RM L50A23

# RESEARCH MEMORANDUM

## A DISCUSSION OF THE DESIGN OF HIGHLY SWEPT PROPELLER BLADES

By Richard T. Whitcomb

Langley Aeronautical Laboratory
Langley Air Force Base, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON

May 4, 1950
Declassified August 15, 1954

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

---

RESEARCH MEMORANDUM

---

# A DISCUSSION OF THE DESIGN OF HIGHLY SWEPT PROPELLER BLADES

By Richard T. Whitcomb

## SUMMARY

A description of two propellers with highly swept blades investigated in the Langley 8-foot high-speed tunnel is presented, together with a discussion of the numerous assumptions and analyses on which the designs of these propellers are based. The blades are swept considerably along the entire blade radius and, in order to allow for reductions in the maximum stresses, are swept forward inboard and backward outboard. The blades have been designed on the basis of the blade-element method primarily to have subcritical efficiencies at the highest possible forward speed. The designs have been controlled primarily by the stresses in the blades.

The blades have 45° of sweep at the design station and have NACA 16-series sections. At the design section at the 0.7-radius station, the design lift coefficient is 0.4, the section thickness is 6 percent of the chord, the design blade angle is 60°, and the solidity is 0.057. One of the swept blades has the same twist as that calculated to be ideal for a comparable unswept blade. The twist of the other blade has been altered to account for the probable changes in the induced effects produced by sweeping the blade. A description is also included of an unswept blade investigated to provide a basis of comparison in the determination of the effectiveness of sweep.

## INTRODUCTION

Results of numerous investigations (reference 1, for example) have indicated that sweeping a wing back or forward results in pronounced delays and reductions in the adverse changes in the wing characteristics associated with the onset of shock and separation. It might be expected that sweeping a propeller blade would result in delays and reductions in the losses in efficiency associated with these effects. Propellers with moderate amounts of sweep have been investigated in Germany and in the Langley 16-foot high-speed tunnel (references 2 to 4). The angle of sweep used had little effect on the high-speed performance.

In order to determine the probable maximum effectiveness of using sweep to delay and reduce the losses in efficiency at high subsonic speeds, two propellers with highly swept blades have been investigated in the Langley 8-foot high-speed tunnel (reference 5). These propellers have been designed to have the highest efficiency at the highest possible Mach number. The blades of these propellers are identical except for the distribution of blade angle. Presented herein are descriptions of the blades together with a discussion of the numerous assumptions and analyses on which the design of these blades is based. A definite general design procedure is not presented. A description of an unswept blade investigated to provide a basis of comparison in the determination of the effectiveness of sweep is also included. Results for tests of this propeller are presented in reference 6.

## SYMBOLS

| | |
|---|---|
| $\Lambda$ | sweep angle of a line through midpoints of chord lines of sections perpendicular to radii through midpoints, as measured from radius of a given section in the plane through radius and chord line of section (fig. 1) |
| $\beta$ | blade angle of a section perpendicular to radius through midpoint of chord line of section measured from plane of rotation to chord line (fig. 1) |
| $\Gamma$ | dihedral angle of a line through midpoints of chord lines of sections perpendicular to radii through midpoints, as measured from radius of a given section in a plane perpendicular to that in which sweep is measured (fig. 1) |
| D | diameter of propeller, feet |
| R | radius of propeller, feet |
| r | radius to any station (fig. 1), feet |
| b | blade-section width perpendicular to radius to midpoint of chord line of section, feet |

## GENERAL CONSIDERATIONS

### Magnitude and Extent of Sweep

An analysis of the principal factors affecting the performance of propellers with swept blades indicates that, in order to obtain a very nearly optimum swept blade, the sweep of the various sections should be approximately $40^{\circ}$ to $50^{\circ}$. The gains obtained through the use of smaller amounts of sweep would probably not justify the increase in the complexity of the construction of the blades, nor the increase in the size and complexity of the pitch-changing mechanism required to overcome the greater centrifugal pitching moments for such blades. An analysis based on the method of reference 7 indicates that the use of larger amounts of sweep requires increases in blade width, section thickness ratio, and taper ratio. These changes result in reductions in performance greater than the increases resulting from the additional sweep. A sweep of $45^{\circ}$ has been selected for the design section, at the 0.7-radius station, of the blades investigated in the Langley 8-foot high-speed tunnel.

When a blade operates at high advance ratios, the effective velocity is nearly as high for the root sections as for the sections farther outboard. As a result, at high forward speeds the root sections, as well as sections farther outboard, experience losses in efficiency due to the onset of shock and separation. Thus, it appears that considerable amounts of sweep should be applied to sections of a blade near the root, as well as along sections farther outboard, if the propeller is to operate at the highest possible efficiencies at high speeds.

### General Plan Form

Ideal plan form.- Assuming that the flow over a swept propeller blade is similar to that over a swept wing, in order to obtain the greatest possible delay in the losses in efficiency, with a given amount of sweep, and the highest possible low-speed cruise efficiency, a blade should have a fairly low solidity (reference 8), moderate taper (reference 9), and should be swept back or forward along the entire radius, as shown in figure 2(a). However, the use of such a plan form with the desired sweep would result in impractically high moments and stresses at the root of the blade because of the centrifugal forces of the elements of the blade.

Actual plan form.- Plan forms incorporating sweep which would have reasonable maximum stresses are shown in figures 2(c) to 2(k). A comparison of these plan forms based on thorough considerations of the aerodynamic, structural, and mechanical problems involved in each resulted in the selection of the plan form shown in figure 2(c) for the blades investigated in the Langley 8-foot high-speed tunnel.

Theoretically, sweepforward is just as effective as sweepback in delaying and reducing the losses due to shock and separation. Sweeping the inboard sections of the blade forward and the outboard sections rearward as shown in figure 2(b) should delay and reduce the efficiency loss of a propeller by the same amount as would sweeping the blade back over the entire radius as in the ideal case. However, at the knee, a stress concentration will develop. In order to reduce this effect, the knee must be faired as shown in figure 2(c). The faired portion of the blade essentially has no sweep, and it would be expected that the losses in efficiency for these sections at high forward speeds would be greater than they would be if the blade were swept back along the entire radius. However, as is pointed out in the appendix, the losses in efficiency incurred by fairing the knee will probably be small.

## General Design Procedure

The design of the propeller was made on the basis of the blade-element method, primarily to obtain the highest possible subcritical efficiency at the highest possible Mach number. Only secondary consideration was given to the take-off, climb, and supercritical conditions.

The elements of the swept blades under consideration will not operate independently of each other, as infinite span surfaces, even when the sections operate at subcritical speeds. Also, the induced velocities normal to the vortex sheet cannot be accurately predicted for a swept blade with the theory available at present. Therefore, the performance of a propeller with swept blades cannot be estimated exactly. However, the use of the blade-element method is regarded as reasonably sound for predicting the cruise performance and the highest Mach numbers at which the subcritical efficiencies may be obtained.

During the aerodynamic design, the stresses in the blades must be considered continually, since the designs of the blades are controlled primarily by these stresses.

The design approach used herein is obviously not the same as that generally followed by the designer in laying out an operational propeller. However, it is suggested that the use of the present method might result in the most satisfactory operational swept propeller as well as the most desirable research propeller incorporating sweep, since the primary requirement for both is that the propeller have the highest possible efficiency at the highest possible Mach number. The blades would be designed by a method similar to that described in the following sections; the required thrust would then be obtained by selecting the proper number of blades and propeller diameter; and the correct engine speed would be obtained by selecting the proper gear ratio between the engine and propeller.

In order to allow the attainment of the highest possible power loading per blade without resorting to a complexly balanced single-bladed propeller, two blades in single rotation were used for the propellers investigated in the Langley 8-foot high-speed tunnel (reference 5).

## SPECIFIC DESIGN OF SWEPT BLADES AND DISCUSSION OF DESIGN

### Design Advance Ratio

An advance ratio of 3.65, and a design blade angle of $60^\circ$ at the 0.7-radius station (the design station) has been selected for the design condition of the propeller to be investigated in the Langley 8-foot high-speed tunnel.

Obviously, the advance ratios for propellers designed to operate with subcritical efficiency at the highest possible forward Mach numbers should be fairly high, since the use of a high advance ratio reduces the section Mach numbers in relation to the forward Mach number and thus increases the forward Mach number at which a given blade experiences losses in efficiency associated with the onset of shock and separation on the blade. The use of high advance ratios also results in a reduction of the centrifugal forces on a blade for operation at a given forward speed. Thus, it allows the use of more sweep, thinner sections, lower solidity, or less taper, all of which would lead to improved aerodynamic performance. However, if the advance ratio is increased to a very high value, the thrust produced by a given propeller becomes relatively small, and small decreases in the lift-to-drag ratios of the blade sections lead to very pronounced losses in efficiency. Thus the advance ratio must be held within certain limits.

### Basic Blade-Width Distribution

Design values.- In the design of the propeller investigated in the Langley 8-foot high-speed tunnel, a basic blade-width distribution, based on knowledge of unswept blade characteristics, was first selected. Corrections were then applied to account for sweep, after the sweep distribution had been chosen, as will be described later.

