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RESEARCH MEMORANDUM

for the

Air Materiel Command, U. S. Air Force

PERFORMANCE OF AXIAL-FLOW SUPERSONIC COMPRESSOR OF XJ55-FF-1 TURBOJET ENGINE

II - PERFORMANCE OF INLET GUIDE VANES AS SEPARATE COMPONENT

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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SUMMARY

The inlet guide vanes for the supersonic compressor of the XJ55-FF-1 engine were studied as a separate component in order to determine the performance prior to installation in the compressor test rig.

Turning angles approached design values, and increased approximately 1° through the inlet Mach number range from 0.30 to choke. A sharp break in turning angle was experienced when the choke condition was reached.

The total-pressure loss through the guide vanes was approximately 1 percent for the unchoked conditions and from 5 to 6 percent when choked.

INTRODUCTION

At the request of the Air Materiel Command, U. S. Air Force, an investigation is being conducted at the NACA Lewis laboratory to determine the performance characteristics of the supersonic axial-flow compressor for the XJ55-FF-1 turbojet engine. Preliminary performance of this compressor is presented in reference 1.

The complete supersonic compressor unit consists of a row of inlet guide vanes, a supersonic rotor, and two rows of stator blades. The purpose of the inlet guide vanes is to provide the desired Mach number distribution relative to the rotating blades at the rotor inlet. As part of the program to determine over-all compressor performance, the inlet guide vanes were investigated as a separate component. Two inlet configurations were used in this investigation: (1) an axial inlet similar to that used in the XJ55-FF-1 engine and (2) a curved inlet comparable to that used in the compressor test rig. Existing compressor-rig parts made the curved inlet passage necessary. Performance characteristics of the guide vanes are presented and evaluated over the range of flows to be encountered in the compressor operation.

APPARATUS

Guide vanes. - The inlet guide vanes (fig. 1) have an NACA 65-(0)10 airfoil section at the tip and an NACA 65-(12)10 section at the root. The constant inside and outside diameters of the flow passages are 10.2 and 13.25 inches, respectively. The 27 blades have a solidity varying from 1.135 at the tip to 1.474 at the root. The guide vanes are designed for an inlet Mach number of 0.60 with uniform flow across the passage. At the rotor inlet, design turning angle varies from 23.9° to 0° from root to tip.

Test rig. - The guide-vane test rig is schematically shown in figure 2. The rig consists of orifice tank, inlet cone, test section, and discharge piping. Air is drawn into the orifice tank from the test cell through a flat-plate orifice, and discharges into the altitude exhaust system. The back pressure required to give the desired Mach number in the rig is obtained by a valve in the exhaust line. The two inlet-section configurations are shown in figure 2. The outer discharge housing of the test section was rotated to provide a circumferential survey downstream of the guide vanes. The tip diameter of the discharge housing reduces 0.25 inch between the outlet of the guide vanes and the position of the rotor. This contraction simulates the rotor-inlet passage used in the XJ55-FF-1 engine.

Instrumentation. - Survey stations were located at the following positions:

(1) 0.875 inch upstream of the leading edge of the guide vanes (3.25 in. upstream of guide vanes in curved-inlet configuration)

(2) in the contracting passage, 0.920 inch downstream of the trailing edge of the vanes

(3) at the rotor positions, 2.80 inches downstream of the trailing edge of the vanes (omitted in axial-inlet configuration)

Combination survey instruments of the type described in reference 2 were used at each station, thus making possible the attainment of data on total pressure, static pressure, and flow angle. The accuracy of pressure readings was ± 0.02 inch of mercury and of angle readings, $\pm 3/4^{\circ}$. Static taps were provided in the flat-plate orifice for weight-flow calculation and were also placed in the discharge system. A total-pressure tube was placed in the inlet cone.

PROCEDURE

The guide-vane investigation was conducted in two sections: (1) with the axial-, and (2) with the curved-inlet configuration. The flow conditions set for each series of runs are summarized in the following table:

Axial-inlet configuration:	
Inlet Mach number, M_1	0.30, 0.40, 0.50, and 0.60
Choke conditions.	1, 2, and 3
Curved-inlet configuration:	
Inlet Mach number, M_1	0.45 and 0.60
Choke conditions.	1 and 2

The prescribed Mach number at the midpoint of the passage upstream of the guide vanes was set by adjustment of the exhaust throttle. Conditions of choke were set by arbitrary valve openings, ranging from slightly greater than that required for an inlet Mach number of 0.60 (back pressure of approximately 27 inches of mercury absolute) to that giving a back pressure of 10 inches of mercury absolute. After the inlet condition was set, data were taken at 0.25-inch radial increments across the passage and at 28 circumferential positions, corresponding to 1° increments across two blade passages. For all computations, pressure and angle readings were arithmetically averaged for the 28 circumferential positions at a given radius. This method resulted in an average of wake and midstream conditions. Integrated weight flows based on these average survey measurements checked orifice weight flows within 3 percent.

With the exception of survey station 1, results from the two configurations were generally comparable and therefore axial-inlet data will be presented in detail with limited curved-inlet data for comparison. Because of similar results for both configurations at station 2, data were not obtained at station 3 for the axial inlet.

RESULTS AND DISCUSSION

Inlet conditions. - A plot of inlet Mach number against radius for the various inlet conditions set in the axial-inlet investigation is presented in figure 3. The Mach number across the passage was essentially constant, decreasing slightly at the tip. As would be expected, the three conditions of choke, representing decreasing back pressures, resulted in the same inlet Mach number of approximately 0.642. Shown also is a curve for a midpassage inlet Mach number of 0.60 for the curved inlet. Because station 1 is not located in the same position relative to the guide vanes in both configurations, a direct comparison of inlet conditions is impossible. The large variation of Mach number with radius can be attributed to the curvature of the inlet passage immediately upstream of the survey instrument. It is probable that at the inlet to the guide vanes the velocity distribution with the curved-inlet configuration approximates that of the axial inlet because of radial redistribution of mass in the 3.25 inches from station 1 to the guide vanes.

Turning angle. - The turning angle at survey station 2 is plotted as a function of radius for the axial-inlet determinations in figure 4. The curve shows an average turning angle for choked and unchoked conditions. The turning angle increased approximately 1° through an inlet Mach number range of 0.30 to choke as is shown in figure 5. This increase substantiates cascade data presented in reference 3. A sharp break in turning angle was obtained at the point of choking but no large reduction in turning angle occurred after this break. If a large enough pressure ratio across the guide vanes was obtained, a substantial reduction in turning angle probably would occur, as has been experienced in cascade investigations (reference 3).

