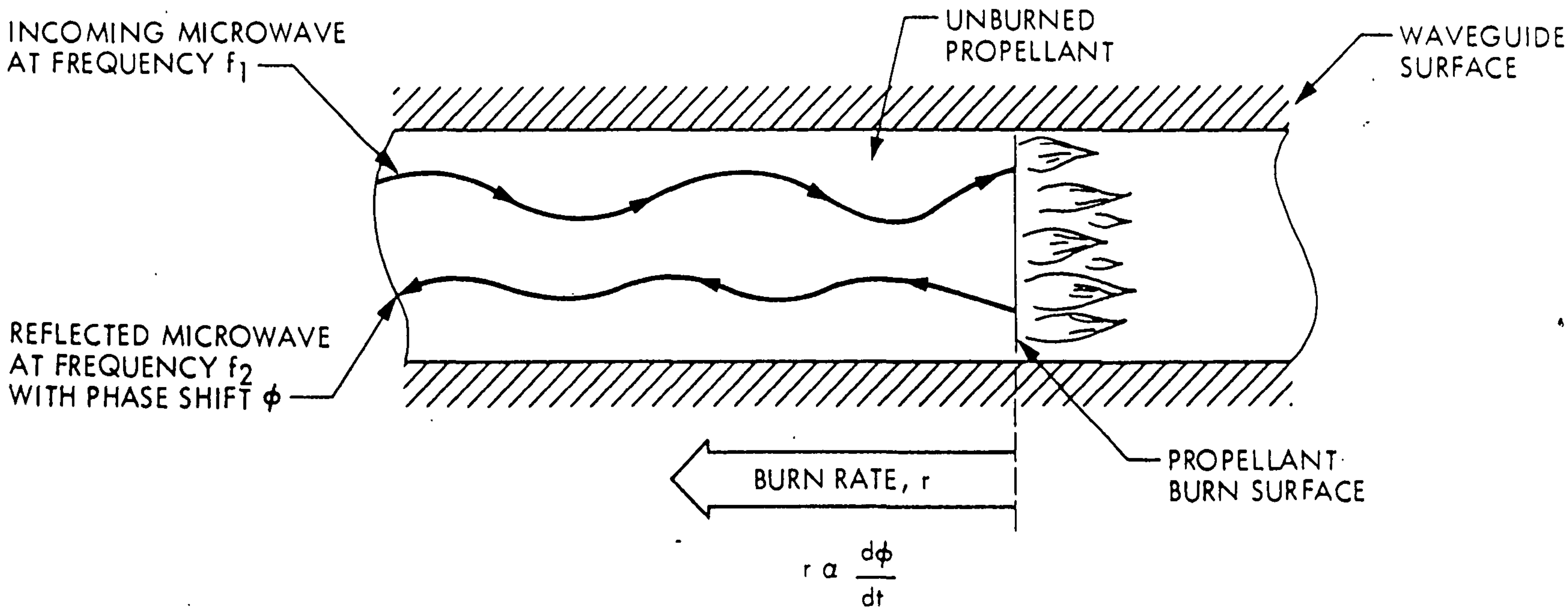

Figure 1. Microwave Regression Rate Measurement Technique

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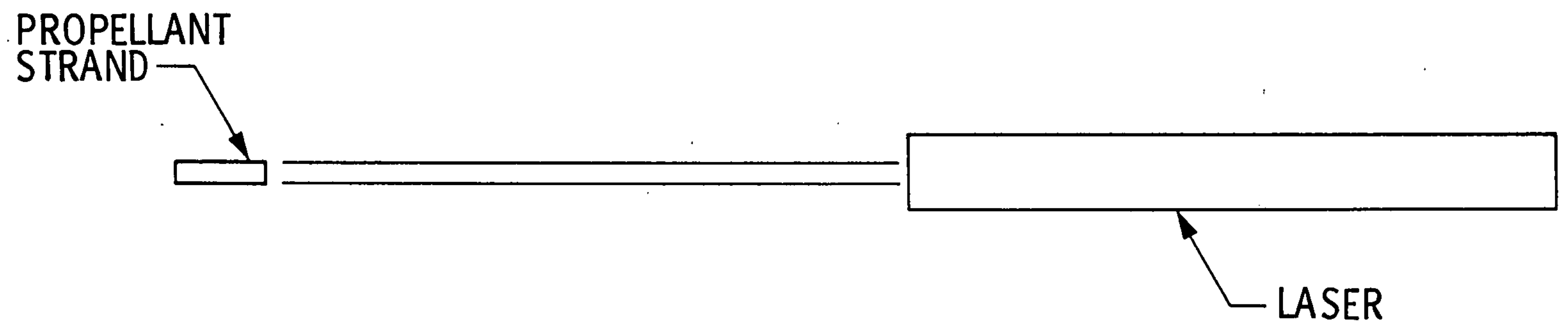
FIG. 2 SCHEMATIC OF TEST CONCEPT



over the frequency range of interest. The measured burning rate response to the thermal radiation, R_q, is related to an equivalent burning rate response to an oscillation in pressure using a transfer function relationship:

$$\begin{aligned} R_p &= R_q * [TF] \\ &= R_q \left[\frac{q'/\bar{q}}{p'/\bar{p}} \right] \end{aligned} \tag{3}$$

The transfer function relationship between dynamic heat flux and pressure is derived from dynamic combustion theory. The test system should yield the frequencies of maximum combustion response and give as close an approximation of the pressure-coupled combustion response magnitude as the rigor of the combustion theory transfer function permits.

In Reference 4 it was shown that to a reasonable accuracy the transfer function can be approximated by its steady state limit value -- the propellant burning rate pressure exponent, n.

TEST DESCRIPTION

The propellants were tested in the following order: RSRM, ASRM, and ASRM Igniter Propellant. The RSRM propellant, formulation TP-H1148, was the same Thiokol processed propellant being tested at JPL by Dr. Steven Peng for the Solid Propulsion Integrity Program with the NASA Marshall Space Flight Center. The ASRM formulation propellant was processed at the JPL Edwards Facility. The particular formulation used is shown in Table 1. The ASRM Igniter Propellant, formulation ANB-3672, batch number 1-3672-M-001, was processed and supplied by the Aerojet Propulsion Division.

The tests were carried out at a burner pressure of 300 psia. The pressure is limited by the 0.25-inch thick zinc-selenide IR window in the burner for the CO_2 laser beam, Figure 3.

