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A COMPUTER PROGRAM FOR COMPOSING COMPRESSOR BLADING FROM SIMULATED CIRCULAR-ARC ELEMENTS ON CONICAL SURFACES

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16. Abstract

A blade-element-layout method is developed and combined with a stacking procedure in a computer program to compose a complete compressor blade. The layout method simulates the circular-arc-type blade element on a cone with the preservation of the constant rate of angle change. The computer program is capable of handling a multiple-circular-arc blade element. It calculates blade cross-section coordinates and geometric properties for mechanical design and stress analysis.

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SUMMARY

In axial flow compressors, the design blade elements lie on conical surfaces which approximate the actual stream flow surfaces. A blade-element-layout method is developed which preserves the constant-angle change characteristic of the circular-arc profile. More specifically, the mean camber line and the suction and pressure surface lines of a blade element are lines with a constant rate of angle change with path distance on a specified conical surface. The layout method developed in this report and incorporated in a computer program has the capability of handling a multiple-circular-arc blade element. A complete blade is composed by stacking design blade elements on a line which may be tilted in the tangential and axial directions to minimize blade stresses.

Blade surface coordinates for plane sections through the blade are computed for use in the mechanical design and fabrication of the blade. The area, center of area, and moments of inertia for each blade section are computed for use in stress analysis of the blade.

INTRODUCTION

In present-day aircraft compressors, the annulus area converges sufficiently through a blade row that the meridional (radial-axial plane) streamlines near the hub and/or tip have significant slopes. Compressor blading is usually constructed from blade elements which are designed to turn the flow on the meridional streamlines. Each individual blade element is generally assumed to lie on a conical surface representation of the axisymmetric streamsurface through a blade row (see fig. 1). However, the layout of a blade element on a cone cannot retain all the properties of a conventional blade shape (e.g., double circular arc). The blade-element-layout problem is to preserve the de-

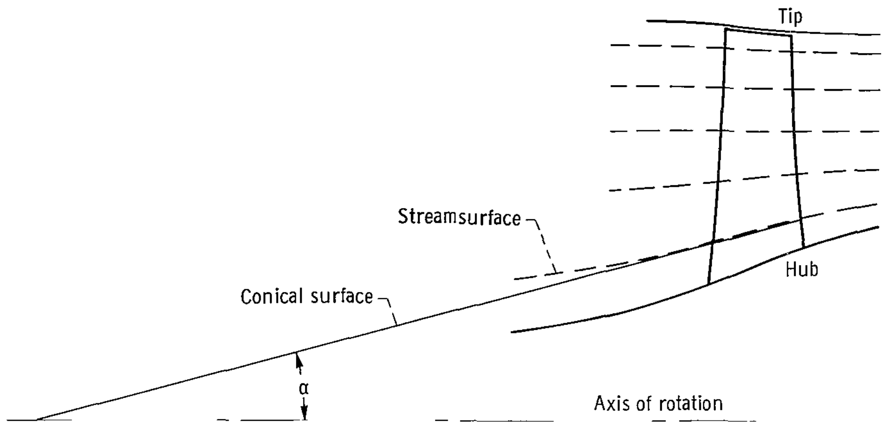


Figure 1. - Axisymmetric streamsurface approximated by conical surface.

sirable properties of a conventional blade shape. There is no standard method of simulating conventional blade shapes on a cone. Commonly used methods are (1) layout of a reference blade element directly on the conical surface and (2) projection of a reference blade element laid out on a plane or a cylindrical surface to the conical surface. With low streamline slopes, each of these methods gives essentially the same shape on a cone. However, with large streamline slopes, these methods can give significantly different blade shapes on a cone.

Blade surface velocities and pressures are influenced by several interacting forces, but probably the most direct factor controlling local flow on a blade element is the rate of surface-angle change (surface curvature) along the streamline. Then, perhaps, the most fundamental method of simulating a desirable blade element is to retain the rate of surface-angle change. This approach is taken in this report to develop a computerized method for simulating circular-arc-type blade elements.

The design of high-speed compressors has made wide use of blade rows composed of double-circular-arc (DCA) blade elements. A DCA blade element consists of one circular arc forming the suction surface and another forming the pressure surface. This type of blade element has performed very successfully, and extensive data from both two- and three-dimensional cascades has been incorporated into blade design procedures (ref. 1).

More recently, the need to control shock loss and throat area in the blade passages of transonic compressors has led to the use of multiple-circular-arc (MCA) blade elements. An MCA blade element consists of two circular arcs forming the suction surface and two others forming the pressure surface. This type of blade permits additional control of the chordwise turning (loading) distribution and aids in controlling the shock loss in blade passages with supersonic flow (refs. 2 to 5).

The main part of this report is a detailed development of a layout method which simulates an MCA blade element on a conical surface. The developed blade-element-layout method preserves the constant rates of angle change of the centerline and the surfaces. Following the layout-method development, a step-by-step procedure for composing a complete blade by stacking the blade elements is given. The layout method and the stacking procedure are incorporated in a computer program to calculate the coordinates, areas, and other related properties of the blade cross-sections. This computer program eliminates the lengthy graphical procedures previously used in the mechanical design of a compressor blade.

COMPARISON OF SOME LAYOUT METHODS

In order to illustrate the potential effect of layout method on the rate of angle change of a blade-element centerline, a comparison of five layout methods is presented. The differences are best shown with an example of a DCA blade element at the hub of a compressor. The blade parameters selected and held constant on the hub cone are the following:

Streamline slope in the meridional (r-z) plane, α, deg	45
Ratio of blade-section outlet radius (trailing edge) to inlet radius (leading edge), r_o/r_i	1.4
Leading-edge blade angle, κ_i, deg	45
Trailing-edge blade angle, κ_o, deg	0

These parameters and other nomenclature for the layout on a cone are shown in figure 2.

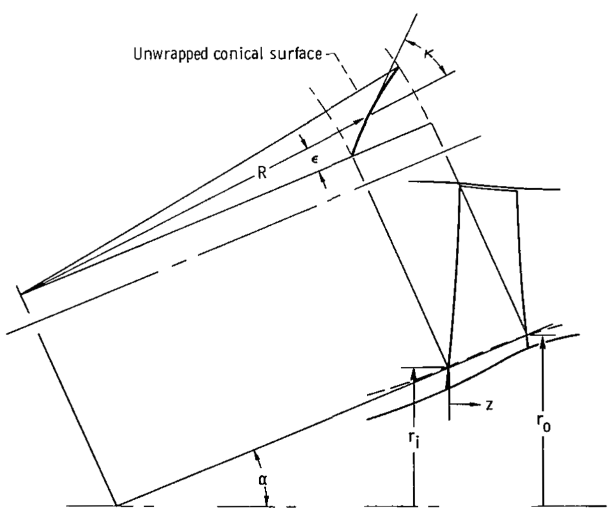


Figure 2. - Conical coordinate system for blade-element layout.

Blade elements which have circular-arc centerlines on a plane were laid on the cone by using the following layout methods: (1) a constant rate of change of local blade angle on the cone with distance (constant $d\kappa/ds$), (2) a circular-arc element laid on a cone, (3) a circular-arc element laid on a plane perpendicular to the stacking axis and projected to the cone by lines parallel to the radial stacking axis, (4) a circular-arc element laid on the cylinder of blade-element outlet radius and projected to the cone by lines parallel to the radial stacking axis, and (5) a circular-arc element laid on the cylinder of blade-element outlet radius and projected to the cone by radial lines from the axis of rotation.

The rates of change of local centerline blade angle with distance along the blade-element centerline on the cone $d\kappa/ds$ were computed for each of the layout methods. The results are compared in figure 3. Each curve has the same κ change from inlet to

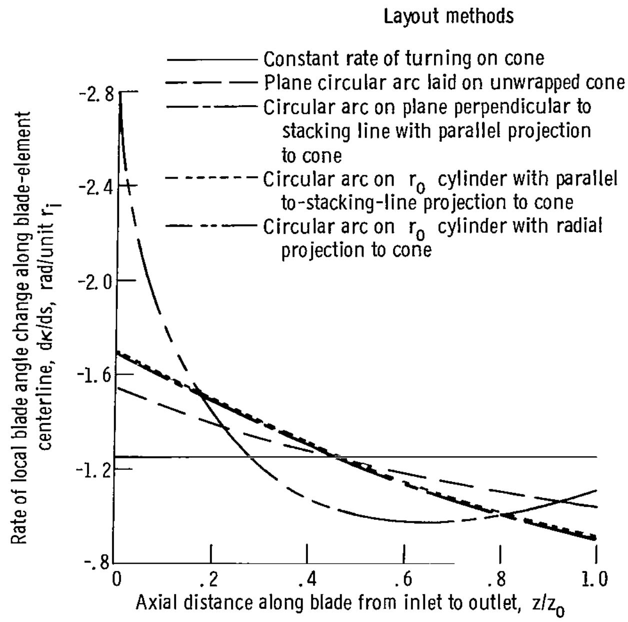


Figure 3. - Comparison of circular-arc-layout methods.

outlet; but the s distance varied slightly to match the specified radius change and cone angle conditions. The values of $d\kappa/ds$ are negative since κ decreases with s.

The line of constant $d\kappa/ds$ in figure 3 is from the first layout method. With all of the other layout methods, κ changes the most rapidly at the leading edge of the blade. The percentage increases of $d\kappa/ds$ for the other layout methods at the blade leading edge, as compared with the constant $d\kappa/ds$ method (method 1) are 23 percent for the geometric layout (method 2), 35 percent for the parallel projection methods (methods 3 and 4), and 127 percent for the radial projection method (method 5). Figure 3 shows that the blade-element-layout method can have a significant effect on the $d\kappa/ds$ properties of a blade airfoil. If an important blade shape property, such as $d\kappa/ds$, is changed significantly by the layout method, similar changes in blade-element performance may also be expected.

DEVELOPMENT OF EQUATIONS FOR BLADE-ELEMENT LAYOUT

The layout of blade elements is one of the latter steps of a compressor design. In the steps preceding the layout, the selections of values for the blade-element properties are made. For the purpose of this report, the following values are presumed to have been established:

(1) Radial distance from the axis of rotation to the leading-edge center, r_{ic}
(2) Radial distance from the axis of rotation to the trailing-edge center, r_{oc}
(3) Thickness at the leading edge, t_i
(4) Thickness at the maximum thickness point, t_m
(5) Thickness at the trailing edge, t_o
(6) Angle of the centerline at the leading edge, κ_{ic}
(7) Angle of the centerline at the transition point, κ_{tc}
(8) Angle of the centerline at the trailing edge, κ_{oc}
(9) Axial distance from the leading-edge center to the maximum thickness point on the centerline, $z_{mc} - z_{ic}$
(10) Axial distance from the leading-edge center to the transition point on the centerline, $z_{tc} - z_{ic}$
(11) Axial distance from the leading-edge center to the trailing-edge center, $z_{oc} - z_{ic}$

These parameters and some of the nomenclature used to describe the blade elements are shown in figures 4 and 5.

In the following development the constant $d\kappa/ds$ property of the MCA blade element is preserved in the layout onto a conical surface. The centerline, pressure surface, and suction surface are each formed by two segments, an inlet segment and an outlet segment. Each segment has its own constant $d\kappa/ds$ value which, generally, is different from that of any other segment. The development and the forms of the equations used in a computerized MCA blade-element-layout method are given in the following sections.

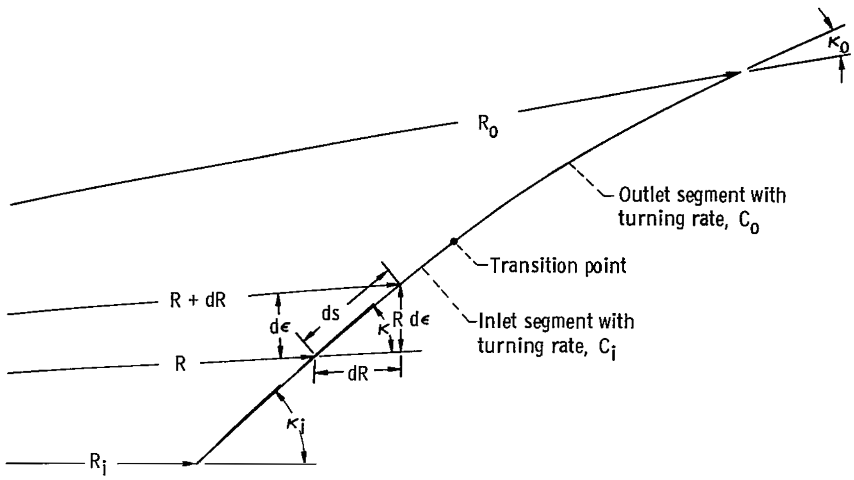


Figure 4. - Blade-element centerline and surface nomenclature.

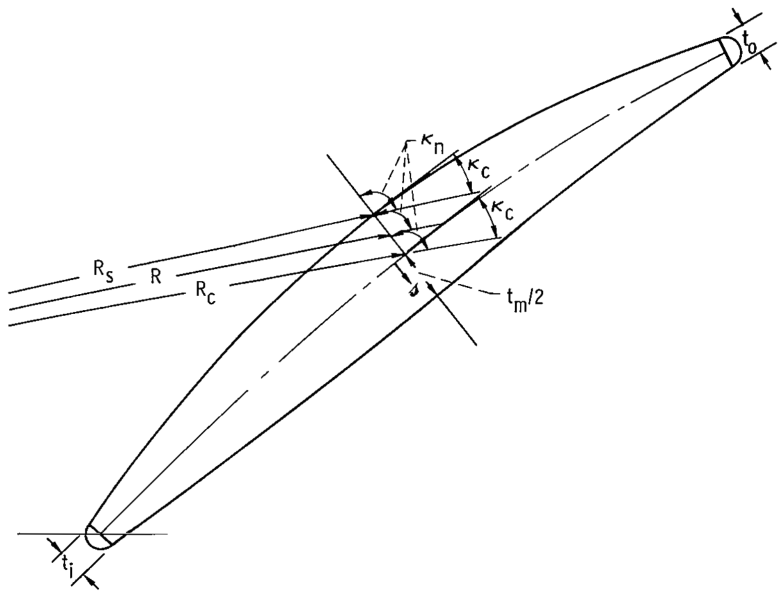


Figure 5. - Definition of blade thickness path.

Coordinate System for Blade Element

The most convenient coordinate system for describing a blade element on a cone is the R-ϵ system shown in figure 2. Since a cone is a single curved surface which can be unwrapped on a plane, the following development can be considered to be carried out on a plane with the R-ϵ coordinate system of a cone. In the R-ϵ system, R is the length of a ray from the cone vertex to an arbitrary point, and ϵ is the angle from a reference ray to a ray passing through the arbitrary point.

Mathematical Description of Constant-Turning-Rate Segment

The blade angle κ is the angle between the ray R and a tangent to the blade centerline or surface path s. For a fixed turning rate, κ decreases at a constant rate C as s is increased; that is,

$$\frac{d\kappa}{ds} = -C$$

or

$$ds = -\frac{d\kappa}{C} \tag{1}$$

From figure 4 note that

$$dR = \cos \kappa \, ds \tag{2}$$

$$R d\epsilon = \sin \kappa \, ds \tag{3}$$

Substituting ds from equation (1) into equations (2) and (3) gives

$$dR = -\frac{\cos \kappa \, d\kappa}{C} \tag{4}$$

$$d\epsilon = -\frac{\sin \kappa}{RC} d\kappa \tag{5}$$

Equation (4) integrated is

$$R - R_1 = \frac{1}{C}(\sin \kappa_1 - \sin \kappa) \tag{6}$$

where the subscript 1 refers to a point where R and κ are known. (All symbols are defined in appendix A.) By regrouping the terms in equation (6), a particular constant ζ is formed.

$$\zeta = RC + \sin \kappa = R_1 C + \sin \kappa_1 \tag{7}$$

Solving equation (7) for R gives

$$R = \frac{\zeta - \sin \kappa}{C} \tag{8}$$

Equation (8) gives R as a function of κ on a segment with known constants, C and ζ.

The differential equation for ϵ is obtained by the substitution of equation (8) into equation (5).

$$d\epsilon = \frac{\sin \kappa}{\sin \kappa - \zeta} d\kappa \tag{9}$$

However, if $C = 0$, κ is a constant, and the following differential equation for ϵ applies:

$$d\epsilon = \tan \kappa \frac{dR}{R} \tag{10}$$

In general, ϵ is given by

$$\epsilon = \epsilon_1 + f(\kappa, \kappa_1, \zeta, R, R_1) \tag{11}$$

where $f(\kappa, \kappa_1, \zeta, R, R_1)$ is the integral of equation (9) if $C \neq 0$, or equation (10) if $C = 0$. The integral of equation (9) has three solutions dependent on the value of ζ. Details of the solutions for $f(\kappa, \kappa_1, \zeta, R, R_1)$ are presented in appendix B.

Definition of Blade-Element Centerline

In this blade-element-layout procedure, it is first necessary to establish the blade-element centerline. Desired blade properties (e.g., $\kappa_i, \kappa_t, \kappa_o, C_i, C_o$) are generally related to the centerline, and the blade thickness is applied to the centerline.

In this development, the blade-element centerline is composed of two constant $d\kappa/ds$ segments, an inlet segment and an outlet segment. These segments are tangent at a point called the transition point (see fig. 4).

In order to determine the R-ϵ coordinates of the centerline segments, it is first necessary to calculate the cone half-angle α. From the input data,

$$\alpha = \tan^{-1}\left(\frac{r_{oc} - r_{ic}}{z_{oc} - z_{ic}}\right) \tag{12}$$

The R coordinate of the leading-edge center is given by

$$R_{ic} = \frac{r_{ic}}{\sin \alpha} \tag{13}$$

Note that $\alpha = 0$ cannot be used in equation (13). However, a separate set of equations for this special case is not warranted. A sufficiently equivalent blade element can be calculated by using a small cone half-angle ($\alpha = 0.1^{\circ}$).

The R coordinates of other points specified on the centerline are determined by equation (14)

$$R = R_{ic} + \frac{z - z_{ic}}{\cos \alpha} \tag{14}$$

After the R coordinates of the leading-edge point, the transition point, and the trailing-edge point on the centerline are determined, the turning constants for both centerline segments can be calculated. Since the blade angles at the endpoints of these segments are given in the input, the turning-rate constant C for a segment is obtained from a rearrangement of equation (6)

$$C = \frac{\sin \kappa_1 - \sin \kappa}{R - R_1} \tag{15}$$

It should be noted that the value of C for the centerline is calculated rather than specified. The reason for this is that small errors in C and in κ for small values of C will produce large errors in R_{tc} and R_{oc}. Thus, the relative axial locations of the segment endpoints are specified instead.

For convenience, the angular coordinates of a blade element are referenced from the leading-edge center (i.e., $\epsilon_{ic} = 0$). The angular coordinates of the other endpoints of the two segments are calculated by equation (11).

Determination of Blade-Element Surfaces

The blade-element surface curves are also composed of two constant $d\kappa/ds$ segments. The pressure surface and the suction surface each have an inlet segment and an outlet segment which are joined at a transition point. These surface curves must satisfy the tangency requirement at the transition point and the thickness specifications. The thickness is specified at three points: the leading edge, the trailing edge, and the maximum thickness point.

The constants for each surface segment are determined from two points on the segment and the slope at one of these points. The general equations needed and the methods used for calculating the coordinates of these points, the surface slopes at these points, and the resulting constants for each segment are given below. Specific applications of these equations are given in appendix B.

The initial points for establishing the surface curves are calculated by applying the thickness specifications at three points on the centerline: the leading edge, the maximum thickness point, and the trailing edge. On a plane surface, thickness is generally measured along a line perpendicular to the blade centerline. On the conical surface, the thickness path is described by a constant angle κ_n path which is normal to the centerline, where

$$\kappa_n = \kappa_c \pm \frac{\pi}{2} \tag{16}$$

(see fig. 5). The plus sign in equation (16) gives the path direction to the suction surface, and the minus sign gives the path direction to the pressure surface.

The differential equations for this slightly curved thickness path are

$$dR = \cos \kappa_n d\mathfrak{s} \tag{17}$$

and

$$R d\epsilon = \sin \kappa_n d\mathfrak{s} \tag{18}$$

where $\mathfrak{s}$ is the distance from the centerline, as shown in figure 5. Equation (17) integrates to

$$R - R_c = \mathfrak{s} \cos \kappa_n \tag{19}$$

Elimination of $d\delta$ by combining equations (17) and (18) gives

$$d\epsilon = \tan \kappa_n \frac{dR}{R} \tag{20}$$

Equation (20) integrates to

$$\epsilon - \epsilon_c = \tan \kappa_n \ln\left(\frac{R}{R_c}\right) \tag{21}$$

For the special case of $\kappa_c = 0$, equation (21) becomes indeterminate because $\kappa_n = \pm \pi/2$, and equation (19) yields $R = R_c$. Since R is constant for this case, equation (18) can be directly integrated to give

$$\epsilon - \epsilon_c = \pm \frac{\delta}{R_c} \tag{22}$$

where the plus sign is for $\kappa_n = \pi/2$ and the minus sign is for $\kappa_n = -\pi/2$.

