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Microwave Measurement of the Solid-Propellant Pressure-Coupled Response Function

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The results of an investigation are presented on the applicability of a microwave doppler shift technique for directly determining propellant response functions over the desired frequency range. The investigation consisted of three phases. In phase 1 the validity of the microwave technique was investigated by comparing measured pressure-coupled response function data to existing data from T-burner and rotating valve tests. In phase 2 a new microwave burner-pressure modulation system capable of achieving frequencies and mean chamber pressures of 1500 Hz and 10.5 MPa (1500 psia), respectively, was developed. Under phase 3 pressure-coupled response function measurements were carried out using the phase 2 system in order to define its frequency limit, response function resolution, and precision. The response function real component results were comparable to those obtained by the T-burner and rotating valve methods, although they were consistently on the high side. The present results also revealed a distinctive multimodal character which may be related to the propellant heterogeneity.

Nomenclature

f	= frequency of pressure oscillations
k_p	= microwave propagation constant in propellant
m	= mass burning rate per unit area of propellant surface
n	= regression rate pressure exponent
P	= pressure
ΔP	= peak-to-peak amplitude of oscillatory component of pressure
r	= propellant regression rate
Δr	= peak-to-peak amplitude of oscillatory component of propellant regression rate
R_b	= pressure-coupled response function
t	= time
θ	= phase relationship, argument of response function
λ_p	= microwave wavelength in test propellant
ρ	= propellant density
ϕ	= phase difference between microwave test and reference signals
$\Delta\phi$	= peak-to-peak amplitude of oscillatory component of phase difference

Superscripts

(i)	= imaginary component (see Fig. 9)
(r)	= real component (see Figs. 6-8)
$\bar{( )}$	= mean- or time-averaged value
$( )'$	= oscillatory component

Subscripts

min	= minimum value

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Index categories: Combustion Stability, Ignition, and Detonation; Microwaves.

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Introduction

An important consideration in the design and development of any solid-propellant rocket motor is the avoidance or the minimization of combustion instability or burning irregularities. Such instability occurs as the result of the dynamical behavior of the burning propellant when exposed to some type of unsteady pressure or velocity fluctuations.

The effect of small amplitude harmonic pressure oscillations on the burning of propellant commonly is characterized by its response function R_b, the dimensionless ratio of the mass flux perturbation (normal to the propellant surface) to the pressure perturbation:

$$R_b = \frac{m'/\bar{m}}{P'/\bar{P}} = |R_b| e^{i\theta} \tag{1}$$

where the argument of the response function, θ, is the phase relationship between m' and P'. Considerable experimental effort has been devoted to determining its magnitude and phase and how it varies with pressure, frequency, and propellant composition.[1]

All existing methods for measuring the pressure-coupled response function, whether based on self-excited combustion systems (T-burners, L^* burners, subscale motors) or externally excited systems (pulsed burners, chambers with variable throat area), are necessarily indirect in the following sense. For all such methods only the transient or oscillating pressure is measured. The data are then interpreted with an analysis of the burner. Knowledge of the losses in the system must be available in order to infer the gains, i.e., the response function. In some instances, the losses may in principle be determined experimentally, but even under those circumstances assumptions and approximations are required. The inevitable consequence is substantial uncertainty in the reduced data, the degree of uncertainty for the various alternative methods varying with the severity of the assumptions used.

What is needed to circumvent the aforementioned problems is a technique capable of directly measuring the transient regression rate of solid propellants. Such a technique has been under development at JPL for more than a decade.[2-4] The regression rate is determined by measuring the doppler frequency phase shift between a reference microwave signal and a microwave signal reflected from the propellant-gaseous zone interface. This paper describes a program that was carried out to utilize the microwave doppler phase shift principle in developing and demonstrating an improved technique for measuring the pressure-coupled response function of solid propellants—improved in the sense of offering greater accuracy and test frequency flexibility, along with lower costs, than current methods and yielding both the real and imaginary components of the response function.

Experimental Technique

In determining the pressure-coupled response function R_b by directly measuring the propellant transient regression rate, an underlying assumption is that the response function, as described in Eq. (1), can be rewritten as

$$R_b = \frac{m'/\bar{m}}{P'/\bar{P}} = \frac{r'/\bar{r}}{P'/\bar{P}} \tag{2}$$

where the mass evolution is related directly to regression rate of the propellant/gaseous-zone interface by the expressions $m' = \rho r'$ and $\bar{m} = \rho \bar{r}$. An important corollary to this assumption is that any apparent movement of this interface due to other considerations, i.e., vibration, propellant compressibility, must be small compared to r'.

