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TURNING-ANGLE DESIGN RULES FOR CONSTANT-THICKNESS CIRCULAR-ARC INLET GUIDE VANES IN AXIAL ANNULAR FLOW

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SUMMARY

A survey of data from investigations of axial-flow-compressor inlet guide vanes with circular-arc, constant-thickness sections and axial air inlet was conducted to establish a relation between vane camber and air turning angle for use in the design of this type of vane. Two design rules were obtained for vanes set at zero angle of incidence, solidities from 1.4 to 1.7, and inlet Mach numbers of approximately 0.3.

From the data as measured, a linear relation between air turning angle and vane-camber angle was deduced for turning angles from 10° to 41° for vanes with greater amounts of turning at the tip than at the hub and with annulus area ratios across the vane of from 0.86 to 0.95. The relation was then generalized to take into account the varying axial velocity across the vanes by correcting the measured data to constant axial velocity on the basis of the inlet velocity and the assumption of constant circulation. A corrected turning-angle design rule applicable over a wide range of axial-velocity ratios was thus obtained for turning angles from 12° to 40°. A correction for vane settings other than zero incidence was also deduced from the data for camber angles from 25° to 40°. The turning-angle relations were compared with existing design rules and data based on two-dimensional cascade and potential flow available in the literature. Design considerations and limitations involved in the use of circular-arc inlet guide vanes are discussed.

INTRODUCTION

In the many types of turbine power plant that involve flow through annular passages, the designs frequently require the use of vanes to deflect or to turn the air circumferentially through some prescribed angle. Turning vanes are principally used as the inlet guide vanes (prerotation vanes) of current steady-flow compressors. For compressor application in particular, inasmuch as the rotor design is based on the attainment of the required variations in velocity direction and magnitude at the outlet from the prerotation vanes, the proper design of guide vanes is an important step in the development of a successful unit.

Methods of design of guide vanes for annular passages are based primarily on considerations of vane air-turning-angle characteristics. The required variation of turning angle along the radial height of the vane is determined from the radial variations of the velocity components desired at the outlet of the blade row. The desired velocity distributions are usually calculated from the variation of tangential velocity required by the type of velocity diagram used in compressor-design theory. The proper vane-angle settings at various radial positions are then determined from the desired turning angles and the available design turning-angle data. Design turning-angle data are usually presented as variations of air turning angle with vane angle of attack for various mean-line cambers. 1366

In present design practice, the two principal sources of available guide-vane turning-angle data are: (1) potential-theory calculations in combination with empirical corrections, and (2) rectangular (two-dimensional) cascade investigations. Examples of potential-theory calculations for circular-arc mean-line airfoil sections are given in reference 1. Turning-angle data for circular-arc airfoil sections for inlet-guide-vane application are deduced from two-dimensional cascade investigations at high inlet-air angles in reference 2. Extensive cascade data for inlet guide vanes based on NACA 65- and 64- series mean-line airfoil sections are reported in reference 3.

In many cases, because of the ease of construction and of the relatively low losses associated with the flow across accelerating vanes, use of sheet-metal guide vanes of constant thickness rather than airfoil or variable-thickness sections has been found to be acceptable. Constant-thickness guide vanes are particularly applicable for designs in which the direction of the inlet velocity remains constant over the operating range of the unit. The simplest type of constant-thickness vane is one of circular-arc curvature, and because of the availability of two-dimensional turning data for circular-arc mean-line airfoil sections (references 1 and 2), the circular-arc vane set at zero incidence angle has been frequently used.

In actual compressor-design practice, however, considerable difficulty has been experienced with annular constant-thickness circular-arc vanes in obtaining the desired magnitude of turning on the basis of the two-dimensional design data for circular-arc airfoil sections. It has been necessary in many cases to investigate the guide vanes independently and to reset or to redesign the blades until an acceptable distribution had been obtained.

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A survey of existing constant-thickness circular-arc guide-vane data obtained from various compressor inlet-guide-vane investigations completed at the NACA Lewis laboratory was therefore conducted in order to establish a more accurate method of turning-angle prediction and to reduce the cost and the time involved in the current trial-and-error procedure. A turning-angle design rule (for the conditions of Mach number of approximately 0.3 and solidities from 1.4 to 1.7) expressed as the variation of air turning angle with vane camber and incidence angles was deduced from the data for use in the design of guide vanes with camber and annulus configurations similar to those of the survey vanes. The relation was then generalized to take into account the varying axial velocity across the vanes by correcting the measured data to constant inlet axial velocity. A corrected design rule applicable over a wide range of axial-velocity ratios across a blade section was thus obtained. The turning-angle relations derived from the survey are compared with existing design rules and data based on two-dimensional cascade and potential flow, which are available in the literature. Design considerations and limitations involved in the use of constant-thickness inlet guide vanes are discussed.

SYMBOLS

The following symbols are used in this report:

A	annulus area
a_1, a_2, b	constants
c	vane chord
D	diameter
d	axial distance from vane trailing edge to downstream measuring station
K_1, K_2	constants
M	Mach number
R	radius of curvature of circular mean profile arc
r	radius at vane element

s spacing between vanes

t vane thickness

V velocity

α angle of attack, angle between inlet air and chord line

β air angle, angle between direction of air and compressor axis

γ incidence angle, angle between inlet air and tangent to mean profile arc at leading edge

θ air turning angle, $\beta_2 - \beta_1$ (β_1 is positive when in same quadrant as β_2)

σ solidity, c/s

φ camber angle, sector angle of circular arc

Subscripts:

0 zero angle of incidence setting

1 inlet to vane (leading edge)

2 outlet measuring station

2' vane trailing edge

a axial component

h inner wall of annulus (hub)

t outer wall of annulus (tip)

v corrected to constant inlet axial velocity

θ tangential component

VANE DESIGNS AND EQUIPMENT

Guide-vane turning-angle data used in the survey were obtained from unreported investigations of conventional circular-arc sheet-metal inlet guide vanes designed for various axial-flow compressors and investigated as separate components in induction-type annular

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cascades of constant outer diameter and with bellmouth inlet. A typical cascade and vane configuration is illustrated in figures 1 and 2. All blades were of the constant-radius-of-arc-curvature type; radial variations in air turning angle were obtained by varying the camber and therefore the chord length along the height of the vane. Vane camber is defined as the ratio of maximum normal deviation of the mean line from the chord line to the chord length. For circular-arc mean lines, the camber is a direct function of the sector angle. Vane edges were rounded along the leading edge and were either rounded or tapered along the trailing edge. The vanes were set at zero incidence angle in nearly all cases.

