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INVESTIGATION OF FREE-STREAM FLUCTUATING PRESSURES IN THE 16-FT TUNNELS OF THE PROPULSION WIND TUNNEL FACILITY

C. D. Riddle
ARO, Inc.

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August 1967

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PROPULSION WIND TUNNEL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
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ARNOLD AIR FORCE STATION, TENNESSEE

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AEDC-TR-67-167

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FOREWORD

The work reported herein was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Elements 6340940F/632A and 6440909F/624A.

The test results presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The work was conducted under ARO Project No. PT0655 from June to July 1966, and the manuscript was submitted for publication on July 14, 1967.

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This technical report has been reviewed and is approved.

Richard W. Bradley	Leonard T. Glaser
Lt Col, USAF	Colonel, USAF
AF Representative, PWT	Director of Test
Directorate of Test	

ABSTRACT

An investigation was conducted to evaluate free-stream pressure fluctuations in the Supersonic (16S) and Transonic (16T) circuits of the Propulsion Wind Tunnel. Pressure fluctuations were observed to be less than 0.5 percent of the dynamic pressure in Tunnel 16S with no apparent discrete-frequency energy concentrations. In Tunnel 16T, unsteady pressure levels varied within an approximate range of 1 to 2 percent of the dynamic pressure for typical test conditions. Maximum values of fluctuating pressure occurred in Tunnel 16T at Mach numbers 0.70 and 0.75, where significantly large acoustical disturbances at a discrete frequency near 570 cps were observed.

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CONTENTS

APPENDIX
Illustrations

NOMENCLATURE

ΔC_p	Coefficient of the rms pressure fluctuations about the mean, $\Delta p/q_\infty$
f	Frequency, cps
M_∞	Free-stream Mach number
p	Pressure fluctuation about the mean, psf
Δp	Root-mean-square value of recorded fluctuating pressure, psf
$p_{t\infty}$	Free-stream total pressure, psf
q_∞	Free-stream dynamic pressure, psf
Re/ft	Reynolds number per foot, V_∞/ν_∞
$R(\tau)$	Autocorrelation of recorded fluctuating pressure, psf^2
t	Time, sec
V_∞	Free-stream velocity, ft/sec
ν_∞	Kinematic viscosity of the free stream, ft^2/sec
τ	Time displacement, sec
Φ	Power spectral density, psf^2/cps
ω	Circular frequency, $2\pi f$, rad/sec

SECTION I
INTRODUCTION

The subject investigation was conducted as a preliminary phase of a recent test program in the Propulsion Wind Tunnels, Supersonic (16S) and Transonic (16T) circuits of the Propulsion Wind Tunnel Facility (PWT). The primary objective of the investigation was to measure tunnel-associated unsteady pressures for subsequent evaluation of pressure fluctuations measured on a test article. This objective was compatible with a needed evaluation of test section disturbances which can influence results from various types of dynamic testing. Previous acoustical measurements have been obtained in Tunnel 16T (Ref. 1). The present investigation extends the frequency range of the Ref. 1 measurements, utilizing a probe design which was expected to influence the measurements to a lesser degree.

A 10-deg cone instrumented with microphones and transducers was used to measure free-stream disturbances at Mach numbers from 0.60 to 1.40 in 16T and at Mach numbers from 1.80 to 3.10 in 16S. Unit Reynolds number was varied from 1.42 to 4.55 million in 16T and from 0.76 to 2.13 million in 16S.

SECTION II
APPARATUS

2.1 TEST FACILITIES

Tunnel 16T is a variable density wind tunnel. The test section is 16 ft square and is lined with perforated plates to allow continuous operation through the Mach number range from 0.55 to 1.60 with minimum wall interference.

Tunnel 16S is also a variable density wind tunnel with a 16-ft-square test section. The Tunnel 16S Mach number range is from 1.70 to 3.10.

Details of the test sections showing model location and support strut arrangement are presented in Figs. 1 through 3 (Appendix). A more extensive description of each tunnel is given in the Test Facilities Handbook (Ref. 2).

2.2 CALIBRATION BODY

The calibration body consisted of a modified 10-deg cone instrumented with microphones and high-response transducers. A sketch of the cone is shown in Fig. 4. A flat surface was machined longitudinally along the top portion of the cone to permit flush-mounting of the microphones and transducers. The bottom portion of the cone was similarly flattened for symmetry. The included angle between the flat portions was 9.44 deg.

The conical design was selected in an effort to minimize body-induced pressure disturbances near the sensing instrumentation. It was assumed that a small-angle cone such as the one used would permit the location of at least a portion of the microphones and transducers under a laminar boundary layer and that the local static pressures would closely approximate the free-stream static pressure.

2.3 INSTRUMENTATION

Three microphones and three high-response transducers were used to sense pressure fluctuations. The microphones and transducers were located in pairs at approximately 5.5, 11, and 17 in. aft of the cone nose. Exact locations are shown in Fig. 4. Details of an installed microphone and transducer pair are given in Fig. 5. The microphones are a capacitor-type with a diaphragm-diameter of 0.234 in. The manufacturer's specifications indicated the microphone responses to be flat from approximately 70 to 40,000 cps. The transducers are a strain-gage type with a diaphragm diameter of 0.125 in. Each transducer was referenced to a steady-state pressure approximately equal in magnitude to the free-stream static pressure. A laboratory calibration showed a flat response from 0 to approximately 10,000 cps for the transducers.

The transducer and microphone outputs were recorded on magnetic tape in a frequency modulated (FM) mode at 120 in./sec in Tunnel 16T and were recorded in both direct and FM modes at 15 in./sec in Tunnel 16S.

SECTION III
TEST DESCRIPTION

3.1 PROCEDURE

The test procedure required a magnetic tape recording of microphone and transducer outputs at a calibration cone angle of attack, α, of 0 deg for various Mach numbers and tunnel pressures. During each recording, pertinent tunnel conditions were computed and tabulated by means of the data processing system described in Ref. 2. The magnetic tape record lengths were approximately 10 sec in Tunnel 16T and 30 sec in Tunnel 16S. The variation of Reynolds number with Mach number for the subject investigation is presented in Fig. 6.

3.2 DATA REDUCTION

Root-mean-square (rms) values of the transducer or microphone outputs were measured by an rms voltmeter which averaged a 10-sec sample length of data. An appropriate conversion constant was then employed to derive rms pressure levels from the rms voltage outputs.

An automatic wave analyzer was utilized to obtain power spectral density (psd) and autocorrelation plots. The psd analyses were conducted for frequency ranges of 0 to 150 cps and 0 to 10,000 cps, using bandpass filters of 1 and 50 cps, respectively. For the autocorrelation plots, the time displacement, τ, was varied from 0 to 0.015 sec.

The psd function, Φ, is related to the mean square value of a fluctuating pressure as follows:

$$(\Delta p)^2 = \frac{1}{2\pi}\int_0^{\omega_1} \Phi d\omega$$

or, more conveniently,

$$(\Delta p)^2 = \int_0^{f_1} \Phi df$$

where f_1 is the highest frequency of the power spectrum analysis (150 or 10,000 cps in the present investigation), and Φ is the power spectral density in units of psf^2/cps.

The autocorrelation function, $R(\tau)$, is a product of two p functions, namely,

$$R(\tau) = E\,[p(t)\;p(t+\tau)]$$

Moreover, when $\tau = 0$,

$$R(\tau) = (\Delta p)^2$$

A more complete description of the autocorrelation and psd functions is given in Ref. 3.

3.3 UNCERTAINTIES

The estimated precision of measurements for tunnel conditions is as follows:

Mach number	0.60 to 1.10	±0.003
	1.20 to 1.40	±0.010
	1.80 to 3.10	±0.020
Dynamic Pressure	$M_\infty \leq 1.40$	±4 psf
	$M_\infty > 1.40$	±3 psf

The uncertainties quoted for Mach number relate to the variation of Mach number in the vicinity of the calibration body. The uncertainty in setting Mach number varied from ±0.003 to ±0.010 with increasing Mach number.

The data uncertainties, estimated as percent of presented value, are as follow:

Φ	±15 percent
$R(\tau)$	±10 percent
ΔC_p	±10 percent

SECTION IV
RESULTS AND DISCUSSION

As noted in Section I, tunnel disturbance data were recorded in both the Supersonic (16S) and Transonic (16T) circuits of the Propulsion Wind Tunnel. The wind-off noise levels of the sensing instrumentation used in Tunnel 16S were a sizeable portion of the air-on output signals and precluded an accurate measurement of the test section pressure disturbances. It was, however, apparent that these pressure levels were consistently low and in no case exceeded 0.5 percent of the free-stream dynamic pressure. Power spectral density analyses of the 16S data revealed no significant discrete-frequency concentrations of energy. In the absence of measurable Tunnel 16S pressure disturbances, data are presented for Tunnel 16T only.

Variations of the rms fluctuating pressure coefficient, ΔC_p, with Mach number are presented for nominal total-pressure levels of 900 and

1600 psf in Fig. 7. Values of ΔC_p are presented for forward, center, and aft microphone locations and for center and aft transducer locations. The microphones yielded larger values of ΔC_p at all Mach numbers for which data were obtained in Tunnel 16T. The difference in microphone and transducer outputs is probably indicative of the more extensive frequency range for which the microphones were responsive to acoustical disturbances (see Section 2.3), and it is likely that the microphone outputs more nearly describe the total fluctuating pressure energy present in the airstream. It is interesting to note that the microphones and transducers exhibited similar trends of ΔC_p with Mach number, an indication that the more significant variations in test section disturbances occurred at frequencies within the transducer response range of 0 to approximately 10,000 cps. Well-defined maximum values of ΔC_p occurred for a total pressure, p_{t_∞}, of 1600 psf at Mach numbers 0.70 and 0.75, where the microphones yielded ΔC_p values of approximately 0.02.

