AIAA 81-4177

Direct Measurements of Acoustic Admittance Using Laser Doppler Velocimetry

L. H. Caveny,* K. L. Collins,† and S. W. Cheng‡
Princeton University, Princeton, N. J.

Research was directed at making measurements of oscillatory velocities in propane/air and solid propellant flames using laser Doppler velocimetry (LDV) instrumentation. Combustors were developed to impose controlled periodic pressure disturbances on burning solid propellants and to excite a propane/air flame. A tracking system was developed to maintain the LDV control volume at a fixed position above the regressing propellant surface so that a large number (over 10,000) of velocity realizations could be recorded. The research demonstrated that unsteady velocities (up to 1000 Hz) could be measured for propane/air flames seeded with micron-sized particles and for solid propellant flames. The simultaneous velocity and pressure measurements were used to obtain acoustic admittances over a range of excitation frequencies, amplitudes, and pressures.

Introduction

FOR more than two decades research efforts have been directed at developing techniques for predicting and understanding the dynamic responses of solid propellants to periodic pressure and velocity oscillations. Since the burning solid propellant is the source of the acoustic energy that drives combustion instabilities in rocket motors, interpretation of dynamic burning responses is often the key to alleviating developmental problems. While results based on experimental measurements of transient combustion phenomena are being applied in developmental programs,[1,2] major improvements in the experimental methodologies are needed. Small differences in propellant composition can produce acoustic responses which trigger the onset of combustion instabilities. A continuing goal is to be able to measure the differences in the dynamic responses of similar propellants. Accordingly, the thrust of this research effort is direct measurements of unsteady flame velocities (i.e., the velocities of the gases above the burning surface) under pressure-coupling conditions using laser-Doppler velocimetry (LDV) instrumentation and data analysis methodology. The resulting unsteady velocities can be related to the phase and amplitude of the imposed pressure to obtain acoustic admittance. Figure 1 presents an overview of the research approach.

This paper reports on two experiments which were devised to evaluate the feasibility of making direct measurements of acoustic admittance. The primary apparatus is centered around a combustor for imposing periodic pressures on solid propellant strands (see Figs. 2 and 3). The other apparatus is an acoustically excited propane/air flame (see Fig. 4). The gas flame apparatus was devised to gain experience with the data acquisition and analysis techniques.

The measurement of velocities in nonsteady propellant flames in the presence of periodic pressure variations requires a nondisturbing technique in order that interference effects between the probe and flame zone may be avoided. LDV is a truly nonintrusive flow-measuring technique which presents very useful features, i.e.:

1) Since LDV is optically based, it can reach regions of a flame which are so hostile as to destroy a mechanical support or probe.

2) LDV can, by means of frequency shifting, resolve directional ambiguities in the flow.

3) The frequency measurement provided by the technique is linearly related to the flow velocity and requires no preliminary equipment calibration (except for the electronic instrumentation).

4) Errors associated with the LDV techniques, when they arise, are generally quantifiable.

A fundamental instability parameter of a solid propellant is the complex acoustic admittance of the burning propellant. For pressure coupling, this is defined as the ratio of the complex flame velocity amplitude (normal to the burning propellant surface) to the complex pressure amplitude $A = v'/p'$ and when normalized by mean values $A = (v'/\bar{v})/(p'/\bar{p})$ where v is gas velocity (m/s) in the flame zone and p is chamber pressure (N/m^2 or Pa) in the vicinity of the flame. Both v' and p' are complex, unsteady components. The bar denotes a temporal mean. In the figures that follow, phase angles (deg) are referenced to pressure. If velocity response leads imposed pressure, phase angle is greater than zero.

will greatly improve, maybe even revolutionize, the methods of evaluating propellant response functions. Presently, nearly all propellant response function information is deduced from T-burner measurements. The limitations and complexities of T-burner data analysis are well known. Improvements in burning rate response measurement techniques are needed for research purposes as well as for propellant and motor development programs. The status of the techniques are reviewed in Refs. 1 and 2.

