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Determination of Aluminized Solid Propellant Admittances by the Impedance Tube Method

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The adaptation of the impedance tube technique in the measurement of the admittances and response functions of aluminized solid propellants is described. These quantities are needed for combustion stability analysis of aluminized solid rocket motors. To determine the acoustic energy gains and losses in the impedance tube, the acoustic pressures (amplitude and phase) are measured in the tube during the quasisteady burn period of a test through a distance covering two standing wave pressure minima. The measured data are then input into a data reduction computer program that is based upon the solution of the impedance tube wave equations and is capable of the simultaneous determination of the propellant admittance and the acoustic energy losses in the gas phase. Results obtained in a series of tests conducted with UTP-3001 and UTP-19360 aluminized propellants are presented. The paper demonstrates that the data measured in tests conducted with aluminized propellants and, hence, the determined propellant properties are more accurate than data measured in tests with nonaluminized propellants. Excellent agreement is demonstrated between the predicted and measured impedance tube wave structures. Finally, the results obtained by this method are utilized to determine the true role of aluminized solid propellants in the damping of combustion instabilities inside the rocket motor.

Introduction

THIS paper describes the adaptation of the impedance tube technique in the measurement of the admittances and response functions of aluminized solid propellants. The quantitative determination of these quantities is critical to the understanding of the true role of aluminized solid propellants in the damping or amplifying of combustion instabilities[1]; instabilities that may result in either mechanical failure, excessive vibrational loads, or abnormal burn rate of the solid propellant.[2,3]

To determine the susceptibility of a given combustion system to combustion oscillations, it is necessary to determine the energy balance that exists between the various sources of energy gains and losses inside the combustor. A rocket combustor is analogous to a self-excited oscillator[4] with the combustion process acting as the energy source, the gas medium in the combustor as the oscillator, and the combination of the nozzle and viscous processes as the dash pot. The coupling between the combustor disturbances and the combustion processes at the burning propellant surface may result in acoustic energy gains and the amplification of these disturbances[5,6] while attenuation of disturbance amplitude occurs due to energy dissipation in the gas phase by such processes as heat transfer to the walls, viscosity, particulate damping,[7] and acoustic energy convection and radiation through the nozzle.[8] Combustion instability occurs when disturbance energy gains outweigh energy losses while stable engine operation is assured when the reverse is true.

The incorporation of aluminum in solid propellants has consistently proven to be an effective way for suppressing high-frequency instabilities.[9] However, it has been shown[10] that the suppressive mechanism of aluminum is ineffective at the lower frequency range of 100-1000 Hz, as the amount of acoustic energy dissipated by the aluminum oxide (Al_2O_3) particles that are present in the gas phase reduces with frequency (below 1000 Hz). Moreover, instances have been observed[11] where the rocket motor became more unstable at lower frequencies by the addition of metals into the solid propellant.

Considering the different effects exerted by metal additives upon engine stability at low and high frequencies, quantitative data describing the manner in which metal additives affect the combustion response of the propellant and the gas phase damping, provided by the oxidized metal particles, are needed. One should also keep in mind that metal particles burning in the gas phase may result in additional driving rather than damping. Both theoretical and experimental capabilities for determining such effects are needed and the present paper describes the application of the modified impedance tube technique in the determination of the response functions and the gas phase damping of aluminized solid propellants.

To date, most response function measurements were performed utilizing the self excited T-burner technique.[12] This technique, in its simplest form, in general cannot be utilized with aluminized propellants because high gas phase damping, resulting from the presence of aluminum oxide particles in the gas phase, prevents the spontaneous growth of the oscillations in the T-burner. Consequently, two other experimental techniques were developed; namely, the variable area T-burner[13] and the pulsed T-burner.[14,15] The first method utilizes propellant samples with burn area sufficiently large to induce spontaneous oscillations in the burner while the pulse technique utilizes explosive charges to pulse the T-burner. Neither of these techniques have produced completely satisfactory data to date and the search for an improved experimental technique has continued in recent years.[16,17]