The coordinates of the leading edge, the maximum thickness point, and the trailing edge on the suction surface and the pressure surface are determined by equations (19) and either (21) or (22). The necessary R_c values for these equations are determined from the input by equations (13) and (14). The κ_c values for the leading and trailing edges are given in the input. The κ_c value for the maximum thickness point is determined from the rearrangement of equation (7), which gives

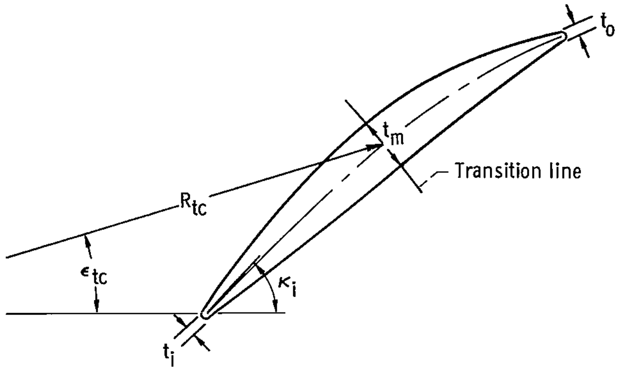
$$\kappa = \sin^{-1}(\zeta - RC) \tag{23}$$

where ζ and C are constants of the segment containing the point.

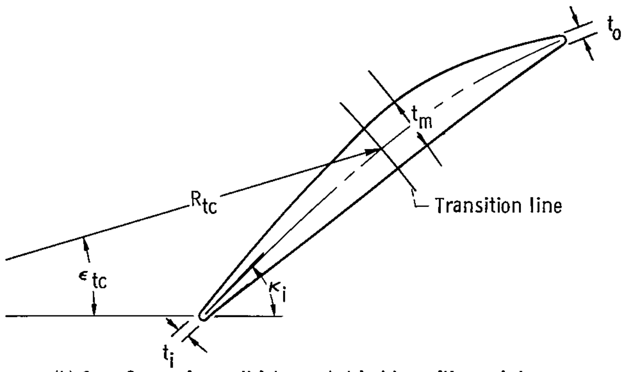
The κ angle at the maximum thickness point on either the suction or pressure surface is equal to the κ angle at the maximum thickness point on the centerline, or

$$\kappa_{mc} = \kappa_{ms} = \kappa_{mp} = \kappa_m \tag{24}$$

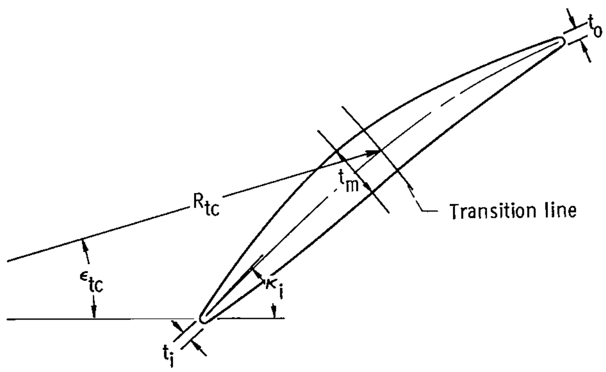
This angle κ_m, along with the coordinates of the maximum thickness point and either the leading-edge point or the trailing-edge point, provides sufficient conditions for establishing the surface curve for the segment containing the maximum thickness point.



(a) Case 1: coincident maximum thickness and transition points.



(b) Case 2: maximum thickness behind transition point.



(c) Case 3: Maximum thickness ahead of transition point.

Figure 6. - Locations of maximum thickness with respect to transition point.

To permit design flexibility, the maximum thickness point can be located on either segment, inlet or outlet, or at the transition point. These three cases, as shown in figure 6, are

(1) Maximum thickness at the transition point

(2) Maximum thickness on the outlet segment behind the transition point

(3) Maximum thickness on the inlet segment ahead of the transition point

In establishing the surface equations, the calculations begin on the segment containing the maximum thickness. On this segment, two points and a slope are known for both the pressure surface and the suction surface. Use of these known surface conditions in equations (7), (11), and (15) gives three equations with three unknowns: ζ, C, and κ. Elimination of ζ and C leaves an equation with one unknown, κ. However, the complexity of this equation makes it difficult to solve explicitly. So an iterative method is used to solve for ζ, C, and κ. This iterative method consists of estimating κ and checking the resulting ϵ-coordinate with the known ϵ-coordinate.

The next step in establishing the surface equations is the calculation of the transition point on both the pressure surface and the suction surface. This calculation involves finding the intersection of the surface curves with the thickness path of the transition point. Use of the known conditions in equations (11), (21) or (22), and (23) gives three equations with three unknowns: κ, R, and ϵ. Again, the complexity of equation (11) makes it difficult to solve for the unknowns explicitly. An iterative method is used to solve for the unknowns. This iterative method consists of estimating R, then comparing a calculated R_{tc} with the known R_{tc}. The calculated R_{tc} is determined by a rearrangement of equation (21)

$$R_{tc}(R) = \frac{R}{\exp\left[\tan \kappa_{tc}(\epsilon_{tc} - \epsilon)\right]} \tag{25}$$

This step does not apply to case 1, where the maximum thickness and the transition points coincide.

The final step in establishing the surface equations is to obtain the unknowns ζ, C, and κ for the surfaces of the remaining segment. Two points, the transition point and either the trailing-edge or the leading-edge point, and the angle at the transition point on the pressure surface and the suction surface of the remaining segment are now known. The iterative method used in the first step is used in this step to calculate the final unknowns.

DESCRIPTION OF COMPLETE BLADE

The complete blade is described from a selected number of blade cross-sections. These cross-sections, hereinafter called blade sections, lie on planes perpendicular to a radial line. The blade-section surface coordinates are obtained by stacking the blade elements (which lie on conical streamsurfaces) in a suitable manner and fairing between them. A primary objective in the stacking process is to minimize blade stresses. This is accomplished by allowing the straight stacking line to be leaned (from a true radial line) at prescribed angles in both the tangential and axial directions.

The blade-element stacking procedure requires an iterative positioning of the blade elements until the centers of area of the blade sections are coincident with the stacking line within a given tolerance. The specific steps used in the stacking procedure are the following:

(1) Initial positioning of blade elements along the stacking line. The intersections of the stacking line with the conical streamsurfaces of the blade elements are called the blade-element stacking points. For the first iteration the stacking points are located at the centers of area of the blade elements.

(2) Calculation of stacking points relative to common reference. The coordinates of the blade-element stacking points are translated into cylindrical coordinates and referenced from the center of the leading edge of the hub blade element.

(3) Calculation of blade-element coordinates. Blade-element surface coordinates in a Cartesian coordinate system (x-y-z) are calculated at specific z values for fairing convenience.

(4) Calculation of blade-section coordinates. Blade sections lying on planes through each blade-element stacking point are defined. The surface coordinates of a blade section are obtained from the intersections of the plane of the blade section and the z-fairings of the blade-element surface coordinates.

(5) Calculation of centers of area of blade sections. The center of area for each blade section is found by integrating over the area defined by the blade-section coordinates.

(6) Calculation of new blade-element stacking points. A new stacking point for each blade element is obtained from the intersection of a line faired through the centers of area of the blade sections and the conical streamsurface of each blade element. If the new stacking points are sufficiently close to the old stacking points, the stacking procedure is considered to be converged or finished. If not, the procedure is repeated starting at step 2 using the new stacking points.

The blade-element stacking procedure, including these steps, is described in detail following a description of the coordinate systems used.

Coordinate Systems for Complete Blade

In addition to the R-ϵ coordinate system for the blade elements, two other coordinate systems are used in the stacking procedure for describing the complete blade. A cylindrical coordinate system (r-θ-z) is used for describing the stacking line and alining the stacking points of the blade elements along the stacking line (see fig. 7). A Cartesian coordinate system (x-y-z) is used for obtaining plane sections of the complete blade (see fig. 8). The z-axis is common to both systems and lies along the machine axis of rotation. The direction of the z-axis is defined as positive from blade inlet toward blade outlet. The origin, z = 0, is defined by the axial location of the center of the hub-blade-element, leading-edge radius.

The orientation of the cylindrical coordinate system is shown in figure 7. The angular coordinate θ is measured from the r-z plane which contains the hub-blade-element, leading-edge center. The positive θ-direction is from the blade pressure (lower) surface toward the blade suction (upper) surface.

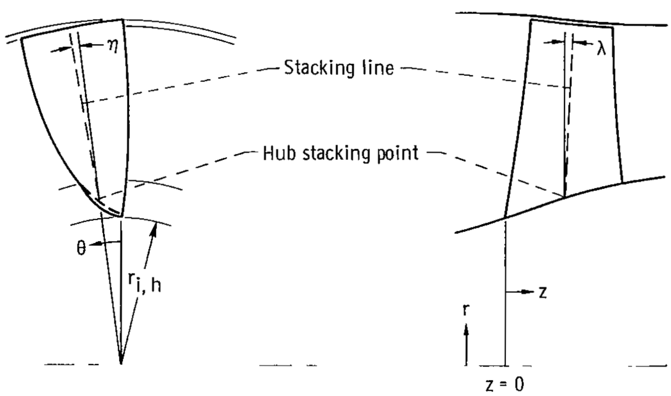


Figure 7. - Cylindrical coordinate system.

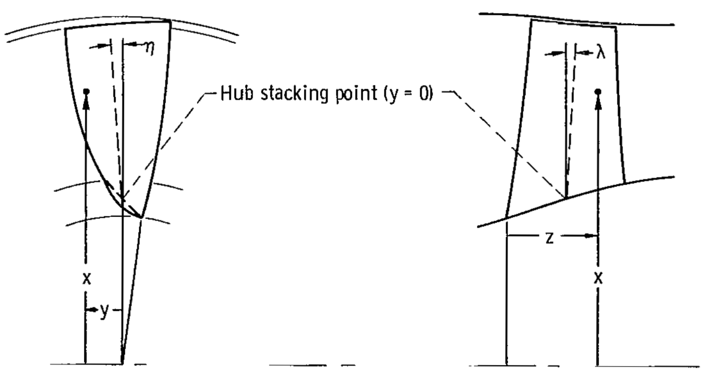


Figure 8. - Cartesian coordinate system for blade.

The orientation of the Cartesian coordinate system is shown in figure 8. The x-axis is parallel to the radial line which passes through the hub-blade-element stacking point. The positive x-direction is from hub to tip. The positive y-direction is from the blade pressure surface toward the blade suction surface.

Stacking Procedure

The objective of the stacking procedure is to position each blade element such that the centers of area of all blade sections lie on the stacking line. The steps in the iterative procedure are as follows:

Initial positioning of blade elements along stacking line. - The first step in the stacking procedure is the initial positioning of the blade element along the stacking line. A good first approximation to the desired stacking of the blade elements is obtained by alining the centers of area of the blade elements along the stacking line. A sufficiently accurate calculation for these centers is given by the following equations:

$$R_{sp} = \frac{\int R \, dA}{\int dA} \tag{26}$$

$$\epsilon_{sp} = \frac{\int \epsilon \, dA}{\int dA} \tag{27}$$

where

$$\int dA = \int_{R_{ic}}^{R_{oc}} \int_{\epsilon_p(R)}^{\epsilon_s(R)} R d\epsilon \, dR = \int_{R_{ic}}^{R_{oc}} R\left[\epsilon_s(R) - \epsilon_p(R)\right] dR \tag{28}$$

$$\int R \, dA = \int_{R_{ic}}^{R_{oc}} \int_{\epsilon_p(R)}^{\epsilon_s(R)} R^2 d\epsilon \, dR = \int_{R_{ic}}^{R_{oc}} R^2\left[\epsilon_s(R) - \epsilon_p(R)\right] dR \tag{29}$$

$$\int \epsilon \, dA = \int_{R_{ic}}^{R_{oc}} \int_{\epsilon_p(R)}^{\epsilon_s(R)} \epsilon R \, d\epsilon \, dR = \frac{1}{2} \int_{R_{ic}}^{R_{oc}} R\left[\epsilon_s^2(R) - \epsilon_p^2(R)\right] dR \tag{30}$$

The integrals in equations (26) to (30) are evaluated by numerical integration techniques since the functions $\epsilon_s(R)$ and $\epsilon_p(R)$ are very difficult to integrate.

Calculation of stacking points relative to a common reference. - The second step in the stacking procedure is the calculation of the cylindrical coordinates of the blade-element stacking points relative to a common reference. For convenience, the reference for the θ-z coordinates is the center of the leading-edge radius of the hub blade element.

The simplest and perhaps most commonly used stacking line is a radial line. However, when blade stresses are high, the maximum blade stress can be lowered by leaning the stacking line slightly to introduce a centrifugal force bending moment to counterbalance the aerodynamic blading moment. In this report the stacking line is a straight line which can be leaned in both the θ-direction and the z-direction from a radial line at the hub-blade-element stacking point. The lean angle η is positive in the positive θ-direction, and the lean angle λ is positive in the positive z-direction (see fig. 7).

From geometric considerations, it can be shown that the blade-element stacking point location on the stacking line is given by

$$z_{sp} = z_{sp,h} + (r_{sp} - r_{sp,h})\tan \lambda \tag{31}$$

$$\theta_{sp} = \theta_{sp,h} + \delta \tag{32}$$

where

$$r_{sp} = R_{sp} \sin \alpha \tag{33}$$

$$\theta_{sp,h} = \frac{\epsilon_{sp,h}}{\sin \alpha_h} \tag{34}$$

$$\delta = \sin^{-1}\left\{\frac{r_{sp,h}}{r_{sp}}\left(\frac{\tan \eta}{1 + \tan^2 \eta}\right)\left[\sqrt{\left(\frac{r_{sp}}{r_{sp,h}}\right)^2 (1 + \tan^2 \eta) - \tan^2 \eta} - 1\right]\right\} \tag{35}$$

The h subscript refers to the hub-blade-element values. The lean angles, η and λ, are input information for the computer program and, therefore, are presumed to have been calculated or estimated.

Calculation of blade-element coordinates. - The third step in the stacking procedure is calculation of the x-y-z coordinates of the blade elements. The general conversion equations for calculating x-y-z coordinates from the R-ϵ coordinates are

$$x = R \sin \alpha \cos\left(\frac{\epsilon}{\sin \alpha} + \theta_{ic} - \theta_{sp,h}\right) \tag{36}$$

$$y = R \sin \alpha \sin\left(\frac{\epsilon}{\sin \alpha} + \theta_{ic} - \theta_{sp,h}\right) \tag{37}$$

$$z = z_{sp} - (R_{sp} - R)\cos \alpha \tag{38}$$

where the z value of the stacking point is z_{sp} and the cylindrical coordinate of the center of the leading-edge radius is

$$\theta_{ic} = \theta_{sp} - (\theta_{sp} - \theta_{ic}) = \theta_{sp,h} + \delta - \frac{\epsilon_{sp}}{\sin \alpha} \tag{39}$$

Since the R-ϵ corrdinates of the leading-edge, transition, maximum thickness, and trailing-edge points on the blade-element surfaces have been calculated previously, the x-y-z coordinates of these particular points can be calculated directly with equations (36) to (38).

The blade surface curve fits are most conveniently made at constant z values. However, before particular values of z are determined, the maximum z range for the complete blade is found. The minimum z is found by searching the leading-edge coordinates of both surfaces of all blade elements. The maximum z is found by the same type of search on the trailing-edge surface coordinates. Then, equally spaced z values are calculated to cover the complete z range of the blade.

Before the surface x and y coordinates can be found, it is necessary to calculate the surface R and ϵ values at the prescribed z values. For a given element the R coordinate is given by equation (14). Before the ϵ-coordinate can be found, the surface tangent angle κ is calculated by equation (23). The ϵ-coordinate then is given by equation (11) when the known values at the transition point are used for reference values. Finally, the x-y coordinates are calculated by the general equations (36) and (37), for each z value on each blade element to complete the information needed for the curve fits across the blade elements.

Calculation of blade-section coordinates. - The fourth step in the stacking procedure is interpolation of the blade-element surface coordinates to define blade sections. Each blade section has a constant x value, so the y-z surface coordinates define the blade-section profile. The x values used in the program are the x-coordinates of the previously calculated stacking points of the blade elements.

A second-order Lagrangian interpolation technique is used to calculate $y_{(p,s)}$ for a given x on each of the surface lines of equal z values. The blade-element coordinates, $\left[x_{1,(p,s)}, y_{1,(p,s)}, z_j\right]$, $\left[x_{2,(p,s)}, y_{2,(p,s)}, z_j\right]$, and $\left[x_{3,(p,s)}, y_{3,(p,s)}, z_j\right]$, are consecutive points along a z-value line. The x-dimension falls within this group of points. The equation for $y_{(p,s)}$ is

$$y_{(p,s)} = y_{1,(p,s)}W_1 + y_{2,(p,s)}W_2 + y_{3,(p,s)}W_3 \tag{40}$$

where

$$W_1 = \frac{\left[x - x_{2,(p,s)}\right]\left[x - x_{3,(p,s)}\right]}{\left[x_{1,(p,s)} - x_{2,(p,s)}\right]\left[x_{1,(p,s)} - x_{3,(p,s)}\right]} \tag{41}$$

$$W_2 = \frac{\left[x - x_{1,(p,s)}\right]\left[x - x_{3,(p,s)}\right]}{\left[x_{2,(p,s)} - x_{1,(p,s)}\right]\left[x_{2,(p,s)} - x_{3,(p,s)}\right]} \tag{42}$$

and

$$W_3 = \frac{\left[x - x_{1,(p,s)}\right]\left[x - x_{2,(p,s)}\right]}{\left[x_{3,(p,s)} - x_{1,(p,s)}\right]\left[x_{3,(p,s)} - x_{2,(p,s)}\right]} \tag{43}$$

The coordinates y_p and y_s are calculated for each z value.

Calculation of centers of area of blade sections. - The fifth step in the stacking procedure is the calculation of the center of area of each blade section. The coordinates of the center of area are determined by dividing the area moments of the blade section by the area of the blade section. Both the area moments and the area of the blade section are determined by numerical integration.

The equations for the area and the area moments of a blade section are as follows:

$$A = \int_{z_{min}}^{z_{max}} \int_{y_p}^{y_s} dy\, dz = \int_{z_{min}}^{z_{max}} \left[y_s(z) - y_p(z)\right] dz \tag{44}$$

$$y_{ca}A = \int_{z_{min}}^{z_{max}} \int_{y_p}^{y_s} y \, dy \, dz = \int_{z_{min}}^{z_{max}} \frac{1}{2} \left[y_s^2(z) - y_p^2(z)\right] dz \tag{45}$$

$$z_{ca}A = \int_{z_{min}}^{z_{max}} \int_{y_p}^{y_s} z \, dy \, dz = \int_{z_{min}}^{z_{max}} z\left[y_s(z) - y_p(z)\right] dz \tag{46}$$

Calculation of new blade-element stacking points. - The sixth step in the stacking procedure is the calculation of the new blade-element stacking points. A new stacking point for each blade element is calculated by curve-fitting the center-of-area coordinates of the blade sections and finding the intersections of the curve-fit with the conic stream-surface of each element. The first approximation for the new y_{sp} and z_{sp} coordinates of a new stacking point is made by interpolating the center-of-area coordinates at the old x_{sp}. Then, using the y_{sp} and z_{sp} approximations, an approximate x_{sp} is calculated from the following equations:

$$r_{sp} = r_{sp,old} + \frac{z_{sp} - z_{sp,old}}{\tan \alpha} \tag{47}$$

$$x_{sp} = \sqrt{r_{sp}^2 - y_{sp}^2} \tag{48}$$

The approximate x_{sp} is then used to interpolate the center-of-area coordinates for the new y_{sp} and z_{sp}. A new x_{sp} is calculated by using the new y_{sp} and z_{sp} in equations (47) and (48).

To determine whether repositioning of the blade elements is necessary, the absolute differences between the old and new y_{sp} and z_{sp} coordinates are summed in the manner of the following equation, and the sum is compared to the specified tolerance limit given in the input. The equation for summing the differences is

$$S = \sum_{i=1}^{n} \left(\left| y_{sp,new} - y_{sp,old} \right| + \left| z_{sp,\ new} - z_{sp,\ old} \right| \right) \tag{49}$$

where n is the number of blade elements. If S is within the specified tolerance limit, the stacking procedure is considered to be converged or finished.

If repositioning is necessary, the new stacking point coordinates, x_{sp}, y_{sp}, and z_{sp}, are used to calculate the cylindrical coordinates of the new blade-element stacking points:

$$\left(\theta_{sp} - \theta_{ic}\right)_{new} = \left(\theta_{sp} - \theta_{ic}\right)_{old} - \delta + \tan^{-1}\left(\frac{y_{sp}}{x_{sp}}\right) \tag{50}$$

$$R_{sp, new} = R_{ic} + \frac{z_{sp} - z_{ic}}{\cos \alpha} \tag{51}$$

$$r_{sp} = \sqrt{x_{sp}^2 + y_{sp}^2} \tag{52}$$

The cylindrical coordinates of the new stacking points are used in the second step of the stacking procedure to begin another iteration.

FINAL CALCULATIONS AND OUTPUTS

The final calculations and outputs of the computer program are primarily intended for use in the mechanical design and fabrication of a compressor blade. However, the calculated parameters and coordinates of the blade elements may be of interest in an analysis of the aerodynamic design. For this purpose, the parameters and coordinates of the blade elements are printed out.