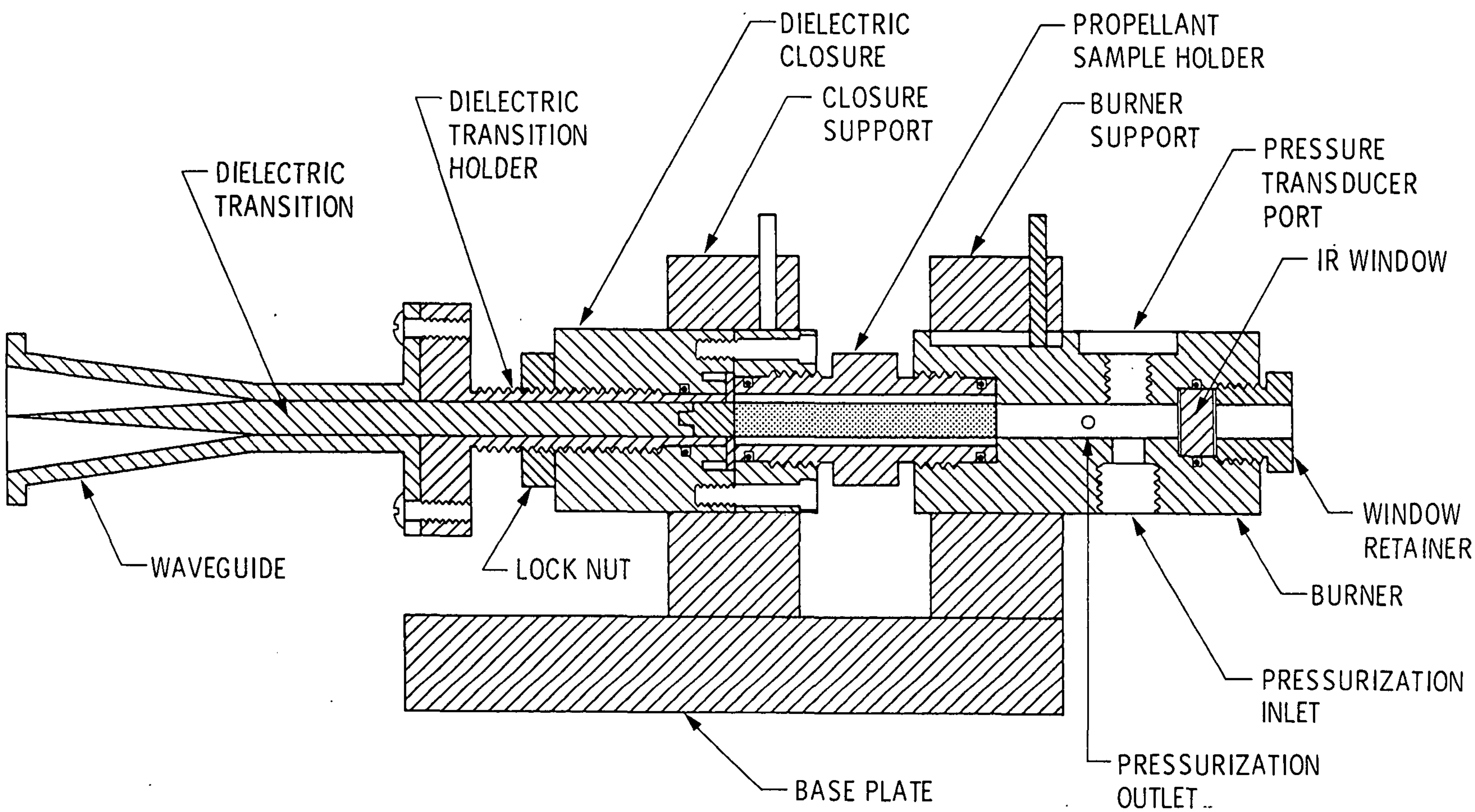
Formulation: ASRM-12 Mod 5
Batch No. JM-150

Ingredients	Wt. %
AP, 250 microns	48.2300
AP, 15 microns	20.6700
R-45 M	8.9765
Aluminum, spherical	19.0000
HX-752	0.3000
AO 2246	0.1000
DOA	2.0000
Ferric Oxide	0.1000
IPDI	0.6235

Table 1. ASRM candidate test formulation

FIG. 3

JPL MICROWAVE WINDOW BURNER ASSEMBLY



These were the first metal-containing (metalized) propellants tested in the new system, and they represented some significant technical challenges. The difficulties were three-fold. Clogging of the vent-line needle valve that is used to control the burner pressure and purge rate was solved by adding an upstream settling chamber in the line.

A second, more formidable difficulty, was attenuation of the laser beam by the particulate aluminum oxide product of combustion. The beam attenuation increases with burn time as the path length through the column of gas/particulates above the regressing propellant surface increases. This same phenomenon had been observed earlier to a much lesser extent in testing non-metal containing propellants.[4] The same approach was used to alleviate the problem. The measured dynamic burning rate was plotted versus burn time, and the zero burn-time intercept was used as the non-attenuated value.

This approach was made more difficult by the third problem. The higher electrical conductivity of the aluminum containing propellants increases the attenuation of the transmitted microwave signal (higher loss tangent). This resulted in the propellant sample having to burn for a number of seconds, reducing the distance traversed, until the strength of the reflected microwave signal was large enough to be analyzed by the phase measuring instrument. This in turn meant that the measured dynamic burning rates had to be significantly extrapolated to obtain the zero-time intercept.

For the first two propellants tested the results should, therefore, be used for relative comparison purposes only, not as absolute numbers. Modifying the pre-test microwave tuning procedure to increase the test signal-strength eliminated this problem for the final propellant tested, the ASRM Igniter Propellant.

RESULTS

RSRM and ASRM formulation propellants

The two propellants were tested up to a frequency of 500 Hz, which covers the predicted frequency range for the longitudinal acoustic modes and the first tangential mode for the RSRM.[5]

The measured absolute values of the heat flux response functions for the RSRM and ASRM formulation propellants are plotted in Figures 4 and 5, respectively. The data are normalized to a value of unity at zero frequency, in accordance with the analysis in Reference 4.

The response function argument results (Equation 2) for the RSRM propellant are shown in Figure 6. The results are depicted as the range and median value of the reduced data points for each individual test firing. Although there is the usual scatter in the results for this particular test parameter (see Reference 4), the theoretically predicted low-frequency value of zero is suggested. Therefore, $\cos\theta = 1$, and the response function real and absolute values are equal.