Investigations of the solidity of unswept propeller blades (reference 10) indicate that the use of a solidity of 0.04 at the design station results in very nearly the optimum subcritical performance, and for the thickness ratios selected there is little tendency for an unswept blade with such a solidity distribution to vibrate. This value has been selected for the solidity at the design station of the basic width distribution of the swept blade. The widths at other radial stations are presented in figure 3. The basic blade-width distribution has a uniform taper along the outboard sections such that, for the plan form made up of extensions of the uniform taper, the chord at the tip is 0.4 the chord at the 0.5-radius station. The basic plan form is untapered from the spinner surface to the 0.5 radius station. The plan form is faired at the 0.5 radius station and tip as shown in figure 3.

Effect of taper ratio.- Because of severe adverse pressure gradients on the outboard sections and an outflow of the boundary layer, it would be expected that the flow over the tip sections of a swept blade would separate earlier than would the flow on a similar unswept blade, when the section angle of attack is increased. Results of wing investigations (reference 7, for example) indicate that reducing the taper would minimize this effect. However, in order to reduce the stresses at the knee to reasonable values, it has been decided to accept reductions in the take-off performance and to use a fairly high degree of taper as was used on the unswept blade of reference 10.

## Blade Sections

General.- The sections at all the stations of each of the blades have been laid out perpendicular to the radii which greatly facilitates the over-all design problem. NACA 16-series sections were selected. These sections are particularly suited to swept propellers since they have more cross-sectional area near the trailing edge than do NACA low-drag sections. This thicker trailing edge reduces the maximum stresses that occur in this region of swept blades. The two swept blades have identical sections at equal radii.

Thickness ratio.- The thickness ratios of the various sections of the blades are indicated in figure 4. At the design station the thickness ratio is 0.06, and varies from 0.10 at the spinner surface, the 0.27-radius station, to 0.03 at the 0.9-radius station.

The results of numerous tests of airfoil sections made near and at sonic speeds indicate that decreasing the thickness ratio greatly delays and reduces the losses in the section lift-to-drag ratios associated with the onset of shock and separation. Obviously, to delay and reduce the losses in efficiency of a propeller operating at high forward speeds, the thickness ratios for the various sections should be as low as structurally possible.

Near the tip, the loads tending to bend the propeller about the major axes of the sections will be relatively small and the thickness ratios for these sections should be reduced to very small values to obtain the highest possible lift-to-drag ratios. Such reductions in the thickness ratios for the tip sections will also reduce the bending moments at the knee produced by the moments of the centrifugal forces of the outboard elements. At stations further inboard, structural considerations dictated the use of thicker sections.

Propellers designed in the future with less conservative structural factors of safety should probably have lower thickness ratios at the knee, since such reductions in the thickness ratio for these sections will probably produce a much greater increase in efficiency at a given high forward speed than would other design changes that could be made with the same reduction in the factor of safety.

Camber.- It has been found that a design lift coefficient of approximately 0.4 at the design section yields the most satisfactory subcritical performance for an unswept blade (reference 11), and such a camber has been chosen for the design section of the swept blades investigated in the Langley 8-foot high-speed tunnel. The distribution of camber along the radius of the swept blades has been selected so that the product of the incompressible design lift coefficient times the basic chord is the value required to obtain the Betz loading for minimum induced losses at the design condition, assuming each section operates at its design lift coefficient.

## Sweep Distribution

Ideal distribution.- If the blade is designed properly, the distribution of sweep should have little effect on the subcritical cruise performance of a swept propeller. In the selection of the sweep, therefore, the attainment of the highest possible Mach number at which low-speed efficiencies may be obtained with a given maximum stress has been the exclusive consideration. This result can probably best be accomplished by selecting the sweep distribution such that each of the sections experiences increases in drag and losses in lift, and thus decreases in efficiency, simultaneously.

If it is assumed that the various sections act as portions of infinite-span surfaces and the force-break Mach number is a linear function of the critical value, such a sweep distribution would be obtained by selecting the sweep so that the following factor is constant for the various sections:

$$\frac{M_{cr}}{(\cos \Lambda)W/V_f}$$

where

$M_{cr}$ section critical Mach number, in a flow perpendicular to the locus of the 50-percent-chord stations

$\Lambda$ local sweep angle

$W$ resultant of rotational and axial velocities

$V_f$ forward velocity

The basic sweep distribution for the blades at the design condition has been selected by using such a method. The radial distributions of section critical Mach number $M_{cr}$ and ratios of local velocity to forward velocity $W/V_f$ used and the distribution of sweep obtained are shown in figure 5. These distributions were obtained for the design advance ratio of 3.65 and the spanwise distribution of thickness and camber for the design sections parallel with the air stream as shown in figure 4. It was assumed that all sections operated at the design lift coefficient.

This sweep was applied to the loci of the 50-percent-chord stations of the design sections in order to simplify the structural problem. As pointed out previously, the sweep has been applied as sweepback along the outboard portion of the blade, sweepforward along the inboard portion. The critical forward Mach number has been calculated to be 0.84.

The knee.- To delay the onset of strong shock losses at the knee to the highest possible forward Mach number, the knee should be placed as far inboard as possible. However, this leads to a reduction of the effective aerodynamic sweepforward of the sections between the knee and the root (see appendix). It is apparent that, to obtain the highest possible efficiencies at high forward speeds, as well as the highest possible speed at which low-speed efficiencies are obtained, a compromise knee position must be selected. The structural problem must also be considered in the selection of the knee location. After making a complete stress analysis for several knee locations, it has been decided that, for the propeller blade to be investigated at the Langley 8-foot high-speed tunnel, the approximate optimum knee location on the basis of aerodynamic and structural considerations (reference 7) is such that the point of zero actual sweep is at the 0.5-radius station.

It is probable that the optimum location for other propeller blades will be at or near this station.

The knee is designed such that the locus of the midchords of the design sections is a circular arc which is tangent to the ideal sweepback and sweepforward. For both the leading and trailing edges, the radii of the knee are equal to one-half the width of the blade at the 0.5-radius station. The actual sweep distribution is shown in figure 6. The radius of the arc has been selected so that the maximum stress at the trailing edge of the section at the plane of symmetry of the knee, or at the point where the sweep is zero, is the same as the stresses at the trailing edges of sections just outboard the knee for the design condition. This procedure effectively eliminates stress concentration at the knee, which probably results in the most efficient use of the blade structure for the design condition; that is, the blade theoretically has the best aerodynamic characteristics for a given maximum stress at this condition.

Effect of blade-angle change on sweep.- When the pitch of the swept blade is changed from the design value, the sweep angles at the various stations change; for example, when the blade angle is reduced by $30^\circ$ from that for the design condition, the sweep angles are altered by approximately $-12^\circ$, $-6^\circ$, $-1^\circ$, $0^\circ$, and $5^\circ$ for the 0.9-, 0.75-, 0.62-, 0.5-, and 0.27-radius stations, respectively. These sweeps were calculated by the method of reference 7.

## Revised Width Distribution

Corrections for sweep.- Assuming that each section operates as a portion of an infinite-span surface and that the sections of the swept blade all operate at the design angles of attack, the actual lift coefficients for each of the sections will be reduced below the design values by a factor equal to approximately the reciprocal of the cosine of the sweep angle. To obtain the same thrust loading and the same thrust for a given condition for the swept blade as for the optimum unswept blades, on which the basic width distribution was based, the chords of the various sections of the basic blade-width distribution have been increased by a factor equal to the reciprocal of the cosine of the local sweep angles. The corrected blade-width distribution is shown in figure 3. The geometric solidity of the swept blades at the design section will be equal to 0.04 times the reciprocal of the cosine of $45^\circ$ or 0.057.

The use of the design blade width chosen should result in fairly good subcritical performance, in a high take-off thrust, and in little tendency toward vibration. The maximum stresses in the blade, which are an indirect linear function of the solidity of the blade, are reasonable within the blade widths chosen.

In the design of a propeller to be used on an operational aircraft, the solidity may have to be increased to a value greater than that used for the present design in order to obtain the required thrust. However, the increase will probably result in a reduction in the efficiencies at both subcritical and supercritical speeds. Increases in power for a swept propeller should be obtained by increasing the propeller diameter or number of blades rather than by increasing the blade solidity if possible.

Width of knee.- In the method described in the previous paragraphs, the blade width at the knee has been determined by using the ideal sweep as described in the subsection pertaining to sweep. When the blade width at the knee is selected on the basis of this method, the loading at the knee will be greater than that for the ideal distribution, although, because of the local induced flows, the loading on these sections of the swept blade will be considerably less than those predicted by assuming that the sections operate independently. Experimental information which is not available at present would be required in order to obtain the ideal loading on the swept blade.

Advantages of wide knee.- The use of the relatively wide knee obtained through the process selected results in large increases in the moments of inertia about the various axes of these knee sections and thus a smaller knee radius is required to reduce the maximum stresses at the trailing edge of the knee to the same values as those in sections just outboard the knee. Also, the use of a wide knee decreases the radius of curvature of the knee in the maximum thickness region for a given radius of curvature at the trailing edge, which is the primary factor controlling the magnitude of the stress concentration at the knee. Thus, the use of the wider knee results in a reduction of the relative extent of the region of the blade which is effectively unswept for a given maximum stress.

The use of the wider blade at the knee leads to an increase in weight ahead of the pitch-change axis, which results in a more satisfactory placement of the knee from aerodynamic considerations when the position of the knee is selected to obtain zero bending moments about an axis perpendicular to the ideally located pitch-change axis as described previously.