The blade-element parameters printed out are

(1) Cone half-angle , α

(2) Blade angle at the maximum thickness, κ_m

(3) Centerline blade angles at the leading edge, the transition point, and the trailing edge, κ_{ic}, κ_{tc}, and κ_{oc}

(4) Pressure surface blade angles at the leading edge, the transition point, and the trailing edge, κ_{ip}, κ_{tp}, and κ_{op}

(5) Suction surface blade angles at the leading edge, the transition point, and the trailing edge, κ_{is}, κ_{ts}, and κ_{os}

(6) Inlet and outlet segment turning rates for the centerline, C_{ic} and C_{oc}

(7) Inlet and outlet segment turning rates for the pressure surface, C_{ip} and C_{op}

(8) Inlet and outlet segment turning rates for the suction surface, C_{is} and C_{os}

The blade-element coordinates printed out define the surface profile and locate particular points of the blade elements. The coordinates which define the surface profiles of the blade elements are given as x and y for the suction surface and the pressure surface at a z value for each element. These are the blade-element coordinates which are curve-fit to obtain the blade-section coordinates. The x-y-z coordinates of particular points are given at the leading-edge point, maximum thickness point, transition point, and trailing-edge point on the suction surface, pressure surface, and centerline for each element.

The blade-section coordinates are the primary output of the computer program. The locations, or x values, of the blade sections are determined in the stacking procedure or can be specified in the input. The blade sections are described in two separate sets of coordinates. One set is called the unrotated coordinates and uses the x-y-z coordinate system of the stacking procedure (see fig. 9). The other set is called the

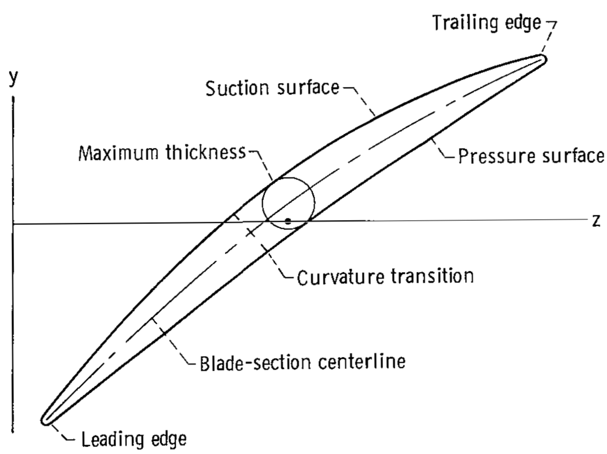


Figure 9. - Unrotated blade section.

rotated coordinates and uses a conventional coordinate system for airfoils. In the rotated coordinate system, the abscissa is tangent to the radii of the leading and trailing edges on the pressure side of the blade, and the ordinate is tangent to the leading-edge radius. The abscissa is labeled L for length, and the ordinate is labeled H for height (see fig. 10).

The unrotated coordinates for each blade section are calculated by interpolation of the blade-element coordinates in the same manner as in the stacking procedure. The y_s and y_p coordinates, which define the suction and pressure surface profiles of the blade section, are calculated for the complete range of z values. Since the z values generally extend beyond both edges of a blade section, a few nonexistent points are calculated. The leading-edge and trailing-edge coordinates on the suction and pressure surfaces of the blade sections are calculated by interpolation of the x-z coordinates of the blade elements to obtain the z-coordinates, and then interpolation of the y-z coordinates of the blade-section surfaces to obtain the y-coordinates. The coordinates of the maximum thickness points and the transition points on the suction and pressure surfaces are calculated in the same manner. The center-of-area coordinates are obtained by interpolation of the x-y and the x-z coordinates of the stacking line. The coordinates of the leading-edge, maximum thickness, transition, and trailing-edge points on the centerline are obtained by interpolation of the x-y and x-z coordinates of the points on the blade elements.

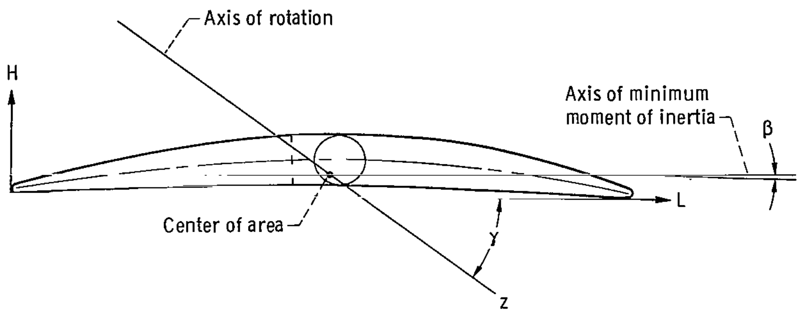


Figure 10. - Rotated blade section.

The rotated coordinates of a blade section are calculated by rotation and translation of the unrotated coordinates. The angle of rotation γ is the angle from the z-axis to the L-axis (see fig. 10) and is calculated by equation (53). The rotated coordinates of the leading-edge, maximum thickness, transition, and trailing-edge points on the centerline, the suction surface, and the pressure surface are directly calculated by equations (54) and (55):

$$\gamma = \sin^{-1}\left[\frac{(y_{oc} - y_{ic})\sqrt{(z_{oc} - z_{ic})^2 + (y_{oc} - y_{ic})^2 - \left(\frac{t_o - t_i}{2}\right)^2} - (z_{oc} - z_{ic})\frac{t_o - t_i}{2}}{(z_{oc} - z_{ic})^2 + (y_{oc} - y_{ic})^2}\right] \tag{53}$$

$$H = (y - y_{ic})\cos\gamma - (z - z_{ic})\sin\gamma + \frac{t_i}{2} \tag{54}$$

$$L = (y - y_{ic})\sin\gamma + (z - z_{ic})\cos\gamma + \frac{t_i}{2} \tag{55}$$

The coordinates of the center of area and a reference point, the stacking point of the hub blade element, are also calculated by equations (54) and (55). These two points will coincide if the stacking line is not tilted.

The rotated coordinates of the suction and pressure surface profiles for a blade section are obtained at equal increments along the L-axis. These coordinates are calculated by interpolation of coordinates obtained by rotation and translation of the unrotated coordinates. These coordinates are calculated only for points actually on the blade-section surfaces.

Along with the blade-section rotated coordinates, several parameters which pertain to the stress analysis of the blade are calculated. These parameters include the following:

(1) Blade-section area, A

(2) Center-of-area coordinates, $\bar{L}$ and $\bar{H}$

(3) Moment of inertia about the L-axis, I_{LL}

(4) Moment of inertia about the H-axis, I_{HH}

(5) Product of inertia associated with the L-H axes, P_{HL}

(6) Moment of inertia about L-axis translated to the center of area, I_{LLCA}

(7) Moment of inertia about H-axis translated to the center of area, I_{HHCA}

(8) Product of inertia associated with the L-H axes translated to the center of area, P_{HLCA}

(9) Angle to the axis of minimum moment of inertia from the L-axis, β

(10) Minimum moment of inertia about an axis through the center of area, I_{min}

(11) Maximum moment of inertia about an axis through the center of area, I_{max}

The equations for calculating these parameters are

$$A = \int_{L=0}^{L_{max}} (H_s - H_p)dL \tag{56}$$

$$\bar{L} = \frac{\int_{L=0}^{L_{max}} L(H_s - H_p)dL}{A} \tag{57}$$

$$\bar{H} = \frac{\int_{L=0}^{L_{max}} \frac{1}{2}\left(H_s^2 - H_p^2\right)dL}{A} \tag{58}$$

$$I_{LL} = \int_{L=0}^{L_{max}} \frac{1}{3}\left(H_s^3 - H_p^3\right)dL \tag{59}$$

$$I_{HH} = \int_{L=0}^{L_{max}} L^2(H_s - H_p)dL \tag{60}$$

$$P_{HL} = \int_{L=0}^{L_{max}} \frac{1}{2} L\left(H_s^2 - H_p^2\right)dL \tag{61}$$

$$I_{LLCA} = I_{LL} - \bar{H}^2 A \tag{62}$$

$$I_{HHCA} = I_{HH} - \bar{L}^2 A \tag{63}$$

$$P_{HLCA} = P_{HL} - \bar{H}\bar{L}A \tag{64}$$

$$\beta = \frac{1}{2} \tan^{-1}\left(\frac{2P_{HLCA}}{I_{HHCA} - I_{LLCA}}\right) \tag{65}$$

$$I_{min} = \frac{1}{2} (I_{LLCA} + I_{HHCA}) + \frac{1}{2} (I_{LLCA} - I_{HHCA})\cos(2\beta) - P_{HLCA} \sin(2\beta) \tag{66}$$

$$I_{max} = I_{LLCA} + I_{HHCA} - I_{min} \tag{67}$$

The integrals in the preceding equations are evaluated by a numerical integration technique.

The form of the output is shown in appendix C for a sample case.

CONCLUDING REMARKS

The equations and procedure for defining a complete compressor blade have been presented in the preceding sections. Specific details of a computer program which incorporates these equations and procedures are given in appendix C. The details include a FORTRAN IV source deck listing of the program, definitions of the program variables, descriptions of the subroutines, the input format, and an output listing for a sample blade.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 26, 1969,
720-03-00-64-22.

APPENDIX A

SYMBOLS

A	area of blade section
C	rate of turning, $-d\kappa/ds$
$f(\kappa, \kappa_1, \zeta, R, R_1)$	function describing relation of $\epsilon - \epsilon_1$ to κ and R for given values of R_1, κ_1, and ζ
H	height coordinate for blade section
I	blade section moment of inertia
L	length coordinate for blade section
R	distance from vertex to point on cone
r	radial coordinate in cylindrical system
s	path length along blade-element centerline or surface
$\mathscr{s}$	path length along blade thickness line
t	blade thickness
x	distance from axis of rotation along radial line passing through hub-element stacking point (fig. 8)
y	coordinate perpendicular to z in constant x-plane (fig. 8)
z	axial coordinate from hub-element, leading-edge center
α	cone half-angle (fig. 1)
β	angle of axis of minimum moment of inertia to L-axis (fig. 10)
γ	angle of axis of rotation to L-axis (fig. 10)
δ	circumferential angle coordinate of stacking line
ϵ	angular coordinate on conic surface as measured from ray passing through blade-element, leading-edge center (fig. 1)
ζ	convenient constant on a segment, eq. (7)
η	lean angle of stacking line in $r-\theta$ plane (fig. 8) (positive in positive θ-direction)
κ	local blade angle, the angle between the local R and the tangent to the local blade-element centerline or surface path (fig. 1)

λ — lean angle of stacking line in r-z plane (fig. 8) (positive in positive z-direction)

θ — circumferential angle coordinate in cylindrical coordinate system (positive θ-direction is from pressure surface to suction surface)

Subscripts:

c — blade centerline

ca — center of area

h — hub element

i — inlet segment or leading edge

j — index denoting axial location

m — maximum thickness point

max — maximum value

min — minimum value

n — normal to blade-element centerline

o — outlet segment or trailing edge

p — pressure surface

s — suction surface

sp — stacking point

t — transition point between segments of blade

1 — arbitrary reference or known value

2 — known value

3 — known value

Superscript:

$\overline{}$ — center-of-area coordinate

APPENDIX B

PARTICULAR FORMS OF THE GENERAL EQUATIONS

Solutions of $f(\kappa, \kappa_1, \zeta, R, R_1)$

For a line of constant turning rate C on a conical surface, the differentials of the radial and angular coordinates can be expressed as follows:

$$dR = -\frac{\cos \kappa}{C} d\kappa \tag{B1}$$

and

$$d\epsilon = -\frac{\sin \kappa}{RC} d\kappa \tag{B2}$$

Equation (B1) integrates to

$$R - R_1 = \frac{1}{C}(\sin \kappa_1 - \sin \kappa) \tag{B3}$$

Rearrangement of equation (B3) yields a characteristic constant ζ for a line of constant C

$$\zeta = RC + \sin \kappa = R_1 C + \sin \kappa_1 \tag{B4}$$

By solving equation (B4) for RC and replacing RC in equation (B3), $d\epsilon$ becomes a function of κ

$$d\epsilon = \frac{\sin \kappa}{\sin \kappa - \zeta} d\kappa \tag{B5}$$

However, if $C = 0$, κ is a constant, and equation (B5) is indeterminate. A different equation is required for this special case. For $C = 0$ or for constant κ, ϵ is a function of R, and the differential can be expressed as follows:

$$d\epsilon = \tan \kappa_1 \frac{dR}{R} \tag{B6}$$

In general, the indefinite integral of $d\epsilon$ is given by

$$\epsilon - \epsilon_1 = f(\kappa, \kappa_1, \zeta, R, R_1) \tag{B7}$$

where the function $f(\kappa, \kappa_1, \zeta, R, R_1)$ has four different solutions dependent on κ, κ_1, and ζ. The forms of the function are as follows:

(1) If $\kappa = \kappa_1$ (i.e., $C = 0$),

$$f(\kappa, \kappa_1, \zeta, R, R_1) = \tan \kappa \ln \left(\frac{R}{R_1}\right) \tag{B8}$$

(2) If $\kappa \neq \kappa_1$ and $\zeta^2 > 1$,

$$f(\kappa, \kappa_1, \zeta, R, R_1) = \kappa - \kappa_1 + \frac{2\zeta}{\sqrt{\zeta^2 - 1}}\left\{\tan^{-1}\left[\frac{1 - \zeta \tan\left(\frac{\kappa}{2}\right)}{\sqrt{\zeta^2 - 1}}\right] - \tan^{-1}\left[\frac{1 - \zeta \tan\left(\frac{\kappa_1}{2}\right)}{\zeta^2 - 1}\right]\right\} \tag{B9}$$

(3) If $\kappa \neq \kappa_1$ and $\zeta^2 < 1$,

$$f(\kappa, \kappa_1, \zeta, R, R_1) = \kappa - \kappa_1 + \frac{\zeta}{\sqrt{1 - \zeta^2}}\left[ln\left|\frac{1 - \zeta \tan \frac{\kappa}{2} - \sqrt{1 - \zeta^2}}{1 - \zeta \tan \frac{\kappa}{2} + \sqrt{1 - \zeta^2}}\right| - ln\left|\frac{1 - \zeta \tan \frac{\kappa_1}{2} - \sqrt{1 - \zeta^2}}{1 - \zeta \tan \frac{\kappa_1}{2} + \sqrt{1 - \zeta^2}}\right|\right] \tag{B10}$$

(4) If $\kappa \neq \kappa_1$ and $\zeta = \pm 1$,

$$f(\kappa, \kappa_1, \zeta, R, R_1) = \kappa - \kappa_1 \pm \left[\tan\left(\frac{\pi}{4} \pm \frac{\kappa_1}{2}\right) - \tan\left(\frac{\pi}{4} \pm \frac{\kappa}{2}\right)\right] \tag{B11}$$

Equations for Inlet Segment of Centerline

The equations for the inlet segment of the centerline are derived from equations (B4) and (B7) with the appropriate constants

$$\zeta_{ic} = R_{ic}C_{ic} + \sin \kappa_{ic} \tag{B12}$$

$$\kappa_c = \sin^{-1}(\zeta_{ic} - C_{ic}R_c) \tag{B13}$$

$$\epsilon_c = \epsilon_{ic} + f(\kappa_c, \kappa_{ic}, \zeta_{ic}, R_c, R_{ic}) \tag{B14}$$

These equations apply for $R_c \leq R_{tc}$. For convenience, the center of the leading edge is used as a reference and, thus, $\epsilon_{ic} = 0$.

Equations for Outlet Segment of Centerline

The equations for the outlet segment of the centerline have the same form as those for the inlet segment centerline, but have different C and ζ constants

$$\zeta_{oc} = R_{tc}C_{oc} + \sin \kappa_{tc} \tag{B15}$$

$$\kappa_c = \sin^{-1}(\zeta_{oc} - C_{oc}R_c) \tag{B16}$$

$$\epsilon_c = \epsilon_{tc} + f(\kappa_c, \kappa_{tc}, \zeta_{oc}, R_c, R_{tc}) \tag{B17}$$

where ϵ_{tc} is evaluated at the end of the inlet segment centerline or centerline transition point by equation (B14). These equations apply for $R_c > R_{tc}$.

Surface Coordinates at Ends of Thickness Path

In the R-ϵ coordinate system, a thickness path is described by a line of constant angle κ_n, which is perpendicular to the centerline

$$\kappa_n = \kappa_c \pm \frac{\pi}{2} \tag{B18}$$

In equation (B18), the angle to the suction surface is given by the plus sign, and the angle to the pressure surface is given by the minus sign.

The differential equations for the thickness path in terms of the path direction κ_n and the path distance s are

$$dR = \cos \kappa_n \, ds \tag{B19}$$

and

$$R d\epsilon = \sin \kappa_n \, ds \tag{B20}$$

Integration of equation (B19) gives

$$R - R_c = s \cos \kappa_n \tag{B21}$$

Substitution of ds from equation (B19) into equation (B20) gives

$$d\epsilon = \tan \kappa_n \frac{dR}{R} \tag{B22}$$

Integration of equation (B22) gives

$$\epsilon - \epsilon_c = \tan \kappa_n \, ln\left(\frac{R}{R_c}\right) \tag{B23}$$

However, if $\kappa_c = 0$, $\kappa_n = \pm\pi/2$ and $R = R_c$, and equation (B23) becomes indeterminate. Since R is a constant for this special case, equation (B20) can be integrated as

$$\epsilon - \epsilon_c = \frac{\sin \kappa_n}{R_c} s \tag{B24}$$

where $\kappa_n = \pm\pi/2$.

Blade thickness is specified at three locations: the leading edge, the maximum thickness point, and the trailing edge. At these three locations, the suction surface and pressure surface coordinates are calculated by the use of the appropriate thickness value and corresponding blade centerline angle in equations (B21) and either (B23) or (B24).

On the suction surface,

$$R_{(i,m,o)s} = R_{(i,m,o)c} - \frac{t_{(i,m,o)}}{2} \sin \kappa_c \tag{B25}$$

$$\epsilon_{(i,m,o)s} = \epsilon_{(i,m,o)c} + \cot \kappa_c \, ln \left[\frac{R_{(i,m,o)c}}{R_{(i,m,o)s}}\right] \tag{B26}$$

Or, if $\kappa_c = 0$,

$$\epsilon_{(i,m,o)p} = \epsilon_{(i,m,o)c} + \frac{t_{(i,m,o)}}{2R_{(i,m,o)c}} \tag{B27}$$

On the pressure surface,

$$R_{(i,m,o)p} = R_{(i,m,o)c} + \frac{t_{(i,m,o)}}{2} \sin \kappa_c \tag{B28}$$

$$\epsilon_{(i,m,o)p} = \epsilon_{(i,m,o)c} + \cot \kappa_c \, ln \left[\frac{R_{(i,m,o)c}}{R_{(i,m,o)p}}\right] \tag{B29}$$

Or, if $\kappa_c = 0$,

$$\epsilon_{(i,m,o)s} = \epsilon_{(i,m,o)c} - \frac{t_{(i,m,o)}}{2R_{(i,m,o)c}} \tag{B30}$$

APPENDIX C

DESCRIPTION OF COMPUTER PROGRAM

The blade coordinate computer program incorporates the equations and calculation procedures presented in this report to compute the cross-section coordinates of a compressor blade composed of multiple-circular-arc elements on conical surfaces. In addition to the coordinates, parameters for stress analysis (such as area, center of area, and moments of inertia) are also computed. The program consists of a main program and several subprograms. It is written in FORTRAN IV. The run time on a direct-coupled IBM 7044-7094 system is approximately 0.01 minute per given blade element.

The information in the following sections is intended to aid in the use of the program and in the understanding of its logic. Included are a description of the input, definitions of program variables, descriptions of subprograms, a listing of the program, and a sample output.

Description of Input

The format for the input cards is shown in table I. The first card in a set of data is the title card. It is used to identify the data with alphanumeric information, which is printed out with the output data. The second card is a general card for specification of single-value variables. The definitions of these variables are as follows:

ETA — tangential lean angle of stacking line η, in degrees (positive in direction from pressure surface toward suction surface)

LAMDA — axial lean angle of stacking line λ, in degrees (positive in direction from inlet toward outlet)

XNR — number of blade elements

OP1 — number of specified radial locations for desired blade sections (If none are specified (i.e., OP1 = 0.0), program computes blade sections at radial locations of stacking points for all blade elements.)

OP2 — control variable for output of calculated blade-element parameters (angles and turning rates) and coordinates (Blade-element output is printed out if OP2 = 1.0.)

TNLMT — tolerance limit for blade-element stacking iteration (If the tolerance limit is set too small, the stacking procedure will require an excessive number of iterations and may not converge.)