Detailed identification data for the various blade designs and annuli included in the survey are presented in table I. (Headings and symbols in table I pertain to figs. 1 and 2.) The vane trailing-edge location, station 2', is taken as the radial plane containing the axial projection of the trailing-edge point of the maximum chord length. Measuring instrument stations were located between 0.25 and 0.84 inch downstream of the blade trailing-edge location for all vanes. The axial distance from the inlet face of the bellmouth to the leading edge of the vanes varied from approximately 10 to 20 inches for designs A through G. For design H, the axial distance from bellmouth face to vane leading edge was 47 inches, but the axial distance from the nose of inner drum to the vane leading edge was only 14 inches. No inlet-boundary-layer data were taken.

The investigations were conducted with ambient inlet air and Reynolds number effects were presumed negligible in all cases. The flow at inlet to the guide vanes was substantially uniform and axial ($\beta_1 = 0$) in all determinations and therefore the angle of the air leaving the blade row was directly adopted as the air turning angle. Outlet-air angles were measured by claw-type instruments for designs A to H and by cone-type instruments for design I and were circumferentially averaged at each radial position. Accuracy of the measured turning angle is estimated to be within $\pm 1/2^\circ$ and the accuracy of the vane setting is estimated as $\pm 1/4^\circ$. Data in the vane-end regions (approximately 20 percent of vane at each end) were not included in the survey in order to eliminate data containing pronounced secondary- and induced-flow effects.

RESULTS OF SURVEY

Design rule for convergent annuli. - The turning-angle data obtained from the survey of investigations of compressor-inlet guide vanes with convergent annuli (blades A to G, table I) are shown in figure 3 as a plot of measured air turning angle at a given radial position at the measuring station against vane angle of attack at that same radius. The angle of attack of the blade setting for a circular-arc blade is calculated from the relation

$$\alpha = \varphi/2 + \gamma \tag{1}$$

where the positive incidence angle is taken in the direction of increasing angle of attack. At zero incidence angles, the angle of attack becomes $\alpha_0 = \varphi/2$. For blade sections set at a constant incidence angle, the data therefore represent the variation of air turning angle with blade camber.

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Actually, in the presence of annulus taper, the streamlines appearing at the measuring station do not flow along the camber line corresponding to a constant radius across the vane. It was felt, however, that a correlation between turning angle and the camber along a cylindrical surface at that same outlet radius rather than some effective camber would be more convenient for design use.

For the setting of zero incidence angle, the turning-angle plot (fig. 3) suggests a linear variation of turning angle with angle of attack. Thus, the turning angle can be expressed by

$$\theta = a_1 \alpha_0 + b \tag{2}$$

or, in terms of camber angle by

$$\theta = a_2 \varphi + b \tag{3}$$

where a_2 is one-half the slope of equation (2). For the solid line drawn through the points at zero incidence in figure 3, equation (3) is evaluated as

$$\theta = 0.985\,\varphi - 9.7 \tag{4}$$

The blades in the range of solidities investigated therefore exhibit the characteristics of a cascade of infinite solidity set at zero incidence for which $d\theta/d\varphi = 1.0$.

The rule of equation (4) is established as representing an inlet Mach number of approximately 0.30 and the representative solidity range for the rule is specified as 1.4 to 1.7 because approximately 70 percent of the data was included in this range. The average solidity was approximately 1.60. For annulus-area ratios across the vane of 0.86 to 0.95 and for vanes with camber angles increasing from hub to tip, the straight-line turning-angle design rule deduced from figure 3 (equation (4)) is expected to be accurate to approximately $\pm 1\frac{1}{4}^{\circ}$ along most of the vane height in the range of turning angle from about 10° to 41°.

The turning-angle rule of equation (4) actually represents the locus of points corresponding to zero incidence angle on the curves of turning angle against angle of attack at constant camber. A representative variation of such a curve for vanes in cascade (reference 4) is shown by the dashed line in figure 3. For values of incidence angle other than zero, the turning angle of an element of given camber can be obtained from the straight-line rule of equation (4) if the variation of θ with α at that camber is known. For a cascade of infinite solidity at constant camber, $d\theta/d\alpha = d\theta/d\gamma = 1.0$. For finite solidity and viscous flow, however, the variation of θ with α at constant camber is not generally linear and the slope of turning angle against angle of attack tends to decrease with increasing angle of incidence until a value approaching zero is obtained in the stalling region.

For the general case of variable incidence angle, an analytical expression for the turning angle for a given camber can be represented by the form

$$\theta = \theta_0 + (K_1 - K_2\gamma)\,\gamma \tag{5}$$

The data taken at angles of incidence other than 0° were insufficient to establish an accurate variation of turning with incidence angle and permitted the approximate evaluation of only the constant K_1. For nonzero incidence angles, the design rule obtained from considering the data values at $\gamma = 6^{\circ}$ and approximately -9° in figure 3 is

$$\theta = 0.985\,\varphi - 9.7 + 0.88\,\gamma \tag{6}$$

Equation (6) necessarily implies a linear variation of θ with γ, but if the range of incidence angles is restricted to about -10° to 5°, equation (6) should be accurate to approximately $\pm 1\frac{1}{2}^{\circ}$ for camber angles from about 25° to 40°.

Example of straight-line rule. - An example of the use of the straight-line turning rule for convergent annuli of equation (4) in predicting the variation of turning angle along the radial height of a typical circular-arc sheet-metal guide vane with axial air inlet is shown in figure 4. The blades used in this illustration correspond to design A in table I. Correlation in the central region of the blade is good, but a slight decrease in turning angle is observed in the end regions. These end-region discrepancies are attributed to the effects of radial flows due to hub taper and to induced flows due to circulation gradients.

Near the inner wall of the annulus, the departure of the streamlines from the cylindrical-surface camber line is greater than that inherently contained in the design rule, which was obtained from data from approximately the central 60 percent of the blade height. Inasmuch as nearly all vanes of the survey had camber angles that decreased with decreasing radius from tip to hub, the flow of a streamline across the vane at a radial position lower than the radial position of the streamline at the measuring station would result in a smaller turning angle. A lower observed turning angle would therefore be expected in the hub region. Near the outer wall the large value of blade circulation in combination with the wall boundary layer tends to decrease the turning angle (reference 5).