## Blade-Angle Distribution

Distribution for first swept blade.- In the design of the cambered, straight unswept propellers previously investigated in the Langley 8-foot high-speed tunnel (reference 12), the radial blade-angle distributions have been selected so that, theoretically at least, the various sections of a blade would operate at the design angles of attack at the design condition. These blade-angle distributions were determined by using reference 13, which is based on the Betz ideal loading for a lightly loaded propeller. A blade-angle distribution obtained through the use of this method has been applied to the first of the swept blades (fig. 7).

The results of both theoretical and experimental studies indicate that the induced flows around swept wings are not the same as those around unswept wings. When a wing is swept back, the induced downwash increases near the root sections and decreases near the tip sections, whereas the converse is true when a wing is swept forward. (See reference 14.) Because of the high advance ratio and large spinner size of the propellers being considered, it would be expected that the induced flows around the swept blade would be altered in a manner similar to that for swept wings. It would be expected that the induced velocities normal to the vortex sheets of the swept blades at the root and tip would be less than those predicted using the Betz theory for a similar unswept blade, while the induced velocities at the knee would be greater than those for an unswept blade. Obviously, twisting the swept blade by the amount required to have each of the sections of an unswept blade operate at the design angles of attack will not result in a similar condition for the swept blade, even if the design load distribution on the swept blade is the same as that on the unswept.

The angles of attack of the tip and root sections will be greater than the design angles at the design condition. The results of the wing investigation of reference 1 indicate that this factor will probably lead to increases in the subcritical profile-drag coefficients for these sections. It will also lead to increases in the induced losses, since the minimum induced losses are obtained with the Betz loading for the swept, as well as for the unswept blades. This factor would also lead to increases in the initial severe separation in these regions for the high thrust coefficients at the take-off and climb conditions.

The load carried by the knee sections of the swept blade will be greater than that required to obtain the ideal Betz loading because of the increased blade width in this region, which will result in an increase in the induced loss above the ideal minimum. The general induced effect associated with blade sweep will reduce the excessive load at the knee, and thus the load distribution will approach the ideal more closely. This induced effect will also further reduce the angles of attack for these sections below the design value at the design operating condition. However, the results of the wing investigation of reference 1 indicate that these reductions should have little effect on the subcritical profile-drag coefficients for these sections.

It appears that the maximum subcritical efficiency of the swept blade with the same twist as the unswept blade will probably be affected only slightly by the variations in the induced velocities associated with sweep. However, the take-off and climb performance might be adversely affected by these variations.

Distribution for second propeller.- To obtain more accurate indications of the most satisfactory blade-angle distribution for the swept propeller under consideration and the corrections that must be applied to the blade-element theory in the design of swept propellers, another blade design with a distribution selected such that each of the sections operate more nearly at the design angle of attack will be investigated. For the second blade, the blade-angle distribution of the first swept blade has been altered by applying, at a uniform rate, three degrees of washout from the 0.5-radius station to the spinner surface and to the tip. The washout has been applied so that the blade angle at the design station at the design condition remains unchanged. The radial blade-angle distribution is shown in figure 7.

The blade-angle distribution required to have all sections operate at their design angles at the design condition cannot be calculated exactly using available theory, even when the effect of the knee is disregarded. However, an estimate of this distribution can be obtained by correcting the required distribution for the straight blade on the basis of the theory of the induced flow around swept wings (reference 14). Because of the high advance ratio, such an estimate should be fairly accurate. The uniform twists incorporated approximate the twist estimated to be needed using such a method.

The over-all cruise and high-speed characteristics should be only slightly affected by this change in twist; however, the additional twist applied to the second swept propeller should reduce the probable initial separation at the root and tip regions at high thrust coefficients for take-off and climb, and thus, will probably improve the performance of the propeller with these blades at these conditions.

Conditions away from design.- Obviously, as with straight blades, when the swept blade is rotated away from the design orientation about the pitch-change axis, the pitch distribution will change. However, the variations of the blade angles for the various sections of the swept blade when the blade is rotated will not be the same as the angle of rotation. The actual blade-angle changes for the various sections can be calculated by using the equations presented in reference 7. The magnitudes of the alterations of the blade-angle distribution for the swept blades from those that would be determined for similar straight blades, when the pitch is reduced by $30^\circ$ from the design condition, are approximately $20^\circ$, $9^\circ$, $0.1^\circ$, $0^\circ$, and $-0.3^\circ$ at the 0.90-, 0.75-, 0.62-, 0.50-, and 0.27-radius stations, respectively.

Because of the special orientation of the blade elements for the design condition as described later in the paper, the centrifugal and aerodynamic forces will have little effect on the effective pitch distribution for this condition. However, when the blade operates at conditions away from those of design, these factors may considerably alter the pitch distribution. These changes in the pitch distribution may be calculated using the method presented in reference 7.

## Dihedral

The dihedral distributions for the design condition of the swept blades investigated in the Langley 8-foot high-speed tunnel are shown in figure 8. The dihedral used was selected to reduce the bending moments about the major axes of the minimum sections for the design blade angle and advance ratio at the design-tunnel Mach number of 0.85 by using the method described in reference 7. An analysis of the geometry of a swept blade indicates that, if the elements of the blade are oriented in the proper manner, the bending moments about the major axes of all the minimum sections may be eliminated. Since the blade sweep angles for each position along the radius for a given design are fixed, it follows that the only variable that can be changed to obtain this proper orientation is the dihedral. The moments may be eliminated for only one operating condition. However, this procedure generally reduces the moments for most other operating conditions.

The use of dihedral may produce adverse effects, however, which may be more important than its advantages. The dihedral required may be so large that the aerodynamic and structural characteristics of the blade would be altered. Such alterations might severely reduce the performance of the propeller. In the case of the propeller tested in the Langley 8-foot high-speed tunnel, the dihedral required to eliminate the moments about the major axes of the sections along the portions of the blade with relatively uniform sweep have been applied. However, the dihedrals required to eliminate the moments at the knee were fairly large. Since the effect of this large dihedral on the performance was unknown, it was reduced, and small stresses about the major axis at the knee were accepted. These stresses were not large enough to limit the final design of the propeller, however.

## Shank

The mechanism used to adjust the pitch of the blade is similar to that used for previous investigations of propellers in the Langley 8-foot high-speed tunnel. It consists of a shank as shown in figure 9 which is clamped into the spinner of the dynamometer. The shank or pitch axis has been placed so that it passes through the spinner surface at approximately the 25-percent-chord station of the root section 0.5 inch below the chord line of this section.

With this location of the shank the moments about axes perpendicular to the pitch axis are eliminated for the design condition as described in reference 7. The use of such a location will have little effect on the moments about the pitch axis. This moment will be approximately 3100 inch-pounds at the design condition for the blades investigated in the Langley 8-foot high-speed tunnel. This moment was determined using the method described in reference 7.

The position of the knee has been selected so that the position of the shank based on the above requirement is very near the leading edge of the root sections. This reduces the stress concentrations at the knee and at the root for a given blade design by reducing the displacement of the knee with respect to the root. This effect is probably great enough to justify the increase in the problems of fairing the root of the blade into the spinner for various pitch settings associated with such a placement.

## Model Blades

The blades investigated in the Langley 8-foot high-speed tunnel have been machined from solid 76S-T aluminum alloy. Front and side views of one of the swept blades for the design condition are presented in figure 9(a). A plan view of the blade is shown in figure 9(b). The diameter of the propellers at the design conditions with these blades will be 4 feet. When the swept blades are rotated from the design condition, the diameters of the propellers with these blades change; when the blade angle is reduced by 30°, the diameters of the propellers are increased by approximately 3.7 percent. This difference was calculated by using the method presented in reference 7.

The blade surface is extended below the surface of the spinner at the trailing edge 1.0 inch for the design condition so that the faired surface in this region extends to the spinner at moderate blade angles. However, at low blade angles, a gap exists near the trailing edge of the juncture.

## Stresses

The construction material used, 76S-T aluminum alloy, has a specific weight of 0.11 pound per cubic inch. For the probable maximum tunnel Mach number of 0.93, the tunnel-stream dynamic pressure is 720 pounds per square foot and the rotational speed is 72.0 revolutions per second for the design advance ratio. By use of these values with the method of reference 7, it has been calculated that, with the design load distribution, the stress at the trailing edge of the blade in the region at and near the knee will be approximately 20,000 pounds per square inch. The stresses in all other parts of the blade have been calculated to be considerably less than the value for this region. This value is approximately equal to one third the minimum yield strength of 60,000 pounds per square inch for the 76S-T alloy.

Further calculations indicate that alterations of the various operating conditions, except for rotational speed, have only secondary effects on the maximum stresses in the blade. Obviously, the stresses are functions of the square of the rotational speed. The rotational speed for take-off and climb conditions should not exceed the value at this high-speed condition, and the stress obtained at these conditions should not exceed the above value; however, at high speeds the propeller may operate at lower advance ratios than the design value. Obviously, the maximum stress will be greater than 20,000 pounds per square inch for these cases.