An important class of LDV techniques is based on the measurement of Doppler-shifted highly coherent radiation scattered by small ($\sim 1\mu$m) particles when they penetrate the measuring volume produced by the intersection (referred to as the control volume) of two focused laser beams from a common source. In a velocimeter, the optical signal is transformed by a light-sensitive device such as a photomultiplier tube into an electrical analog signal which is decoded electronically. The basic concepts of LDV systems were described in several recent review articles (e.g., Refs. 3 and 4). Depending on the flow and application, the type of electronic instrumentation can vary. In the present research, a counter-type signal processor is used.

The number of data points required to make a single measurement of velocity depends on the nature of the flow. In

Received May 6, 1980; revision received Feb. 6, 1981.

*Senior Member of Professional Staff, Mechanical and Aerospace Engineering Department; presently with AFOSR/NA, Bolling AFB, Washington, D. C.. Associate Fellow AIAA.

†Undergraduate Student, Mechanical and Aerospace Engineering Department.

‡Research Assistant, Mechanical and Aerospace Engineering Department.

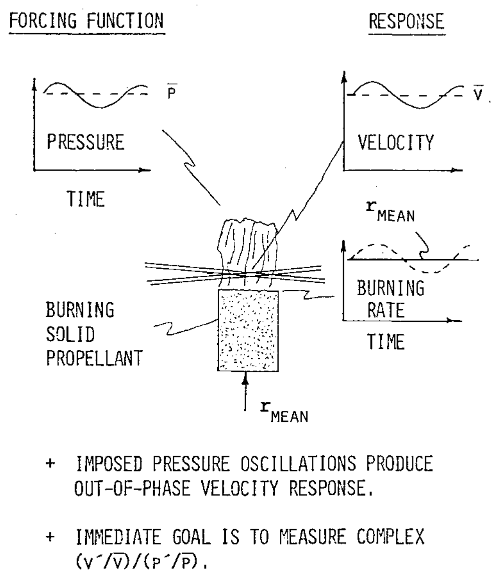

Fig. 1 Direct measurement of unsteady solid propellant flame velocities for the purpose of determining acoustic admittance.

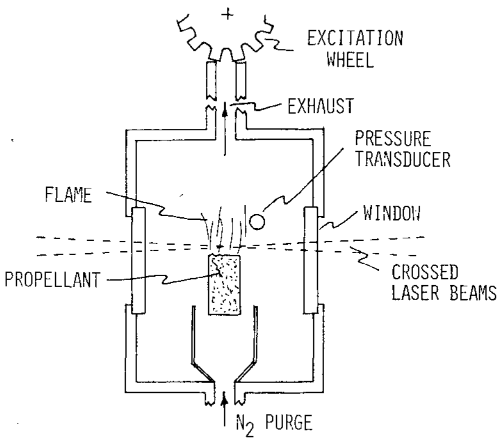

Fig. 2 Combustor for imposing periodic pressure excitations on burning solid propellants.

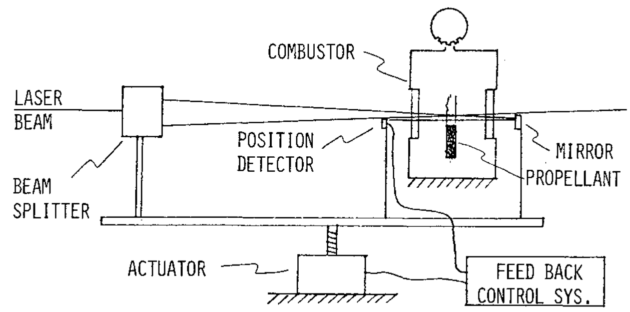

Fig. 3 Optical system for maintaining the optical control volume a prescribed distance from the propellant surface.

