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# SOLID PROPELLANT COMBUSTION MECHANISM RESEARCH

## 1978-1979 ANNUAL REPORT TO THE OFFICE OF NAVAL RESEARCH

Prepared by

L. H. Caveny, W. A. Sirignano, and
S. W. Cheng

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Princeton, New Jersey 08544

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research is directed at making direct measurements of the acoustic admittance of flames and interpreting those measurements in terms of flame models. Laser Doppler velocimetry (LDV) instrumentation, pressure detectors, and data analysis techniques were set up and used successfully to measure the acoustic response of a propane/air burner system. Applications of the techniques to solid propellants are described and are the subjects of the continuing research.

## PREFACE

This research was carried out under Contract N00014-75-C-0705 from the Power Branch, Office of Naval Research. Dr. Richard S. Miller, of the Power Branch, is the Project Monitor. The U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, provided partial support for this research. Mr. C. W. Nelson is providing technical liaison with the Army.

The text of this report summarizes work that is in progress; by the end of 1979, more complete reports and papers will be available.

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## INTRODUCTION AND TECHNICAL OBJECTIVES

Research is being performed on steady and unsteady combustion and reacting flow processes. The analytical and experimental approaches are motivated by broad scientific objectives. The immediate applications of the research are to new developments in propellant solid rocketry.

Investigations of items such as flame responses, high speed reacting flows, unsteady chamber flows, chemical kinetics, and mechanistic chemical interactions are conducted largely independently of each other. A continuing requirements exists for the investigators working in the various disciplines to interact and to give more attention to applying the results of research evolving from their areas of specialization. The physical measurements and mathematical models which are being developed and refined as part of this study are providing many opportunities to use data and theories of other investigators. This is accomplished as data are acquired for use in the models and incorporated into the models. Also, chemical mechanisms proposed by others are being evaluated by using the mathematical models in attempts to interpret observed phenomena. During the reporting period, attention was directed at three research topics: 1) Monopropellant flames (i.e., HMX, RDX, TATB, and NGU)*, 2) Nonsteady reacting flows in solid rocket motor chambers;* 3) Direct measurements of nonsteady flames by LDV.

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* BenReuven, M., Caveny, L. H., Vichnevetsky, R., and Summerfield, M., "Reacting Gas Flows in Unsteady Rocket Chambers and in Monopropellant Flames," MAE Report, July 1979.

Topics 1 and 2 have progressed to the point that a comprehensive technical report (1) will be released in July 1979. Accordingly, topics 1 and 2 will not be treated in this progress report. During the last year, topic 3 was undertaken as an exploratory research item since its success depended on the development of an ambitious laser Doppler velocimetry (LDV) instrumentation and data analysis techniques. The initial success in making direct measurements of flame velocities in oscillating pressure fields exceeded our expectatons. We believe that the techniques that have been developed will permit rapid progress during the next year.

During the forthcoming year, the major emphasis is on research associated with direct measurements of velocities and acoustic admittances of flames and the interpretation of those measurements in terms of flame measurements. Since the approach and initial results have not been described elsewhere, they will be summarized in this progress report.

# DIRECT MEASUREMENTS OF NONSTEADY FLAME RESPONSES USING LASER DOPPLER VELOCIMETRY

## Motivation and Background for Research

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 energies that drive combustion instabilities in rocket motors, interpretation of dynamic burning responses is often the key to solving developmental problems. While the research results on transient combustion phenomena are being applied to developmental programs, they have not been successful in predicting whether small differences in propellant composition can result in the onset of combustion instabilities which often lead to propulsion system failures. The thrust of this portion of the research effort is direct measurements of acoustic admittance under pressure-coupling conditions using recently developed laser-Doppler velocimetry (LDV) instrumentation and data reduction and analysis methodology. Subsequent research will investigate direct measurements of acoustic admittances under velocity coupled conditions. Figure 1 presents an overview of the research on non-steady flame responses. The concepts indicated in Fig. 1 will be developed more completely in the sections that follow. The measurement of nonsteady propellant flames in the presence of periodic pressure variations requires a non-disturbing technique in order that interference effects between the probe and flame zone may be avoided. LDV is a truly non-intrusive flow-measuring technique which presents four other very useful features:

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

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

iii) 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).

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

The second feature is important in the consideration of velocity coupling effects.

The fundamental instability parameter of a solid propellant is the complex dimensionless acoustic admittance of the burning propellant. For pressure coupling, this is defined as the normalized ratio of the complex flame velocity amplitude (normal to the burning propellant surface) to the complex pressure amplitude

$$A = (dv/v)/(dp/p)$$

where v is gas velocity in the flame zone and p is chamber pressure in the vicinity of the flame. Both dv and dp are complex. The bar denotes a temporal mean. In the figures that follow, the results are presented using the following definitions:

i) Phase angle (in degrees) are referenced to pressure: If dv leads dp, phase angle greater than zero (which is inductance type). If dv lags dp, phase angle less than zero (which is capacitance type).

ii) The real part of the acoustic admittance is (dv/v)/(dp/p) cos(phase angle)

Direct measurements of acoustic admittance, if successful, will revolutionize the methods of evaluating propellant response functions. Until now, nearly all propellant response function information was 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. More recently, measure pressure coupled response functions are being obtained using rotating- valve methods (Ref. 1).

The LDV techniques are based on the measurement of Doppler shifted highly coherent radiation scattered by small (approximately one micrometer) particles when they penetrate the measuring volume produced by the intersection 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 analogue signal which is decoded electronically. The basic concepts of the LDV system were described in several recent review articles. 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 our research, it is usually in the range of 4,000 to 8,000 individual realizations of velocity. Each one of these realizations must be measured by a counter and stored temporarily until a statistical treatment of the sample can be performed. The process must be repeated several times to determine the variation in the velocities.

The LDV system provides velocity and concentration profiles of the scattering particles in the flame. The gaseous flames are seeded with particles. Initial tests indicate that the micrometer size particles that occur normally in many solid propellant flames can be used. Initial tests indicate that the micrometer size particles that occur normally in many solid propellant flames can be used. However, if necessary, the propellants will be seeded with high melting point particles (e.g., one micrometer size alumina). For the situations in which the particles are uniformly distributed, particle concentrations can be used to calculate flow densities.

## Data Acquisition and Processing System

The Hewlett-Packard 21 MXE-based digital data system used in this research is capable of both data acquisition and data processing. It is equipped with 96 K of memory, two dual disc drives, a Versatec electrostatic printer/plotter, an operator console and several remote terminals. The HP RTE-IV real-time operating system and the ability to use Direct Memory Access (DMA) methods permit very fast data transfer rates (i.e., one million words/sec).

The Series 900 laser-Doppler velocimeter was assembled from components purchased from Thermo Systems Inc. (TSI) and is shown schematically in Fig. 2 in the forward scatter mode. It consists 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 directional ambiguity in the measurements) can be 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 2m long aluminum beam which in turn was placed on a positioning table with x,y (parallel to the floor) traversing directions. The table and mounting arrangement allows three axes movement to within 0.02 mm. The electronic instrumentation associated with the velocimeter is also shown schematically in Fig. 2. It includes a Scimetrics (Model 300 A) counter, a Tektronix (Model 7603) oscilloscope, and a custom designed multiplexer. The costs associated with purchasing and implementing the equipment were shared with a NASA/Lewis grant to investigate turbulent flows in internal combustion engines.

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 wave form. The filtered and amplified signal is the input to the oscilloscope. When a pre-set threshold level on the oscilloscope is surpassed by a Doppler burst, a gate pulse of +5 volts 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 pre-set 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, band width 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 correctly data from the experiment, via cable, to the computer in an adjoining room. Figure 3 illustrates the interaction of the interface components which were developed during the present study.

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 DMA 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. To date, two such programs have been written. The first, designed for high-speed time dependent experiments, stores raw data directly on disc. In order not to lose data during the time-consuming disc 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 disc. When the first is full, it begins dumping its contents and the empty buffer starts filling. The second data collection routine pre-processes the data before writing it out. Ater 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 disc file. For both types of data collection routines, appropriate analysis programs have been written to calculate such parameters as mean velocity, skewness, kurtosis, cross-and autocorrelation functions.

## Measured Results

The initial experiments are being performed using an acoustically excited air/propane flame. The air/propane flames provide well-regulated and continuous sources of data, whereas the solid propellant flame must be sampled quickly. Direct measurements of response of gaseous fuel flames are of scientific interest and, thus, the experiments should produce data which will be worthy of publication.

The results measured using the Fig. 4 apparatus are overall system responses which include the coupling between the open tube combustion chamber and the flame. The purpose of the apparatus is to provide a simple source for measuring simultaneously pressure and velocity, which are the elements of the eventual acoustic admittance measurements. Of course in the Fig. 4 apparatus, the driving provided by the flame can not be separated from the overall response.

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 to 1000 Hz) for:

A. Noncombustion

B. Combustion

2. Maintain the pressure near the flame constant and scan the range of frequencies for:

A. Noncombustion

B. Combustion

3. Maintain the frequency constant and change the pressure amplitude (25 to 200 N/M2) for:

A. Noncombustion at 420 Hz

B. Combustion at 420 Hz. and 450 Hz.

The discussions that follow are progress reports which summarize the results obtained at several intermediate steps.

The conditions used to obtain the initial data are given in Table 1. The overall configuration of the apparatus is similar to that shown in Figs. 2 and 4, i.e., a tube open at each end which contains a flame excited by a driver upstream of the flame. (The apparatus for flame experiments at elevated pressure, see Fig. 5, is being fabricated and will be used during the continuation effort.) Figure 6 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 n/m . The figure displays velocities which have been classified into the 360 bins. The high density sinusoidal shaped region contains 10 to 20 velocity measurement for each bin. (Normally three to four times that many measurements are taken to improve the accuracy of the averages, but that much data obscures the plot.) Statistical treatment is applied to the raw velocity data for the purposes of obtaining a single velocity for each bin. Figure 7 shows mean unsteady velocities and the imposed pressure for two conditions. The two conditions were selected since they illustrate the transition from phase lag to phase lead as the frequency is increased.

Figure 8 contains results similar to those of Fig. 7, except that they are for a jet of air at 22C rather than a flame. This will be referred to as the noncombustion condition.

Figures 9a and 9b show the details of the measured velocities and pressures for the condition of constant power to the driver over the frequency range of 500 to 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 raw data summarized in Fig. 9, phase angles and acoustics admittances were calculated. 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, subsequent discussions will show how non-burning jets have 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. The experiment was conducted by adjusting the power to the driver so that the measured pressure amplitude was always 25 Pa over the range of excitation frequencies. As shown in Fig. 11, the trends up to 750 Hz are similar to those of Fig. 10. However, 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. Indeed, as either frequency or power is increased beyond a threshold, instabilities accompanied the higher harmonics. Near 770 Hz the input power limit of our present system was reached. To avoid these difficiulties, another series was conducted with the pressure amplitude maintained at 10 Pa. At the lower power level the higher harmonics did not develop and the frequency range was extended to 950 without the nonlinearities occurring. Note that the features of Fig. 12 are very similar to those of Fig. 10.