To obtain regression rate data under transient pressure conditions, a technique capable of determining very small changes in the propellant regression rate is required, which in turn requires high spatial and time resolution. For example, consider a propellant burning in a chamber in which the pressure $\bar{P}$ is being modulated sinusoidally at a peak-to-peak amplitude ΔP and a frequency of 400 Hz. If the propellant-burner characteristics are $\bar{r} = 1$ cm/s, $R_b = 1$, and $\Delta P/\bar{P} = 0.2$, then, in order to see such a variation, a technique must be developed capable of resolving changes in the regression rate r' of the order of 0.2 cm/s in a time of less than 2.5 ms. To achieve this requires a system capable of resolving spatial differences on the micrometer level. The development at JPL of a microwave doppler phase shift technique capable of meeting these resolution requirements was initiated by Shelton more than a decade ago.[2]

The principal of the regression rate measurement technique is illustrated in Fig. 1. A microwave signal propagates through a propellant strand enclosed in a waveguide and is reflected from the burning-surface/gas-phase interface. The phase angle ϕ between the incident and reflected signals shifts with reduction in length of the burning strand. It can be shown[3,4] that the propellant regression rate is directly proportional to the rate of change of this phase shift,

$$r = \frac{1}{2k_p} \frac{\mathrm{d}\phi}{\mathrm{d}t} \tag{3}$$

where the proportionality constant is the microwave phase constant in the propellant, a function of the geometry of the waveguide and the dielectric constant of the propellant. The test system used for making the phase shift measurement is shown in block diagram form in Fig. 2.

In the present test system the propellant-filled waveguide connects to a small burner chamber which is pressurized in an oscillatory manner with nitrogen. The mean and oscillatory regression rate components of the burning propellant strand are measured by this phase shift technique. From Eq. (3):

$$r = \dot{\phi}/2k_p \tag{4}$$

and for a sinusoidally varying P'

$$r' = (\pi f \Delta\phi \cos 2\pi f t)/2k_p \tag{5}$$

and

$$\Delta r = (2\pi f \Delta\phi)/2k_p \tag{6}$$

Combining the $\bar{r}$ and Δr results with the measured pressure information ($\Delta P, \bar{P},$) and the phase relationship between the oscillatory regression rate and pressure (θ) allows the propellant response function to be determined directly at the desired test conditions. From Eqs. (1), and (2):

$$R_b = \frac{\Delta r/\bar{r}}{\Delta P/\bar{P}} e^{i\theta} = \frac{2\pi f \Delta\phi}{\dot{\phi}} \frac{\bar{P}}{\Delta P} e^{i\theta} \tag{7}$$

From Eq. (6), a phase shift resolution of approximately 0.04 deg is required to resolve the previously described 0.2 cm/s change in regression rate. It is also seen from Eq. (6) that the magnitude of the required phase resolution becomes smaller with increasing pressure modulation frequency. It is the resolution of the phase shift measurement system which determines the upper frequency limit of the test technique, and the goal of this program, as will be elaborated on further, was essentially to raise this frequency limit.

As stated earlier, the entire basis for this technique is that the propellant response function R_b can be determined by observing the movement of the propellant/gaseous interface. Investigations of possible system and test limitations that might lead to erroneous measurement of the propellant regression rate were reported in Refs. 3 and 4. These included the effects of: 1) roughness of the propellant burning surface, 2) propellant compressibility, 3) transient flame zone ionization level, and 4) test system vibration. The results will be briefly summarized here.

If the surface roughness is small compared to the microwave wavelength in the propellant (typically on the order of 1-2 cm) and the diameter of the propellant strand is large compared to the surface roughness, the microwave signal may be thought to be reflected from a plane defined by the rms of the roughness. In Ref. 3 it was verified that for the typical roughness scale of burning propellants the propellant surface still appears planar to the microwave signal.

Compressibility of the propellant has been found to be a significant effect in tests involving large pressure variations (rapid-depressurization or pressurization-type tests).[3,5,6] For the small pressure perturbations (P') generated in this response function measurements technique, however, numerous cold-flow tests revealed no measurable movement of the propellant surface.[4] This null result was attributed to the slow relaxation time of the propellant, i.e., it is not able to respond to the rapid, small pressure variations.