<u>Design rule for constant axial velocity.</u> - The use of the straight-line turning-angle rule of equation (4) will be valid only for vanes with annulus configurations and radial distributions of velocity similar to those from which the data were obtained. This limitation arises from the consideration that the turning angle measured downstream of a blade row is a function of the change in axial velocity across the section as well as of the imparted circulation; the accuracy of the rule would thus depend on the similarity of the axial velocity ratios. Therefore, in order to generalize the measured data and to deduce design information applicable to a wider range of blade designs and annulus configurations than permitted by the convergent-annulus rule, the measured turning-angle data were corrected to constant axial velocity across the blade element based on the inlet velocity. The correction assumes that the circulation about a vane element at fixed angle of attack and inlet velocity remains constant with variations in outlet velocity (constant tangential velocity). In the actual flow, small changes in circulation probably do occur as the outlet velocity is varied because of the effects of radial flow, compressibility, and changes in surface boundary layer. If the change in axial velocity across the vane is not large, these effects can be considered negligible for the purposes of this report. The velocity diagram for the constant axial-velocity correction is illustrated in figure 5. The inlet axial velocity was selected as the reference axial velocity for the turning-angle correction because it results in a corrected turning angle corresponding to given values of circulation and inlet Mach number that is independent of the magnitude of the outlet axial velocity.

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Values of corrected turning angle are plotted against vane angle of attack in figure 6. The corrected turning angles are several degrees higher than the measured turning angles of figure 3 over most of the angle-of-attack range and indicate a significant apparent effect due to change in axial velocity. The scatter of the data at a given angle of attack is reduced in this corrected plot. The turning-angle variation is no longer linear when corrected to constant inlet axial velocity and exhibits a tendency to decrease with increasing angle of attack. Corrected angles for blade D could not be obtained to establish further the trend at high angles of attack because of insufficient velocity data.

The design rule for zero incidence angles deduced from figure 6 (solid line) for turning angles from 12° to 40° is parabolic in form and can be represented by the equation

$$\theta = -0.0348\ \alpha^2 + 2.985\ \alpha - 13.87 \tag{7}$$

or, in terms of camber angle by

$$\theta = -0.0087\ \varphi^2 + 1.492\ \varphi - 13.87 \tag{8}$$

The accuracy of the corrected-turning-angle curve is expected to be about ±1° over most of the blade height if the axial-velocity changes across the vane are within about a 25-percent increase to a 10-percent decrease. For nonzero angles of incidence, the slope-correction value 0.88, obtained from the measured data, can also be used for the corrected turning angle for the same ranges of incidence and camber angle. Thus, in general

$$\theta = -0.0087\ \varphi^2 + 1.492\ \varphi - 13.87 + 0.88\ \gamma \tag{9}$$

Comparison of design rules. - A comparison between the turning-angle rules deduced from the data of figures 3 and 6 and the variation of turning angle with vane camber angle calculated from turning data and design rules for the conditions of zero incidence, approximate solidity of 1.6, and substantially incompressible flow for circular-arc turning vanes available in the literature is shown in figure 7. Curve A was obtained from reference 2, which presented outlet-angle-deviation data deduced for inlet-guide-vane application from low-speed two-dimensional cascade investigations of airfoil sections with nonzero inlet-air angles. Curve B is the Eckert-Weinig angle-exaggeration method of reference 1 with design blade settings corrected to zero incidence. The zero-incidence-angle correction was calculated on the basis of $d\theta/d\gamma = 0.88$.

A substantial discrepancy between the two-dimensional turning angle data and the deduced curves of the present survey is shown in figure 7. The discrepancies tend to substantiate the generally observed occurrence of underturning in the case of inlet vanes designed according to previously available methods (curve A principally), particularly in the low turning-angle range. The effect on turning angle due to changes in the axial-velocity ratio across the blades in convergent annuli is clearly shown by a comparison of curves C and D. 1366

Although comparison of the curves over the full turning-angle range is not precisely valid because of a lack of uniformity of solidity along the entire length of curves C and D, the trend of corrected curve C agrees very well with the trend of the two-dimensional experimentally determined variation of curve A over the upper part of the turning-angle range where the solidities are comparable. The relatively greater discrepancy at the lower end of the curves is attributed to the fact that the survey-data points in the lower part of the curve were generally obtained from blade elements that contained lower solidities than the elements contributing the points in the high turning-angle part of the data. In addition, the vane sections of the low turning-angle part were in regions of radial-flow displacement caused by hub taper, which, for the type of vanes investigated, tended to reduce the measured turning angle of the section. For regions near the hub therefore the rules tend to contain values that are smaller at a given outlet radius than would be obtained from constant radius flow across the vane. The principal factors contributing to the discrepancy between the corrected annular curve C and the two-dimensional curves are considered to be the difference in the type of cascade, the differences in chordwise thickness distribution and trailing-edge thickness, and the setting of the blade corresponding to zero incidence for curve A at nonzero inlet-air angles (up to 15°). At an inlet-air angle slightly greater than 0°, the axial-velocity ratio across the vanes is smaller than for zero inlet angle for the same circulation and annulus-area ratio and thus tends to produce a larger turning angle.

Use of design rules. - For general use within the limitations of the survey and the assumption of the axial-velocity correction, the corrected turning-angle rule of equation (8) (fig. 6) is recommended for best accuracy in the design of circular-arc inlet guide vanes. The design of guide vanes based on the use of vane turning-angle characteristics involves the calculation of the required variation of turning angle along the radial height of the vane at an outlet station a short distance downstream of the vane trailing edge (0.25 to 0.75 in.). In the absence of very large radial-flow components, the

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required radial variation of turning angle is generally calculated from the variations of axial and tangential velocity desired at the guide-vane outlet (fig. 5). The variation of one velocity component is usually prescribed by the design application and the other component can then be accurately calculated by the use of the condition of simple radial pressure equilibrium (balance between static-pressure gradient and centrifugal force). If the outlet velocities are known, the corrected turning angle θ_v can be determined for the design inlet velocity on the basis of the assumption of constant tangential component, as shown in figure 5. The required vane camber angle at each radial position is then obtained from the corrected turning angle calculated at that radius and the turning curve of figure 6 or from equation (8). If the vane design requires greater amounts of turning at the tip than at the hub and an annulus-area ratio across the vane of from 0.86 to 0.95, the design camber angles can be determined directly from the design turning angles calculated from the outlet velocity components and the linear rule of equation (4) (fig. 3).

In the use of the corrected turning-angle rule for predicting the turning angles of a vane of given camber distribution, a solution cannot be directly obtained because the outlet axial velocities are at first unknown. The outlet axial velocities, however, can be calculated from the variation in tangential velocity corresponding to the corrected turning angles obtained from the turning rule and the design inlet velocity. Methods of calculating the axial velocity distribution are given in references 6 and 7. From the outlet axial velocities, the actual outlet angles can be easily determined. If the annulus ratio and the blade design are suitable, the linear rule for convergent annuli may be used directly to estimate the turning angle.

In using the corrected design rule for the selection of vane camber for small amounts of turning ($\leq 15^\circ$) for sections in constant-area annuli or across which very little radial displacement of the flow occurs, it should be kept in mind that the design rule at low turning angles was obtained from blade sections near the hub of convergent annuli and therefore tends to contain values that are somewhat smaller than would be obtained from constant-radius flow across the vane.