The previous investigation of Tunnel 16T fluctuating pressure characteristics (Ref. 1) utilized separate, transducer-instrumented installations of a wedge, a probe-wing, and an ogive-cylinder. The frequency range of the transducers employed in the previous study varied from 5 to 1000 cps. A conclusive comparison of Ref. 1 data with results reported herein is inhibited by differences in configuration geometry and instrumentation specifications, but certain similarities are evident. In particular, the ogive-cylinder yielded variations of ΔC_p with Mach number which correlate reasonably well with the data presented in Fig. 7.

The variations of ΔC_p with p_{t_∞} are presented for Mach numbers 0.60 and 1.40 in Fig. 8. For the microphones at Mach number 0.60, ΔC_p tended to decrease as p_{t_∞} was increased. At Mach number 1.40, the center and aft microphones exhibited decreasing ΔC_p with increasing p_{t_∞}; however, the forward microphone displayed a lower and invariant ΔC_p.

The lower values of ΔC_p for the forward microphone at Mach number 1.40 would suggest a change in boundary-layer conditions between the forward and center microphones. Accordingly, unpublished results from a previous investigation were reviewed in an effort to predict the boundary-layer characteristics along the calibration body. The previous data consisted of surface temperature measurements on a 5-deg cone and revealed a transition Reynolds number of approximately three million at Mach number 1.40. Neglecting cone angle effects, the previous data predict the calibration body transition locations shown in Fig. 9. It is apparent in Fig. 9 that the forward and center microphones were likely within a laminar boundary layer at most of the p_{t_∞} levels for which acoustical data are presented. The differences noted in Fig. 8b are therefore probably not related to boundary-layer effects. It is also interesting to note that, although transition may have occurred between the center and aft microphones as indicated in Fig. 9, there was no significant change in the relative fluctuating pressure levels exhibited by these two microphones in Fig. 8b.

Power spectra and autocorrelograms are presented for the forward microphone in Figs. 10 and 11, respectively. The power spectra were obtained for a frequency range of 0 to 10,000 cps, utilizing a 50-cps bandwidth filter. Variations in the power spectra were negligible at frequencies above approximately 3000 cps. A 0- to 6000-cps range was arbitrarily chosen for the Fig. 10 presentation. Significant fluctuating pressure energy concentrations were observed at Mach numbers 0.70 and 0.75 (Figs. 10a and b) where the power spectra exhibited peaks of uniquely large density near 600 cps. The contribution of these energy peaks to the total fluctuating pressure level is apparent in Fig. 7b where, as previously noted, ΔC_p was of maximum magnitude at Mach numbers 0.70 and 0.75. Autocorrelograms at Mach numbers 0.70 and 0.75 (Fig. 11a) reveal a discrete frequency of approximately 570 cps which corresponds to the peaks in the power spectra. Peaks near 600 cps were also evident in the power spectra at Mach numbers 0.60 and 0.80, but were not of sufficient strength to define a discrete frequency in the corresponding autocorrelograms. Discrete frequency disturbances could in fact be ascertained only at Mach numbers 0.70 and 0.75.

A smaller peak in the power spectra occurs at Mach numbers 0.70 and 0.75 at a frequency near 1750 cps. This "secondary" peak remains at the higher Mach numbers but occurs at an increasingly higher frequency as Mach number is increased from 0.75 to 1.30, its highest frequency location being approximately 2900 cps at Mach numbers 1.30 and 1.40.

Because the microphone responses were of questionable accuracy at frequencies below approximately 70 cps, analyses of the center transducer outputs were conducted in an effort to better determine the low frequency fluctuating pressure characteristics. The transducer data were analyzed from 0 to 150 cps using a 1-cps bandwidth filter. The power spectra for the transducer indicated little variation in density from 150 cps down to near 20 cps, with a sharp increase in density as frequency approached 0 cps. The low-frequency rise in the power spectra was not associated with any significant variations in ΔC_p magnitudes (see Fig. 7b) and therefore probably had a minimal effect on the disturbance energy level at these Mach numbers.

The effects of tunnel-associated acoustical disturbances on acoustical data measured for a test model are of obvious interest to the investigator. State-of-the-art knowledge regarding such effects is unfortunately quite limited at present. Tunnel 16T tests involving the measurement of model surface acoustical characteristics have revealed rms pressure levels which were in some cases lower than free-stream levels presented herein. Specific examples can be found in Ref. 4 where values of ΔC_p presented for cone-cylinder configurations are lower than the values shown in Fig. 7 at certain test conditions. Such comparisons indicate that a direct subtraction of the measured free-stream noise level from the corresponding model data does not yield a valid correction.

SECTION V
CONCLUSIONS

The following conclusions resulted from the investigation of free-stream fluctuating pressures in the 16-ft tunnels of PWT:

1. Fluctuating pressure levels measured in Tunnel 16S were less than 0.5 percent of the dynamic pressure, and those measured in Tunnel 16T varied within an approximate range of 1 to 2 percent of the dynamic pressure.
2. Maximum values of the fluctuating pressure coefficient occurred in Tunnel 16T at Mach numbers 0.70 and 0.75.
3. Significant fluctuating pressure energy concentrations exhibiting a discrete frequency of approximately 570 cps occurred at Mach numbers 0.70 and 0.75. Discrete-frequency disturbances were not evident at the other Mach numbers for which data were obtained.

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1. Chevalier, H. L. and Todd, H. E. "Measurement of the Pressure Fluctuations in the Test Section of the 16-Foot Transonic Circuit in the Frequency Range from 5 to 1000 cps." AEDC-TN-61-51 (AD255763), May 1961.
2. Test Facilities Handbook (6th Edition). "Propulsion Wind Tunnel Facility, Vol. 5." Arnold Engineering Development Center, November 1966.
3. Bendat, Julius S. and Piersol, Allan G. "Measurement and Analysis of Random Data." John Wiley and Sons, Inc., New York, 1966.
4. Robertson, J. E. "Wind Tunnel Investigation of the Effects of Reynolds Number and Model Size on the Steady and Fluctuating Pressures Experienced by Cone-Cylinder Missile Configurations at Transonic Speeds." AEDC-TR-66-266 (AD808699), March 1967.

APPENDIX
ILLUSTRATIONS

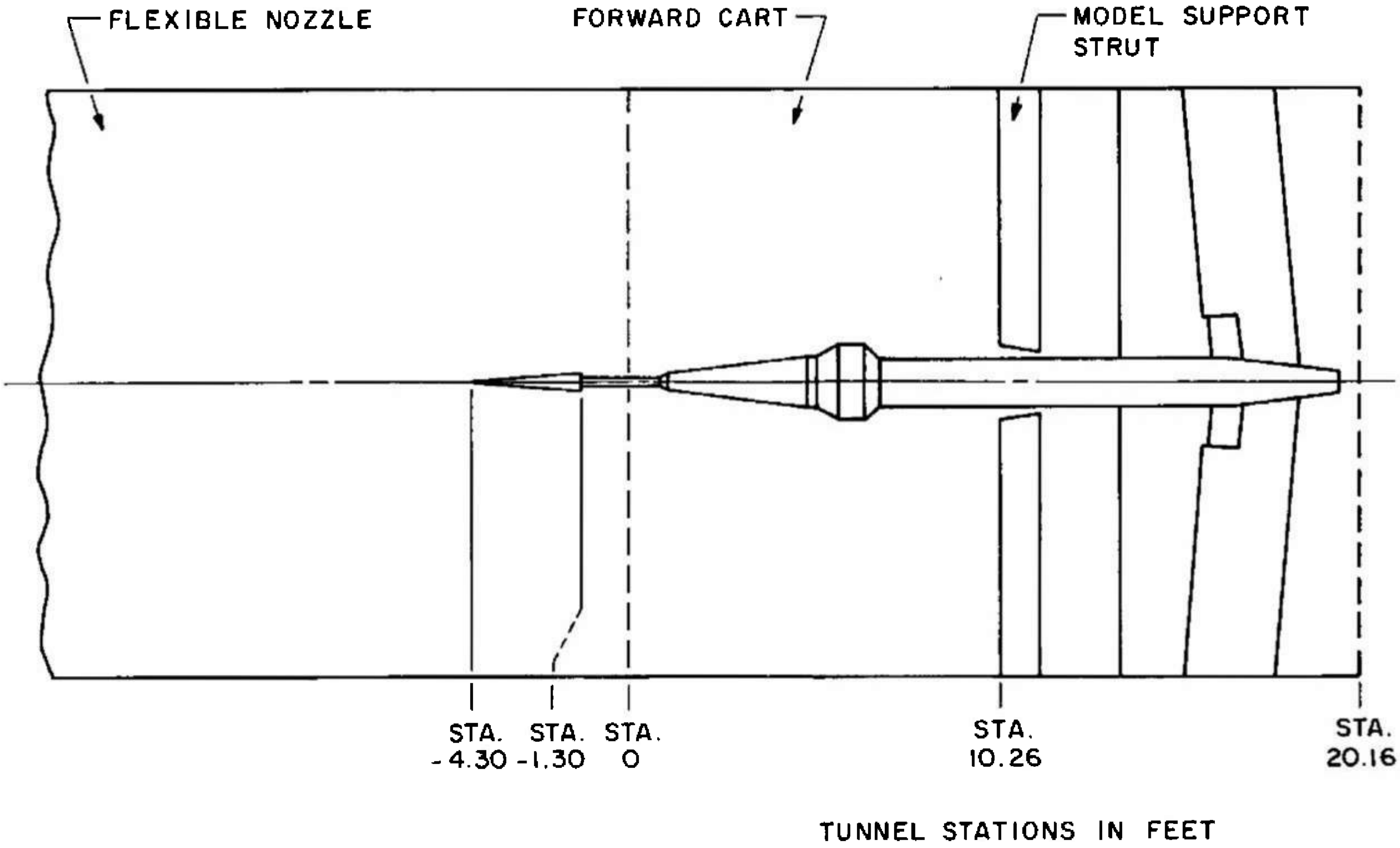


Fig. 1 Sketch of the Tunnel 16S Test Section Showing the Calibration Body Installation