The variation of turning angle with radius at station 2 for the curved-inlet configuration is shown in figure 6. The turning angle near the root is approximately 1° higher than in the axial-inlet determinations (fig. 4), which may be attributed to higher velocities at the root caused by the curved configuration. The variation of turning angle with Mach number for the curved-inlet runs was essentially the same as shown in figure 5.

The turning angle measured at station 3, the position of the rotor, is also shown in figure 6 with the design turning angle at the rotor inlet. The reduction in turning between stations 2 and 3 ranges from 1° to 2°. Experimental data showed essentially constant tangential velocity along the streamlines, and therefore the reduction in turning can be attributed to the contraction just upstream of the rotor position that causes an increased axial velocity. In the mid-passage, the actual turning angle closely approximates the design turning angle but near the root the air was underturned whereas at the tip it was overturned. The divergence at the extremities of the passage can probably be attributed to secondary induced radial effects.

Outlet-velocity distribution. - The outlet Mach number M_2 distribution, as measured at station 2, is shown in figure 7 for the axial inlet. For comparison, a plot of outlet Mach number is shown for the curved-inlet investigation. In both configurations, the outlet velocity was essentially constant across the passage, decreasing somewhat near the tip. Despite the completely different velocity profiles at station 1, the outlet Mach numbers for both configurations were nearly the same. In choke conditions 1, 2, and 3, outlet velocity continued to increase with lowering back pressure after the critical inlet velocity had been reached. Choke condition 3, which occurred at wide-open throttle, produced an outlet Mach number of over 0.82. The area reduction between stations 2 and 3, which is entirely from the tip, causes an increase in velocity across the entire passage but the effect was especially pronounced near the tip.

Choke characteristics. - A plot of inlet against outlet Mach number for sections at five radii for the axial-inlet investigation is presented in figure 8. Shown also is the ideal curve for the pitch section, calculated solely on the basis of area change due to turning. The discrepancy between the two curves in the unchoked range is due to boundary layer, wake effects, and losses. Inlet velocity increases with outlet velocity until the 'choking' condition is reached and then the inlet velocity remains essentially constant. The maximum portion of these curves represents the Mach number giving maximum mass flow for a given section. For the purpose of this investigation, this Mach number is called choking inlet Mach number. By use of the maximum inlet Mach number for each blade section, a plot of measured choking inlet Mach number against radius is shown in figure 9.

In a hypothetical case, a blade passage will be completely choked when sonic velocities are obtained across the entire passage. For essentially constant inlet Mach number, variations in turning angle and blade thickness along the span would prevent sonic velocity from being simultaneously obtained across the entire passage. Instead, choking would progress from the section with the lowest critical Mach number to that with the highest. This progression results in a mixed-flow condition where part of the passage is sonic and the remainder is subsonic. As the outlet pressure is lowered, the mass-flow increase through the subsonic portion causes an increase in the portion of the passage that is sonic. The increasing flow must be deflected through the subsonic portion of the passage because that part which is sonic will allow no more mass to pass. The increment increase in flow between the attainment of the first local sonic velocities and complete choking is dependent on the critical Mach number gradient across the passage, or more generally, is a function of the passage and the blade geometry. The magnitude of this increment will determine how large the radial redistribution of mass will be and how far upstream it will be felt.

In the particular guide vanes being investigated, local sonic velocities would be expected first at the root where the greatest turning exists. The sonic region would then progress across the passage and toward the tip until the flow is choked. Because the design variation of Mach number from root to tip is small, the increase in mass flow as the passage was choking would be expected to be small. Radial redistributions in the mixed-flow condition therefore would probably not be felt at survey station 1. The choking inlet Mach number distribution as measured at station 1 would therefore be expected to be comparable to the unchoked distribution. As is shown in figure 3, this condition was essentially obtained in this investigation.

In order to obtain some correlation between the choking Mach number obtained in this investigation and that which might be predicted from published data, an attempt was made to obtain correlating data from reference 3, but the necessity of extrapolating from large stagger angles made this correlation impossible. An estimate of critical Mach number for the blade sections used in this investigation is presented in reference 4 and is shown in figure 9. These approximate critical Mach numbers were obtained by use of the von Kármán-Tsien equations. This curve represents the inlet Mach numbers that would give local sonic velocities on the blade surface at a particular section. The choking Mach number, measured at station 1, would be expected to occur somewhere between the extremities of this curve. Local sonic velocities will be obtained first at the root, and if in the mixed-flow condition the increment increase in mass and thus the radial redistributions are assumed to be small, complete choking will be obtained at a station 1

Mach number only slightly greater than that giving local sonic velocities at the root. On this basis, a good prediction of choking Mach number could be made by selecting a velocity only slightly greater than the critical velocity for the root section.

Equilibrium considerations. - In these blades, where high velocities tend to magnify any radial-flow tendencies, a consideration of equilibrium conditions seemed necessary. Evaluation of simple-radial equilibrium downstream of the guide vanes by the equation

$$\frac{dp}{dr} = \rho \frac{V_\theta^2}{gr}$$

where

p static pressure, (lb/sq ft)

r radius, (ft)

ρ density, (lb/cu ft)

V_θ tangential component of velocity, (ft/sec)

g acceleration due to gravity, (ft/sec^2)

was difficult because of the inaccurcies involved in determining

$\frac{dp}{dr}$. An estimate of equilibrium was therefore made by a comparison between the measured and calculated axial-velocity distribution. The method applies energy, continuity, and simple-radial-equilibrium relations to the flow through the blades. It utilizes measured inlet conditions and turning angles and assumes constant total pressure across the passage upstream and downstream of the guide vanes. Experimental results show that the total pressure across the passage was essentially constant and therefore, if the calculated and measured axial velocities were in agreement, simple-radial equilibrium must have been established at the point of comparison.

The comparison between the calculated and measured axial velocity at survey station 2, 0.920 inch downstream of the trailing edge of the vanes is shown in figure 10. The density across the passage was essentially constant. Thus by use of the density based on wall static pressure, the calculated and measured axial velocities agreed within 1 percent except near the walls. It seems reasonable that this disagreement can be attributed primarily to the absence of boundary-layer considerations in the analytical method. Simple-radial equilibrium was therefore assumed to be established 0.920 inch downstream of the guide vanes. The curved-inlet configuration showed similar comparison between measured and calculated axial velocities.

Losses. - At an inlet Mach number of 0.60, the average loss in total pressure through the guide vanes was very small, approximately 1 percent, and in the choked condition the loss in total pressure increased to 5 or 6 percent.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the inlet guide vanes for the XJ55-FF-1 engine:

1. Both the curved- and axial-inlet configurations gave essentially the same downstream flow conditions.

2. The turning angle obtained in the midsection of the passage closely approximated design, but underturning at the root and overturning at the tip were experienced.

3. Turning angle increased approximately 1° through the Mach number range from 0.30 to choke and a sharp decrease in turning angle was obtained at the choke condition.

