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Abstract

In this paper are presented burner pressure oscillations and interelectrode voltage oscillations measured in an open-cycle supersonic flow Hall generator. The ionized gas for the channel was supplied by seeding the approximately 1 lb/sec of hydrogen-oxygen combustion products with cesium. Since both the burner and the channel were located within magnetic fields exceeding 4 Tesla during operation, an infinite probe pressure measurement technique was used to measure burner pressure oscillations. Calibration of the burner pressure transducer using a resonance tube technique is presented. Evidence is presented for the existence of the first longitudinal mode of oscillations (5000 Hz) within the burner. Interelectrode voltage oscillations were simultaneously measured at two separate axial stations. The magnitude change and the phase shift between the two signals was interpreted as a decaying magneto-acoustic wave driven by the burner that propagates at local gas plus sonic velocities. The amplitude of the electrical voltage oscillations at the start of the power producing region of the channel varied with the magnetic field. This variation is compared with the results of a simple perturbation analysis. Arguments are presented for using an unsteady model for analyzing wave processes in channels.

I. Introduction

An important property of an electrical generator is its stability. In a formal sense, the stability can be recognized as the sensitivity of the generator to disturbances that will cause a time varying output in the electrical power. An MHD generator with its closely coupled fluid mechanical and electrical fields is particularly susceptible to a variety of instabilities. These can arise from variations in operation of one or more of the systems connected to the generator, or they can arise from the generator itself. In order to achieve a power generation capability suitable for commercialization, it is important that these instabilities be understood and their effects minimized. Open-cycle MHD generators are particularly sensitive to disturbances that arise within the burner that supplies the ionized gas to the generator. Depending on whether the channel is operated as a sub- or supersonic generator, any burner-generated disturbances may be able to couple back to the burner, resulting in serious system instabilities with potentially damaging results. While there has been no evidence presented in the literature for the existence of these damaging instabilities, it is useful to recall the history of development of the large liquid and solid propellant rocket engines used for space propulsion. The smaller engines, that were used for preliminary and subscale development, were either stable or the instabilities were not serious. Only when the larger engines were under development did we see the destruction that high amplitude pressure oscillations could cause. The increased importance of these oscillations as the scale is increased is related to the decrease in the relative wall damping and the proximity of the burner or engine time scales with those of the combustion processes.

In order to experimentally study the nature of instabilities in open-cycle MHD generators, it is convenient initially to decompose what can be a very complex problem into its more simple components. For the case of burner-coupled oscillations, this can be achieved most readily by operating the generator supersonically. Thus any disturbance in the burner can be used to study the ability of the generator to amplify or decay it without a feedback to the burner. The most obvious requirement for this study is a source of disturbances within the burner. Either a pulse or oscillatory disturbance would be suitable. Based on the requirements stated above, it appeared that the H_2-O_2 Fired MHD Generator Experiment at the NASA Lewis Research Center would be suitable for this study. The output of the generator was of the order of 100 MW/m^3, the channel was capable of instrumentation for transient measurements, and, most important of all, there was some evidence that the natural frequency for the first longitudinal mode of oscillation with the combustor was in the range of a few kilocycles which would be easily measured. Therefore, this mode could be used as a source of oscillation propagating into the channel.

II. H_2-O_2 Burner and Channel

The MHD channel used in this investigation has been more completely described in previous papers.[1] Briefly, it consisted of a gaseous hydrogen, gaseous oxygen fueled water-cooled rocket combustor, operating stoichiometrically, with a nominal flow rate of 1 lb/sec, a chamber pressure of 10 atmospheres, and seeded with a cesium hydroxide water solution. Both steady and transient combustor pressures were measured. The nozzle exit (channel entrance) Mach number is 2 with a diameter of 2 inches. The channel is a segmented Hall design with half-inch uncooled copper heat sink electrode plates separated by mica insulators. The channel is approximately 2 feet long with a conical bore, a 4 to 1 area ratio, and a single resistance load. Steady-state static pressures and voltages are measured at various axial positions down the channel. Oscillatory voltage signals were measured at two positions. The first position was at the start of the power producing region of the channel and the other at a position ~6 inches downstream. The liquid neon cooled cryomagnet used can achieve B fields in excess of 5 Tesla for short (5 sec) runs. The maximum field strength used in this investigation was 4 Tesla. A pictorial sketch of the magnet, generator, and burner used is shown in Fig. 1.

III. Measurement of Chamber Pressure Oscillations

In order to characterize the pressure oscillations within a combustor, it is necessary, in general, to have one or more high frequency pressure transducers flush mounted in the chamber wall. Thus, for normal rocket engine operation, the transducers must be cooled, and if necessary, mounted to avoid the effects of wall vibrations on the signal. In the case of the channel being studied, the channel together with the burner is inserted within the narrow magnet bore. Both the high magnetic fields present during operation and space limitations prevented installation of such a flush mounted transducer. Therefore, in order to measure the chamber pressure oscillations, it was necessary to separate the transducer from the chamber by a long small diameter tube. A review of the literature indicated that the most promising approach was to use a very long tube with the high frequency pressure transducer flush mounted to the inside of the tube ("infinite probe") as shown in Fig. 2. In principle, the damping created by the tubes excess length would prevent establishing any standing wave patterns and give a flat frequency response curve up to the point where viscous and thermal dissipation would cause significant signal decay. In Ref. 2, the authors present a technique for including damping material within the tube at a location calculated to eliminate any standing [illegible] patterns and insure a flat response. Although this technique was demonstrated to be suitable for the oscillations studied in that reference, it was not possible to include damping material in the present study since the tube was used as part of the steady-state pressure measurement and burner purge system. Consequently, it was necessary to provide a means of calibrating the pressure transducer in its "infinite probe" configuration.