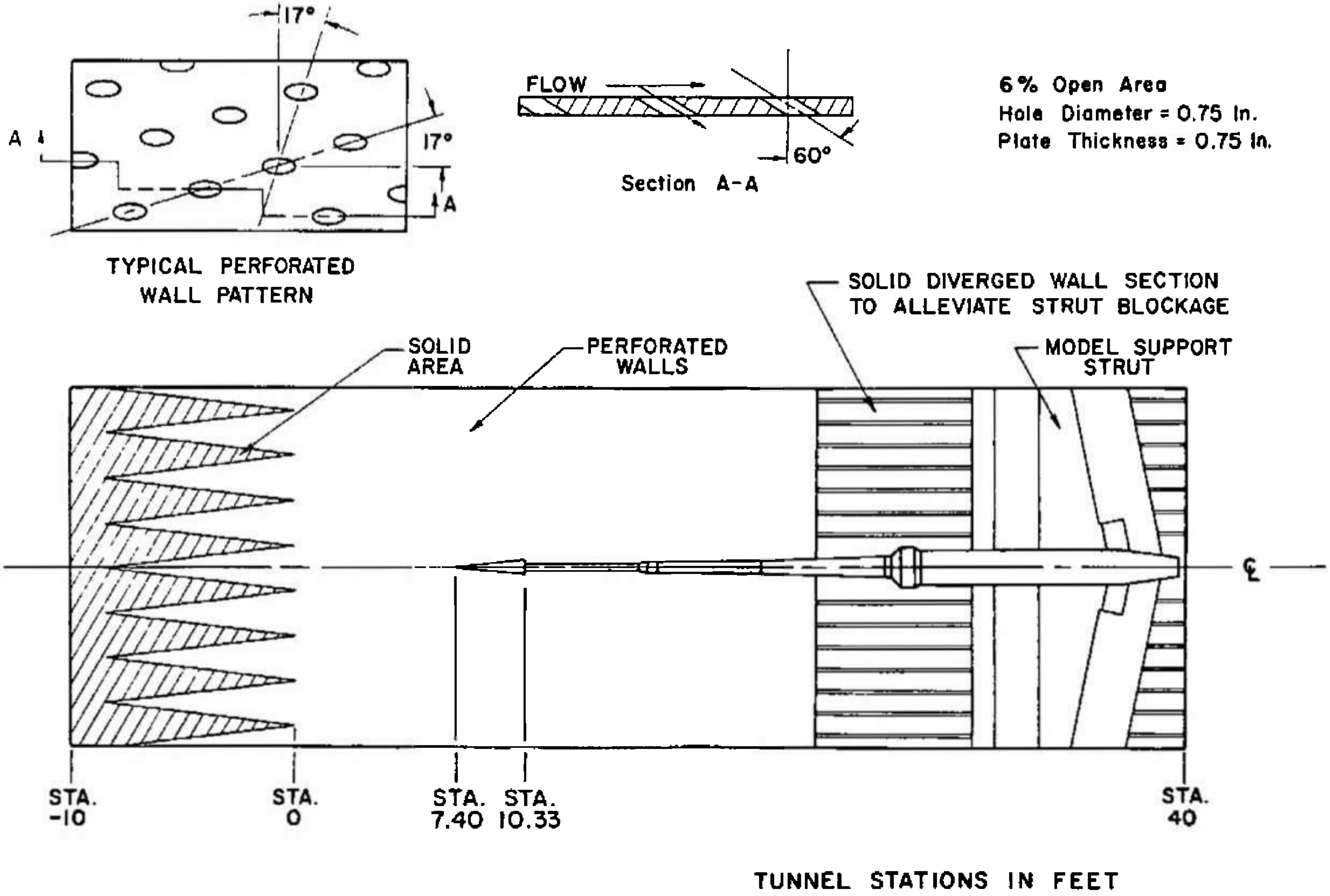


Fig. 2 Sketch of the Tunnel 16T Test Section Showing the Calibration Body Installation

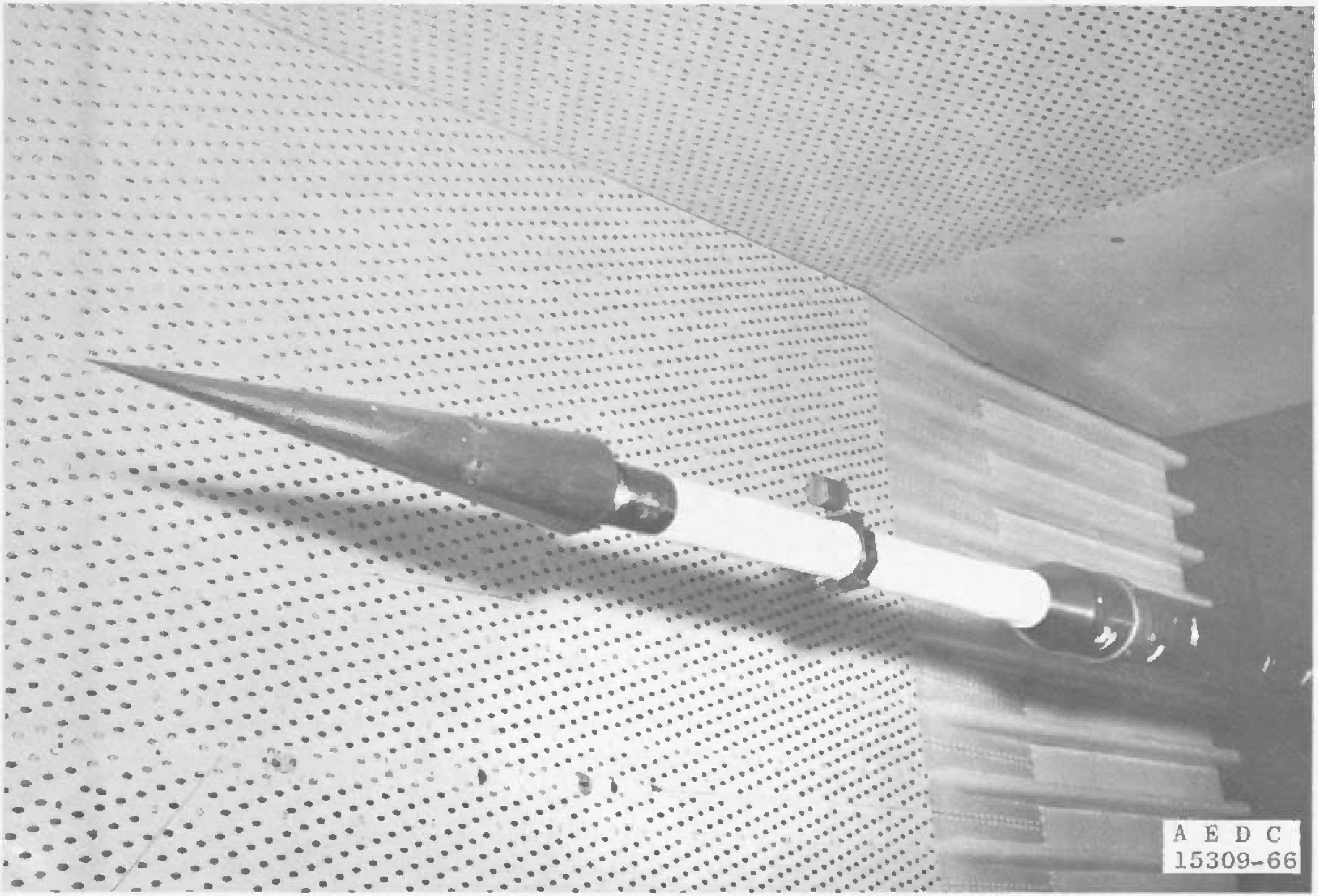
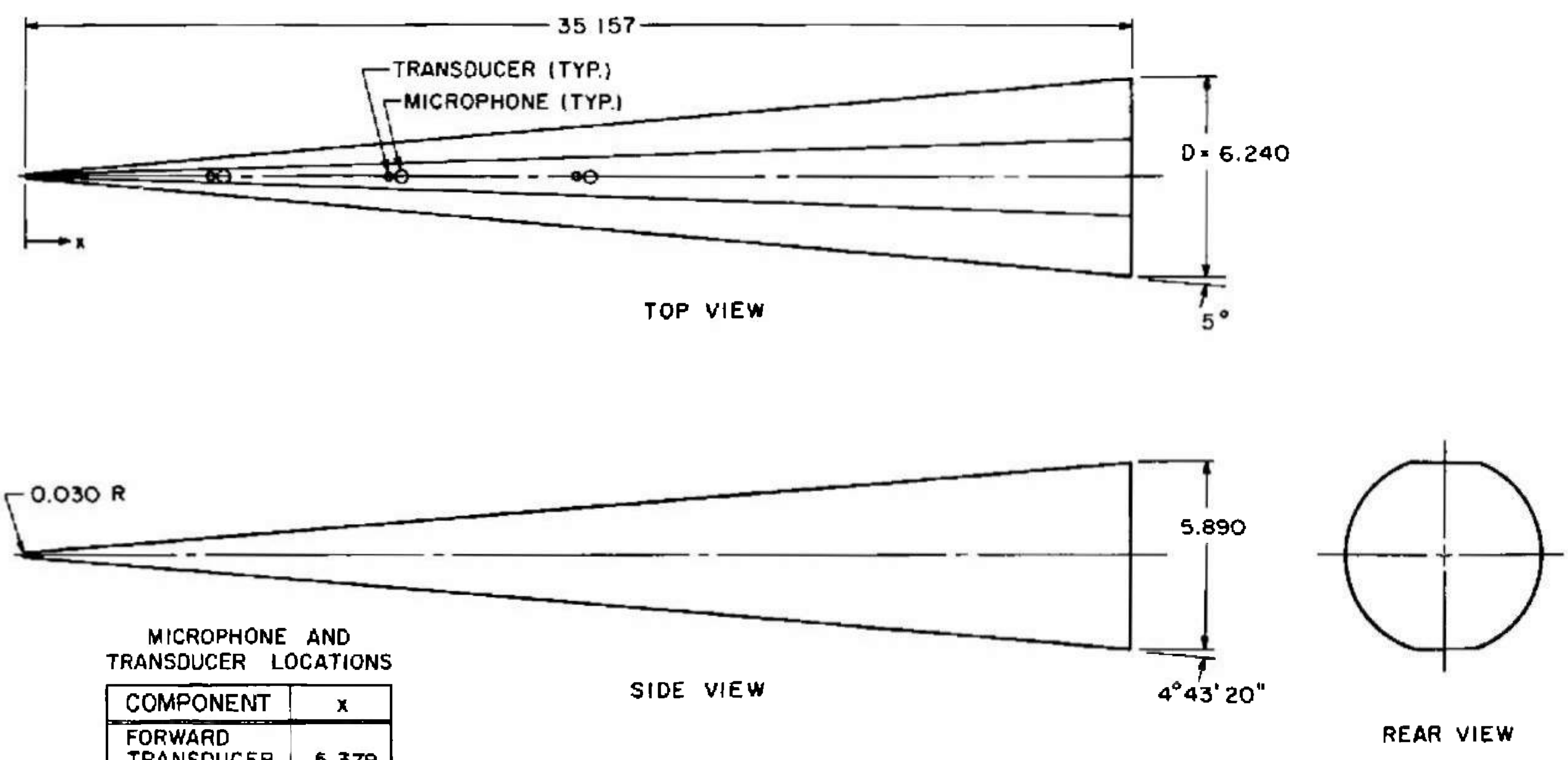