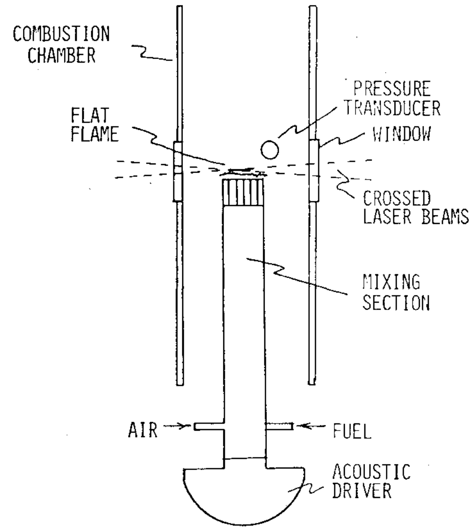

Fig. 4 Diagram of apparatus for measuring velocities in fuel/air flames subjected to acoustic excitation.

this research, 8000-12,000 individual realizations of velocity (taken over hundreds of periods during a single burn) were used. Each one of these realizations was measured by a counter, related to a phase angle, and stored until a statistical treatment of the sample could be performed. The process must be repeated a number of times to determine the variation of the velocities.

To satisfy the requirements of the LDV sensing system, the gaseous flames were seeded with entrained micrometer-size alumina or NaCl particles (formed by atomized saline solutions). Experiments revealed that the micrometer size particles that occur normally in certain solid propellant flames are adequate. Also, infrequent large particles (or agglomerates) produced by the combustion process presented no problems since the processor was set so as not to validate the data produced by large particles obscuring the control volume.

Data Acquisition and Processing System

The Hewlett-Packard 21MXE-based digital data system used in this research is capable of both data acquisition, data processing, and graphics. A Series 900 laser-Doppler velocimeter was assembled from Thermo Systems Inc. (TSI) components and used in the forward scatter mode. It consisted of a 15 mW He-Ne Spectra-Physics laser (wavelength of 633 nm), a beam splitter and focusing lens, collecting lenses, and photomultiplier tube with power supply. Frequency shifting of the Doppler signal (required when there is either a wide range of velocities or directional ambiguity in the measurements) was obtained by the inclusion of a TSI (Model 980) Bragg Cell frequency shifter (with electronic down-mixing) between the beam splitter and focusing lens. The complete optical system was mounted and aligned on a 2-m-long beam which in turn was placed on a positioning table with *x*, *y*, and *z* traversing directions (allowing movement to within 0.02 mm). The system includes a Scimetrics (Model 800 A) counter, a Tektronix (Model 7603) oscilloscope, and a custom designed multiplexer and clock.

The Doppler signal from the photomultiplier tube is the input to the Scimetrics counter. The counter high-pass filters the signal (thus eliminating the pedestal component) and amplifies the resulting waveform. The filtered and amplified signal is the input to the oscilloscope. When a preset threshold level on the oscilloscope is surpassed by a Doppler burst, a gate pulse is sent by the oscilloscope to the counter. The counter then proceeds to measure first 5 and then 8 cycles of the burst and compares the results. If these differ by less than a preset amount, the second count is validated and displayed until a new validated count appears. Front panel controls on the counter include a variable threshold level setting, bandwidth selector, signal amplifier settings, and allowed data (percent) variation settings. Additional line driver and receiver electronics were devised for the laser-Doppler processor (counter) in order to transmit data from the experiment, via cable, to the computer in an adjoining room.

Two types of programming were required to collect data in the HP 21MXE computer, the I/O device driver and the high-level language application routines. The driver is a small dedicated memory-resident subroutine, written in assembly language, which accesses the appropriate interface card and initiates and supervises the direct memory access data transfer into memory. The data collection programs call this driver and receive data from it, which they operate on in accordance with what is necessary for the particular type of experiment being conducted. The first data acquisition program designed for high-speed time dependent experiments, stores raw data directly on disk. In order not to lose data during the time-consuming disk transfers, a double-buffer scheme was included. While one buffer is being filled with data from the driver, the other is being emptied onto the disk. When the first is full, it begins dumping its contents and the empty buffer starts filling. The second data collection routine preprocesses the data before writing it out. After collecting the specified number of channels, it compresses them by calculating the sum and sum of squares of the data. The results are stored on a disk file. For both types of data collection routines, appropriate analysis programs were used to calculate such parameters as mean velocity, skewness, kurtosis, cross- and auto-correlation functions.