The argument results for the ASRM formulation are shown in Figure 7. The confidence level in the elevated values at the upper three test frequencies is quite low. Since $R_p^{(r)}$ and $|R_p|$ appear to be equal over this frequency range for the RSRM propellant and the

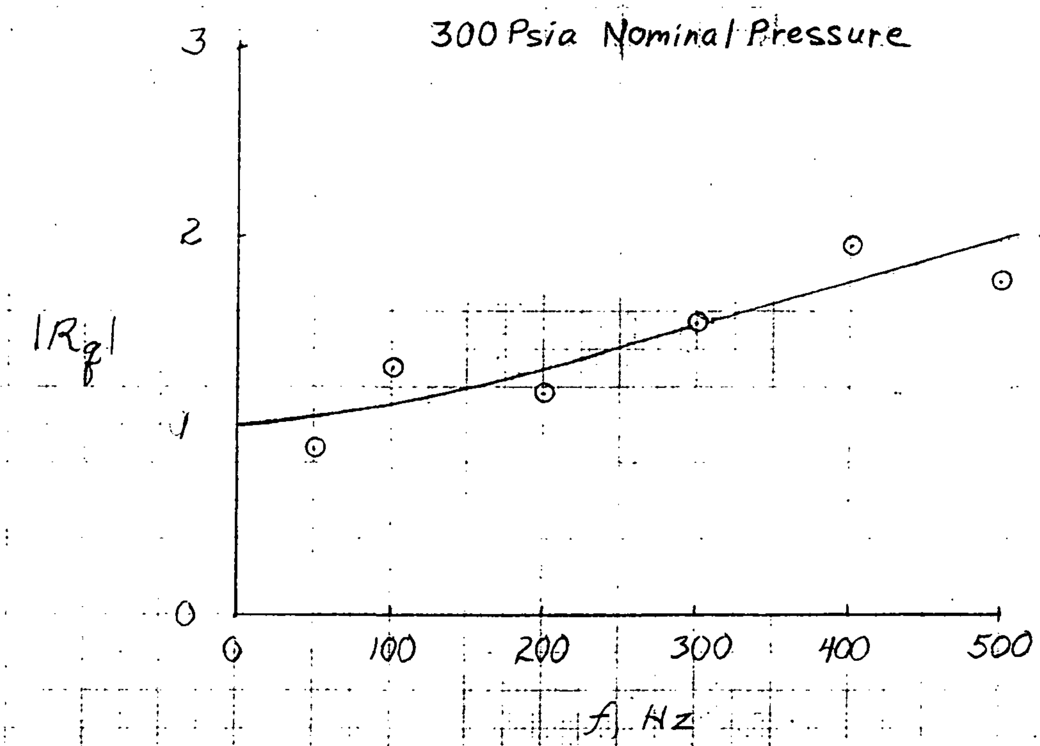


Figure 4. Absolute value of heat flux response function vs. frequency for RSRM propellant

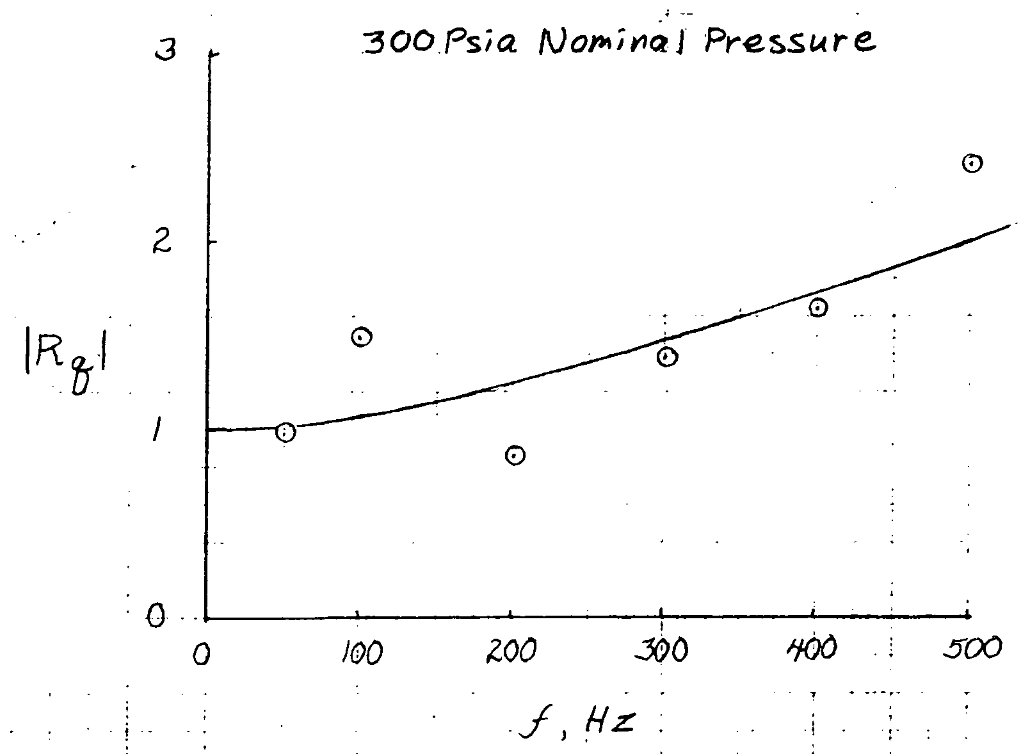


Figure 5. Absolute value of heat flux response function vs. frequency for ASRM formulation propellant