Burner Pressure Calibration

A convenient method for the generation of high frequency pressure oscillations together with elevated mean pressures is the resonance tube (Fig. 2). This simple device depends on the initiation of longitudinal organ pipe oscillations within a small closed-ended cylindrical cavity by having a high pressure gas jet pointed into the open end of the cavity at specific distances from the open end. This device has been extensively studied and is well characterized. For a frequency range of 1000 to 5000 Hz, the anticipated frequency range for any burner pressure oscillation, cavity depths of 1/2 to 3 inches are required, using air as the driving gas.

For a selected pressure of the air, the spacing between the air jet and the cavity inlet is preset at a point where maximum oscillations occur. Frequency of oscillations is varied by adjusting the position of the cavity piston.

With a resonance tube diameter of 1/4", it was possible to achieve oscillation frequencies in excess of 6500 Hz using 125 psig air as the driving gas. In order to assure that the oscillations generated did not have a significant component of harmonic distortion, which would have complicated the calibration process, the output from the flush mounted pressure transducer was displayed on an oscilloscope screen and photographs were taken of the wave shape. A typical example is shown in Fig. 3. The shape is remarkably sinusoidal considering that the amplitude of the signal is 15 psi peak-to-peak out of a mean pressure of 40 psia. The frequency of the displayed wave is 5000 Hz with some small variation about the value as seen by the thickness of the trace. The amplitude of the pressure oscillations varied from 10 to 15 psi as the frequency of the wave was increased from 1000 to over 6500 Hz, providing a relatively constant input for calibration purposes. In addition, the static pressure within the tube, as measured by a Bourdon gauge at the end of the infinite probe coil, was 40 psia.

The signals from the pressure transducer flush mounted to the inside of the resonance tube and the transducer attached to the infinite probe were recorded on magnetic tape.

The recorded signals were then analyzed using a Model 400B Nicolet Scientific Corporation Fast Fourier Transform Analyzer. This digital-type analyzer readily produces the time variation of the individual signals Power Spectral Density as well as the Cross Spectral Density of the two signals. The result is a capability to observe the time variation of the phase angle between the two signals, the ratio of the magnitude of the two signals or transfer function, and a measure of the correlation between the two signals, i.e., the coherence. The transfer function and the coherence for the recorded data are shown in Figs. 4 and 5. Up to 4000 Hz, the transfer function indicates a series of resonant peaks within the probe, perhaps due to wave reflections off of area discontinuities, superimposed on a straight line decrease due to viscous and thermal losses within the probe. Beyond 4000 Hz there is a break in the slope of the viscous/thermal loss curve. Referring now to the coherence between the two signals, shown on Fig. 5, it can be seen that the coherence drops off very rapidly beyond 4000 Hz, indicating that data in this area are either insufficient or that the signals are uncorrelated. Rather than repeat the calibration process using the digital analyzer, both signals were displayed on an oscilloscope screen and a series of photographs were taken of the wave shapes. The amplitude ratio of the waves, based on the oscilloscope photographs, is given as the circular symbols on Fig. 4. At frequencies less than 4000 Hz, the two methods of analysis agree whereas at frequencies above 4000 Hz, the scope photographs confirm a constant slope in the transfer function due to viscous and thermal losses in the infinite probe. Based on Fig. 4, an infinite probe transfer function of 28 dB was used to convert the measured 5000 Hz chamber pressure oscillations to actual values.

Burner Pressure Oscillations

During a test, the output from the infinite probe transducer was recorded on magnetic tape for analysis of the pressure oscillations. Using the analyzer previously discussed, plots of power spectral density as a function of either time or averaged over the 5 second run could be readily obtained. A typical time averaged plot is shown in Fig. 6. The magnitude of the peak at approximately 5000 Hz is several dB above the background and corresponds to a measured pressure oscillation of 0.84 psi (p.t.p.), providing an unmistakable signature of burner combustion oscillation. The burner was cylindrical in cross section, 2.5 inches in diameter with a distance from the injector to the throat of seven inches. Based on a calculated chamber Mach number of 0.23 and adopting the convention that the pressure wave will reflect from a position midway between the start of the convergent section of the burner chamber and the throat, a first longitudinal mode resonant frequency of 5262 Hz was calculated. Considering the assumption of the proper reflection point for an axial pressure wave in a convergent duct, the agreement between the experimentally measured frequency and that predicted confirms the nature of the oscillation mode within the burner.

The amplitude of the oscillations, using the previously discussed calibration procedure, was 21.3 psi peak-to-peak or approximately 15 percent of the mean chamber pressure of 10 atmospheres.