To determine the effect of combustion on the measured responses, a series of experiments were conducted using an equivalent mass flux of air in place of the combusting premixed propane and air. Figures 13 and 14 summarize the responses. Note that the general trends are similar to those for the combustion case but the corresponding natural frequencies are lower because the gases are not heated. A direct comparison of the non-dimensional acoustic admittances is difficult because the velocity of combustion gases is about seven times higher than the air velocity. However, the dimensional acoustic admittance under combustion conditions is higher than the noncombustion condition by a factor of 1.5.

A series of experiments were performed to determine the range of linear responses as pressure amplitude increases. As shown on

Fig. 15 (for the frequency considered), the noncombustion conditions tended to be linear over the entire range. However, for the combustion condition, nonlinearities were observed and their degree of nonlinearity is frequency dependent.

For the particular burner and tube considered in the evaluation the observations can be summarized as follows:

1. The data demonstrate the feasibility and fidelity of the LDV system for measuring the acoustic admittance and for investigating the instability phenomena.

2. Due to the existence of combustion, the dimensional acoustic admittance is increased by a factor of approximately 1.5 and the corresponding frequency increases.

3. The combustion driving instability tends to occur when the phase angle between the pressure and the velocity is within 90 degrees.

4. The instabilities in the burner are usually copuled with the appearance of higher harmonics in the tube.

## Expected Payoff

The results summarized in the foregoing section are a proof of principle that direct measurements of acoustic admittance can be made. During the next year, the techniques will be broadened to include a wider variety of combustion conditions. Many of the flames and their associated combustors present problems to be overcome, e.g., very high frequency oscillations which are difficult to track, flames containing large particles that obscure the fringe volume, high pressure combustors for which high quality optical paths are difficult to achieve. The solution to some of these problems go beyond our present research but do not contradict the notion that direct measurements can be made.

The research is focused on the immediate payoff of making direct measurements on high energy smokeless propellants. These propellants are of considerable current interest but their application has been accompanied by serious combustion instabilities. Often, combustion instability problems are not identified until full-scale rocket motors are tested. Indeed, the propulsion system developed often is forced to do cut-and-try propellant testing in full-scale motors in order to find a propellant formulation which will be stable. The reasonably complete mathematical models which account for the acoustic energy within a rocket chamber can be used more effectively if measured acoustic admittance values can be used as input.

With respect to solid propellants, the important payoff will be achieved once this research yields acoustic admittances for a set of candidate propellants, all of which meet the performance requirements for a high performance system. Furthermore, those acoustic admittances must reveal statistically significant propellant-to-propellant differences. Hopefully, the results obtained during the next year will be a precursor to achieving that goal.

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

## RECENT PUBLICATIONS UNDER ONR FUNDING

### Manuscript Submission Since Last Renewal Proposal

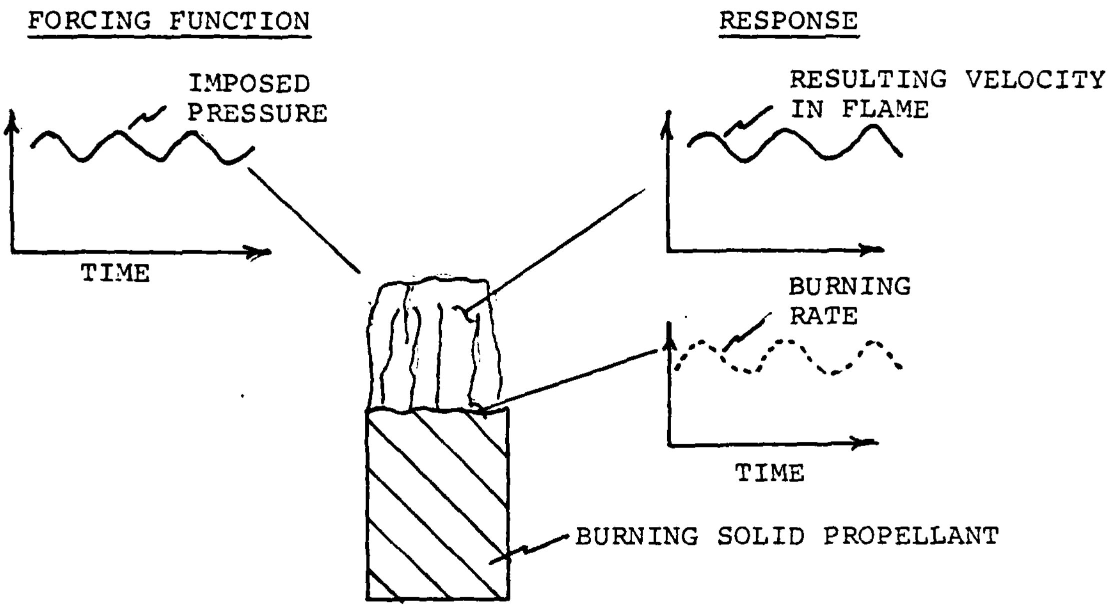
1. BenReuven, M.; Caveny, L. H.; Vichnevetsky, R.; and Summerfield, M.; "Unsteady Reacting Flows in Solid Rocket Chambers," AIAA Propulsion Meeting 1978.
2. Caveny, L. H.; BenReuven, M.; "Nitramine Flame Chemistry and Deflagration Interpreted in Terms of a Flame Model," accepted for presentation at the AIAA Propulsion Conference, June, 1979.
3. Bellan, J. and Summerfield, M., "A Theoretical Study of Droplet Extinction by Depressurization," accepted by Combustion and Flame for publication.

### Publications That Have Appeared During Reporting Period

1. Bellan, J. and Summerfield, M., "Theoretical Examination of Assumptions Commonly Used for the Gas Phase Surrounding a Burning Droplet," Combustion and Flame, Vol. 33, No. 2, 1978, pp. 107-122.

## REFERENCES

1. Brown, R. S., Culick, F. E. C., and Zinn, B. T., "Experimental Methods for Combustion Admittance Measurements," Experimental Diagnostics in Combustion of Solids, Vol. 63, Progress in Astronautics and Aeronautics, 1978 American Institute of Aeronautics and Astronautics, New York, NY.



- o SUBJECTING A FLAME (IN THIS CASE A SOLID PROPELLANT FLAME) TO AN IMPOSED PERIODIC PRESSURE FIELD PRODUCES OUT-OF-PHASE PERIODIC VELOCITY RESPONSES.
- o THE OVERALL OBJECTIVE OF THIS RESEARCH IS TO MEASURE AND UNDERSTAND THOSE RESPONSES.
- o A SPECIFIC GOAL IS TO REPORT THE REAL AND IMAGINARY PART OF THE ACOUSTIC ADMITTANCE,

$$(\Delta v/\bar{v})/(\Delta p/\bar{p})$$

Fig. 1 Overview of nonsteady flame responses

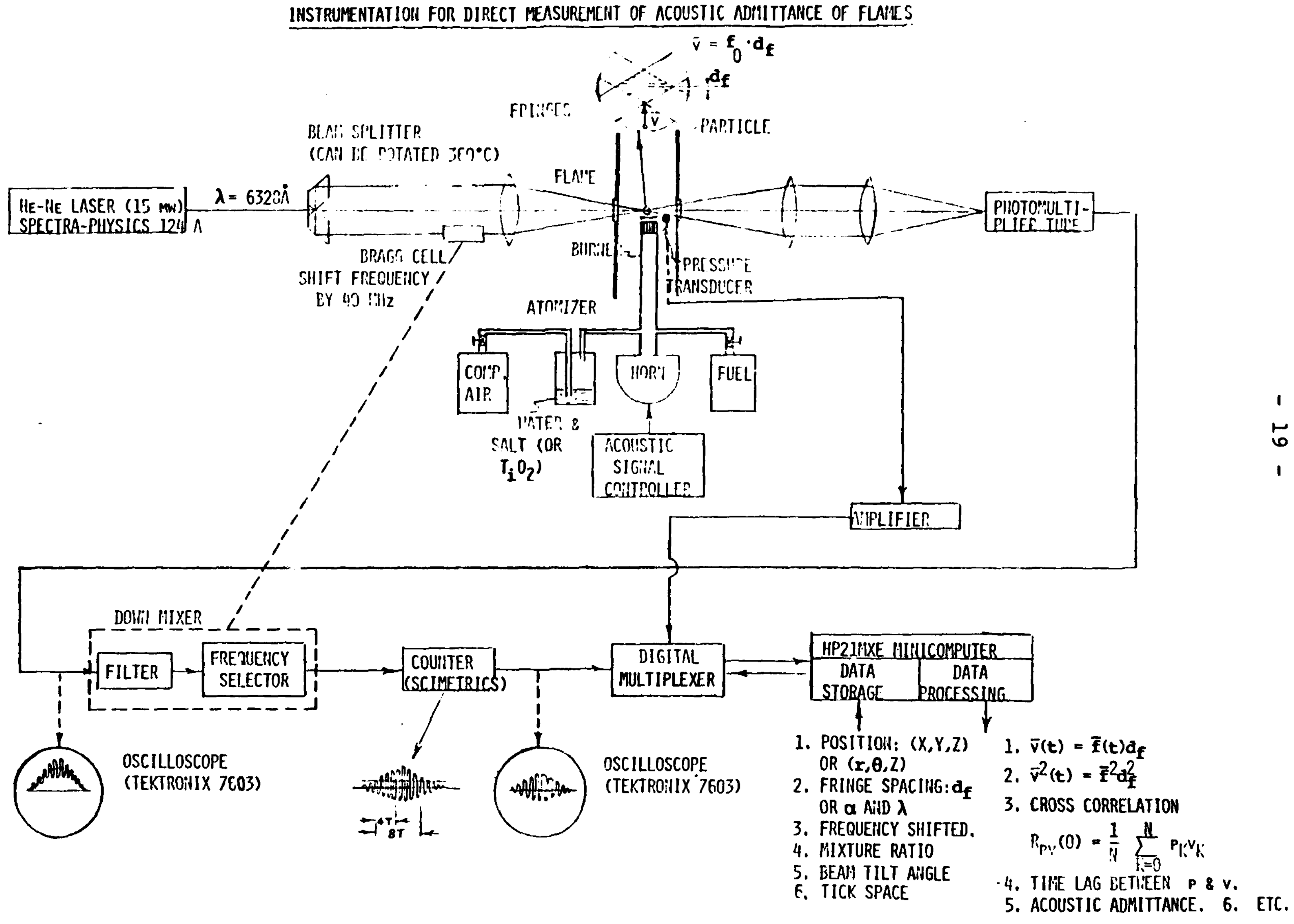


Fig. 2 Instrumentation for direct measurement of acoustic admittance of flames.