4. Three-dimensional adjustments took place very rapidly with simple-radial equilibrium established within 0.920 inch downstream of the trailing edge of the vanes for both configurations.

5. For these particular guide vanes, a good estimate of the choking characteristics could be obtained by use of the von Kármán-Tsien equations.

6. In the unchoked condition, the loss in total pressure through the guide vanes was in the order of 1 percent and in the choked condition from 5 to 6 percent.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
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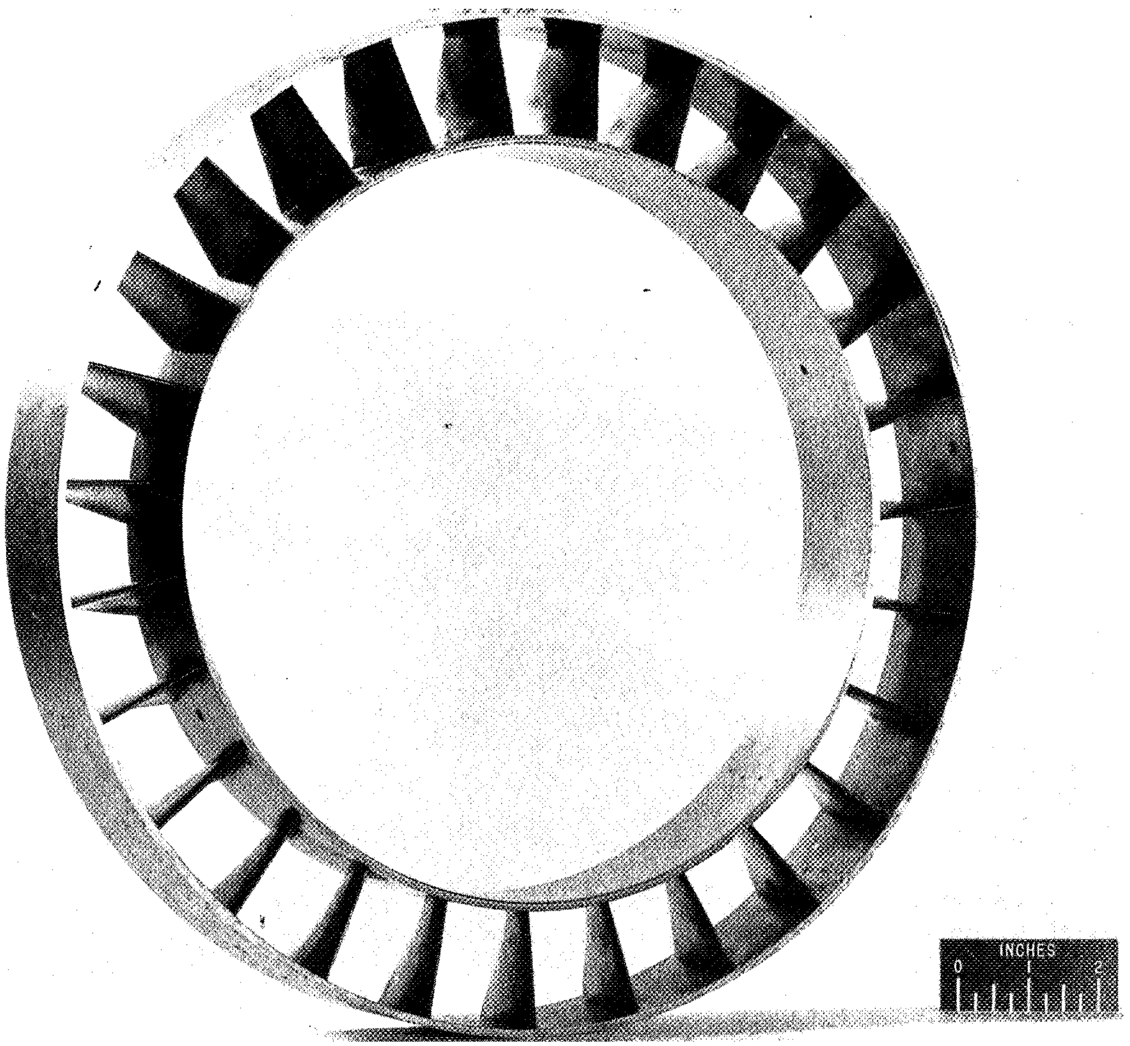

Figure 1. - Inlet guide vanes.

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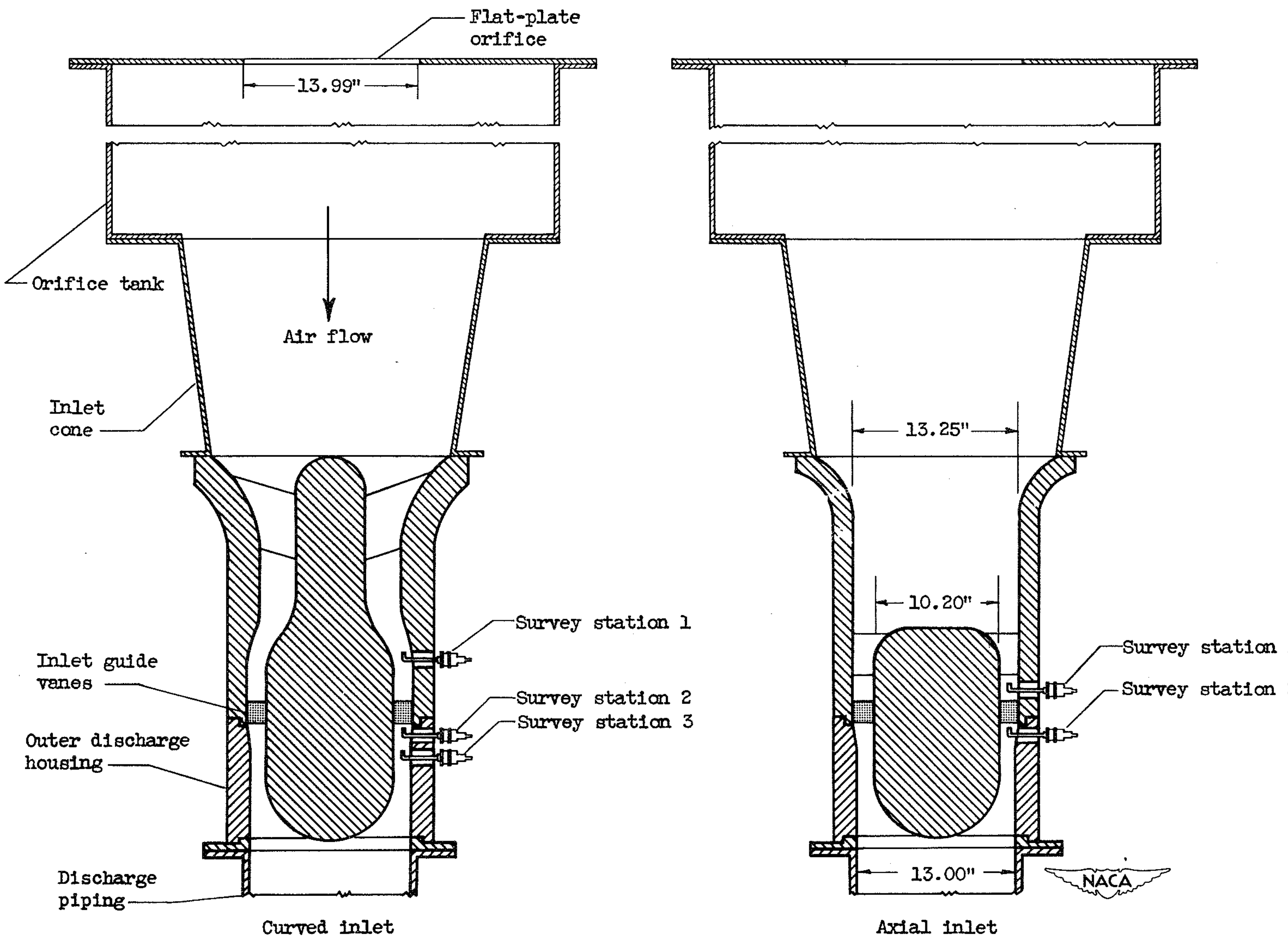