IV. Measurement of Channel Electrical Oscillations

Hall Voltage Oscillations

During a typical test run, the voltage between two sets of electrodes, one set at the start of the power producing region of the channel and the other approximately 6 inches downstream, was recorded on magnetic tape. Using the digital analyzer previously discussed, a variety of approaches were available to analyze the data. Power spectral density plots were used to identify the oscillation frequency and determine the signal-to-noise ratio. A typical plot is shown in Fig. 7 for the two recorded signals. While there is considerable noise, the peaks at 5000 Hz are readily distinguishable. In this case, the signal-to-noise level is of the order of 3 dB only. The effect of the high noise level is to decrease the coherence of the signals for phase lag measurements. Both coherence and phase lag are shown in Fig. 8. For the frequency of interest, the coherence is in excess of 0.50. The averaged value of the phase lag for that frequency was taken as 72°.

Estimate of Channel Wave Propagation Velocity

In order to determine whether the oscillations from the combustion chamber propagated at the local gas velocity in the channel, corresponding to entropy wave production within the burner, or at the sum of both gas and local sonic velocity, corresponding to an acoustic wave, it is necessary to compare the measured wave velocity based on the electrical signal phase lag, the frequency, and the distance between the measurement stations with an estimate of the gas and sonic velocities within the channel. The measured wave velocity based on phase angle and frequency was, from Table I, 11,250 ft/sec.

A one-dimensional analysis of channel performance was used to estimate the channel conditions that could not be readily measured. The results of the channel analysis are shown in Fig. 9 for a nominal B field of 3 Tesla. On the plot are shown the variations of static pressure, Hall voltage, and the sum of gas plus sonic velocities. For the acoustic wave velocity, pressure, and steady-state Hall voltage, sufficient data were taken to assure the validity of the calculation procedure. The average wave velocity between the two measurement points as indicated by the figure and Table I is 11,075 ft/sec which agrees sufficiently well with the theoretical number to verify that the electrical wave propagates as an acoustic-like wave rather than an entropy wave.

Relative Magnitude of the Electrical Oscillations

Facility limitations prevented the measurement of oscillatory pressures at the same position as the electrical signal so that in order to determine whether the data were meaningful, it was necessary to try to simulate the electrical signal amplitude. The first or upstream position at the front of the power producing region was 6.6 inches from the channel entrance and corresponded to 0.5 inches downstream from the electrodes used for current lead-ins. Based on the short distance and without any other information, a simplified perturbation model with no wave damping mechanisms, based on the work of Marble and Candel,[3] was used to estimate the oscillations in pressure, velocity, and temperature at that location, given only the magnitude of the chamber pressure oscillations. Using the value from the burner pressure measurement, a relative magnitude (oscillating Hall voltage/steady Hall voltage) of 0.258 was calculated. This value, as shown on Table I compares very favorably with the experimentally measured value of 0.268. The agreement is probably fortuitous, considering the assumptions involved, but does indicate that the electrical oscillations near the entrance to the channel are explainable.

Variation of the oscillations at the first axial position with imposed B-field was also calculated using the perturbation analysis already discussed. A comparison of the analyses with experimental data is shown in Fig. 10. Both the data and simple perturbation theory indicate that the relative level of the oscillations at that position decrease as B field is increased. The one-dimensional channel model incorporated in the perturbation analysis is not valid for very low B fields so that the curve was not continued. Additional measurements and analyses are necessary to verify this trend.

Oscillatory Pressure and Electrical Signal Decay

The results shown in Table I for the change in relative magnitude (oscillating Hall voltage/steady Hall voltage) of the electrical oscillation with axial position in the channel are related to the loss mechanisms for oscillations within the MHD duct. Oscillatory loss mechanisms are generally based on heat transfer and frictional losses to the walls together with MHD-related amplification or loss mechanisms. One of the approaches commonly taken[4] to analyze these phenomena is to assume that the frictional and heat loss mechanisms are the same for the oscillatory flows as for the steady flows (quasi-steady assumption). The validity of the assumption can be viewed in terms of the ability of the momentum thermal boundary layers to respond to osillatory changes. Boundary layers have a finite time to react to variations in the external potential flow that is proportional to the square of the boundary layer (B.L.) thickness divided by the kinematic viscosity. The proportionality factor is of the order 0.1, based on exact solutions of boundary layer startup and boundary layer oscillations. The ratio of B.L. relaxation time to wave time should then provide a measure of the validity of the quasi-steady assumption for analyzing wave damping processes. For the case of the present channel study, the ratio of B.L. relaxation time/wave time is approximately 50:1. Thus the quasi-steady assumption does not appear to be valid for analyzing this system. As a comparison, a 500 MW thermal coal-fired channel with a 50 msec residence time coal-fired combustor will have a B.L. time wave time ratio of the order of 100 to 300 depending on the nature of the oscillations and other factors. Thus, it appears to be necessary to develop estimates of the unsteady B.L. loss mechanisms in order to accurately characterize wave processes in these channels.