TABLE I. - INPUT FORMAT FOR COMPUTER PROGRAM

TITLE	PROJECT NUMBER	ANALYST	SHEET ____ OF ____
INPUT FORMAT FOR BLADE COORDINATE PROGRAM			

STATEMENT NUMBER (1–5)	CONT (6)	FORTRAN STATEMENT (7–72)	IDENTIFICATION (73–80)
		TITLE CARD	
ETA		LAMDA XNR OP1 OP2 TNLMT	
RI(1)		RI(2)	RI(8)
RI(9)			RI(16)
RI(17)			RI(24)
RO(1)			
TI(1)			
TM(1)			
TO(1)			
KMC(1)			
KTC(1)			
KOC(1)			
ZMC(1)			
ZTC(1)			
ZOC(1)			
		IF OP1 #0.0, THEN BLADE SECTION LOCATIONS ARE SPECIFIED:	
XQ(1)			XQ(8)
XQ(9)			XQ(16)
XQ(17)			XQ(24)

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The next set of cards specifies the geometry of the blade elements. As shown in table I for the first variable, RI, data for each variable begins in the first data space on a card and continues in succeeding spaces and cards for a total of XNR spaces. The maximum number of data per variable (i.e., number of blade elements) is 24. The definitions of the input blade-element variables are given in the main text under the section DEVELOPMENT OF EQUATIONS FOR BLADE-ELEMENT LAYOUT. The correspondence between variable names and variable symbols is as follows:

RI	inlet radius, r_{ic}
RO	outlet radius, r_{oc}
TI	inlet blade thickness, t_i
TM	maximum blade thickness, t_m
TO	outlet blade thickness, t_o
KIC	blade centerline angle at inlet, κ_{ic}
KTC	blade centerline angle at transition point, κ_{tc}
KOC	blade centerline angle at outlet, κ_{oc}
ZMC	axial distance to maximum thickness point from inlet, $z_{mc} - z_{ic}$
ZTC	axial distance to transition point from inlet, $z_{tc} - z_{ic}$
ZOC	axial distance to outlet from inlet, $z_{oc} - z_{ic}$

The last set of cards specifies the radial locations XQ of the desired blade sections. The XQ input begins in the first data space and continues in succeeding spaces for a total of OP1 spaces. The maximum number of blade sections is 24.

All input data are floating-point numbers. All input angles are in degrees. All variables with length dimensions must have the same unit length. The inlet and outlet radii r_{ic} and r_{oc} of a blade element cannot be identical. A difference in radii of at least 0.1 percent of the axial length of the blade element is recommended.

Main Program Variables and Definitions

The following is a list of program variable names with their corresponding symbols or definitions.

FORTRAN variable	Mathematical symbol	Definition
AREA	A	Area of blade section

FORTRAN variable	Mathematical symbol	Definition
ALP(I)	α	Cone half-angle
BETA	β	Angle of I_{min} axis (eq. (65))
BIC(I)	ζ_{ic}	Blade centerline, inlet segment constant (eq. (7)
BIP(I)	ζ_{ip}	Pressure surface, inlet segment constant (eq. (7))
BIS(I)	ζ_{is}	Suction surface, inlet segment constant (eq. (7))
BOC(I)	ζ_{oc}	Blade centerline, outlet segment constant (eq. (7))
BOP(I)	ζ_{op}	Pressure surface, outlet segment constant (eq. (7))
BOS(I)	ζ_{os}	Suction surface, outlet segment constant (eq. (7))
CAPPA	κ	Local blade angle (eq. (23))
CAPRZ	R	Distance from vertex to point on cone (eq. (14))
CAS(I)	C_{os}	Suction surface, outlet segment, rate of turning (eq. (15))
CIC(I)	C_{ic}	Blade centerline, inlet segment, rate of turning
CIP(I)	C_{ip}	Pressure surface, inlet segment, rate of turning
CIS(I)	C_{is}	Suction surface, inlet segment, rate of turning
COC(I)	C_{oc}	Blade centerline, outlet segment, rate of turning
COP(I)	C_{op}	Pressure surface, outlet segment, rate of turning
CRCG(I)	R_{sp}	Stacking point radius
DZ	Δz	Axial coordinate increment
EIC	ϵ_{ic}	Blade centerline, inlet segment, angular coordinate (EIC = 0.0)
EIP(I)	ϵ_{ip}	Pressure surface, inlet segment, angular coordinate (eq. (11))
EIS(I)	ϵ_{is}	Suction surface, inlet segment, angular coordinate
EMC(I)	ϵ_{mc}	Blade centerline, maximum thickness point, angular coordinate
EMP(I)	ϵ_{mp}	Pressure surface, maximum thickness point, angular coordinate

FORTRAN variable	Mathematical symbol	Definition
EMS(I)	ϵ_{ms}	Suction surface, maximum thickness point, angular coordinate
EOC(I)	ϵ_{oc}	Blade centerline, outlet segment, angular coordinate
EOP(I)	ϵ_{op}	Pressure surface, outlet segment, angular coordinate
EOS(I)	ϵ_{os}	Suction surface, outlet segment, angular coordinate
EPC	ϵ_c	Blade centerline, angular coordinate on z cuts
EPP	ϵ_p	Pressure surface, angular coordinate on z cuts
EPS	ϵ_s	Suction surface, angular coordinate on z cuts
ETA	η	Lean angle of stacking line in r-θ plane
ETC(I)	ϵ_{tc}	Blade centerline, transition point, angular coordinate
ETP(I)	ϵ_{tp}	Pressure surface, transition point, angular coordinate
ETS(I)	ϵ_{ts}	Suction surface, transition point, angular coordinate
GAMX(K)	γ	Angle of L-axis from axis of rotation (eq. (53))
HBAR	$\overline{H}$	Blade section, center-of-area coordinate (eq. (58))
I	----	Index used to denote blade element
ICASE(I)	----	Integers 1, 2, or 3 denoting whether transition is ahead of, equal to, or behind maximum thickness
IHH	I_{HH}	Blade section moment of inertia (eq. (60))
IHHCG	I_{HHCA}	Blade section moment of inertia (eq. (63))
ILL	I_{LL}	Blade section moment of inertia (eq. (59))
ILLCG	I_{LLCA}	Blade section moment of inertia (eq. (62))
IMAX	I_{max}	Blade section, maximum moment of inertia (eq. (67))
IMIN	I_{min}	Blade section, minimum moment of inertia (eq. (66))

FORTRAN variable	Mathematical symbol	Definition
J	j	Index denoting position in z-direction
K	----	Index denoting position in x-direction
KIC(I)	κ_{ic}	Blade centerline, leading-edge, local blade angle
KIP(I)	κ_{ip}	Pressure surface, leading-edge, local blade angle
KIS(I)	κ_{is}	Suction surface, leading-edge, local blade angle
KM(I)	κ_{m}	Maximum thickness point, local blade angle
KOC(I)	κ_{oc}	Blade centerline, trailing-edge, local blade angle
KOP(I)	κ_{op}	Pressure surface, trailing-edge, local blade angle
KOS(I)	κ_{os}	Suction surface, trailing-edge, local blade angle
KTC(I)	κ_{tc}	Blade centerline, transition point, local blade angle
KTP(I)	κ_{tp}	Pressure surface, transition point, local blade angle
KTS(I)	κ_{ts}	Suction surface, transition point, local blade angle
LAMDA	λ	Lean angle of stacking line in r-z plane
NR	----	Number of input radii
NXQ	----	Number of blade sections
NZ	----	Number of z values
OP1	----	Number of blade-section locations specified in input
OP2	----	Control variable for printed output of blade-element coordinates and parameters
PHL	P_{HL}	Blade section product of inertia (eq. (61))
PHLCG	P_{HLCA}	Blade section product of inertia (eq. (64))
RCG(I)	R_{sp}	Stacking point radius
RI(I)	r_{ic}	Blade centerline, leading-edge, radial coordinate
RIC(I)	R_{ic}	Blade centerline, leading-edge radius
RIP(I)	R_{ip}	Pressure surface, leading-edge radius
RIS(I)	R_{is}	Suction surface, leading-edge radius

FORTRAN variable	Mathematical symbol	Definition
RMC(I)	R_{mc}	Blade centerline, maximum thickness point radius
RMP(I)	R_{mp}	Pressure surface, maximum thickness point radius
RMS(I)	R_{ms}	Suction surface, maximum thickness point radius
RO(I)	r_{oc}	Blade centerline, trailing-edge, radial coordinate
ROC(I)	R_{oc}	Blade centerline, trailing-edge radius
ROP(I)	R_{op}	Pressure surface, trailing-edge radius
ROS(I)	R_{os}	Suction surface, trailing-edge radius
RTC(I)	R_{tc}	Blade centerline, transition point radius
RTP(I)	R_{tp}	Pressure surface, transition point radius
RTS(I)	R_{ts}	Suction surface, transition point radius
T, T1, T2, T3, T4, T5	----	Temporary storage locations
THECG(I)	$\theta_{sp} - \theta_{ic}$	Relative stacking point, circumferential angle coordinate
THETA(I)	θ_{ic}	Blade centerline, leading-edge, circumferential angle coordinate
THETAC(I, J)	θ_c	Blade centerline, circumferential angle coordinate
THETAP(I, J)	θ_p	Pressure surface, circumferential angle coordinate
THETAS(I, J)	θ_s	Suction surface, circumferential angle coordinate
TI(I)	t_i	Leading-edge blade thickness
TM(I)	t_m	Blade thickness at maximum thickness point
TNLMT	----	Blade-element stacking tolerance limit
TNORM1	S	Blade-element stacking tolerance (eq. (99))
TO(I)	t_o	Trailing-edge blade thickness
V_1, V_2, V_3, V_4	----	Temporary storage locations
X(K)	x	Computed values of x-coordinate for blade sections
XCG(I)	x_{sp}	Stacking point x-coordinates
XHCG	----	Blade section, center-of-area H-coordinate
XHIC	----	Blade section, centerline, leading-edge H-coordinate

FORTRAN variable	Mathematical symbol	Definition
XHIP	----	Blade section, pressure surface, leading-edge H-coordinate
XHIS	----	Blade section, suction surface, leading-edge H-coordinate
XHMC	----	Blade section, centerline, maximum thickness point H-coordinate
XHMP	----	Blade section, pressure surface, maximum thickness point H-coordinate
XHMS	----	Blade section, suction surface, maximum thickness point H-coordinate
XHOC	H_{oc}	Blade section, centerline, trailing-edge H-coordinate
XHOP	H_{op}	Blade section, pressure surface, trailing-edge H-coordinate
XHOS	H_{os}	Blade section, suction surface, trailing-edge H-coordinate
XHTC	H_{tc}	Blade section, centerline, transition point H-coordinate
XHTP	H_{tp}	Blade section, pressure surface, transition point H-coordinate
XHTS	H_{ts}	Blade section, suction surface, transition point H-coordinate
XIC(I)	x_{ic}	Blade centerline, leading-edge x-coordinate
XIP(I)	x_{ip}	Pressure surface, leading-edge x-coordinate
XIS(I)	x_{is}	Suction surface, leading-edge x-coordinate
XLCG	----	Blade section, center-of-area L-coordinate
XLIC	L_{ic}	Blade section, centerline, leading-edge L-coordinate
XLIP	L_{ip}	Blade section, pressure surface, leading-edge L-coordinate

FORTRAN variable	Mathematical symbol	Definition
XLIS	L_{is}	Blade section, suction surface, leading-edge L-coordinate
XLMC	L_{mc}	Blade section, centerline, maximum thickness point L-coordinate
XLMP	L_{mp}	Blade section, pressure surface, maximum thickness point L-coordinate
XLMS	L_{ms}	Blade section, suction surface, maximum thickness point L-coordinate
XLOC	L_{oc}	Blade section, centerline, trailing-edge L-coordinate
XLOP	L_{op}	Blade section, pressure surface, trailing-edge L-coordinate
XLOS	L_{os}	Blade section, suction surface, trailing-edge L-coordinate
XLSP	----	Blade section, reference point (hub blade element stacking point) L-coordinate
XLTC	L_{tc}	Blade section, centerline, transition point L-coordinate
XLTP	L_{tp}	Blade section, pressure surface, transition point L-coordinate
XLTS	L_{ts}	Blade section, suction surface, transition point L-coordinate
XMC(I)	x_{mc}	Blade centerline, maximum thickness point x-coordinate
XMP(I)	x_{mp}	Pressure surface, maximum thickness point x-coordinate
XMS(I)	x_{ms}	Suction surface, maximum thickness point x-coordinate
XOC(I)	x_{oc}	Blade centerline, trailing-edge x-coordinate
XOP(I)	x_{op}	Pressure surface, trailing-edge x-coordinate
XOS(I)	x_{os}	Suction surface, trailing-edge x-coordinate

FORTRAN variable	Mathematical symbol	Definition
XQ(K)	----	Input values of x-coordinate for desired blade sections
XP(I, J)	----	Blade pressure surface abscissa
XTC(I)	x_{tc}	Blade centerline, transition point x-coordinates
XTP(I)	x_{tp}	Pressure surface, transition point x-coordinates
XTS(I)	x_{ts}	Suction surface, transition point x-coordinates
YIC(I)	y_{ic}	Blade centerline, leading-edge y-coordinates
YIP(I)	y_{ip}	Pressure surface, leading-edge y-coordinates
YIS(I)	y_{is}	Suction surface, leading-edge y-coordinates
YMC(I)	y_{mc}	Blade centerline, maximum thickness point y-coordinates
YMP(I)	y_{mp}	Pressure surface, maximum thickness point y-coordinates
YMS(I)	y_{ms}	Suction surface, maximum thickness point y-coordinates
YOC(I)	y_{oc}	Blade centerline, trailing-edge y-coordinates
YOP(I)	y_{op}	Pressure surface, trailing-edge y-coordinates
YOS(I)	y_{os}	Suction surface, trailing-edge y-coordinates
YP(I, J)	y_p	Blade pressure surface y-coordinates
YS(I, J)	y_s	Blade suction surface y-coordinates
YTC(I)	y_{tc}	Blade centerline, transition point y-coordinates
YTP(I)	y_{tp}	Pressure surface, transition point y-coordinates
YTS(I)	y_{ts}	Suction surface, transition point y-coordinates
YICX(K)	----	Value of y_{ic} at a given blade section
YIPX(K)	----	Value of y_{ip} at a given blade section
YISX(K)	----	Value of y_{is} at a given blade section
YMCX(K)	----	Value of y_{mc} at a given blade section
YMPX(K)	----	Value of y_{mp} at a given blade section

FORTRAN variable	Mathematical symbol	Definition
YMSX(K)	----	Value of y_{ms} at a given blade section
YOCX(K)	----	Value of y_{oc} at a given blade section
YOPX(K)	----	Value of y_{op} at a given blade section
YOSX(K)	----	Value of y_{os} at a given blade section
YTCX(K)	----	Value of y_{tc} at a given blade section
YTPX(K)	----	Value of y_{tp} at a given blade section
YTSX(K)	----	Value of y_{ts} at a given blade section
ZCG(I)	z_{sp}	Stacking point axial coordinate
ZIC(I)	z_{ic}	Blade centerline, leading-edge z-coordinates
ZIP(I)	z_{ip}	Pressure surface, leading-edge z-coordinates
ZIS(I)	z_{is}	Suction surface, leading-edge z-coordinates
ZMC(I)	z_{mc}	Blade centerline, maximum thickness point z-coordinates
ZMP(I)	z_{mp}	Pressure surface, maximum thickness point z-coordinates
ZMS(I)	z_{ms}	Suction surface, maximum thickness point z-coordinates
ZOC(I)	z_{oc}	Blade centerline, trailing-edge z-coordinates
ZOP(I)	z_{op}	Pressure surface, trailing-edge z-coordinates
ZOS(I)	z_{os}	Suction surface, trailing-edge z-coordinates
ZTC(I)	z_{tc}	Blade centerline, transition point z-coordinates
ZTP(I)	z_{tp}	Pressure surface, transition point z-coordinates
ZTS(I)	z_{ts}	Suction surface, transition point z-coordinates
ZX(J)	z_j	Values of equally spaced z-increments computed to obtain x-y cuts
ZICX(K)	----	Value of z_{ic} at a given blade section
ZIPX(K)	----	Value of z_{ip} at a given blade section
ZISX(K)	----	Value of z_{is} at a given blade section

FORTRAN variable	Mathematical symbol	Definition
ZMCX(K)	----	Value of z_{mc} at a given blade section
ZMPX(K)	----	Value of z_{mp} at a given blade section
ZMSX(K)	----	Value of z_{ms} at a given blade section
ZOCX(K)	----	Value of z_{oc} at a given blade section
ZOPX(K)	----	Value of z_{op} at a given blade section
ZOSX(K)	----	Value of z_{os} at a given blade section
ZTCX(K)	----	Value of z_{tc} at a given blade section
ZTPX(K)	----	Value of z_{tp} at a given blade section
ZTSX(K)	----	Value of z_{ts} at a given blade section

Description of Subroutines

The subroutines used in this program are listed below along with their call sequence, purpose, and variable definitions.

Subroutine ITER(K2, C, B, K1, E1, R1, E2, R2, XK). - A routine to iteratively solve for the equation of a constant $d\kappa/ds$ curve which passes through two known points and at a given slope at one of the points. Refer to equations (7), (11), and (15) for the functional relations.

K2	κ_2	Unknown slope at point 2
C	C	Unknown curvature constant
B	ζ	Unknown curve constant
K1	κ_1	Known slope at point 1
E1	ϵ_1	Angular coordinate of point 1
R1	R_1	Radial coordinate of point 1
E2	ϵ_2	Angular coordinate of point 2
R2	R_2	Radial coordinate of point 2
XK	---	An initial estimate of κ_2

Subroutine ITER1(KT, RT, ET, KM, RM, EM, B, C, RTC, ETC, KTC). - A routine to iteratively solve for the $R-\epsilon$ coordinates of the transition point on either the pressure surface or the suction surface. Refer to equations (11), (21) to (23), and (25) for the functional relations.

FORTRAN variable	Mathematical symbol	Definition
KT	$\kappa_{t(p,s)}$	Unknown surface transition point blade angle
RT	$R_{t(p,s)}$	Unknown surface transition point radial coordinate
ET	$\epsilon_{t(p,s)}$	Unknown surface transition point angular coordinate
KM	$\kappa_{m(p,s)}$	Surface maximum thickness point blade angle
RM	$R_{m(p,s)}$	Surface maximum thickness point radial coordinate
EM	$\epsilon_{m(p,s)}$	Surface maximum thickness point angular coordinate
B	$\zeta_{(i,o)(p,s)}$	Surface curve constant
C	$C_{(i,o)(p,s)}$	Surface curvature constant
RTC	R_{tc}	Blade centerline, transition point, radial coordinate
ETC	ϵ_{tc}	Blade centerline, transition point, angular coordinate
KTC	κ_{tc}	Blade centerline, transition point, blade angle

Subroutine SINTP(Z, W, N, X1, Y2). - A routine which uses a second-order Lagrangian algorithm for interpolation and a linear extrapolation method. Refer to equations (40) to (43) for the functional relations.

FORTRAN variable	Mathematical symbol	Definition
Z	$x_{j(p,s)}$	Abscissa vector
W	$y_{j(p,s)}$	Corresponding ordinate vector
N	---	Number of points in the given vector
X1	x	Given argument
Y1	$y_{(p,s)}$	Interpolated ordinate, (i.e., Y1 = W(X1))

Subroutine CGS(YCG, ZCG, YIPX, ZIPX, YISX, ZISX, YPX, YSX, NZ, ZX, YOPX, ZOPX, YOSX, ZOSX). - A routine to calculate the center of area of a blade section.

FORTRAN variable	Mathematical symbol	Definition
YCG	---	Value of y_{ca} of the blade section
ZCG	---	Value of z_{ca} of the blade section
YIPX	---	Value of y_{ip} of the blade section
ZIPX	---	Value of z_{ip} of the blade section
YISX	---	Value of y_{is} of the blade section
ZISX	---	Value of z_{is} of the blade section
YPX(J)	y_p	Blade pressure surface ordinates of the blade section
YSX(J)	y_s	Blade suction surface ordinates of the blade section
NZ	---	Number of z stations
ZX(J)	z_j	Values of z for all z stations
YOPX	---	Value of y_{op} of the blade section
ZOPX	---	Value of z_{op} of the blade section
YOSX	---	Value of y_{os} of the blade section
ZOSX	---	Value of z_{os} of the blade section

Subroutine FIX(A, B). - A routine to determine the arcsin of a given value and prevent computation of the arcsin of a value greater than 1.0 or less than -1.0.

A	---	Given value
B	---	Computed arcsin (A)

Subroutine CGS1(X). - A routine to calculate the center of area, moment of inertia, minimum moment of inertia, and axis of minimum moment of inertia for a blade section in the L-H coordinate system.

X	L	Chordwise abscissa
HP	H_p	Blade pressure surface ordinate
HS	H_s	Blade suction surface ordinate

FORTRAN variable	Mathematical symbol	Definition
N	---	Number of chordwise abscissas
X1	---	Chordwise abscissa
V	---	Blade suction surface ordinate associated with X1
V1	---	Blade pressure surface ordinate associated with X1
V2	---	Temporary storage for function value
V3	---	Temporary storage for integral value
AREA	A	Blade-section area
LBAR	$\bar{L}$	Center-of-area coordinate
HBAR	$\bar{H}$	Center-of-area coordinate
IHH	I_{HH}	Moment of inertia about H-axis
ILL	I_{LL}	Moment of inertia about L-axis
PHL	P_{HL}	Product of inertia, $P_{HL} = \iint HL\, dA$

Subroutine XMAX(X, XM, N). - A routine which selects the maximum value of a vector.

