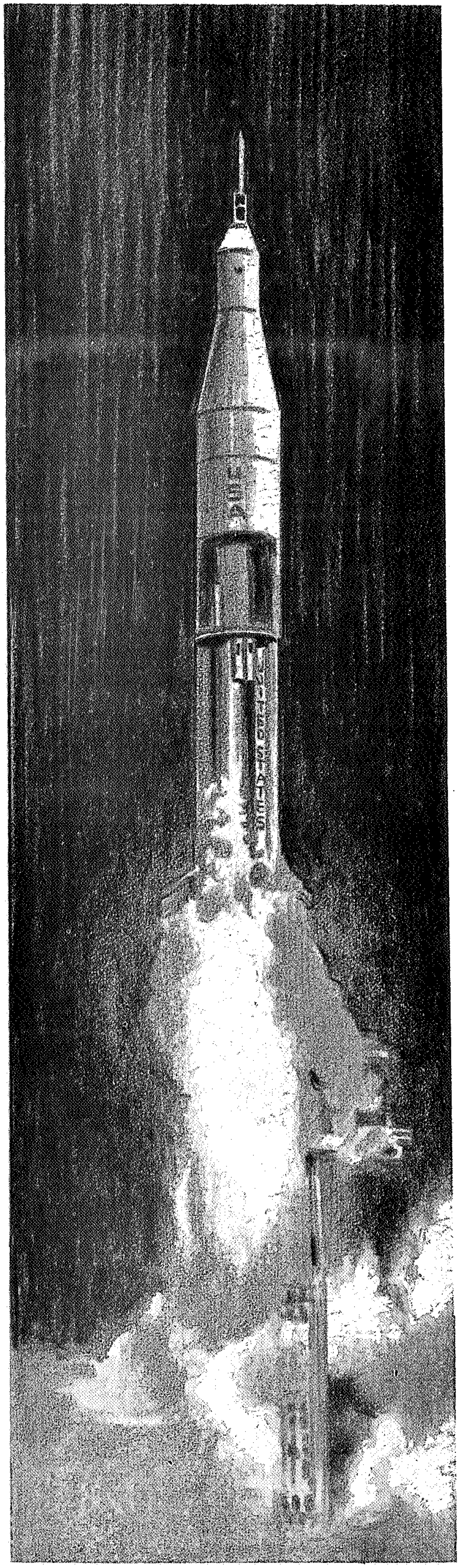

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ADDITIONAL CORRECTION OF 4% SATURN V PROTUBERANCE TEST DATA

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TECHNICAL REPORT HSM-R1-71

NAS8-30517

ADDITIONAL CORRECTION OF 4% SATURN V PROTUBERANCE TEST DATA

By

George F. McCanless, Jr.

January 21, 1971

FOREWORD

This report was prepared by the Aero-Space Mechanics Branch, Structures and Mechanics Engineering Department, Huntsville Operations, Chrysler Corporation. The work was authorized by NASA Contract NAS8-30517 which was issued by the Unsteady Aerodynamics Branch, Aerodynamics Division, Aero-Astrodynamics Laboratory, Marshall Space Flight Center in Huntsville, Alabama. The purpose of this study was to provide additional information about the unsteady aerodynamic environment of the Saturn Apollo vehicles. Previously, tests were conducted in the AEDC 16 ft transonic wind tunnel with a four percent model of this vehicle. It was instrumented with acoustic pressure transducers. The transducers sensed the fluctuating pressures generated by the flow of air over the model. However, the background noise of the wind tunnel was also sensed. The specific objective of the study was to establish the characteristics of the background noise so that the acoustic data from the four percent model tests can be interpreted properly. An additional objective was to determine methods of reducing this noise so that greater accuracy can be achieved if further acoustic tests are required.

ABSTRACT

Tests measuring wind tunnel background pressure fluctuations were conducted in the AEDC 16 ft transonic wind tunnel. The objective of these tests was to obtain data that can be used to correct Saturn V test data obtained in this facility. The model and instrumentation were fabricated and installed by MSFC personnel and the data reduction was performed by Chrysler personnel. This report describes the results of the calibration of this wind tunnel and also summarizes the calibration of numerous other transonic facilities. The frequencies and amplitudes are discussed. The noise sources are identified and methods of reducing the test section noise levels are enumerated.

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1.0 INTRODUCTION

Background noise exist in test sections of transonic wind tunnels and this noise interferes with unsteady aerodynamic tests. These facilities have been used for transonic buffeting tests of Saturn Apollo configurations. The tests have utilized rigid models instrumented with acoustic pressure transducers and also aeroelastic models. Unsteady aerodynamic data is required from these facilities because air flows tend to become unstable just below the speed of sound. The resulting transonic buffeting pressures impose dynamic loads on vehicle structures. Thus, acoustic data from transonic wind tunnels is required to assure the structural integrity of vehicles.

Unfortunately, these facilities have high level background pressure fluctuations. Numerous investigators have conducted acoustic calibrations in transonic wind tunnels through-out the world. These calibrations indicate that, in general, the background noise consisted of high-level narrow-band oscillations superimposed on low-level broad-band oscillations. The narrow-band oscillations were strong disturbances which concentrate near discrete frequencies. The broad-band oscillations were weak disturbances which occurred at virtually all of the measured frequencies. The investigations have shown that the amplitude of the background noise is generally within the range of the transonic buffeting data which is the objective of the tests. In the center of test sections the fluctuation pressure coefficients were found to range from $\Delta C_p = 0.9\%$ to $\Delta C_p = 4.5\%$. The amplitudes of the required measurements vary from $\Delta C_p = 0.5\%$ under a turbulent boundary layer of a body to $\Delta C_p = 10.0\%$ under an oscillating shock wave of a body. Thus the background noise levels in the test sections must be reduced so that the required acoustic data can be obtained.

This report describes the characteristics of the background noise in test sections of transonic wind tunnels and gives methods of reducing it. This information will ultimately result in greater precision in the measurement of transonic buffeting loads. The report contains summaries of acoustic calibrations of numerous transonic wind tunnels. The calibrations revealed that the background noise in the test sections was significantly influenced by the openings in the test section walls and by the surrounding plenum chambers.

These test sections utilize either porous walls or slotted walls to pass portions of the air streams to the plenum chambers. This passage of air to the plenum chambers surrounding the test sections compensates for the space in the test sections occupied by models. Porous wall test sections have numerous holes drilled in their walls and these holes act as whistles by generating edge tones. Brown[1,2,3] conducted studies of edge tones ten years before the first practical transonic wind tunnels were built. Edge tones were found to occur in four distinct frequency stages and a criterion for their occurrance was established. The wind tunnel calibrations reveal that the edge tone mechanism causes porous wall oscillations to occur in four distinct narrow-band frequency stages. A formula is developed in this report for the four frequency stages of the porous wall fluctuations. An occurance criterion is also considered. The slotted walls utilize open slots that traverse the test sections in the direction of flow. The open slots generate noise by the same mechanism that rocket exhaust jets generate noise. The sheering between the air in the test sections and air in the plenum chambers creates large eddies that cause pressure fluctuations. Pressure surges in the plenum chambers of both porous and slotted wall test sections have been observed to generate test section noise. In addition, turbulent boundary layers on the solid portions of test sections generate noise.

Test section noise has also been observed to be generated externally and transmitted to test sections either through the air or through the structures of wind tunnels. Control valve jets have been found to be external noise sources in blow-down wind tunnels. Compressor noise has been established as a noise source in continuous facilities. Unstable flow in the diffuser of both types of transonic wind tunnels could be transmitted to the test sections through the structures.

2.0 AEDC 16 FT TRANSONIC WIND TUNNEL

2.1 FACILITY DESCRIPTION

The AEDC 16 ft transonic wind tunnel operates from Mach No. 0.5 to 1.6. The Mach No. is continuously variable over this range. This tunnel is equipped with fixed porosity walls. The porosity is 6.0% of the wall area. Removable plates are provided for viewing of the model under test conditions. Stagnation pressures up to 28 psi can be achieved under most test conditions. This will provide Reynolds numbers of up to 8.4 million under most test conditions. Additional information concerning the AEDC 16 ft transonic tunnel can be found in Reference 4.

2.2 TEST SCHEDULE

The schedule of the test is shown in Figure 1. The AEDC 16 ft tunnel test schedule is organized to yield as much comparative data between the AEDC 16 ft tunnel and the MSFC 14 in. tunnel as possible. Wherever possible, both unit Reynolds number (Reynolds number per foot) and local Reynolds number were matched between the AEDC and MSFC test schedules. Some test conditions are included that match those used by other investigators who have conducted acoustic tests in this tunnel. Test points that match some of this test data were also included. The test is also arranged to provide information concerning the interrelationship between pressure fluctuations in various sections of the wind tunnel. The effects of Mach number, stagnation pressure, stagnation temperature, tunnel diffuser, tunnel compressor, and scaling on the background pressure fluctuation were investigated.

Run No.	Mach No.	Stagnation Pres.(psi)	Stagnation Temp.(°R)	Plenum Suction	Purpose	Similar Test In MSFC Tunnel
1	0.60	8.23	585	Standard	Match Local Reynolds No.	Yes
2	0.65	↓	↓	↓		↓
3	0.70	↓	↓	↓	↓	↓
4	0.75	↓	↓	↓	↓	↓
5	0.80	↓	↓	↓	↓	↓
6	0.90	↓	↓	↓	↓	↓
7	1.00	↓	↓	↓	↓	↓
8	1.05	↓	↓	↓	↓	↓
9	1.10	↓	↓	↓	↓	↓
10	1.30	↓	↓	↓	↓	↓
11	1.20	11.10	↓	↓	Match AEDC Cone Tests	
12	1.10	↓	↓	↓		
13	1.00	↓	↓	↓	↓	
14	0.90	↓	↓	↓	↓	
15	0.80	↓	↓	↓	↓	
16	0.75	↓	↓	↓	↓	
17	0.60	↓	↓	↓	↓	
18	0.60	14.70	↓	↓	Pressure Effects	Yes
19	0.65	↓	↓	↓		
20	0.70	↓	↓	↓	↓	Yes
21	0.75	↓	↓	↓	↓	
22	0.80	↓	↓	↓	↓	
23	0.85	↓	↓	↓	↓	Yes
24	0.90	↓	↓	↓	↓	
25	0.95	↓	↓	↓	↓	
26	0.80-1.05-0.52	↓	↓	↓	Mach Sweep	
27	0.75	22.00	560	↓	Temperature Effects	
28	0.90	↓	↓	↓		