V. Discussion

The results obtained from this study indicate that the acoustic waves produced by a combustor operating at the first longitudinal mode of oscillation decay within the duct. While the amplitudes of the oscillations in Hall voltage at the first or upstream station are consistent with a simplified perturbation model, analysis of the decay of the oscillations down the channel should be based on an unsteady boundary layer model rather than a quasi-steady model. In addition, the use of an infinite probe approach for measuring pressure oscillations within an MHD combustor has been assessed as being reasonable provided that some means for calibrating the probe can be found. The resonance tube approach for calibration appears to be suitable for this purpose.

VI. References

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3. Marble, F. E. and Candel, S. M.: Acoustic Disturbance from Gas Non-Uniformities Convected Through a Nozzle. Journal of Sound and Vibration, 55, 225, (1977).

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Table I. - HALL VOLTAGE ANALYSIS

[B Field = 3 Tesla, frequency of oscillation = 5000 Hz amplitude of burner pressure oscillation = 21 psi (ptp).]

Location of transient voltage sensor (inches from inlet)	6.6	12.0
Steady-state interelectrode voltage	20.	32.
Transient interelectrode voltage	5.37	3.25
Transient/steady ratio (experimental)	.268	.101
Transient/steady ratio (theoretical)	.258	
Phase lag	72 degrees (0.00004 sec)	
Wave velocity (experimental)	11,250 ft/sec	
Wave velocity (theoretical)	11,075 ft/sec (Mach No. = 1.86)	

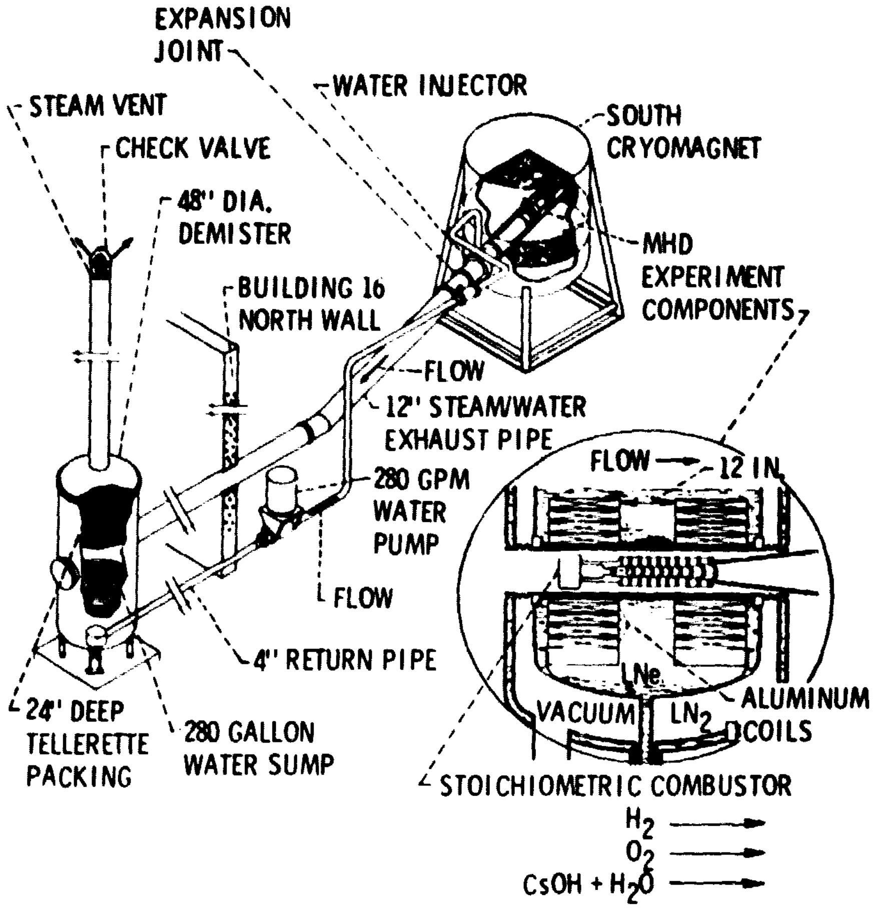


Figure 1. - GH_2-GO_2 combustion MHD experiment installation.