Fig. 3 Photograph of the Calibration Body Installed in Tunnel 16T



MICROPHONE AND TRANSDUCER LOCATIONS

COMPONENT	x
FORWARD TRANSDUCER	5.379
FORWARD MICROPHONE	5.741
CENTER TRANSDUCER	10.982
CENTER MICROPHONE	11.350
AFT TRANSDUCER	16.973
AFT MICROPHONE	17.347

ALL DIMENSIONS IN INCHES

Fig. 4 Details of the Calibration Body Showing Microphone and Transducer Locations

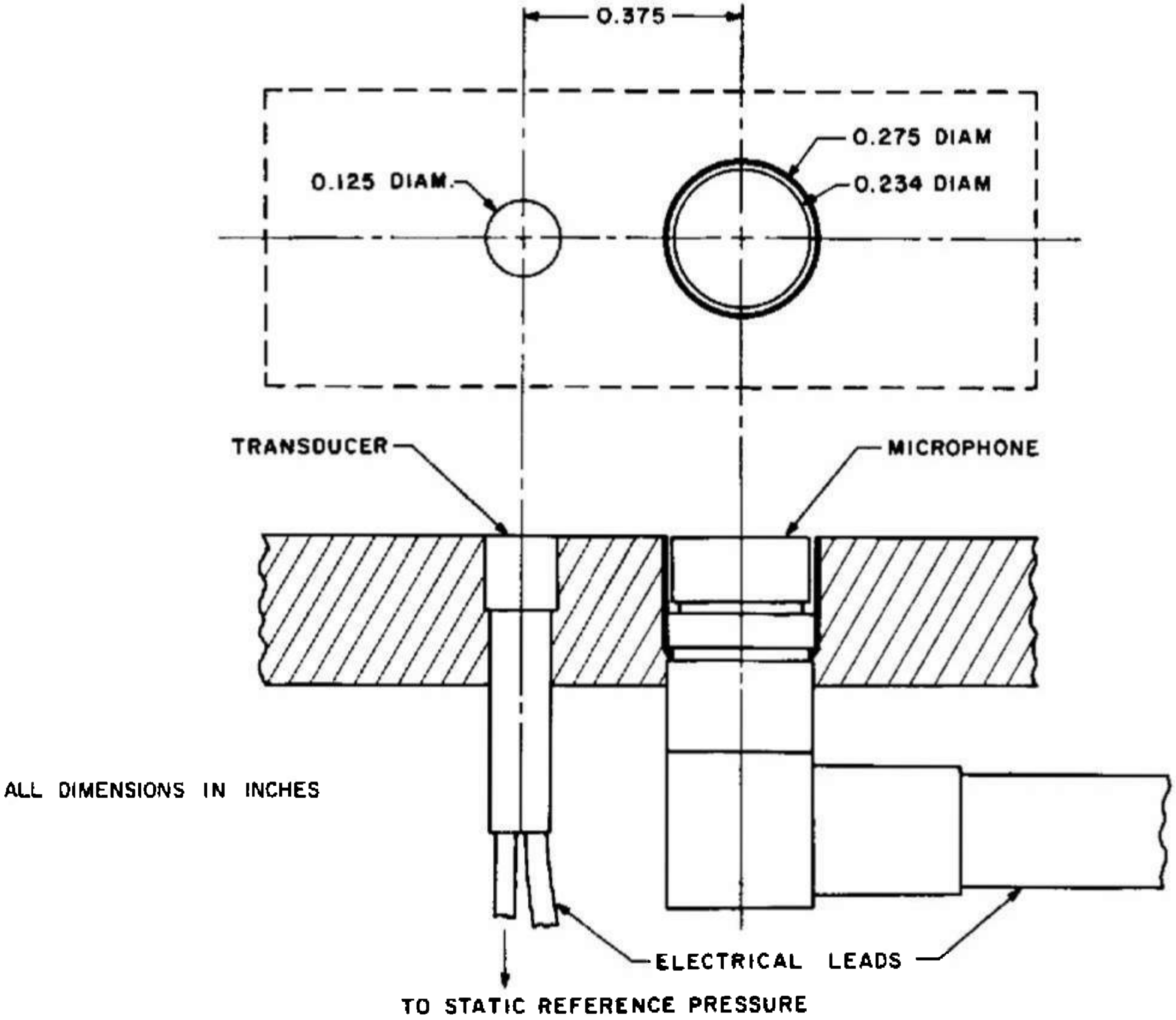


Fig. 5 Microphone and Transducer Installation Details

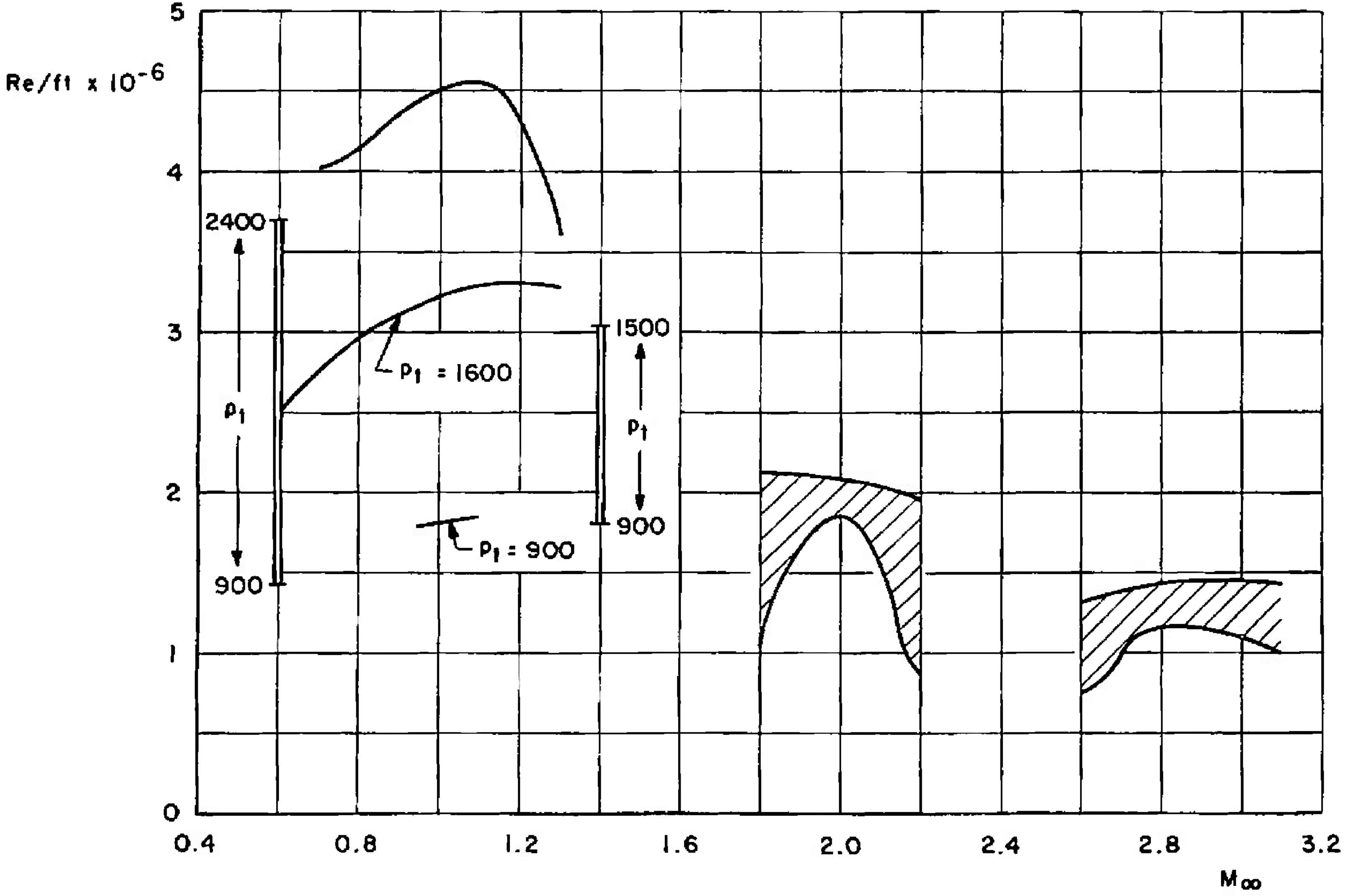
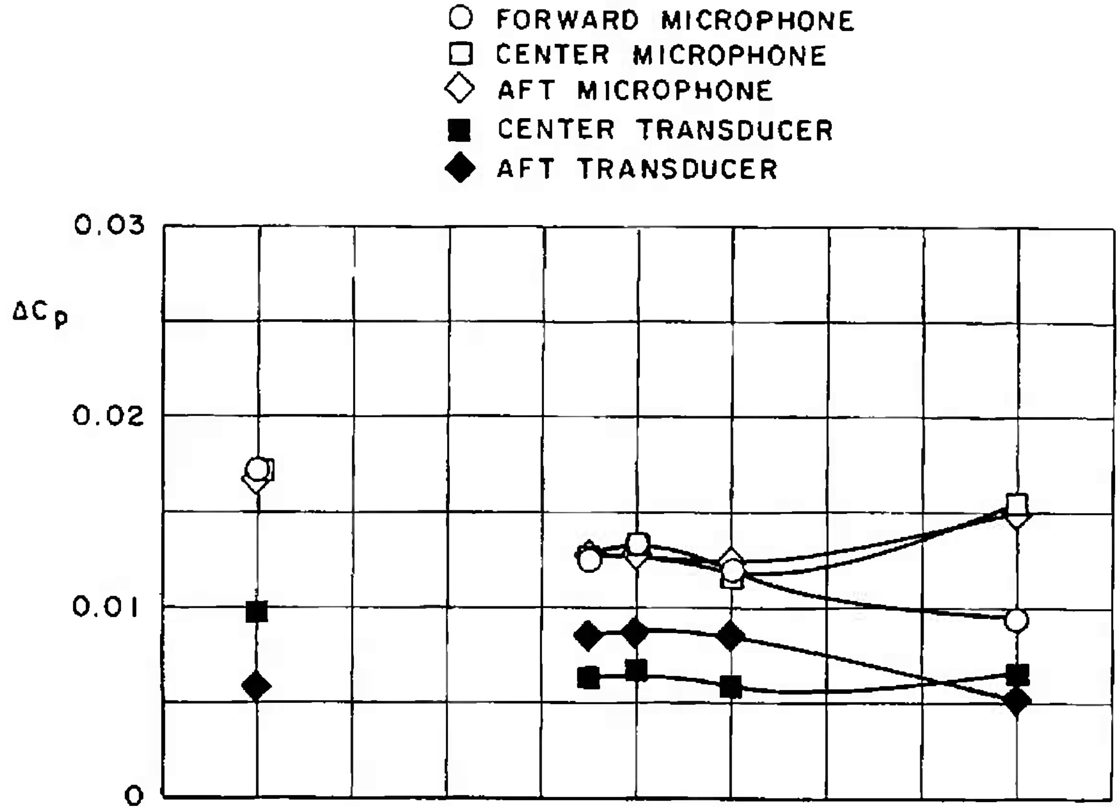
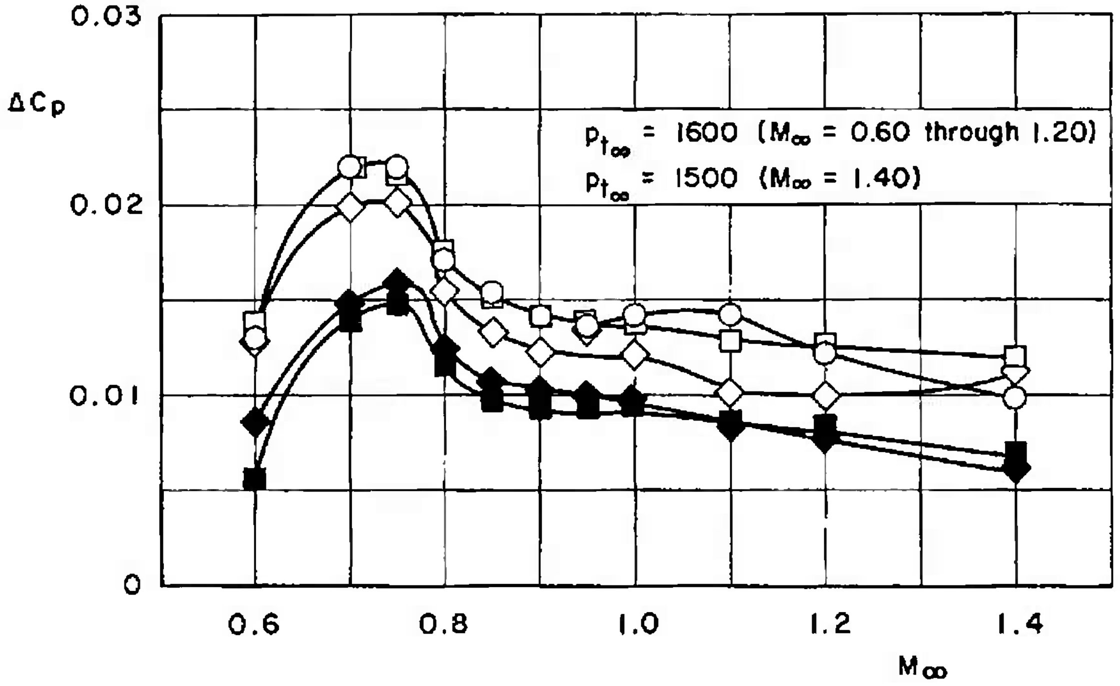