Possible effects of the transient flame zone ionization level on the transient regression rate determined by the microwave phase shift technique have been investigated both theoretically and experimentally.[3,4] The analyses predicted that the presence of a measureable reflection from the gaseous flame zone above the propellant surface should be indicated by large shifts in the amplitude and phase of the reflected microwave signal. In a variety of tests designed to reveal such effects, no changes in signal amplitude or phase traceable to plasma effects were ever observed and, therefore, it was concluded that the flame zone plasma had no measurable effect on the observed regression rates.

Unlike the propellant compressibility and flame zone plasma, vibration of the test apparatus is an observable effect, limiting the response function measurements to test frequencies below a few hundred Hz prior to initiating this program.[4] The 10-mdeg resolution of the phase detection system shown in Fig. 2 is equivalent to a spatial resolution of approximately 0.2 μm. Therefore, it is easy to see that the phase detection system is exceedingly sensitive to any vibration introduced by the burner pressure modulating

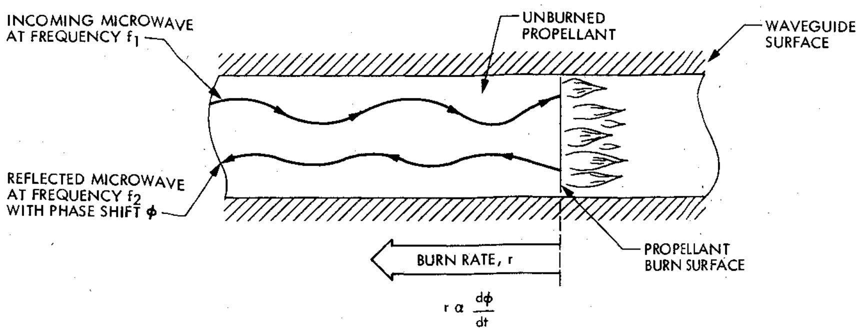

Fig. 1 Microwave burning rate measurement technique.

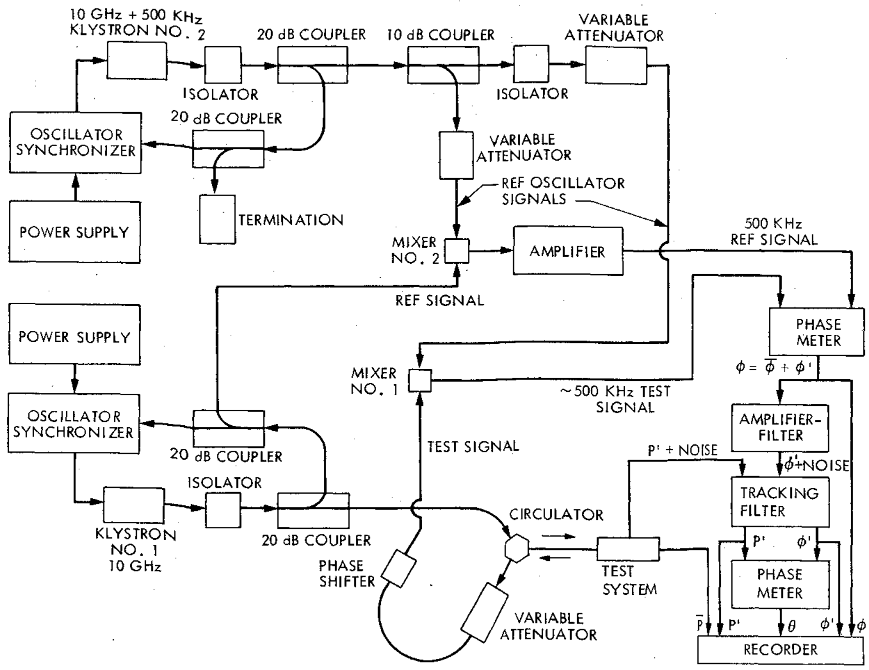

Fig. 2 Block diagram of microwave doppler phase shift measurement system.