## DESIGN OF A COMPARABLE UNSWEPT BLADE

In order to provide a basis of comparison in the determination of the effectiveness of sweep in delaying and reducing the losses in propeller efficiency at high subsonic speeds, an unswept blade, similar to the swept blades, has been investigated in the Langley 8-foot high-speed tunnel (reference 6). The blade is shown in figure 9(b). All sections of the blade are the same as those of the two swept blades (fig. 3); the blade-width distribution is the same as the basic blade-width distribution for the swept blades (fig. 4) and the blade-angle distribution is the same as that for the first swept propeller (fig. 7). No dihedral was applied to the unswept blade. The maximum stress in this blade at a given operating condition is considerably less than that in the swept blade. This unswept blade has been designed to produce the same thrust as the swept blade at the design condition.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va.

# APPENDIX

## A STUDY OF THE POSSIBLE FLOW OVER SWEPT BLADES

### Take-Off and Climb Conditions

The results of investigations of swept wings indicate that, when the sections of the swept propeller blade operate at high angles of attack for low speeds, as they usually do at the take-off or climb condition, the separation on the tip and root sections will be considerably more severe than that predicted on the basis of infinite-span data. These effects are due to a thickening of the boundary layer in these regions produced by an outflow and inflow of the boundary-layer air along the sweptback and sweptforward portions of the blade and to very severe increases in the peak pressures at the leading edges of these sections, associated with the induced flows.

On the other hand, the wing data indicate that separation on the swept sections near the knee may be delayed to higher lift coefficients than those at which separation occurs on infinite-span sections due to a thinning of the boundary layer and a reduction of the peaks near the leading edge for these sections.

### The Critical Condition

The pressure measurements made on and behind the sections of the wing with various amounts of sweep in the Langley 8-foot high-speed tunnel (reference 1) indicate that, for sections of the swept blade outboard of the knee and between the knee and the root, the separation associated with the onset of shock should probably occur at speeds slightly less than those predicted on the basis of infinite-span theory. The differences would probably be due to reductions of the effective sweep of the elements of the blade in these regions associated with the flow around the finite-span surfaces.

Because of the presence of a region of relatively high induced velocities near the leading edge of the root sections (indicated by unpublished wing data) separation should occur on these sections at much lower speeds than those speeds predicted on the basis of the infinite-span theory.

The critical Mach numbers for sections near the center of the knee should be somewhat less than those for an infinite-span surface with a sweep similar to that of the blade near the knee, although they should be considerably greater than those for a two-dimensional unswept section.

Pressure data obtained on the root sections of a swept wing without a fuselage (reference 13) indicate that a normal shock should form on the knee at a Mach number slightly greater than the critical Mach number of this region. Because of a stabilization of the boundary layer in this region, separation should not occur with the initial onset of this shock. This stabilization of the boundary layer, would be associated with the spanwise variations of the lateral pressure gradients. These variations near the knee should probably be considerably less than those present near the wing-fuselage juncture on the wing of reference 1, and thus it would be expected that the stabilization in the present case should be less pronounced than that indicated for the same region of the wing.

A study of the probable flow over the knee based on these assumptions indicates that the speed at which the flow over the sections at the center of the actual knee separates due to the onset of shock should be somewhat greater than the speed at which such a change would occur for a two-dimensional section, but somewhat less than that at which the losses would occur on such a section with the same sweep as have the sections near the knee.

## Supercritical Condition

Further study of the flow over the swept wings of reference 6 indicates that the sections near the tip should probably experience much more severe separation due to the presence of a shock than would similar infinite-span sections, primarily because of a destabilization of the boundary layer in this region associated with an outflow of the separated boundary layer of sections further inboard. This outflow is associated with the spanwise pressure gradients as it is for the wing. It would be accentuated by the centrifugal action on the particles in the boundary layer in the case of a propeller. Because of inflow of the boundary layer on the sweptforward portion of the blade, the root sections of the swept blade should also experience very much larger increases in the separation than do similar infinite-span sections.

The data obtained on the swept wings of reference 1 indicate that separation at the center of the knee should be more severe than for infinite-span sections with the sweep of sections near the knee, but be considerably less than that on unswept infinite-span sections.

When the Mach number for the knee sections approaches and exceeds a value of 1.0, the increases in the drag coefficients for these sections may be severe because of a large increase in the strength of the normal shock near the trailing edge and the onset of a bow shock ahead of the knee.

## REFERENCES

1. Whitcomb, Richard T.: An Investigation of the Effects of Sweep on the Characteristics of a High-Aspect-Ratio Wing in the Langley 8-Foot High-Speed Tunnel. NACA RM L6J01a, 1947.

2. Quick, A.: Tests on Airscrews with Swept Curved Blade Axes. Reps. and Translations No. 48, British M.A.P. Völkenrode, Jan. 1946. (Available from CADO, Wright-Patterson Air Force Base, as ATI 9086.)

3. Gray, W. H.: Wind-Tunnel Tests of a Swept-Blade Propeller and Related Straight Blades Having Thickness Ratios of 5 and 6 Percent. NACA RM L8H19, 1948.

4. Evans, Albert J., and Klunker, E. Bernard: Preliminary Investigation of Two Full-Scale Propellers to Determine the Effect of Swept-Back Blade Tips on Propeller Aerodynamic Characteristics. NACA RM L6J21, 1947.

5. Delano, James B., and Harrison, Daniel E.: Investigation of the NACA 4-(4)(06)-057-45A and NACA 4 (4)(06)-057-45B Two-Blade Swept Propellers at Forward Mach Numbers to 0.925. NACA RM L9L05, 1950.

6. Delano, James B., and Harrison, Daniel E.: Investigation of the NACA 4-(4)(06)-04 Two-Blade Propeller at Forward Mach Numbers to 0.925. NACA RM L9I07, 1949.

7. Whitcomb, Richard T.: Method for Stress Analysis of a Swept Propeller. NACA RM L8F11, 1948.

8. Adler, Alfred A.: Effects of Combinations of Aspect Ratio and Sweepback at High Subsonic Mach Numbers. NACA RM L7C24, 1947.

9. Sleeman, William C., Jr., and Becht, Robert E.: Aerodynamic Characteristics of a Delta Wing with Leading Edge Swept Back 45°, Aspect Ratio 4, and NACA 65A006 Airfoil Section. Transonic-Bump Method. NACA RM L9G22a, 1949.

10. Stack, John, Draley, Eugene C., Delano, James B., and Feldman, Lewis: Investigation of Two-Blade Propellers at High Forward Speeds in the NACA 8-Foot High-Speed Tunnel. II - Effects of Compressibility and Solidity. NACA 4-308-045 Blade. NACA ACR 4B16, 1944.

11. Delano, James B.: Investigation of Two-Blade Propellers at High Forward Speeds in the NACA 8-Foot High-Speed Tunnel. III - Effects of Camber and Compressibility. NACA 4-(5)(08)-03 and NACA 4-(10)(08)-03 Blades. NACA ACR L5F15, 1945.

12. Stack, John, Draley, Eugene C., Delano, James B., and Feldman, Lewis: Investigation of Two-Blade Propellers at High Forward Speeds in the NACA 8-Foot High-Speed Tunnel. I - Effect of Compressibility. NACA 4-308-03 Blade. NACA ACR 4A10, 1944.

13. Hartman, Edwin P., and Feldman, Lewis: Aerodynamic Problems in the Design of Efficient Propellers. NACA ACR, Aug. 1942.

14. Diederich, Franklin W.: A Simple Approximate Method for Obtaining Spanwise Lift Distributions over Swept Wings. NACA RM L7I07, 1948.

15. Johnston, J. Ford, and Danforth, Edward C. B.: Some Pressure-Distribution Measurements on a Swept Wing at Transonic Speeds by the NACA Wing-Flow Method. NACA RM L7D22, 1947.