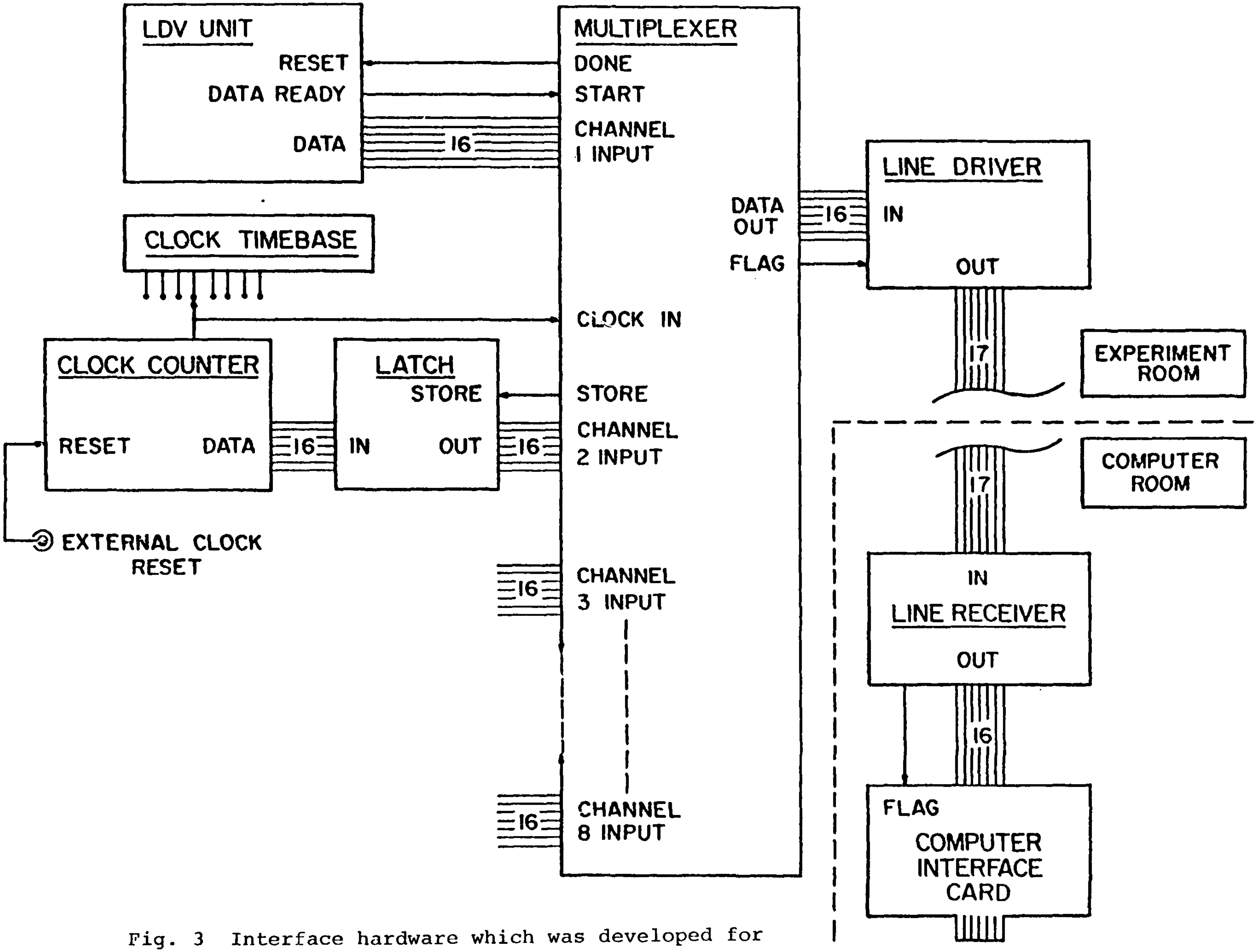


Fig. 3 Interface hardware which was developed for LDV system

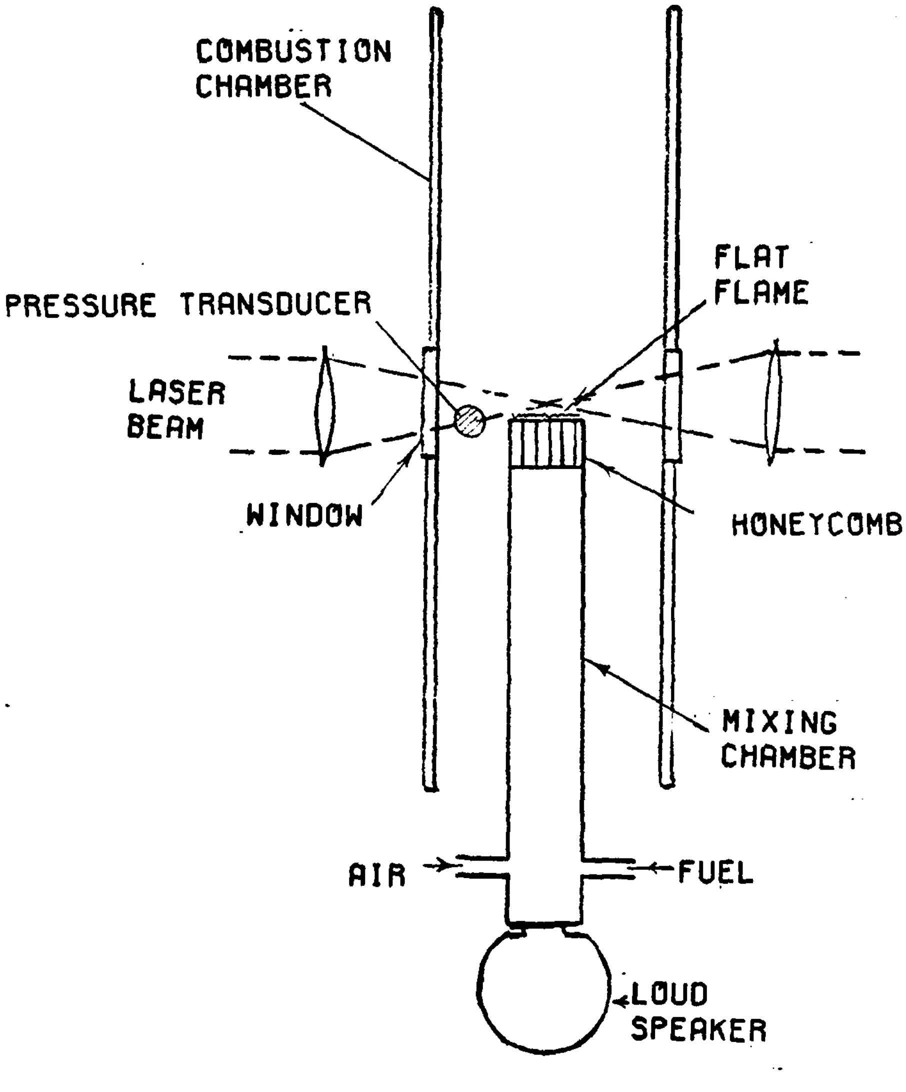


FIG.4 DIAGRAM OF PREMIXED FLAME APPARATUS USED TO DEMONSTRATE THE FEASIBILITY OF MEASURING ACOUSTIC ADMITTANCE.