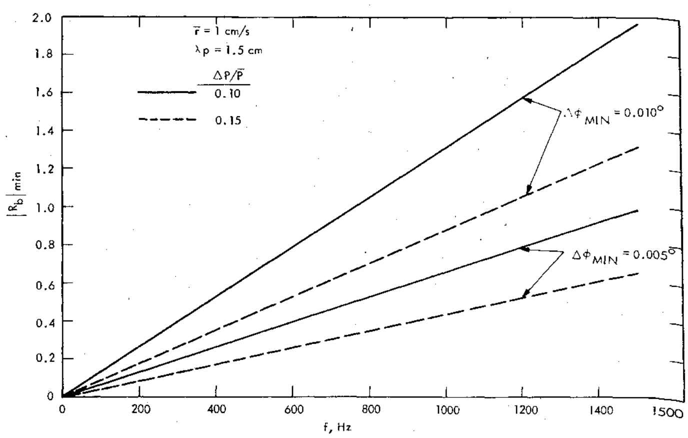

Fig. 3 Calculated minimum measurable response function absolute value vs frequency.

system. Extending the oscillation-frequency test range of the response function measurement technique required a burner and pressure modulation system with substantially reduced vibration.

Test Program

In phase I of this program response function measurements were made on two solid propellants, using basically the test system of Ref. 4, and the results compared to pressure-coupled data in the literature from T-burner and rotating valve tests. On the basis of these results it was concluded that the validity of the microwave phase shift technique had been demonstrated to the extent that, within its operating frequency limits, the measured response functions were comparable to those obtained by the other methods.

In phase 2, described in the next section, techniques for extending the oscillatory frequency test range were identified. A new microwave burner-pressurization system capable of achieving the goals of frequencies of at least 1500 Hz and mean chamber pressures of at least 10.5 MPa (1500 psi) was designed and fabricated. The signal processing and data acquisition system was also upgraded.

Under phase 3, pressure-coupled response measurements were carried out on the two phase 1 propellants plus a third propellant using the phase 2 system in order to define its frequency limit, response function resolution, and precision.

Improved Test System

Using the theoretical analysis of Ref. 4, predicted minimum measurable absolute magnitudes of the response function as a function of pressure modulation frequency are shown in Fig. 3. In essence, the curves show the calculated conditions for a signal-to-noise ratio of unity. Typical values were used for the mean regression rate $\bar{r}$ and microwave wavelength in the propellant λ_p. The other major parameters governing the upper frequency limit of the test technique are the minimum measurable phase shift of the test system, $\Delta\phi_{min}$, which is controlled by either the system vibrational noise or the minimum resolution of the microwave/phase shift measurement instrumentation, and the peak-to-peak amplitude of the pressure oscillations driven in the microwave burner, ΔP.

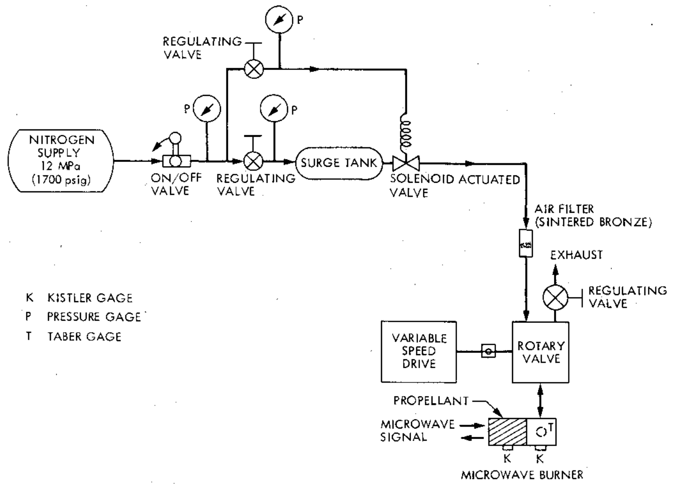

Fig. 4 Flow circuit for microwave burner pressurization.

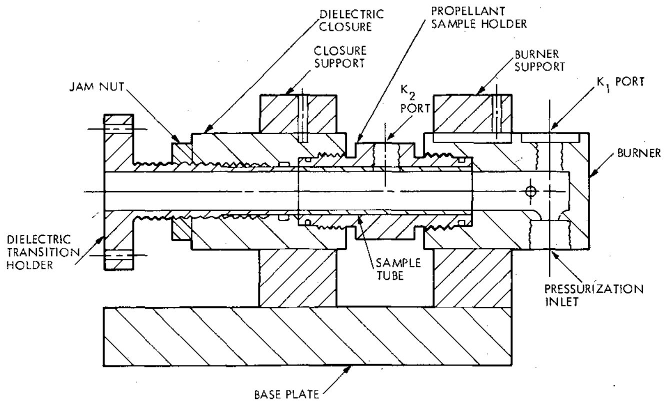

Fig. 5 Microwave burner assembly.