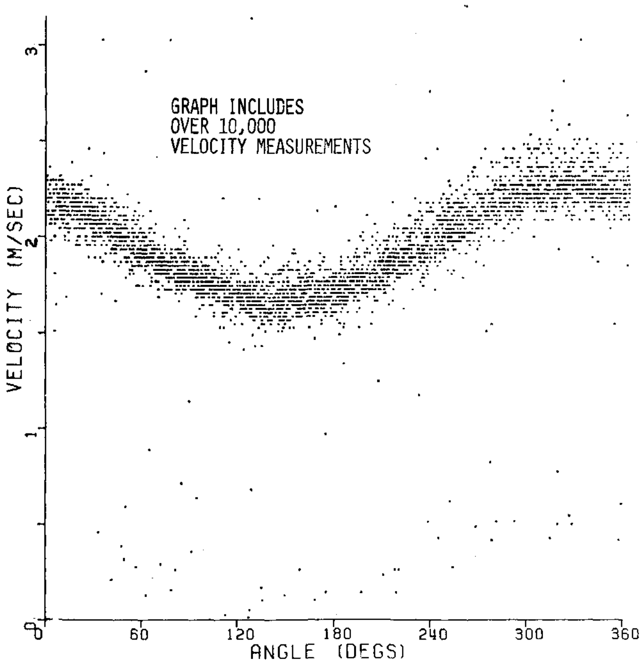

Fig. 5 Individual propane/air flame velocities prior to statistical analysis (flame excited at 450 Hz and peak-to-peak pressure of 189 Pa).

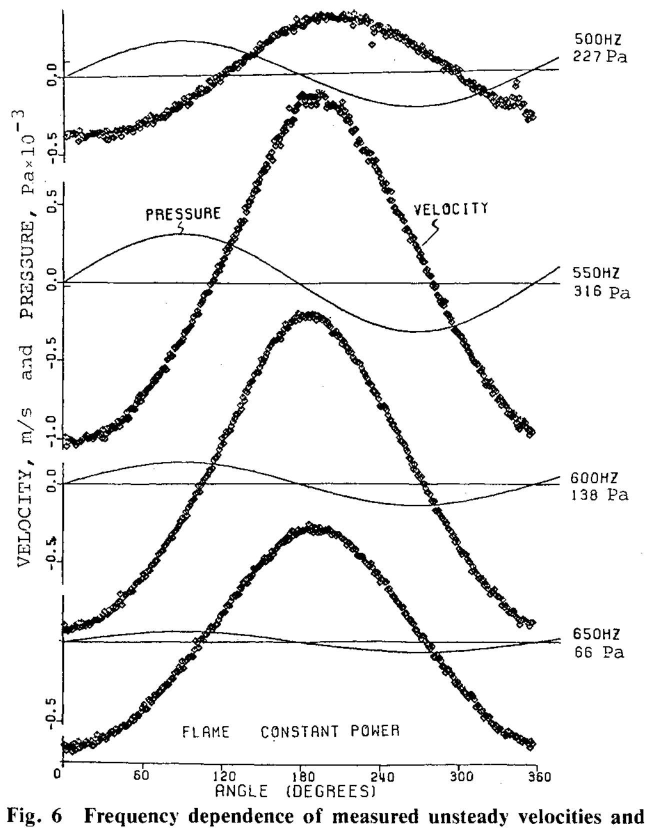

Fig. 6 Frequency dependence of measured unsteady velocities and pressures for burner excited at constant power to the driver.

The phase angle between the imposed pressure signal and each of the observed velocities is established by recording the difference between the zero-crossing time of the unsteady pressure and the time of the velocity realization. The zero-crossing time is the instant that the unsteady pressure equals the mean pressure. The imposed pressures were recorded, referenced to the zero-crossing time, and analyzed to determine the amplitude and phase at the fundamental frequency.

Measured Results

Air Propane Flow

The experiments to check out the procedures were performed using an acoustically excited air/propane flame. The air/propane flames provided well-regulated and continuous sources of data, whereas solid propellant flame must be sampled within a few seconds. The results measured using the Fig. 4 apparatus are overall system responses which include the coupling between the open tube combustion chamber and the air/propane flame. The driving from the flame was not separated from the overall response. The purpose of the apparatus was to provide a simple source for simultaneously measuring pressure and velocity, which are the elements of the eventual acoustic admittance measurements. Thus, the Fig. 4 apparatus was not intended to simulate a particular burner system. To evaluate the data acquisition and analysis system, data were acquired over the following range of conditions:

1) Maintain the imposed power constant and scan the frequencies (250-1000 Hz) for both noncombustion and combustion conditions.