FIGURE 1. AEDC 16 FT WIND TUNNEL TEST SCHEDULE

Run No.	Mach No.	Stagnation Pres. (psi)	Stagnation Temp. (°R)	Plenum Suction	Purpose	Similar Test In MSFC Tunnel
29	1.10	22.00	560	Standard	Temperature Effects	
30	1.10	↓	585	↓		
31	1.10	↓	↓	↓	↓	
32	1.10	↓	↓	↓	↓	
33	1.10	↓	↓	↓	Match Unit Reynolds No.	Yes
34	1.05	↓	↓	↓		Yes
35	1.00	↓	↓	↓	↓	Yes
36	0.95	↓	↓	↓	↓	Yes
37	0.90	↓	↓	↓	↓	Yes
38	0.85	↓	↓	↓	↓	Yes
39	0.80	↓	↓	↓	↓	Yes
40	0.75	↓	↓	↓	↓	
41	0.70	↓	↓	↓	↓	
42	0.65	↓	↓	↓	↓	
43	0.60	↓	↓	↓	↓	Yes
44	0.75	↓	↓	Variations	Plenum Suction Effects	
45	0.75	↓	↓	↓		
46	0.75	↓	↓	↓	↓	
47	0.90	↓	↓	↓	↓	
48	0.90	↓	↓	↓	↓	
49	0.90	↓	↓	↓	↓	
50	0.80	28.00	↓	Standard	Pressure Effects	Yes
51	0.75	↓	↓	↓		
52	0.70	↓	↓	↓	↓	
53	0.60	↓	↓	↓	↓	Yes
54	0.75	22.00	610	↓	Temperature Effects	
55	0.90	↓	↓	↓		
56	1.10	↓	↓	↓	↓	

FIGURE 1. AEDC 16 FT WIND TUNNEL TEST SCHEDULE

3.0 INSTRUMENTATION OF AEDC FACILITY

Three types of instrumentation were chosen for measuring the fluctuations in static pressure in the AEDC 16 ft transonic wind tunnel. A cone calibration device was fabricated. The instrumentation was installed on it and on the side walls of this wind tunnel.

3.1 INSTRUMENTATION FOR FLUCTUATIONS IN STATIC PRESSURE

All fluctuating pressures are recorded by three types of pressure transducers. These transducers are:

- Schaevitz - Bytrex Corp., Model HFD-25
- Kulite Corp., Model CPL-070-4
- Kistler Instrument Corp., Model 601L

All acoustic transducers were calibrated using a 1000 cps signal from a Photocon Research Products, Model PC 125, calibrator. Both the Schaevitz-Bytrex Corp., Model HFD transducer, and the Kulite Corp., Model CPL-070-4, transducer are strain gauge transducers. A part of the strain gauge is located outside the transducer as a compensation module. The Tektronic, Inc., Model RM 122, low level amplifiers are used to amplify the output of both these transducers. The Kistler Instrument Corp., Model 601L, transducer is a Quartz crystal transducer. The Kistler Instrument Corp., Model 553, charge amplifier is used to amplify the output signal of the Kistler transducers. The amplified transducer outputs is then input to a Data Control Systems, Inc., Model GOV-4, voltage controlled oscillator which converts the output to a FM signal. The FM signal is then recorded on one of the nine channels of a Consolidated Electrodynamics Corp., Model VR-3600, tape system. Each of the nine channels has a ± 40 KC range and a FM separation of 80 KC. A monitor station is provided between the amplifier and the voltage controlled oscillators. A Ballantine Laboratories, Inc., Model 320A, true rms voltmeter and a Tektronic, Inc., Model 502, oscilloscope are provided at the tunnel monitor station.

3.2 DYNAMIC CALIBRATION CONE FOR THE AEDC 16 FT TRANSONIC TUNNEL

In Reference 5 it was shown that several types of calibration devices have been used in wind tunnel acoustic testing. A brief evaluation of each type of calibration device is presented in Reference 5. It was shown in this evaluation that the most acceptable pressure fluctuation data can be obtained from a combination of calibration devices. This combination was shown to be a slender cone with flat surfaces for mounting instrumentation and sidewall mounted instrumentation. Figures 2 and 3 show the calibration cones.

The AEDC dynamic calibration cone is geometrically similar to the MSFC dynamic calibration device. The instrumentation that was installed was capable of measuring fluctuating pressures in the same frequency range as measured in the MSFC 14 in. tunnel. Figure 4 is a scaled drawing of this calibration device.