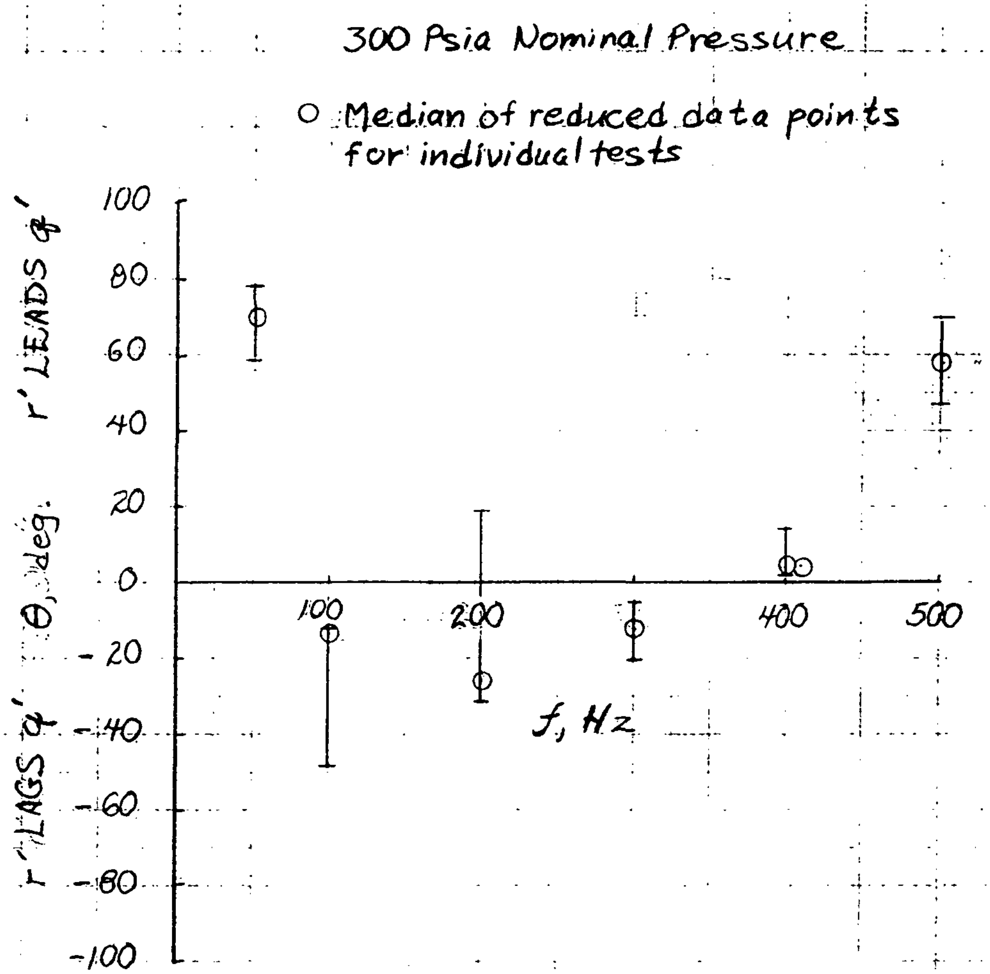


Figure 6. Argument of response function vs. frequency for RSRM propellant

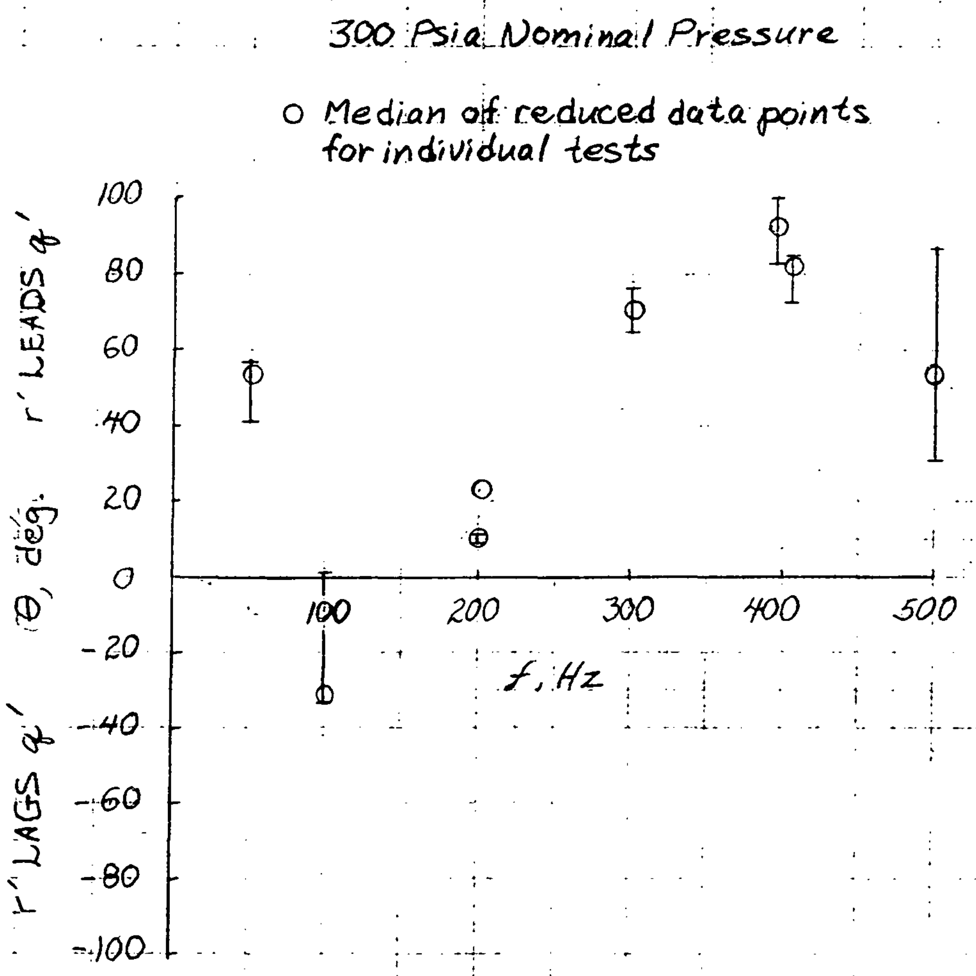


Figure 7. Argument of response function vs. frequency for ASRM formulation propellant

argument results for the ASRM formulation are suspect, the decision was made to compare the absolute values, rather than the real components of the pressure-coupled response for the two propellants.

$|R_p|$ was determined for each propellant by multiplying the curve fit to the $|R_q|$ data by the propellant's burning rate pressure exponent, in accordance with the analysis in Reference 4. The results for the two propellants are compared in Figure 8. The gradients in the response curves with increasing frequency are unrealistically low due to the difficulties described in the TEST DESCRIPTION section, and the results again should be used for comparison purposes only. The differences between the two curves are very small and within the scatter in the data correlations.

ASRM Igniter Propellant

The high burning rate of the ASRM Igniter Propellant (~ 2 in./s at 2000 psia[6]) increased the dynamic burning rate signal-to-noise capability of the test system considerably. Tests were run up to a frequency of 1400 Hz, 50% higher than the previous test upper limit.[4] This encompassed the fundamental longitudinal mode frequency of the igniter motor, stated to be 725 Hz in Reference 6, but not quite the 2000 Hz fundamental tangential mode frequency. This issue will be treated later in the analysis of the test results.