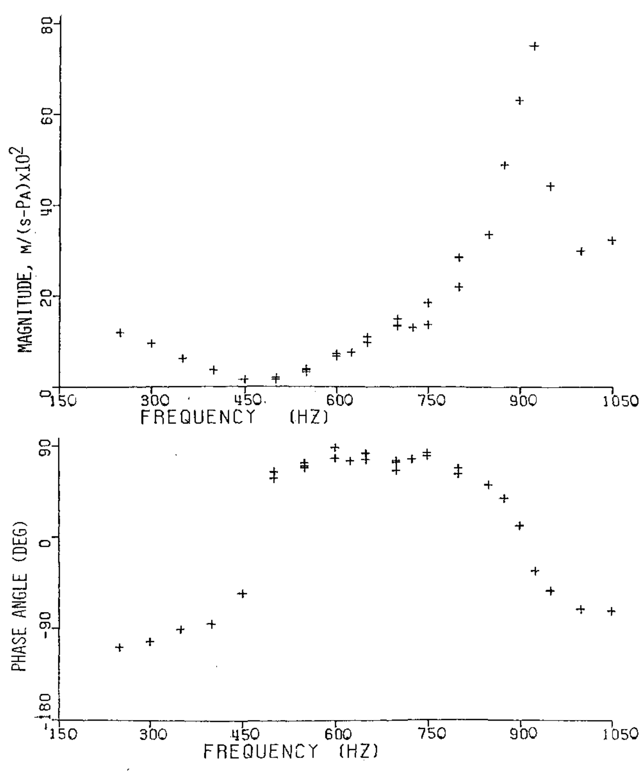

Fig. 7 Measured acoustic admittance magnitudes and phase angles for burner excited at constant power (corresponds to Fig. 6).

2) Maintain the pressure near the flame constant and scan the range of frequencies for both noncombustion and combustion conditions.

3) Maintain the frequency constant and change the pressure amplitude (25-200 N/m^2) for noncombustion at 420 and combustion at 420 and 450 Hz.

The discussions that follow summarize results obtained at several intermediate steps.

Figure 5 is a plot of the raw data for a prescribed driving frequency (450 Hz) and power level. The corresponding peak-to-peak pressure oscillations produced by the excitation was measured to be 189 Pa. The figure displays velocities which have been classified into the 360 bins, i.e., one storage region for each degree. The high density sinusoidal shaped region contains 20 to 30 velocity measurements for each bin. Statistical treatment was applied to the raw velocity data for the purposes of obtaining a single velocity for each bin.

Figure 6 shows mean unsteady velocities and the imposed pressure for a constant power to the driver over a frequency range of 500-950 Hz. The pressure and velocity amplitudes grow between 500 and 550 Hz and then decay gradually between 600 and 950 Hz. Near resonance acoustic admittance is not affected appreciably. A natural frequency of the burner and the tube system occurs near 550 Hz. From the reduced data summarized in Fig. 6, phase angles and amplitude were calculated (see Fig. 7). For the in-phase condition, minimum velocity of the fuel/air burner corresponds to maximum pressure. Thus, the phase angle is the angle between the maximum pressure and the minimum velocity. The magnitude is the ratio of the maximum values of v' and p'. The shifts in the vicinity of 500 and 900 Hz are primarily characteristics of the burner and tube system and should not be considered as uncoupled responses of the flame. Indeed, experiments with nonburning jets revealed similar responses. The first shift in phase angle is associated with the maximum pressure and the second shift in phase is a result of the velocity decreasing. An experiment was conducted by adjusting the power to the driver so that the measured pressure amplitude was always 10 Pa. As shown in Fig. 8, the trends are similar to those of Fig. 7. However, when the experiment was repeated at constant amplitude of 25 Pa, above 750 Hz, higher harmonics developed rapidly and begin to dominate. As the frequency was increased, the power required to maintain 25 Pa increased and nonlinear responses became evident.