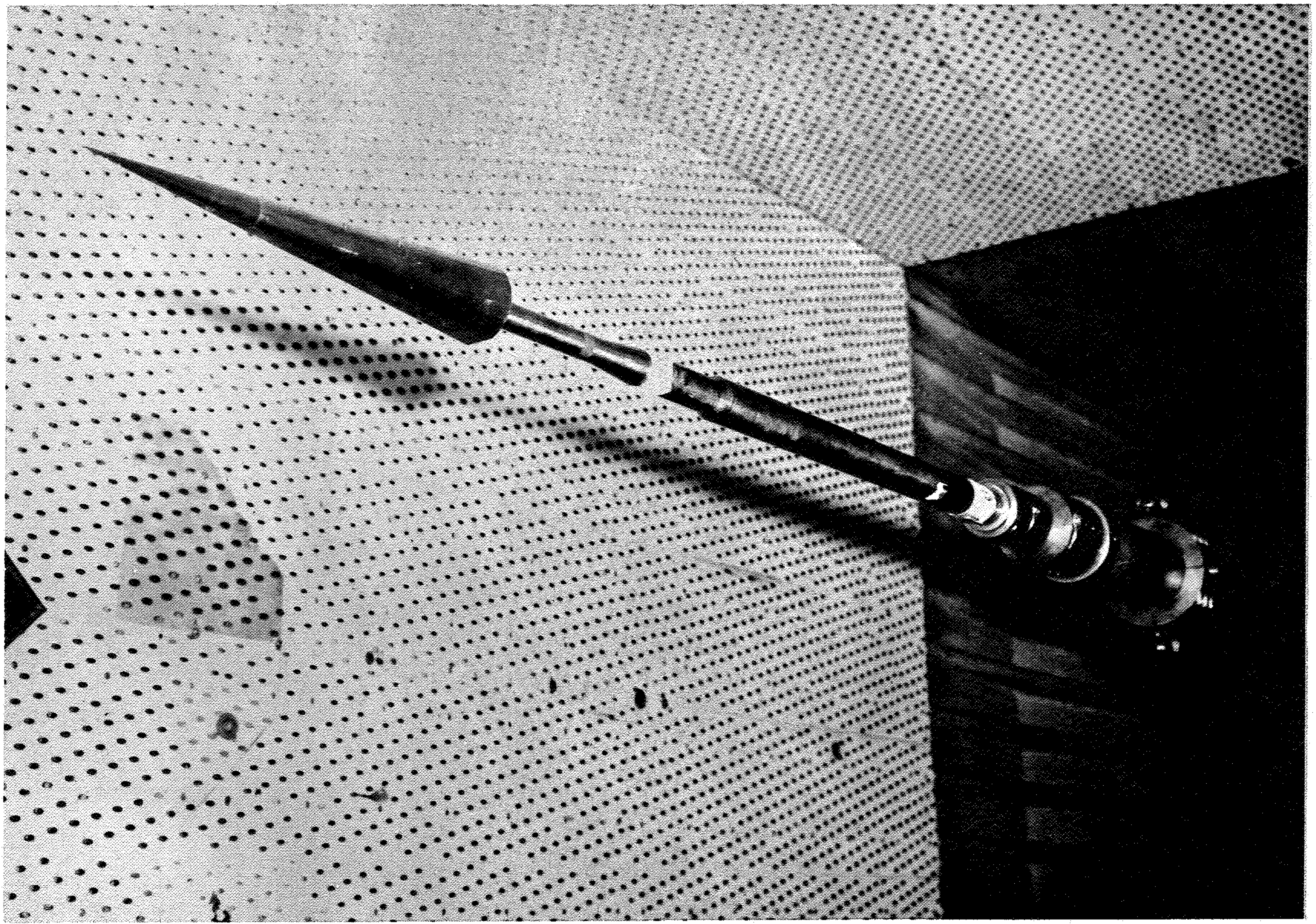


FIGURE 2. DYNAMIC CALIBRATION CONE WITH EXTENSION IN AEDC FACILITY

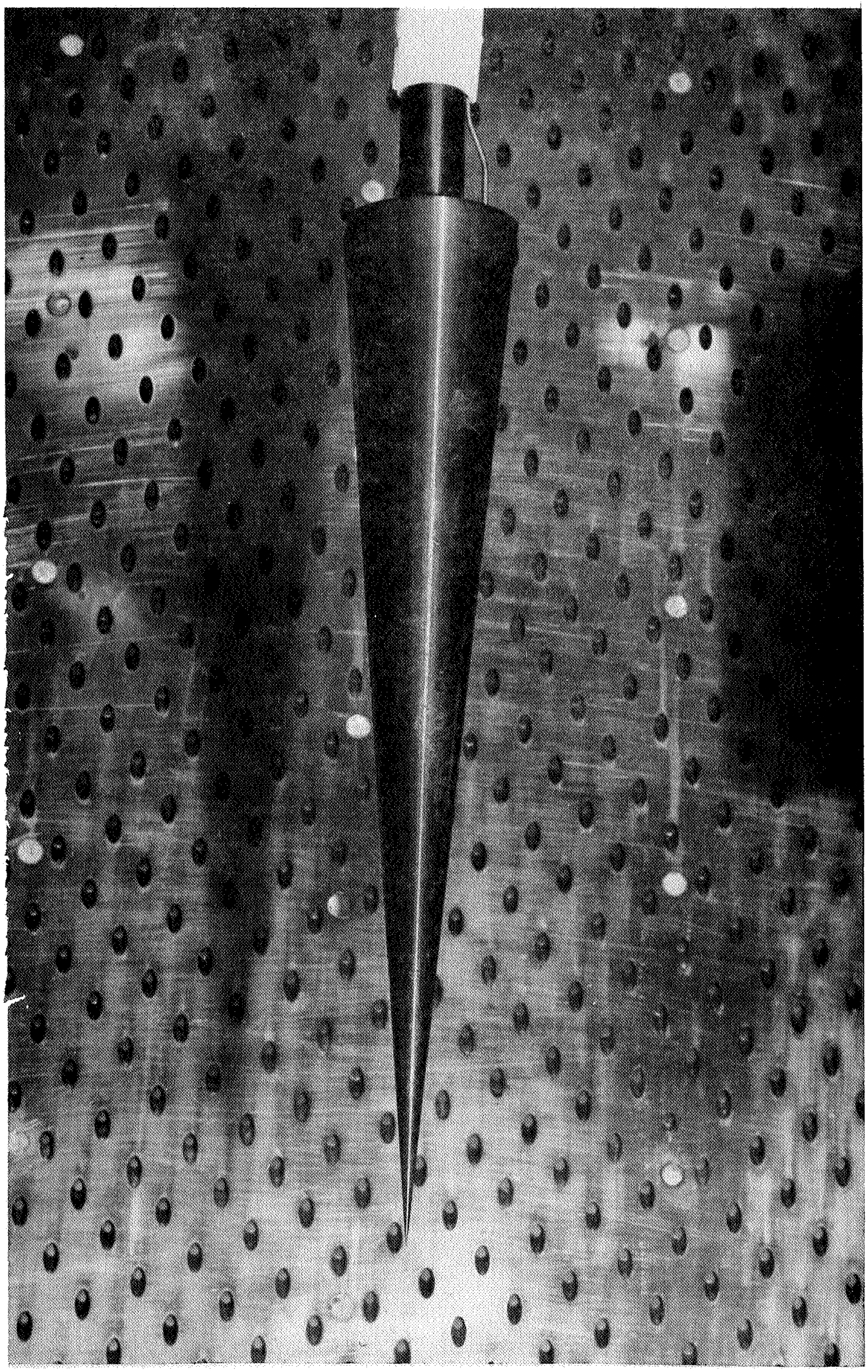
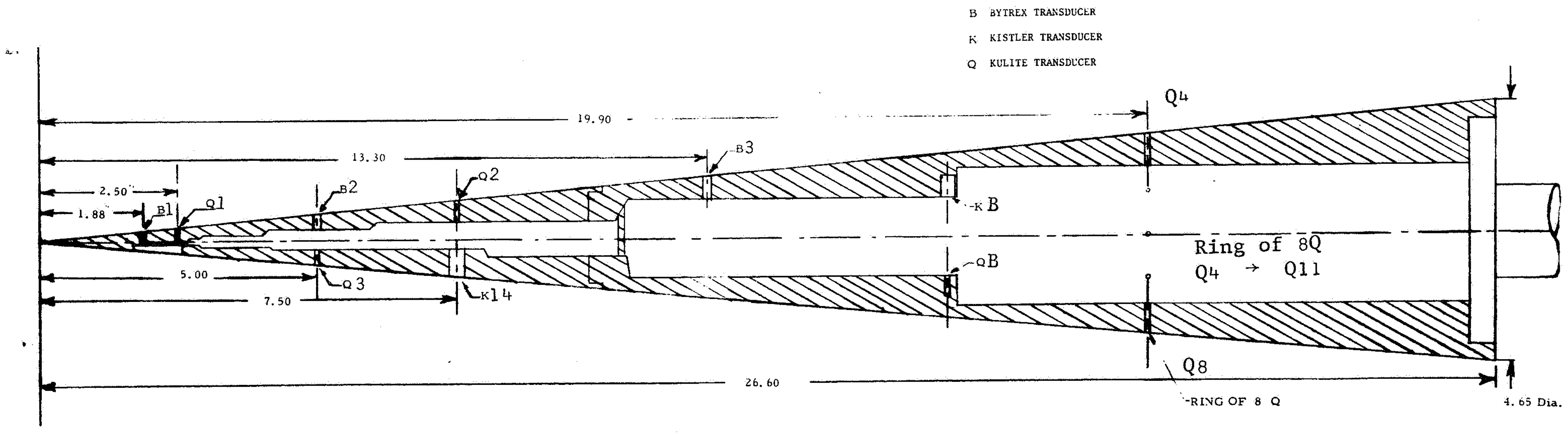


FIGURE 3. DYNAMIC CALIBRATION CONE WITHOUT EXTENSION IN MSFC FACILITY



ALL DIMENSIONS IN INCHES

FIGURE 4. INSTRUMENTATION OF THE EXTENDED CALIBRATION CONE

As can be seen, three different types of transducers were used. The instrumentation location and type are shown in Figure 4. The Bytrex and Kolite transducers require venting. The area and shape of the venting cavity is identical with that of the MSFC 14 in. dynamic calibration cone. The flat surfaces of the cone were mounted facing the upper and lower walls of the tunnel. A ring of transducers is provided at dimensionless model station 0.75 to determine the ring correlation.

3.3 DYNAMIC CALIBRATION SIDEWALL MOUNTED INSTRUMENTATION FOR THE AEDC 16 FT TUNNEL

Wall mounted transducers were used in the AEDC tests to determine the sources of fluctuating pressures and the interdependence of the fluctuating pressures in various sections of the wind tunnel. The locations and designations of the sidewall transducers is shown in Figure 5. Kistler transducers were used for these measurements.

3.4 DATA REDUCTION INSTRUMENTATION

Partial data reduction was conducted. The schedule of the transducer connections to the tape recorder is given in Figure 6. The equipment used in this data reduction was similar to that used in the data acquisition. Tapes were played on a Consolidated Electrodynamics Corp., Model VR-3600, tape system through output voltage controlled oscillators. The output was monitored and rms voltages recorded using a Ballantine Laboratories, Inc., Model 320A, true rms voltmeter. A Tektronic, Inc., Model 502, oscilloscope was also used and a tape monitor.

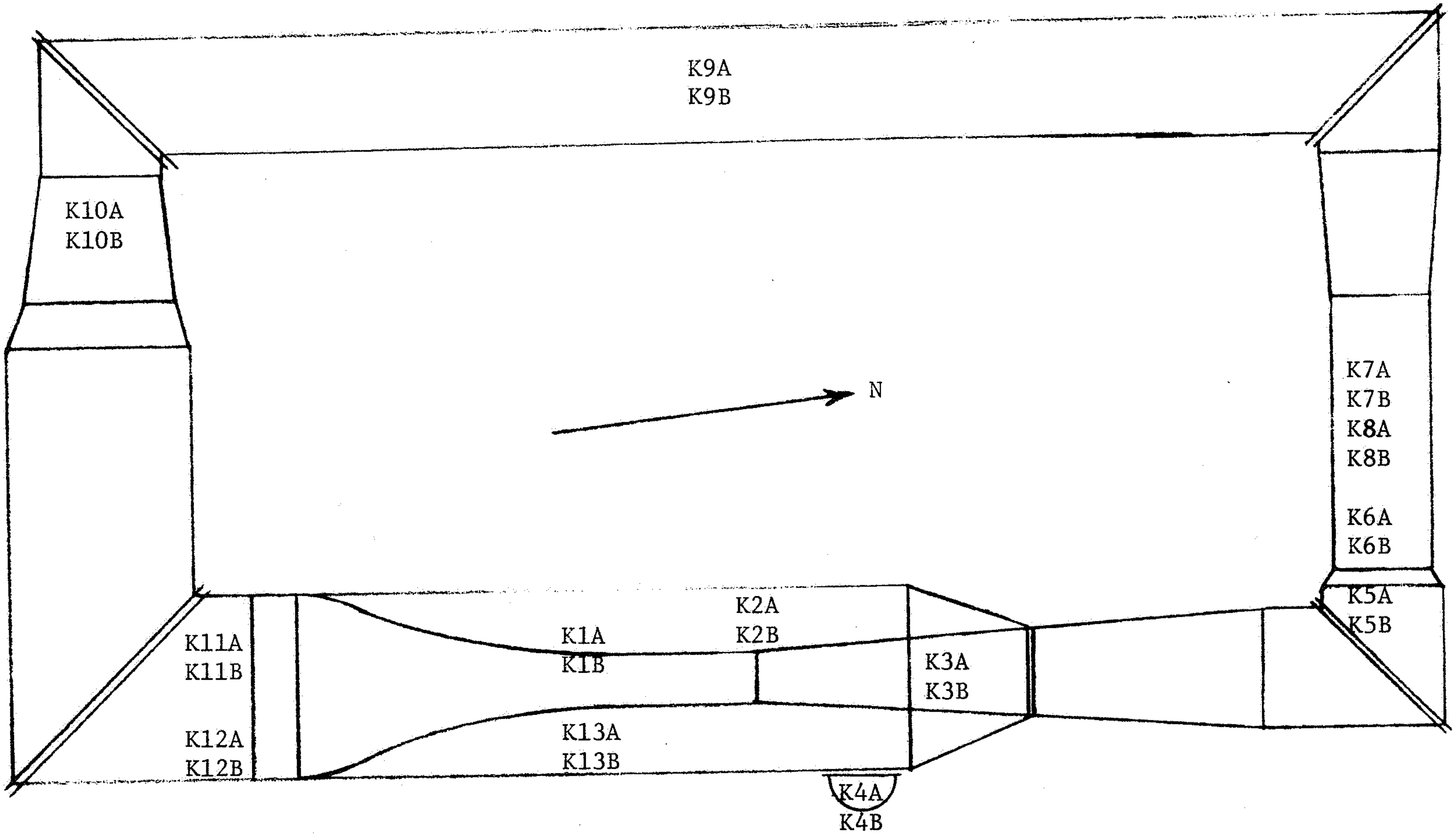


FIGURE 5. LOCATION OF SIDEWALL TRANSDUCERS IN AEDC 16 FT WIND TUNNEL

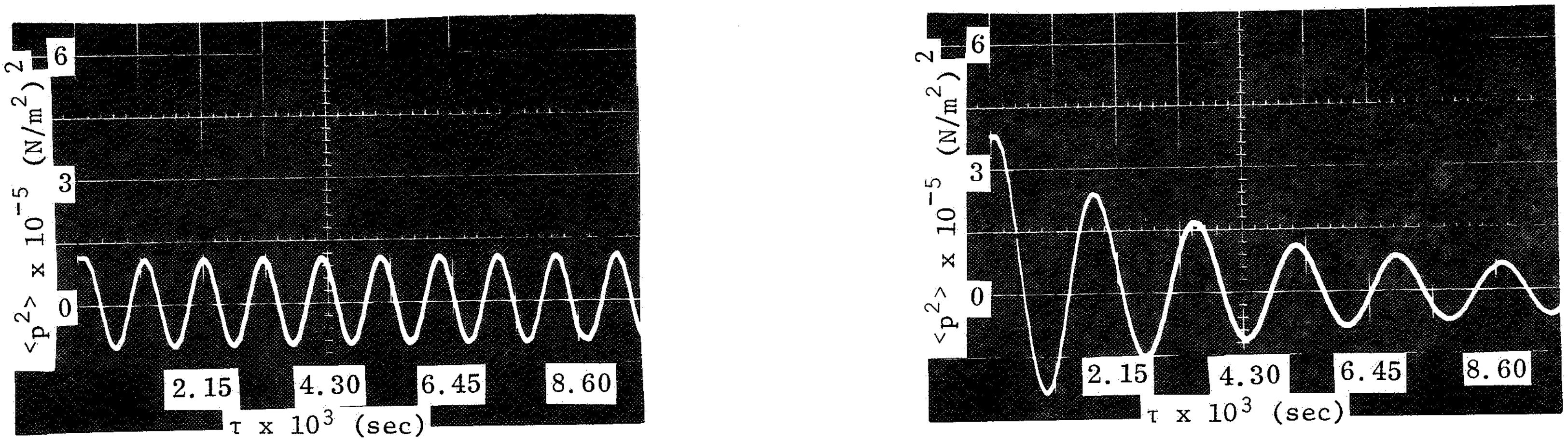
Transducer	VCO-Tape Ch.	Transducer	VCO-Tape Ch.	Transducer	VCO-Tape Ch.
K1A	1-2	K10A	4-4	B3	7-6
K1B	2-2	K10B	5-4	Q4	8-6
K2A	3-2	K11A	6-4	QB	9-6
K2B	4-2	K11B	7-4	Q3	1-9
K3A	5-2	K12A	8-4	K1A	2-9
K3B	6-2	K12B	9-4	K2A	3-9
K4A	7-2	K12A	1-5	Q4	4-9
K4B	8-2	K13A	2-5	Q8	5-9
K5A	9-2	K13B	3-5	B2	6-9
K4A	1-3	K1A	4-5	Q2	7-9
K5A	2-3	K1B	5-5	Q4	8-9
K5B	3-3	K2A	6-5	QB	9-9
K6A	4-3	K2B	7-5	KB	1-10
K6B	5-3	K1A	8-5	K14	2-10
K7A	6-3	K2A	9-5	Q5	3-10
K7B	7-3	K1A	1-6	Q6	4-10
K8A	8-3	K2A	2-6	Q7	5-10
K8B	9-3	B1	3-6	Q8	6-10
K8A	1-4	Q1	4-6	Q9	7-10
K9A	2-4	B2	5-6	Q10	8-10
K9B	3-4	Q2	6-6	Q11	9-10