The modified impedance tube was one of the alternate techniques that were developed in recent years for the measurement of the admittances of solid propellants.[18] Investigations conducted with nonaluminized propellants[19] have shown that this technique is capable of the simultaneous measurement of both the propellant driving and the gas phase damping. Consequently, this technique offered itself as an excellent candidate for the investigation of the effect of metal additives upon solid rocket stability. This paper shows that the modified impedance tube technique indeed is capable of

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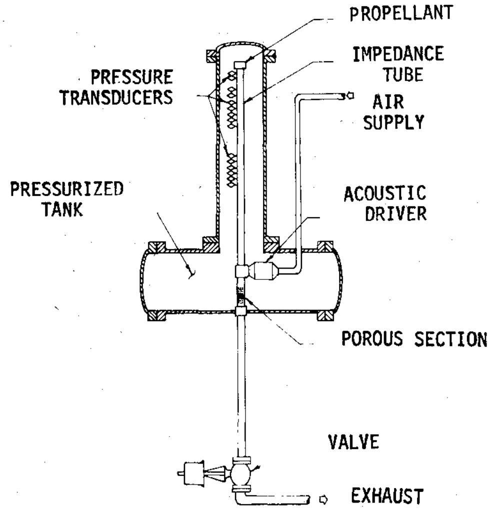

Fig. 1 Schematic diagram of the pressurized impedance tube facility.

the simultaneous determination of both the gas phase damping and amplification provided by aluminized solid propellants. Finally, data describing the characteristics of two metallized propellants are presented.

Impedance Tube Technique

The experimental set up (shown in Fig. 1) consists of a two inch diameter tube with a disk of solid propellant sample placed at one end and a combination of an exhaust valve and an acoustic driver placed at the other end, all contained within a high-pressure tank. Performing a test consists of turning on the acoustic driver to excite a standing wave of a predetermined frequency in the tube and the ignition and burnout of the tested solid propellant sample. Interaction with the combustion process at the burning surface, heat losses to the wall, and gas phase losses all modify the characteristics of the standing wave initially established by the acoustic driver. During a test, 15 piezoelectric and condenser type acoustic pressure transducers, distributed along a distance covering at least two standing wave pressure minima, are used to measure the acoustic pressure amplitudes and phases. The system of pressure transducers utilized in this experiment is calibrated to measure the 110-165 dB range that is needed to obtain the desired experimental accuracy. To acquire the pressure amplitude and phase data measured by the 10 piezoelectric transducers, a minicomputer data acquisition system is utilized. This system consists of a Hewlett Packard 2100S minicomputer with an HP 7901 disk system and a Preston GMAD-1 analog to digital converter. By passing the signals measured by the pressure transducers through high-pass filters, the dc components are filtered out and the remaining ac components are amplified to levels below the A to D input voltage limitation. The software utilized for data acquisition via this system includes direct memory access, and it is capable of transferring up to 600,000 words per second to the minicomputer. The data measured by the condenser type (photocon) transducers are recorded on a tape recorder and subsequently are played back at a reduced speed. The output data includes the axial distributions of the pressure amplitudes and phases along the impedance tube at any instant during the test. Of special interest are standing wave structures during the quasisteady phase of the test when the tube's standing wave structure remains relatively unchanged.

The measured amplitude and phase data are then input into a data reduction computer program that is capable of the determination of the admittance and response function of the propellant and the gas phase losses in the tube. Repeating this computation for different instants during the quasisteady burn period of the test provides the time histories of these quantities and repeating the tests at different frequencies

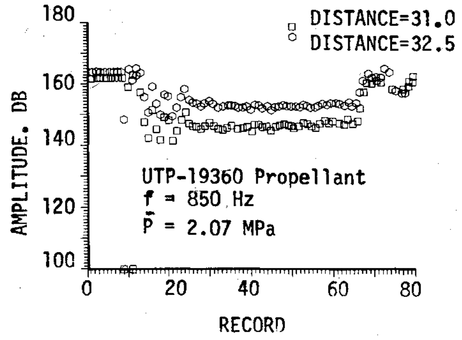

Fig. 2 Time evolution of pressure amplitude.