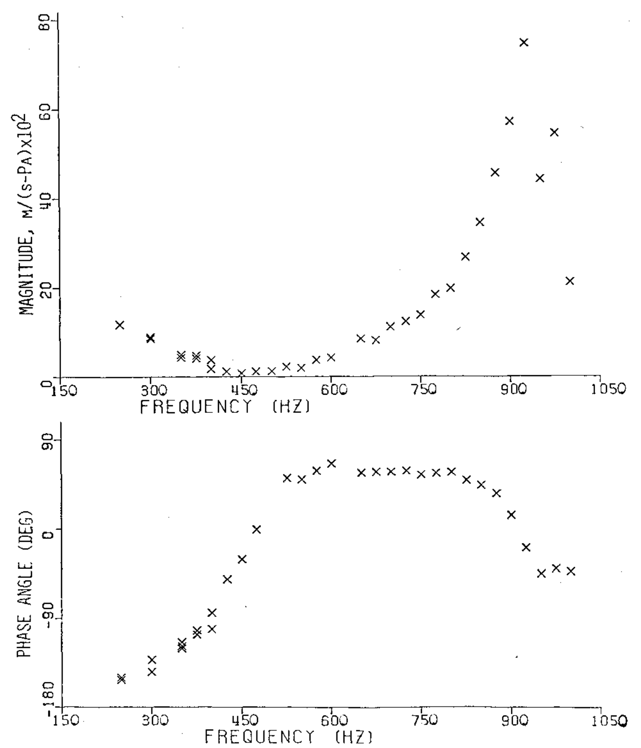

Fig. 8 Measured acoustic admittance magnitudes and phase angles for burner excited so that pressure amplitude is maintained at 10 Pa.

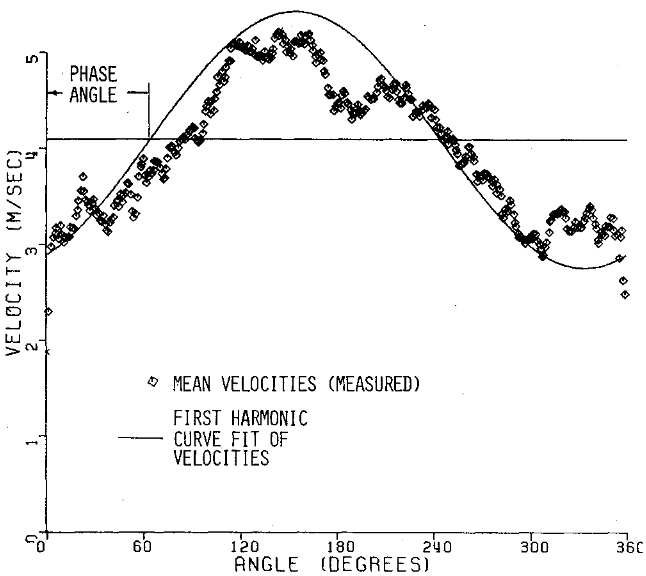

Fig. 9 Measured velocities for M26 double base propellant burning at 0.59 MPa.

Solid Propellant

During this part of the research, attention was directed at measuring unsteady velocities corresponding to an idealized pressure-coupling of burning propellants. To achieve this objective several items were important in the design of the combustor, i.e., 1) the imposed pressure nearly sinusoidal; 2) the frequency controllable; 3) the LDV control volume at a constant position above the burning surface; and 4) the windows and optical path not obscured. As indicated in Fig. 2, the mean pressure in the combustor was maintained by regulating the flow of N_2 into the base. The N_2 flow also served to purge the combustion products from window and optical paths. The precision machined, slotted wheel rotating above the vent orifice produced the periodic pressure excitation. The combustor functioned as an externally executed Helmholtz resonator, i.e., increasing the length of the vent stack decreased the characteristic frequency in the combustor. The speed of the excitation wheel was selected so as to excite the characteristic frequency of the combustor.

