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PRELIMINARY AERODYNAMIC CALIBRATION OF THE SPINNING MODE SYNTHESIZER FLOW DUCT FACILITY

By

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Richard J. Silcox

SUMMARY

Results of the initial aerodynamic calibration of the spinning mode synthesizer flow duct facility in the Aircraft Noise Reduction Laboratory are presented. The system is shown to be operable over an inlet Mach number range of zero to 0.6. Mach number profiles are presented at several axial stations along the duct. Diffuser performance is reviewed. Spatial and temporal variations in the mean flow are pointed out and their effect on acoustic propagation is discussed.

INTRODUCTION

Testing of fan rotors in static test rigs is proving to have major shortcomings for simulating the inflight acoustic performance of modern turbofan engines. References 1, 2 and 3 discuss the way in which test stand induced flow distortions influence the noise source during static testing. Thus, different sources may become significant or even dominant depending upon the nature and intensity of the flow distortions being ingested. Another problem of concern for research testing is the complexity of the fan noise source in fan test facilities. In order to validate theoretical propagation models or optimize acoustic liner material properties, the structure of the noise source must be accurately known. However, precise control or even measurement of the noise source in static engine or fan tests is extremely difficult.

The Spinning Mode Synthesizer (SMS) in the flow duct facility of the Aircraft Noise Reduction Laboratory (ANRL) is a research apparatus designed to overcome some of the problems outlined above. The SMS generates arbitrary combinations of acoustic sound patterns in the presence of air flow in a 0.3 meter diameter duct. Specified duct modes are generated by controlling the amplitude and phase of 24 acoustic drivers located around the duct wall in a plane perpendicular to the duct centerline. The noise field thus produced is monitored by an array of wall mounted microphones located upstream of the drivers. The pressure field sensed at this location is operated on by a control computer to generate correction signals to the drivers in order to optimize the noise field to that desired in the experiment. Thus, the source is not affected by flow inhomogeneities the way a fan-stator or rotor-stator assembly would be. In addition, since the SMS is a readily controllable source, propagation models may be validated with either simple or complex noise source fields. In addition, the effectiveness of acoustic duct liners may be determined either at design or off-design conditions.

A significant problem with the SMS can be flow inhomogeneities in the flow duct that can affect the propagation of sound thru the duct, rather than the source. At the source reference plane (source microphone plane), the commanded pressure distribution is approximated to some arbitrary accuracy. As this known disturbance propagates upstream in the duct, asymmetries in the mean flow can distort the acoustic pressure field. This can result in an acoustic field that is not only a function of the source and duct geometries but also of radial and circumferential mean flow variations. Complicating the situation further, if time dependent fluctuations are present in the mean flow, the sound pressure level at the microphones becomes a function of these fluctuations since the microphones, which are monitored sequentially, may not all sample the same acoustic field. Therefore; even if the microphone data is averaged over a large number of samples, the proper content of the acoustic signal may become unclear.

The details of the mean duct flow in the SMS flow duct facility of ANRL are the primary subject of this report in order to demonstrate the level of inhomogeneities in its flow. These results should also prove useful for using experimental data from this facility to validate theoretical models. This report will also document the performance of the diffuser on the flow duct facility. Since the capability of the flow facility is limited, the flow rates attainable up to choking of the duct are directly dependent on the pressure recovery in the diffuser. Since this relates to the maximum Mach number in the test sections, the diffuser performance parameters must also be included.

The author wishes to thank Professor P. Stephan Barna of Old Dominion University for providing most of the data included in Figure 11 and Table 1 on diffuser performance.

SYMBOLS

A	cross sectional area of duct, m^2
C_p	coefficient of pressure recovery
M	Mach number
$\bar{M}$	average Mach number
$\dot{m}$	mass flow rate, kg/sec
p	pressure, N/m^2

R	radial position
Rg	gas constant
T	temperature, °K
V	velocity, m/sec
X	axial distance downstream of reference plane, m
γ	ratio of specific heats
θ	circumferential angle measured clockwise looking into inlet, degrees
ρ	density, kg/m^3

Subscripts

amb	ambient anechoic room condition
atm	atmospheric condition
C_L	center line
ent	diffuser entrance plane
exit	diffuser exit plane
in	indicates quantity 2.54 cm downstream of reference plane
max	maximum
t	total condition

APPARATUS AND METHOD

Tests were conducted in the SMS-flow duct facility to determine the aerodynamic characteristics of the flow into and thru the duct. These tests utilized two slightly different configurations of the duct facility. During the first series of tests, the facility was configured as for acoustic tests shown in Figures la and lb. Pitot static traverses of the flow at two locations just downstream of the inlet were taken as well as forty-five wall static pressures. These pressure taps provided both axial and circumferential variations. The diffuser performance was also defined during this sequence. For the second series of tests, radial traverse probes were installed at two locations in the test sections, as shown in Figure 2. Mean velocity traverses were obtained for these two locations.

FACILITY

A schematic plan of the ANRL spinning mode synthesizer-flow duct facility as configured for the first series of tests is shown in Figures 1a and 1b. This is essentially an open circuit wind tunnel, consisting of an inlet, constant area section and diffuser. Air to the anechoic room is supplied through a duct, with an inlet on the roof of the building, discharging into the room through an opening located on the wall opposite from the inlet section. Air is drawn through the inlet from the anechoic room which serves as a settling chamber. This air then flows through an inlet coupler, the instrumented test sections and the source section. All of these sections have a common 0.30 meter inner diameter with a common flange design and may be interchanged to suit the test requirements. The muffler section follows with a perforated plate inner wall of 0.30 meter diameter lined with a foam type bulk liner.

The diffuser (Fig. 1b) is comprised of two sections. The leading section is a conventional straight wall conical diffuser with a taper angle of 2.4 degrees. The following section is of similar construction but with a taper angle of 4.76 degrees. This arrangement allows for most of the pressure recovery to occur in the leading section where flow separations are not likely to be a problem. Both sections have a 4 to 1 area ratio and couple the 0.30 meter diameter SMS sections to the 1.22 meter air exhaust system in ANRL.

Downstream from the diffuser, the 1.22 meter diameter duct expands to 2.44 meters and the low velocity air is ducted to a centrifugal blower. Powered by a 1119 Kilowatt electric motor, this blower has a mass flow capacity of 24.86 kg/sec and draws a maximum vacuum of 36197 N/m^2.

Instrumentation and Method

The reference Mach number or inlet Mach number used in this experiment is computed from the atmospheric pressure and a mean value of four static pressures from taps located 2.54 cm downstream from the beginning of the constant area section. It is computed from the isentropic relation

$$M_{in} = \sqrt{\frac{2}{\gamma-1}\left[\left(p_{atm}/p_{in}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (1)$$

Then, if homenergic flow is also assumed along the length of the inlet, then the expression for the rate of mass flow becomes a function of the inlet Mach number and the room conditions

$$\dot{m} = \frac{A p_{atm}}{\sqrt{R_g T_{atm}}} \sqrt{\gamma}\, M_{in}\left(1 + \frac{\gamma-1}{2} M_{in}^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \qquad (2)$$

The reference station from which axial distance is measured, is the cross section at the exit of the inlet section. Positive axial distance is measured in the downstream direction. Aximuthal position is referenced from the top of the duct, positive in a clockwise sense when looking into the inlet. A reference to a negative radius corresponds to a radial position 180^0 opposite the positive radius.