# DIAGRAM OF FORCED PRESSURE OSCILLATION COMBUSTOR

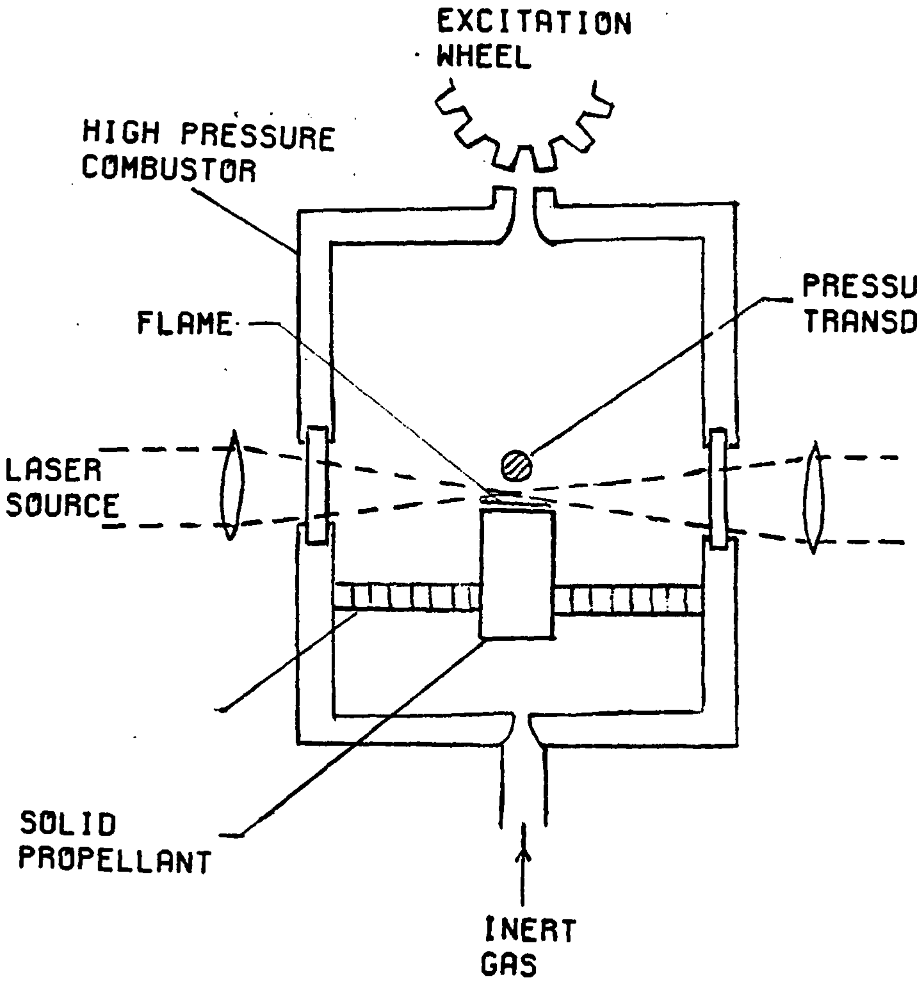


FIG.5 DIAGRAM OF APPARATUS FOR MEASURING VELOCITIES IN SOLID PROPELLANT FLAMES SUBJECTED TO FORCED PRESSURE OSCILLATIONS

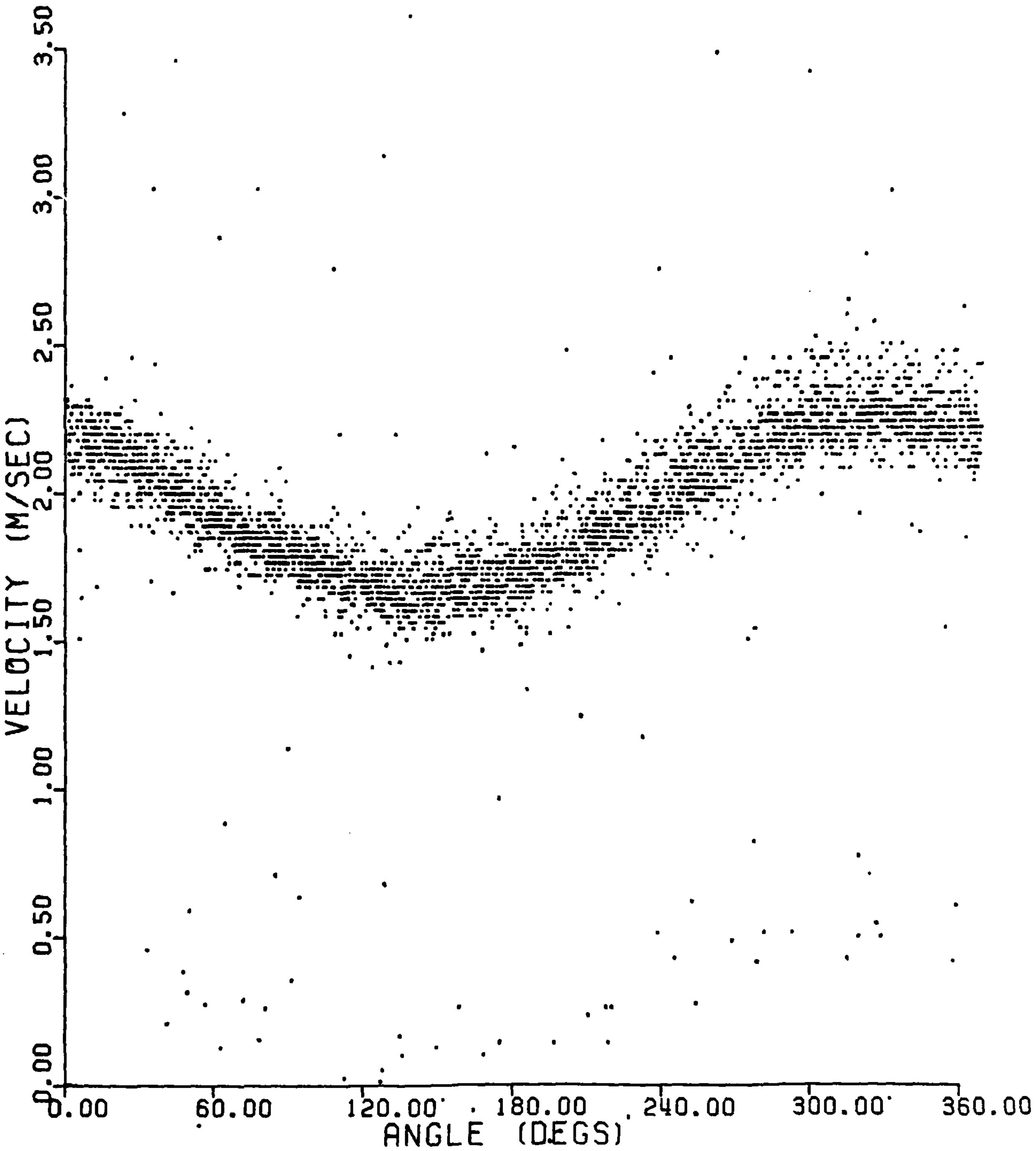
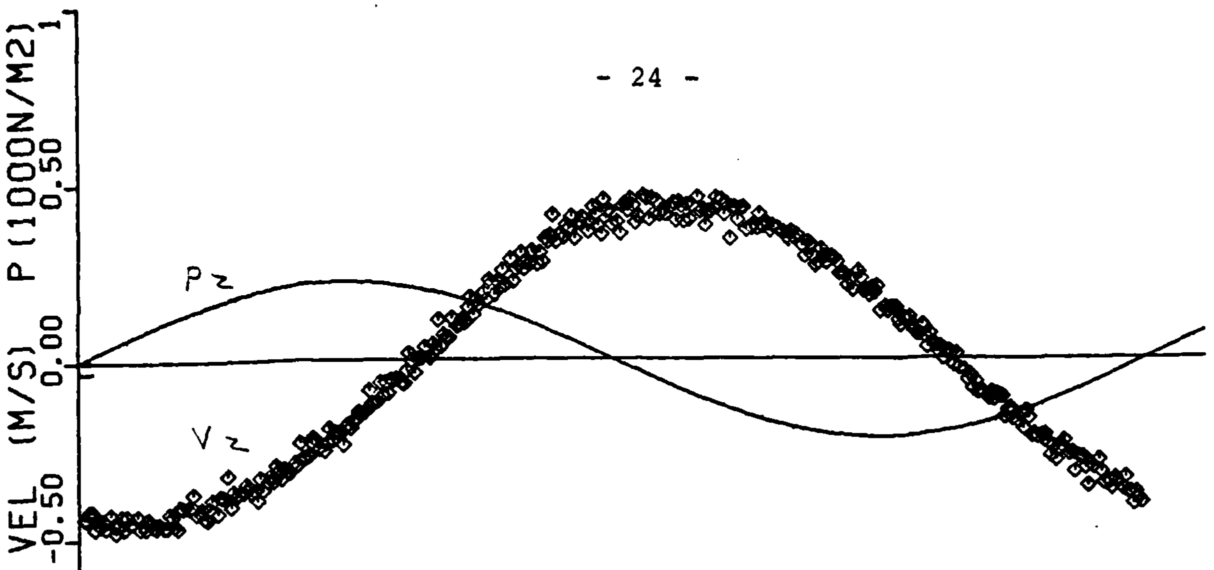
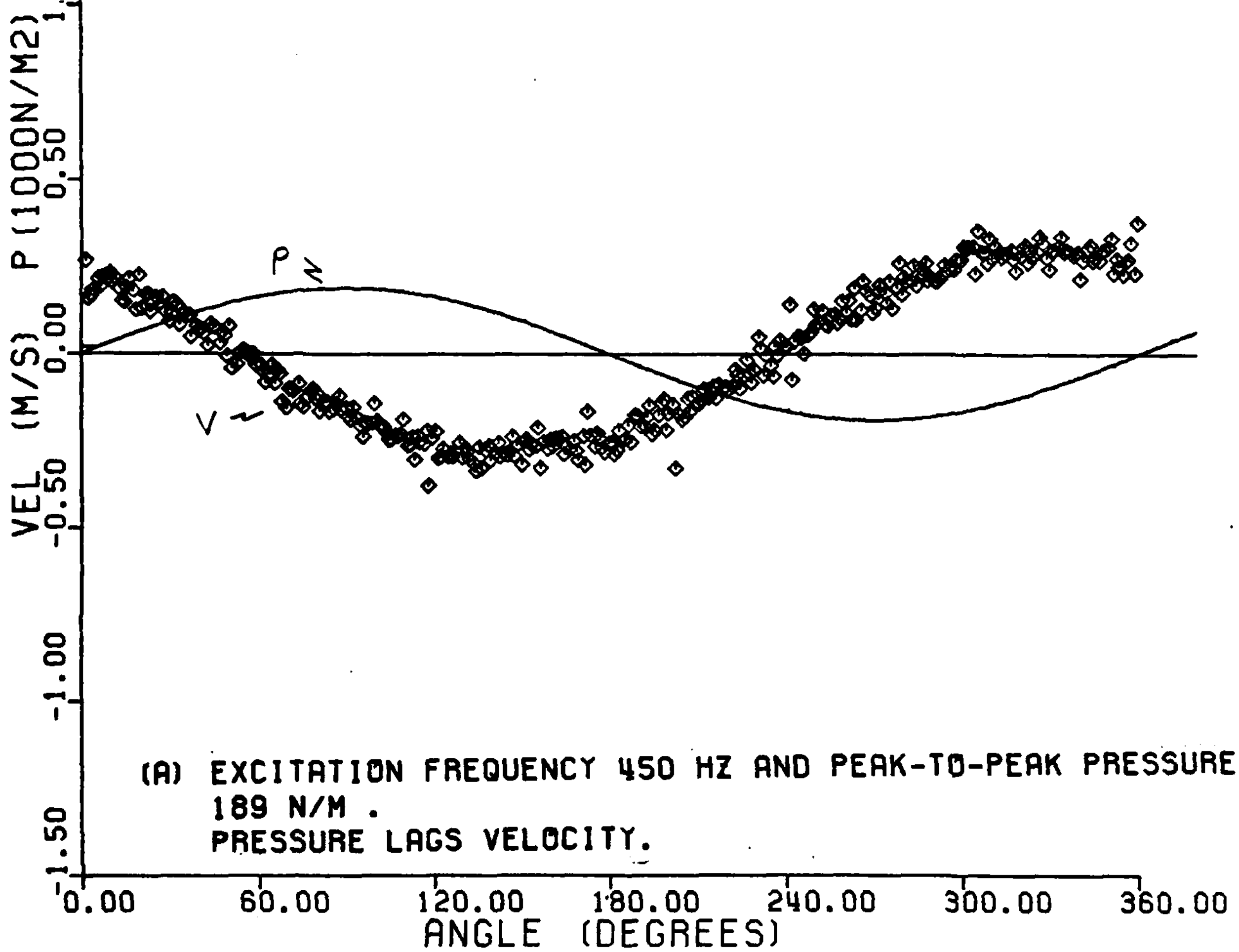


FIG.6 INDIVIDUAL FLAME VELOCITIES PRIOR TO STATISTICAL ANALYS
(FLAME EXCITED AT 450 HZ AND PEAK-TO-PEAK PRESSURE OF
189 N/M )