X	---	Given vector
XM	---	Maximum value of X
N	---	Number of points in X

Subroutine XMIN(X, XM, N). - A routine which selects the minimum value of a vector.

X	---	Given vector
XM	---	Minimum value of X
N	---	Number of points in X

Subroutine NEED(IC, I). - A routine which directs the computation of the curves for the pressure and suction surfaces of a blade element.

IC	---	Integer (1, 2, or 3) denoting whether transition point is at, ahead of, or behind maximum thickness point
I	---	Index corresponding to blade element to be computed

Function SUBF(X, XO, B, R, RO). - A subprogram to compute the function $f(\kappa, \kappa_o, \zeta, R, R_o)$ as given in appendix B.

FORTRAN variable	Mathematical symbol	Definition
X	κ	Slope of curve at a point
XO	κ_o	Slope of curve at a reference point
B	ζ	Curve constant
R	R	Radial coordinate of point
RO	R_o	Radial coordinate of reference point

Subroutine INTGR(L, X1, X2, X3). - A routine to evaluate three definite integrals defined by equations (28), (29), and (30).

L	---	Index denoting blade element
X1	---	Value of integral $\int \epsilon \, dA$
X2	---	Value of integral $\int R \, dA$
X3	---	Value of integral $\int dA$

Function ADJ(D). - A subprogram to adjust the increment D to a value not less than D and having a single significant figure of 1, 2, or 5.

D	---	Increment

Subroutine RAEP(RP, RS, EP, ES, RC, EC, XKC, TC). - A routine to calculate the conical coordinates of surface points at the ends of a thickness path of a blade element. Refer to equations (16), (19), (21), and (22) for functional relations.

RP	$R_{(i,m,o)p}$	R-coordinate for pressure surface point
RS	$R_{(i,m,o)s}$	R-coordinate for suction surface point
EP	$\epsilon_{(i,m,o)p}$	ϵ-coordinate for pressure surface point
ES	$\epsilon_{(i,m,o)s}$	ϵ-coordinate for suction surface point
RC	$R_{(i,m,o)c}$	R-coordinate for centerline point
EC	$\epsilon_{(i,m,o)c}$	ϵ-coordinate for centerline point
XKC	$\kappa_{(i,m,o)c}$	κ at centerline point
TC	$t_{(i,m,o)}$	Blade thickness

Subroutine FNTGRL(N, DX, FX, SFX). - A Lewis system subroutine to numerically evaluate the integral of a function defined at any number of equally spaced intervals.

FORTRAN variable	Mathematical symbol	Definition
N	---	Number of stations
DX	dx	Size of interval
FX	f(x)	Values of function at each station
SFX	$\int_0^{x_n} f(x)dx$	Values of integral

Subroutine SORTXY(X, Y, N). - A Lewis system subroutine to rearrange the N values in the X-array in order of increasing size and move the values of the Y-array to maintain the original pair relations.

X	---	Independent array
Y	---	Dependent array
N	---	Number of values

FORTRAN IV Source Deck Listing

```
C              BLADE COORDINATE PROGRAM FOR BLADE WITH
C              2 PARTS OF DIFFERENT CURVATURE
C
C      OP1---ENTER OWN X COORDS
C      OP2---X-Y-Z CONICAL SECTION COORDINATES
       DIMENSION ALP(24), BIC(24), BIP(24), BIS(24), BOC(24), BOP(24), BO
      1S(24), CIC(24), CIP(24), CIS(24), COC(24), COP(24), CAS(24), DELT(
      224), EIP(24), EIS(24), EMC(24), EMP(24), EMS(24), FOC(24), EOP(24)
      3, EOS(24), ETC(24), ETP(24), ETS(24), ICASE(24), KIC(24), KIP(24),
      4 KIS(24), KM(24), KOC(24), KOP(24), KOS(24), KTC(24), KTP(24), KTS
      5(24), RCG(24), RI(24), RIC(24), RIP(24), RIS(24), RMC(24), RMP(24)
      6, RMS(24), ROC(24), ROP(24), ROS(24), RTC(24), RTP(24), RTS(24), T
      7HECG(24), THETA(24), TI(24), TM(24), TO(24), XCG(24), XIC(24), XIP
      8(24), XIS(24), XMC(24), XMP(24), XMS(24), XOC(24), XOP(24), XOS(24
      9), XIC(24), XTP(24), XTS(24), YCG(24), YIC(24), YIP(24), YIS(24),
      $YMC(24), YMP(24), YMS(24), YOC(24), YOP(24), YOS(24), YTC(24), YTP
      $(24), YTS(24), ZCG(24), ZIC(24), ZIP(24), ZIS(24), ZMC(24), ZMP(24
      $), ZMS(24), ZOC(24), ZOP(24), ZOS(24), ZTC(24), ZTP(24), ZTS(24)
       DIMENSION ZX(32), YPX(32), YSX(32), XP(32,24), XS(32,24), YP(32,24
      1), YS(32,24), THETAC(32,24), THETAP(32,24), THETAS(32,24)
       DIMENSION V(56), V1(56), V2(56), V3(56), V4(56), V5(56)
       DIMENSION X(24), XQ(24), GAMX(24), TIX(24), TMX(24), TOX(24), YCGX
      1(24), YICX(24), YIPX(24), YISX(24), YMCX(24), YMPX(24), YMSX(24),
      2YOCX(24), YOPX(24), YOSX(24), YTCX(24), YTPX(24), YTSX(24), ZCGX(2
      34), ZICX(24), ZIPX(24), ZISX(24), ZMCX(24), ZMPX(24), ZMSX(24), ZO
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     4CX(24), ZOPX(24), ZOSX(24), ZTCX(24), ZTPX(24), ZTSX(24)
      DIMENSION XL(56), XHP(56), XHS(56)
      DIMENSION RO(24), ZI(24), CRCG(24), TITLE(12)
      DIMENSION TALP(24), SALP(24), CALP(24)
      COMMON ALP,BOC,BIC,BIP,BIS,BOP,BOS,CIP,CIS,COP,CAS,CIC,EIP,EIS,EMC
     1,EMP,EMS,EOC,EOP,EOS,ETC,ETP,ETS,KIC,KIP,KIS,KM,KOC,KOP,KOS,KTC,KT
     2P,KTS,RI,RO,RIC,RIP,RIS,RMC,RMP,RMS,ROC,ROP,ROS,RTC,RTP,RTS,TI,TM,
     3TO,ZMC,ZOC,ZTC,NR,COC
      REAL KIC,KIP,KIS,KM,KOC,KOP,KOS,KTC,KTP,KTS,LAMDA
      REAL LBAR,ILL,IHH,ILLCG,IHHCG,IMIN,IMAX
      COMMON /EXTRA/ XL,XHS,XHP,LOUT,LBAR,HBAR,ILL,IHH,PHL,AREA,ILLCG,IH
     1HCG,PHLCG,BETA,IMIN,IMAX
      DATA DEGRAD/57.2958/
C                                 INPUT
1     READ (5,43) TITLE
      READ (5,44) ETA,LAMDA,XNR,OP1,OP2,TNLMT
      REWIND 2
      NR=XNR
      READ (5,44) (RI(I),I=1,NR)
      READ (5,44) (RO(I),I=1,NR)
      READ (5,44) (TI(I),I=1,NR)
      READ (5,44) (TM(I),I=1,NR)
      READ (5,44) (TO(I),I=1,NR)
      READ (5,44) (KIC(I),I=1,NR)
      READ (5,44) (KTC(I),I=1,NR)
      READ (5,44) (KOC(I),I=1,NR)
      READ (5,44) (ZMC(I),I=1,NR)
      READ (5,44) (ZTC(I),I=1,NR)
      READ (5,44) (ZOC(I),I=1,NR)
      WRITE (6,45) TITLE
      WRITE (6,46) ETA,LAMDA,OP1,OP2,TNLMT
      DO 2 I=1,NR
2     WRITE (6,47) I,RI(I),RO(I),TI(I),TM(I),TO(I),KIC(I),KTC(I),KOC(I),
     1ZMC(I),ZTC(I),ZOC(I)
C                 CALC. OF BLADE ELEMENT PARAMETERS
      ETA=ETA/DEGRAD
      LAMDA=LAMDA/DEGRAD
      DO 3 I=1,NR
      KIC(I)=KIC(I)/DEGRAD
      KTC(I)=KTC(I)/DEGRAD
3     KOC(I)=KOC(I)/DEGRAD
      EIC=0.0
      DO 4 I=1,NR
      SINKTC=SIN(KTC(I))
      SINKOC=SIN(KOC(I))
      SINKIC=SIN(KIC(I))
      TNALP=(RO(I)-RI(I))/ZOC(I)
      TALP(I)=TNALP
      ALP(I)=ATAN(TNALP)
      CALP(I)=SQRT(1./(TALP(I)**2+1.))
      SALP(I)=TALP(I)*CALP(I)
      SNALP=SALP(I)
      CSALP=CALP(I)
      RIC(I)=RI(I)/SNALP
      ROC(I)=RIC(I)+ZOC(I)/CSALP
      RTC(I)=RIC(I)+ZTC(I)/CSALP
      RMC(I)=RIC(I)+ZMC(I)/CSALP
      CIC(I)=(SINKIC-SINKTC)/(RTC(I)-RIC(I))
      COC(I)=(SINKTC-SINKOC)/(ROC(I)-RTC(I))
      T1=ZTC(I)
      T2=ZMC(I)
```

```
      IF (T1.EQ.T2) ICASE(I)=1
      IF (T1.LT.T2) ICASE(I)=2
      IF (T1.GT.T2) ICASE(I)=3
      CALL RAEP (RIP(I),RIS(I),EIP(I),EIS(I),RIC(I),EIC,KIC(I),TI(I))
      BIC(I)=CIC(I)*RTC(I)+SINKTC
      BOC(I)=COC(I)*RTC(I)+SINKTC
      ETC(I)=SUBF(KTC(I),KIC(I),BIC(I),RTC(I),RIC(I))
      EOC(I)=ETC(I)+SUBF(KOC(I),KTC(I),BOC(I),ROC(I),RTC(I))
      CALL RAEP (ROP(I),ROS(I),EOP(I),EOS(I),ROC(I),EOC(I),KOC(I),TO(I))
C
      CALL NEED (ICASE(I),I)
C
      CALL INTGR (I,XINT1,XINT2,XINT3)
C
      THECG(I)=XINT1/XINT3/SNALP
      CRCG(I)=XINT2/XINT3
4     RCG(I)=CRCG(I)*SNALP
C
      TAE=TAN(ETA)
      TNL=TAN(LAMDA)
      TAE2=TAE**2
5     THECGO=THECG(NR)
      ZCGO=(CRCG(NR)-RIC(NR))*CALP(NR)
      RCGO=RCG(NR)
C
C               CALC. OF BLADE ELEMENT COORDINATES
      DO 6 I=1,NR
      T1=TAE2
      T2=RCG(I)/RCGO
      T3=TAE/T2/(1.+T1)*(SQRT(T2**2*(1.+T1)-T1)-1.)
      DELT(I)=ARSIN(T3)
      ZCG(I)=ZCGO+(RCG(I)-RCGO)*TNL
      T1=TALP(I)
      T=SALP(I)
      ZIC(I)=ZCG(I)-(CRCG(I)-RIC(I))*CALP(I)
      T4=DELT(I)-THECG(I)
      THETA(I)=THECGO+T4
      XIC(I)=RI(I)*COS(T4)
      XIP(I)=RIP(I)*T*COS(EIP(I)/T+T4)
      XIS(I)=RIS(I)*T*COS(EIS(I)/T+T4)
      XTC(I)=RTC(I)*T*COS(ETC(I)/T+T4)
      XTP(I)=RTP(I)*T*COS(ETP(I)/T+T4)
      XTS(I)=RTS(I)*T*COS(ETS(I)/T+T4)
      XMC(I)=RMC(I)*T*COS(EMC(I)/T+T4)
      XMP(I)=RMP(I)*T*COS(EMP(I)/T+T4)
      XMS(I)=RMS(I)*T*COS(EMS(I)/T+T4)
      XOC(I)=ROC(I)*T*COS(EOC(I)/T+T4)
      XOP(I)=ROP(I)*T*COS(EOP(I)/T+T4)
      XOS(I)=ROS(I)*T*COS(EOS(I)/T+T4)
C
      T5=ZIC(I)-RIC(I)*CALP(I)
      T6=CALP(I)
      ZIP(I)=T5+RIP(I)*T6
      ZIS(I)=T5+RIS(I)*T6
      ZTC(I)=T5+RTC(I)*T6
      ZTP(I)=T5+RTP(I)*T6
      ZTS(I)=T5+RTS(I)*T6
      ZMC(I)=T5+RMC(I)*T6
      ZMP(I)=T5+RMP(I)*T6
      ZMS(I)=T5+RMS(I)*T6
      ZOC(I)=T5+ROC(I)*T6
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      ZOP(I)=T5+ROP(I)*T6
      ZOS(I)=T5+ROS(I)*T6
C
      YCG(I)=RCG(I)*SIN(DELT(I))
      YIC(I)=RI(I)*SIN(T4)
      YIP(I)=RIP(I)*T*SIN(EIP(I)/T+T4)
      YIS(I)=RIS(I)*T*SIN(EIS(I)/T+T4)
      YTC(I)=RTC(I)*T*SIN(ETC(I)/T+T4)
      YTP(I)=RTP(I)*T*SIN(ETP(I)/T+T4)
      YTS(I)=RTS(I)*T*SIN(ETS(I)/T+T4)
      YMP(I)=RMP(I)*T*SIN(EMP(I)/T+T4)
      YMC(I)=RMC(I)*T*SIN(EMC(I)/T+T4)
      YMS(I)=RMS(I)*T*SIN(EMS(I)/T+T4)
      YOC(I)=ROC(I)*T*SIN(EOC(I)/T+T4)
      YOP(I)=ROP(I)*T*SIN(EOP(I)/T+T4)
      YOS(I)=ROS(I)*T*SIN(EOS(I)/T+T4)
6     XCG(I)=RCG(I)*COS(DELT(I))
C
      NX=NR
      DO 7 K=1,NX
      L=NR+1-K
7     X(K)=XCG(L)
C
      DO 8 K=1,NX
      CALL SINTP (XIP,ZIP,NR,X(K),ZIPX(K))
      CALL SINTP (XIS,ZIS,NR,X(K),ZISX(K))
      CALL SINTP (XOP,ZOP,NR,X(K),ZOPX(K))
      CALL SINTP (XOS,ZOS,NR,X(K),ZOSX(K))
8     CONTINUE
C
      CALL XMIN (ZIPX,Z1,NX)
      CALL XMIN (ZISX,Z2,NX)
      ZMIN=AMIN1(Z1,Z2)
      CALL XMAX (ZOSX,Z1,NX)
      CALL XMAX (ZOPX,Z2,NX)
      ZMAX=AMAX1(Z1,Z2)
      DZ=(ZMAX-ZMIN)/30.
      DZ=ADJ(DZ)
      ZX(I)=DZ*(AINT(ZMIN/DZ)-1.)
      DO 9 I=2,32
      ZX(I)=ZX(I-1)+DZ
9     IF (ZX(I).GT.ZMAX) GO TO 10
10    NZ=I
C
      DO 17 J=1,NZ
      DO 17 I=1,NR
      T=SALP(I)
      T2=TALP(I)
      RZ=RI(I)+(ZX(J)-ZIC(I))*T2
      CAPRZ=RIC(I)+(ZX(J)-ZIC(I))/CALP(I)
      IF (CAPRZ.GT.RTC(I)) GO TO 11
      SNCP=BIC(I)-CIC(I)*CAPRZ
      CALL FIX (SNCP,CAPPA)
      EPC=SUBF(CAPPA,KIC(I),BIC(I),CAPRZ,RIC(I))
      GO TO 12
11    SNCP=BOC(I)-COC(I)*CAPRZ
      CALL FIX (SNCP,CAPPA)
      EPC=ETC(I)+SUBF(CAPPA,KTC(I),BOC(I),CAPRZ,RTC(I))
12    IF (CAPRZ.GT.RTP(I)) GO TO 13
      SNCP=BIP(I)-CIP(I)*CAPRZ
      CALL FIX (SNCP,CAPPA)
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      EPP=EIP(I)+SUBF(CAPPA,KIP(I),BIP(I),CAPRZ,RIP(I))
      GO TO 14
13    SNCP=BOP(I)-COP(I)*CAPRZ
      CALL FIX (SNCP,CAPPA)
      EPP=ETP(I)+SUBF(CAPPA,KTP(I),BOP(I),CAPRZ,RTP(I))
14    IF (CAPRZ.GT.RTS(I)) GO TO 15
      SNCP=BIS(I)-CIS(I)*CAPRZ
      CALL FIX (SNCP,CAPPA)
      EPS=EIS(I)+SUBF(CAPPA,KIS(I),BIS(I),CAPRZ,RIS(I))
      GO TO 16
15    SNCP=BOS(I)-CAS(I)*CAPRZ
      CALL FIX (SNCP,CAPPA)
      EPS=ETS(I)+SUBF(CAPPA,KTS(I),BOS(I),CAPRZ,RTS(I))
16    THETAC(J,I)=THETA(I)+EPC/T
      THETAP(J,I)=THETA(I)+EPP/T
      THETAS(J,I)=THETA(I)+EPS/T
      XP(J,I)=RZ*COS(THETAP(J,I)-THECGO)
      XS(J,I)=RZ*COS(THETAS(J,I)-THECGO)
      YP(J,I)=RZ*SIN(THETAP(J,I)-THECGO)
      YS(J,I)=RZ*SIN(THETAS(J,I)-THECGO)
17    CONTINUE
C
C               CALC. OF BLADE SECTION COORDINATES THRU BLADE ELEMENT
C               STACKING POINTS
      DO 20 K=1,NX
      DO 19 J=1,NZ
      DO 18 I=1,NR
      V(I)=XP(J,I)
      V1(I)=YP(J,I)
      V2(I)=XS(J,I)
18    V3(I)=YS(J,I)
      CALL SINTP (V,V1,NR,X(K),YPX(J))
19    CALL SINTP (V2,V3,NR,X(K),YSX(J))
      WRITE (2) (YSX(J),J=1,NZ),(YPX(J),J=1,NZ)
      CALL SINTP (ZX,YSX,NZ,ZISX(K),YISX(K))
      CALL SINTP (ZX,YSX,NZ,ZOSX(K),YOSX(K))
      CALL SINTP (ZX,YPX,NZ,ZIPX(K),YIPX(K))
      CALL SINTP (ZX,YPX,NZ,ZOPX(K),YOPX(K))
20    CONTINUE
      REWIND 2
      TNORM1=0.
C
C               CALC. OF BLADE SECTION CENTER OF AREA
      DO 21 K=1,NX
      READ (2) (YSX(J),J=1,NZ),(YPX(J),J=1,NZ)
21    CALL CGS (YCGX(K),ZCGX(K),YIPX(K),ZIPX(K),YISX(K),ZISX(K),YPX,YSX,
     1NZ,ZX,YOPX(K),ZOPX(K),YOSX(K),ZOSX(K))
C
C               CALC. OF DIFFERENCES BETWEEN BLADE ELEMENT STACKING
C               POINTS AND BLADE SECTION CENTERS OF AREA
      DO 22 I=1,NR
      CALL SINTP (X,ZCGX,NX,XCG(I),ZCGR)
      CALL SINTP (X,YCGX,NX,XCG(I),YCGR)
      DRCG=(ZCGR-ZCG(I))*TALP(I)
      XCGR=SQRT((RCG(I)+DRCG)**2-YCGR**2)
      CALL SINTP (X,ZCGX,NX,XCGR,ZCGR)
      CALL SINTP (X,YCGX,NX,XCGR,YCGR)
      DRCG=(ZCGR-ZCG(I))*TALP(I)
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      XCGR=SQRT((RCG(I)+DRCG)**2-YCGR**2)
      V(I)=ZCGR
      V1(I)=YCGR
      V2(I)=XCGR
22    TNORM1=TNORM1+ABS(ZCGR-ZCG(I))+ABS(YCGR-YCG(I))
      WRITE (6,48) TNORM1,(THECG(I),I=1,NR)
      WRITE (6,49) (CRCG(I),I=1,NR)
      IF (TNORM1.LT.TNLMT) GO TO 24
C              REALINEMENT OF BLADE ELEMENTS
      DO 23 I=1,NR
      THECG(I)=THECG(I)-DELT(I)+ATAN(V1(I)/V2(I))
      CRCG(I)=RIC(I)+(V(I)-ZIC(I))/CALP(I)
23    RCG(I)=SQRT(V1(I)**2+V2(I)**2)
      REWIND 2
      GO TO 5
24    REWIND 2
      IF (OP2.EQ.0.) GO TO 27
C              PRINT OUT BLADE ELEMENT PARAMETERS AND COORDINATES
      DO 25 I=1,NR
      KIC(I)=KIC(I)*DEGRAD
      KIP(I)=KIP(I)*DEGRAD
      KIS(I)=KIS(I)*DEGRAD
      KM(I)=KM(I)*DEGRAD
      KTC(I)=KTC(I)*DEGRAD
      KTP(I)=KTP(I)*DEGRAD
      KTS(I)=KTS(I)*DEGRAD
      KOC(I)=KOC(I)*DEGRAD
      KOP(I)=KOP(I)*DEGRAD
      KOS(I)=KOS(I)*DEGRAD
25    ALP(I)=ALP(I)*DEGRAD
      WRITE (6,50) (I,ALP(I),KM(I),KIC(I),KTC(I),KOC(I),KIP(I),KTP(I),KO
     1P(I),KIS(I),KTS(I),KOS(I),I=1,NR)
      WRITE (6,51) (I,CIC(I),COC(I),CIP(I),COP(I),CIS(I),CAS(I),I=1,NR)
      WRITE (6,52)
      DO 26 J=1,NZ
26    WRITE (6,53) ZX(J),(I,YS(J,I),XS(J,I),YP(J,I),XP(J,I),I=1,NR)
      WRITE (6,54)
      WRITE (6,55) (I,YIS(I),XIS(I),ZIS(I),YIP(I),XIP(I),ZIP(I),YIC(I),X
     1IC(I),ZIC(I),I=1,NR)
      WRITE (6,56)
      WRITE (6,55) (I,YMS(I),XMS(I),ZMS(I),YMP(I),XMP(I),ZMP(I),YMC(I),X
     1MC(I),ZMC(I),I=1,NR)
      WRITE (6,57)
      WRITE (6,55) (I,YTS(I),XTS(I),ZTS(I),YTP(I),XTP(I),ZTP(I),YTC(I),X
     1TC(I),ZTC(I),I=1,NR)
      WRITE (6,58)
      WRITE (6,55) (I,YOS(I),XOS(I),ZOS(I),YOP(I),XOP(I),ZOP(I),YOC(I),X
     1OC(I),ZOC(I),I=1,NR)
27    CONTINUE
      IF (OP1.EQ.0.) GO TO 28
C              READ IN X-VALUES FOR BLADE SECTIONS
      NXQ=OP1
      READ (5,44) (XQ(K),K=1,NXQ)
      GO TO 30
C              BLADE SECTION X-VALUES AT BLADE ELEMENT STACKING POINTS
28    NXQ=NX
      DO 29 K=1,NXQ
29    XQ(K)=X(K)
      GO TO 34
C                  CALC. OF UNROTATED BLADE SECTION COORDINATES
30    DO 33 K=1,NXQ
```