Fig. 6 Variation of Reynolds Number with Mach Number

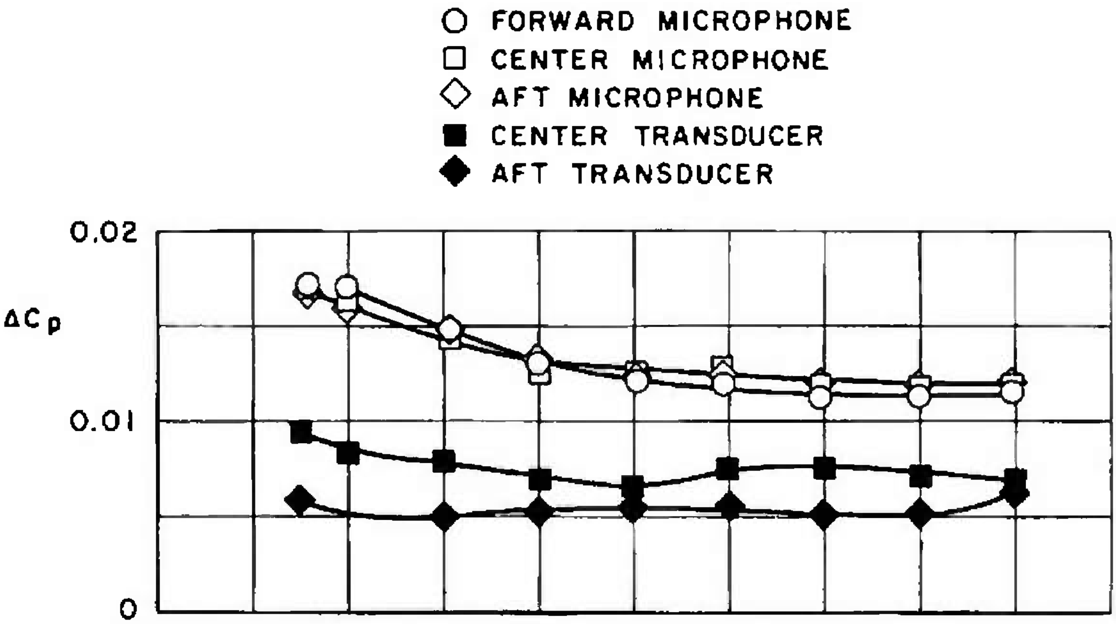


a. $p_{t_\infty} = 900$

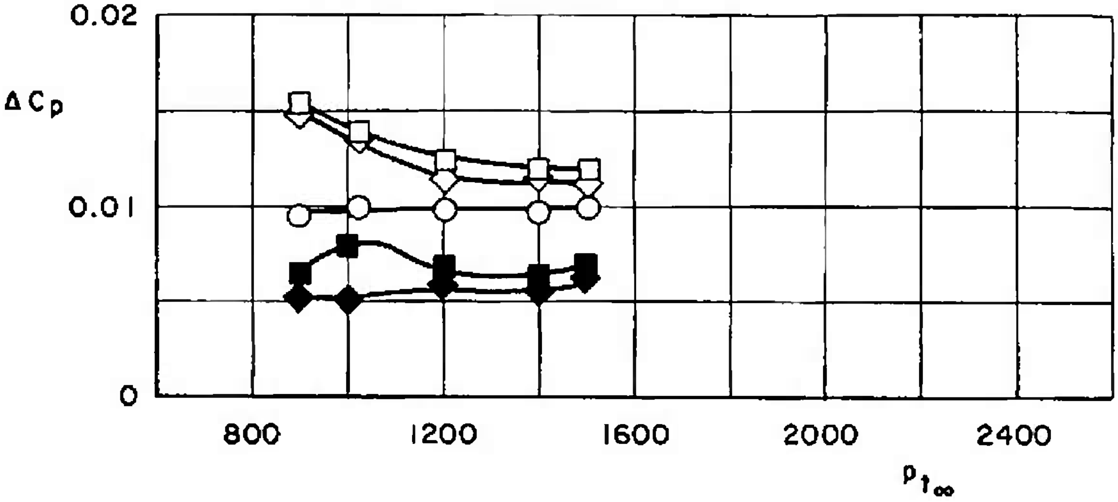


b. $p_{t_\infty} = 1600$

Fig. 7 Variation of Fluctuating Pressure Coefficient with Mach Number