FIGURE 6. TRANSDUCER CONNECTIONS WITH TAPE RECORDER

4.0 RESULTS OF AEDC CALIBRATION

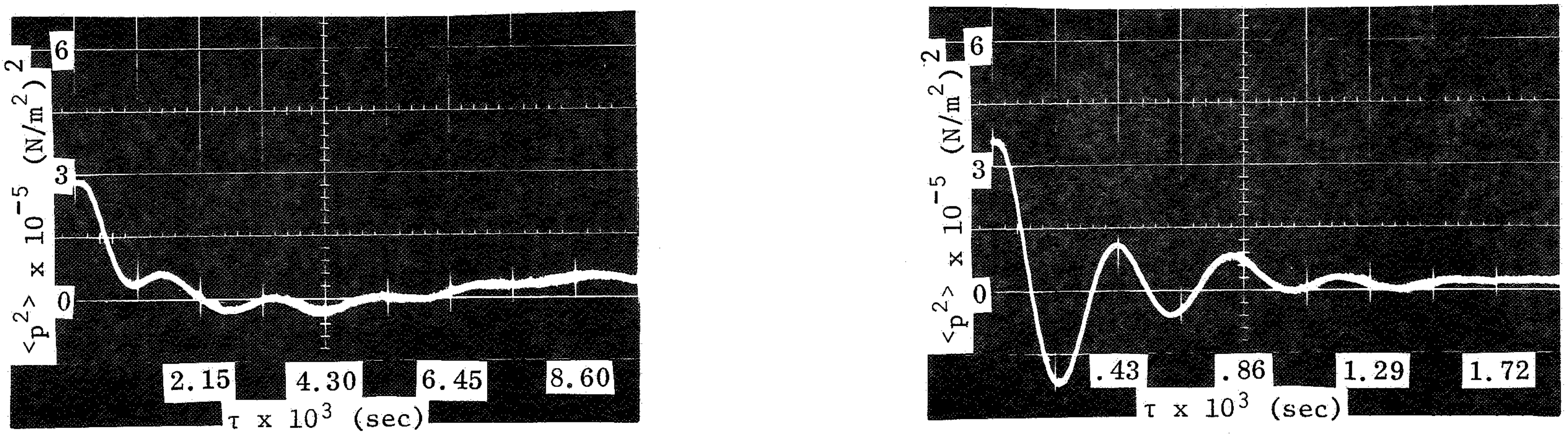
The data from the noise tests in the AEDC 16 ft wind tunnel were fed to the correlator. Some of the autocorrelations are shown in Figure 7. The upper left illustration shows the autocorrelation of the 1000 Hz calibration signal. The illustration at the upper right gives the autocorrelation of the noise obtained from a Kulite transducer on the calibration cone. The signal obtained at Mach 0.75 was filtered at frequencies below 30 Hz and above 950 Hz. The reduced data indicate that strong 595 Hz narrow band fluctuations exist in the center of the test section at Mach 0.75. The lower left is the autocorrelation of a signal from a sidewall Kistler transducer at the same conditions. It shows that the disturbances at the sidewall are random instead of narrow band oscillations. The 595 Hz fluctuations are, however, clearly detected at the side wall. The illustration in the lower right gives the autocorrelation of the signal from Kulite transducers on the cone. The data which was filtered below 950 Hz and above 3500 Hz was obtained at Mach 1.05. It showed a narrow band oscillation of 2,630 Hz at Mach 1.05. Additional autocorrelations showed narrow band oscillations at approximately twice this frequency.

The amplitude of the fluctuations were measured with a rms voltmeter. These amplitudes were then reduced to fluctuation pressure coefficients. Figures 8 and 9 show the reduced data obtained from a Kulite transducer on the calibration cone and a Kistler transducer located on the wind tunnel wall. The coefficients over the entire measurement frequency range are given. Also data from discrete frequency bands are shown. The amplitude of the over-all fluctuation coefficient was found to be less in the center of the test section than at the side wall. The coefficients were observed to attain their maximum value at Mach 0.70 to 0.75. These test data were used in conjunction with data gathered by numerous investigators in various wind tunnels to establish the characteristics of transonic wind tunnel noise. These characteristics are described in the two following sections.