Figure 2. - Schematic drawing of guide-vane test rig.

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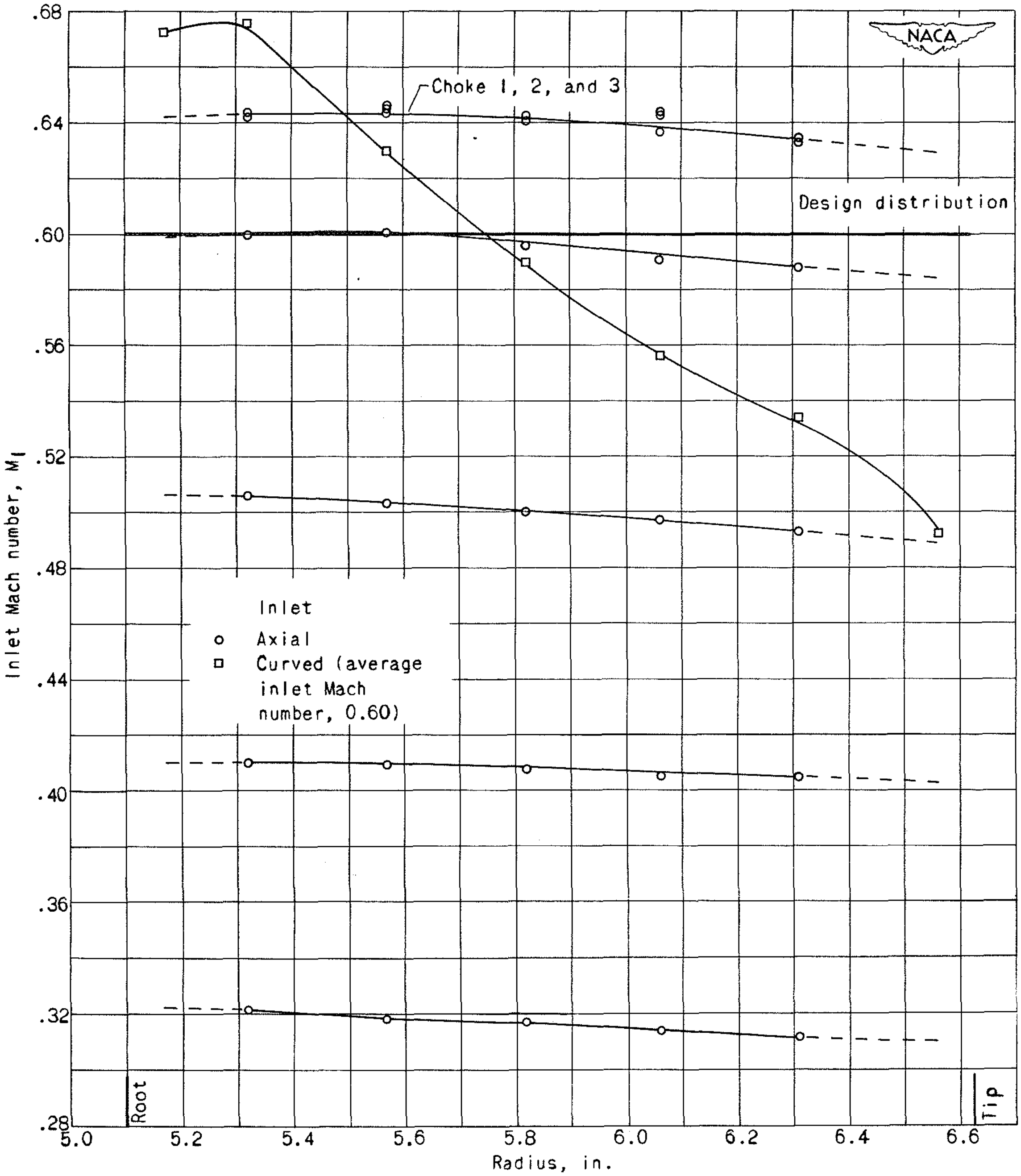

Figure 3. - Inlet Mach number distribution measured at survey station 1.