In conjunction with other tests, pitot-static tube traverses were taken at axial locations of 2.16 cm and 46 cm downstream from the reference plane. The radial distribution of the dynamic head was recorded on an X-Y plotter for inlet Mach numbers ranging from 0.1 to 0.5. Since the duct area remains constant, the static pressure at both axial locations was assummed equal to that of the wall pressure taps at 2.54 cm. The Mach number was again determined from the isentropic relation

$$M = \sqrt{\frac{2}{\gamma-1}\left[\left(P_t/p\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{3}$$

The velocity was determined using the isentropic relation for temperature, assuming the ambient anechoic room temperature as being the total temperature.

$$V = M\sqrt{\gamma R_g T_{amb}/\left(1 + \frac{\gamma-1}{2}M^2\right)} \tag{4}$$

Wall static pressures were taken at 33 axial locations from 2.2 meters to 3.68 meters. Also, 12 taps were circumferentially spaced 30^0 apart at a cross section 3.14 meters from the reference plane. These pressure taps and the four taps used to determine the inlet Mach number were monitored by a scanning valve switch and a differential pressure sensor.

The sensor output was digitized and pressures and Mach numbers were printed out on-line by a computer. The Mach number was again determined using equation (3), where p is the wall static pressure and p_t the anechoic room pressure, p_{atm}. Viscous losses along the pipe associated with p_t were neglected.

Diffuser performance was evaluated with three pitot-static tubes; an inlet probe 5.24 cm downstream of the diffuser inlet, a probe 6.35 cm downstream of the beginning of the wide angle diffuser section and a probe 26.2 cm upstream of the diffuser exit plane. Differential pressure from each probe was recorded using long averaging time D.C. voltmeters. The absolute static pressure of the entrance and exit probes was recorded from a pressure gauge and a water manometer. Mach numbers and velocities are determined using equations 3 and 4. The pressure recovery coefficient is defined by

$$C_p = \frac{p_{exit} - p_{ent}}{\frac{1}{2}\rho V_{CL}^2} \tag{5}$$

where V_{CL} is the center line velocity at the diffuser entrance.

For the second phase of the test, the duct sections were reconfigured as shown in Figure 2. This resulted in a constant area section 7.62 cm shorter than that of Figure 1. Also, the traversing section contained a traversing boom pod projecting into the duct that blocked 7.6 percent of the duct cross sectional area. However, model studies, equation (4), have shown this blockage to have negligible effect several diameters upstream in subsonic flow.

Pitot-static probes located in the test sections at axial locations of 2.19 meters and 2.93 meters were at circumferential positions of 0^o and -90^o, respectively. Measurements were taken at radial increments of 0.635 cm. Each data point recorded was the average of 25 samples taken at 10 microseconds intervals. Mach numbers and velocities were evaluated using equations (3) and (4), and the inlet Mach numbers ranged from 0.1 to 0.5. An indication of the time variation of the flow was obtained by positioning the probe against each wall and at the duct centerline and sampling the flow at 20 second intervals for a period of 4 minutes at each location.

During all tests, ambient conditions in the anechoic room were monitored continuously.

RESULTS AND DISCUSSION

Figure 3 presents the inlet Mach number and accompanying mass flow rate as a function of compressor rpm. The shape of both curves indicate that the system attains a sonic choking condition at an inlet Mach number of about 0.6 with a corresponding 13.75 kg/sec mass flow rate. The sonic condition occurs physically at the end of the constant area duct sections at the juncture of the muffler section with the first diffuser section.

Note that both the Mach number and the mass flow rate are dependent on ambient conditions (eqs. 1 and 2), thus these curves can be taken only as representative of the conditions prevailing during the tests. However, since the ambient conditions and inlet pressures can be monitored continuously, the desired inlet Mach number can be set.

Mach number profiles in the vertical plane for two axial stations are given in Figures 4 and 5. Figure 4 shows a relatively uniform Mach number across the duct for inlet Mach numbers 0.1 to 0.5 at an axial distance 2.16 cm downstream of the reference plane. Boundary layer thickness is minimal at the lower Mach numbers, thickening to a maximum of about 7 percent of the radius for the highest Mach number. In Figure 5, increased boundary layer thickness and continued uniform mean flow is shown 46.1 cm downstream from the reference plane. A slight acceleration of the mean flow occurs due to the boundary layer growth.

The data presented in Figures 6, 7, and 8 were taken with the facility configured as shown in Figure 2. The overall length of the constant area sections was shorter by 7.4 cm than the configuration of Figure 1a. This change should result only in a negligibly small change in the overall Mach number for a given compressor rpm. Also, as noted previously, the blockage in the traversing probe section has little effect on the flow upstream in subsonic flow.

Figure 6 shows the Mach number profiles in the vertical plane, 2.19 meters downstream from the reference plane. The Mach number distribution appears to be distorted at the bottom ($\theta = 180^0$) of the duct, especially at the higher inlet Mach numbers. Scatter of the individual data points (not shown) in this region indicates a temporal variation as well. No indication of this distortion appears in Figures 4 and 5.

The Mach number profiles shown in Figure 7 were taken in a horizontal plane from $\theta = 270^0$. These distributions show a uniform core flow and profiles that are relatively axisymmetric. Acceleration of the mean flow becomes significant at this axial station due to the rapid growth of the boundary layer. However, the highly asymmetric Mach number profile observed 74 cm upstream in the vertical plane does not reappear in this horizontal traverse.

Figure 8 presents the variation over a 4 minute period of the mean Mach number near each wall and at the center line of the duct for five inlet Mach numbers and two axial positions. These data were taken with pitot-static probes at axial stations of 2.19 and 2.93 meters in the vertical and horizontal planes respectively. Variation of the mean center line Mach number is relatively small, but at either wall the variation becomes significant. Note that the microphones which monitor the acoustic amplitude and phase were flush mounted at the duct wall and the amplitude and phase are flow field dependent. Therefore, these temporal fluctuations in the mean flow are important in that they cause the acoustic field to be unsteady at the fixed microphone locations.

The data shown in Figures 9, 10 and 11 were taken with the original facility configuration shown in Figure 1a and 1b.

A survey of the circumferential wall pressure taps, Figure 9, reflects no significant asymmetry in the flow. A slight increase in the calculated Mach number was consistently observed between $\theta = 180^0$ and $\theta = 240^0$, but only of the order shown in Figure 9. The axial Mach number distribution in the test sections is shown in Figure 10. The observed gradual increase in the Mach number with axial distance can be attributed to boundary layer growth within the duct.

Diffuser performance data is shown in Figure 11 and Table I. A non-dimensional representation of the diffuser velocity profiles near the inlet and exit planes is shown in Figure 11 for an inlet Mach number of 0.197. The velocity distribution near the inlet is seen to be a smooth variation from the wall but that a drop in velocity occurs over a region encompassing the center. The contour indicates the boundary layer extends across the duct but the flow is stable and no boundary layer separation occurs. However, the velocity profile 26 cm upstream of the diffuser exit is not nearly as well defined. The dip in velocity still occurs near the center, but the scatter in the velocity profile closer to the wall indicates a significant unsteady flow. Scale model studies (ref. 5) of this flow apparatus have verified that flow separations and unsteady flow do exit in the downstream diffuser section. However, unpublished data of the author show that propagation of these flow disturbances upstream into the test section is negligible.

Table 1 indicates the diffuser recovery for four values of inlet Mach number. It is of interest to note that the efficiency of the diffuser at choking conditions appears to be higher than under subsonic conditions. One explanation for this may be due to the compressor rpm being increased to a value higher than that required for choking. This would cause an expansion wave to occur somewhere downstream of the diffuser inlet. The loss in static pressure would be sensed by the inlet pitot-static probe since it is located downstream of the diffuser inlet. This would cause p_{ent} (eq. 5) to be erroneously low since it reflects the effect of the expansion wave and C_p to be high.

Table 1. Diffuser Recovery Factors

Inlet Mach number M_{in}	Recovery factor C_p
.22	72.6
.42	69.3
.5[illegible]	67.6
.583 (choking)	84.3

The overall pressure recovery is approximately that found on the scale models in references 4 and 5, although somewhat lower. However, since the diffuser allows the facility to attain fully choked conditions, the SMS-flow duct facility can operate over its full design range.