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      DO 32 J=1,NZ
      DO 31 I=1,NR
      V(I)=XP(J,I)
      V1(I)=YP(J,I)
      V2(I)=XS(J,I)
31    V3(I)=YS(J,I)
      CALL SINTP (V,V1,NR,XQ(K),YPX(J))
32    CALL SINTP (V2,V3,NR,XQ(K),YSX(J))
      CALL SINTP (XIP,ZIP,NR,XQ(K),ZIPX(K))
      CALL SINTP (XIS,ZIS,NR,XQ(K),ZISX(K))
      CALL SINTP (XOP,ZOP,NR,XQ(K),ZOPX(K))
      CALL SINTP (XOS,ZOS,NR,XQ(K),ZOSX(K))
      CALL SINTP (ZX,YSX,NZ,ZISX(K),YISX(K))
      CALL SINTP (ZX,YSX,NZ,ZOSX(K),YOSX(K))
      CALL SINTP (ZX,YPX,NZ,ZIPX(K),YIPX(K))
      CALL SINTP (ZX,YPX,NZ,ZOPX(K),YOPX(K))
      WRITE (2) (YSX(J),J=1,NZ),(YPX(J),J=1,NZ)
33    CONTINUE
      REWIND 2
C
34    DO 35 K=1,NXQ
      ZICX(K)=.5*(ZISX(K)+ZIPX(K))
      CALL SINTP (XMC,ZMC,NR,XQ(K),ZMCX(K))
      CALL SINTP (XMP,ZMP,NR,XQ(K),ZMPX(K))
      CALL SINTP (XMS,ZMS,NR,XQ(K),ZMSX(K))
      ZOCX(K)=.5*(ZOSX(K)+ZOPX(K))
      CALL SINTP (XTC,ZTC,NR,XQ(K),ZTCX(K))
      CALL SINTP (XTP,ZTP,NR,XQ(K),ZTPX(K))
      CALL SINTP (XTS,ZTS,NR,XQ(K),ZTSX(K))
      YICX(K)=.5*(YISX(K)+YIPX(K))
      CALL SINTP (XMC,YMC,NR,XQ(K),YMCX(K))
      READ (2) (YSX(J),J=1,NZ),(YPX(J),J=1,NZ)
      CALL SINTP (ZX,YPX,NZ,ZMPX(K),YMPX(K))
      CALL SINTP (ZX,YSX,NZ,ZMSX(K),YMSX(K))
      YOCX(K)=.5*(YOSX(K)+YOPX(K))
      CALL SINTP (XTC,YTC,NR,XQ(K),YTCX(K))
      CALL SINTP (ZX,YPX,NZ,ZTPX(K),YTPX(K))
      CALL SINTP (ZX,YSX,NZ,ZTSX(K),YTSX(K))
      TIX(K)=SQRT((ZISX(K)-ZIPX(K))**2+(YISX(K)-YIPX(K))**2)
      TOX(K)=SQRT((ZOSX(K)-ZOPX(K))**2+(YOSX(K)-YOPX(K))**2)
      CALL SINTP (XMC,TM,NR,XQ(K),TMX(K))
      CALL SINTP (XCG,YCG,NR,XQ(K),YCGX(K))
      CALL SINTP (XCG,ZCG,NR,XQ(K),ZCGX(K))
35    CONTINUE
      REWIND 2
C              PRINT OUT UNROTATED BLADE SECTION COORDINATES
      DO 36 K=1,NXQ
      WRITE (6,59) XQ(K),ZICX(K),ZMCX(K),ZTCX(K),ZOCX(K),ZIPX(K),ZMPX(K)
     1,ZTPX(K),ZOPX(K),ZISX(K),ZMSX(K),ZTSX(K),ZOSX(K),ZCGX(K),YICX(K),Y
     2MCX(K),YTCX(K),YOCX(K),YIPX(K),YMPX(K),YTPX(K),YOPX(K),YISX(K),YMS
     3X(K),YTSX(K),YOSX(K),YCGX(K),TIX(K),TMX(K),TOX(K)
      READ (2) (YSX(J),J=1,NZ),(YPX(J),J=1,NZ)
      DO 36 J=1,NZ
36    WRITE (6,60) ZX(J),YPX(J),YSX(J)
      REWIND 2
C              CALC. OF ROTATED BLADE SECTION COORDINATES
      DO 42 K=1,NXQ
      READ (2) (YSX(J),J=1,NZ),(YPX(J),J=1,NZ)
      T1=ZOCX(K)-ZICX(K)
      T2=.5*(TOX(K)-TIX(K))
      T3=YOCX(K)-YICX(K)
```

```
      SGX=(-T1*T2+T3*SQRT(T1**2+T3**2-T2**2))/(T1**2+T3**2)
      GX=ARSIN(SGX)
      CGX=COS(GX)
      GAMX(K)=DEGRAD*GX
      T2=TIX(K)/2.
      DO 37 J=1,NZ
      T=ZX(J)-ZICX(K)
      V1(J)=(YSX(J)-YICX(K))*CGX-T*SGX+T2
      V2(J)=(YPX(J)-YICX(K))*CGX-T*SGX+T2
      V3(J)=(YSX(J)-YICX(K))*SGX+T*CGX+T2
37    V4(J)=(YPX(J)-YICX(K))*SGX+T*CGX+T2
      XHIC=T2
      XHOC=TOX(K)/2.
      T3=YICX(K)
      T4=ZICX(K)
      XHMC=(YMCX(K)-T3)*CGX-(ZMCX(K)-T4)*SGX+T2
      XHTC=(YTCX(K)-T3)*CGX-(ZTCX(K)-T4)*SGX+T2
      XHIP=(YIPX(K)-T3)*CGX-(ZIPX(K)-T4)*SGX+T2
      XHMP=(YMPX(K)-T3)*CGX-(ZMPX(K)-T4)*SGX+T2
      XHOP=(YOPX(K)-T3)*CGX-(ZOPX(K)-T4)*SGX+T2
      XHTP=(YTPX(K)-T3)*CGX-(ZTPX(K)-T4)*SGX+T2
      XHIS=(YISX(K)-T3)*CGX-(ZISX(K)-T4)*SGX+T2
      XHMS=(YMSX(K)-T3)*CGX-(ZMSX(K)-T4)*SGX+T2
      XHOS=(YOSX(K)-T3)*CGX-(ZOSX(K)-T4)*SGX+T2
      XHTS=(YTSX(K)-T3)*CGX-(ZTSX(K)-T4)*SGX+T2
      XHSP=(YCG(NR)-T3)*CGX-(ZCG(NR)-T4)*SGX+T2
      XHCG=(YCGX(K)-T3)*CGX-(ZCGX(K)-T4)*SGX+T2
      XLIC=T2
      XLMC=(YMCX(K)-T3)*SGX+(ZMCX(K)-T4)*CGX+T2
      XLOC=(YOCX(K)-T3)*SGX+(ZOCX(K)-T4)*CGX+T2
      XLTC=(YTCX(K)-T3)*SGX+(ZTCX(K)-T4)*CGX+T2
      XLIP=(YIPX(K)-T3)*SGX+(ZIPX(K)-T4)*CGX+T2
      XLMP=(YMPX(K)-T3)*SGX+(ZMPX(K)-T4)*CGX+T2
      XLOP=(YOPX(K)-T3)*SGX+(ZOPX(K)-T4)*CGX+T2
      XLTP=(YTPX(K)-T3)*SGX+(ZTPX(K)-T4)*CGX+T2
      XLIS=(YISX(K)-T3)*SGX+(ZISX(K)-T4)*CGX+T2
      XLMS=(YMSX(K)-T3)*SGX+(ZMSX(K)-T4)*CGX+T2
      XLOS=(YOSX(K)-T3)*SGX+(ZOSX(K)-T4)*CGX+T2
      XLTS=(YTSX(K)-T3)*SGX+(ZTSX(K)-T4)*CGX+T2
      XLSP=(YCG(NR)-T3)*SGX+(ZCG(NR)-T4)*CGX+T2
      XLCG=(YCGX(K)-T3)*SGX+(ZCGX(K)-T4)*CGX+T2
C
      XL(1)=0.
      DL=XLOC/53.
      DL=ADJ(DL)
C
      XHS(1)=XHIC
      XHP(1)=XHS(1)
      XL(2)=XLIC
      XL(3)=DL
      DO 38 J=4,55
      LOUT=J
      XL(J)=XL(J-1)+DL
38    IF (XL(J).GE.XLOC) GO TO 39
39    LOUT=LOUT+1
      XL(LOUT-1)=XLOC
      XL(LOUT)=XLOC+XHOC
      XHS(LOUT)=XHOC
      XHP(LOUT)=XHS(LOUT)
      JM=LOUT-1
      DO 40 J=2,JM
```

```
      CALL SINTP (V3,V1,NZ,XL(J),XHS(J))
40    CALL SINTP (V4,V2,NZ,XL(J),XHP(J))
C
      CALL CGS1
      BETA=BETA*DEGRAD
C              PRINT OUT ROTATED BLADE SECTION COORDINATES
      WRITE (6,61) XQ(K),GAMX(K),TIX(K),XLSP,LBAR,AREA,IMIN,ILLCG,PHLCG,
     1ILL,PHL,TMX(K),TOX(K),XHSP,HBAR,BETA,IMAX,IHHCG,IHH,XLIC,XLMC,XLTC
     2,XLOC,XLIP,XLMP,XLTP,XLOP,XLIS,XLMS,XLTS,XLOS,XLCG,XHIC,XHMC,XHTC,
     3XHOC,XHIP,XHMP,XHTP,XHOP,XHIS,XHMS,XHTS,XHOS,XHCG
      DO 41 J=1,LOUT
41    WRITE (6,60) XL(J),XHP(J),XHS(J)
42    CONTINUE
C
      GO TO 1
C
C
43    FORMAT (12A6)
44    FORMAT (8F10.5)
45    FORMAT (1H1//12A6)
46    FORMAT (1HK/30X,34HINPUT FOR BLADE COORDINATE PROGRAM//34X,3HETA,7
     1X,5HLAMDA,5X,3HOP1,7X,3HOP2,7X,5HTNLMT/29X,5F10.5//1X,7HELEMENT,4X
     2,2HRI,9X,2HRO,9X,2HTI,9X,2HTM,9X,2HTO,9X,3HKIC,8X,3HKTC,8X,3HKOC,8
     3X,3HZMC,8X,3HZTC,8X,3HZOC)
47    FORMAT (3X,I2,2X,11F11.5)
48    FORMAT (1HJ/43H BLADE ELEMENT STACKING PARAMETER--TNORM1 =,G10.3//
     16H THECG/8G16.7/8G16.7/8G16.7)
49    FORMAT (1HJ/5H CRCG/8G16.7/8G16.7/8G16.7)
50    FORMAT (1H1//20X,20HBLADE ELEMENT ANGLES//1X,7HELEMENT,4X,3HALP,8X
     1,2HKM,9X,3HKIC,8X,3HKTC,8X,3HKOC,8X,3HKIP,8X,3HKTP,8X,3HKOP,8X,3HK
     2IS,8X,3HKTS,8X,3HKOS/(3X,I2,2X,11F11.5))
51    FORMAT (1HK,20X,24HBLADE ELEMENT CURVATURES//1X,7HELEMENT,4X,3HCIC
     1,8X,3HCOC,8X,3HCIP,8X,3HCOP,8X,3HCIS,8X,3HCAS/(3X,I2,2X,6F11.5))
52    FORMAT (1H1//20X,25HBLADE ELEMENT COORDINATES)
53    FORMAT (1HL/30X,3HZ =,F10.5,//20X,7HELEMENT,15X,2HYS,12X,2HXS,28X,
     12HYP,12X,2HXP/(22X,I2,10X,2F14.5,16X,2F14.5))
54    FORMAT (1HL/1X,7HELEMENT,9X,3HYIS,9X,3HXIS,9X,3HZIS,13X,3HYIP,9X,3
     1HXIP,9X,3HZIP,13X,3HYIC,9X,3HXIC,9X,3HZIC)
55    FORMAT (3X,I2,6X,3F12.4,4X,3F12.4,4X,3F12.4)
56    FORMAT (1HL/1X,7HELEMENT,9X,3HYMS,9X,3HXMS,9X,3HZMS,13X,3HYMP,9X,3
     1HXMP,9X,3HZMP,13X,3HYMC,9X,3HXMC,9X,3HZMC)
57    FORMAT (1HL/1X,7HELEMENT,9X,3HYTS,9X,3HXTS,9X,3HZTS,13X,3HYTP,9X,3
     1HXTP,9X,3HZTP,13X,3HYTC,9X,3HXTC,9X,3HZTC)
58    FORMAT (1HL/1X,7HELEMENT,9X,3HYOS,9X,3HXOS,9X,3HZOS,13X,3HYOP,9X,3
     1HXOP,9X,3HZOP,13X,3HYOC,9X,3HXOC,9X,3HZOC)
59    FORMAT (1H1/40X,44HBLADE SECTION COORDINATES (UNROTATED) AT X =,F9
     1.4/5X,3HZIC,7X,3HZMC,7X,3HZTC,7X,3HZOC,7X,3HZIP,7X,3HZMP,7X,3HZTP,
     27X,3HZOP,7X,3HZIS,7X,3HZMS,7X,3HZTS,7X,3HZOS,7X,3HZCG/13F10.4/5X,3
     3HYIC,7X,3HYMC,7X,3HYTC,7X,3HYOC,7X,3HYIP,7X,3HYMP,7X,3HYTP,7X,3HYO
     4P,7X,3HYIS,7X,3HYMS,7X,3HYTS,7X,3HYOS,7X,3HYCG/13F10.4/5X,2HTI,8X,
     52HTM,8X,2HTO/3F10.4/44X,1HZ,9X,2HYP,8X,2HYS)
60    FORMAT (39X,3F10.4)
61    FORMAT (1H1/40X,42HBLADE SECTION COORDINATES (ROTATED) AT X =,F9.4
     1/5X,5HGAMMA,5X,2HTI,8X,5HL(SP),5X,5HL-BAR,5X,4HAREA,8X,4HIMIN,8X,5
     2HILLCG,7X,5HPHLCG,7X,5HI(LL),7X,3HPHL/4F10.4,2X,6G12.4/5X,2HTM,8X,
     32HTO,8X,5HH(SP),5X,5HH-BAR,5X,4HBETA,8X,4HIMAX,8X,5HIHHCG,19X,5HI(
     4HH)/4F10.4,2X,3G12.4,12X,G12.4/5X,5HL(IC),5X,5HL(MC),5X,5HL(TC),5X
     5,5HL(OC),5X,5HL(IP),5X,5HL(MP),5X,5HL(TP),5X,5HL(OP),5X,5HL(IS),5X
     6,5HL(MS),5X,5HL(TS),5X,5HL(OS),5X,5HL(CG)/13F10.4/5X,5HH(IC),5X,5H
     7H(MC),5X,5HH(TC),5X,5HH(OC),5X,5HH(IP),5X,5HH(MP),5X,5HH(TP),5X,5H
     8H(OP),5X,5HH(IS),5X,5HH(MS),5X,5HH(TS),5X,5HH(OS),5X,5HH(CG)/13F10
     9.4/44X,1HL,9X,2HHP,8X,2HHS)
      END
```

```
      SUBROUTINE ITER (K2,C,B,K1,E1,R1,E2,R2,XK)
      REAL K1,K2
      Z=E2-E1
      K2=XK
      IGO=1
      IT=0
      DK=.1
1     C=(SIN(K1)-SIN(K2))/(R2-R1)
      B=C*R1+SIN(K1)
      F=Z-SUBF(K2,K1,B,R2,R1)
      IT=IT+1
      IF (IT.GE.10) IGO=3
      GO TO (2,3,6),IGO
2     TK=K2
      TF=F
      K2=TK+DK
      IGO=2
      GO TO 1
3     IF (F*TF.LE.0.0) GO TO 5
      IF (ABS(F).GT.ABS(TF)) GO TO 4
      TK=K2
      TF=F
      K2=TK+DK
      GO TO 1
4     DK=-DK
      K2=TK+DK
      GO TO 1
5     IF (ABS(R2*F).LT..0001) IGO=3
      DK=TF*DK/(TF-F)
      K2=TK+DK
      GO TO 1
6     RETURN
      END
```

```
      SUBROUTINE ITER1 (KT,RT,ET,KM,RM,EM,B,C,KTC,RTC,ETC)
      REAL KM,KT,KTC
      IGO=1
      IT=0
      RT=RTC
1     SNKT=SIN(KM)+C*(RM-RT)
      CALL FIX (SNKT,KT)
      ET=EM+SUBF(KT,KM,B,RT,RM)
      RTC2=RT/EXP(TAN(KTC)*(ETC-ET))
      F=RTC-RTC2
      IT=IT+1
      IF (IT.GE.10) IGO=3
      GO TO (2,3,6),IGO
2     R2=RT
      F2=F
      DEL=F
      RT=RT+DEL
```

```
      IGO=2
      GO TO 1
3     IF (F*F2.LE.0.0) GO TO 5
      IF (ABS(F).GT.ABS(F2)) GO TO 4
      R2=RT
      F2=F
      RT=RT+DEL
      GO TO 1
4     DEL=-DEL
      RT=R2+DEL
      GO TO 1
5     IF (ABS(F2).LT..0001) IGO=3
      DEL=F2*DEL/(F2-F)
      RT=R2+DEL
      GO TO 1
6     RETURN
      END
```

```
      SUBROUTINE SINTP (Z,W,N,X1,Y1)
      DIMENSION X(56), Y(56), Z(56), W(56)
      DO 1 I=1,N
      X(I)=Z(I)
1     Y(I)=W(I)
      CALL SORTXY (X,Y,N)
C
      K=1
      DO 2 I=1,N
      IF (X1.GT.X(I)) GO TO 2
      IF (X1.EQ.X(I)) GO TO 3
      IF (X1.LT.X(I)) GO TO 4
2     K=I+1
      GO TO 4
3     Y1=Y(K)
      RETURN
4     IF (K.EQ.1) GO TO 5
      IF (K.GT.N) GO TO 6
      IF (K.EQ.N) K=N-1
      W1=(X1-X(K))*(X1-X(K+1))/(X(K-1)-X(K))/(X(K-1)-X(K+1))
      W2=(X1-X(K-1))*(X1-X(K+1))/(X(K)-X(K-1))/(X(K)-X(K+1))
      W3=(X1-X(K-1))*(X1-X(K))/(X(K+1)-X(K-1))/(X(K+1)-X(K))
      Y1=Y(K-1)*W1+Y(K)*W2+Y(K+1)*W3
      RETURN
5     J=1
      L=2
      GO TO 7
6     J=N-1
      L=N
7     Y1=Y(J)+(X1-X(J))*(Y(L)-Y(J))/(X(L)-X(J))
      RETURN
      END
```