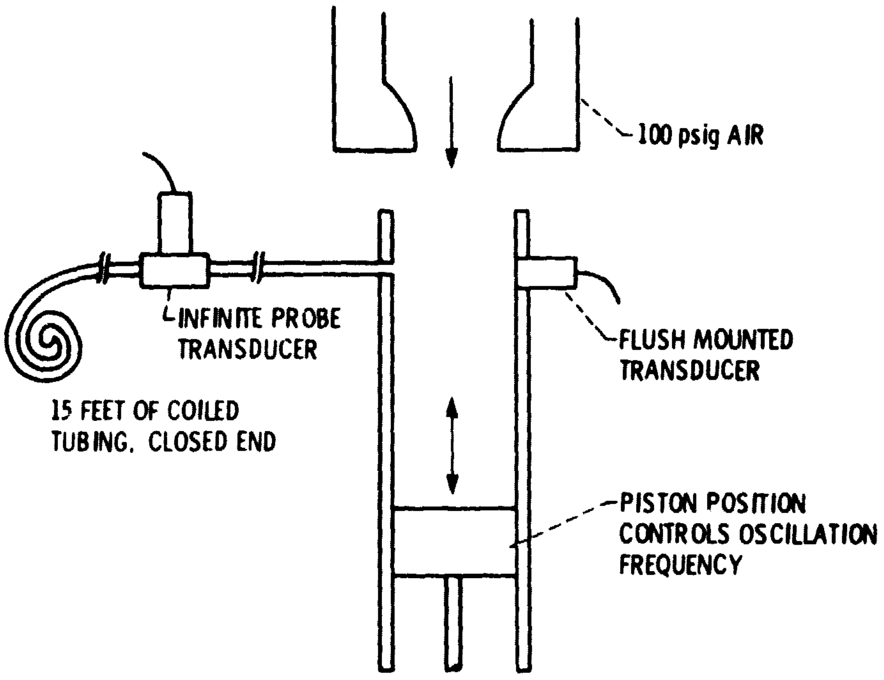


Figure 2. - Resonance tube calibration apparatus for infinite probe.

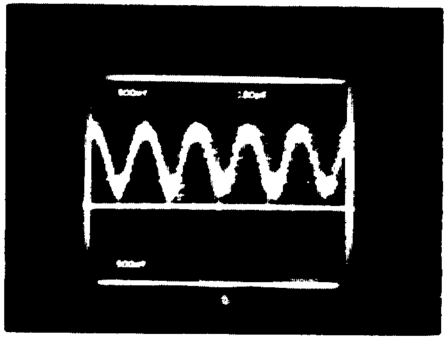


Figure 3. - Wave shape of resonance tube pressure oscillation.

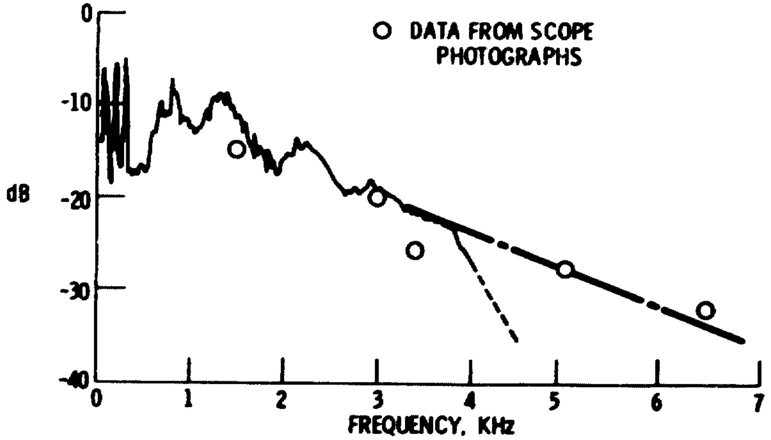


Figure 4. - Infinite probe transfer function.

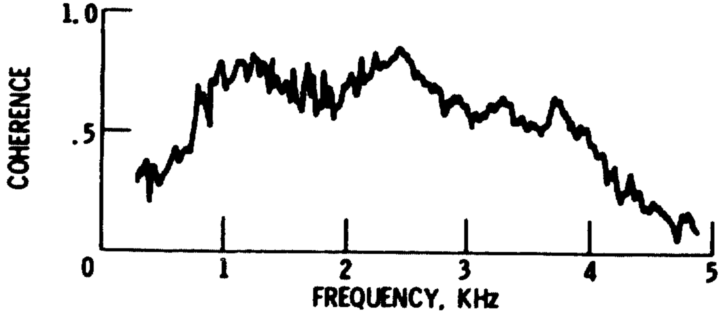


Figure 5. - Coherence for infinite probe pressure calibration.