CONCLUDING REMARKS

The SMS-flow duct facility in ANRL has been shown to be operable over an inlet Mach number range of 0.1 to 0.6. Data are presented documenting the flow characteristics at various axial, radial and circumferential stations in this facility. Several deficiencies of the mean flow have been observed. Although the flow just downstream of the inlet is uniform and axisymmetric, further downstream, distortion of the Mach number profile near the lower wall is obeserved. This may be attributable to an inlet vortex or vortices mixing the low energy boundary layer with the mean core flow at larger axial distances from the inlet. This type of distortion may be expected to influence the acoustical system such that modes defined at the source microphone plane would be scattered into different modes as they propagate through the distorted flow. In addition to the above, significant temporal fluctuations of the mean axial Mach number were observed. Since the phase and amplitude of the acoustic signal at any fixed location in the duct is dependent upon the duct flow, the acoustic signals recorded by both the source monitoring microphones and the test section microphones will reflect these temporal fluctuations of the mean flow. Thus, the sound source optimization procedure and the analysis of acoustical test data would be adversely affected by the observed flow unsteadiness.

In using the SMS-flow duct facility in ANRL, the deficiencies outlined above must be recognized. The use of the acoustic optimization procedure is limited and data acquisition methods must allow for the temporal variations.

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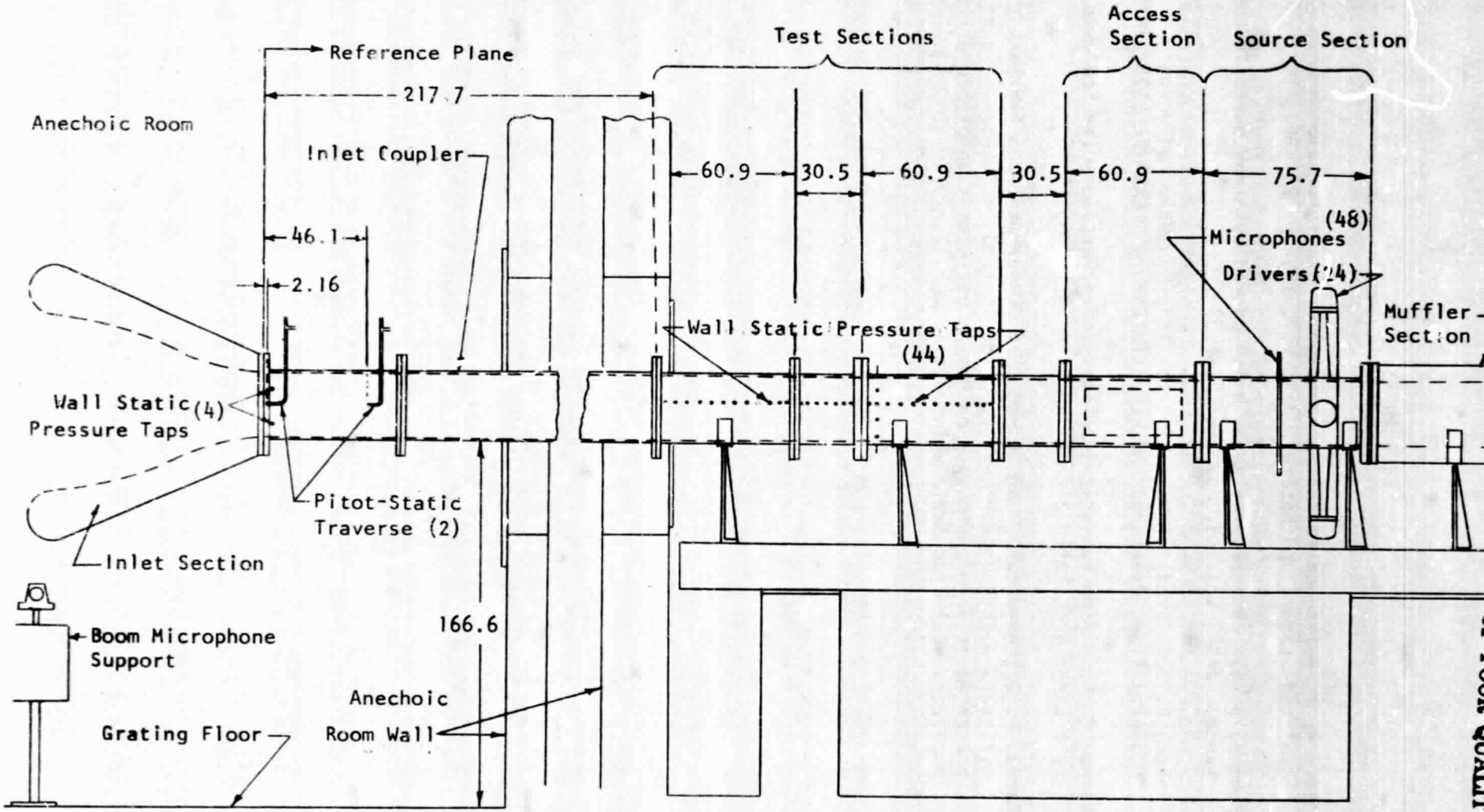

Fig. 1A. Schematic view of forward sections of flow duct-SMS facility in ANRL. All dimensions are in centimeters.

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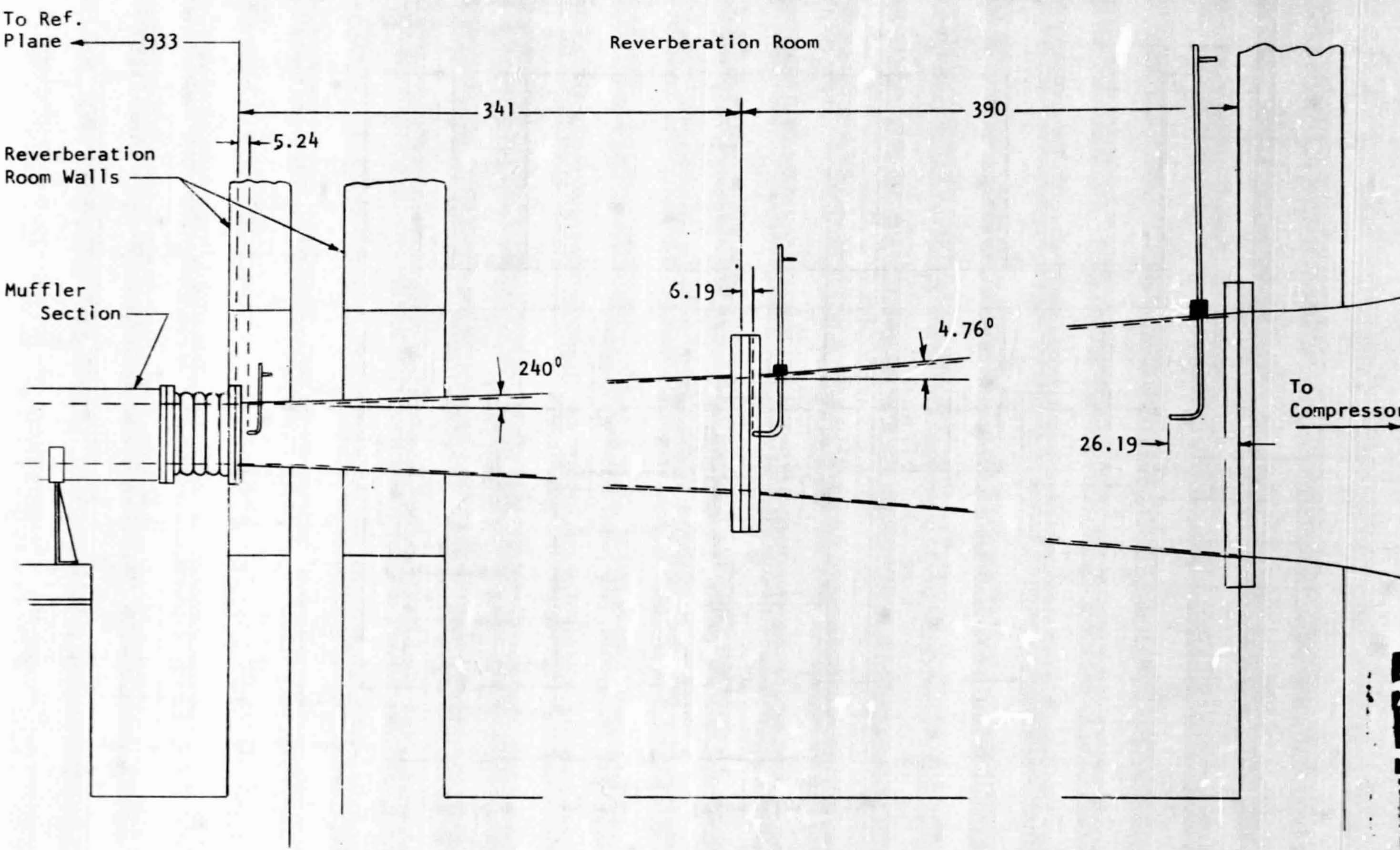