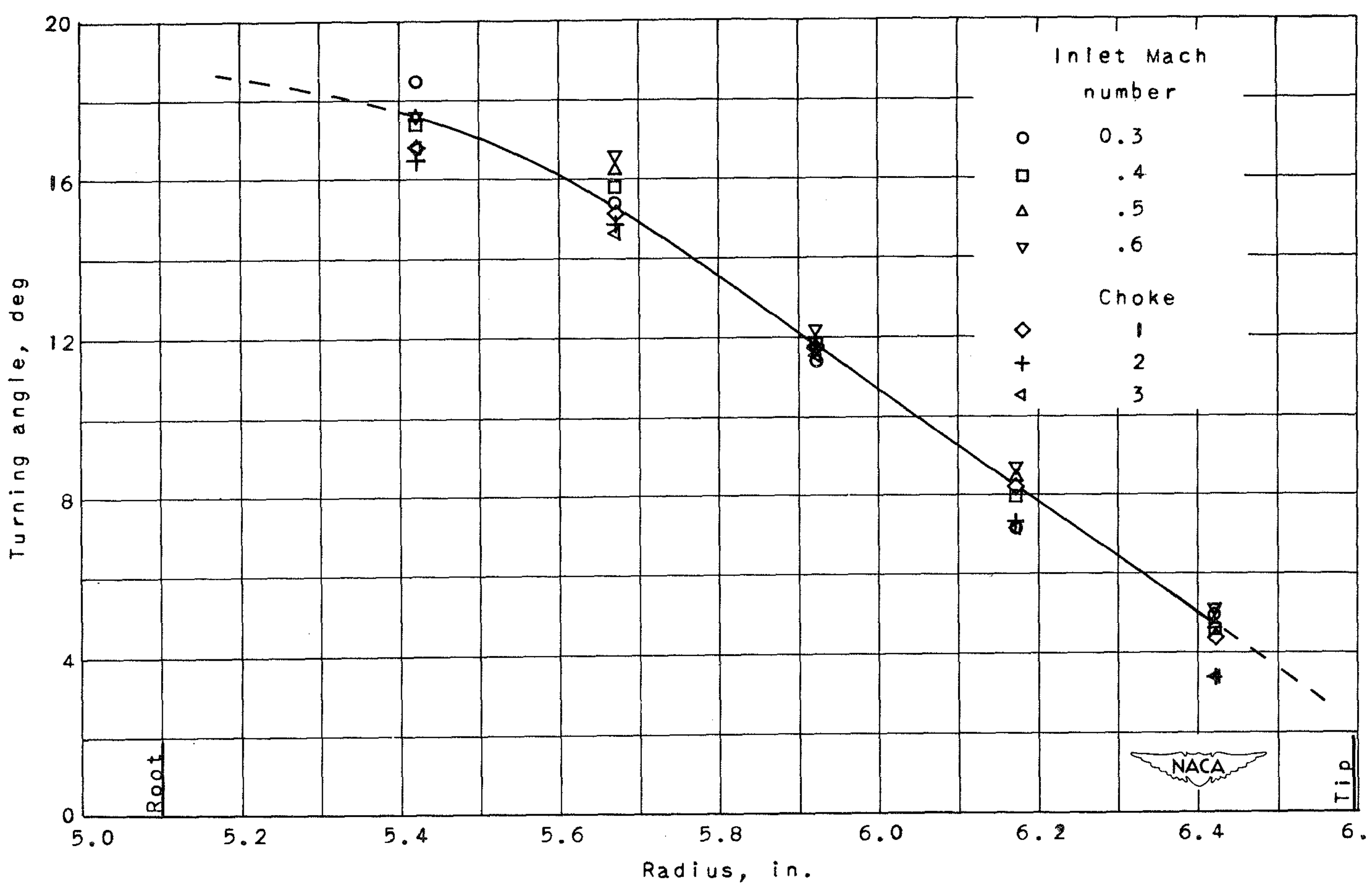

Figure 4. - Variation of turning angle with radius for axial-inlet configuration at station 2.

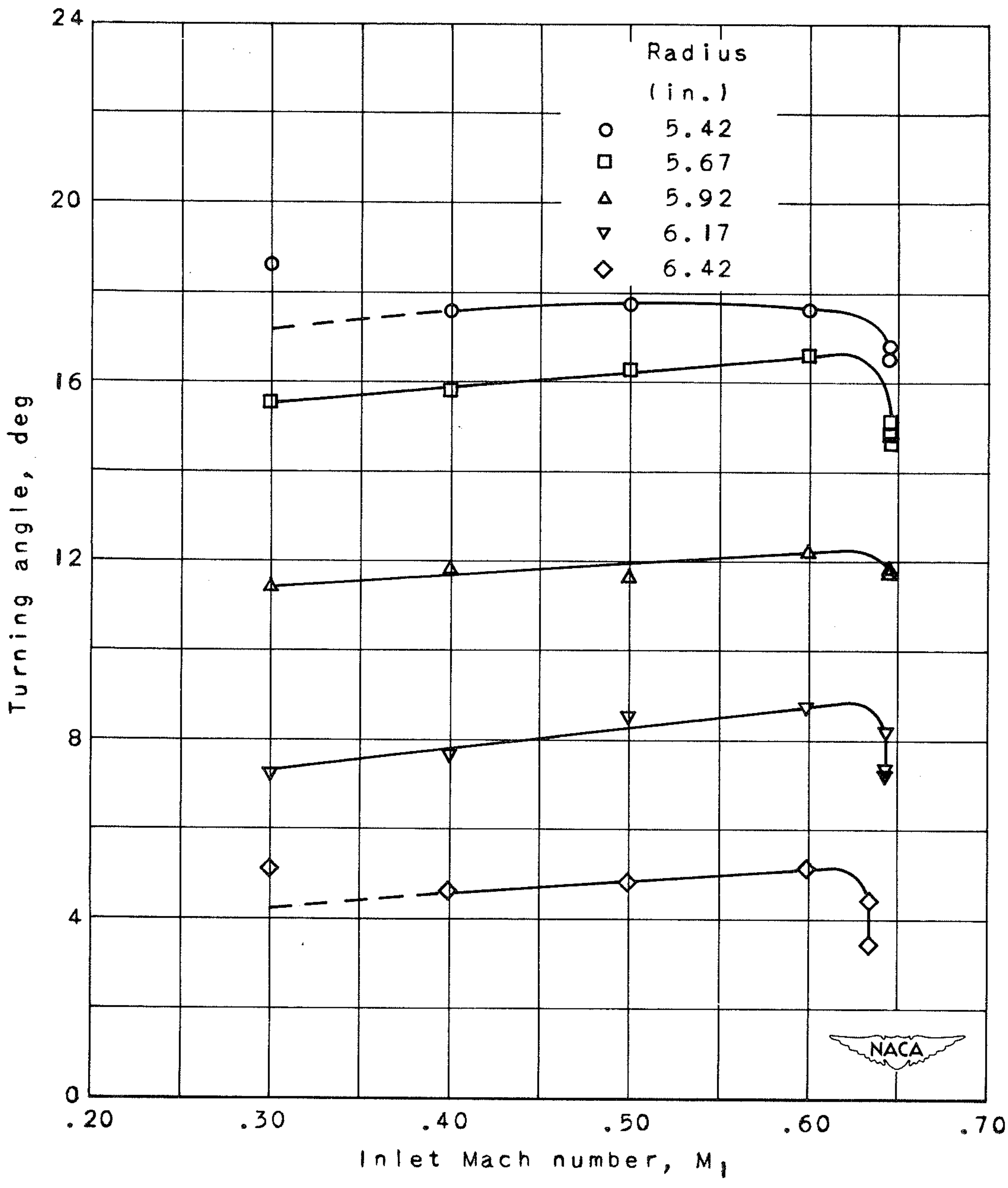

Figure 5. - Variation of turning angle with Mach number for axial-inlet configuration. Root radius, 5.10 inches; tip radius, 6.59 inches.