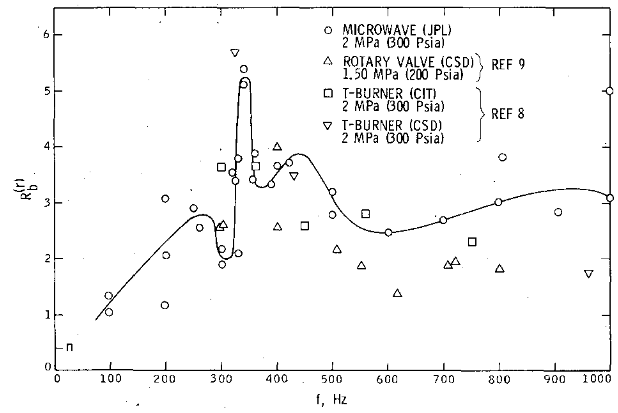

Fig. 6 Real component of response function vs frequency, propellant formulation A-13.

With the results of Fig. 3 as a guide, the following critical factors were addressed in increasing the frequency test range: 1) phasemeter resolution and time response, 2) burner pressure modulation—increasing amplitude/frequency range and avoiding acoustic resonant modes, 3) burner vibration, and 4) signal processing and data acquisition system.

From a comparison with the latest model of the phasemeter being used, it was concluded that the gains in phase resolution from replacing the existing meter would be small. With its 1-ms constant option, the frequency response of this meter was flat up to approximately 1000 Hz. Modifications to the meter suggested by the manufacturer raised this frequency to 1800 Hz, but with a corresponding increase in the high-frequency noise on the meter output signal. Filtering the output improved the signal quality to about that of the filtered output of the unmodified meter.

After reviewing possible techniques for the oscillatory pressurization of the microwave burner, the decision was made to use a rotary valve, similar in design to that developed at the Naval Weapons Center,[7] to sequentially pressurize and vent a burner. The burner both fills and vents through the valve (Fig. 4), eliminating the sonic nozzle.

In designing a new burner, primary goals were to keep vibration to a minimum and to try to keep the fundamental mechanical resonance frequency of the burner above the pressurization frequency upper goal of 1500 Hz. The resulting design, shown in cross-sectional view in Fig. 5, is essentially a free-free supported beam with the structural weight kept to a minimum. The internal dimensions were arrived at from cold-flow experiments. The burner and dielectric closure slip fit into supports that are mounted on a base plate, which in turn bolts to the heavy test stand. The propellant sample holder acts as a turnbuckle, drawing the burner inward as it is screwed into the left-hand threaded closure and right-hand threaded burner. Dowel pins keep the system in alignment during the assembly process.

The design has two high-frequency pressure transducers. The first is mounted in the burner cavity, the second in the propellant sample holder. Transducer 1 is used in the prefiring cold-flow tests carried out to set the desired test conditions and gives a small-error (~5%) approximation for the oscillatory pressure conditions at the burning surface for the first portion of the propellant sample length. As the burning surface passes over transducer 2 and it begins to sense pressure, it provides an accurate indication of the burning surface pressure conditions (both amplitude and phase with respect to the oscillatory component of the propellant regression rate) for the approximately 100 ms that it takes the flame to pass over the transducer surface and an increasingly approximate measurement as the propellant surface recedes away from the transducer.

Cold-flow tests with the new burner showed that the desired reduction in the level of burner vibration had been achieved, the filtered $\Delta\phi$ signal varying from 30 to less than 10 mdeg over the frequency range of 200 to 1300 Hz. Although the actual signal-to-noise level has to be kept in mind in any given test, the reduced vibration levels essentially allowed the test frequency to be arbitrarily chosen, instead of having to test at the nodes in the burner vibration.

The signal processing and data acquisition system arrived at is shown in Fig. 2. The input signals to the phasemeter used to measure relative phase angle θ between the oscillatory components of the phase shift and pressure have to be relatively free of high harmonic content or noise. Therefore, the signals are first passed through an externally tuned dual-channel tracking filter (calibrated for unity gain and zero relative phase shift). A signal generated from the rotating valve is used for externally tuning the dual-channel filter. A switching circuit (not shown in Fig. 2) was also developed to automatically switch the input to the tracking filter from the microwave burner pressure transducer (No. 1) to the propellant sample holder transducer (No. 2) at the desired time. This circuit allows one channel of the tracking filter to be utilized for conditioning both oscillatory pressure signals.