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Fig. 1B. Schematic view of diffuser sections of flow duct-SMS facility. Locations of three pitot-static traverses are shown along with details of diffuser design. Dimensions are in centimeters.

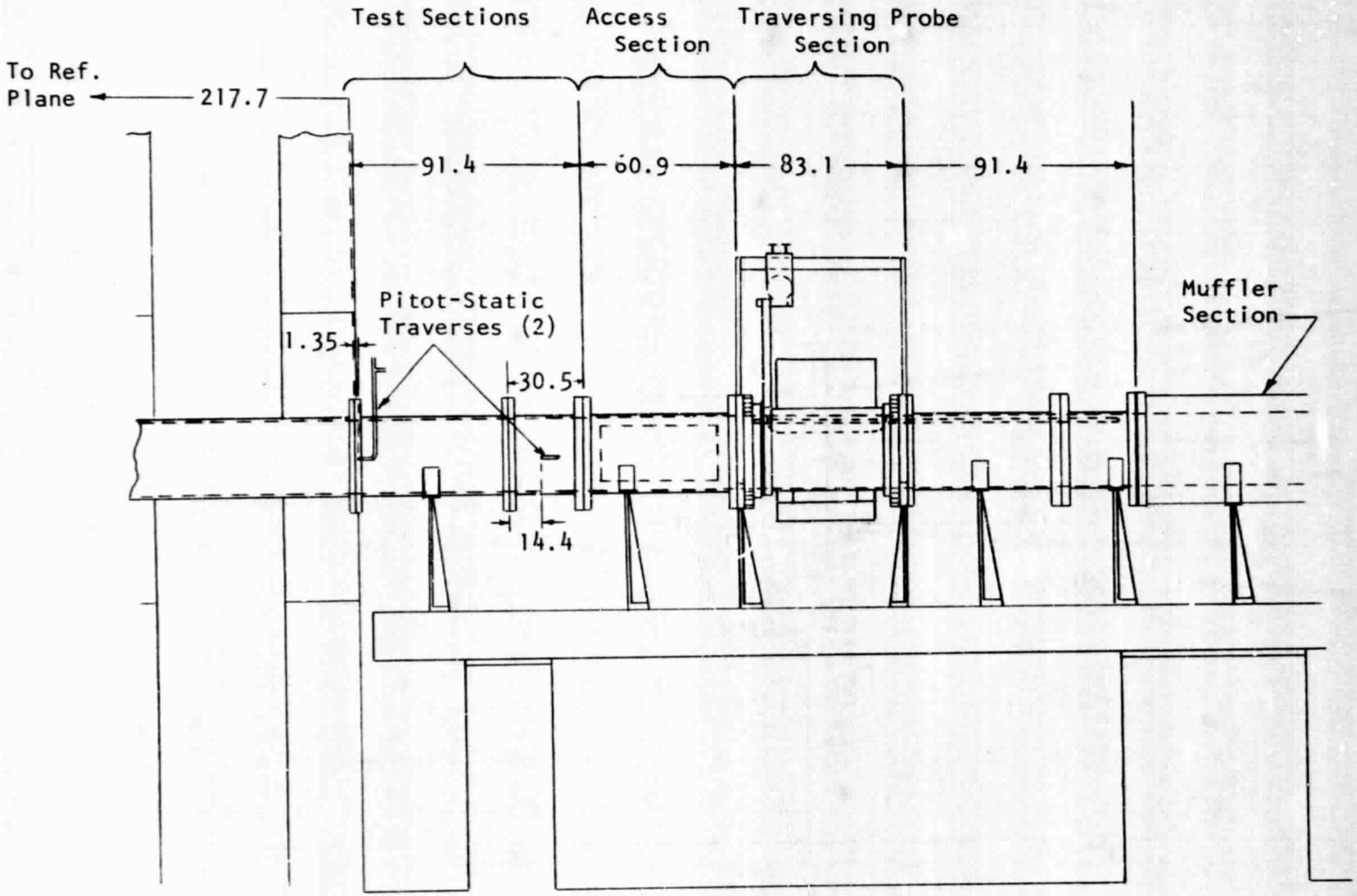

Fig. 2. Facility reconfiguration for the second phase of aerodynamic testing.

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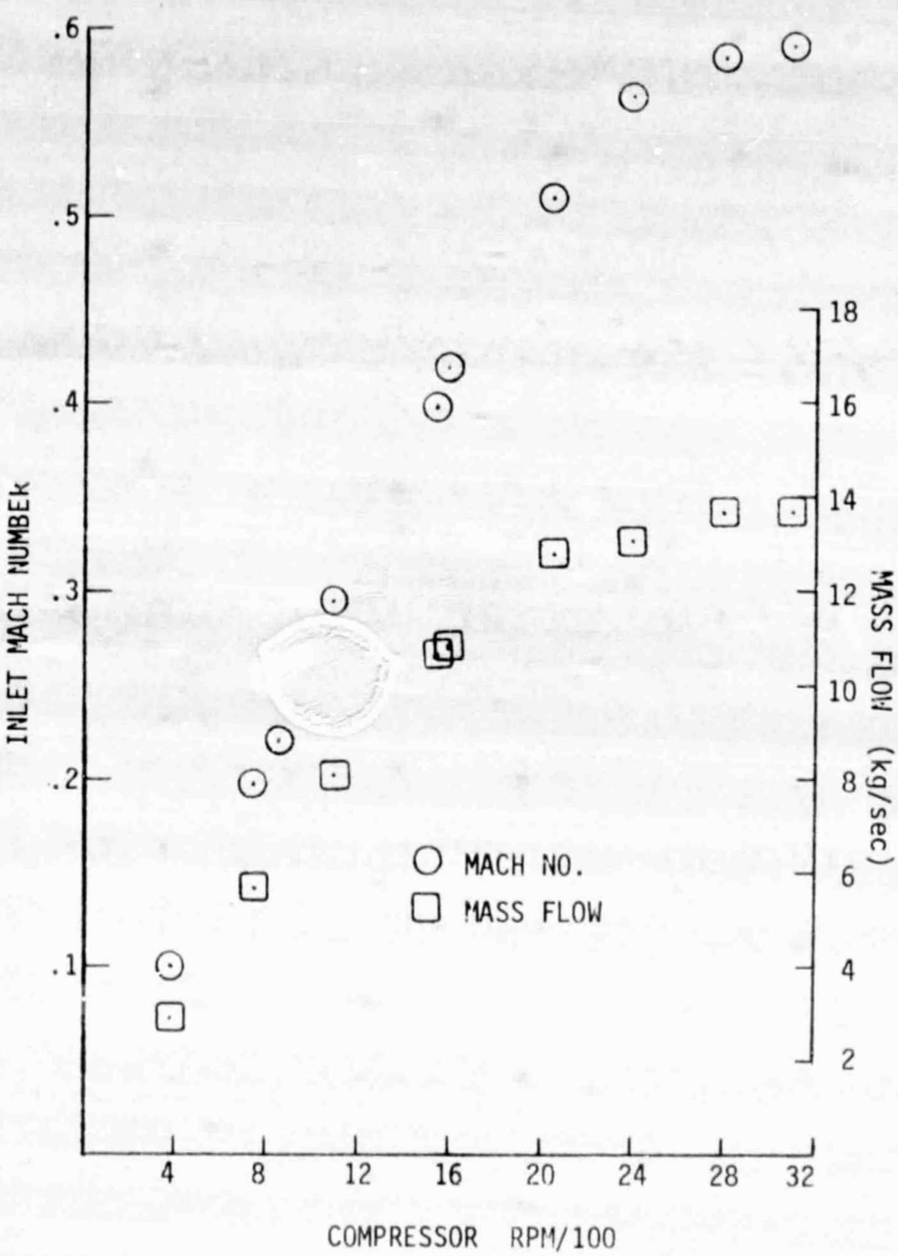