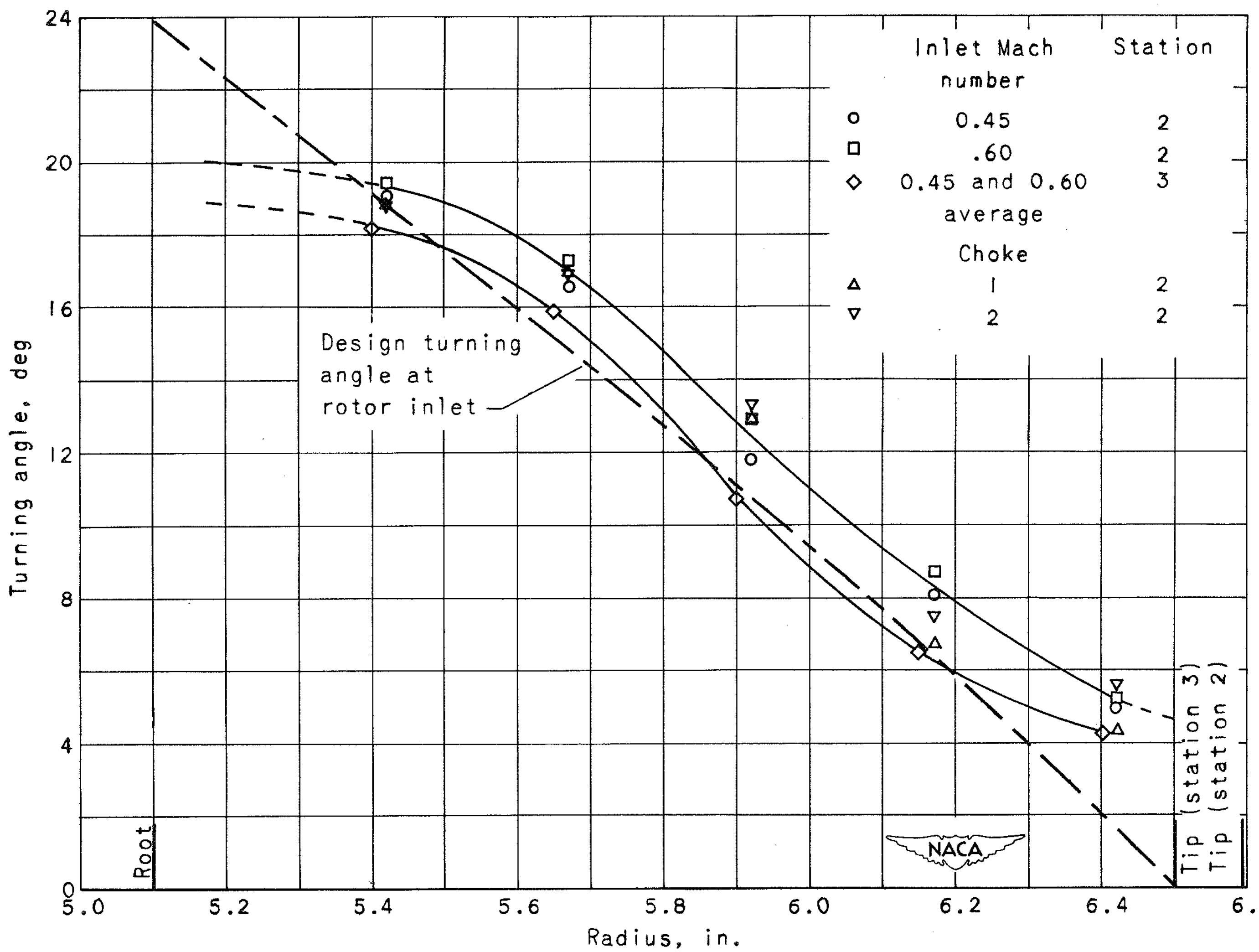

Figure 6. - Variation of turning angle with radius for curved-inlet configuration at stations 2 and 3.

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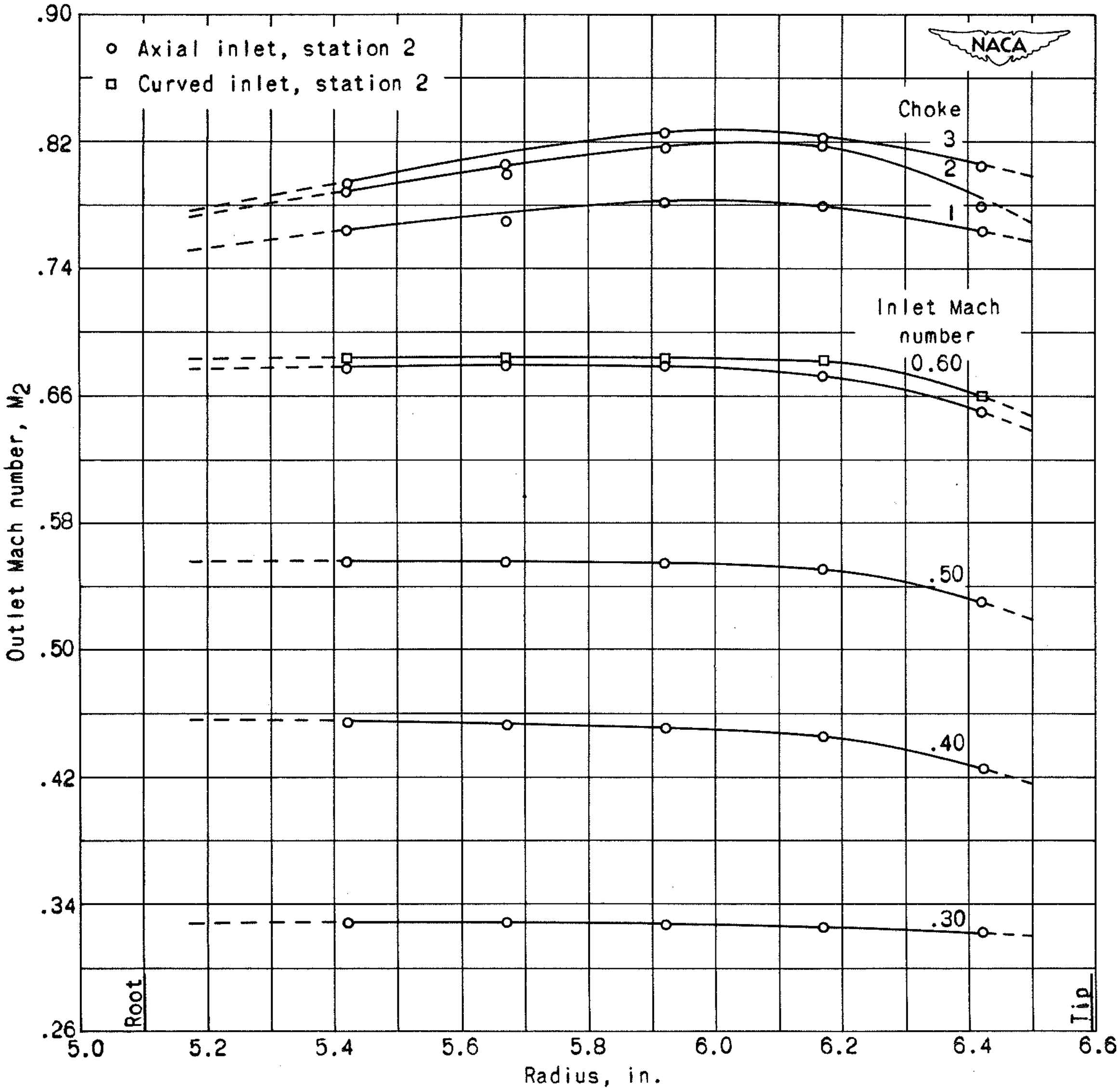