The combustor pressure was measured using a closely coupled, piezoelectric pressure transducer located about 1.2 cm from the optical control volume. Real time digital circuitry established the zero-crossing time for each period and thus provided the time base for the recorded phase angle between the measured velocity and imposed pressure. The data collection interval was between 3 and 5 s.

In order to maintain the LDV control volume at a prescribed position above the burning surface (about 4 ± 1 mm), the entire beam containing the LDV optics was lowered at the same rate as the propellant burning rate. The feedback control on the rate was achieved by sensing the degree to which one of the reflected laser beams interfered with the burning surface. The drive and control system is a digital version of the approach described in Ref. 5. Recording the retraction rate provides a measure of the mean burning rate of the propellant. Maintaining the relative position of the control volume is essential for success, since it permits a statistically significant data sample to be collected.

Two propellants were used, a nitrocellulose/nitroglycerin composition [M26] and a composite propellant [86.5% AP (20% 45 μm, 20% 180 μm, 60% 400 μm) and 13.5% HTPB]. Several other propellants were tried but they either did not produce well-defined optical signals or they burned with an ash that interfered with the optical path. The former situation

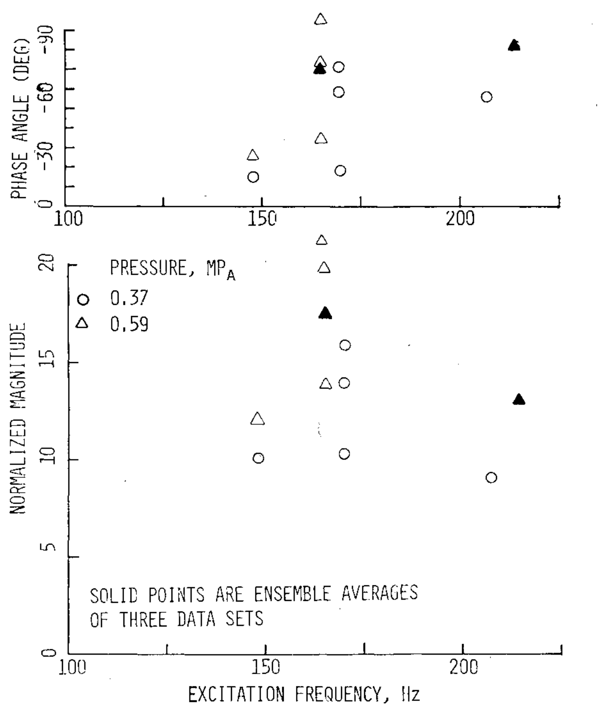

Fig. 10 Measured acoustic admittance magnitudes and phase angles for M26 double base propellant.

can probably be overcome with more advanced optical systems. The later problem is not likely to occur when higher energy propellants are used. The width of the strands was 3 mm and a light coat of silicon grease was used to prevent burning down the side.

The solid propellant data were taken and analyzed at a time coinciding with the departure of the senior author and immediately prior to dismantling of the laboratory. Accordingly, emphasis was placed on evaluating the feasibility of the approach rather than taking large amounts of systematic data.

Figure 9 illustrates data from a successful M26 test. The data were taken for the frequency range 145 to 230 Hz, which produced strong responses. The data are approximately represented by sine wave, but they also have an appreciably higher harmonic content. The imposed pressure oscillation had 99% of its power at the fundamental frequency. The higher harmonic velocity response was observed repeatedly and is believed to be an actual response of the propellant. In all cases, the data scatter was much greater for propellant flames than for the air/propane flame. Clearly defined velocity responses were obtained using relatively small pressure amplitudes ($p'/\bar{p}<0.03$). The resulting variations in flame velocities were large ($v'/\bar{v}>0.2$) and outside the linear range. Figure 10 summarizes the acoustic admittance and phase angles at three frequencies. Several of the data points are the result of ensemble averages of three separate data sets. The data analysis technique suppressed effects of the higher frequency content by a numerical low pass filter. Spectral analysis to interpret higher harmonic content of velocity was not completed in time for this paper.