Fig. 3. Variation of inlet Mach number and mass flow with compressor speed. Values shown were taken with anechoic room ambient conditions of 101490.8 N/m^2 and 26.7° C.

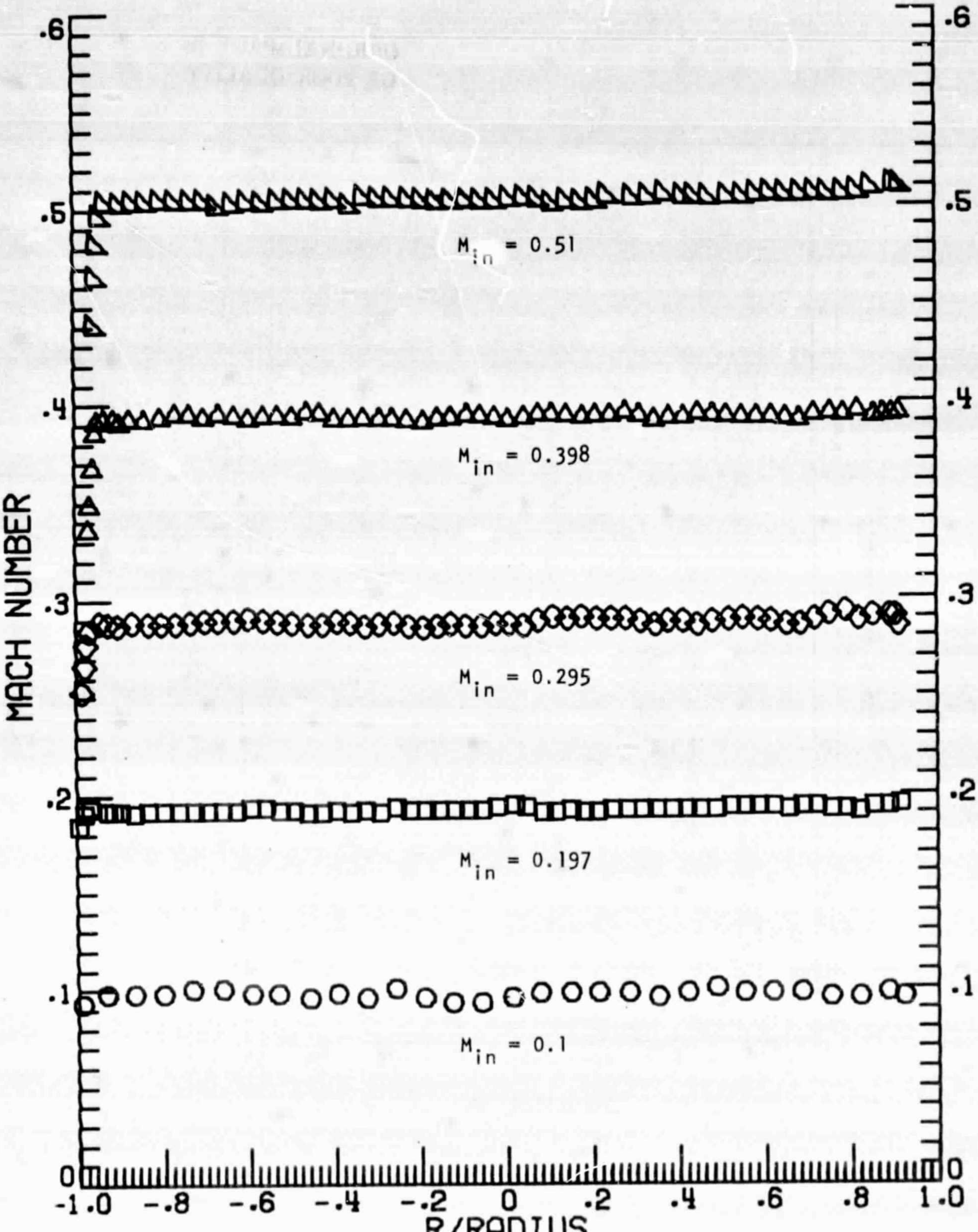

Fig. 4. Duct Mach number profile at an axial station 2.16 cm downstream from the duct reference plane for five values of inlet Mach number.