Figure 7. - Outlet Mach number distribution at station 2 for axial- and curved-inlet configuration.

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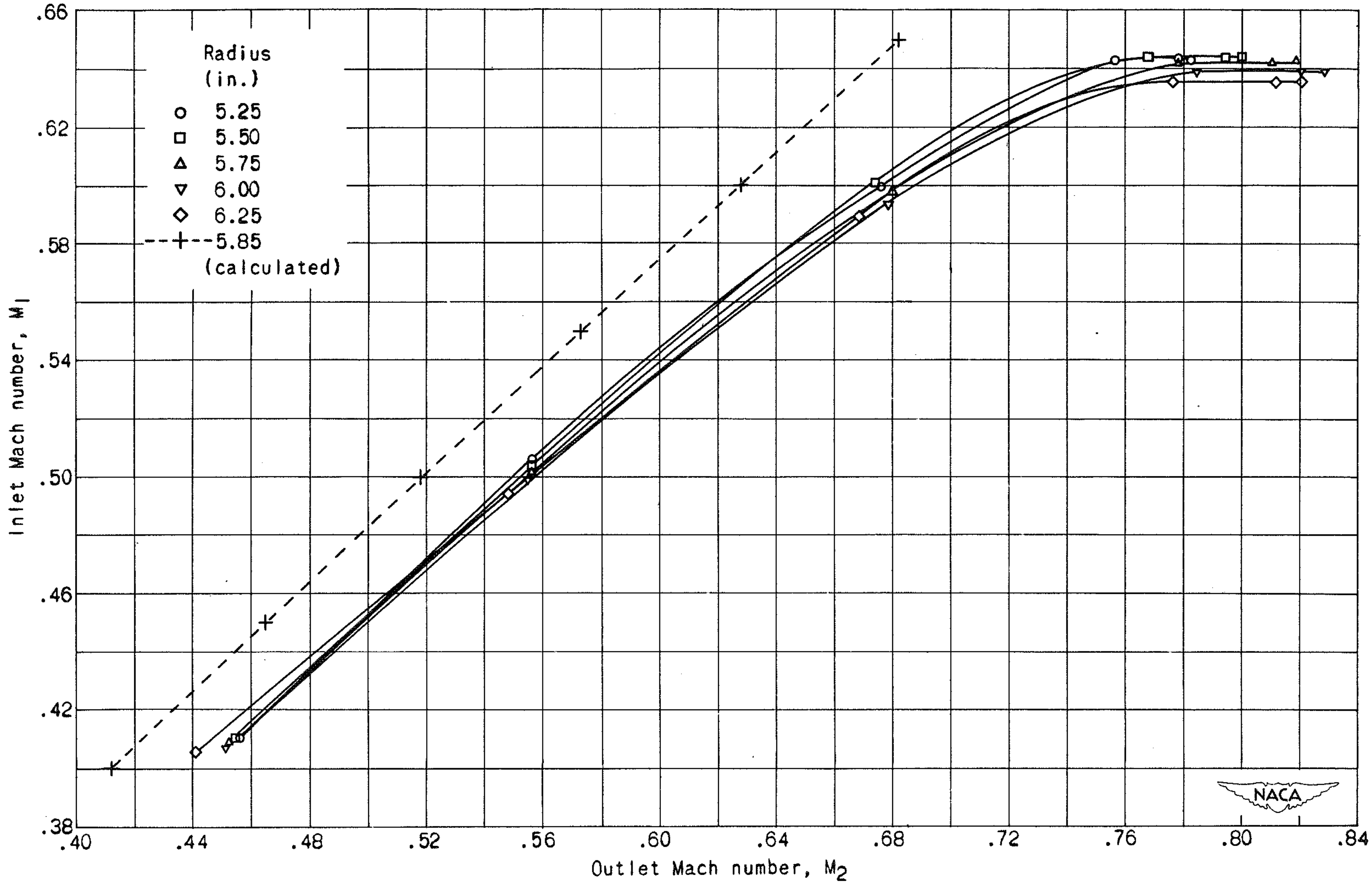

Figure 8. - Variation of inlet with outlet Mach number for axial-inlet configuration. Root radius, 5.10 inches; tip radius at station 1, 6.62 inches.