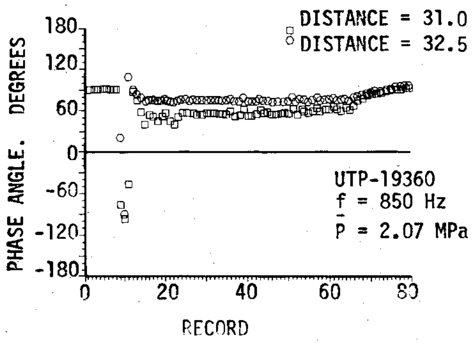

Fig. 3 Time evolution of pressure phase.

provides the frequency dependence of the propellant driving and gas phase losses. More details of the experimental setup, data acquisition system, and data reduction procedure are provided in Ref. 20.

Results

Considering the complexity of the propellant admittance measurement technique, the repeatability of the experimental data was investigated earlier in this program.[19] Two different tests were conducted with an A-13 propellant under identical conditions and good repeatability of the measured data was observed.

In this study the admittances of two aluminized solid propellants, UTP-3001 and UTP-19360, and the gas phase damping were measured in the modified impedance tube setup over the frequency range of 400-1100 Hz; a frequency range over which the effectiveness of the suppression mechanism[10] of aluminum is unclear. A typical time history of acoustic pressure amplitudes and phases measured during a test conducted with the UTP-19360 propellant at the frequency of 850 Hz and at chamber pressure of 2.07 MPa (300 psig) are presented in Figs. 2 and 3. Examination of these figures indicates that for this test the quasisteady burn period occurred between record points 26 and 64 (where a given record point corresponds to a given time constant). Figures 4 and 5 describe the instantaneous spatial dependence of the acoustic pressure amplitude and phase in the impedance tube at record point 34. Examination of these figures shows that the slopes of the acoustic pressure phase-space curves near both pressure minima are positive, indicating that the presence of aluminum oxide particles in the flow results in acoustic energy losses in the gas phase.

The determined propellant admittance and response function, together with the gas phase losses can be used[20] in conjunction with impedance tube wave equations to theoretically predict the distribution of the acoustic pressure, velocity, entropy, and density in the impedance tube. Figures 6 and 7 provide comparisons between the predicted and measured instantaneous acoustic pressure amplitude and phase distributions in the impedance tube for a test conducted

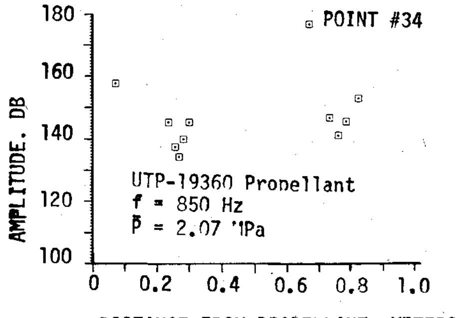

Fig. 4 Axial variation of pressure amplitude.

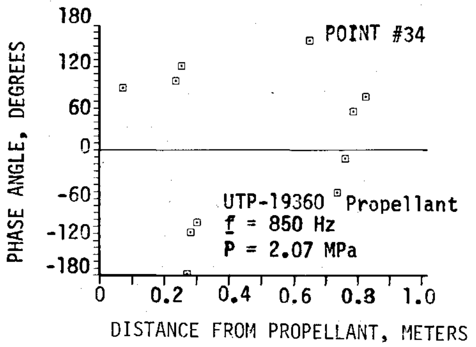

Fig. 5 Axial variation of pressure phase.

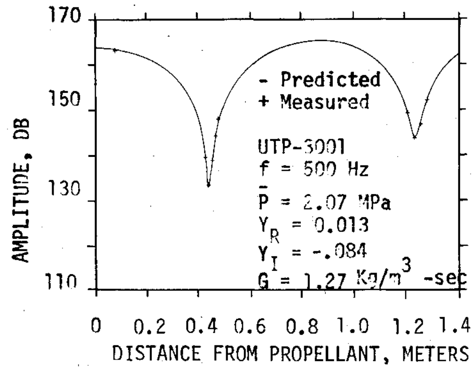

Fig. 6 Comparison of predicted and measured axial variations of pressure amplitude.