a. $M_\infty = 0.60$



b. $M_\infty = 1.40$

Fig. 8 Variation of Fluctuating Pressure Coefficient with Total Pressure

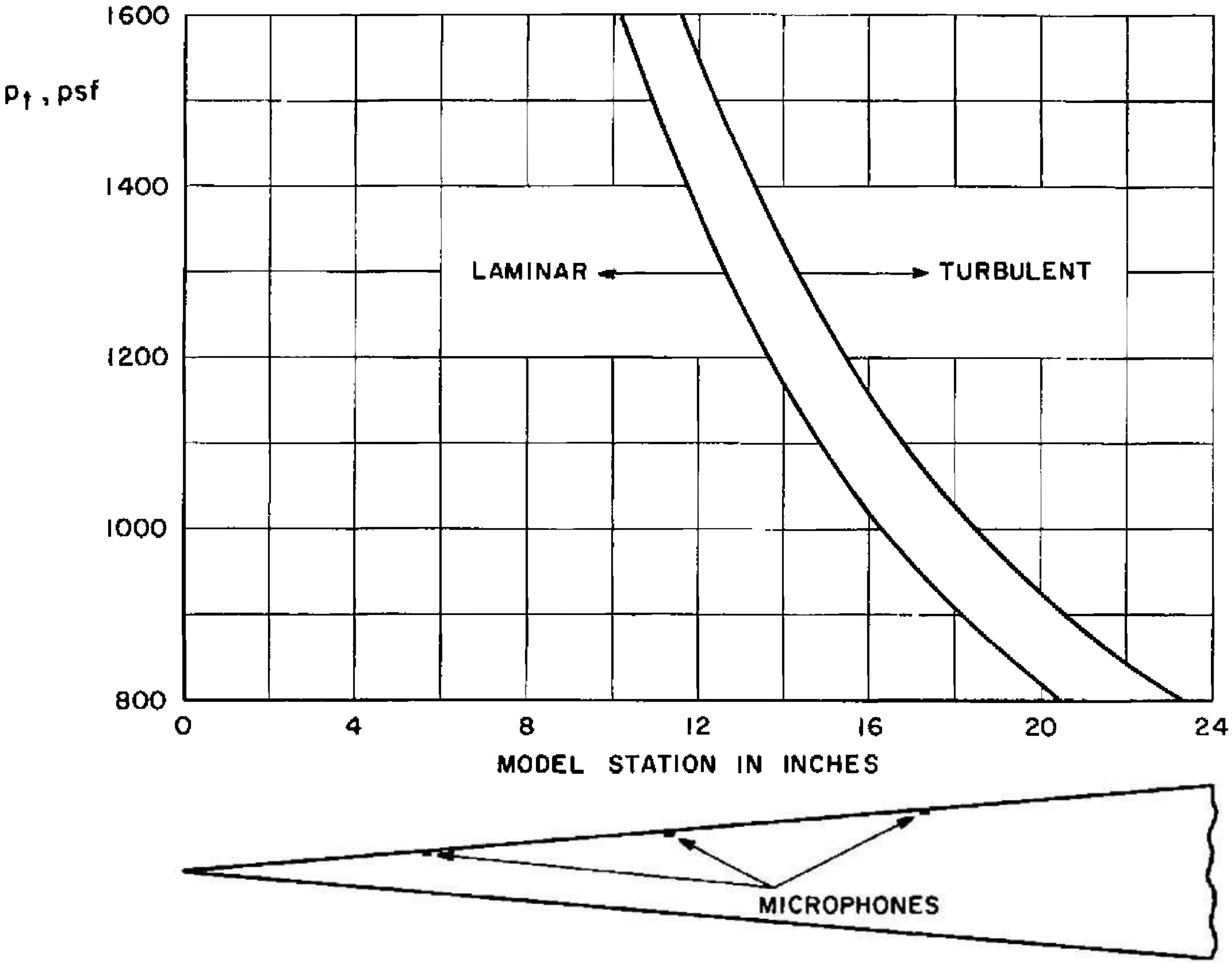
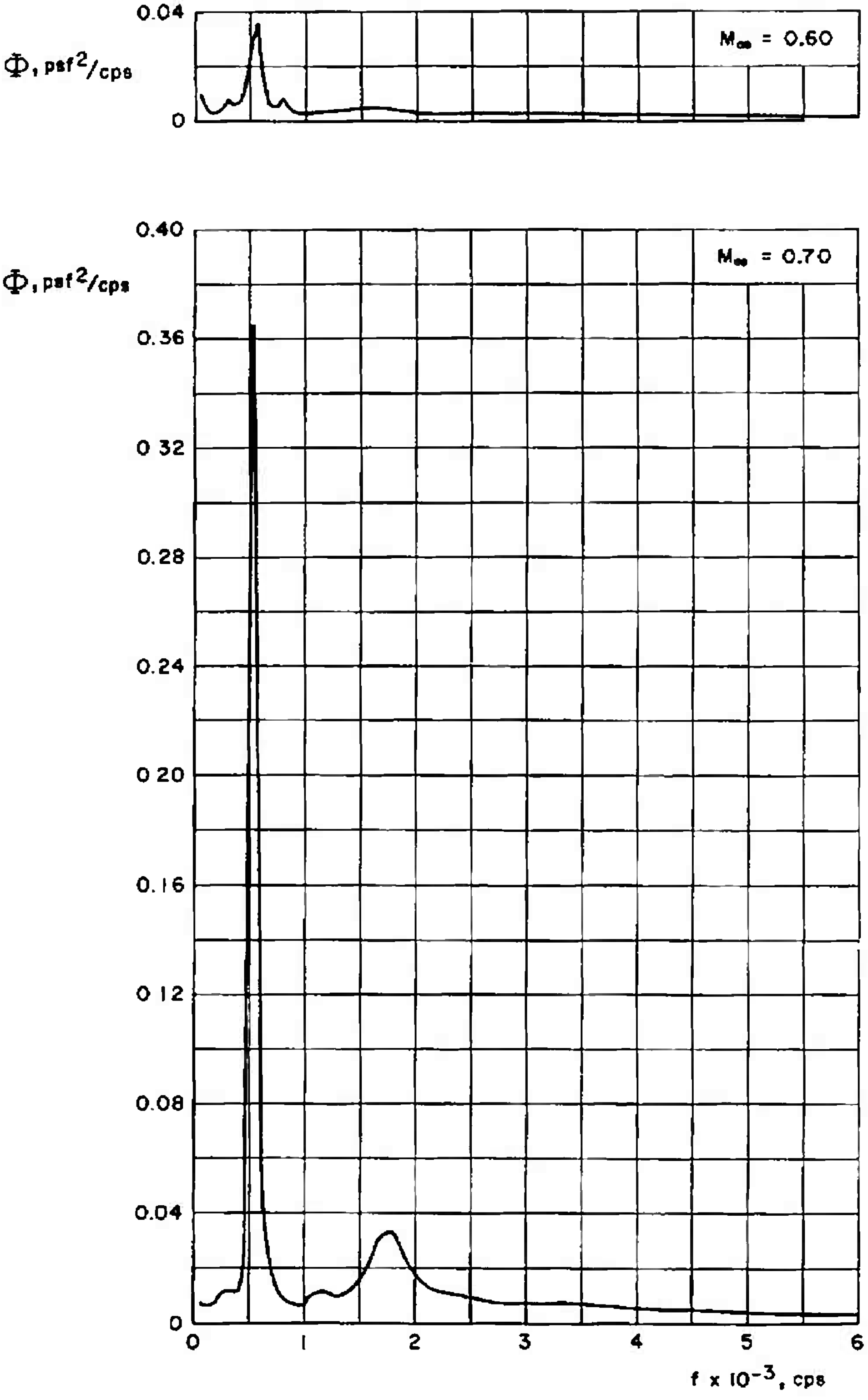
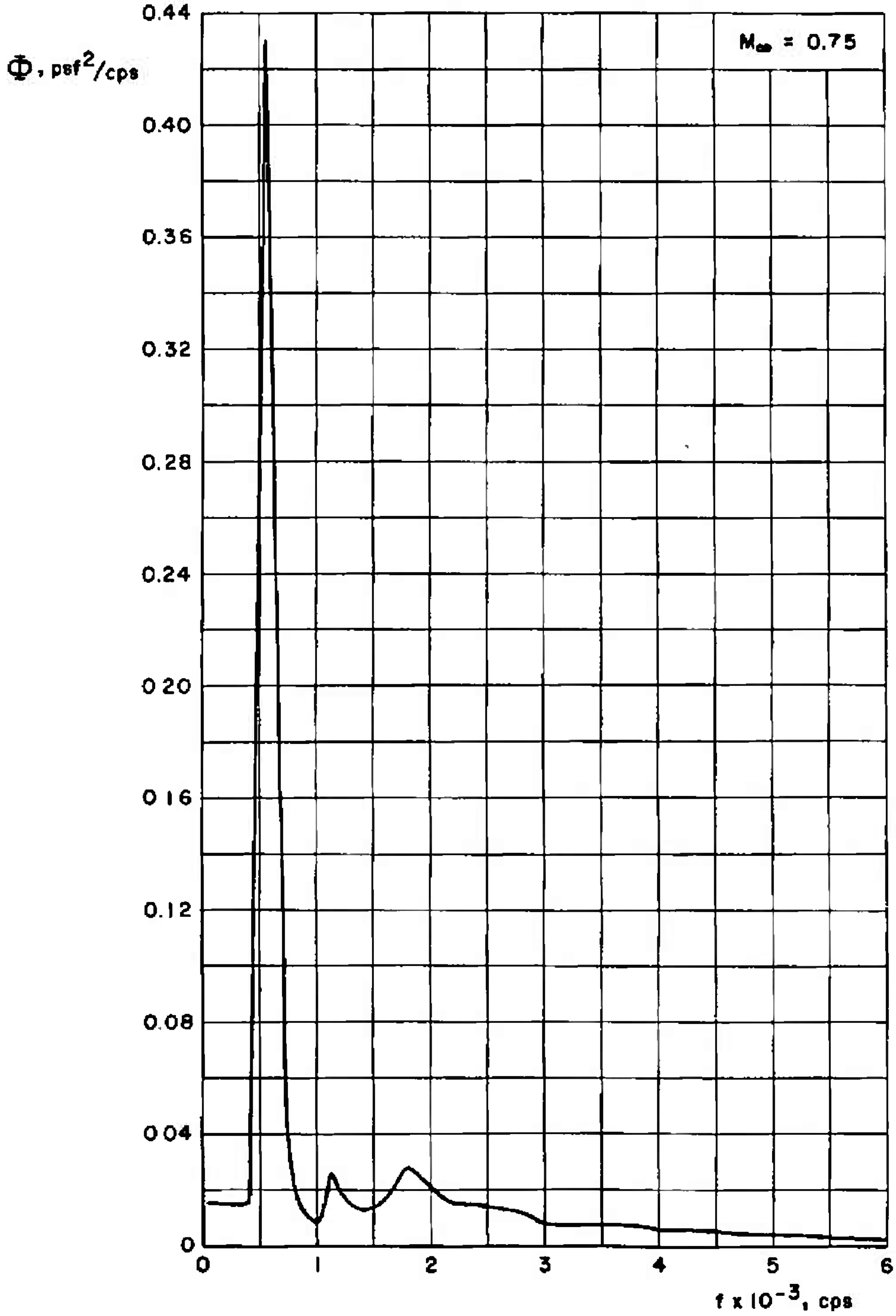