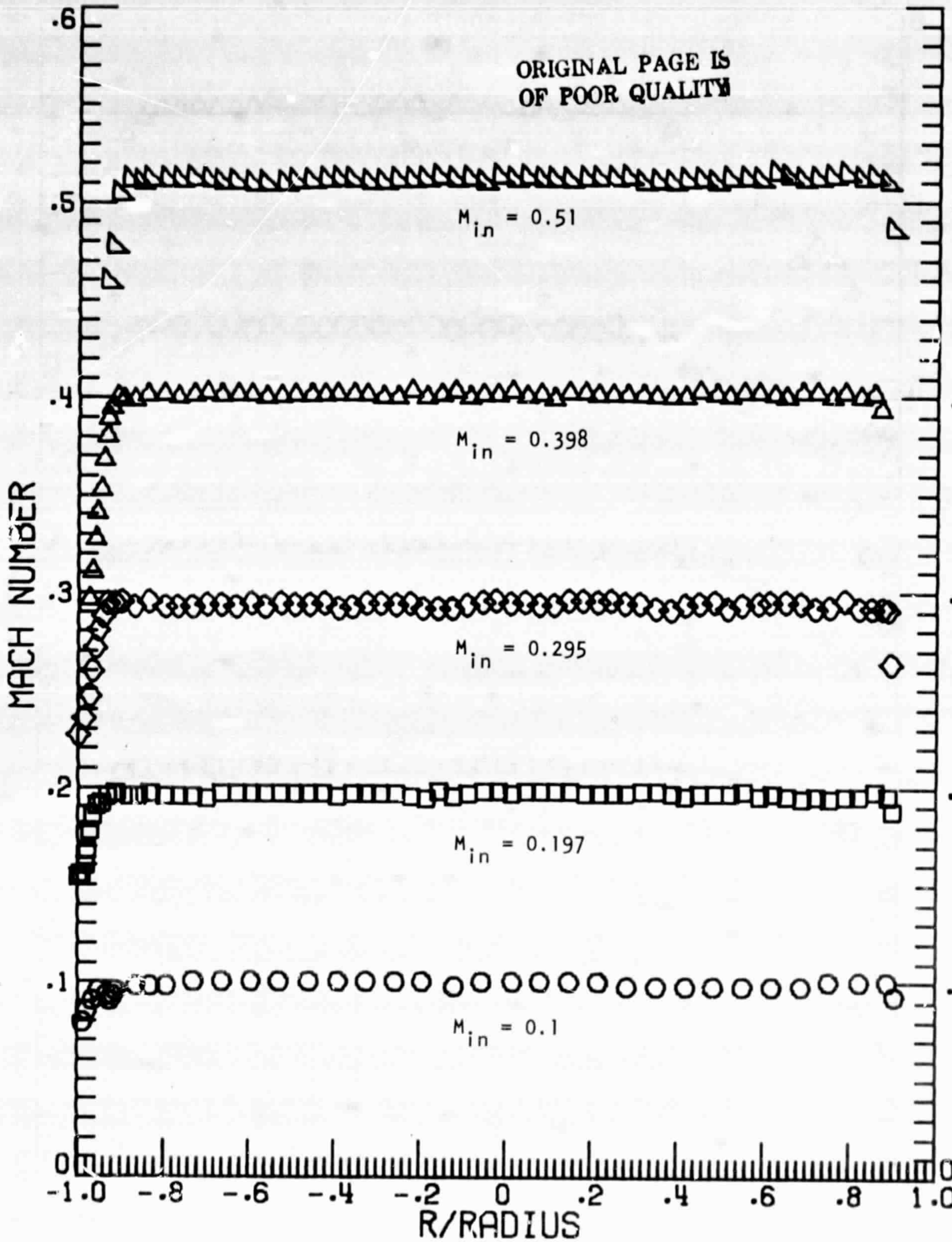

Fig. 5. Duct Mach number profile at an axial station 46.1 cm downstream from the duct reference plane for five inlet Mach numbers.

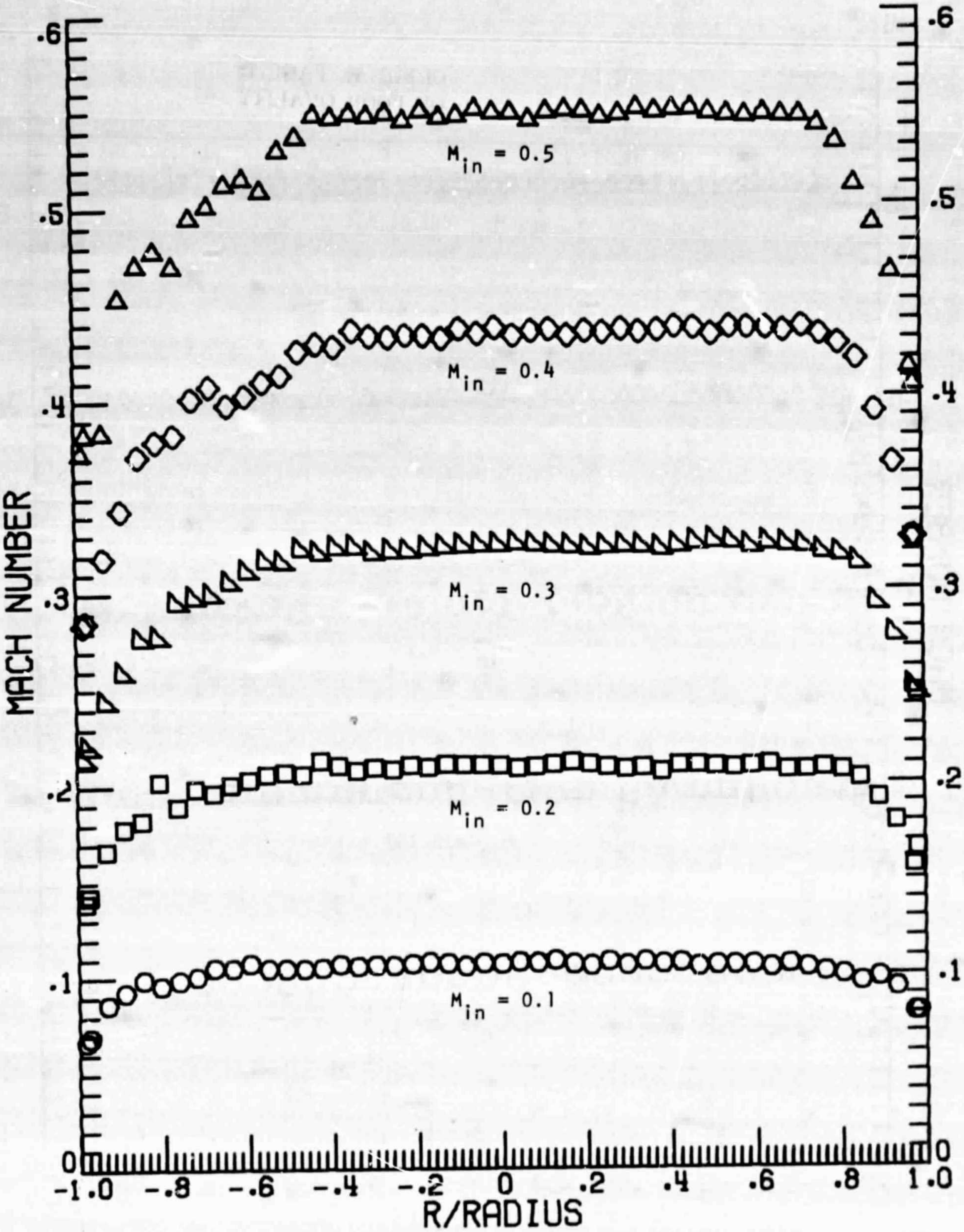

Fig. 6. Mach number profiles for inlet Mach numbers of 0.1 to 0.5. Traverses were at an axial location 2.19 meters downstream from the reference plane at an angle of 0 degrees to the vertical.

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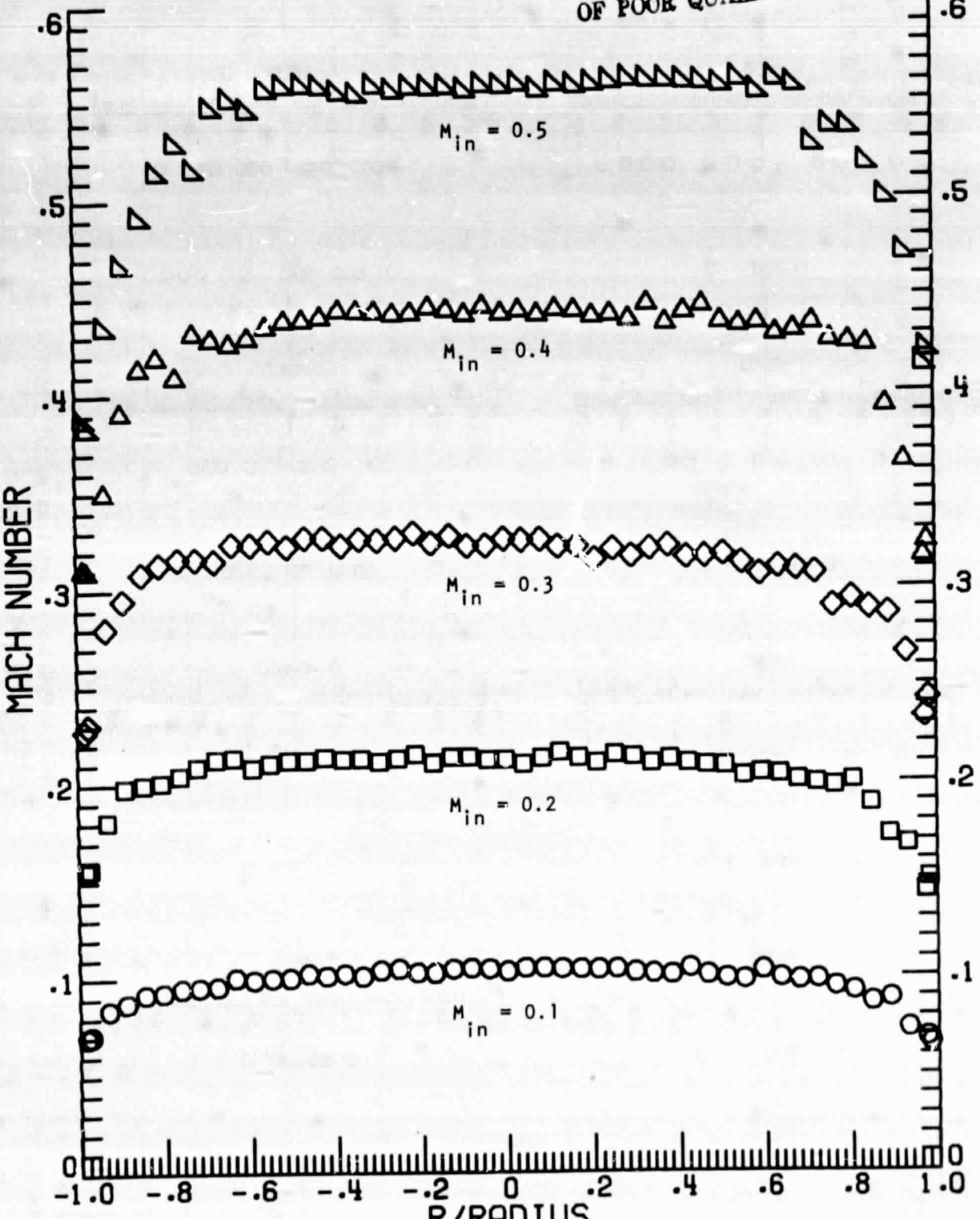