DESIGN CONSIDERATIONS

Important considerations in the design of circular-arc constant-thickness inlet guide vanes are those of angle of incidence, solidity, and limits of blade operation. Because of the constant and comparatively small blade thickness in the inlet region of constant-thickness vanes, large variations in velocity occur on the surface of the vanes if the blade setting is appreciably removed from its optimum position. The range of angle of attack for best performance at a given turning angle (that is, minimum energy loss and maximum critical inlet Mach number) is therefore small, and it is desirable to set constant-thickness vanes to receive the inlet air at the best angle of incidence at all radii. For circular-arc blade sections, the best setting for both minimum drag-lift ratio and maximum critical inlet Mach number for solidities from 1 to 1.7 is obtained when the incidence angle of the inlet velocity is close to 0° within a range of values from about -3° to 3° (references 2 and 8). Although the cascade investigations mentioned herein were conducted on circular-arc blades with varying thickness along the chord (airfoil sections) in decelerating flow, there is little reason to doubt that the occurrence of peak performance at approximately zero incidence is also valid for the presently considered case of constant-thickness sections in accelerating flow.

The selection of vane solidity depends on the magnitude of the design turning angle and of the inlet Mach number because both maximum turning angle and critical inlet Mach number increase with increasing solidity. Large values of turning angle require relatively high solidities to avoid stalling. Although the exact limits of operation of circular-arc sheet-metal inlet guide vanes are unknown, data have been obtained from investigations of circular-arc airfoil sections (reference 2) that present an indication of the approximate range of stalling camber angle for the zero-incidence-angle setting. The variation of angle of incidence at which stall occurred with blade camber angle at several solidities for blades set with tangent to mean profile arc at the leading edge parallel to the axial direction is shown in figure 8. The occurrence of stall at zero incidence angle for these curves would then correspond to the stall condition for the presently considered design setting of zero incidence at zero inlet-air angle. The extrapolation of the stalling curves of figure 8 to zero incidence suggests that the upper limit of camber angle for stall-free operation at zero incidence be taken at about 60° for solidities of approximately 1.5.

Relatively high solidities should also be prescribed in high inlet Mach number designs in order to reduce the lift coefficient and therefore increase the critical Mach number value for that design. No experimental or theoretical data on critical inlet Mach numbers for circular-arc constant-thickness inlet guide vanes are presently available. The blade drag or loss in available energy associated with flow through circular-arc sheet-metal vanes is not quantitatively

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known, although relatively high solidities, near-limit operation with respect to blade loading and inlet Mach number, and thick trailing edges result in increased energy losses. Thin trailing edges should be used whenever practicable. If vanes with constant radius of curvature are used, the arc radius may be set to allow the chord lengths for the low-cambered sections to give sufficiently high design Reynolds numbers in order to avoid possible drag increases and turning-angle deviations at low Reynolds numbers. If a varying chord length is undesirable because of the deviation of the blade edges from directions normal to the flow streamlines, circular-arc vanes of constant chord length can be obtained by varying the radius of curvature from base to tip. The corrected turning rule is expected to be valid for vanes with variable arc curvature as well.

SUMMARY OF RESULTS

The following results have been obtained from a survey of investigations on compressor inlet guide vanes of circular-arc constant-thickness sections for the conditions of inlet Mach number of approximately 0.30, solidities from 1.4 to 1.7, and axial air inlet:

1. From the data measured, for vanes with greater amounts of turning at the tip than at the hub and with annulus-area ratios across the vane of from 0.86 to 0.95, it was deduced that the variation of air turning angle with vane camber angle for this type of vane at zero incidence angles can be given by the linear relation

$$\theta = 0.985\ \varphi - 9.7$$

where θ is the air turning angle and φ is camber angle. The design rule was believed to be accurate to $\pm 1\frac{1}{4}^{\circ}$ along most of the vane span for turning angles from 10° to 41°.

2. From the turning-angle data corrected to constant axial velocity across the vane on the basis of inlet velocity and the assumption of constant circulation (tangential velocity), it was deduced that the variation of corrected air turning angle with camber angle at zero incidence can be given by the parabolic relation

$$\theta = -0.0087\ \varphi^2 + 1.492\ \varphi - 13.87$$

The corrected turning-angle rule was believed to be accurate to about $\pm 1^\circ$ along most of the vane span for turning angles from 12° to 40° and for approximately a 25-percent increase to a 10-percent decrease in axial velocity across the vane.

3. For vanes set at angles of incidence other than 0°, the turning angle for both variations can be approximated for angles of incidence γ from -10° to 5° by using a value of slope $d\theta/d\gamma = 0.88$ in the range of camber angles from about 25° to 40°.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, April 27, 1950.

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TABLE I - BLADE DESIGN AND ANNULUS DATA

Blade design	Outer (tip) diameter, D_t (in.)	Inner diameter at blade leading edge, $D_{h,1}$ (in.)	Inner diameter at blade exit, $D_{h,2}$ (in.)	Inlet Mach number M_1	Chord at tip, c_t (in.)	Chord at hub, c_h (in.)	Camber angle at tip, φ_t (deg)	Camber angle at hub, φ_h (deg)	Thickness, t (in.)	Radius of arc curvature, R (in.)	Angle of incidence, γ (deg)	Location of measuring station, d (in.)	Inner diameter at measuring station, $D_{h,3}$ (in.)	Number of data points	Range of solidity of data points	Annulus-area ratio across blade A_2'/A_1
A	14.0	7.27	8.14	0.28	2.00	1.23	34.27	21.00	0.060	3.39	0	0.25	8.25	5	1.62-1.70	0.906
B	14.0	7.27	8.05	.28	2.00	1.23	34.27	21.00	.060	3.39	6	.32	8.25	4	1.62-1.70	.917
C	14.0	10.53	11.08	.41	1.73	1.28	33.61	24.71	.060	3.00	0	.84	11.20	4	1.53-1.56	.861
D	14.0	6.16	6.80	.27	2.39	.67	61.40	16.60	.060	2.35	0	.45	6.90	5	1.11-1.90	.947
E	14.0	6.16	6.86	.27	2.74	1.08	71.40	26.60	.060	2.35	0	.28	6.90	4	1.82-2.13	.942
F	14.0	6.16	6.76	.33	2.01	.70	50.80	17.17	.060	2.35	0	.62	6.90	7	1.33-1.67	.949
G	30.0	22.96	23.94	.30	3.76	2.79	49.10	36.00	.120	4.52	Variable (approx. -9)	.25	23.96	3	1.53-1.58	.877
H	14.0	12.60	12.60	.35	1.68	1.68	32.50	32.50	.060	3.00	0	.25	12.60	1	1.46-1.54	1.000
I	16.0	12.00	12.00	.44	2.00	2.34	22.50	26.37	.060	5.09	0	.30	12.00	3	1.02-1.26	1.000