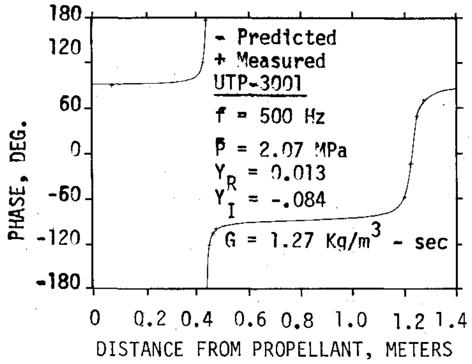

Fig. 7 Comparison of predicted and measured axial variations of pressure phase.

with a UTP-3001 aluminized propellant. Excellent agreement between these two sets of data is noted, providing further support for the applicability of the impedance tube technique. Comparison of these plots with corresponding plots[19] obtained in tests with nonaluminized propellants shows that the presence of high gas-phase damping in the case of aluminized propellants results in higher amplitudes at the minima points and phase-space curves having positive slopes throughout. In contrast, the phase-space curves obtained in tests conducted with nonaluminized propellants have negative slopes along a portion or throughout the measured impedance tube standing wave.

A comparison of acoustic pressure data (amplitude and phase) measured in tests conducted with aluminized propellants with corresponding data obtained in tests with nonaluminized propellants[19] shows that the presence of high gas-phase damping in the case of aluminized propellants resulted in higher amplitudes at the minima points of the standing wave. This resulted in the improvement of the accuracy of both the measured data and the propellant properties determined in tests conducted with aluminized propellants. This is due to the fact that the accuracy of the results obtained by the impedance tube technique are strongly dependent upon the accuracy of the acoustic pressure measurements near the standing wave minima points.[20] Furthermore, the standing wave measured in tests conducted with aluminized propellants was considerably more stable than the standing wave measured in tests with nonaluminized propellants; a fact that further simplified the data acquisition and reduction procedures in the investigation of the driving and damping characteristics of aluminized propellants.

In addition to the excellent agreement that had been demonstrated between the theoretically predicted and experimentally measured acoustic pressure wave structures, the capability of the impedance tube technique to predict simultaneously the axial distribution of the acoustic velocity (amplitude and phase), density (amplitude and phase), and entropy (amplitude and phase) is demonstrated in Figs. 8-10, respectively. These results were obtained by numerically solving the impedance tube wave equations[20] utilizing the real and imaginary parts of the burning surface admittance (as boundary conditions) and the bulk loss coefficient that yielded the best agreement between the predicted and measured instantaneous acoustic pressure amplitude and phase distributions in the tube.

Typical time variations of the real and imaginary parts of the admittance Y and the bulk loss coefficient G, obtained in a test conducted with UTP-3001 aluminized propellant at 2.07 MPa (300 psig) chamber pressure, are presented in Fig. 11 where different record points correspond to different times. This figure demonstrates the ability of the impedance tube technique to measure simultaneously the time variation of the acoustic energy gains and losses inside the tube during the quasisteady burn period of a test. It is noted that for this test the real and imaginary parts of the admittance as well as the bulk loss parameter G vary little with time. Thus, one may conclude that the driving of the gas-phase oscillations by the combustion processes and the acoustic energy losses inside the tube remain unchanged during the quasisteady burn period of a test. In contrast, it has been previously shown[19] that in tests conducted with nonaluminized propellants (i.e., A-13 and A-14) the admittance varied little with time while the bulk loss parameter G varied significantly with time. In this connection, it should be pointed out that the average value of the bulk loss parameter G (averaged over the quasisteady burn period) measured in an experiment conducted with a nonaluminized A-14 propellant at the frequency of 675 Hz is $G=0.332$ kg/m^3 s (12×10^{-6} lbm/in.^{3} s) while the corresponding value of G measured in an experiment conducted with UTP-3001 aluminized propellant at the frequency of 725 Hz is $G=1.937$ kg/m^3 s (70×10^{-6} lbm/in.^{3} s). This drastic increase in gas-phase damping undoubtedly is caused by the presence of aluminum oxide particles in the gas phase in tests conducted with aluminized propellants.