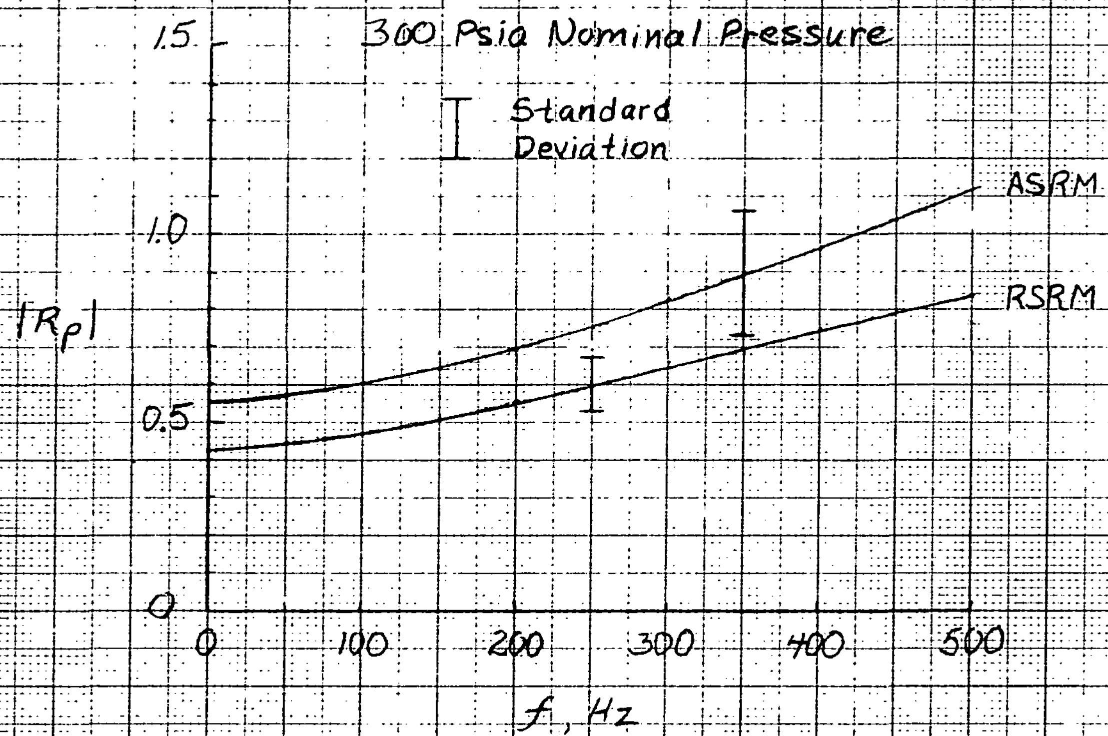


Figure 8 Absolute value of pressure-coupled response function vs. frequency for RSRM and ASRM formulation propellants

The measured absolute values of the heat flux response function for this propellant are plotted in Figure 9, the data again normalized to a value of unity at zero frequency. The response function argument results are shown in Figure 10. The results show the same range of variation over the burn time duration of the individual tests as observed in previous experiments.[4] Although there are a couple of outlying test points, the trend of the data is fairly clear -- the dynamic burning rate leading the heat flux driver over the frequency range of approximately 300 to 1500 Hz.

Figure 11 is a plot of $|R_p|$, calculated in the same manner as for the previous two propellants. It is the upper limiting envelope of the actual response versus frequency characteristics for this propellant. The results look very reasonable.

Since the pressure-coupled response is a function of pressure (or burning rate), it is necessary to normalize these results if they are to be applicable to pressures other than the 300 psia test pressure. Dynamic combustion theory, with some highly simplifying assumptions, predicts this can be accomplished by plotting the results versus a nondimensionalized frequency, Ω, equal to $f\alpha/r^2$, where α is the propellant thermal diffusivity.[7] Although experimental verification has been rather mixed[7], the theory should be more applicable to the fine-sized AP (more homogeneous) ASRM Igniter Propellant. When comparing a single propellant (constant α) at different burning pressures, the same effect is realized by plotting the results versus f/r^2. The Figure 11 results are normalized in this fashion in Figure 12.

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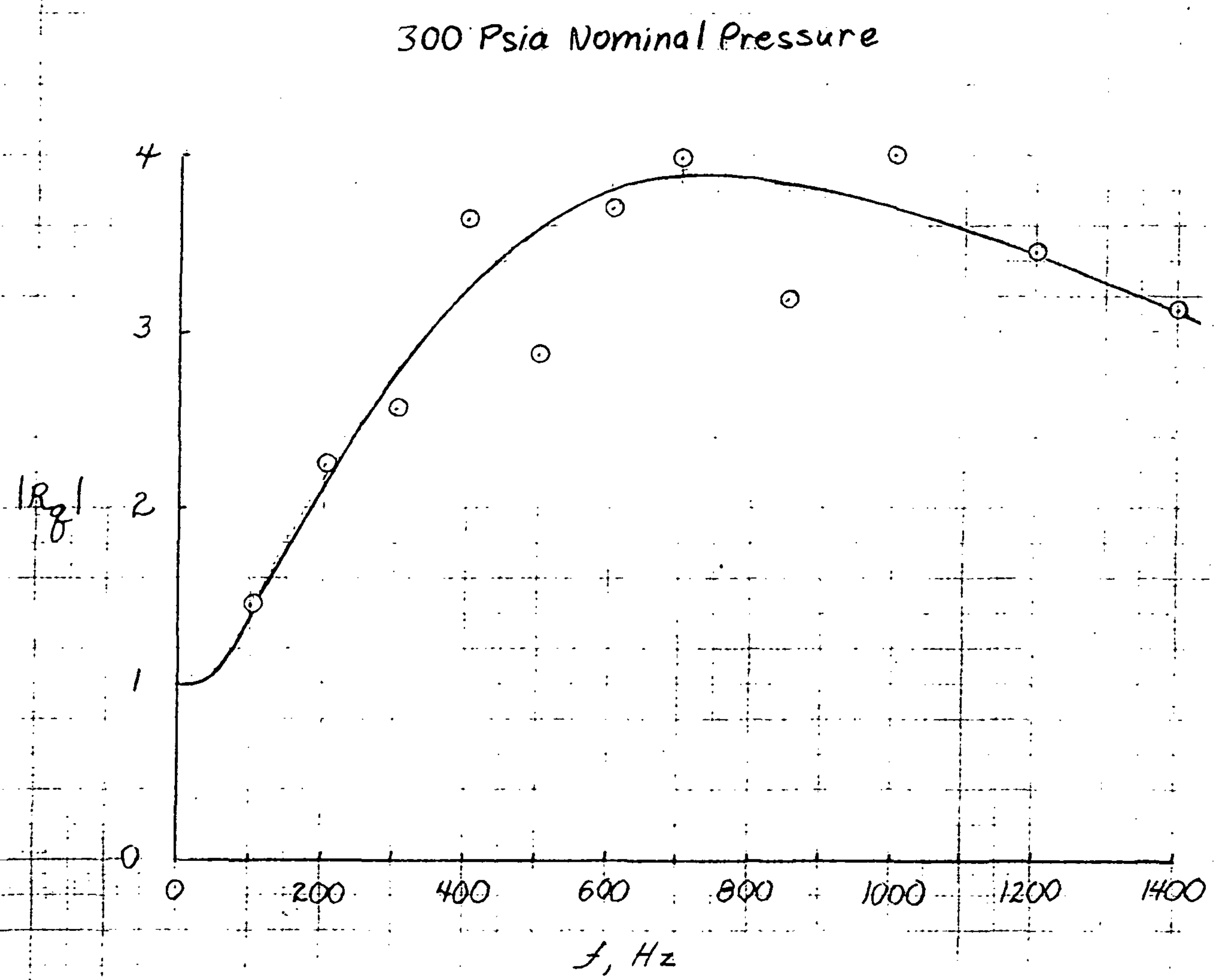