Fig. 7. Mach number profiles for inlet Mach numbers of 0.1 to 0.5. Traverses were at an axial location 2.93 meters downstream of the reference plane at an angle of 270° clockwise from the vertical.

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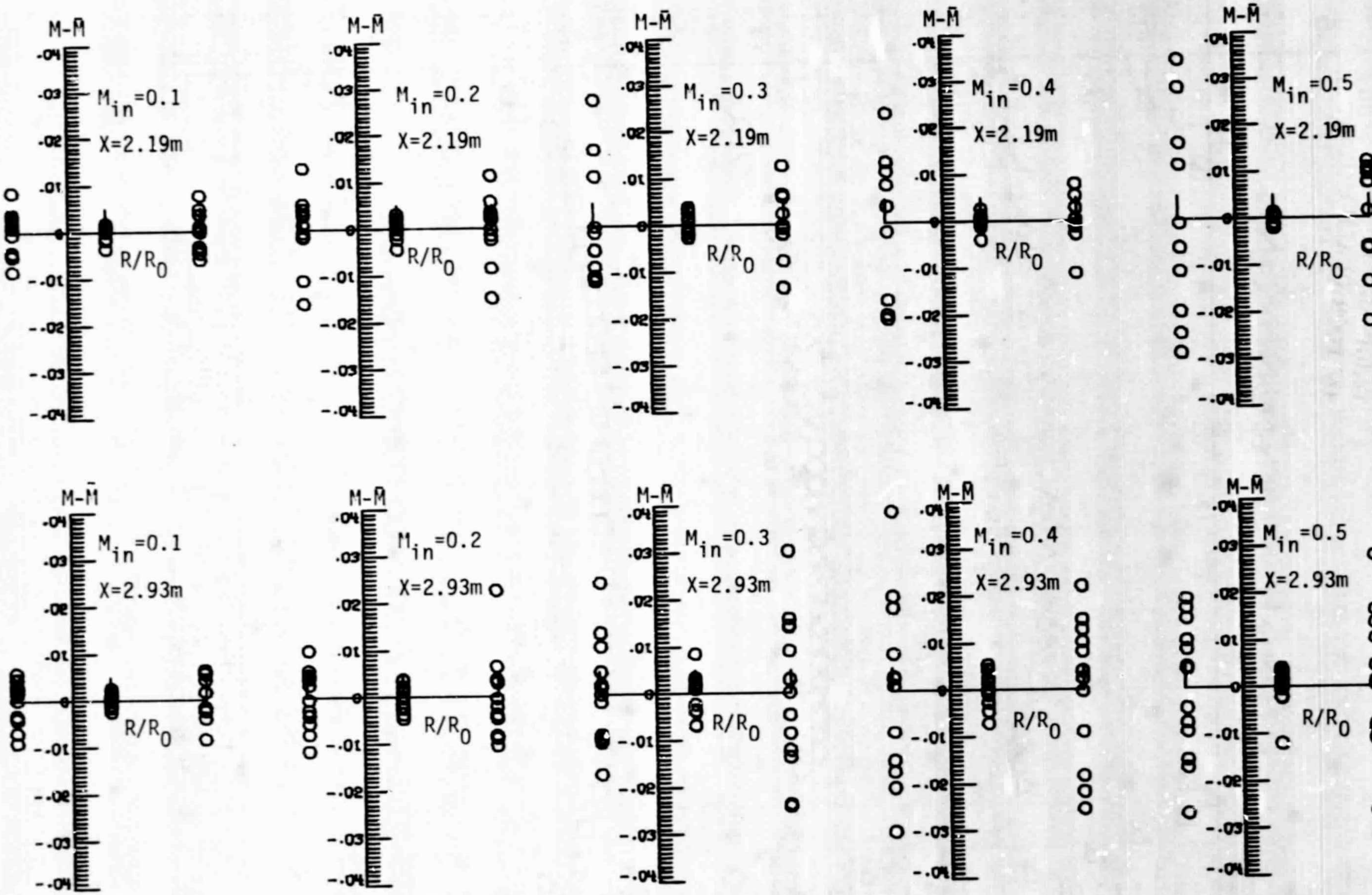

Fig. 8. Variation of the wall and centerline Mach numbers is shown at axial stations 2.19 m and 2.93 m for five values of inlet Mach number. R_o refers to the duct radius.

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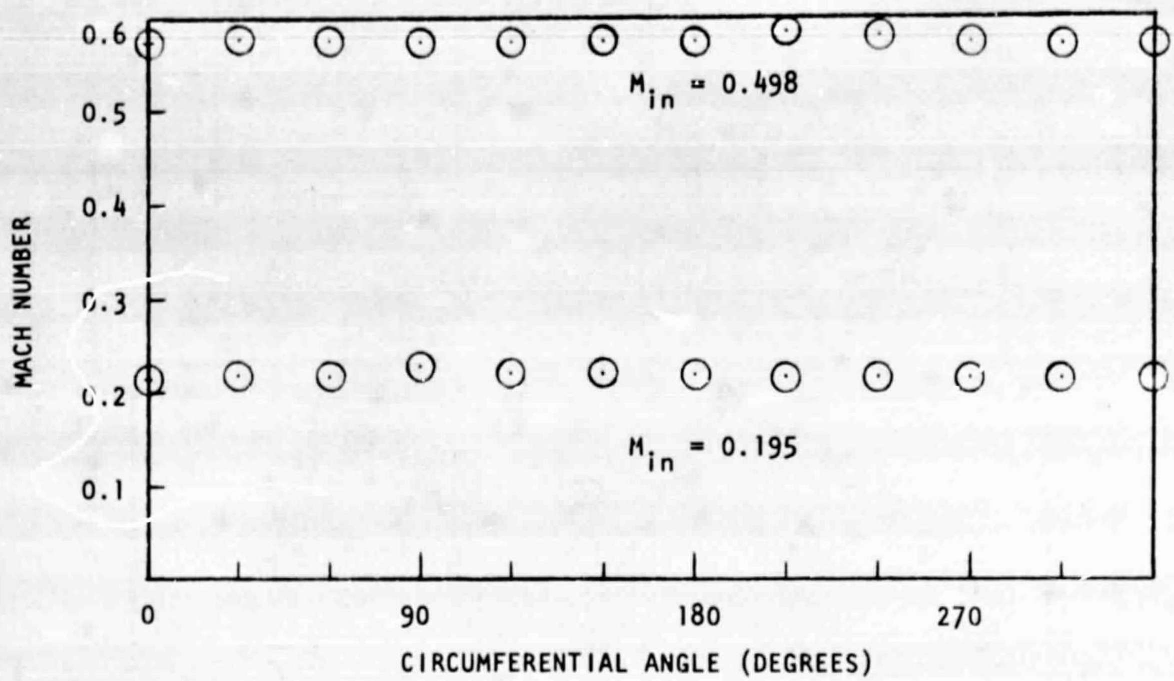

Fig. 9. Circumferential Mach number distribution at axial station 3.14 meters for inlet Mach numbers of 0.195 and 0.498. Mach numbers were determined from wall static pressure taps.