Figures 12 and 13 describe the frequency dependence of the real part of the admittance Y_R and the bulk loss parameter G obtained in experiments conducted with UTP-3001 and UTP-19360 aluminized propellants. The Y_R curves indicate that this quantity peaks at around 600 Hz and then peaks again at

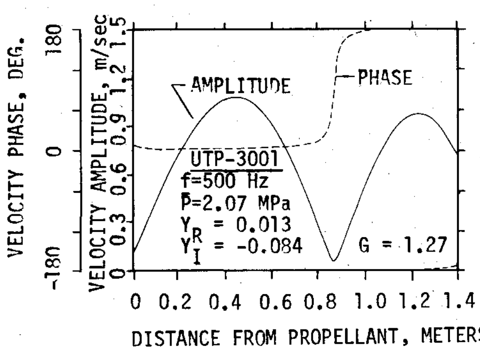

Fig. 8 Predicted axial variations of the velocity amplitude and phase in the impedance tube.

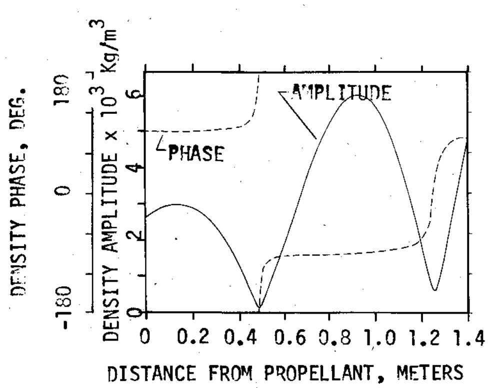

Fig. 9 Predicted axial variation of the density amplitude and phase in the impedance tube.

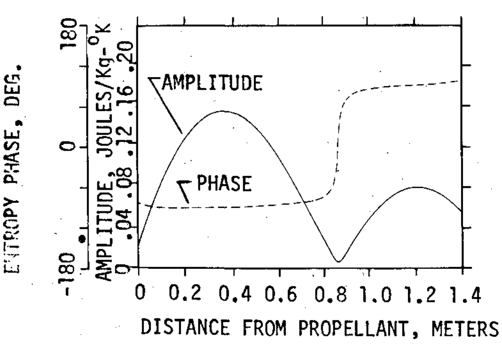

Fig. 10 Axial variation of entropy amplitude and phase.

a frequency higher than 1100 Hz for the UTP-3001 propellant, while the Y_R curve for the UTP-19360 propellant indicates that this quantity varies little with frequency over the frequency range of 400-700 Hz and that a peak exists at a frequency higher than 1100 Hz. The bulk loss parameter G curves indicate that this quantity increases monotonically with frequency for the two aluminized propellants tested. In this connection, it should be pointed out that the bulk loss coefficient G was a priori assumed to be a real number. Thus, the gas phase losses, which are expressed as Gu', are in phase with the velocity perturbation and 90 deg out of phase with the pressure perturbation.

The measured values of the real part of the admittance Y_R for both aluminized propellants indicate that acoustic energy is added to the gas-phase oscillations upon interaction with the combustion processes at the propellant surface, a phenomenon defined previously as driving by the solid propellant. These results have been confirmed by other experimental techniques.[16,17] Thus, it can be concluded that acoustic energy lost in the gas phase due to the presence of aluminum oxide particles is the process controlling the stability of metallized solid rockets.