Fig. 9 Predicted Location of Boundary-Layer Transition for the Calibration Body at Mach Number 1.40

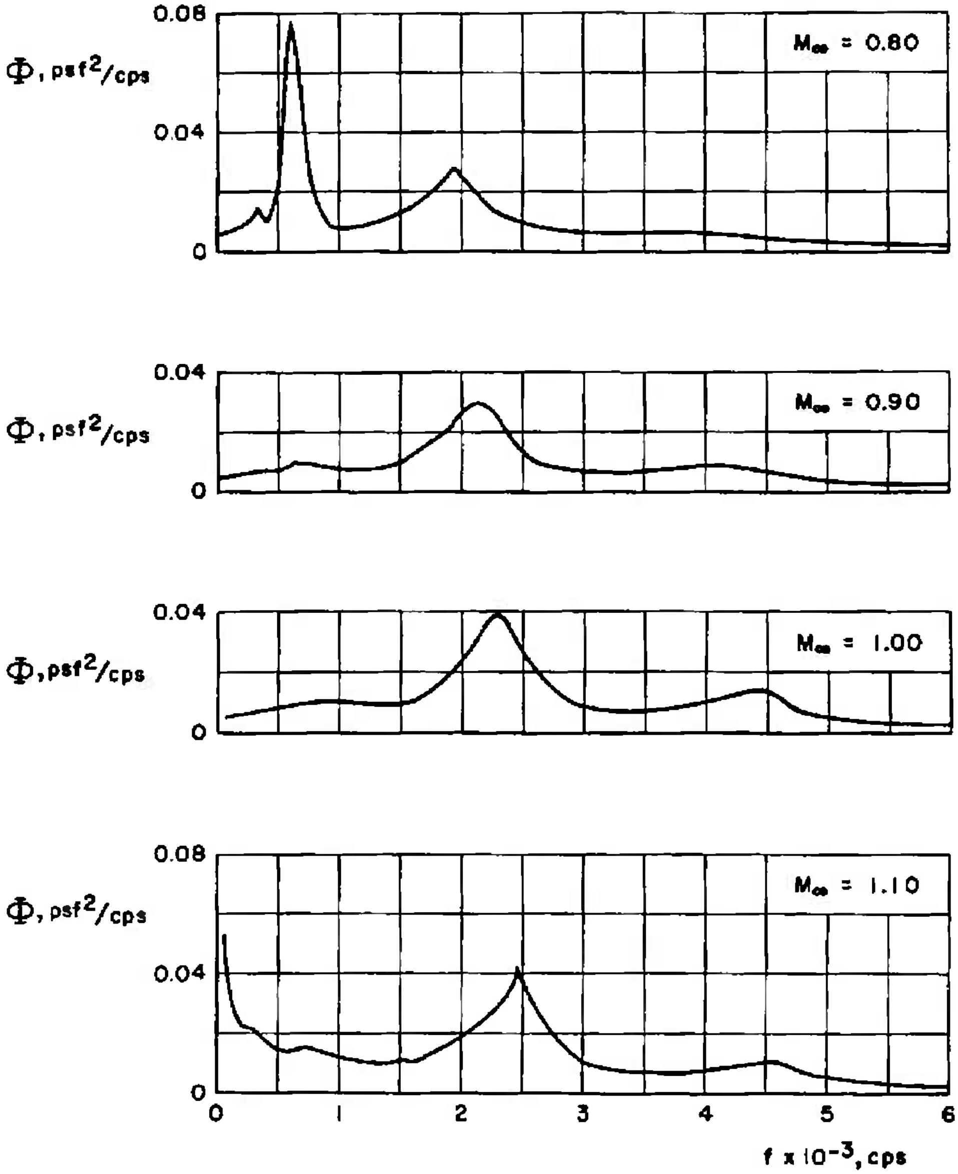


a. M_∞ = 0.60 and 0.70

Fig. 10 Variation of Power Spectral Density with Frequency for the Forward Microphone at p_{t_∞} = 1600 psf