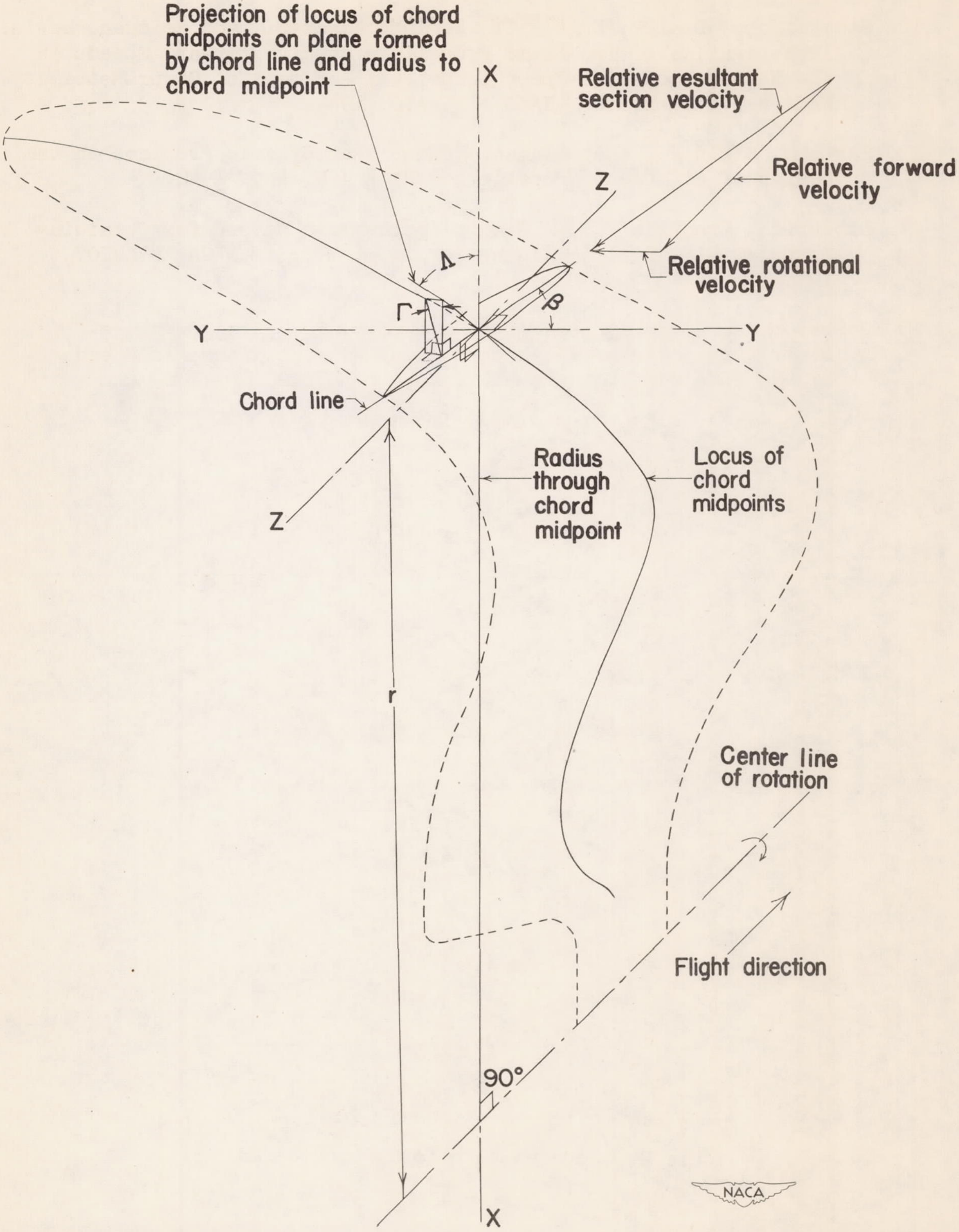


Figure 1.- Illustration of blade-section orientation and definitions of symbols. X-X, Y-Y, and Z-Z are orthogonal axes.

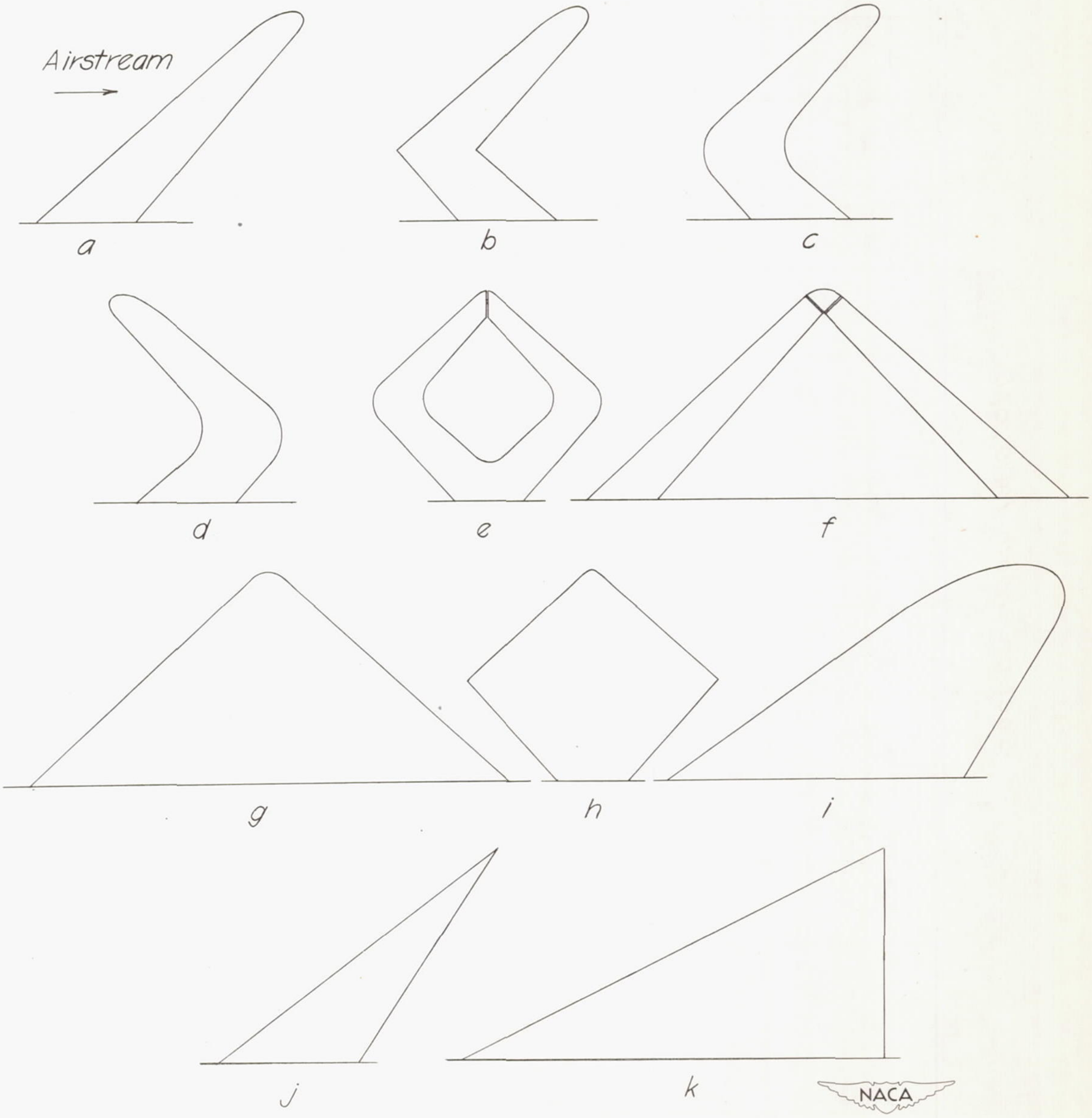


Figure 2.- General plan forms considered.

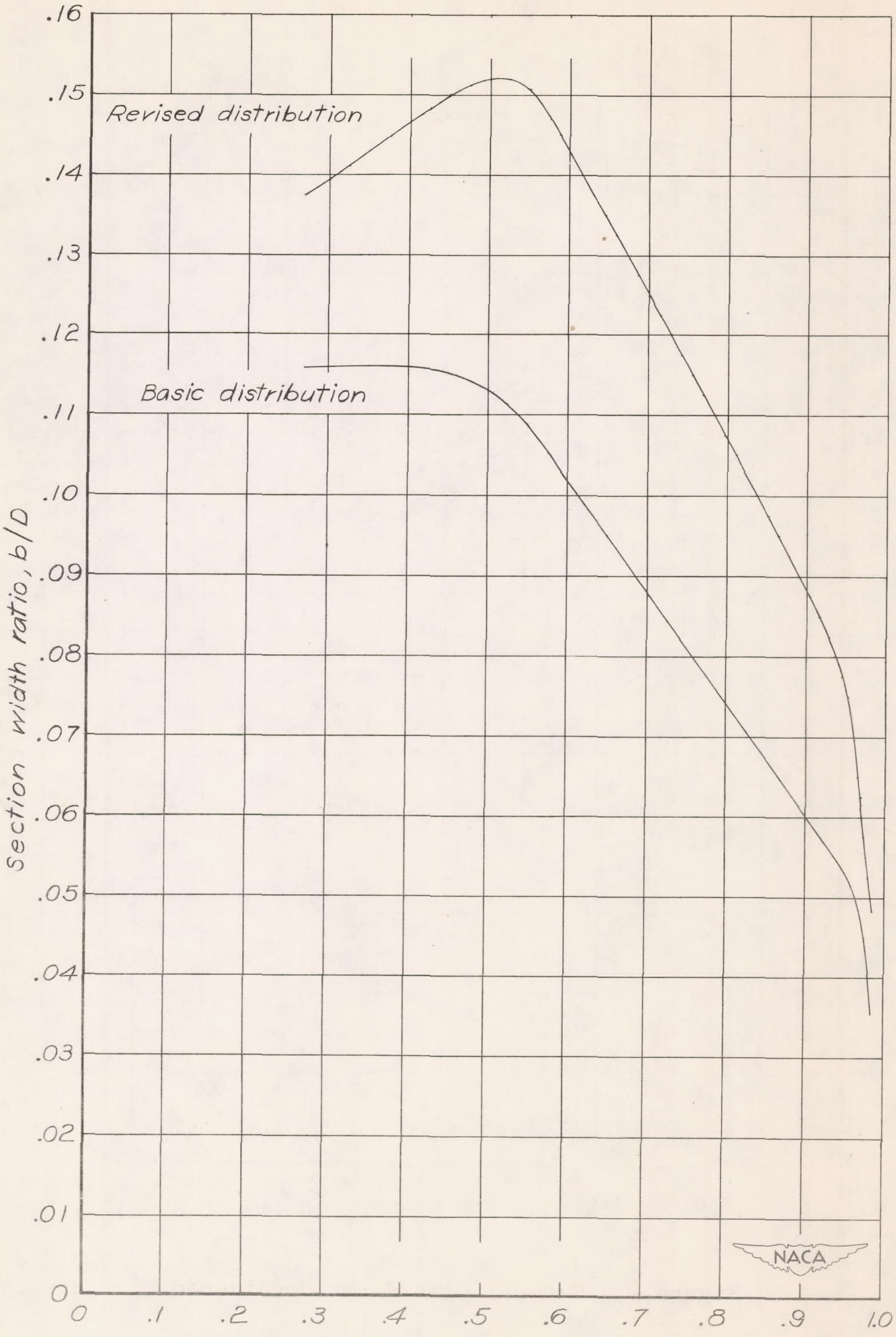


Figure 3.- Radial distribution of section width.