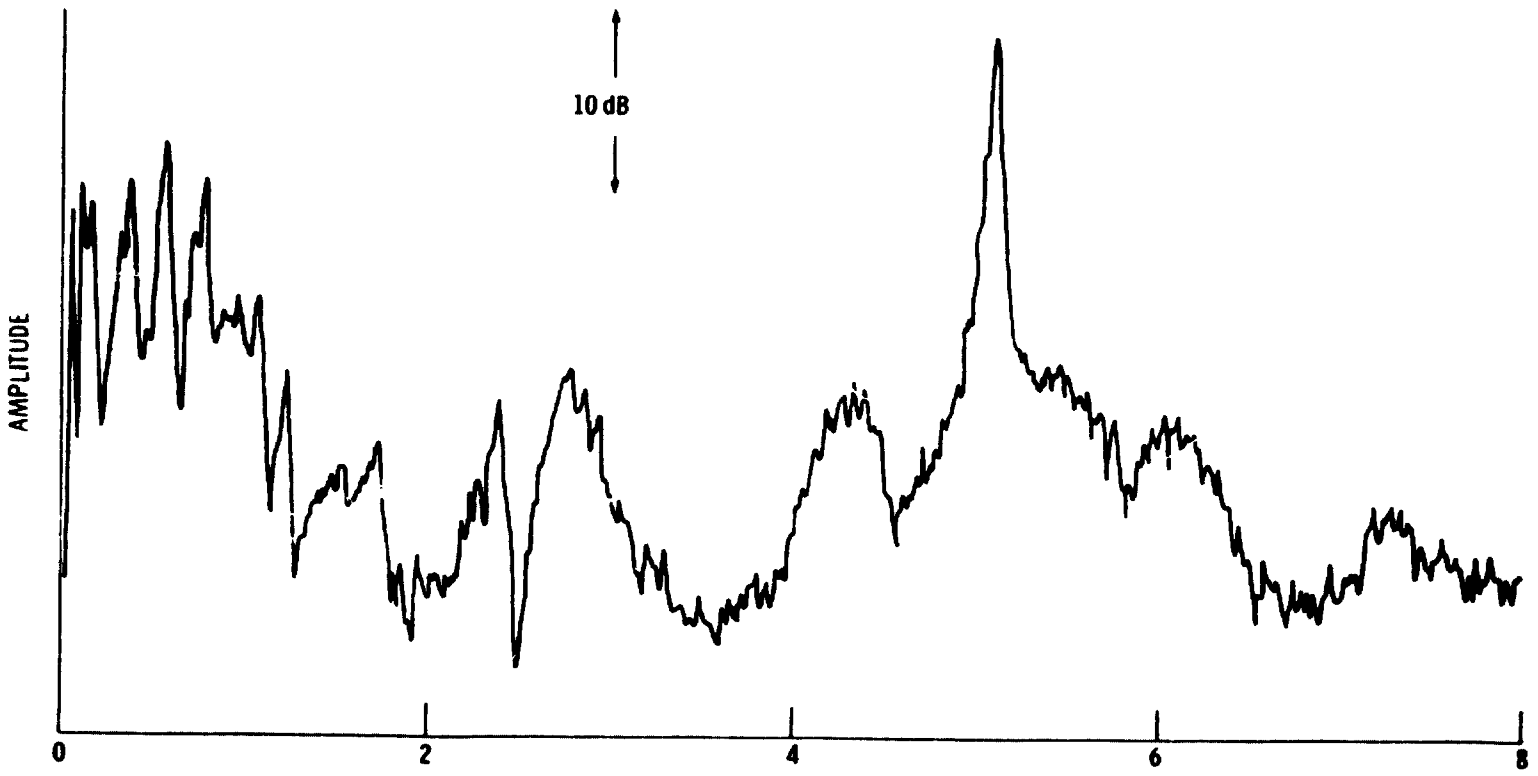


Figure 6. - Power spectral density analysis of combustor chamber pressure oscillations.