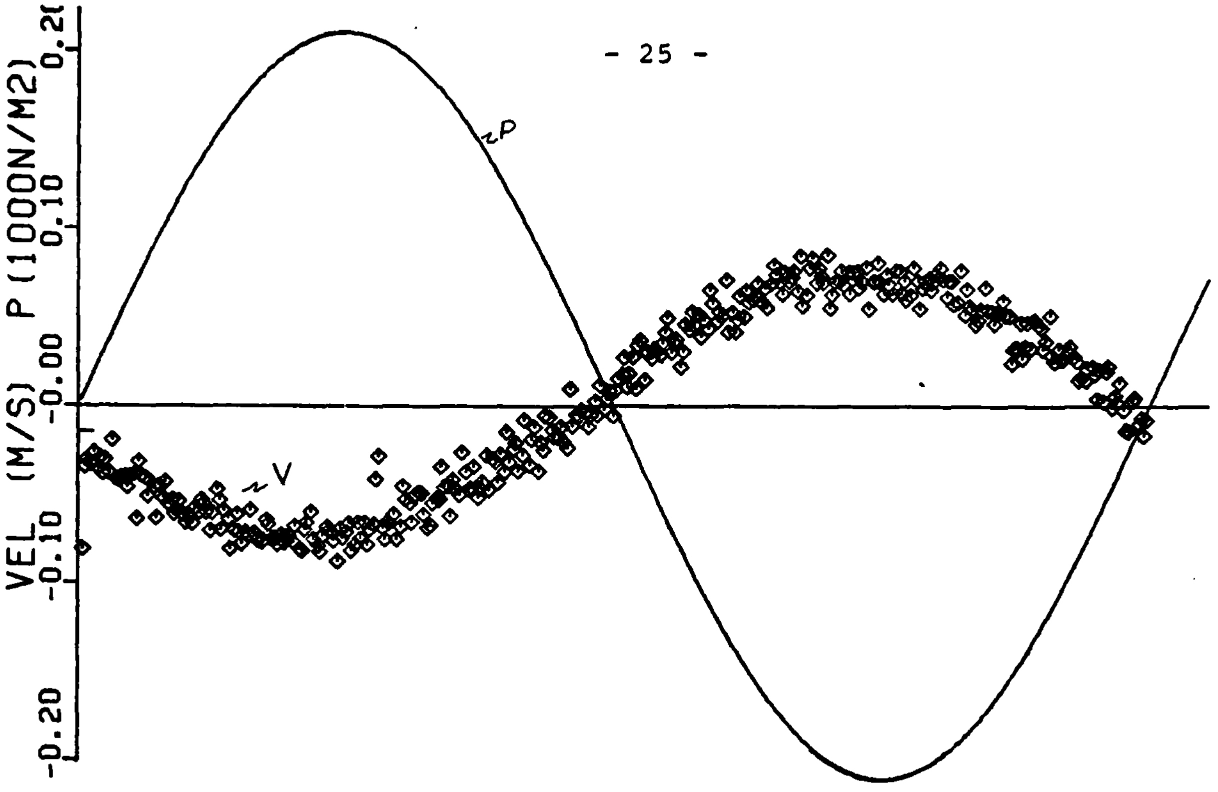


(B) EXCITATION FREQUENCY 500 HZ AND PEAK-TO-PEAK PRESSURE 222 N/M .
PRESSURE LEADS VELOCITY.

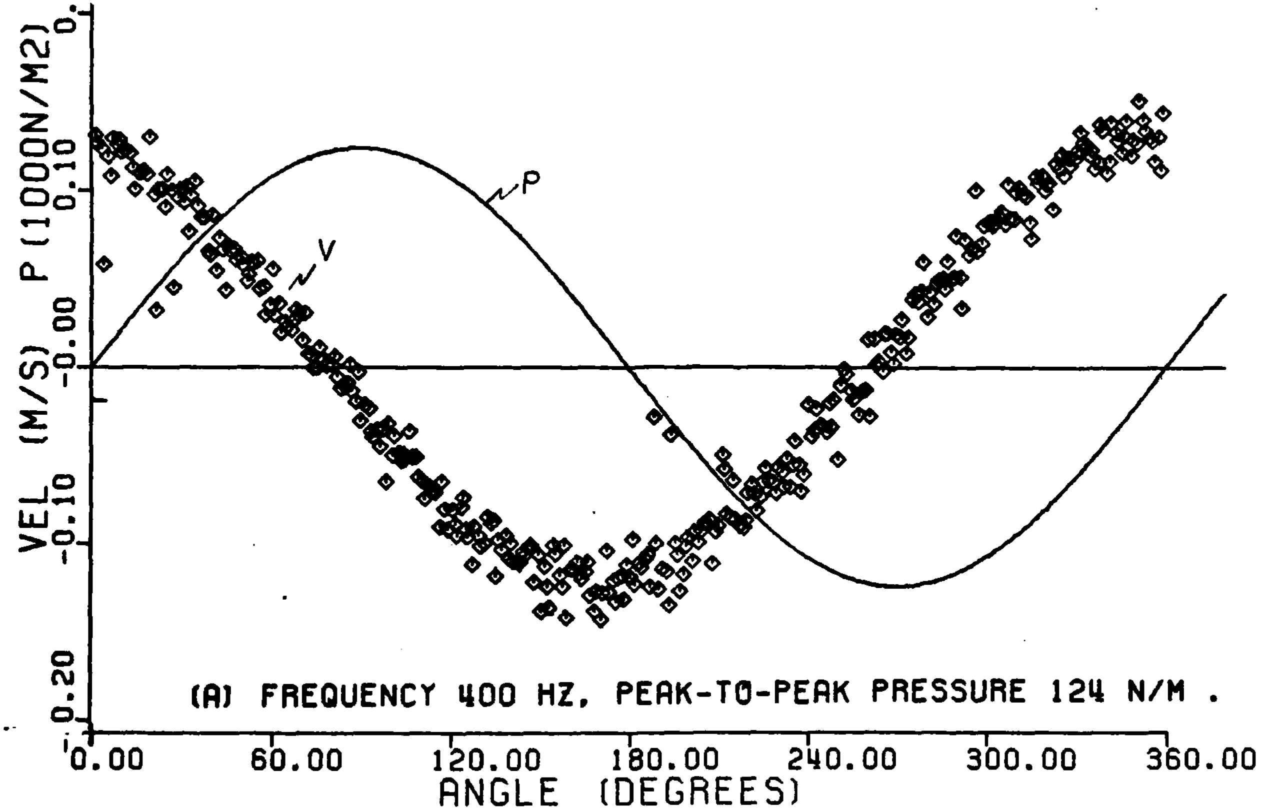


(A) EXCITATION FREQUENCY 450 HZ AND PEAK-TO-PEAK PRESSURE 189 N/M .
PRESSURE LAGS VELOCITY.

FIG.7 UNSTEADY COMPONENTS OF FLAME VELOCITY PRODUCED BY CONSTANT POWER EXCITATION. INCREASING FREQUENCY CAUSES TRANSFORMATION FROM PRESSURE LAGING VELOCITY TO PRESSURE LEADING VELOCITY.



(B) FREQUENCY 420 HZ, PEAK-TO-PEAK PRESSURE 211 N/M .



(A) FREQUENCY 400 HZ, PEAK-TO-PEAK PRESSURE 124 N/M .

FIG.8 MEASURED GAS JET UNSTEADY VELOCITY COMPONENTS FOR CONSTANT EXCITATION POWER AND VARYING FREQUENCY.
NOTE THAT FIRST PLOT IS NEAR THE THRESHOLD FOR TRANSITION

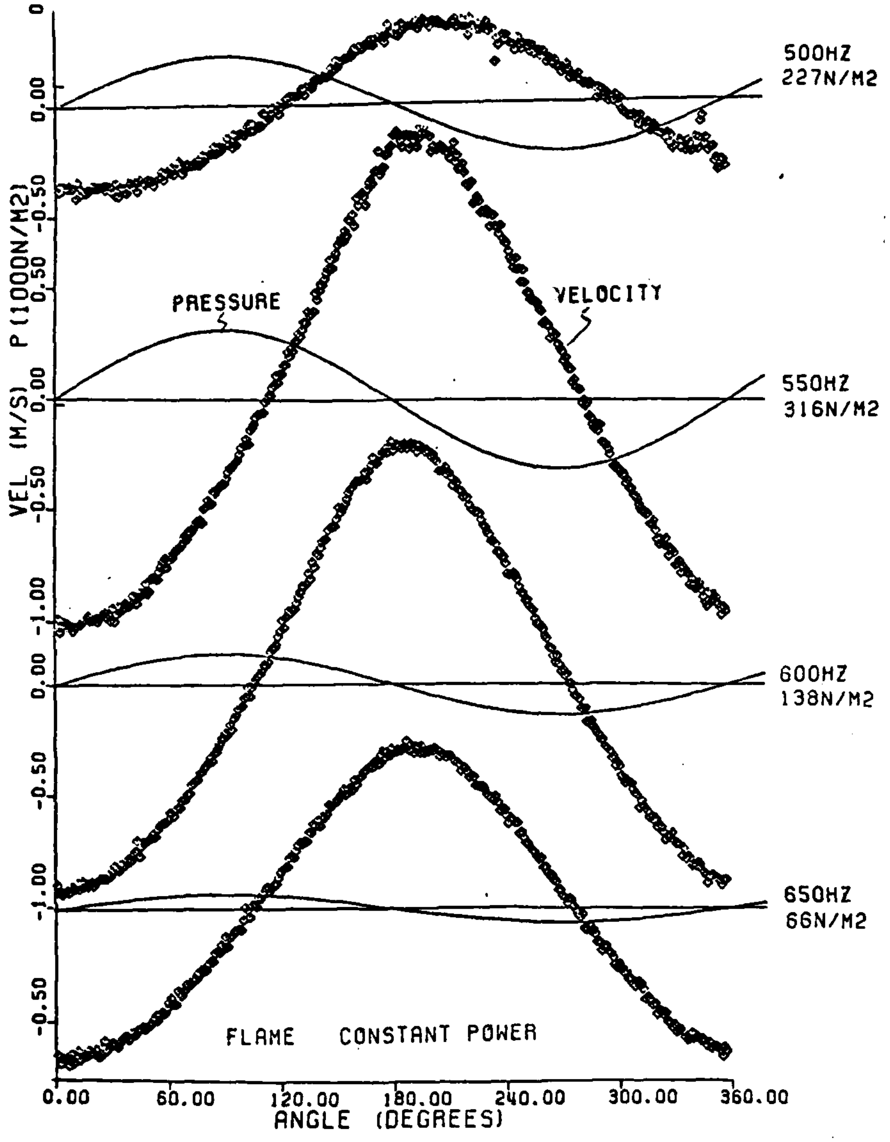


FIG.9A FREQUENCY DEPENDENCE OF MEASURED VELOCITIES AND PRESSURES FOR BURNER EXCITED AT CONSTANT POWER.