Test Results

Response function measurements with the new test system were carried out on a nonmetalized propellant, Naval Weapons Center formulation A-13, and two metalized propellants, ANB-3066 (Aerojet Solid Propulsion Co. formulation) and UTP 19360 (Chemical Systems Division of United Technologies Corp.). The propellants were tested at a single pressure each over the frequency range of 100 to 1100-1200 Hz at 100 Hz intervals. Although the phase 2 test system was designed for burner mean pressures up to 10.5 MPa, the

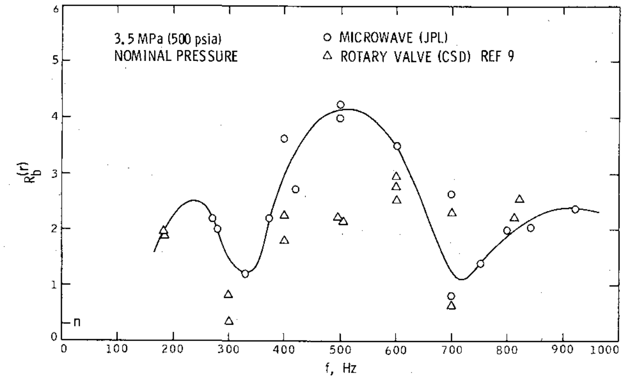

Fig. 7 Real component of response function vs frequency, propellant formulation ANB-3066.

high-pressure nitrogen system in the test facility limited the burner mean pressures to the 4-5 MPa region and below.

The modified time constant phasemeter and Kistler transducer switching circuit were used for the 1000 Hz and higher frequency tests.

The results for the real component of the response function for A-13 are shown in Fig. 6 and are compared with T-burner[8] and Chemical Systems Division (CSD) rotary valve[9] technique data for this formulation. It should be kept in mind that these data also include the real component of any oscillations with pressure of the burner flame temperature. A line fit to the microwave data yields a multimodal response function curve that appears to be approaching the value of the propellant burning rate pressure exponent n as frequency goes to zero. The T-burner and rotary valve data appear to exhibit a similar multimodal structure.

There was generally less than a 10% spread in the measured ϕ' amplitude values for the lower frequency tests, below 500 Hz, where the P' and ϕ' amplitudes were relatively large. Below 500 Hz, the reproducibility of the response function results also appeared to be relatively good. At higher frequencies the uncertainty in the measured ϕ' amplitudes increased with decreasing signal-to-noise level, approaching the noise-limiting region at about 1000 Hz.

The response function real component data for ANB-3066 is shown in Fig. 7. A multimodal response function-frequency curve was again obtained. The propellant burned very erratically and several tests had to be rerun because of anomalous (excessive) burning rate behavior. (Ignition problems, etc. have also been reported with this particular batch of ANB-3066 propellant in various tests carried out at the Air Force Rocket Propulsion Laboratory.[10]) The burner peak-to-peak pressure amplitudes during burning were considerably (50% or more) below the pretest cold flow values for this more rapid burning propellant and dropped off to less than 5% of the mean pressure at the higher frequencies, reducing the upper test frequency attainable with this propellant.

The magnitude and general nature of the Fig. 7 test results are in reasonable agreement with the extensive response function data for the ANB-3066 formulation measured by the rotary valve technique over the same frequency range.[9,11] One set of rotary valve data is also shown in Fig. 7 for comparison. A comparison with existing variable area or pulsed T-burner data[12] for this formulation resulted in considerably poorer agreement, the T-burner response function maximum occurring at a frequency of approximately 1000 Hz, rather than the 500 Hz measured here. This may be due to batch-to-batch variations in propellant, or it may be real differences in the results of the two test techniques.

The measured real component of the response function vs frequency results for UTP 19360, shown along with CSD rotary valve data[13] for the same formulation (but a different batch) in Fig. 8, produced a bimodal curve. For interest, the imaginary component of the response function is also shown in Fig. 9.

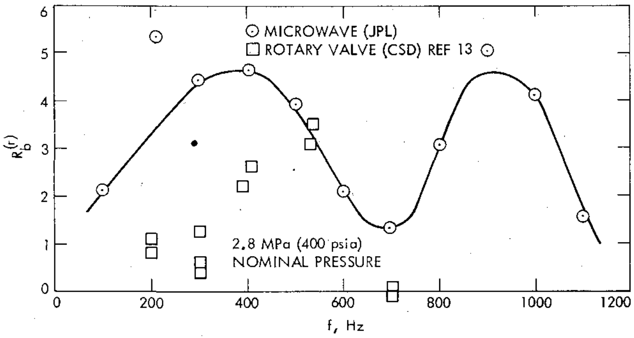

Fig. 8 Real component of response function vs frequency, propellant formulation UTP 19360.