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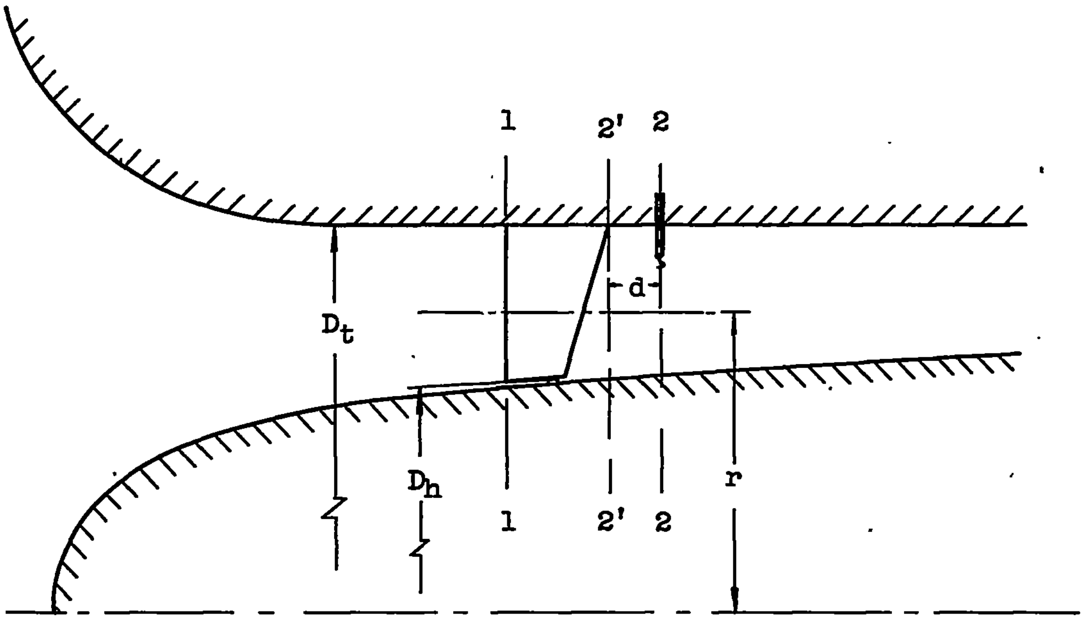

Figure 1. - Schematic diagram of typical annular inlet-guide-vane cascade setup.

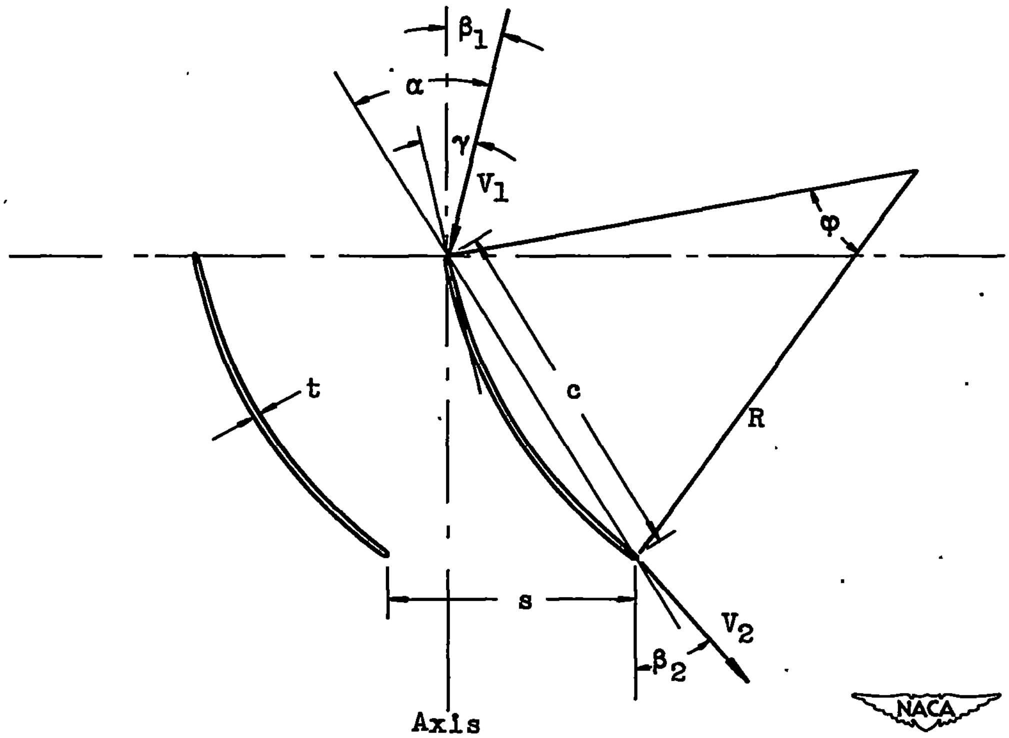

Figure 2. - Geometry of circular-arc constant-thickness inlet guide vanes.