Cone Transducer 354.5 N/m^2 Calibration Signal at 1000 Hz

Cone Transducer at M = .75 from 30 Hz to 950 Hz



Wall Transducer at M = .75 from 80 Hz to 950 Hz

Cone Transducer at M = 1.05 from 950 Hz to 3500 Hz

FIGURE 7. AEDC 16 FT AUTOCORRELATION

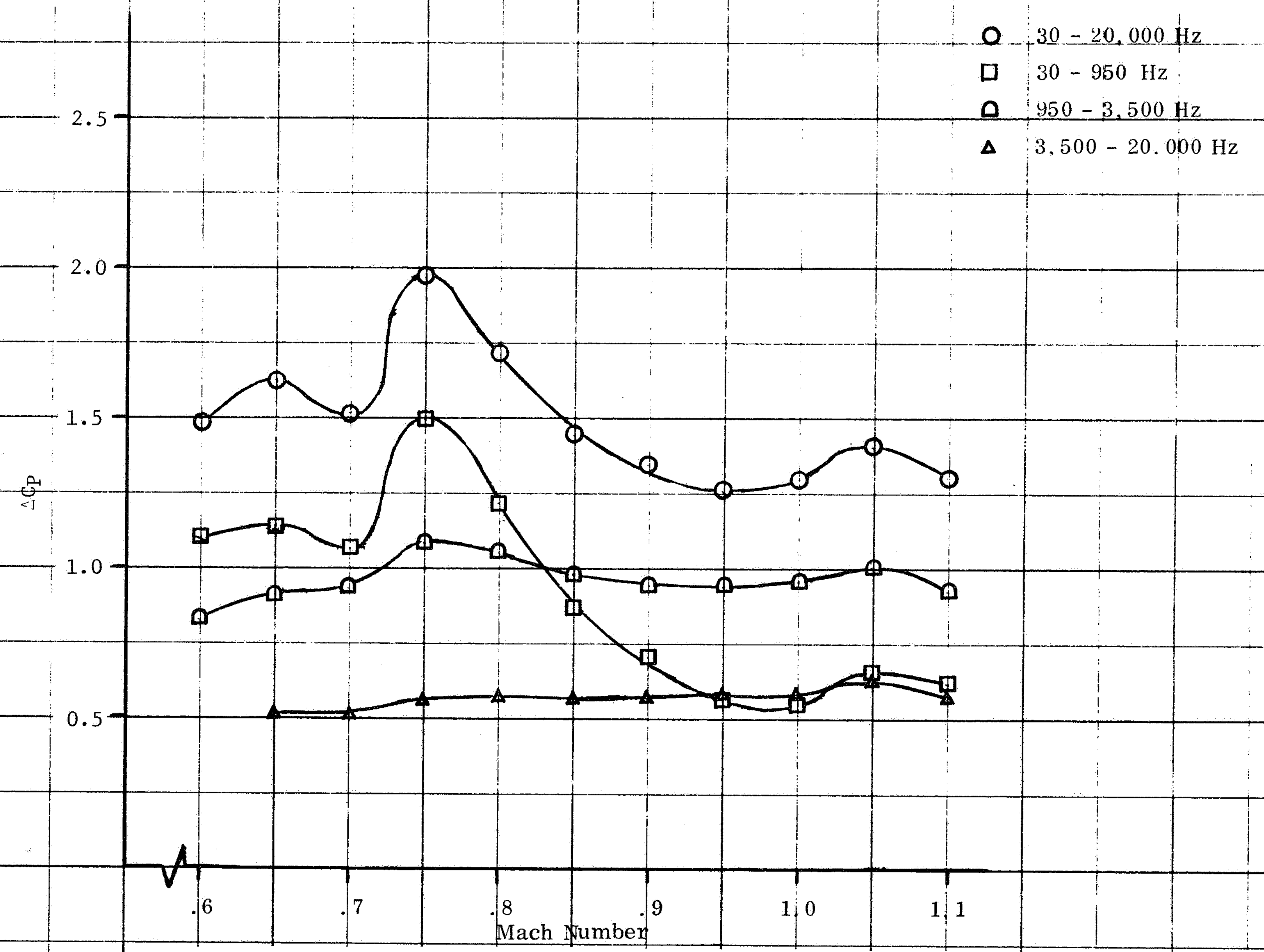


FIGURE 8. AEDC 16 FT CENTER LINE FLUCTUATION PRESSURE COEFFICIENTS

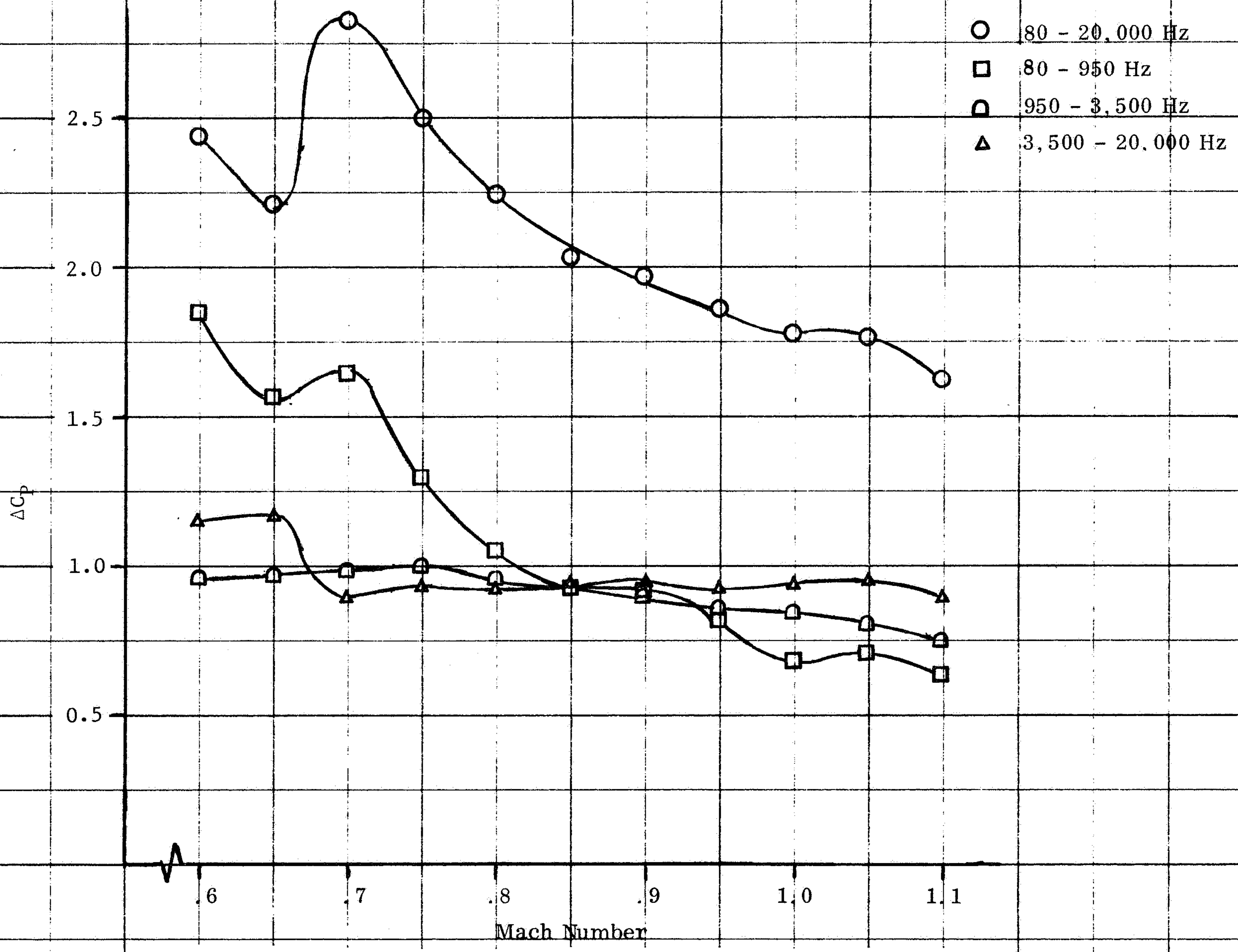


FIGURE 9. AEDC 16 FT WALL FLUCTUATION PRESSURE COEFFICIENTS

5.0 SUMMARY OF TRANSONIC WIND TUNNEL NOISE INVESTIGATIONS

Murphy[6,7] reported in March 1958 the dynamic calibration of the MACDAC 1 ft transonic wind tunnel. It is located at the McDonnell Douglas Astronautics Company, Aerophysics Laboratory in El Segundo. This blow-down, porous wall facility has 22% porosity with holes oriented perpendicular to the flow stream. The calibration data was obtained in the center of the test section. The frequency range of the instrumentation was below that of the porous wall generated fluctuations. None of these disturbances are reflected in the calibration data since the upper limit of the measurements was 1,000 Hz. The original test section fluctuation pressure coefficient was determined as $\Delta C_p = 2.80\%$. The noise generated by the free jet following the control jet was found to be a major contributor to the test section noise. This was established by installation of a muffler between the control valve and the test section. It reduced the measured test section noise by 60%.

King, Boyle and Ogle[8] described in July 1958 dynamic measurements made in a 7 in. blow-down wind tunnel, a 12 in. continuous water tunnel, and a 30 in. continuous water tunnel. These facilities were located at Admiralty Research Laboratory in Teddington, Middlesex, England. All of these subsonic facilities have longitudinal slotted wall test sections. Oscillations were detected in all three facilities. In the wind tunnel discrete oscillations were found. One source of the instability was traced to sheer in the slots between the moving working fluid in the test section and the fluid in the surrounding plenum chamber. The introduction of smoke showed that these disturbances were axisymetric. Removal of the outer wall of the plenum chamber eliminated the discrete oscillations. Holes were drilled in the outer walls of the plenum chamber and it was then replaced. This venting of 1/2% of the total surface area reduced the amplitude of these oscillations by 90%. Decreasing the area of the wind tunnel slots from 20% to 7% also reduced the amplitude of the disturbances. Amplitude data for the wind tunnel was not given. Little data was obtained in the small 12 in. water tunnel. In the continuous 30 in. water tunnel, the sheer flow at the slots, the plenum chamber, and return path were determined to control the fluctuations. Altering the configuration of the rear of the test section and plenum chamber reduced the disturbances. The frequency composition of the oscillations was altered by varying the amount of air in the resorber which is a part of the return path.

Chevalier and Todd[9] discussed in May 1961 the calibration of the AEDC 16 ft transonic wind tunnel. It is located at the USAF, Arnold Engineering Development Center near Tullahoma. This continuous facility utilizes a porous wall test section with 6% porosity. The holes are oriented at 30° divergence with respect to the air stream velocity, and this slanting of the holes causes some of the flow to pass from the test section to the plenum chamber. Data was obtained in the center of the test section over a frequency range that includes a portion of the porous wall oscillations. The upper frequency of the measurements was 1,000 Hz. Significant noise factors are large narrow band disturbances in the 500 to 700 Hz range. They occur up through Mach 0.8 but disappear above this Mach number. The narrow band fluctuations are now known to be the stage 1 oscillations generated by the porous walls. The frequency range of the instrumentation was too low to detect the higher stage oscillations. The disturbances below 1,000 Hz yield a fluctuation pressure coefficient of $\Delta C_p = 1.50\%$.

Robertson[10] reported in May 1962 measurements made in the AEDC 1 ft transonic wind tunnel near Tullahoma. The porous wall test section utilized holes that yielded 6% porosity which are oriented with 30° divergence. Acoustic transducers were located on a test section wall. Unfortunately, the frequency range of the measurements was below the frequency range of the porous wall disturbances. The measurements were limited to 1,250 Hz. Compressor fluctuations at the blade frequency of 1,030 Hz. were found in the test section. Subharmonic oscillations, which are characteristic of non-linear phenomena, were also detected at half this frequency. The maximum fluctuation pressure coefficient was $\Delta C_p = 2.20\%$ at Mach 0.60.

Ailman[11] described in August 1963 the results of his study of the MACDAC 4 ft transonic wind tunnel in El Segundo. This blow-down wind tunnel, like the MACDAC 1 ft wind tunnel, contains a 22% porosity test section with perpendicular holes. Data were obtained in the center of the test section well through the frequency range of the porous wall noise. This included oscillations through 100 k Hz. The acoustic data was obtained in the usual manner with the transducer mounted with its surface parallel to the air stream. Narrow band disturbances were detected at 3,000, 9,000, and 20,000 Hz near Mach 1.00. These are currently classified as stage 1, 2, and 3 porous wall oscillations. The measurements yield $\Delta C_p = 0.90\%$ near Mach 1.00. This facility is exceptionally quiet. Data was also obtained with an acoustic transducer mounted perpendicular to the air stream. It resembled a total pressure probe. The data from the perpendicular transducer was radially different from that obtained with the transducers mounted in the usual manner.

Murphy, Bies, Speaker and Franken[12] reported in April 1964 the results of boundary layer measurements also made in the MACDAC 1 ft transonic wind tunnel in El Segundo. The control valve was by-passed in these tests and a large air storage tank was used to supply the facility. It contained air at the operating stagnation pressure of the wind tunnel. Measurements were made at a wall of the test section through the range of the porous wall frequencies. These measurements extended to 88,000 Hz. Porous wall narrow band fluctuations were not detected. This was probably because the frequency bands of the data were relatively coarse and because, paradoxically, the porous wall fluctuations are not as strong between the holes at the walls as they are in the center of test sections.

Doggett and Hanson discussed informally in June 1966 the calibration of the Langley 16 ft transonic wind tunnel. This facility is located at the NASA, Langley Research Center near Hampton. The continuous wind tunnel contains a slotted wall test section. The side walls each have two slots and the floor and ceiling each have three slots. The side wall calibrations were conducted with freon, instead of air, as the working fluid in the wind tunnel. The frequency of the maximum disturbances occurred in the neighborhood of 40 Hz. Above this frequency they diminished with increasing frequency. The maximum amplitude, $\Delta C_p = 1.19\%$ occurred at Mach 0.85. Although no acoustic calibrations have been conducted in the center of the test section, acoustic measurements have been made on aircraft in this facility. The amplitudes at the smooth regions of the aircraft fuselage resulted in $\Delta C_p = 1.45\%$ at Mach 0.85.

Riddle[13] related in August 1967 another calibration of the AEDC 16 ft wind tunnel near Tullahoma. Data was measured in the center of the test section up to 10,000 Hz. Discrete fluctuations were obtained near 600 Hz at Mach 0.75. A second peak in the power spectra occurred near 1,750 Hz at Mach 0.70. This second peak increased in frequency to 2,900 Hz at Mach 1.40. Both of these oscillations are currently identified as stage 1 and 2 porous wall generated disturbances. The maximum amplitude coefficient was $\Delta C_p = 2.20\%$ at Mach 0.75.

Christophe and Lonieswki discussed informally in April 1968 the acoustic calibration of the ONERA 6 ft transonic wind tunnel. It is located at the Office National Études et de Recherches Aerospatiales, Modane Center in Chatillon, France. This continuous facility utilizes solid side walls and a variable porosity floor and ceiling. A maximum porosity of 6% can be achieved, though it is not stated whether this percentage is based on the total wall area of the test section or just the floor and ceiling. The holes are oriented at a divergence angle of 30° with respect to the air stream. Data was measured at a wall over a frequency range that includes the stage 1 porous wall oscillations. These measurements extended through 1050 Hz. Narrow band fluctuations were observed which ranged from 480 to 670 Hz at Mach 0.62 to 0.85. The air flow over the holes in the porous walls was shown to be a factor in these narrow band disturbances. This was illustrated by sliding the plates of the variable porosity ceiling closed while leaving the floor open which eliminated the disturbances. The same result was obtained by closing the floor and leaving the ceiling open. The narrow band oscillations are now known to be a stage 1 porous wall fluctuation. Unfortunately, no amplitude data was reported.