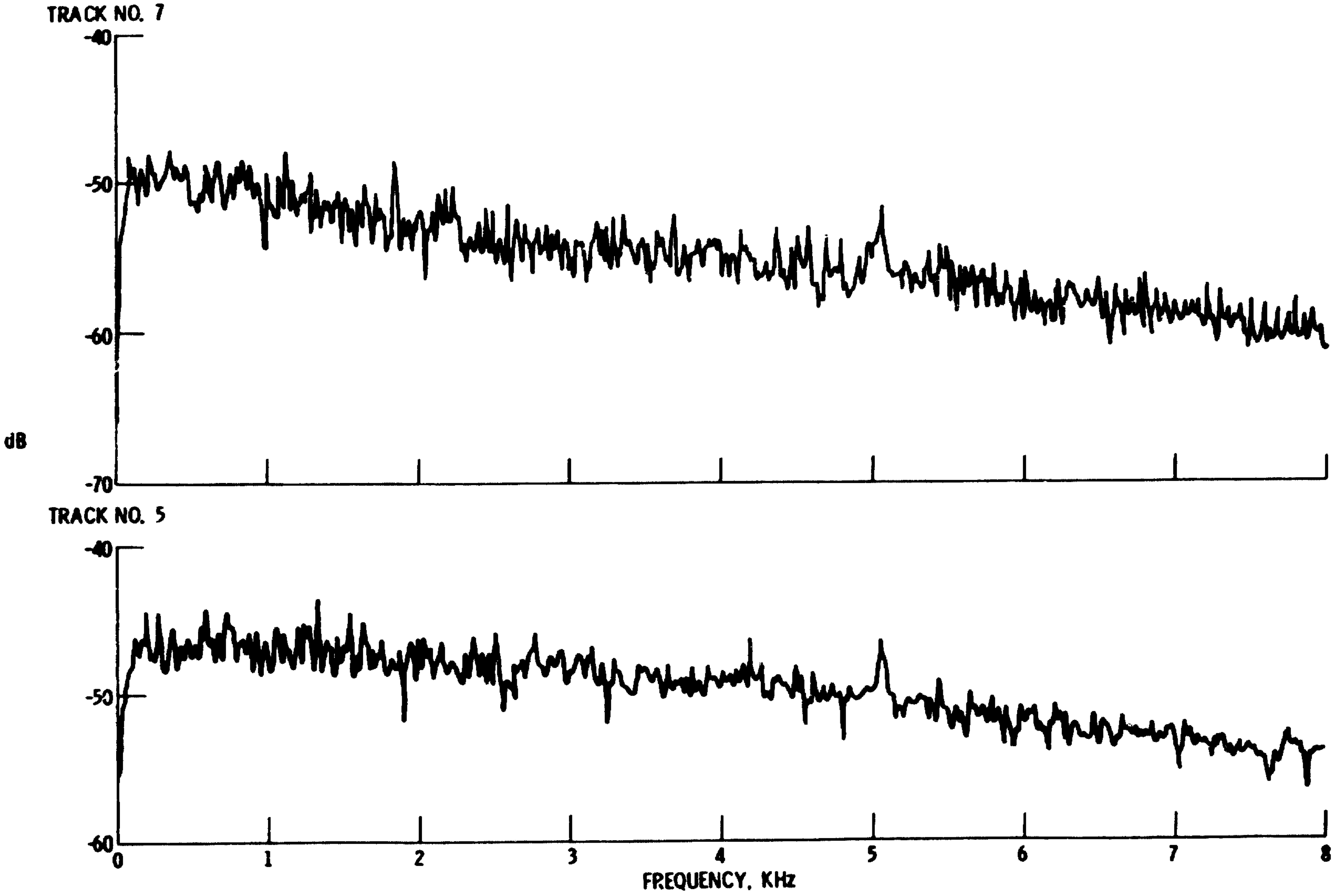
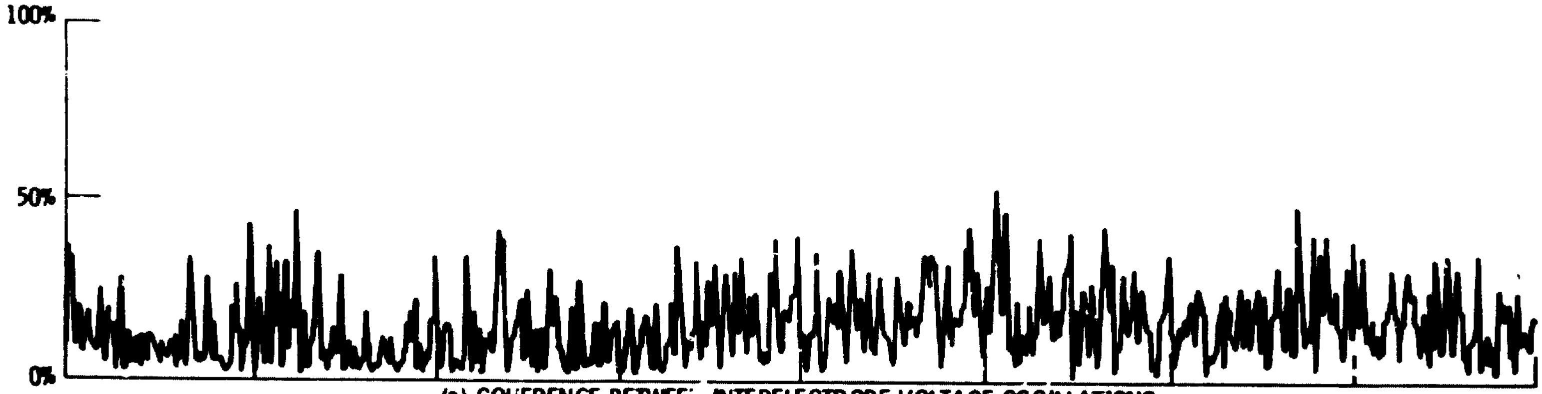
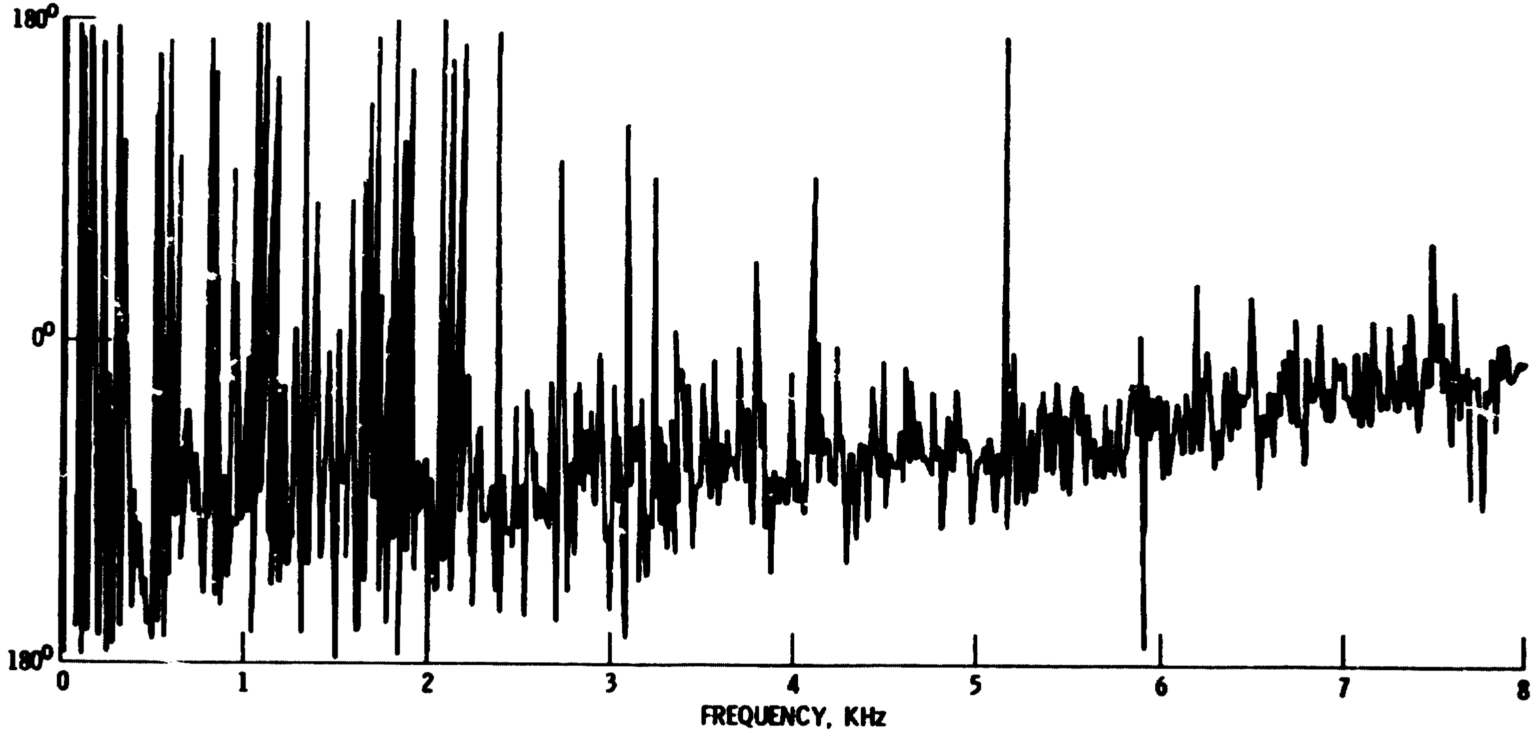