```
      SUBROUTINE CGS (YCG,ZCG,YIPX,ZIPX,YISX,ZISX,YPX,YSX,NZ,ZX,YOPX.ZOP
     1X,YOSX,ZOSX)
C
      DIMENSION V(51), V1(51), V2(51), V3(51), YPX(50), YSX(50), ZX(50)
C
      DYI=YISX-YIPX
      DZI=ZISX-ZIPX
      DZO=ZOSX-ZOPX
      DYO=YOSX-YOPX
C
      TI2=DYI**2+DZI**2
      TO2=DYO**2+DZO**2
C
      TIX=SQRT(TI2)
      TOX=SQRT(TO2)
C
      SINBI=-DZI/TIX
      SINBO=-DZO/TOX
      COSBI=DYI/TIX
      COSBO=DYO/TOX
C
      KZI=2
      IF (DZI.GE.0.0) KZI=1
C
      GO TO (1,2),KZI
1     ZMIN=ZIPX
      ZMIN2=ZISX
      GO TO 3
2     ZMIN=ZISX
      ZMIN2=ZIPX
3     KZO=2
      IF (DZO.GE.0.0) KZO=1
C
      GO TO (4,5),KZO
4     ZMAX=ZOSX
      ZMAX2=ZOPX
      GO TO 6
5     ZMAX=ZOPX
      ZMAX2=ZOSX
C
6     DZ=(ZMAX-ZMIN)/50.
      Z=ZMIN
C
      DO 14 I=1,51
      IF (Z.GE.ZMIN2) GO TO 9
      GO TO (7,8),KZI
7     YS=YIPX+(Z-ZIPX)*DYI/DZI
      CALL SINTP (ZX,YPX,NZ,Z,YP)
      GO TO 13
8     YP=YISX+(Z-ZISX)*DYI/DZI
```

```
      CALL SINTP (ZX,YSX,NZ,Z,YS)
      GO TO 13
9     IF (Z.GT.ZMAX2) GO TO 10
      CALL SINTP (ZX,YSX,NZ,Z,YS)
      CALL SINTP (ZX,YPX,NZ,Z,YP)
      GO TO 13
10    GO TO (11,12),KZO
11    YP=YOPX+(Z-ZOPX)*DYO/DZO
      CALL SINTP (ZX,YSX,NZ,Z,YS)
      GO TO 13
12    YS=YOSX+(Z-ZOSX)*DYO/DZO
      CALL SINTP (ZX,YPX,NZ,Z,YP)
C
13    V(I)=YS-YP
      V1(I)=.5*(YS+YP)*V(I)
      V2(I)=Z*V(I)
14    Z=Z+DZ
      PIRAD=3.1415927
C
      T=PIRAD/8.0
      AI=TI2*T
      AO=TO2*T
C
      T=2./3./PIRAD
C
      YBI=(YISX+YIPX)/2.-T*TIX*SINBI
      YBO=(YOSX+YOPX)/2.+T*TOX*SINBO
C
      ZBI=(ZISX+ZIPX)/2.-TIX*COSBI*T
      ZBO=(ZOSX+ZOPX)/2.+T*TOX*COSBO
C
      CALL FNTGRL (51,DZ,V,V3)
      A=V3(51)+AI+AO
C
      CALL FNTGRL (51,DZ,V1,V3)
      YCG=(V3(51)+YBI*AI+YBO*AO)/A
C
      CALL FNTGRL (51,DZ,V2,V3)
      ZCG=(V3(51)+ZBI*AI+ZBO*AO)/A
C
      RETURN
      END
```

```
      SUBROUTINE FIX (A,B)
      IF (ABS(A).LT.1.) GO TO 1
      T=1.
      IF (A.LT.0.) T=-1.
      B=T*1.570795
      RETURN
1     B=ARSIN(A)
      RETURN
      END
```

```
      SUBROUTINE CGS1
      DIMENSION X(56), HS(56), HP(56), V(56), V1(56), V2(56), V3(56), X1
     1(56)
      COMMON /EXTRA/ X,HS,HP,N,LBAR,HBAR,ILL,IHH,PHL,AREA,ILLCG,IHHCG,PH
     1LCG,BETA,IMIN,IMAX
      REAL LBAR,ILL,IHH,ILLCG,IHHCG,IMIN,IMAX
      DX=X(N)/49.
      X1(1)=0.
      DO 1 I=1,50
      CALL SINTP (X,HS,N,X1(I),V(I))
      CALL SINTP (X,HP,N,X1(I),V1(I))
    1 X1(I+1)=X1(I)+DX
      DO 2 I=1,50
    2 V2(I)=V(I)-V1(I)
      CALL FNTGRL (50,DX,V2,V3)
      AREA=V3(50)
      DO 3 I=1,50
    3 V2(I)=V2(I)*X1(I)
      CALL FNTGRL (50,DX,V2,V3)
      LBAR=V3(50)/AREA
      DO 4 I=1,50
    4 V2(I)=V2(I)*X1(I)
      CALL FNTGRL (50,DX,V2,V3)
      IHH=V3(50)
      DO 5 I=1,50
    5 V2(I)=V(I)**2-V1(I)**2
      CALL FNTGRL (50,DX,V2,V3)
      HBAR=V3(50)/2./AREA
      DO 6 I=1,50
    6 V2(I)=V2(I)*X1(I)
      CALL FNTGRL (50,DX,V2,V3)
      PHL=V3(50)/2.
      DO 7 I=1,50
    7 V2(I)=V(I)**3-V1(I)**3
      CALL FNTGRL (50,DX,V2,V3)
      ILL=V3(50)/3.
      IHHCG=IHH-AREA*LBAR**2
      ILLCG=ILL-AREA*HBAR**2
      PHLCG=PHL-AREA*HBAR*LBAR
      BETA=ATAN(2.*PHLCG/(IHHCG-ILLCG))
      IMIN=(ILLCG+IHHCG)/2.+(ILLCG-IHHCG)/2.*COS(BETA)-PHLCG*SIN(BETA)
      IMAX=(ILLCG+IHHCG)-IMIN
      BETA=BETA/2.
      RETURN
      END
```

```
      SUBROUTINE XMAX (X,XM,N)
      DIMENSION X(100)
      XM=X(1)
      DO 1 I=2,N
      IF (X(I).LT.XM) GO TO 1
      XM=X(I)
    1 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE XMIN (X,XM,N)
      DIMENSION X(100)
      XM=X(1)
      DO 1 I=2,N
      IF (X(I).GT.XM) GO TO 1
      XM=X(I)
1     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE NEED (IC,I)
      DIMENSION ALP(24), BOC(24), BIC(24), BIP(24), BIS(24), BOP(24), BO
     1S(24), CIS(24), COP(24), CAS(24), CIC(24), EIP(24), EIS(24), EMC(2
     24), EMP(24), EMS(24), EOC(24), EOP(24), EOS(24), ETC(24), ETP(24),
     3 ETS(24), KIC(24), KIP(24), KIS(24), KM(24), KOC(24), KOP(24), KOS
     4(24), KTC(24), KTP(24), KTS(24), RI(24), RO(24), RIC(24), RIP(24),
     5 RIS(24), RMC(24), RMP(24), RMS(24), ROC(24), ROP(24), ROS(24), RT
     6C(24), RTP(24), RTS(24), TI(24), TM(24), TO(24), ZMC(24), ZOC(24),
     7 ZTC(24), COC(24), CIP(24)
      COMMON ALP,BOC,BIC,BIP,BIS,BOP,BOS,CIP,CIS,COP,CAS,CIC,EIP,EIS,EMC
     1,EMP,EMS,EOC,EOP,EOS,ETC,ETP,ETS,KIC,KIP,KIS,KM,KOC,KOP,KOS,KTC,KT
     2P,KTS,RI,RO,RIC,RIP,RIS,RMC,RMP,RMS,ROC,ROP,ROS,RTC,RTP,RTS,TI,TM,
     3TO,ZMC,ZOC,ZTC,NR,COC
      REAL KIC,KIP,KIS,KM,KOC,KOP,KOS,KTC,KTP,KTS,LAMDA
C
C     CALC. OF BLADE ELEMENT SURFACE PARAMETERS
C
      GO TO (1,2,3),IC
C
C     TRANSITION AT MAX. THICKNESS
C
1     KM(I)=KTC(I)
      EMC(I)=ETC(I)
      CALL RAEP (RMP(I),RMS(I),EMP(I),EMS(I),RMC(I),EMC(I),KM(I),TM(I))
      KTP(I)=KTC(I)
      KTS(I)=KTC(I)
      ETP(I)=EMP(I)
      ETS(I)=EMS(I)
      RTP(I)=RMP(I)
      RTS(I)=RMS(I)
C
      CALL ITER (KIP(I),CIP(I),BIP(I),KTP(I),ETP(I),RTP(I),EIP(I),RIP(I)
     1,KIC(I))
      CALL ITER (KIS(I),CIS(I),BIS(I),KTS(I),ETS(I),RTS(I),EIS(I),RIS(I)
     1,KIC(I))
      CALL ITER (KOP(I),COP(I),BOP(I),KTP(I),ETP(I),RTP(I),EOP(I),ROP(I)
     1,KOC(I))
      CALL ITER (KOS(I),CAS(I),BOS(I),KTS(I),ETS(I),RTS(I),EOS(I),ROS(I)
     1,KOC(I))
      RETURN
C
C     TRANSITION AHEAD OF MAX. THICKNESS
C
2     SINKM=BOC(I)-COC(I)*RMC(I)
      KM(I)=ARSIN(SINKM)
      EMC(I)=ETC(I)+SUBF(KM(I),KTC(I),BOC(I),RMC(I),RTC(I))
      CALL RAEP (RMP(I),RMS(I),EMP(I),EMS(I),RMC(I),EMC(I),KM(I),TM(I))
      CALL ITER (KOP(I),COP(I),BOP(I),KM(I),EMP(I),RMP(I),EOP(I),ROP(I),
     1KOC(I))
      CALL ITER (KOS(I),CAS(I),BOS(I),KM(I),EMS(I),RMS(I),EOS(I),ROS(I),
```

```
     1KOC(I))
      CALL ITER1 (KTP(I),RTP(I),ETP(I),KM(I),RMP(I),EMP(I),BOP(I),COP(I)
     1,KTC(I),RTC(I),ETC(I))
      CALL ITER1 (KTS(I),RTS(I),ETS(I),KM(I),RMS(I),EMS(I),BOS(I),CAS(I)
     1,KTC(I),RTC(I),ETC(I))
      CALL ITER (KIP(I),CIP(I),BIP(I),KTP(I),ETP(I),RTP(I),EIP(I),RIP(I)
     1,KIC(I))
      CALL ITER (KIS(I),CIS(I),BIS(I),KTS(I),ETS(I),RTS(I),EIS(I),RIS(I)
     1,KIC(I))
      RETURN
C
C     TRANSITION BEHIND MAX. THICKNESS
C
3     SINKM=BIC(I)-CIC(I)*RMC(I)
      KM(I)=ARSIN(SINKM)
      EMC(I)=ETC(I)+SUBF(KM(I),KTC(I),BIC(I),RMC(I),RTC(I))
      CALL RAEP (RMP(I),RMS(I),EMP(I),EMS(I),RMC(I),EMC(I),KM(I),TM(I))
      CALL ITER (KIP(I),CIP(I),BIP(I),KM(I),EMP(I),RMP(I),EIP(I),RIP(I),
     1KIC(I))
      CALL ITER (KIS(I),CIS(I),BIS(I),KM(I),EMS(I),RMS(I),EIS(I),RIS(I),
     1KIC(I))
      CALL ITER1 (KTP(I),RTP(I),ETP(I),KM(I),RMP(I),EMP(I),BIP(I),CIP(I)
     1,KTC(I),RTC(I),ETC(I))
      CALL ITER1 (KTS(I),RTS(I),ETS(I),KM(I),RMS(I),EMS(I),BIS(I),CIS(I)
     1,KTC(I),RTC(I),ETC(I))
      CALL ITER (KOP(I),COP(I),BOP(I),KTP(I),ETP(I),RTP(I),EOP(I),ROP(I)
     1,KOC(I))
      CALL ITER (KOS(I),CAS(I),BOS(I),KTS(I),ETS(I),RTS(I),EOS(I),ROS(I)
     1,KOC(I))
      RETURN
      END
```

```
      FUNCTION SUBF (X,XO,B,R,RO)
      IF (X.EQ.XO) GO TO 3
      B2=B*B
      IF (B2.LT.1.) GO TO 1
      IF (B2.GT.1.) GO TO 2
      T=1.
      IF (B.EQ.-1.0) T=-1.
      T1=.7854+T*X/2.
      T2=.7854+T*XO/2.
      SUBF=(X-XO)-T*(TAN(T1)-TAN(T2))
      RETURN
1     T=TAN(X/2.)
      T1=TAN(XO/2.)
      T2=SQRT(1.-B2)
      SUBF=(X-XO)+B/T2*(ALOG(ABS((-B*T+1.-T2)/(-B*T+1.+T2)))-ALOG(ABS((-
     1B*T1+1.-T2)/(-B*T1+1.+T2))))
      RETURN
2     T=TAN(X/2.)
      T1=TAN(XO/2.)
      T2=SQRT(B2-1.)
      SUBF=2.*B/T2*(ATAN((-B*T+1.)/T2)-ATAN((-B*T1+1.)/T2))+(X-XO)
      RETURN
3     SUBF=TAN(X)*ALOG(R/RO)
      RETURN
      END
```

```
      SUBROUTINE INTGR (L,X1,X2,X3)
      DIMENSION ALP(24), BOC(24), BIC(24), BIP(24), BIS(24), BOP(24), BO
     1S(24), CIS(24), COP(24), CAS(24), CIC(24), EIP(24), EIS(24), EMC(2
     24), EMP(24), EMS(24), EOC(24), EOP(24), EOS(24), ETC(24), ETP(24),
     3 ETS(24), KIC(24), KIP(24), KIS(24), KM(24), KOC(24), KOP(24), KOS
     4( 24), KTC(24), KTP(24), KTS(24), RI(24), RO(24), RIC(24), RIP(24),
     5 RIS(24), RMC(24), RMP(24), RMS(24), ROC(24), ROP(24), ROS(24), RT
     6C(24), RTP(24), RTS(24), TI(24), TM(24), TO(24), ZMC(24), ZOC(24),
     7 ZTC(24), COC(24), CIP(24)
      COMMON ALP,BOC,BIC,BIP,BIS,BOP,BOS,CIP,CIS,COP,CAS,CIC,EIP,EIS,EMC
     1,EMP,EMS,EOC,EOP,EOS,ETC,ETP,ETS,KIC,KIP,KIS,KM,KOC,KOP,KOS,KTC,KT
     2P,KTS,RI,RO,RIC,RIP,RIS,RMC,RMP,RMS,ROC,ROP,ROS,RTC,RTP,RTS,TI,TM,
     3TO,ZMC,ZOC,ZTC,NR,COC
      REAL KIC,KIP,KIS,KM,KOC,KOP,KOS,KTC,KTP,KTS,LAMDA
      DIMENSION F1(101), F2(101), F3(101), V(101)
      RMAX=ROC(L)
      RMIN=RIC(L)
      DR=(RMAX-RMIN)/100.
      R=RMIN
      SNKTS=SIN(KTS(L))
      SNKTR=SIN(KTP(L))
C
      DO 5 I=1,101
      IF (R.GE.RTS(L)) GO TO 1
      SNKS=BIS(L)-R*CIS(L)
      XKS=ARSIN(SNKS)
      EMAX=ETS(L)+SUBF(XKS,KTS(L),BIS(L),R,RTS(L))
      GO TO 2
C
1     SNKS=BOS(L)-R*CAS(L)
      XKS=ARSIN(SNKS)
      EMAX=ETS(L)+SUBF(XKS,KTS(L),BOS(L),R,RTS(L))
C
2     IF (R.GE.RTP(L)) GO TO 3
      SNKP=BIP(L)-R*CIP(L)
      XKP=ARSIN(SNKP)
      EMIN=ETP(L)+SUBF(XKP,KTP(L),BIP(L),R,RTP(L))
      GO TO 4
C
3     SNKP=BOP(L)-R*COP(L)
      XKP=ARSIN(SNKP)
      EMIN=ETP(L)+SUBF(XKP,KTP(L),BOP(L),R,RTP(L))
4     F3(I)=(EMAX-EMIN)*R
      F2(I)=R*F3(I)
      F1(I)=.5*(EMAX+EMIN)*F3(I)
5     R=R+DR
      CALL FNTGRL (101,DR,F1,V)
      X1=V(101)
      CALL FNTGRL (101,DR,F2,V)
      X2=V(101)
```

```
      CALL FNTGRL (101,DR,F3,V)
      X3=V(101)
      RETURN
      END
```

```
      FUNCTION ADJ (D)
      A=1.0
1     IF (D.GT.1.0) GO TO 2
      A=A/10.
      D=D*10.0
      GO TO 1
2     IF (D.LE.10.0) GO TO 3
      A=A*10.0
      D=D/10.0
      GO TO 2
3     IF (1.0.LT.D.AND.D.LE.2.0) ADJ=2.0*A
      IF (2.0.LT.D.AND.D.LE.5.0) ADJ=5.0*A
      IF (5.0.LT.D.AND.D.LE.10.0) ADJ=10.0*A
      RETURN
      END
```