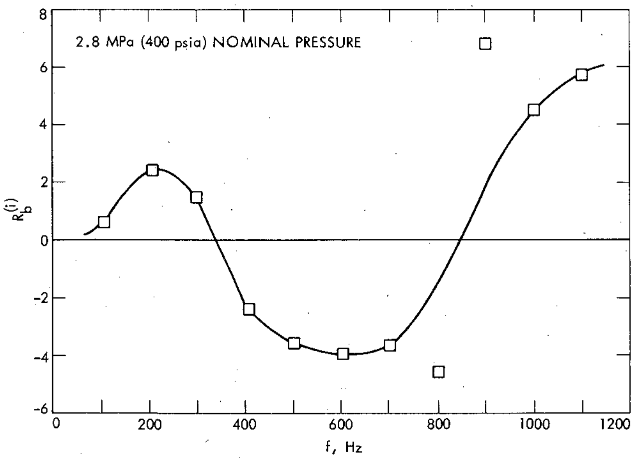

Fig. 9 Imaginary component of response function vs frequency, propellant formulation UTP 19360.

The microwave results are again somewhat higher than those obtained by the rotary valve technique. As with the ANB-3066 propellant, the measured regression rates were quite irregular at the pressure tested. This is probably due to the irregular burning surface of these very heterogeneous, metalized propellants—aluminum agglomerating and leaving the burning surface, and droplets possibly reimpinging on the surface. These random inflections in the ϕ signal produced corresponding large-amplitude modulations in the ϕ' signal.

In reviewing the possible experimental errors, the critical measurement parameter in this technique is ϕ', the oscillatory component of the microwave phase shift, both its value and its relative phase with respect to P'. All the other experimental parameters, $\bar{\phi}$, $\bar{P}$, and ΔP, should be measurable with an error no greater than a few percent. The ϕ' signal can have spurious components, including some or all of the following: 1) structural vibration of the burner system, 2) debris impingement on the propellant burning surface (especially for metalized propellants), 3) transients in the burner mean pressure, 4) localized fluctuations in $\bar{\phi}$, and 5) microwave-phasemeter system noise. They, along with the magnitude of the burner pressure oscillations, determine the accuracy and limiting frequency of the test technique. Future plans include incorporating a computerized data acquisition and processing system with corrections for some or all of the above phenomena, which will help to reduce the scatter and uncertainty in the data at the higher frequencies.

Summary and Conclusions

In summary, an improved microwave burner-oscillatory pressurization system was developed for directly measuring the pressure-coupled response function of solid propellants by the microwave doppler phase shift technique, and tests were carried out on three propellant formulations.

Test turnaround times, excluding periodic instrument calibration, of an hour or less for a two-man crew (test engineer and technician) were attained.

The two items requiring any significant maintenance were the rotary valve, which was periodically disassembled and cleaned, and the dielectric transition to the burner test propellant. The inner surface of the Melmac transition gradually erodes, due to exposure to the hot combustion products following burnout of the propellant test samples. It and its holder were removed from the dielectric closure (Fig. 5) and remilled flat four times during the course of the test program.

The more extensively tested A-13 propellant showed good repeatability in the test results below a frequency of roughly 500-600 Hz. With increasing frequency the uncertainty and scatter in the results increased as the magnitude of the test signal approached the system noise limit.

The results for the real component of the response function were compared with existing data obtained by the T-burner and rotating valve methods. While being comparable in magnitude, the microwave results were consistently on the high side. The present results also exhibited a distinctive multimodal character which may be related to the propellant heterogeneity, per the Cohen model.[14] Such variations are more readily discernable with the present technique because of the fine frequency resolution possible and the ability to now measure the phase lead/lag relationship between the experimentally determined dynamic burning rate and pressure and its variation with frequency.

Goals of future work will be to 1) continue the increase in the upper frequency limits of the test technique that has been accomplished under this program and 2) demonstrate the feasibility of using the microwave phase shift technique to measure the velocity-coupled transient response of solid propellants.

Acknowledgments

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