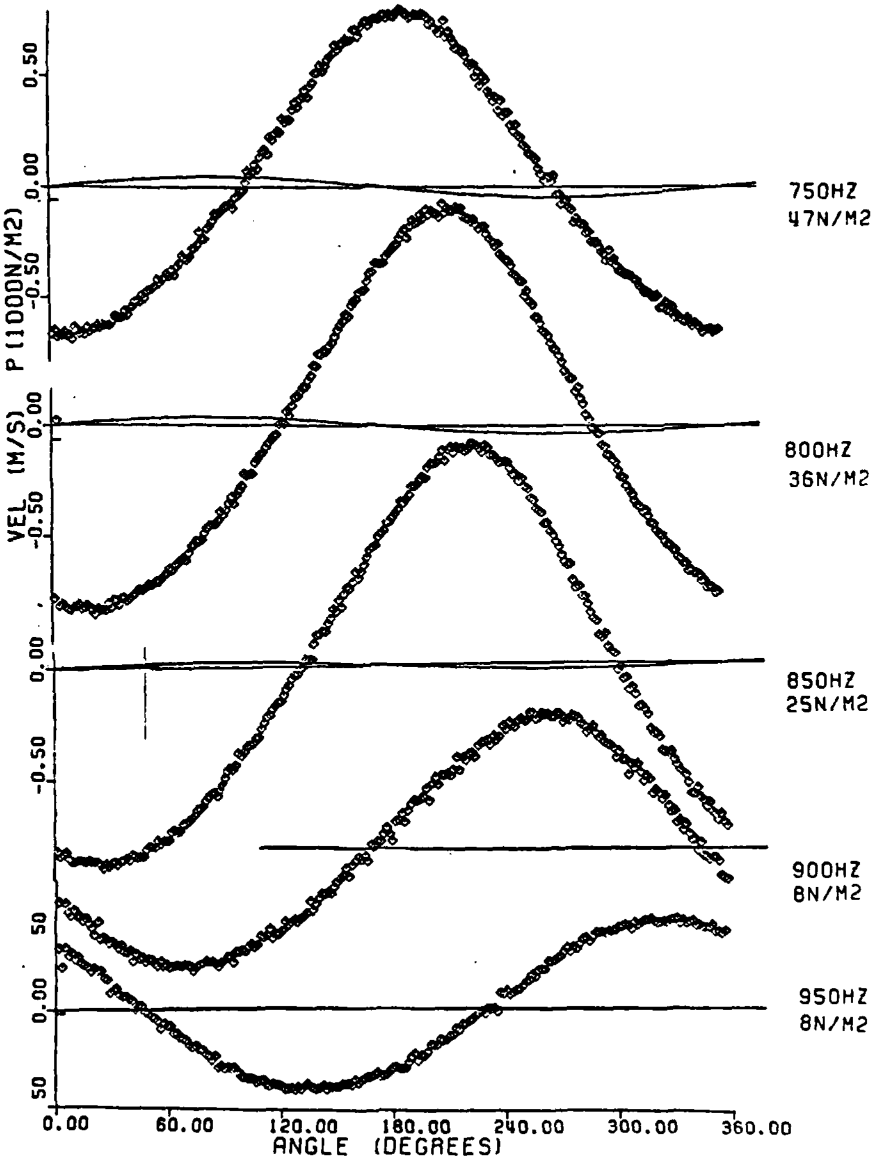


FIG.9B CONTINUATION OF FIG.9A.

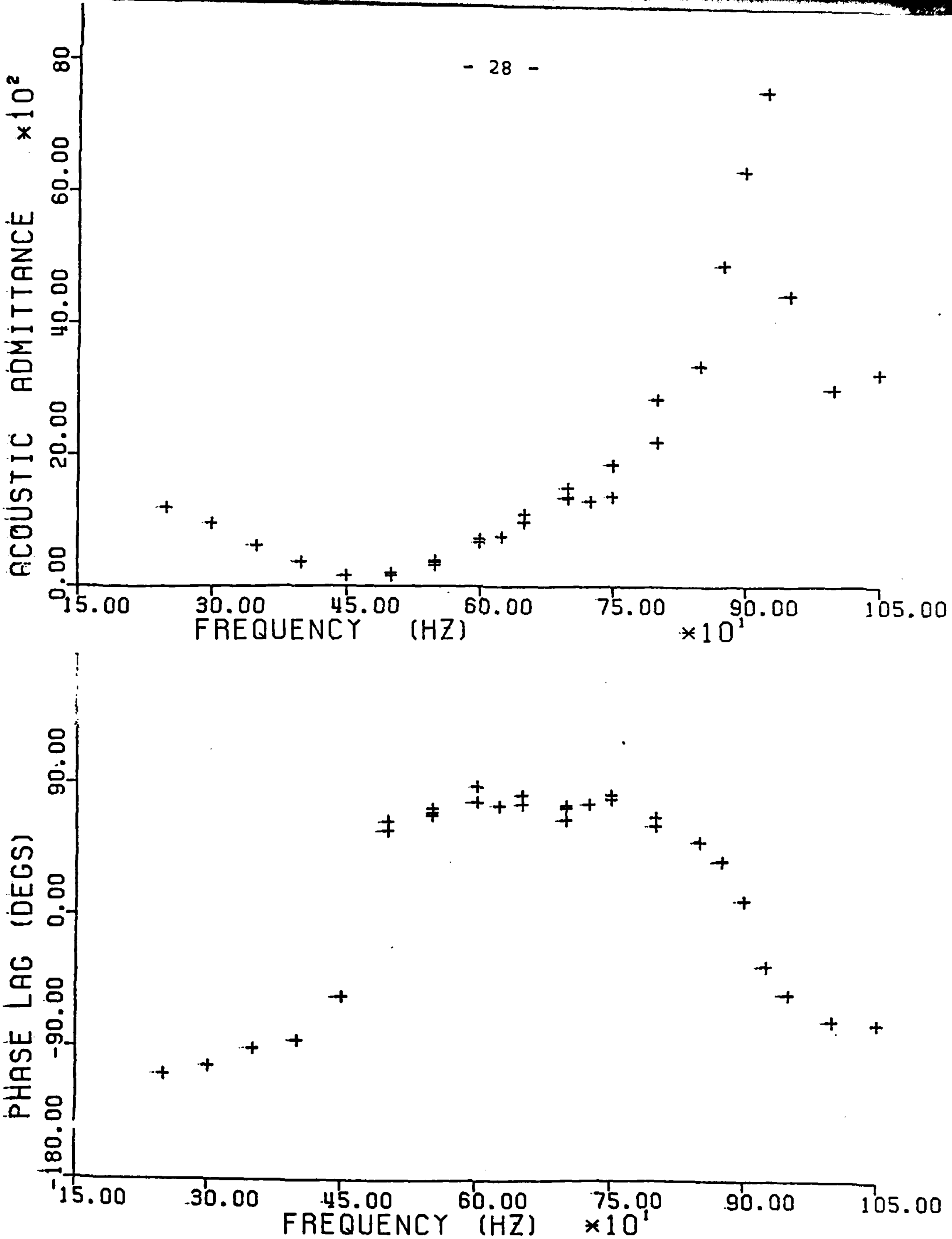


FIG.10 MEASURED ACOUSTIC ADMITTANCES AND PHASE ANGLE FOR BURNER EXCITED AT CONSTANT POWER ( CORRESPONDS TO FIG.9 )

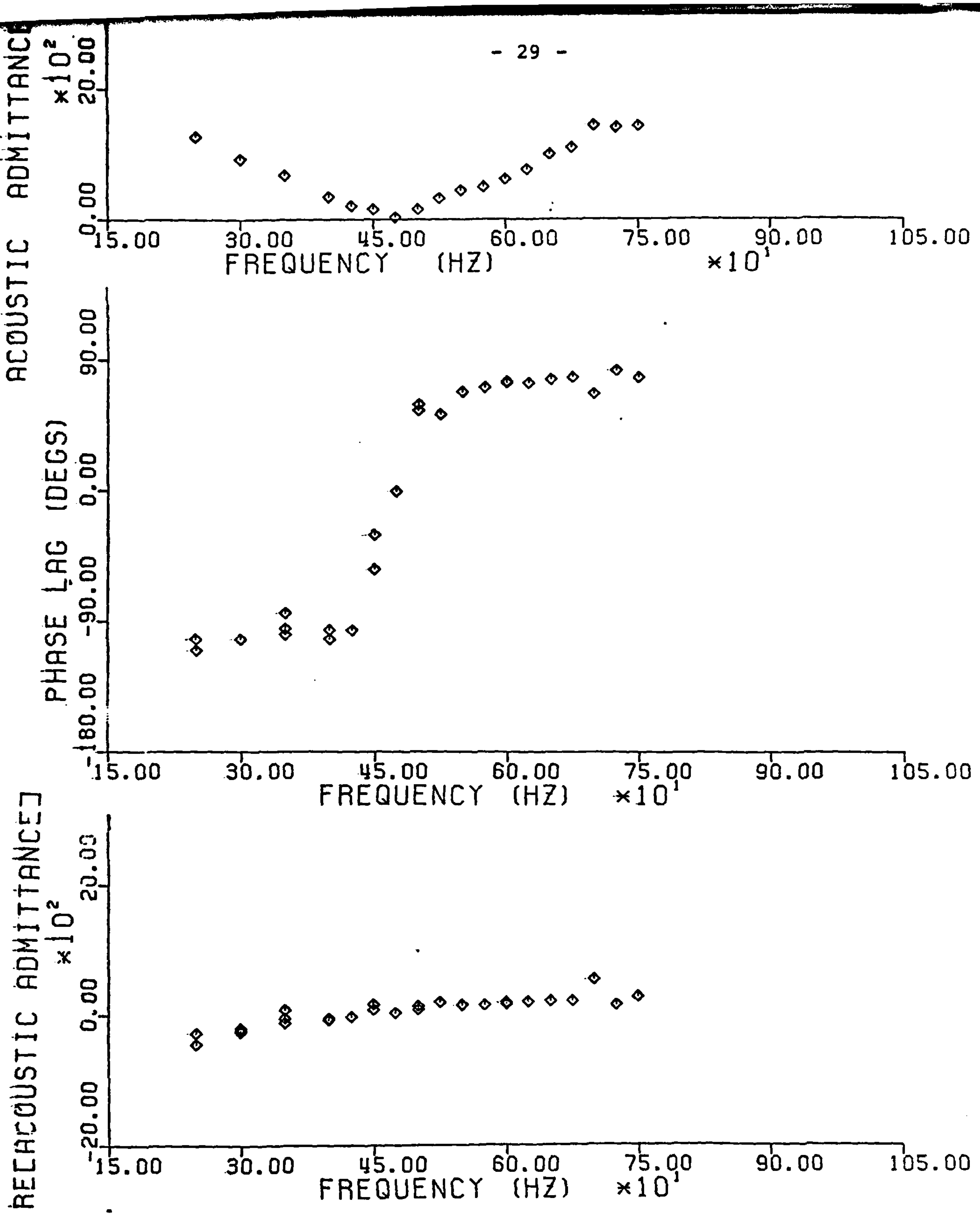
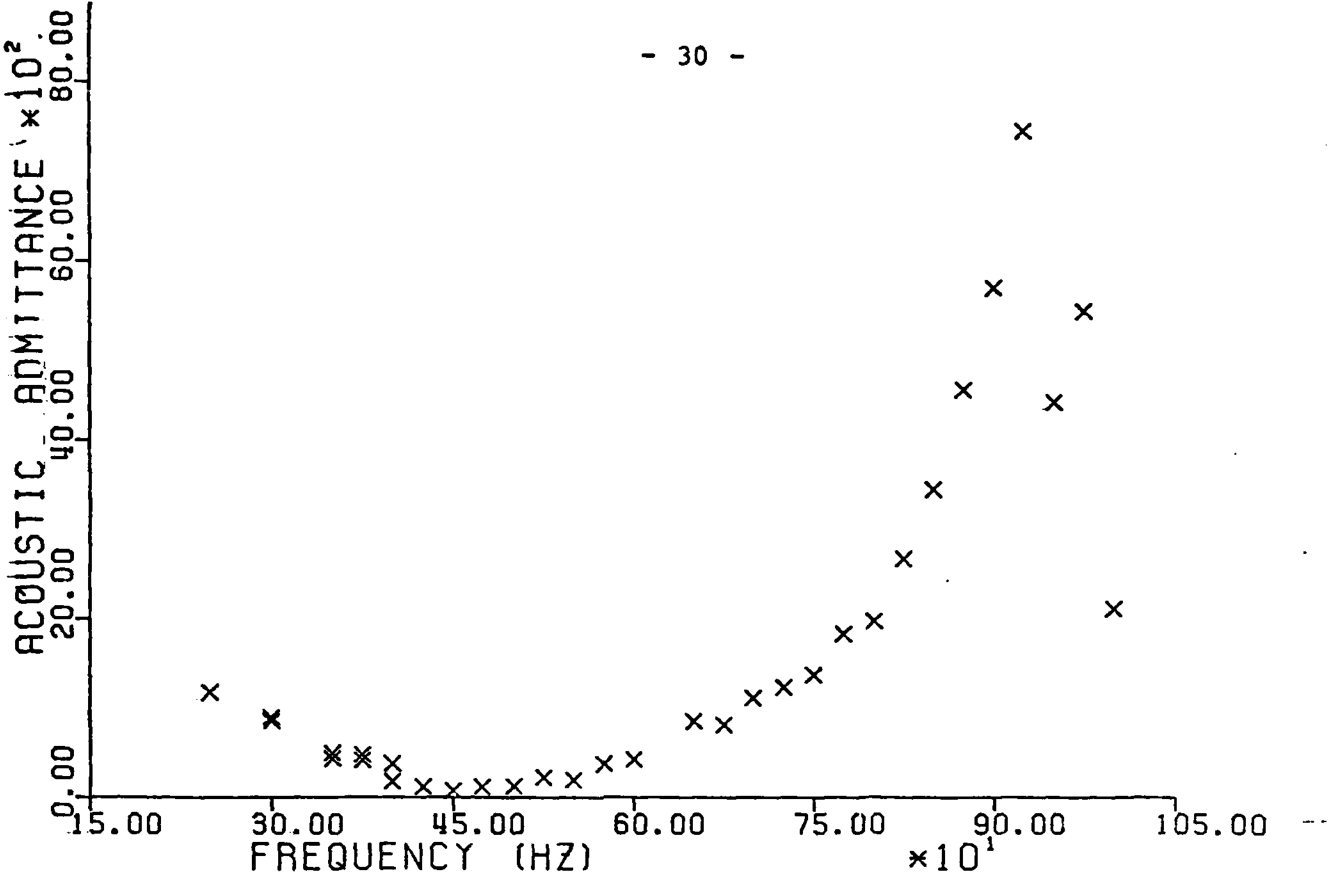