Figure 9. Absolute value of heat flux response function vs. frequency for ASRM Igniter Propellant

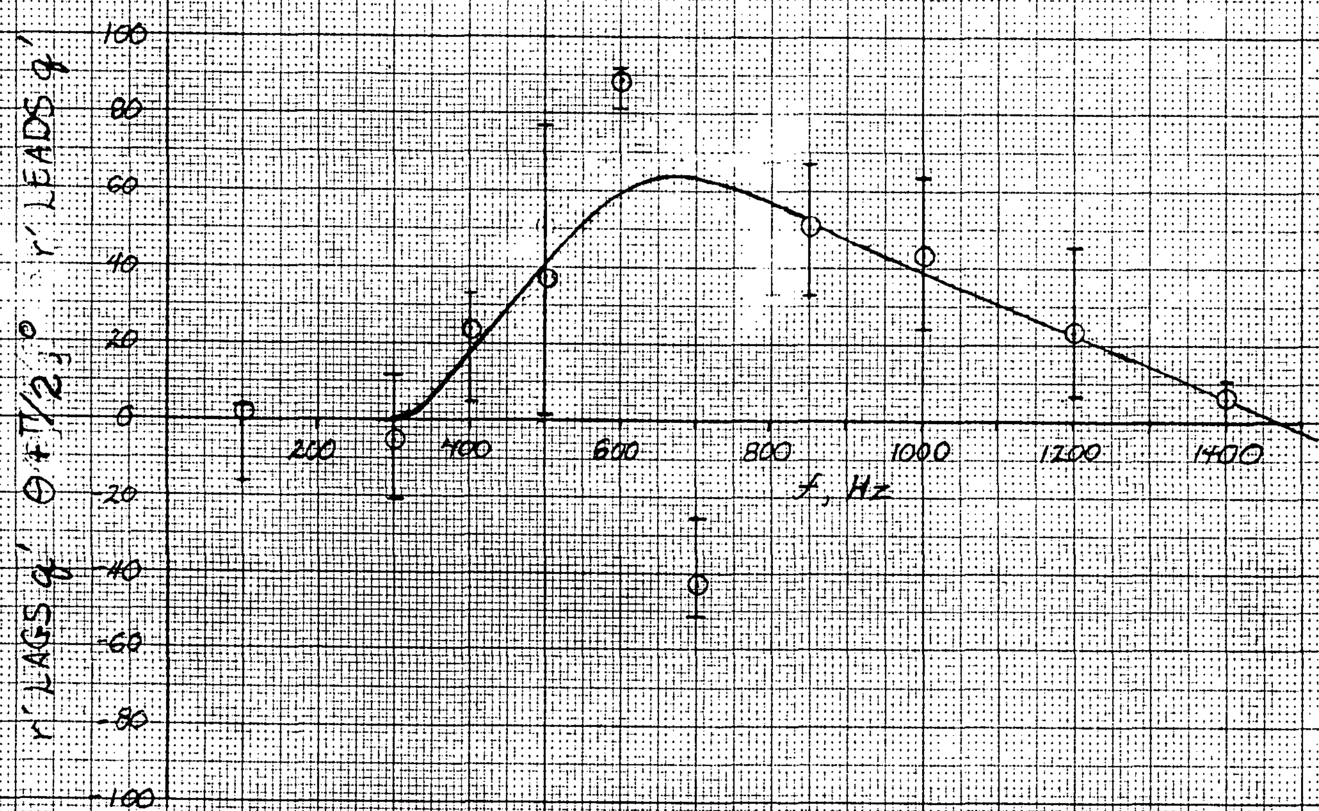

Figure 10. Argument of response function vs frequency for ASRM Igniter propellant

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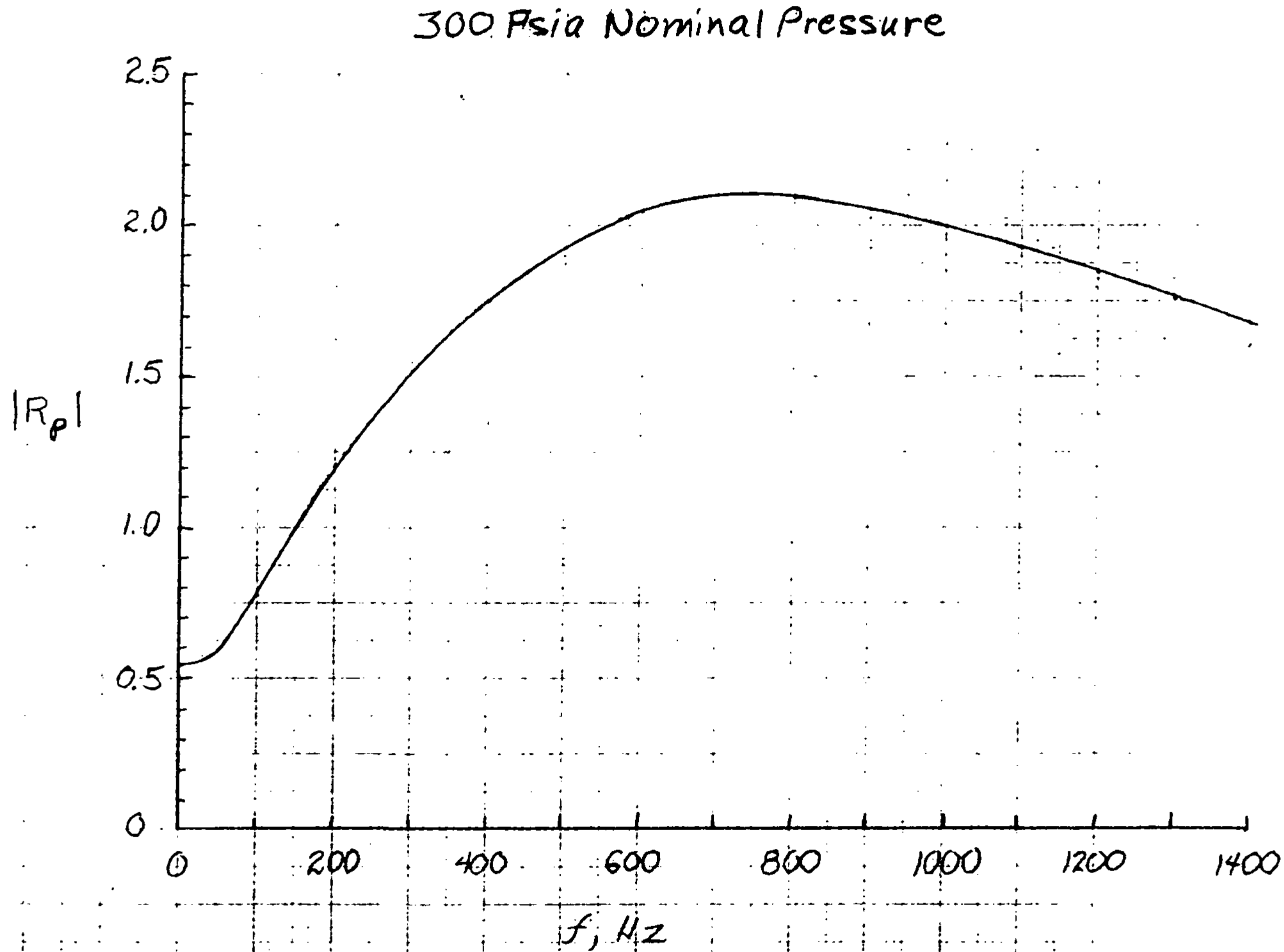