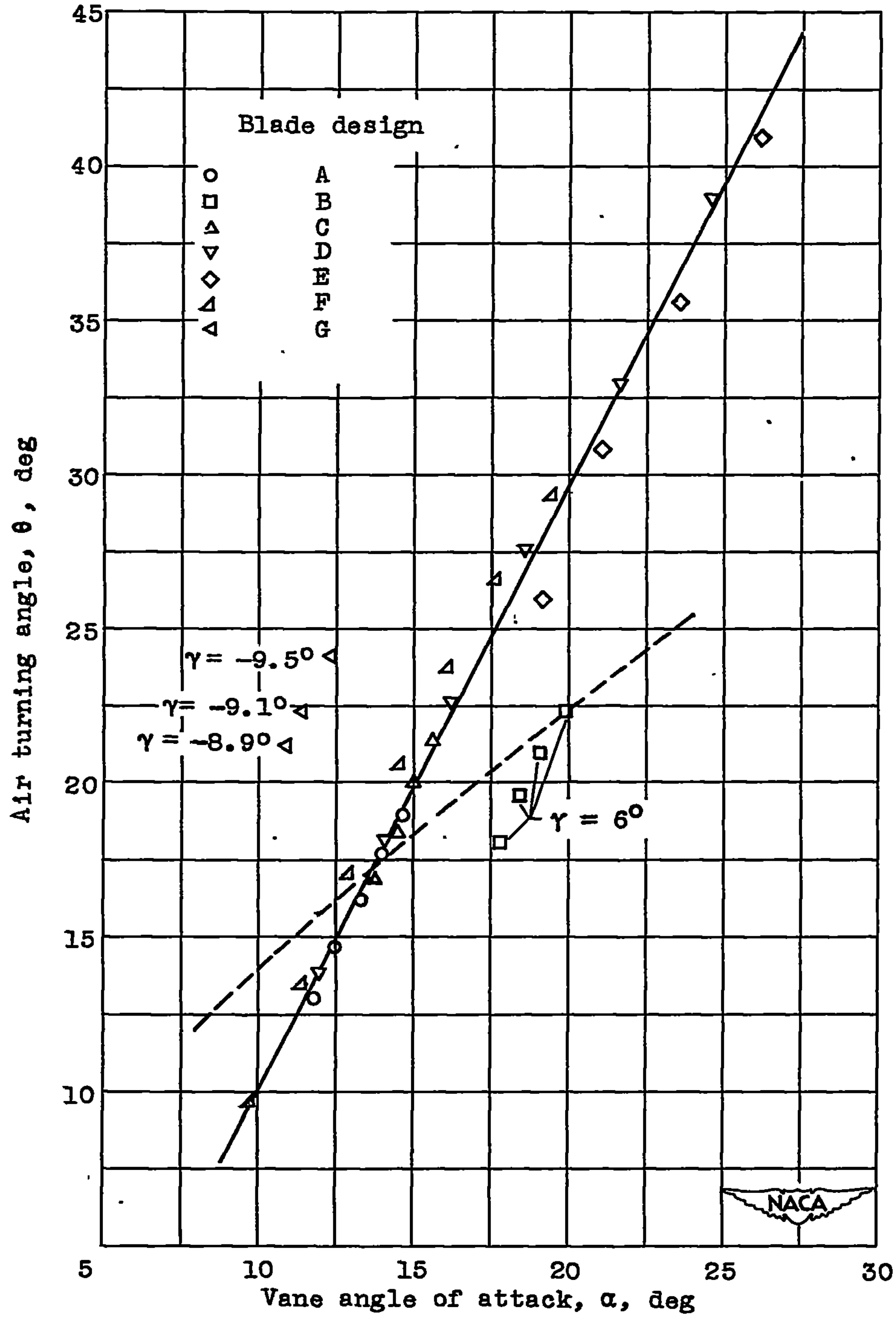

Figure 3. – Turning-angle characteristics of circular-arc constant-thickness inlet guide vanes. Data measured for vanes in convergent annuli. Incidence angle equals γ. Dashed line represents typical variation of turning angle with angle of attack at constant camber for blades in cascade. (Except where otherwise indicated, data are for γ = 0°.)

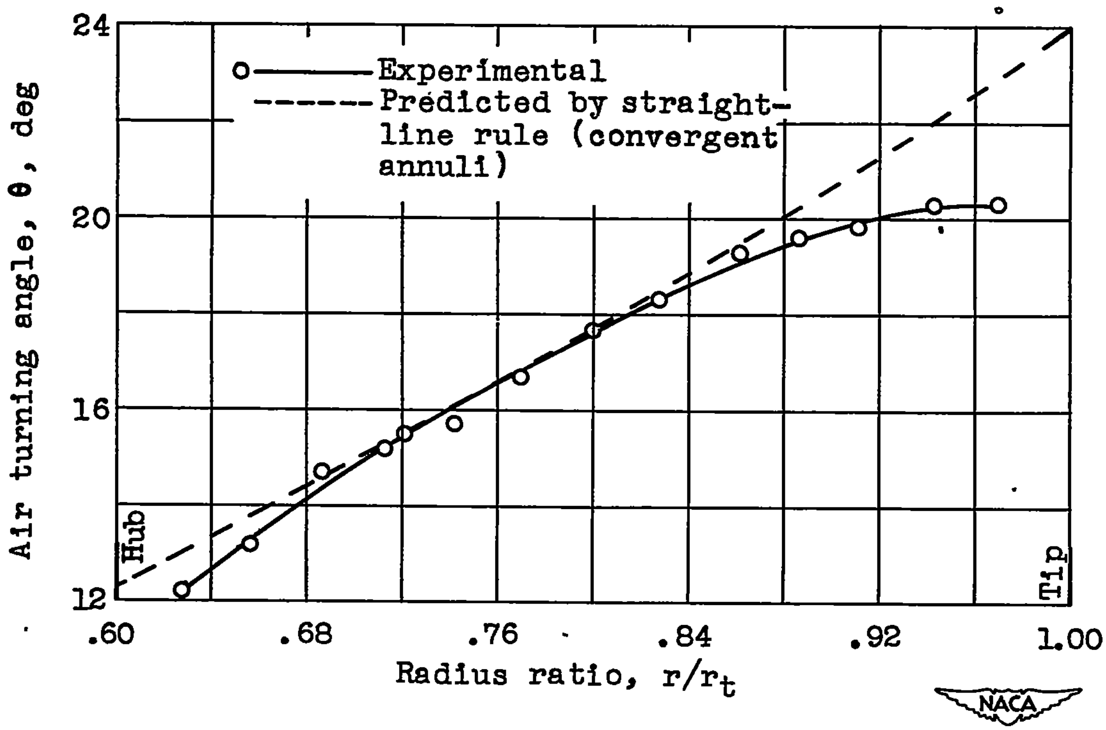

Figure 4. - Radial variation of turning angle for typical circular-arc, sheet-metal inlet guide vane for conventional axial-flow compressor. Angle of incidence, 0°; annulus-area ratio, 0.91; inlet Mach number, 0.28; average solidity, 1.66. (Blade A, table I.)