Spree discussed informally in April 1968 measurements that were made in the NRL 0.27 x 0.27 m and 16 x 2.0 m transonic wind tunnel. These facilities are located at the Nationaal Luct-en Ruimtevaartlaboratorium in Amsterdam, Netherlands. The smaller facility is a blow-down wind tunnel where as the larger is continuous. Both have solid side walls and slotted floors and ceilings. Both developed unstable flow in their test sections in the vicinity of Mach 1.25. Data was obtained with wall transducers. The test section fluctuations were found to be caused by unstable, or bistable, flow in the diffusers. The disturbances were transmitted to the test sections through the plenum chambers. The slotted floors and ceilings were extended down stream into the diffusers. These alterations were similar to those made in the large water tunnel at ARL. These changes eliminated the fluctuations near Mach 1.25 in the smaller facility and greatly reduced them at this Mach number in the larger facility. Measurements were also made in the larger facility at Mach 0.80 and the extension of the slotted floor and ceiling reduced the fluctuations to 50% of their previous value. Unfortunately, values of the fluctuation pressure coefficient were not given.

Mabey discussed informally in April 1968 the unsteady flow characteristics of the RAE 3 ft wind tunnel. It is located at the Royal Aeronautical Establishment in Bedford, England. Three test sections of this continuous facility were described. The 3 x 2.2 ft test section utilized solid side walls and a slotted floor and ceiling. The noise in this test section apparently was not excessive. However, the 3 x 2.9 ft test section, which utilized slots in all four walls, contained such high level noise that model vibration limited its use even for static tests. Placing perforated sheet metal over the plenum chamber side of the slots significantly reduced the fluctuation level. The third test section, which has a 3 x 2.7 ft cross section, is a porous wall chamber. Its porosity is 6% and its holes are oriented at 30° divergence in all four walls. Data was taken in this test section at a wall and in the plenum chamber. Up through Mach 0.7 it contained high level narrow band noise in the frequency range of 30 to 50 Hz. The plenum chamber was established as a major factor in these low frequency disturbances, as was the case at ARL and NLR. The narrow band disturbances were reduced by placing baffels adjacent to the knife edges leading to the diffuser. They were reduced further by placing baffels longitudinally in the four corners of the plenum chamber. Further reduction was achieved by placing baffels in the holes in the structural I-beams which were located in the plenum chamber. The air-flow over the porous walls was determined to be a factor in noise generation, confirming the results at ONERA. This was established by sealing all of the holes and observing that this eliminated the narrow band oscillations. Narrow band oscillations were also detected in the neighborhood of 600 Hz. These high frequency disturbances are now known to be a stage 1 porous wall oscillation. In the usual operating configuration, the amplitude of the test section disturbance yields $\Delta C_p = 3.3\%$ at Mach 0.80.

Boone and McCanless[14] reported in March 1969 the acoustic calibration of the MSFC 14 in. wind tunnel. This installation is located at the NASA, Marshall Space Flight Center near Huntsville. The transonic test section of this blow down wind tunnel has variable porosity walls which can be opened to a porosity of 5.4%. The holes are oriented at 30° divergence. Measurements were made at both the center and at a wall of the test section. These included frequencies through 20,000 Hz. This frequency range includes the major portion of the porous wall oscillations. Narrow band oscillations near 11,000 Hz were found in center of the test section. These were found to be caused by the porous walls, thus confirming the results at ONERA. Reducing the porosity from 5.40 to 0.75% caused the frequency to decrease by 20% at Mach 0.90. The reduction in porosity increased the amplitude of the oscillations by 55%. Completely sealing the holes with tape eliminated the narrow band disturbances. However, this change resulted in other fluctuations which prevented the overall amplitude of the test section fluctuations from decreasing significantly. The narrow band disturbances ranged from 10,800 Hz at Mach 0.80 to 12,100 Hz at Mach 1.30. They have now been established as a stage 2 porous wall fluctuations. Neither stage 1 or 3 fluctuations were detected. The maximum noise in the test section resulted in $\Delta C_p = 2.8\%$ in the center of the test section and $\Delta C_p = 4.5\%$ at a side wall. Tests were also conducted to determine the effects of upstream flow on the test section noise. The high pressure air supply was disconnected and the wind tunnel was driven by the downstream vacuum system. In one case, the facility was operated by letting air from the atmosphere enter the front end of the settling chamber, pass through the heat exchanger, and then enter the test section. In this operating mode the fluctuation level decreased to 50% of the usual level. In the other case, the settling chamber and heat exchanger were removed. Air from the atmosphere entered the test section by passing over the sharp corners of the test section where the settling chamber is normally mounted to it. In this operating mode, the noise level in the test section was as high as it had been in normal operation. This high level was attributed to the turbulence generated by the control valve jet and the sharp corners. During the standard operation of the facility, periodic flow instability was measured in the diffuser. Fortunately this disturbance did not propogate to the test section. The frequency of the disturbance in the diffuser was 550 Hz, but no oscillations at this frequency were detected in the test section.

Mabey reported in September 1969 additional studies conducted in the 3 x 2.7 ft test section of the RAE facility in Bedford. Acoustic data was obtained at a test section side wall. Above Mach 0.20, stage 1 and 2 porous wall oscillations were obtained. At Mach 0.90 they occurred at 980 and 3,940 Hz, well above the frequency of the plenum chamber disturbances. The establishment of the porous walls as the noise source confirmed the results at ONERA and MSFC[14]. This was accomplished by progressively taping the porous walls from the rear. The narrow band disturbances ceased when the tape reached a critical point along the wall. The effect of varying the porosity on the amplitude of the porous wall oscillations was opposite to that observed at MSFC[14]. The reduction of porosity from 6.0 to 2.2% in the RAE facility almost eliminated the lower narrow band disturbance generated by the porous walls.

Credel[15] described in November 1969 data obtained in the AEDC 4 ft transonic wind tunnel near Tullahoma. This continuous facility utilizes variable porosity walls that normally can be set from 0 to 10%. However, at the time of the calibration, some of the holes were selectively plugged so the maximum porosity was reduced to 6.7%. The holes slant at 30°. Data was obtained over the entire porous wall frequency range. The cut-off frequency was 10,000 Hz. These measurements were made both in the center of the test section and at a side wall. Narrow band disturbances were detected in the transonic region which are now known to be stage 2 and 3 porous wall oscillations. These oscillations occurred at frequencies of 3,950 and 7,600 Hz at Mach 1.10. Reducing the porosity from 6 to 1% caused the frequency of the porous wall disturbances to decrease by 25% at Mach 0.52. This result confirmed the data obtained by Boone and McCanless[13]. The reduction in porosity also increased the amplitude of the porous wall fluctuations which again confirmed the trend observed by Boone and McCanless[13]. Credel produced further evidence that the holes in the porous walls are a source of wind tunnel disturbance. With no flow in the wind tunnel, an air jet was blown over a hole in one of the porous walls. Oscillations were generated at the frequency of the lower narrow band oscillations. In addition to the porous wall disturbances, low frequency plenum chamber fluctuations were also found. These disturbances which occurred near 180 Hz were similar to those found at RAE. The center fluctuations yield $\Delta C_p = 3.4\%$ and the wall fluctuations yield $\Delta C_p = 5.0\%$.

Karabinas and Sanders[16] reported in May 1970 the calibration of the Lewis 8 x 6 ft transonic wind tunnel. It is located at the NASA, Lewis Research Center in Cleveland. This continuous, open return facility utilizes a 6.2%

porous wall test section. It contains 30° divergent holes. Measurements were made in the center of the test section and at a wall. Data was obtained through 10,000 Hz which included the frequency range of the porous wall disturbances. Porous wall oscillations of all four stages were detected. The frequencies were 430, 1,600, 3,000, and 5,500 Hz at Mach 0.80. The first stage oscillations disappeared above Mach 0.80. Reducing the porosity from 6.2 to 3.1% did not cause observable shifts in the porous wall frequency. However, this change did increase the amplitude, primarily by causing stronger stage 1 oscillations. The increase in amplitude was much stronger at the side walls than in the center of the section. The increase in amplitude with decreasing porosity was consistent with the findings of Boone and McCanless[13] and Credle[15]. Completely closing the porous walls caused the amplitude of the disturbances to drop to the same level that occurs with 6% porosity. Strong compressor fluctuations were detected in the test section which is located just downstream from the compressor. The blade frequency of the compressor is 800 Hz and strong disturbances were detected at this frequency at all operating conditions. These compressor fluctuations are similar to those found in the test section of the AEDC 1 ft transonic wind tunnel[10]. The maximum fluctuations in the center of the test section yield $\Delta C_p = 4.5\%$ and at a wall, $\Delta C_p = 6.5\%$.

McCanless describes, in Section 3.0 of this report, the third acoustic calibration of the AEDC 16 ft transonic wind tunnel at Tullahoma. Data was obtained at the test section center at a porous wall and also at various locations around the facility. The instrumentation measured disturbances up through the frequency range of the porous wall fluctuations. These extended to 20,000 Hz. Fluctuations of the first three stages were detected in the test section. The porous wall oscillations occurred at frequencies of 620, 1,800, and 4,300 Hz at Mach 0.80. The stage 1 oscillations disappear above this Mach number as they did in the Lewis facility [16]. The noise at the center of the test section consists of narrow band fluctuations, whereas, the noise at the side wall is primarily random. The maximum fluctuations at the center yield $\Delta C_p = 2.0\%$ and the side wall fluctuations yield $\Delta C_p = 2.8\%$. Oscillations at the compressor frequency of 345 Hz were measured down stream of the compressor. However, they disappear in the process of passing through three 90° turns and the heat exchanger.

6.0 COMBINED RESULTS OF CALIBRATIONS

The results of the investigations conducted in various facilities indicate that the porous walls are a significant factor in the generation of test section noise. Brown's[1,2,3] experiments with smoke jets demonstrate the porous wall noise phenomena. Figure 10 shows the effects of noise generated by a periodic sound source on smoke jets. The experiments demonstrate that the jets respond very actively to sound excitation at various critical conditions. Figure 11 shows the jets bisected with wedges. The wedges generate large oscillations even though no sound generator is present. The jet disturbances occur only at certain operating parameters of the jet and wedge. The oscillations exist in four distinct stages which occur at four distinct frequencies.

Four distinct oscillatory stages are also detected in the wind tunnel noise calibration. Figure 12 gives the frequency ranges of these tests and the stages detected. It gives the fluctuation pressure coefficients measured at the centers of the test sections and those measured at the side wall. It also shows that valve jets and compressors can generate significant noise in test sections.

The frequencies of the four stages of the porous wall wind tunnel noise is given by the following equation:

$$fh/V = 0.15\, n^{1.68} / (M+1)$$

$$\text{with } n = 1,\ 2,\ 3, \text{ or } 4$$

where:

f frequency of the fluctuations, Hz

h resonant hole separation distance, i.e., the distance between the leading and trailing edge of the holes - .0014, m

M free stream Mach Number

V free stream velocity, m/sec

The four stages are represented by the four values of n. In some cases two or more stages are excited simultaneously. Figure 13 shows the frequency data from seven porous wall wind tunnels plotted as function of Mach No.