FIG.11 MEASURED ACOUSTIC ADMITTANCES AND PHASE ANGLES FOR BURNER (WITH COMBUSTION) EXCITED SO THAT PRESSURE AMPLITUDE IS MAINTAINED AT 25 PA.



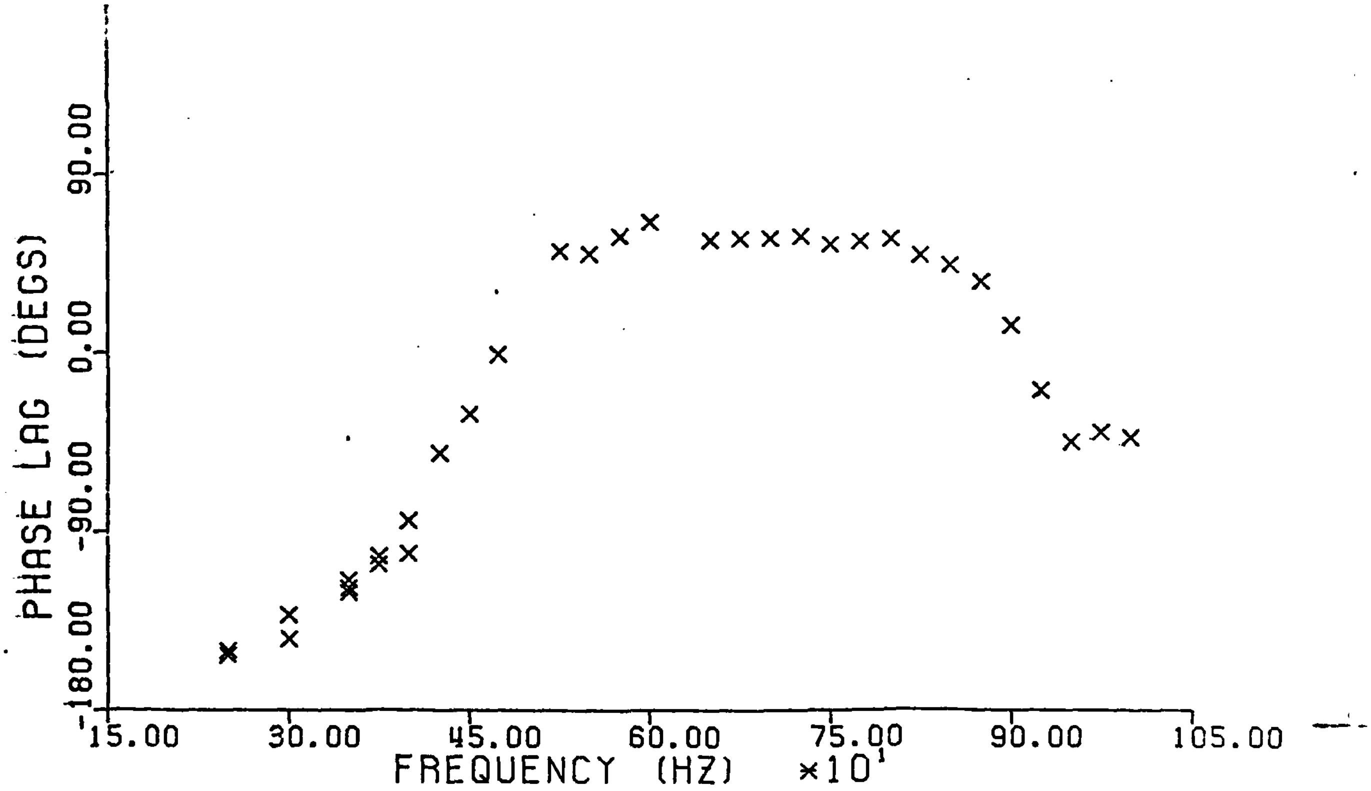
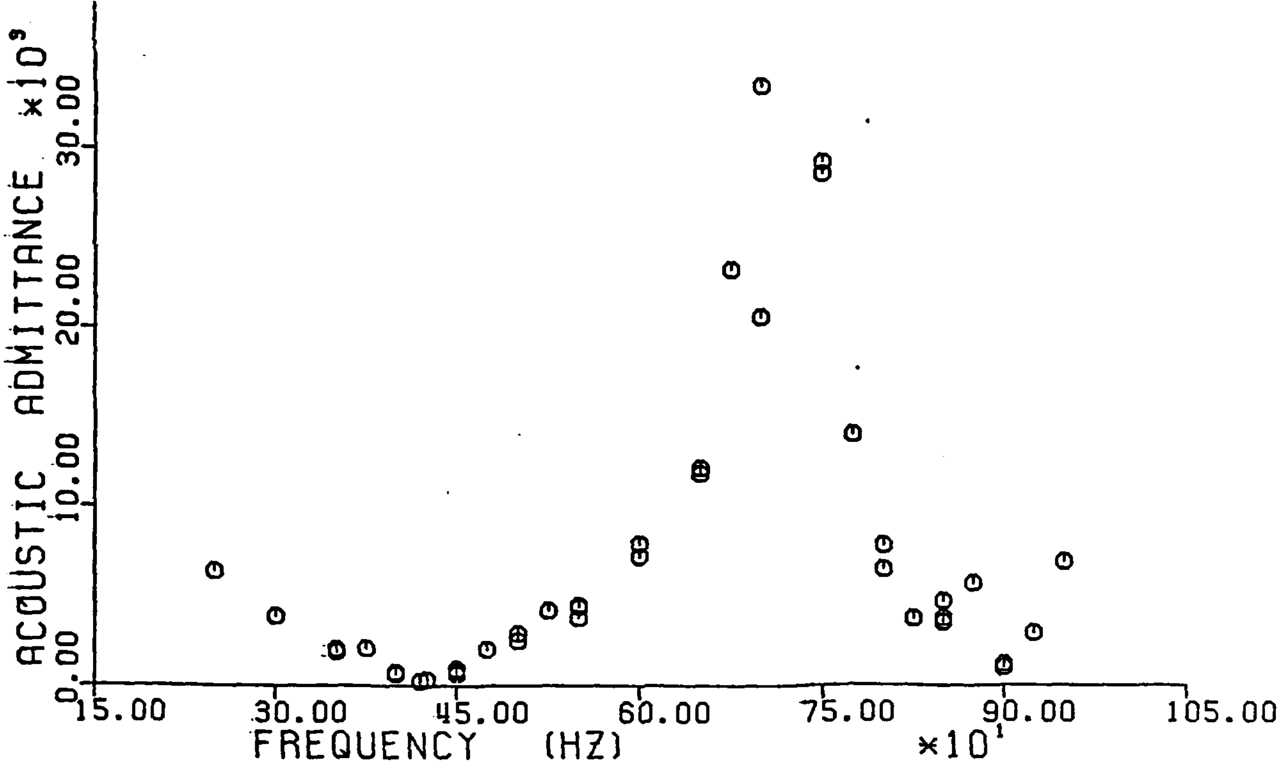


FIG.12 MEASURED ACOUSTIC ADMITTANCES AND PHASE ANGLE FOR BURNER EXCITED SO THAT PRESSURE AMPLITUDE IS MAINTAINED AT 10 PA.