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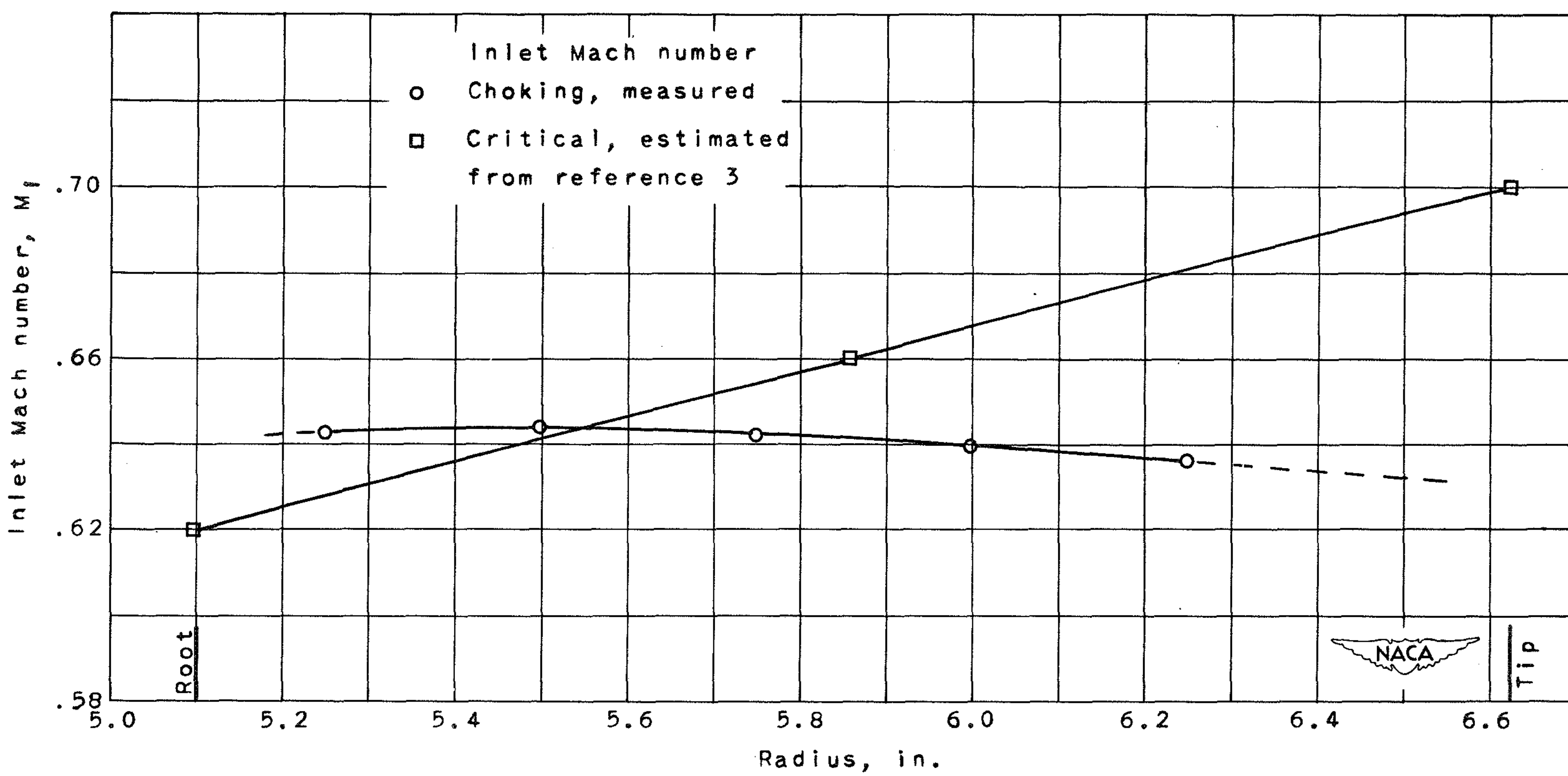

Figure 9. - Comparison of estimated and measured limiting inlet Mach number for axial-inlet configuration.

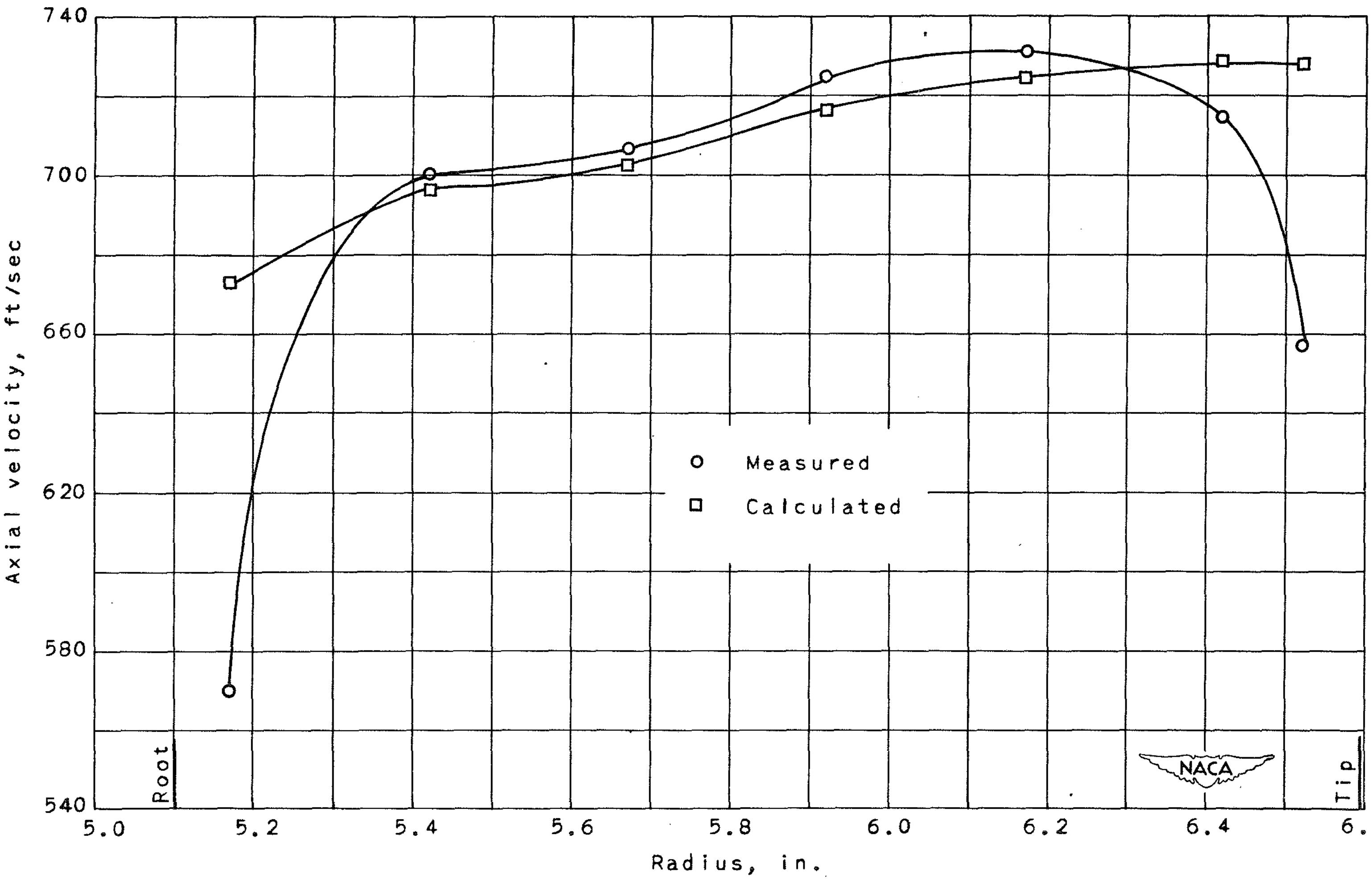

Figure 10. - Comparison of measured and calculated axial velocity for axial-inlet configuration at station 2, 0.920 inch downstream of trailing edge of vanes. Inlet Mach number M_1, 0.60.

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