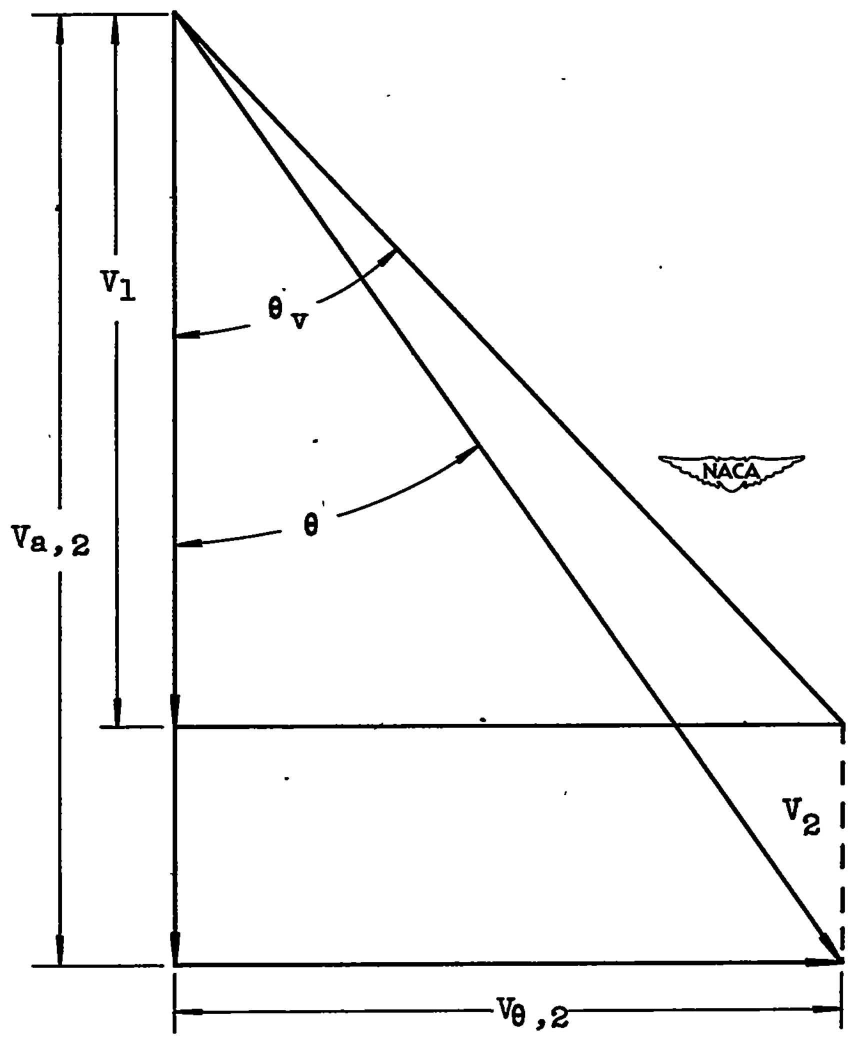

Figure 5. - Velocity diagram for flow across inlet guide vanes with axial air inlet and correction of turning angle to constant axial velocity based on inlet velocity and constant circulation (constant tangential velocity).

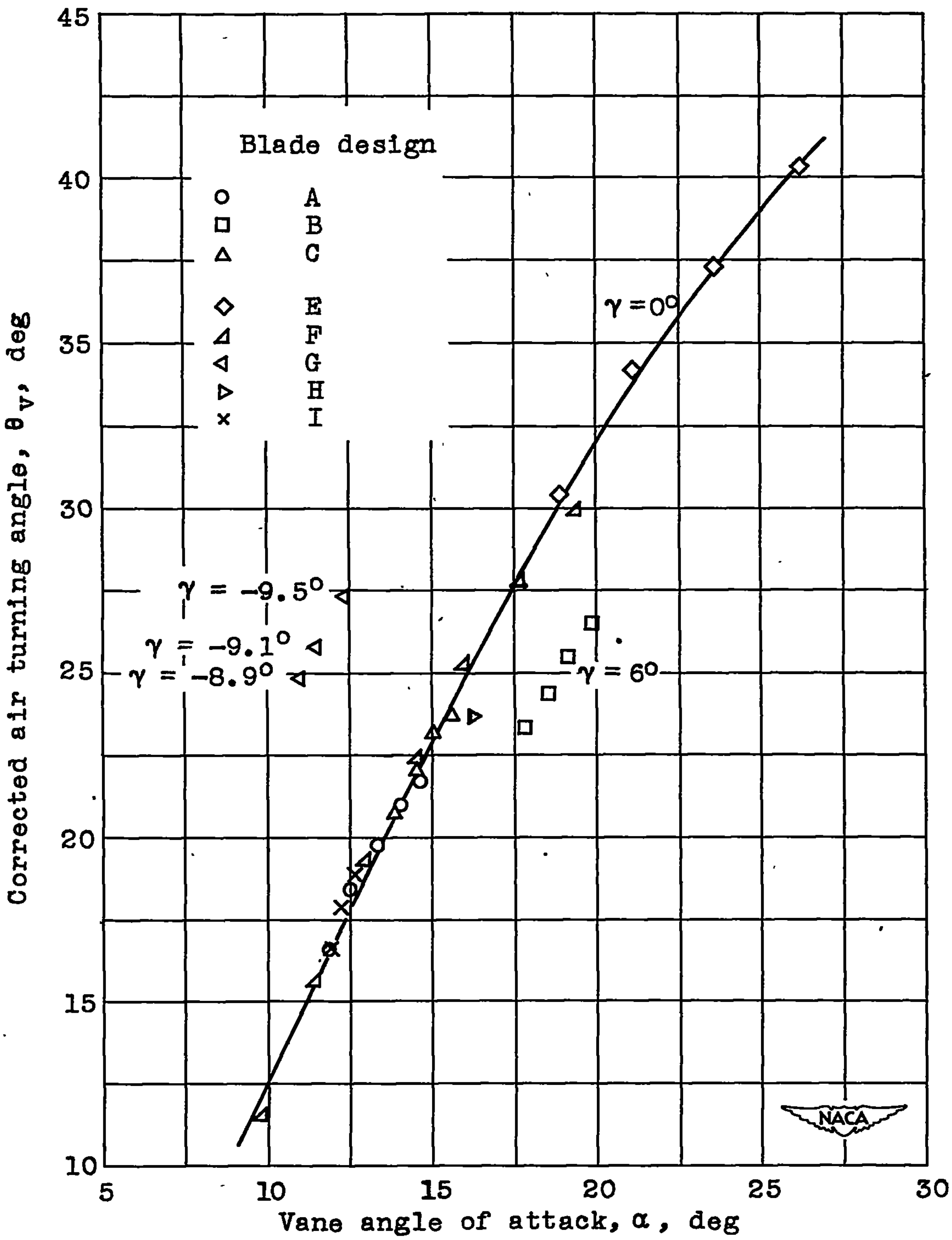

Figure 6. - Turning-angle characteristics of circular-arc constant-thickness inlet guide vanes. Measured data corrected to constant inlet axial velocity across vane. Incidence angle equals γ.