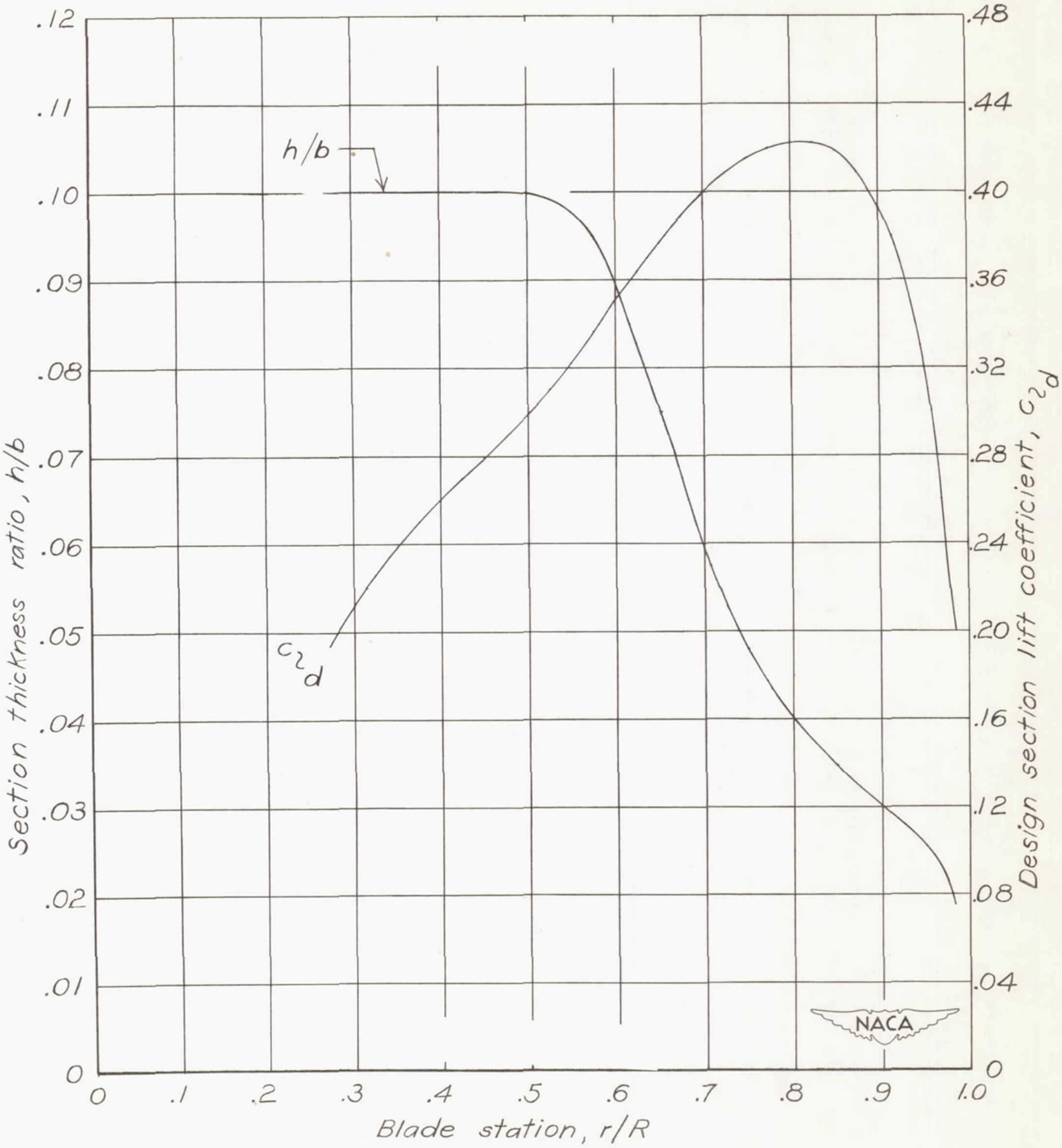


Figure 4.- Radial distribution of section camber and thickness.

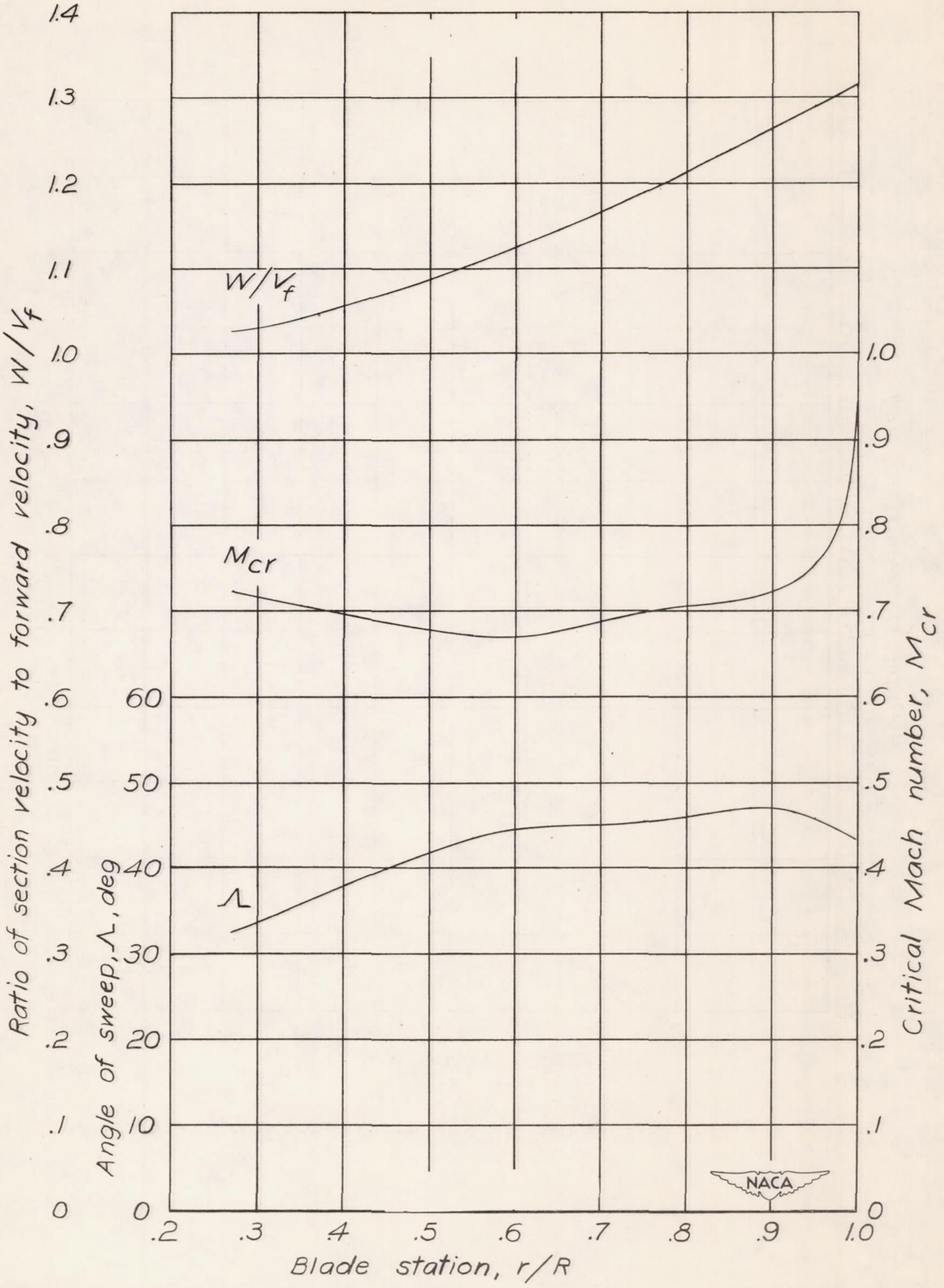


Figure 5.- Radial distribution of sweep design parameters.