Figure 11. Absolute value of pressure-coupled response function vs. frequency for ~~ASRM~~ Igniter propellant

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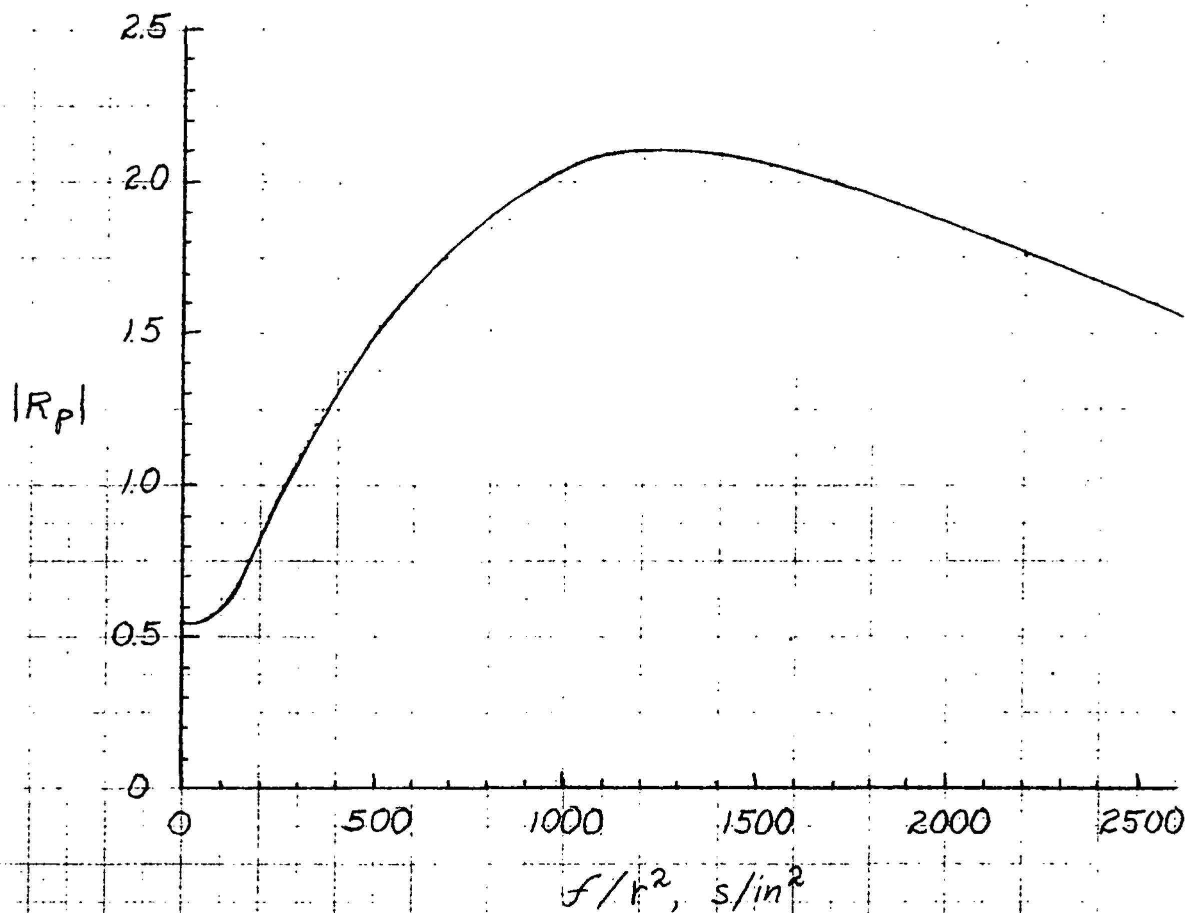

Figure 12. Absolute value of pressure-coupled response function vs. normalized frequency for ASRM Igniter Propellant

The product of the $|R_p|$ curve, Figure 11, and the cosine of the curve fit to the argument data, Figure 10, yield the real component of the pressure-coupled response function, Figure 13. The argument results produce a characteristic bimodal response, with peaks at frequencies of 400 and approximately 1250 Hz (at this test pressure).

The $R_p^{(r)}$ results are plotted versus the normalized frequency in Figure 14. For any operating pressure, the frequencies of peak response can be estimated by multiplying the respective f/r^2 value by the square of the burning rate at that pressure. At the 2,000 psia pressure burning rate of approximately 2 in./s, the peak frequencies are predicted to be 2800 Hz (700×2^2) and 8400 Hz (2100×2^2).