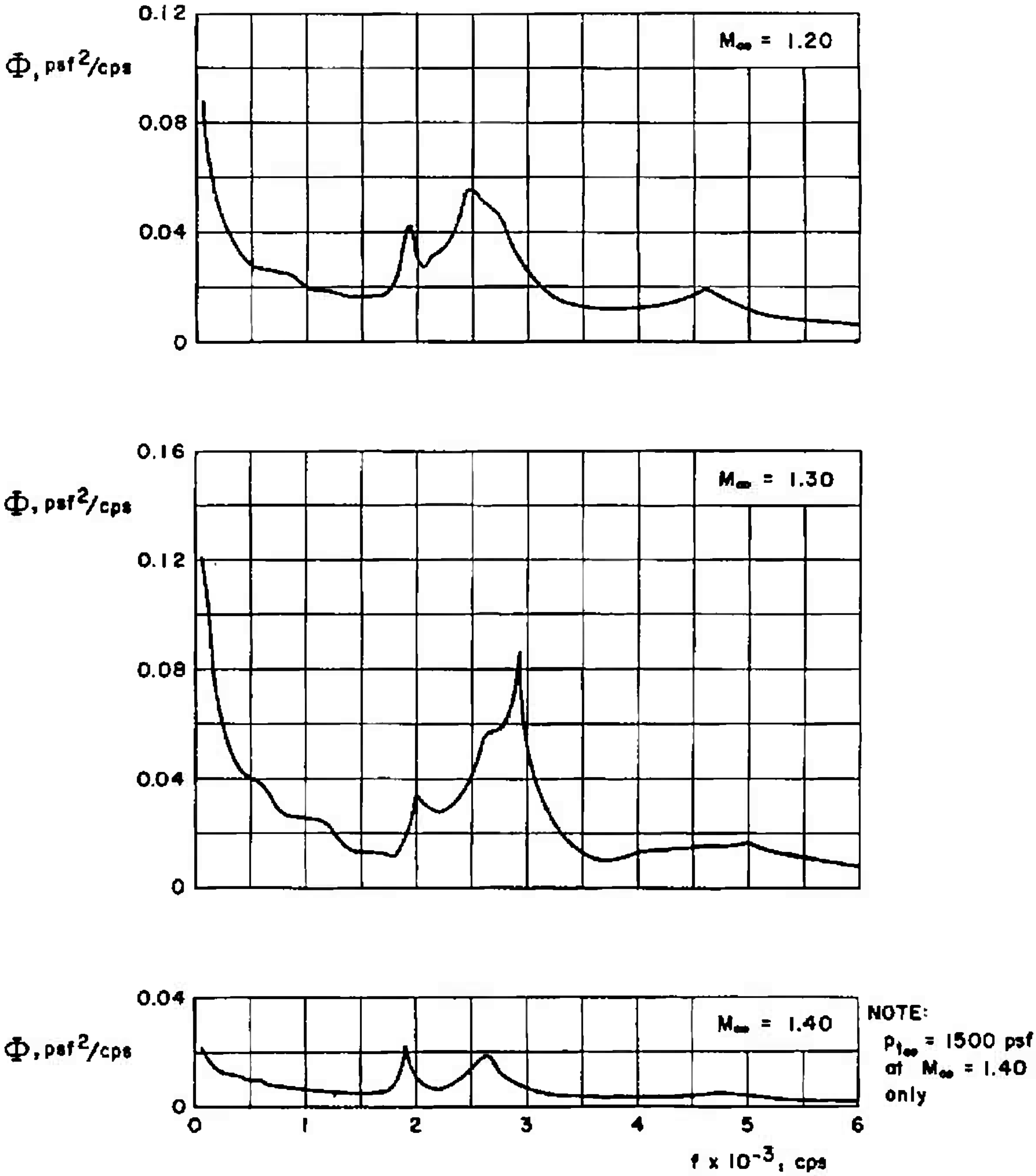


b. M_∞ = 0.75
Fig. 10 Continued



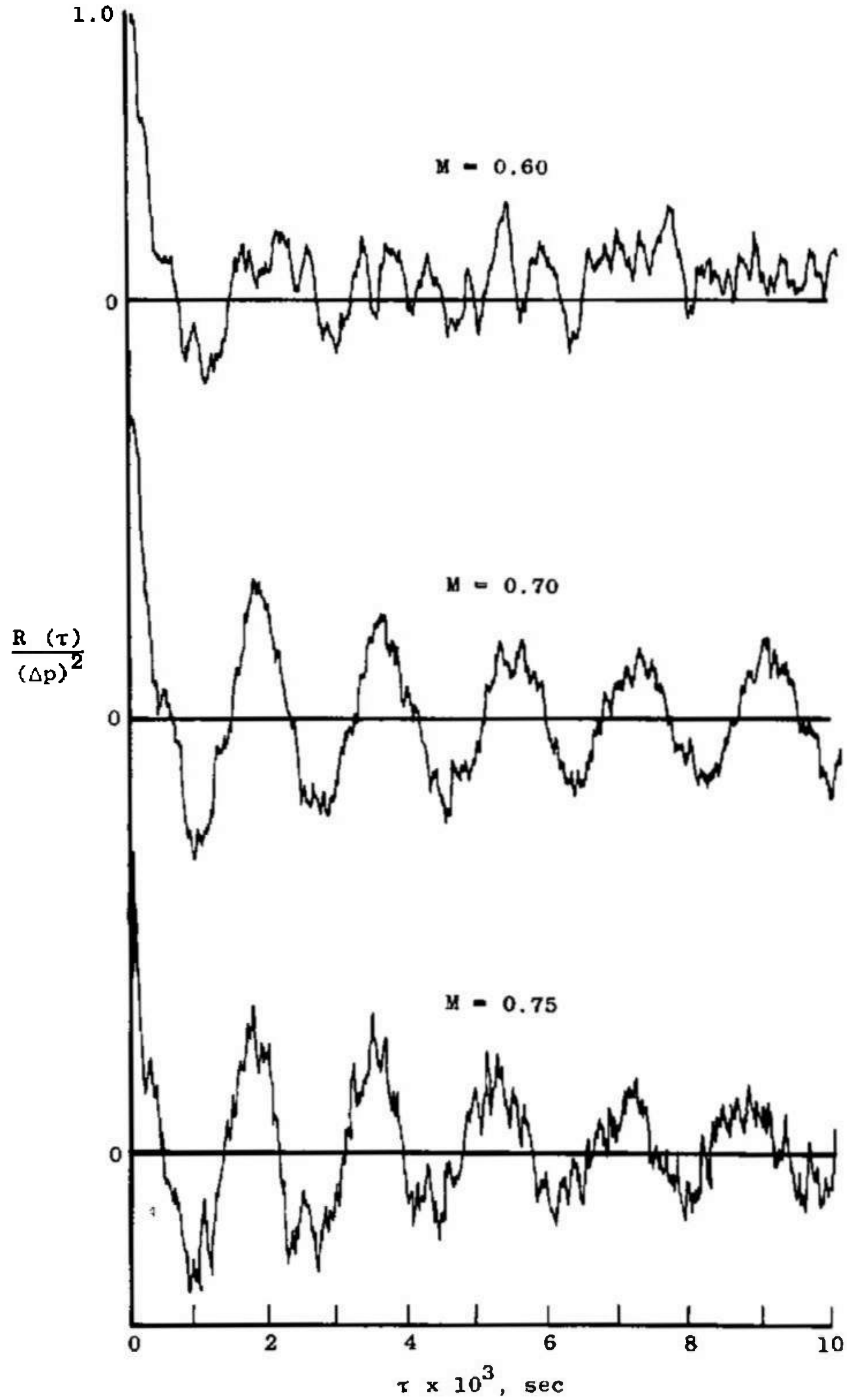
c. M_∞ = 0.80, 0.90, 1.00, and 1.10

Fig. 10 Continued



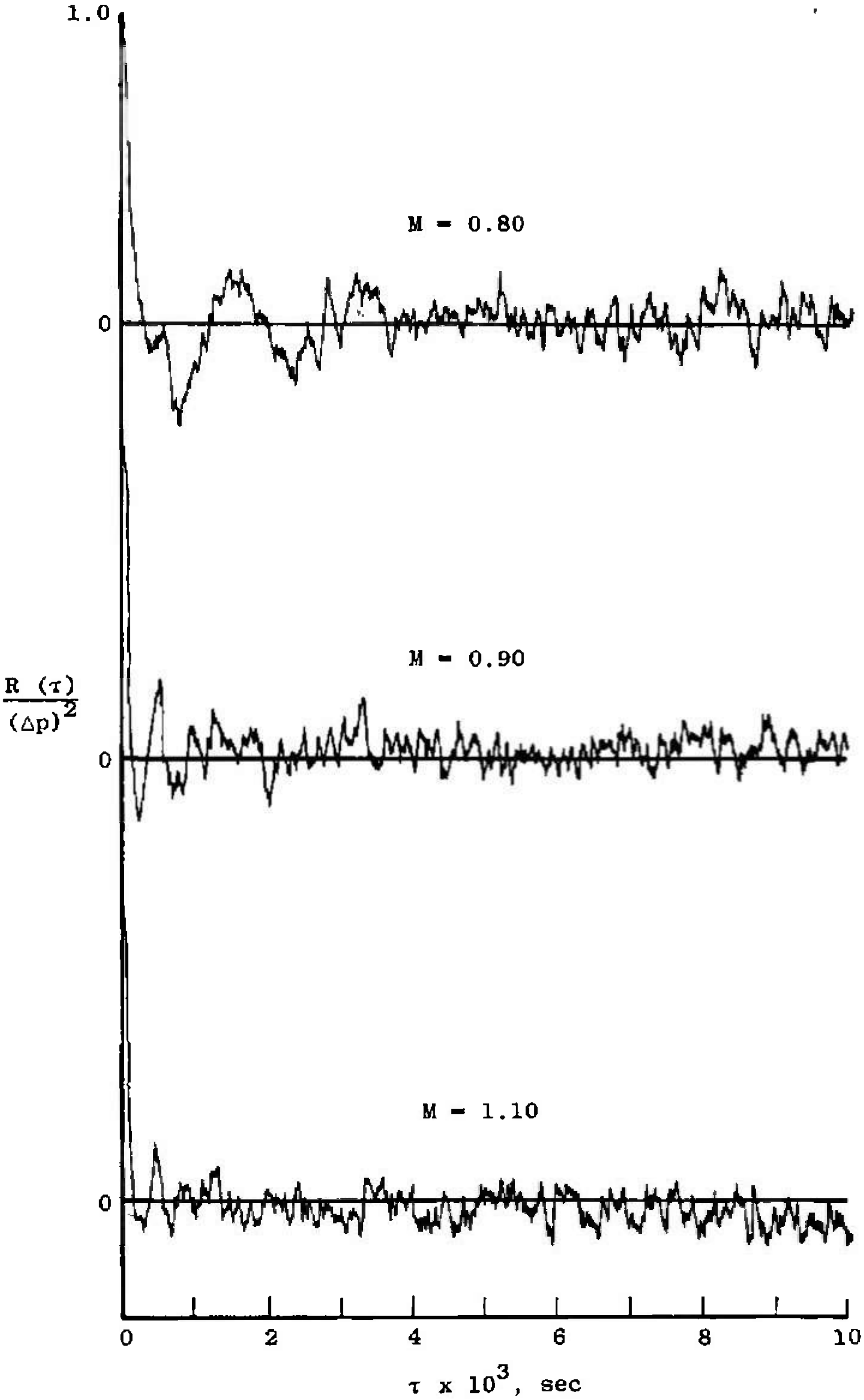
NOTE:
p_{t_∞} = 1500 psf
at M_∞ = 1.40
only

d. M_∞ = 1.20, 1.30, and 1.40
Fig. 10 Concluded



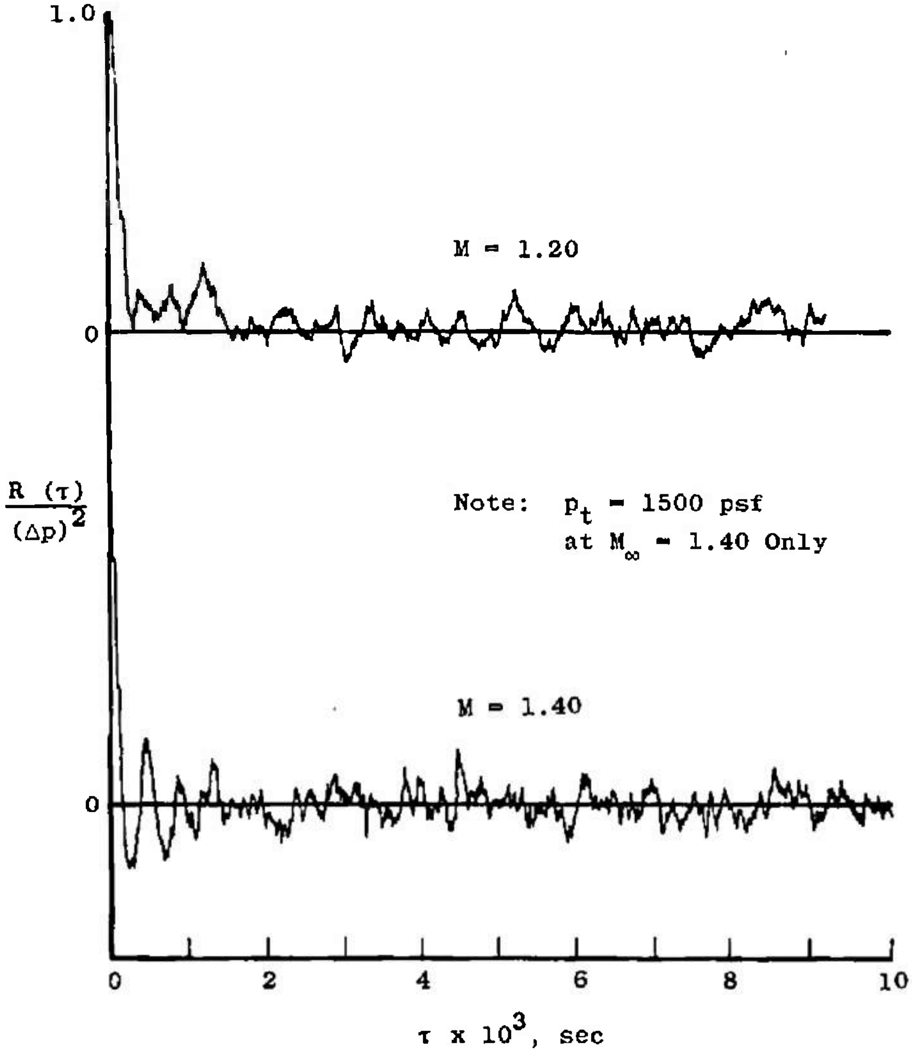
a. M_∞ = 0.60, 0.70, and 0.75

Fig. 11 Variation of the Autocorrelation Function with Time Displacement for the Forward Microphone at p_{t_∞} = 1600 psf



b. M_∞ = 0.80, 0.90, and 1.10

Fig. 11 Continued



c. M_∞ = 1.20 and 1.40
Fig. 11 Concluded

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13. ABSTRACT

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1 wind tunnels --						
pressure fluctuations						
supersonic flow						
hypersonic flow						
acoustical measurements						

1- 2

2. Supersonic wind Tunnels -- PWT

3 Transonic "