The test-to-test variation is to a large extent a direct result of data being taken in a region of very high response. However, improvements in the velocity measuring techniques will certainly reduce the variations. The ±1 mm error in locating the control volume above the burning surface is responsible for some to the variation. Another source of error is velocity data taken before the tracking system locks on and after the strand burns out of the range of the tracking system. The latter problem can be overcome by rejecting data during periods of large tracking system errors.

Other investigators have considered LDV measurements of solid propellant flames. Abbott completed a research program (Ref. 6) to measure solid propellant flame velocities and admittance. He attempted to acquire sufficient data as the propellant burned by the fixed LDV control volume. Thus, Abbott was limited to relatively few velocities in the region of interest. He concluded that velocity measurements can be made but had no success in achieving accurate admittance measurements. He attributed his problems to excessive data scatter and cited a variety of reasons for the scatter. From what we could determine the difficulties experienced by Abbott were overcome by our apparatus and data analysis methodology. In particular, after learning of the approach described in this paper, one of Abbott's co-workers[7] concluded that maintaining the LDV control volume fixed relative to the propellant surface was the important innovation. Cogh and DeLuca[8] are engaged in a research program to measure velocities in solid propellant flames under constant pressure conditions; they have not yet reported systematic velocity data.

Conclusion and Recommendations

The results summarized in this paper are a proof-of-principle that direct measurements of acoustic admittance can be made. Additional efforts to refine the data acquisition techniques should markedly improve the uniformity of the velocity data. The techniques can be broadened to include a wider variety of combustion conditions.

With respect to solid propellants, the important payoff will be achieved once this approach yields acoustic admittances for a set of candidate propellants, all of which meet the performance requirements for a particular propulsion system. Furthermore, those acoustic admittances must reveal any statistically significant propellant-to-propellant differences.

Knowledge and measurements of acoustic admittances are equally important in other applications. For example, the analyses of furnace roar and instabilities require accurate information on the driving energies provided by flames. Also, the optimization of burners can be performed more effectively if the combustion chambers are tuned to account for the various acoustical interactions.

Acknowledgment

This research was sponsored by the Power Branch of the Office of Naval Research and supplemented by the Army Ballistic Research Laboratory. The initial phase of setting up the data acquisition system benefited from a collaboration with J. A. C. Humphrey, now at the University of California, Berkeley, Calif.

References

[1] Brown, R. S., Culick, F. E. C., and Zinn, B. T., "Experimental Methods for Combustion Admittance Measurements," *Progress in Astronautics and Aeronautics: Experimental Diagnostics in Combustion of Solids,* Vol. 63, edited by T. L. Boggs and B. T. Zinn, AIAA, New York, 1978, pp. 191-200.

[2] Levine, J. N. and Andrepont, W. C., "Measurement Methods of Transient Combustion Response Characteristics of Solid Propellants - An Assessment," AIAA Paper 79-1209, June 1979.

[3] Stevenson, W. H., "Principles of Laser Velocimetry," *Progress in Astronautics and Aeronautics: Experimental Diagnostics in Gas Phase Combustion Systems,* Vol. 53, edited by B. T. Zinn, AIAA, New York, 1976, pp. 307-336.

[4] Mayo, W. T. and Smart, A. E. (Editors), "Photon Correlation Techniques in Fluid Mechanics," *Proceedings from the 4th International Conference of the Joint Institute for Aeronautics and Acoustics,* Stanford, Calif., 1980.

[5] Derr, R. L. and Osborn, J. R., "An Experimental Investigation of the Gaseous Phase Reaction Zone in a Composite Solid Propellant," TM-67-6, Jet Propulsion Center, Purdue University, Lafayette, Ind., Sept. 1967.

[6] Abbott, D. J. "Measurement of the Acoustic Admittance of Solid Rocket Propellants by a Laser Technique," Rept. HIC 304, University of Sheffield, Sheffield, England, July 1978.

[7] Swithenbank, J., Personnal communication, Jan. 1980.

[8] Coghe, A., DeLuca, L., Sensalari, G. L., and Volpi, A., "Gas Phase Velocity Measurements in Solid Rocket Propellants by Laser Doppler Anemometry," Article 31, AGARD Conference Proceedings No. 259, Solid Rocket Motor Technology, July 1979.