Figure 7. - Power spectral density analyses of interelectrode voltage oscillations.



(a) COHERENCE BETWEEN INTERELECTRODE VOLTAGE OSCILLATIONS.



(b) PHASE ANGLE BETWEEN INTERELECTRODE VOLTAGE OSCILLATIONS.

Figure 8.

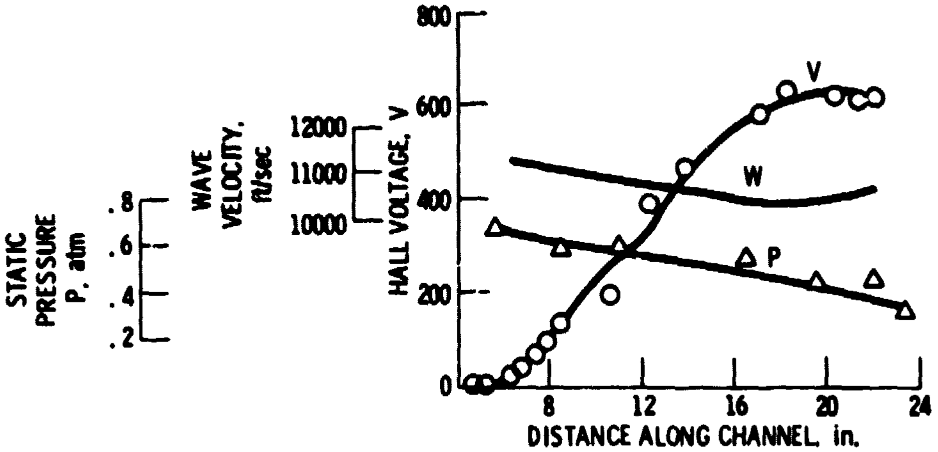


Figure 9. - Variation of hall voltage, statis pressure, and wave velocity along channel, analysis, and experimental data.

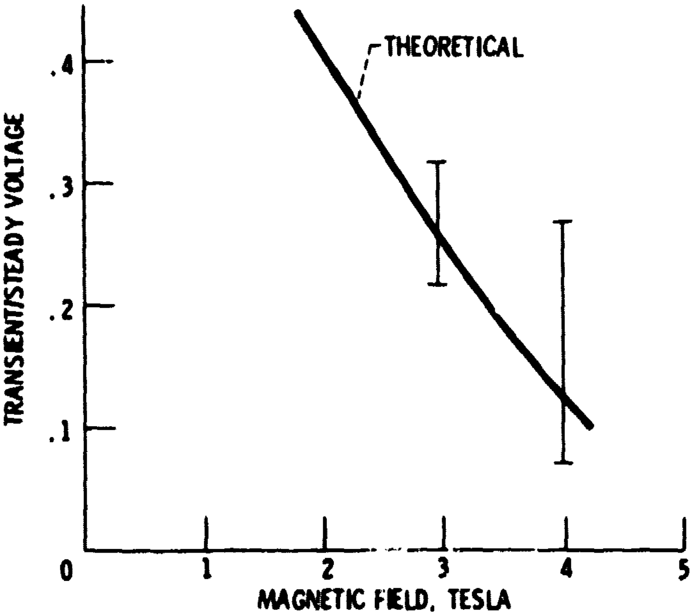


Figure 10. - Ratio of transient/steady interelectrode voltage (upstream position).