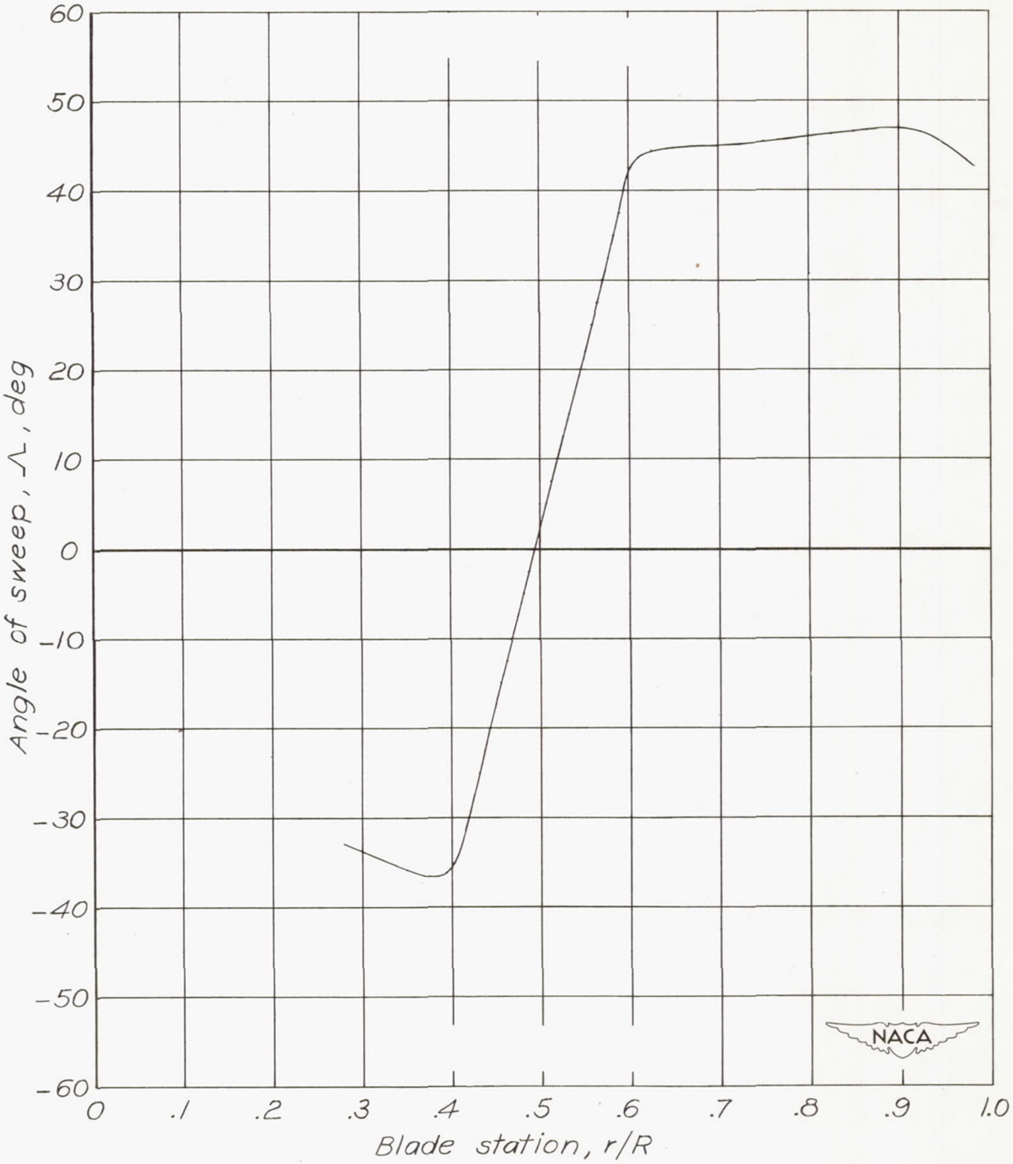


Figure 6.- Actual radial distribution of sweep.

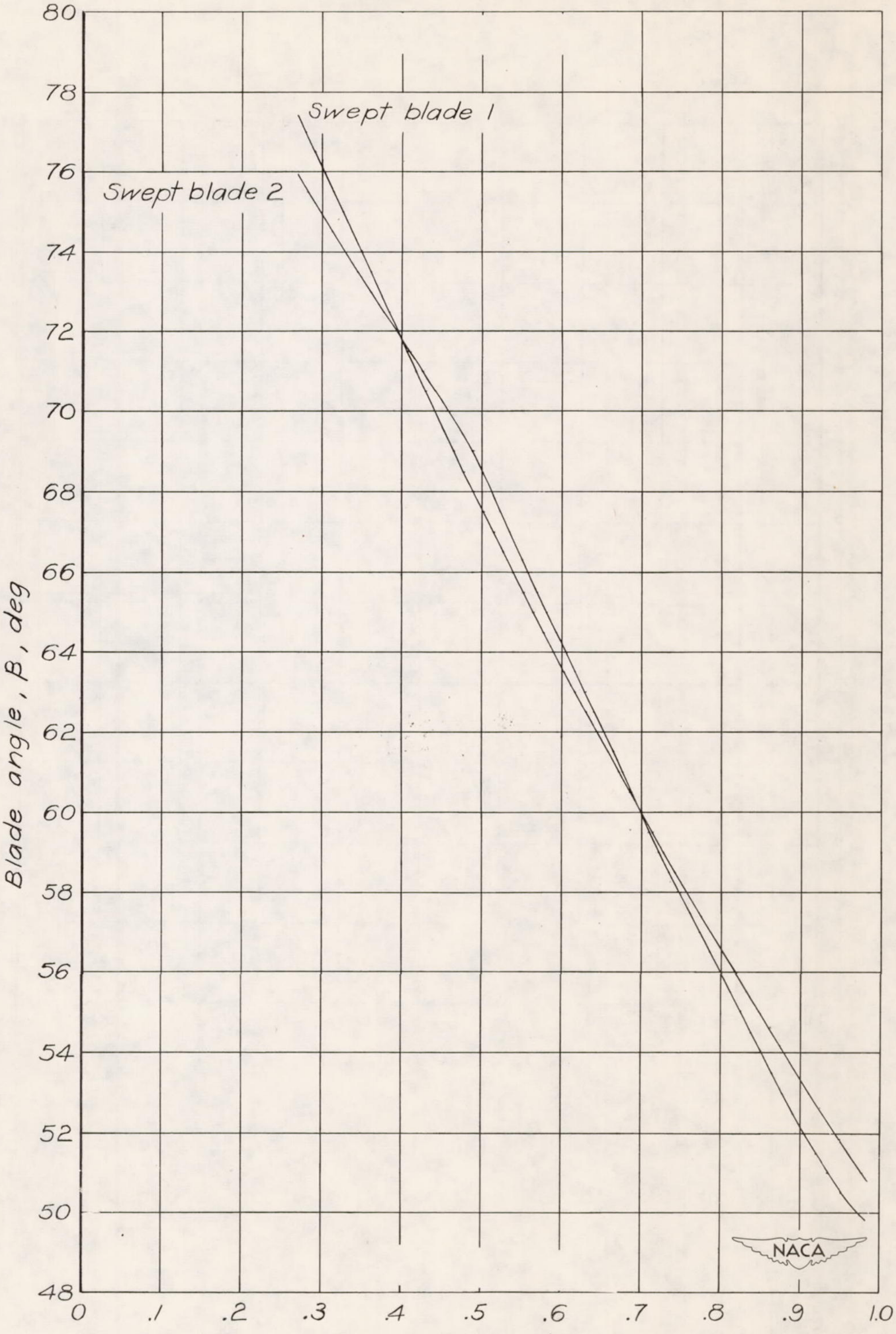


Figure 7.- Radial distribution of blade angle.