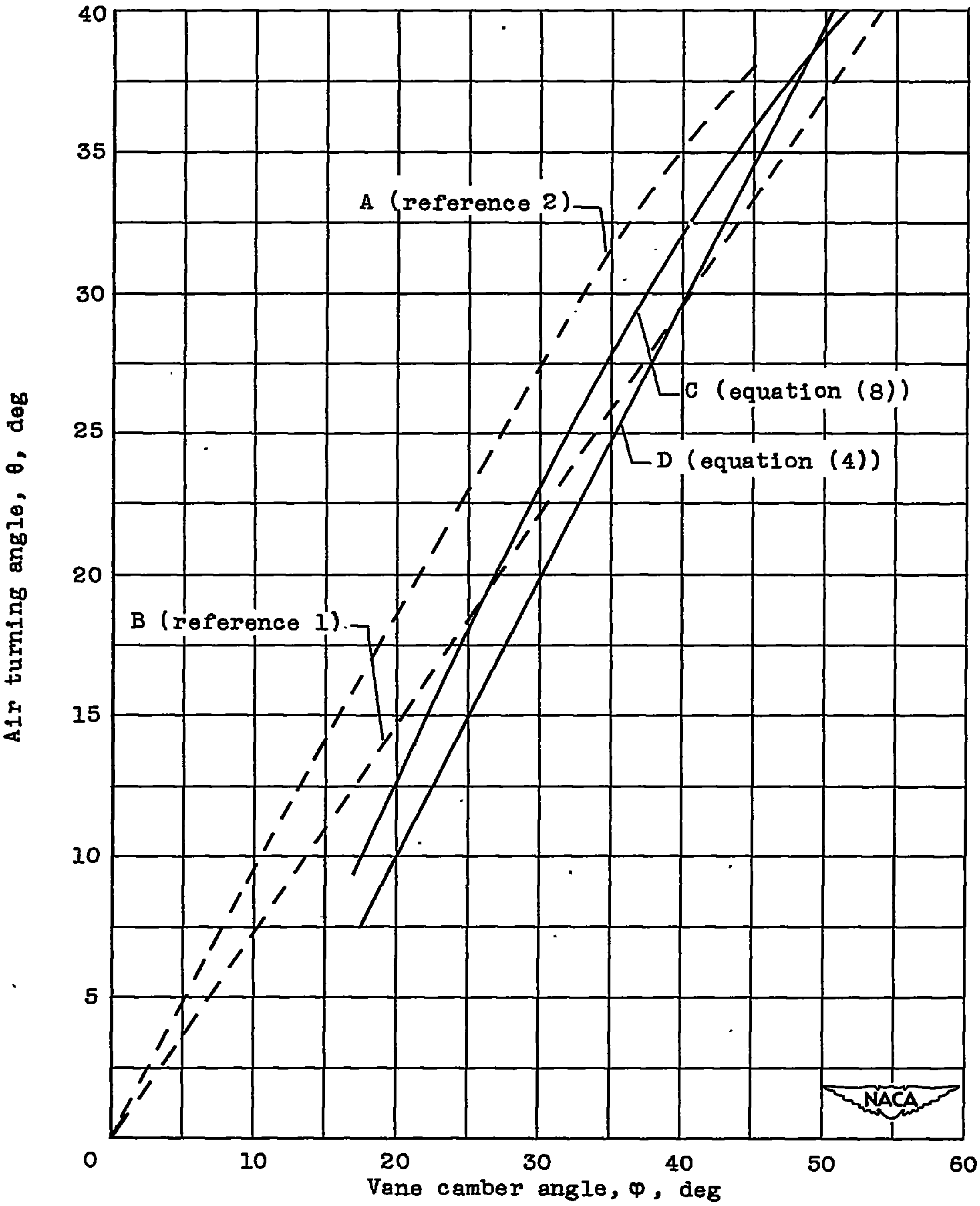

Figure 7. - Comparison of turning-angle rules for circular-arc vanes at zero incidence angle and inlet Mach number not greater than 0.3. Solidity of curves A and B, constant at 1.6; solidity of curves C and D variable, average approximately 1.6.

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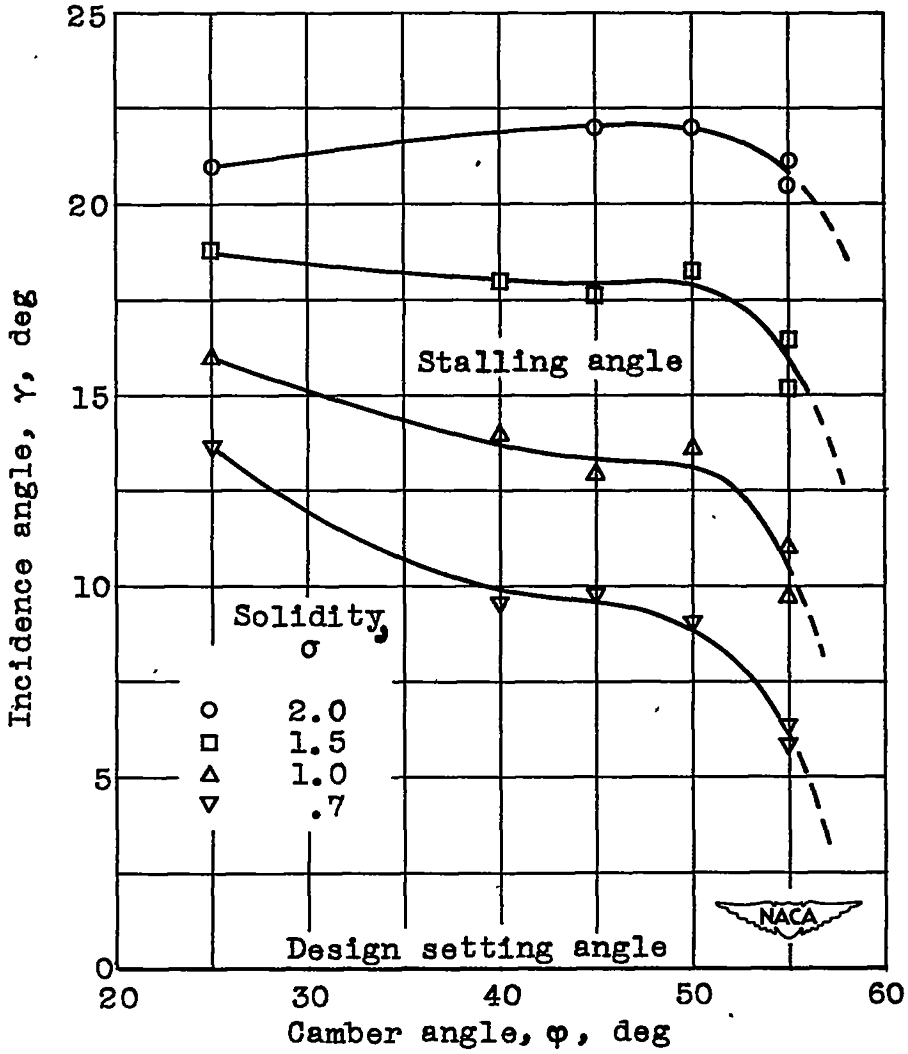

Figure 8. - Variation of stalling incidence angle with camber for circular-arc airfoil sections set with tangent to mean profile arc at leading edge parallel to axis. Data deduced from reference 2.