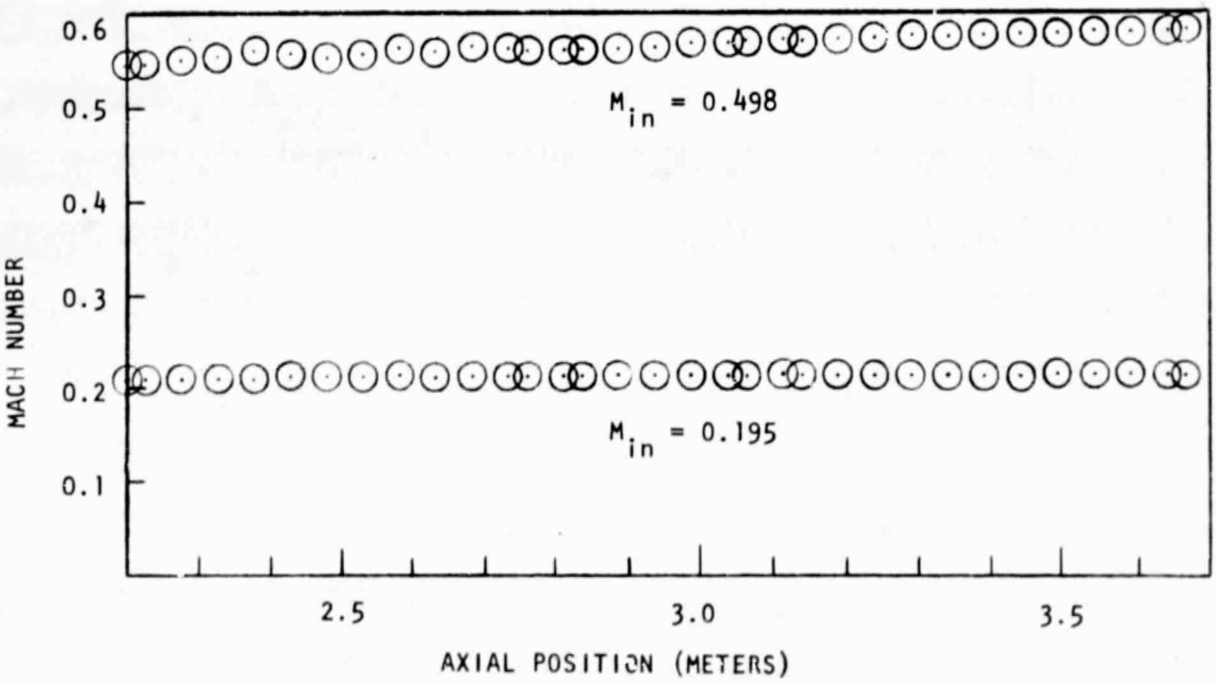

Fig. 10. Axial Mach number distribution in the flow duct test sections as determined from wall static pressure taps for inlet Mach numbers of 0.195 and 0.498.

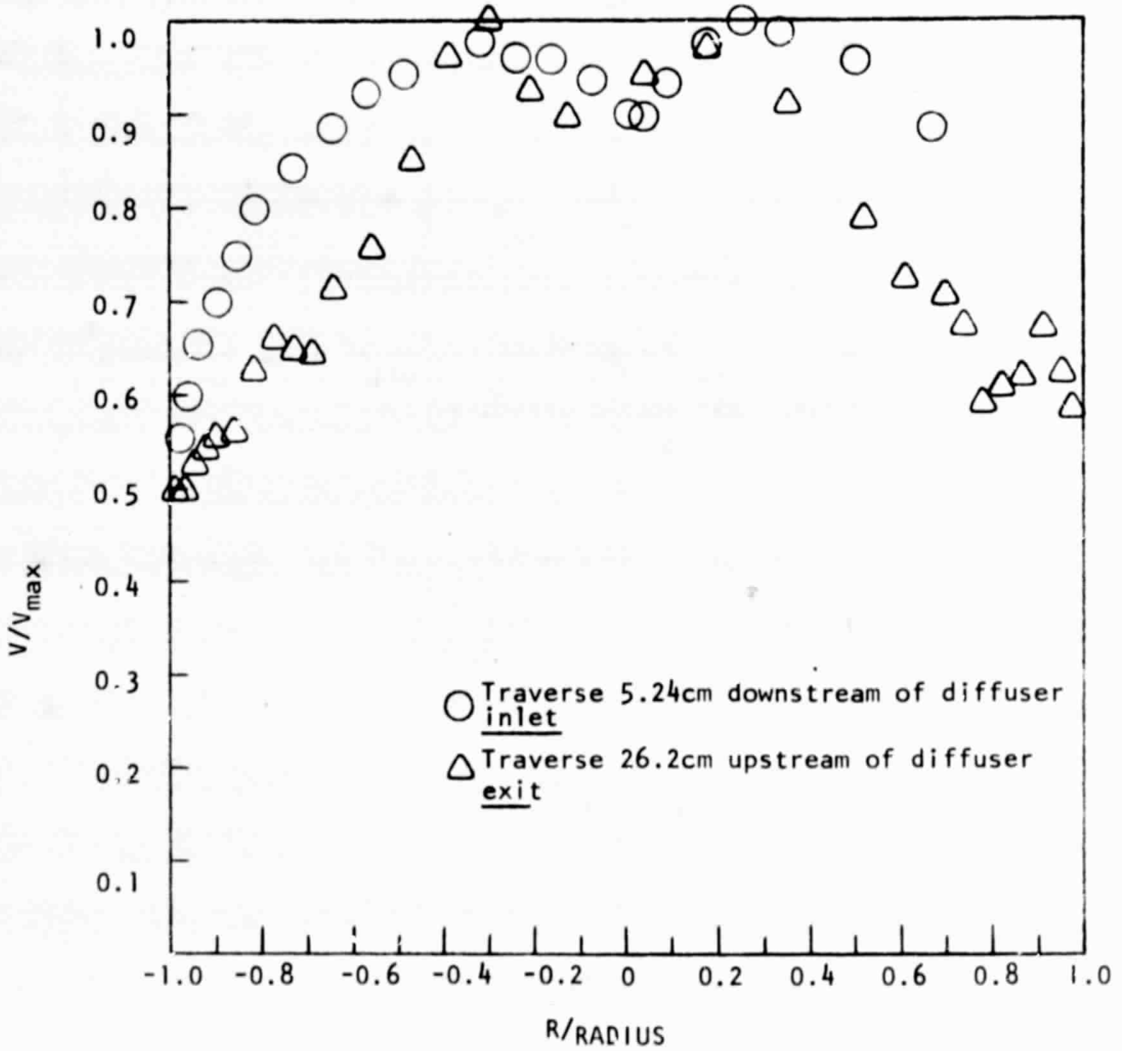

Fig. 11. Comparison of velocity profiles at diffuser inlet and exit for a duct inlet Mach number of 0.197.

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15. Supplementary Notes

16. Abstract

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