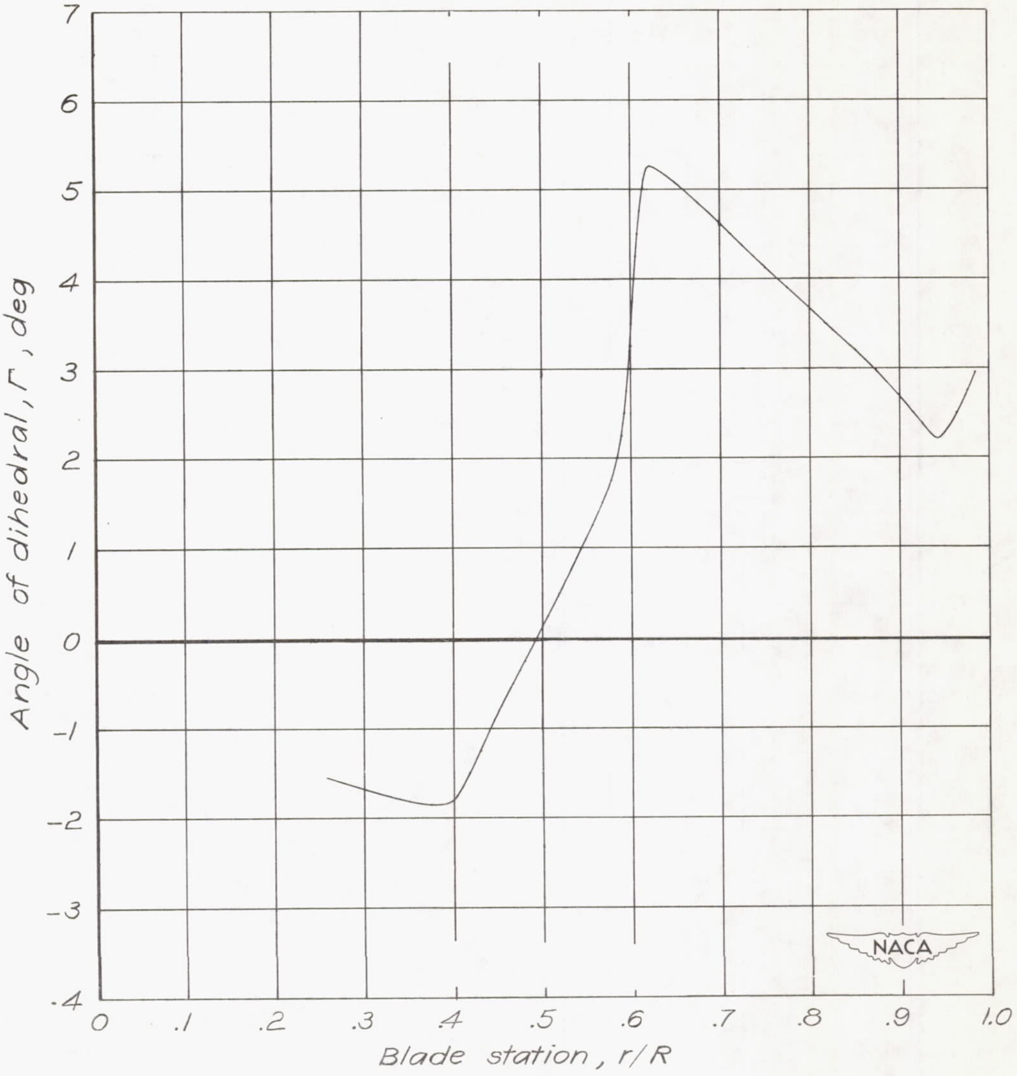
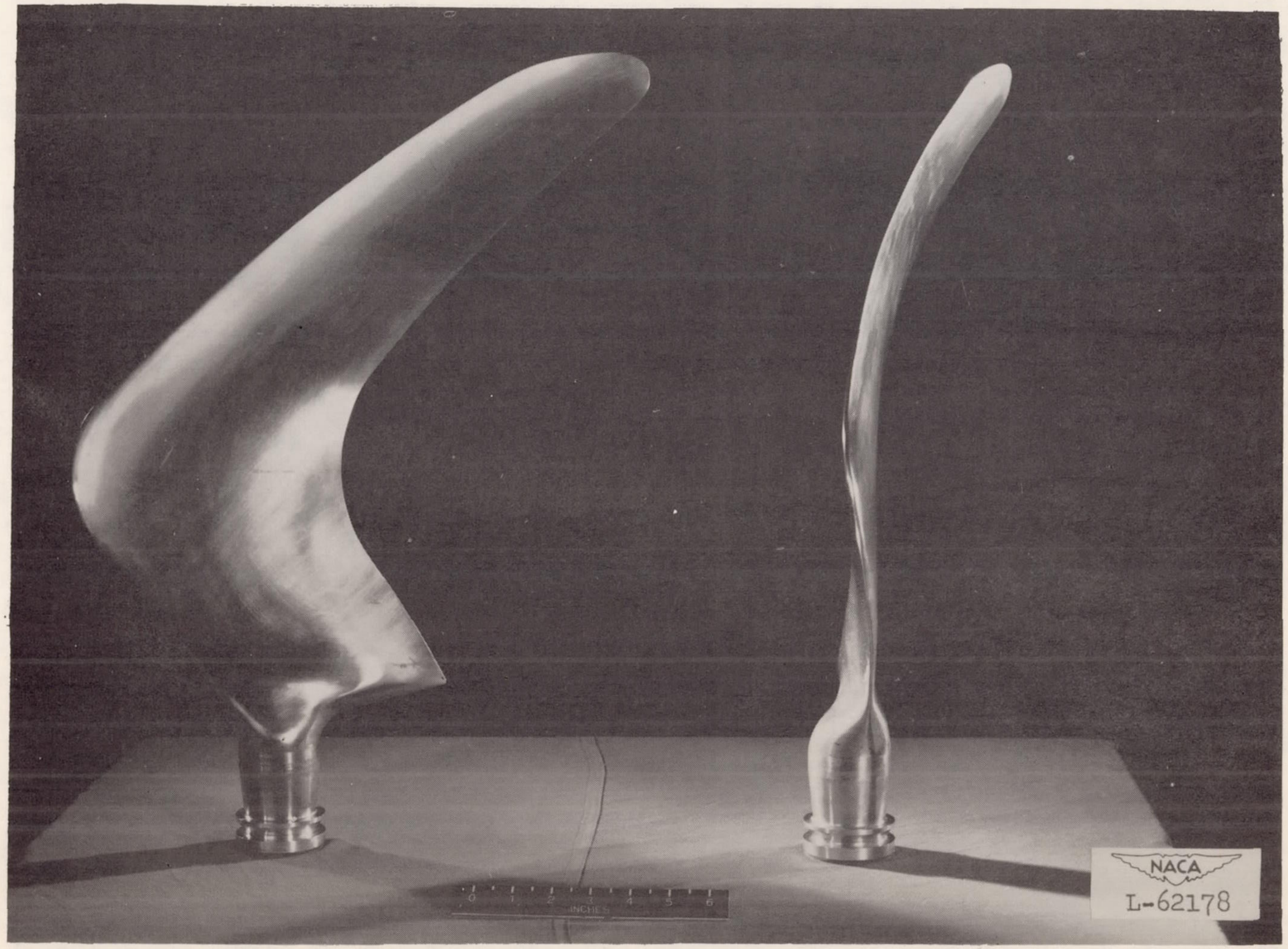
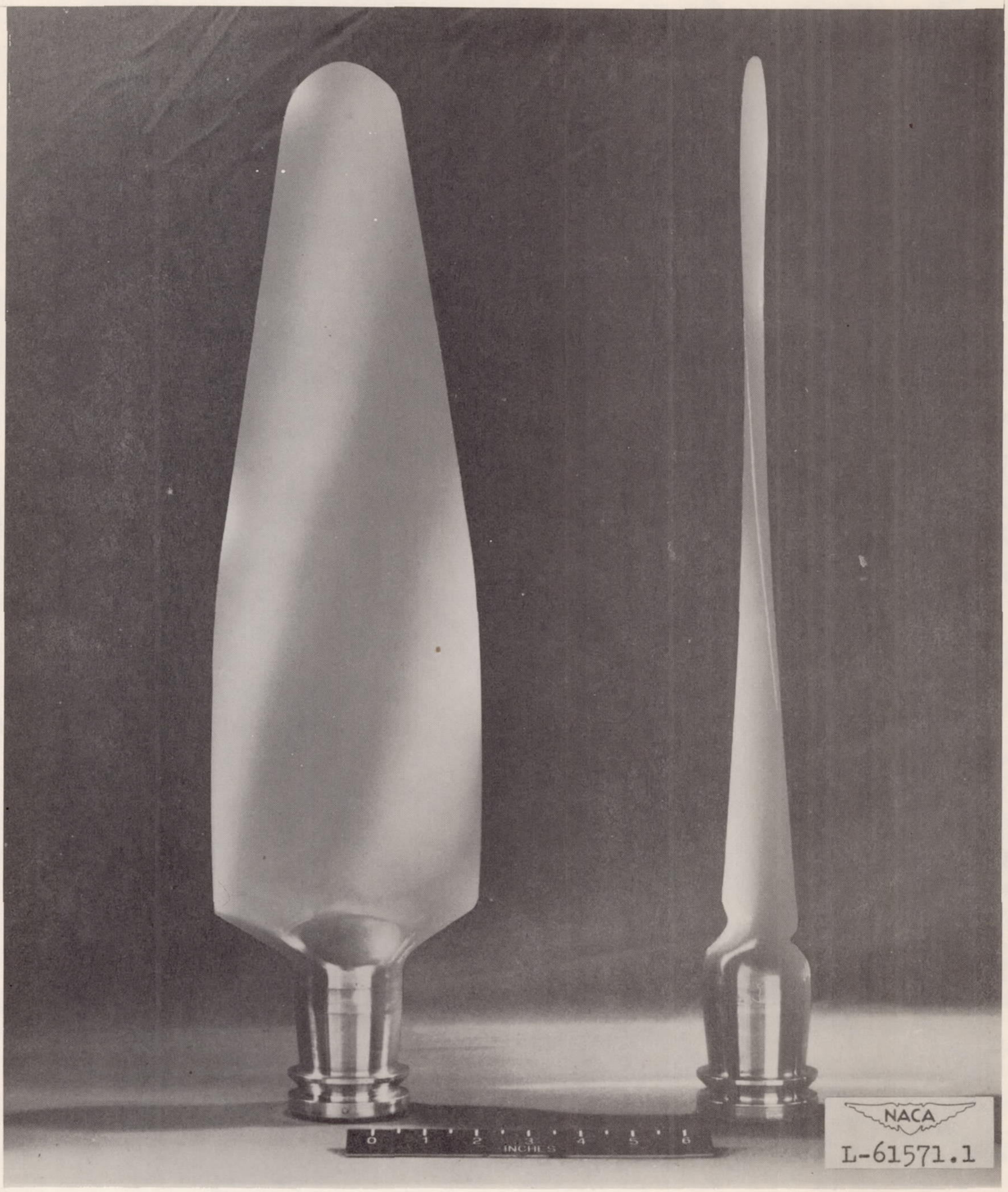


Figure 8.- Radial distribution of dihedral.



(a) Plan and front view of highly swept propeller blade.

Figure 9.- Model propeller blades.



(b) Plan and front view of comparable unswept propeller blade.

Figure 9.- Concluded.