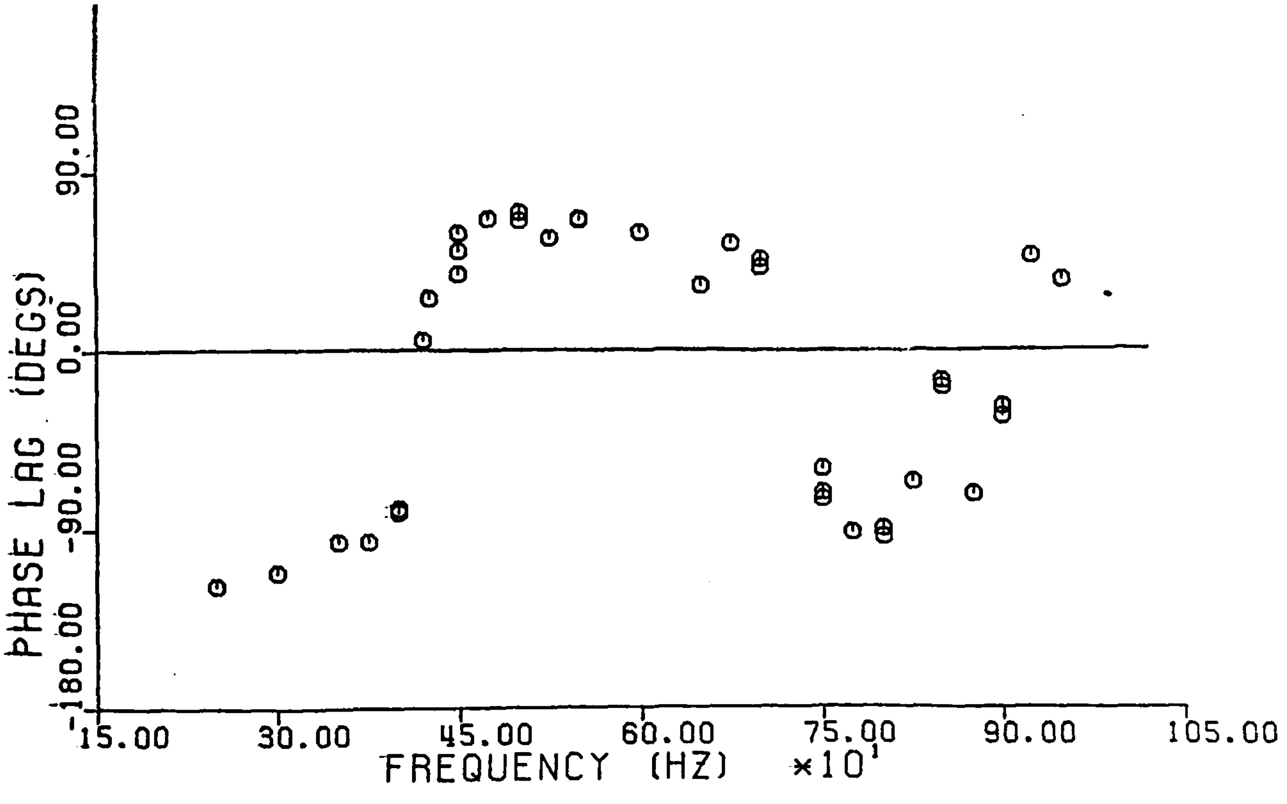


FIG.13 MEASURED ACOUSTIC ADMITTANCES AND PHASE ANGLES FOR BURNER (WITHOUT COMBUSTION) EXCITED AT CONSTANT DRIVER POWER.

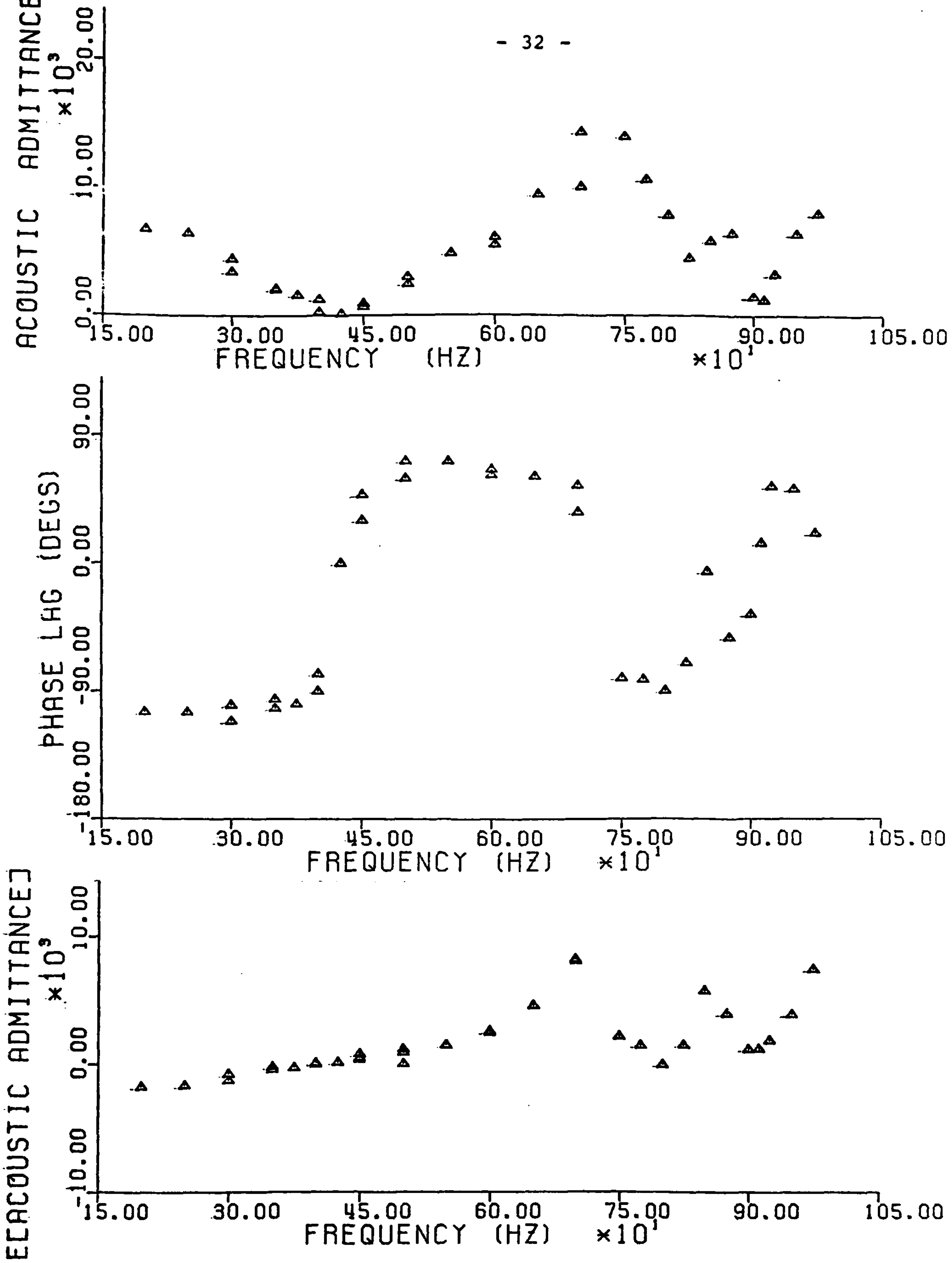


FIG.14 MEASURED ACOUSTIC ADMITTANCES AND PHASE ANGLE FOR BURNER (WITHOUT COMBUSTION) EXCITED SO AS TO MAINTAIN PRESSURE AMPLITUDE AT 25 PA.

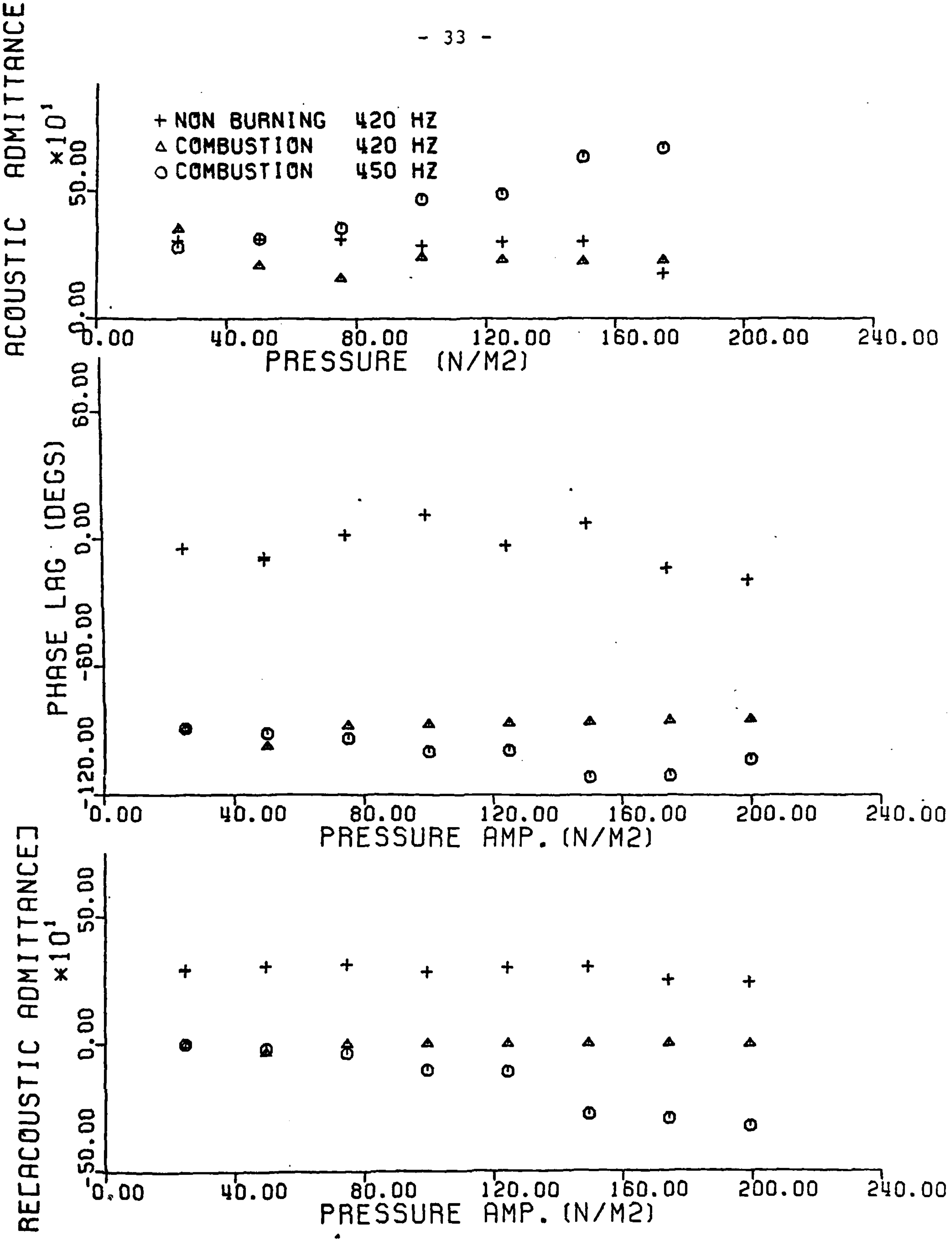


FIG.15 RESPONSES AT CONSTANT FREQUENCY OVER A RANGE OF PRESSURE AMPLITUDES.

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