A criterion for the occurance of the oscillatory stages in the wind tunnels is indicated by the results of smoke jet tests. Figure 14 shows a criterion for jets bisected with wedges. The critical parameter is the ratio of the jet width to the separation distance between the base of the jet and the tip of the wedge. If this parameter is too large or too small, oscillations of a

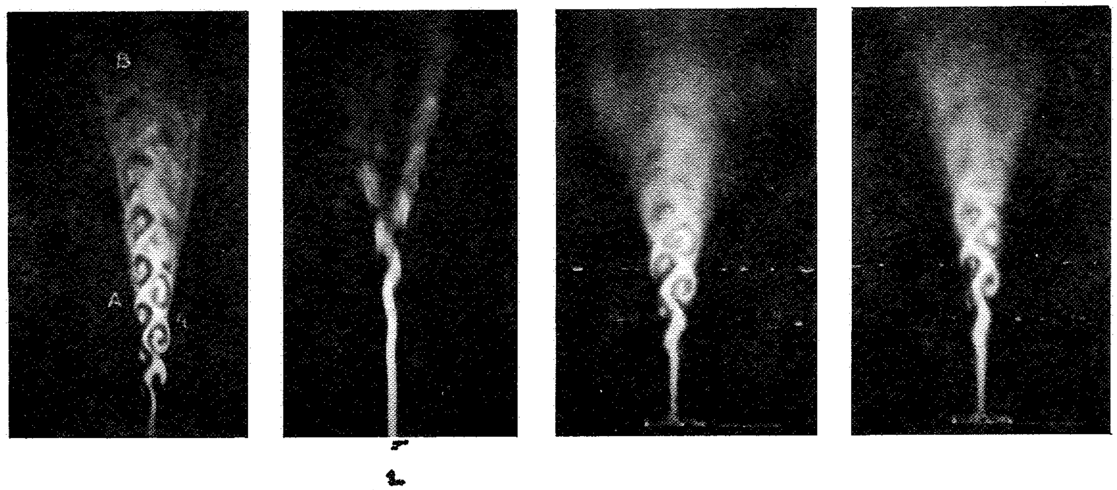
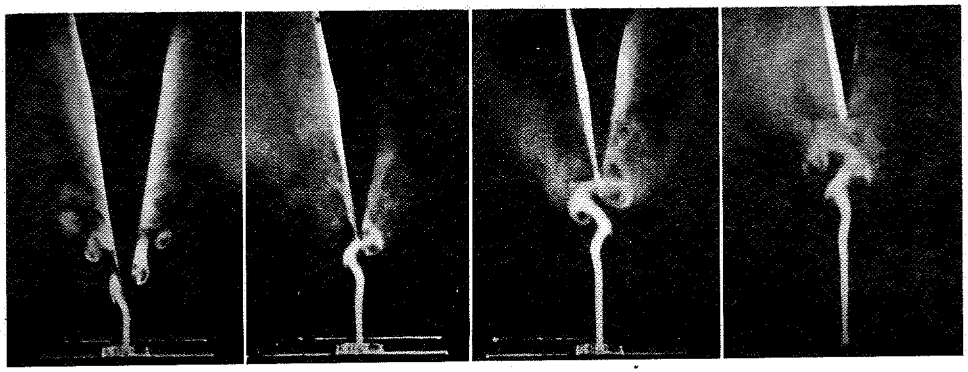


FIGURE 10. BROWN'S SOUND SENSITIVE JET STUDIES



STAGE 1 STAGE 2 STAGE 3 STAGE 4

FIGURE 11. BROWN'S EDGE TONE STUDIES

FACILITY	HOLE DIAMETER (x 10^3m)	RANGE OF FREQ. (KHz) MEASUREMENT	1st STAGE FREQ.(KHz) AT M = 0.8	4th STAGE FREQ.(KHz) AT M = 0.8	STAGES DETECTED	RANGE δ^*/h	OUTSIDE DISTURBANCE DETECTED	ΔC_{pmax} AT CENTER LINE	ΔC_{pmax} AT WALL
MACDAC 1'	3.18(1/8 in)	0+ - 1.0	4.2	43.6			VALVE JET	2.8 - 1.0	
AEDC 1'	3.18(1/8 in)	0+ - 1.3	4.4	44.6			COMPRESSOR		2.2
MSFC 14"	3.96(5/32 in)	.10 - 20.0	3.3	33.9	2	0-.527		2.8	4.5
RAE 3'x 3'	9.52(3/8 in)	0+ - 4.2	1.3	13.2	1,2	0-.495			3.3
MACDAC 4'	9.52(3/8 in)	.20 - 100.0	2.6	26.5	1,2,3	0-2.040		0.9	
AEDC 4'	12.7(1/2 in)	.03 - 10.0	.9	9.4	2,3,4	0-.558		3.4	5.0
ONERA 6'x 6'	18(11/16 in)	.05 - 1.1	.7	6.8	1	0-.464			
LEWIS 6'x 8'	25.4(1 in)	0+ - 10.0	.5	5.2	1,2,3,4	0-.490	COMPRESSOR	4.5	6.5
AEDC 16'	19.2(3/4 in)	.03 - 20.0	.6	6.3	1,2,3	0-.945		2.0	2.8
LANGLEY 16'	SLOTS	0+ - 20.0						1.4	1.2