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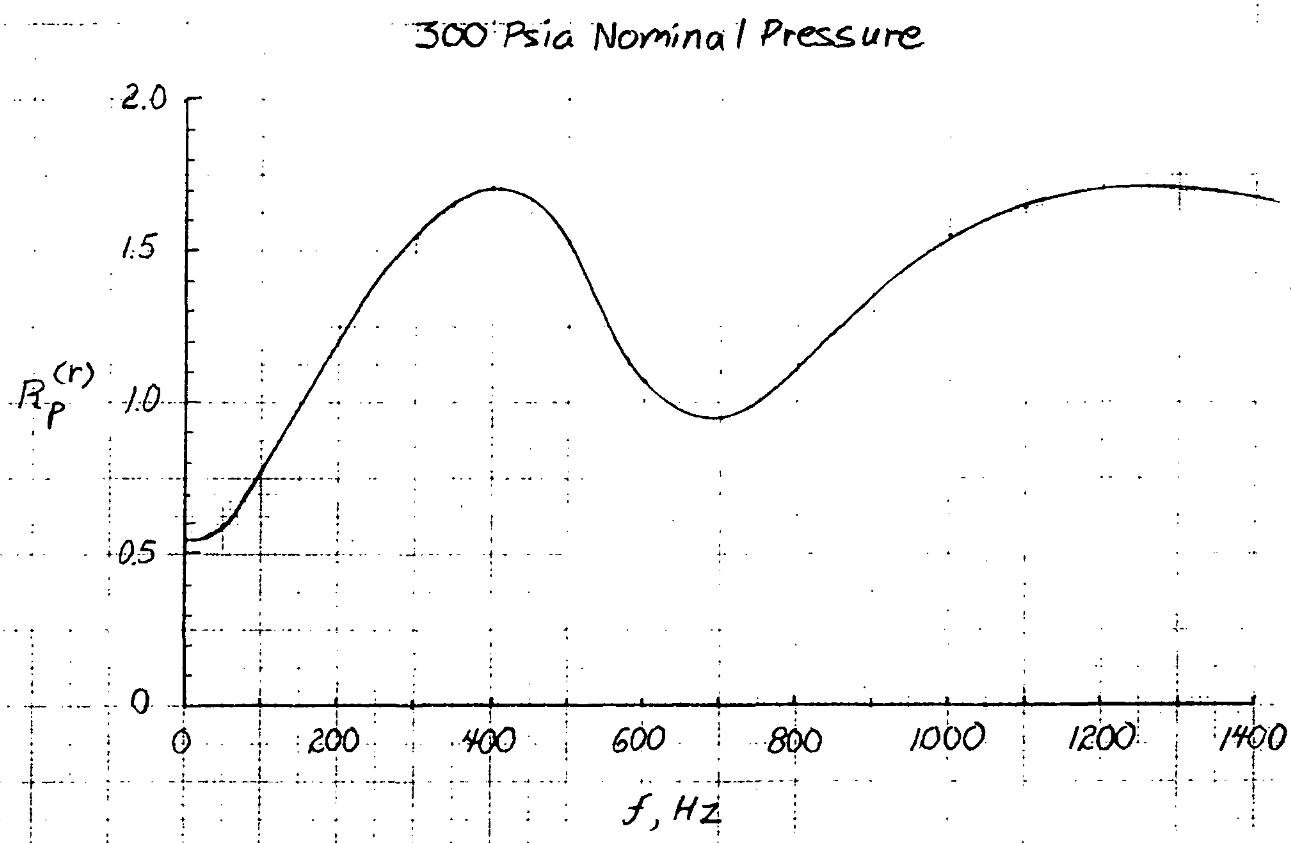

Figure 13. Real component of pressure-coupled response function vs. frequency for ASRM Igniter propellant

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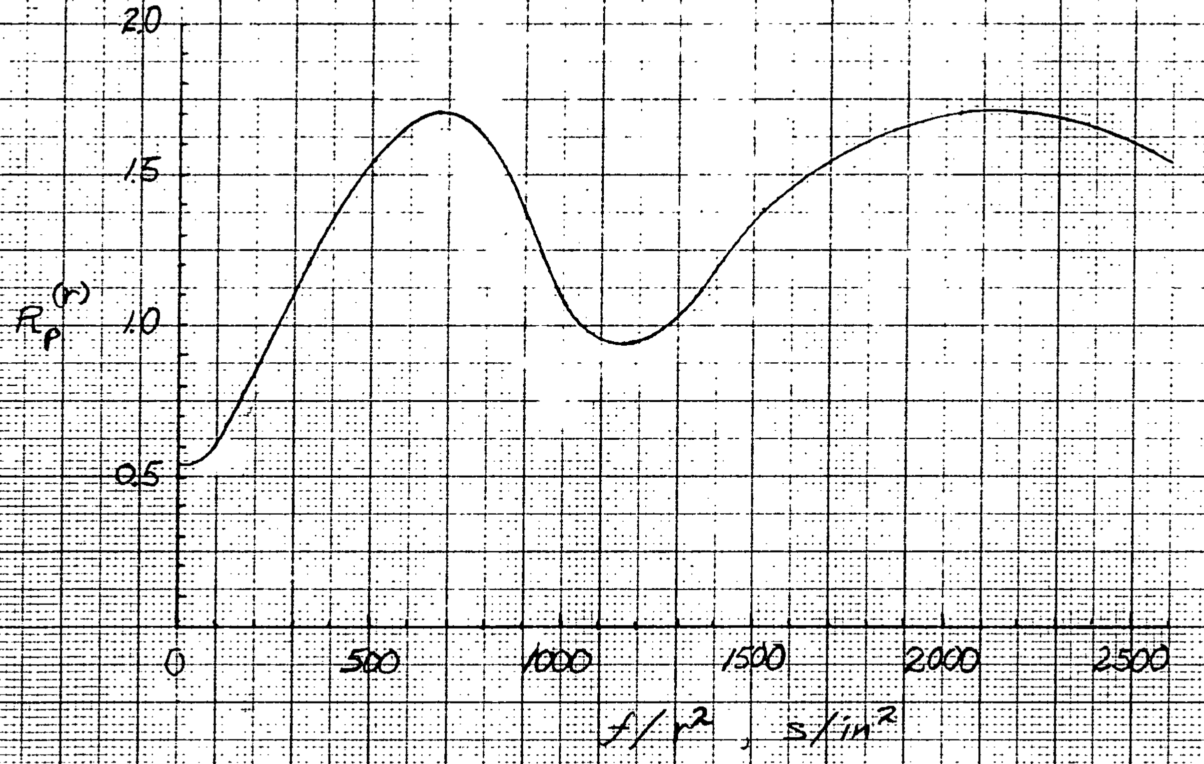

Figure 14. Real component of pressure-coupled response function vs frequency for ASRM Igniter Propellant

CONCLUSIONS

The following conclusions are drawn from these test results. The differences between the pressure-coupled response curves deduced for the RSRM and ASRM formulation propellants are very small and within the scatter in the data correlations. Therefore, the results predict that the pressure-coupled combustion response characteristics of the two propellants should be roughly the same. For motor stability prediction calculations at the ASRM's fundamental longitudinal acoustic mode, it is recommended that $R_p^{(r)}$ be set equal to the zero frequency intercept value (the burning rate pressure exponent, n).

The pressure-coupled response function results for the ASRM Igniter Propellant were normal in amplitude, typical of propellants of this type. The results yielded a bimodal distribution with frequency for the real component. At the 2,000 psia pressure burning rate, the peak responses are predicted to occur at frequencies of approximately 2800 and 8400 Hz, above the longitudinal and tangential acoustic mode frequencies indicated for the igniter motor.

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