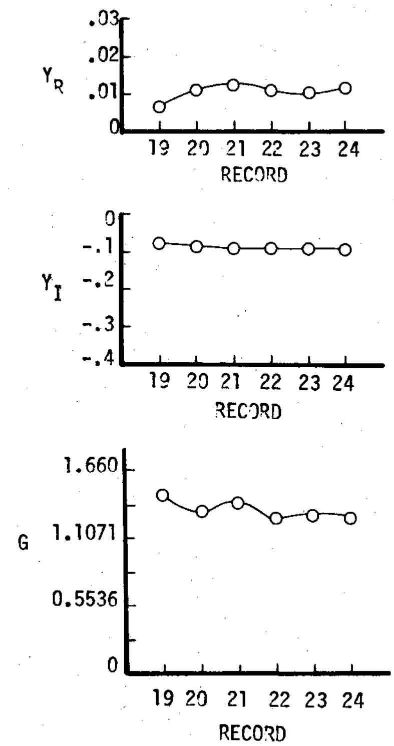

Fig. 11 Typical data measured during a run with UTP-3001 propellant; $f = 500$ Hz, $\bar{P} = 2.07$ MPa.

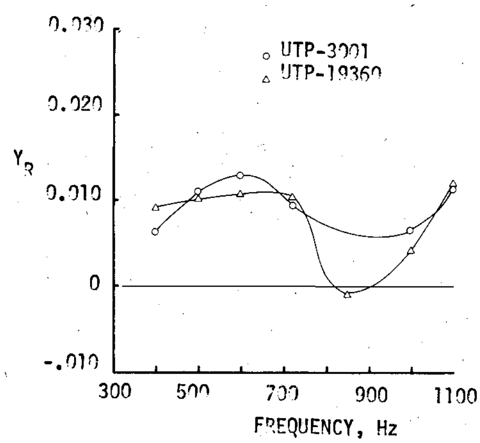

Fig. 12 Frequency dependence of the real part of the admittances of the tested aluminized propellants.

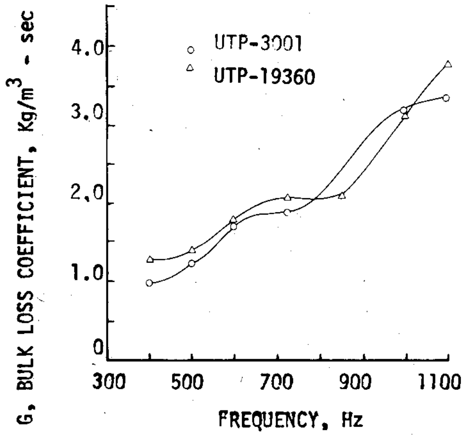

Fig. 13 Frequency dependence of the bulk loss coefficients of the tested aluminized propellants.

Conclusions

The applicability of the impedance tube technique for the measurement of the admittances and response functions of aluminized solid propellants was investigated in this research program. Reproducibility of the measured quantities has been demonstrated as well as the capability of this experimental technique to measure gas-phase losses in the impedance tube simultaneously with the measurement of the burning solid propellant surface admittance. High levels of damping were measured in tests conducted with aluminized propellants. The high level of damping that acts to suppress any instability excited in the gas phase, results in admittance and bulk loss coefficient G values that vary little with time during the quasisteady burn period. It has been shown that the real part of the admittance Y_R obtained in tests conducted with aluminized propellants has a positive value, indicating that the burning solid propellant is driving the gas-phase oscillations. Thus, it has been concluded that the high gas-phase damping is responsible for the stability of metallized solid rockets.

The capability of the impedance tube technique to determine simultaneously the axial distribution of the acoustic pressure, velocity, entropy, and density has been demonstrated. Finally, it has been shown that the high gas-phase damping results in higher amplitudes at the minimum points of the standing wave compared to tests conducted with nonaluminized propellants. This, in turn, results in improved accuracy of both the measured experimental data and the determined propellant properties. The improved accuracy achieved in the determination of the propellant properties and the excellent agreement that has been demonstrated between the predicted (based upon the determined values of the propellant admittance and the parameters G and C[20]) and measured impedance tube wave structures, demonstrate the suitability of the impedance tube technique for the measurement of the admittances and response functions of aluminized solid propellants.

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