FIGURE 12. SUMMARY OF WIND TUNNEL CHARACTERISTICS

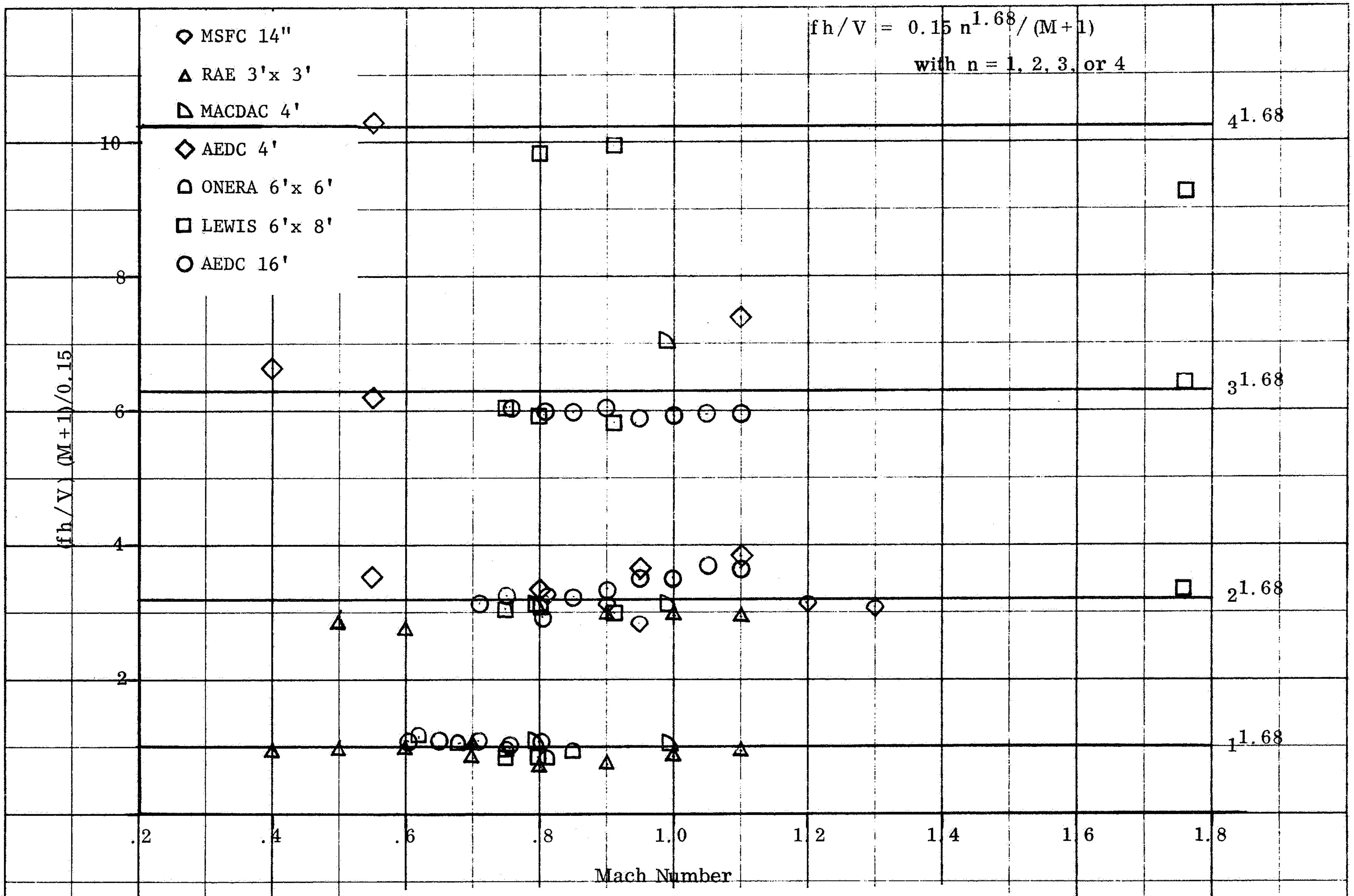


FIGURE 13. FREQUENCY EQUATION AND TEST DATA

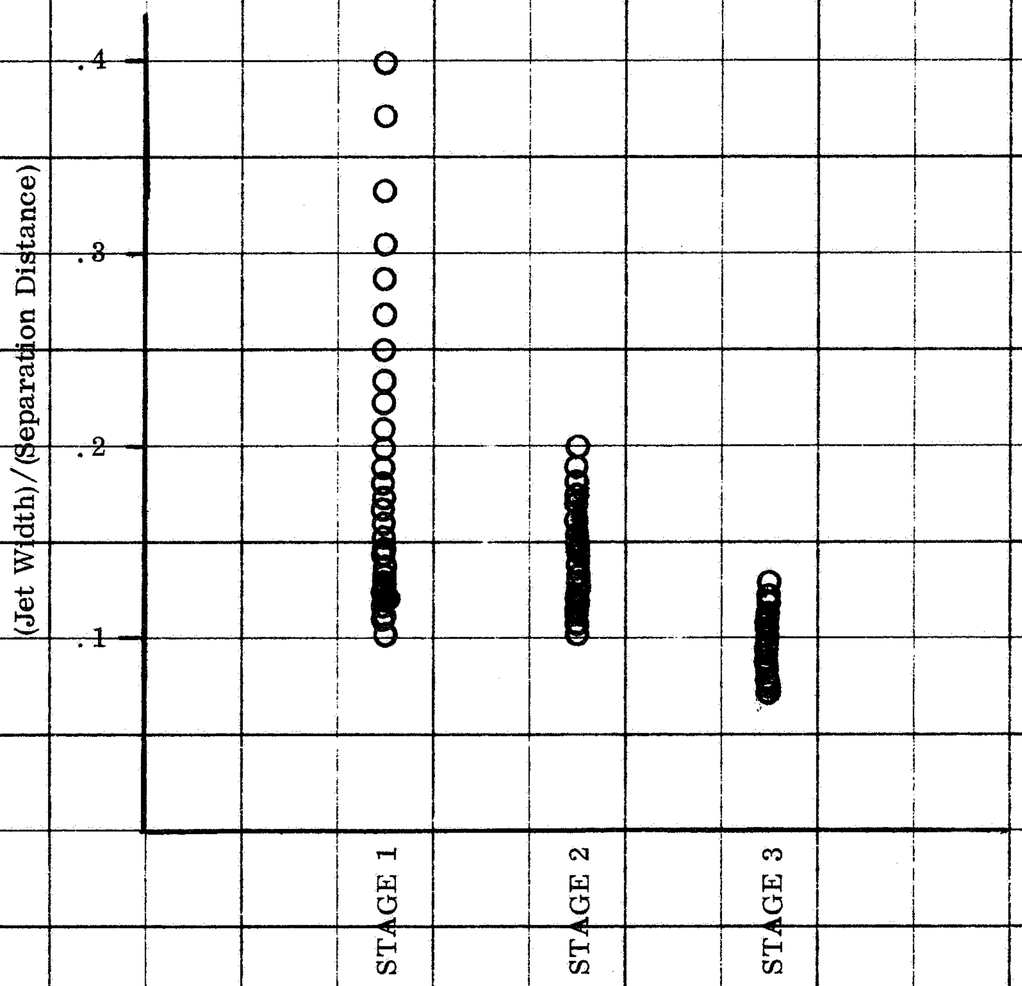


FIGURE 14. EXPERIMENTAL RANGE OF EDGE TONE STAGES

given stage will not occur. The higher stage oscillations occur at the smaller values of this parameter.

The criterion for porous wall stage oscillations is based on the ratio of the flat plate displacement boundary layer thickness to the resonant hole separation distance. Figure 15 shows values of this parameter for several wind tunnels. These calculations are made without considering mass removal through the porous walls. The open bars at the right of the figure show the values of the parameter that correspond to the four stages of oscillation.

Figure 16 shows the fluctuation pressure coefficients for various wind tunnels. The amplitudes of the disturbances are approximately fifty percent smaller in the center of the test section than at the side wall. The data from the MACDAC 1 ft and the AEDC 1 ft wind tunnels were restricted to very low frequency ranges and cannot be compared directly to data obtained in the facilities. The amplitudes of the fluctuations in the centers of the porous wall test sections yield maximum fluctuation pressure coefficients in the neighborhood of three percent. However, this coefficient is near one percent in the porous wall MACDAC 4 ft wind tunnel and in the slotted wall Langley 16 ft wind tunnel.

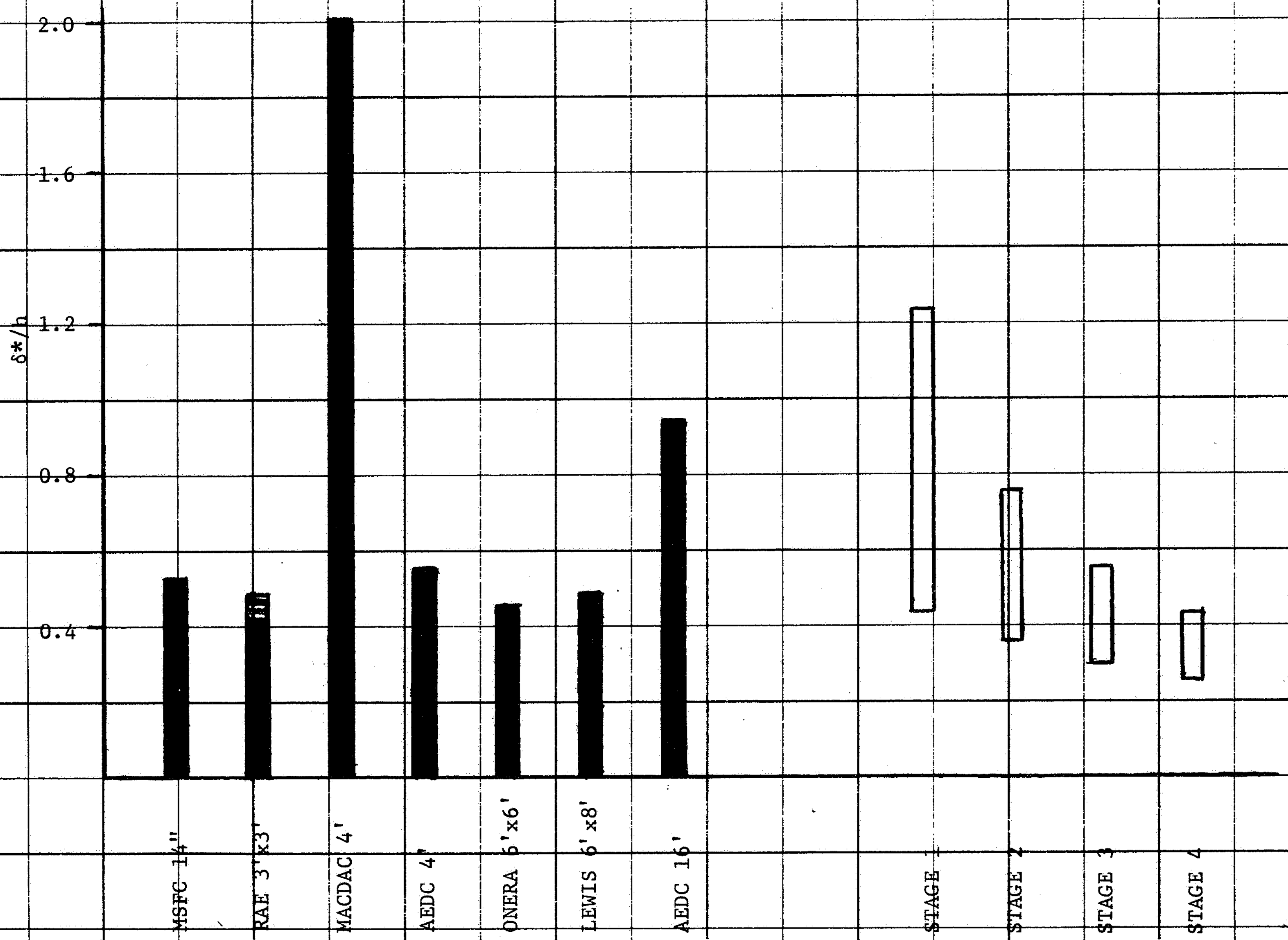


FIGURE 15. RANGE OF THE RATIO OF THE FLAT PLATE DISPLACEMENT BOUNDARY LAYER THICKNESS TO RESONANT HOLE SEPARATION DISTANCE

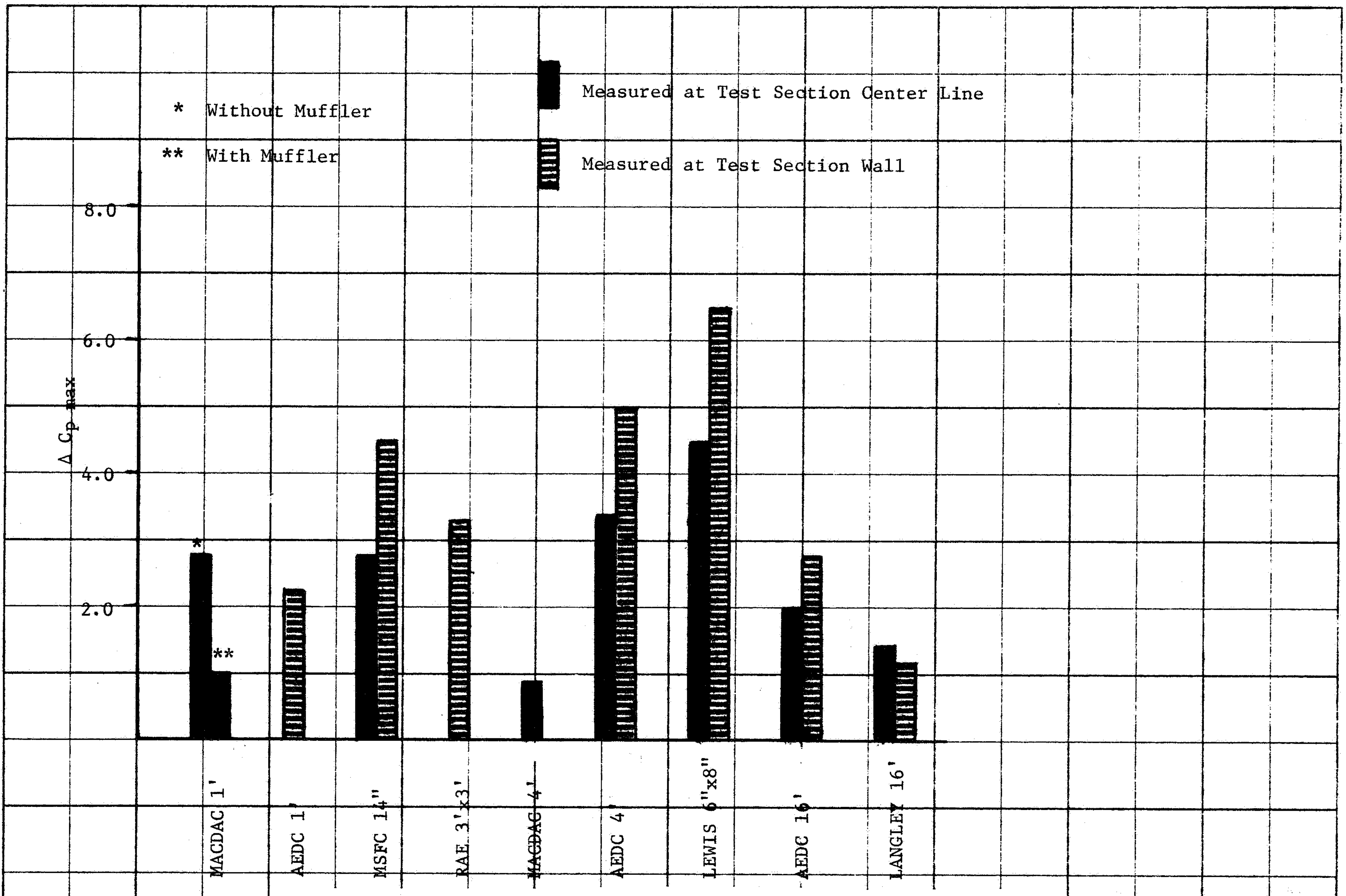


FIGURE 16. MAXIMUM FLUCTUATION PRESSURE COEFFICIENTS

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TECHNICAL REPORT HSM-R1-71

ADDITIONAL CORRECTION OF 4% SATURN V PROTUBERANCE TEST DATA

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