```
      SUBROUTINE RAEP (RP,RS,EP,ES,RC,EC,XKC,TC)
      IF (XKC.EQ.0.0) GO TO 1
      V=TC/2.*SIN(XKC)
      RP=RC+V
      RS=RC-V
      V=COTAN(XKC)
      EP=EC+V*ALOG(RC/RP)
      ES=EC+V*ALOG(RC/RS)
      RETURN
1     RP=RC
      RS=RC
      V=TC/2./RC
      EP=EC-V
      ES=EC+V
      RETURN
      END
```

SAMPLE BLADE FOR BLADE COORDINATE PROGRAM

INPUT FOR BLADE COORDINATE PROGRAM

ETA	LAMDA	OP1	OP2	TNLMT
-1.00000	1.00000	5.00000	1.00000	0.00010

ELEMENT	RI	RO	TI	TM	TO	KIC	KTC	KOC	ZMC	ZTC	ZOC
1	20.00000	19.00000	0.10000	0.10000	0.10000	0.	0.	0.	1.00000	1.00000	2.00000
2	18.00000	17.80000	0.10000	0.10000	0.10000	8.50000	0.	-8.50000	1.00000	1.00000	2.00000
3	15.00000	15.01000	0.10000	0.10000	0.10000	24.00000	0.	-24.00000	1.00000	1.00000	2.00000
4	12.00000	13.00000	0.10000	0.10000	0.10000	37.00000	0.	-37.00000	1.00000	1.00000	2.00000
5	10.00000	12.00000	0.10000	0.10000	0.10000	45.00000	0.	-45.00000	1.00000	1.00000	2.00000

BLADE ELEMENT STACKING PARAMETER--TNORM1 = 0.287E-01

THECG
0 0.2764833E-02 0.9418329E-02 0.2063697E-01 0.3865755E-01

CRCG
-43.605685 -179.89311 3001.0398 27.955353 15.570537

BLADE ELEMENT STACKING PARAMETER--TNORM1 = 0.116E-02

THECG
0.2971571E-04 0.2676411E-02 0.9004142E-02 0.1988389E-01 0.3824395E-01

CRCG
-43.604660 -179.89522 3001.0386 27.954099 15.569048

BLADE ELEMENT STACKING PARAMETER--TNORM1 = 0.106E-03

THECG
0.2260716E-04 0.2676398E-02 0.9004064E-02 0.1984415E-01 0.3823225E-01

CRCG
-43.604774 -179.89527 3001.0386 27.954002 15.568880

BLADE ELEMENT STACKING PARAMETER--TNORM1 = 0.407E-04

THECG
0.2267188E-04 0.2676431E-02 0.9004018E-02 0.1983933E-01 0.3823117E-01

CRCG
-43.604771 -179.89527 3001.0386 27.953982 15.568888

BLADE ELEMENT ANGLES

ELEMENT	ALP	KM	KIC	KTC	KOC	KIP	KTP	KOP	KIS	KTS	KOS
1	-26.56506	0.	0.	0.	0.	-0.12886	0.	-0.13253	0.12886	0.	0.13253
2	-5.71060	0.	8.50000	0.	-8.50000	8.46652	0.	-8.53109	8.53185	0.	-8.46941
3	0.28648	0.	24.00000	0.	-24.00000	23.99986	0.	-24.00399	23.99423	0.	-24.00585
4	26.56506	0.	37.00000	0.	-37.00000	37.20314	0.	-36.80192	36.80208	0.	-37.19270
5	45.00002	0.	45.00000	0.	-45.00000	45.36453	0.	-44.65568	44.64384	0.	-45.33531

BLADE ELEMENT CURVATURES

ELEMENT	CIC	COC	CIP	COP	CIS	CAS
1	0.	0.	-0.00201	0.00207	0.00201	-0.00207
2	0.14708	0.14708	0.14759	0.14870	0.14655	0.14548
3	0.40674	0.40674	0.41517	0.41525	0.39853	0.39873
4	0.53828	0.53828	0.55577	0.55063	0.52177	0.52651
5	0.50000	0.50000	0.51607	0.50973	0.48476	0.49065

BLADE ELEMENT COORDINATES

Z = -0.00000

ELEMENT	YS	XS	YP	XP
1	-0.10329	20.07893	-0.20284	20.07817
2	-0.13970	18.01263	-0.24102	18.01156
3	-0.18675	14.99844	-0.29811	14.99664
4	-0.22718	11.98179	-0.35505	11.97868
5	-0.31272	9.99511	-0.45418	9.98968

Z = 0.10000

ELEMENT	YS	XS	YP	XP
1	-0.10276	20.02893	-0.20261	20.02817
2	-0.12341	18.00274	-0.22456	18.00177
3	-0.14173	14.99943	-0.25078	14.99800
4	-0.14975	12.03301	-0.27015	12.03091
5	-0.19367	10.09814	-0.32172	10.09487

Z = 0.20000

ELEMENT	YS	XS	YP	XP
1	-0.10225	19.97893	-0.20236	19.97817
2	-0.10867	17.99284	-0.20965	17.99195
3	-0.10180	15.00025	-0.20891	14.99914
4	-0.08308	12.08366	-0.19779	12.08232
5	-0.09354	10.19957	-0.21232	10.19779

Z = 0.30000

ELEMENT	YS	XS	YP	XP
1	-0.10177	19.92893	-0.20208	19.92817
2	-0.09545	17.98291	-0.19628	17.98210
3	-0.06673	15.00095	-0.17217	15.00011
4	-0.02594	12.13391	-0.13626	12.13318
5	-0.00916	10.30000	-0.12132	10.29929

Z = 0.40000

ELEMENT	YS	XS	YP	XP
1	-0.10131	19.87893	-0.20177	19.87817
2	-0.08375	17.97297	-0.18444	17.97222
3	-0.03630	15.00155	-0.14035	15.00094
4	0.02258	12.18392	-0.08436	12.18365
5	0.06156	10.39982	-0.04582	10.39990

Z = 0.50000

ELEMENT	YS	XS	YP	XP
1	-0.10088	19.82893	-0.20144	19.82817
2	-0.07357	17.96302	-0.17413	17.96232
3	-0.01033	15.00209	-0.11323	15.00167
4	0.06314	12.23378	-0.04121	12.23387
5	0.12006	10.49931	0.01608	10.49999

Z = 0.60000

ELEMENT	YS	XS	YP	XP
1	-0.10047	19.77894	-0.20109	19.77817
2	-0.06489	17.95305	-0.16533	17.95241
3	0.01128	15.00259	-0.09066	15.00232
4	0.09625	12.28356	-0.00617	12.28394
5	0.16732	10.59868	0.06570	10.59980

Z = 0.70000

ELEMENT	YS	XS	YP	XP
1	-0.10009	19.72894	-0.20070	19.72817
2	-0.05770	17.94307	-0.15804	17.94247
3	0.02869	15.00307	-0.07250	15.00292
4	0.12228	12.33334	0.02120	12.33392
5	0.20405	10.69805	0.10389	10.69950

Z = 0.80000

ELEMENT	YS	XS	YP	XP
1	-0.09972	19.67894	-0.20031	19.67817
2	-0.05202	17.93309	-0.15226	17.93252
3	0.04199	15.00354	-0.05866	15.00348
4	0.14147	12.38313	0.04125	12.38387
5	0.23069	10.79754	0.13126	10.79920

Z = 0.90000

ELEMENT	YS	XS	YP	XP
1	-0.09939	19.62894	-0.19988	19.62817
2	-0.04781	17.92310	-0.14797	17.92256
3	0.05119	15.00401	-0.04905	15.00402
4	0.15402	12.43299	0.05418	12.43382
5	0.24752	10.89719	0.14814	10.89899

Z = 1.00000

ELEMENT	YS	XS	YP	XP
1	-0.09909	19.57894	-0.19942	19.57818
2	-0.04510	17.91311	-0.14518	17.91258
3	0.05640	15.00449	-0.04363	15.00453
4	0.16002	12.48292	0.06013	12.48380
5	0.25468	10.99705	0.15469	10.99891

Z = 1.10000

ELEMENT	YS	XS	YP	XP
1	-0.09881	19.52894	-0.19894	19.52818
2	-0.04386	17.90311	-0.14388	17.90259
3	0.05762	15.00499	-0.04239	15.00504
4	0.15948	12.53293	0.05914	12.53380
5	0.25207	11.09714	0.15098	11.09897

Z = 1.20000

ELEMENT	YS	XS	YP	XP
1	-0.09854	19.47894	-0.19844	19.47818
2	-0.04411	17.89311	-0.14408	17.89259
3	0.05484	15.00550	-0.04528	15.00553
4	0.15232	12.58302	0.05122	12.58384
5	0.23947	11.19744	0.13689	11.19916

Z = 1.30000

ELEMENT	YS	XS	YP	XP
1	-0.09826	19.42894	-0.19796	19.42818
2	-0.04582	17.88311	-0.14577	17.88257
3	0.04806	15.00602	-0.05235	15.00601
4	0.13843	12.63318	0.03626	12.63389
5	0.21659	11.29792	0.11208	11.29944

Z = 1.40000

ELEMENT	YS	XS	YP	XP
1	-0.09796	19.37894	-0.19750	19.37819
2	-0.04901	17.87310	-0.14897	17.87255
3	0.03723	15.00655	-0.06363	15.00646
4	0.11764	12.68340	0.01404	12.68393
5	0.18293	11.39853	0.07601	11.39975

Z = 1.50000

ELEMENT	YS	XS	YP	XP
1	-0.09763	19.32894	-0.19707	19.32819
2	-0.05366	17.86309	-0.15367	17.86251
3	0.02234	15.00708	-0.07917	15.00689
4	0.08966	12.73363	-0.01574	12.73393
5	0.13783	11.49917	0.02794	11.49997

Z = 1.60000

ELEMENT	YS	XS	YP	XP
1	-0.09728	19.27895	-0.19666	19.27819
2	-0.05979	17.85307	-0.15988	17.85245
3	0.00327	15.00760	-0.09905	15.00727
4	0.05414	12.78383	-0.05351	12.78383
5	0.08034	11.59972	-0.03320	11.59995

Z = 1.70000

ELEMENT	YS	XS	YP	XP
1	-0.09690	19.22895	-0.19627	19.22819
2	-0.06739	17.84304	-0.16760	17.84238
3	-0.02008	15.00808	-0.12342	15.00759
4	0.01059	12.83394	-0.09982	12.83355
5	0.00921	11.70000	-0.10889	11.69949

Z = 1.80000

ELEMENT	YS	XS	YP	XP
1	-0.09650	19.17895	-0.19592	19.17819
2	-0.07647	17.83300	-0.17683	17.83229
3	-0.04779	15.00852	-0.15239	15.00782
4	-0.04163	12.88387	-0.15543	12.88300
5	-0.07736	11.79975	-0.20119	11.79828

Z = 1.90000

ELEMENT	YS	XS	YP	XP
1	-0.09607	19.12895	-0.19558	19.12819
2	-0.08704	17.82296	-0.18757	17.82218
3	-0.08005	15.00888	-0.18612	15.00794
4	-0.10337	12.93353	-0.22136	12.93205
5	-0.18187	11.89861	-0.31315	11.89588

Z = 2.00000

ELEMENT	YS	XS	YP	XP
1	-0.09561	19.07895	-0.19528	19.07819
2	-0.09910	17.81289	-0.19985	17.81205
3	-0.11702	15.00914	-0.22486	15.00791
4	-0.17575	12.98275	-0.29899	12.98050
5	-0.30808	11.99604	-0.44947	11.99158

Z = 2.10000

ELEMENT	YS	XS	YP	XP
1	-0.09513	19.02895	-0.19499	19.02819
2	-0.11265	17.80281	-0.21366	17.80189
3	-0.15899	15.00926	-0.26886	15.00769
4	-0.26034	13.03134	-0.39029	13.02810
5	-0.46201	12.09118	-0.61809	12.08420

Z = 2.20000

ELEMENT	YS	XS	YP	XP
1	-0.09463	18.97896	-0.19474	18.97819
2	-0.12772	17.79271	-0.22900	17.79169
3	-0.20613	15.00918	-0.31845	15.00722
4	-0.35933	13.07901	-0.49816	13.07445
5	-0.65448	12.18243	-0.83470	12.17141

ELEMENT	YIS	XIS	ZIS	YIP	XIP	ZIP	YIC	XIC	ZIC
1	-0.1025	19.9997	0.1584	-0.2025	19.9990	0.1584	-0.1525	19.9994	0.1584
2	-0.1197	18.0003	0.1243	-0.2186	17.9979	0.1390	-0.1691	17.9992	0.1317
3	-0.1591	14.9991	0.0600	-0.2505	14.9980	0.1007	-0.2048	14.9986	0.0804
4	-0.2229	11.9845	0.0052	-0.3033	12.0096	0.0590	-0.2631	11.9971	0.0321
5	-0.3460	9.9690	-0.0250	-0.4185	10.0163	0.0250	-0.3822	9.9927	-0.

ELEMENT	YMS	XMS	ZMS	YMP	XMP	ZMP	YMC	XMC	ZMC
1	-0.0987	19.4997	1.1584	-0.1986	19.4990	1.1584	-0.1487	19.4994	1.1584
2	-0.0438	17.8999	1.1317	-0.1438	17.8994	1.1317	-0.0938	17.8998	1.1317
3	0.0577	15.0049	1.0804	-0.0423	15.0049	1.0804	0.0077	15.0050	1.0804
4	0.1606	12.4990	1.0321	0.0606	12.4999	1.0321	0.1106	12.4995	1.0321
5	0.2547	10.9971	1.0000	0.1547	10.9989	1.0000	0.2047	10.9981	1.0000

ELEMENT	YTS	XTS	ZTS	YTP	XTP	ZTP	YTC	XTC	ZTC
1	-0.0987	19.4997	1.1584	-0.1986	19.4990	1.1584	-0.1487	19.4994	1.1584
2	-0.0438	17.8999	1.1317	-0.1438	17.8994	1.1317	-0.0938	17.8998	1.1317
3	0.0577	15.0049	1.0804	-0.0423	15.0049	1.0804	0.0077	15.0050	1.0804
4	0.1606	12.4990	1.0321	0.0606	12.4999	1.0321	0.1106	12.4995	1.0321
5	0.2547	10.9971	1.0000	0.1547	10.9989	1.0000	0.2047	10.9981	1.0000

ELEMENT	YOS	XOS	ZOS	YOP	XOP	ZOP	YOC	XOC	ZOC
1	-0.0948	18.9998	2.1584	-0.1948	18.9990	2.1584	-0.1448	18.9994	2.1584
2	-0.1184	17.7989	2.1390	-0.2172	17.7994	2.1243	-0.1678	17.7992	2.1317
3	-0.1593	15.0093	2.1007	-0.2506	15.0078	2.0600	-0.2049	15.0086	2.0804
4	-0.2241	13.0115	2.0590	-0.3034	12.9830	2.0052	-0.2638	12.9973	2.0321
5	-0.3437	12.0201	2.0250	-0.4128	11.9679	1.9750	-0.3782	11.9940	2.0000

BLADE SECTION COORDINATES (UNROTATED) AT X = 11.0000

ZIC	ZMC	ZTC	ZOC	ZIP	ZMP	ZTP	ZOP	ZIS	ZMS	ZTS	ZOS	ZCG
0.0161	1.0000	1.0000	1.9681	0.0424	1.0000	1.0000	1.9462	-0.0102	1.0001	1.0001	1.9900	1.0087
YIC	YMC	YTC	YOC	YIP	YMP	YTP	YOP	YIS	YMS	YTS	YOS	YCG
-0.3126	0.2046	0.2046	-0.4496	-0.3519	0.1546	0.1546	-0.4796	-0.2732	0.2545	0.2545	-0.4196	0.0002
TI	TM	TO										
0.0947	0.1000	0.0743										

Z	YP	YS
-0.0000	-0.3977	-0.2636
0.1000	-0.2938	-0.1694
0.2000	-0.2040	-0.0869
0.3000	-0.1263	-0.0147
0.4000	-0.0591	0.0483
0.5000	-0.0014	0.1028
0.6000	0.0473	0.1491
0.7000	0.0872	0.1875
0.8000	0.1186	0.2181
0.9000	0.1412	0.2405
1.0000	0.1546	0.2545
1.1000	0.1573	0.2583
1.2000	0.1492	0.2519
1.3000	0.1291	0.2340
1.4000	0.0953	0.2032
1.5000	0.0454	0.1573
1.6000	-0.0224	0.0936
1.7000	-0.1145	0.0084
1.8000	-0.2349	-0.1037
1.9000	-0.3925	-0.2500
2.0000	-0.6003	-0.4417
2.1000	-0.8798	-0.6961
2.2000	-1.2713	-1.0437

BLADE SECTION COORDINATES (UNROTATED) AT X = 13.0000

ZIC	ZMC	ZTC	ZOC	ZIP	ZMP	ZTP	ZOP	ZIS	ZMS	ZTS	ZOS	ZCG
0.0479	1.0420	1.0420	2.0322	0.0732	1.0420	1.0420	2.0057	0.0226	1.0421	1.0421	2.0587	1.0436
YIC	YMC	YTC	YOC	YIP	YMP	YTP	YOP	YIS	YMS	YTS	YOS	YCG
-0.2407	0.0889	0.0889	-0.2641	-0.2827	0.0390	0.0390	-0.3029	-0.1987	0.1390	0.1390	-0.2252	-0.0348
TI	TM	TO										
0.0981	0.1000	0.0940										

Z	YP	YS
-0.0000	-0.3358	-0.2143
0.1000	-0.2645	-0.1482
0.2000	-0.2024	-0.0902
0.3000	-0.1484	-0.0396
0.4000	-0.1020	0.0041
0.5000	-0.0626	0.0414
0.6000	-0.0299	0.0725
0.7000	-0.0036	0.0976
0.8000	0.0164	0.1167
0.9000	0.0301	0.1301
1.0000	0.0377	0.1376
1.1000	0.0389	0.1392
1.2000	0.0338	0.1346
1.3000	0.0219	0.1237
1.4000	0.0030	0.1061
1.5000	-0.0234	0.0815
1.6000	-0.0579	0.0491
1.7000	-0.1013	0.0084
1.8000	-0.1548	-0.0416
1.9000	-0.2197	-0.1022
2.0000	-0.2981	-0.1751
2.1000	-0.3955	-0.2655
2.2000	-0.5198	-0.3796

BLADE SECTION COORDINATES (UNROTATED) AT X = 15.0000

ZIC	ZMC	ZTC	ZOC	ZIP	ZMP	ZTP	ZOP	ZIS	ZMS	ZTS	ZOS	ZCG
0.0804	1.0803	1.0803	2.0802	0.1007	1.0803	1.0803	2.0598	0.0601	1.0803	1.0803	2.1005	1.0785
YIC	YMC	YTC	YOC	YIP	YMP	YTP	YOP	YIS	YMS	YTS	YOS	YCG
-0.2048	0.0079	0.0079	-0.2052	-0.2504	-0.0421	-0.0421	-0.2508	-0.1591	0.0579	0.0579	-0.1596	-0.0697
TI	TM	TO										
0.1000	0.1000	0.0999										

Z	YP	YS
-0.0000	-0.2980	-0.1867
0.1000	-0.2508	-0.1417
0.2000	-0.2089	-0.1018
0.3000	-0.1722	-0.0667
0.4000	-0.1403	-0.0363
0.5000	-0.1132	-0.0103
0.6000	-0.0906	0.0114
0.7000	-0.0724	0.0288
0.8000	-0.0585	0.0421
0.9000	-0.0489	0.0513
1.0000	-0.0435	0.0566
1.1000	-0.0422	0.0578
1.2000	-0.0451	0.0550
1.3000	-0.0521	0.0483
1.4000	-0.0634	0.0374
1.5000	-0.0790	0.0225
1.6000	-0.0989	0.0034
1.7000	-0.1233	-0.0200
1.8000	-0.1524	-0.0477
1.9000	-0.1862	-0.0801
2.0000	-0.2251	-0.1172
2.1000	-0.2692	-0.1593
2.2000	-0.3189	-0.2067

BLADE SECTION COORDINATES (UNROTATED) AT X = 18.0000

ZIC	ZMC	ZTC	ZOC	ZIP	ZMP	ZTP	ZOP	ZIS	ZMS	ZTS	ZOS	ZCG
0.1317	1.1334	1.1334	2.1360	0.1391	1.1334	1.1334	2.1298	0.1243	1.1334	1.1334	2.1422	1.1309
YIC	YMC	YTC	YOC	YIP	YMP	YTP	YOP	YIS	YMS	YTS	YOS	YCG
-0.1691	-0.0972	-0.0972	-0.1644	-0.2185	-0.1472	-0.1472	-0.2140	-0.1197	-0.0472	-0.0472	-0.1148	-0.1220
TI	TM	TO										
0.0999	0.1000	0.1000										

Z	YP	YS
-0.0000	-0.2412	-0.1399
0.1000	-0.2246	-0.1234
0.2000	-0.2096	-0.1087
0.3000	-0.1964	-0.0955
0.4000	-0.1848	-0.0841
0.5000	-0.1748	-0.0742
0.6000	-0.1664	-0.0659
0.7000	-0.1595	-0.0592
0.8000	-0.1542	-0.0540
0.9000	-0.1504	-0.0502
1.0000	-0.1481	-0.0480
1.1000	-0.1472	-0.0472
1.2000	-0.1478	-0.0478
1.3000	-0.1497	-0.0497
1.4000	-0.1530	-0.0530
1.5000	-0.1576	-0.0576
1.6000	-0.1635	-0.0635
1.7000	-0.1706	-0.0705
1.8000	-0.1789	-0.0787
1.9000	-0.1884	-0.0880
2.0000	-0.1989	-0.0984
2.1000	-0.2104	-0.1097
2.2000	-0.2228	-0.1219

BLADE SECTION COORDINATES (UNROTATED) AT X = 19.5000

ZIC	ZMC	ZTC	ZOC	ZIP	ZMP	ZTP	ZOP	ZIS	ZMS	ZTS	ZOS	ZCG
0.1523	1.1584	1.1584	2.1695	0.1540	1.1584	1.1584	2.1726	0.1505	1.1584	1.1584	2.1664	1.1571
YIC	YMC	YTC	YOC	YIP	YMP	YTP	YOP	YIS	YMS	YTS	YOS	YCG
-0.1565	-0.1487	-0.1487	-0.1326	-0.2064	-0.1987	-0.1987	-0.1821	-0.1066	-0.0987	-0.0987	-0.0831	-0.1482
TI	TM	TO										
0.0999	0.1000	0.0992										

Z	YP	YS
-0.0000	-0.2134	-0.1138
0.1000	-0.2087	-0.1088
0.2000	-0.2047	-0.1046
0.3000	-0.2015	-0.1012
0.4000	-0.1990	-0.0986
0.5000	-0.1973	-0.0968
0.6000	-0.1962	-0.0956
0.7000	-0.1956	-0.0951
0.8000	-0.1957	-0.0951
0.9000	-0.1961	-0.0957
1.0000	-0.1969	-0.0966
1.1000	-0.1980	-0.0978
1.2000	-0.1992	-0.0993
1.3000	-0.2004	-0.1007
1.4000	-0.2014	-0.1019
1.5000	-0.2022	-0.1028
1.6000	-0.2024	-0.1031
1.7000	-0.2019	-0.1027
1.8000	-0.2005	-0.1013
1.9000	-0.1979	-0.0986
2.0000	-0.1938	-0.0944
2.1000	-0.1878	-0.0884
2.2000	-0.1797	-0.0801

BLADE SECTION COORDINATES (ROTATED) AT X = 11.0000

GAMMA	TI	L(SP)	L-BAR	AREA	IMIN	ILLCG	PHLCG	I(LL)	PHL
-3.7191	0.0947	1.0177	1.0143	0.2252	0.8117E-02	0.8394E-02	0.4536E-02	0.4830E-01	0.1007
TM	TO	H(SP)	H-BAR	BETA	IMAX	IHHCG		I(HH)	
0.1000	0.0743	0.4236	0.4209	3.4890	0.8279E-01	0.8251E-01		0.3142	

L(IC)	L(MC)	L(TC)	L(OC)	L(IP)	L(MP)	L(TP)	L(OP)	L(IS)	L(MS)	L(TS)	L(OS)	L(CG)
0.0473	0.9956	0.9956	2.0041	0.0761	0.9989	0.9989	1.9842	0.0185	0.9924	0.9924	2.0240	1.0176
H(IC)	H(MC)	H(TC)	H(OC)	H(IP)	H(MP)	H(TP)	H(OP)	H(IS)	H(MS)	H(TS)	H(OS)	H(CG)
0.0473	0.6272	0.6272	0.0371	0.0098	0.5773	0.5773	0.0058	0.0849	0.6770	0.6770	0.0685	0.4238

L	HP	HS
0.	0.0473	0.0473
0.0473	-0.0254	0.1168
0.0500	-0.0221	0.1198
0.1000	0.0378	0.1734
0.1500	0.0932	0.2233
0.2000	0.1444	0.2699
0.2500	0.1919	0.3134
0.3000	0.2360	0.3541
0.3500	0.2770	0.3921
0.4000	0.3150	0.4275
0.4500	0.3503	0.4605
0.5000	0.3830	0.4912
0.5500	0.4131	0.5196
0.6000	0.4408	0.5459
0.6500	0.4660	0.5699
0.7000	0.4890	0.5919
0.7500	0.5096	0.6117
0.8000	0.5279	0.6293
0.8500	0.5439	0.6449
0.9000	0.5575	0.6582
0.9500	0.5689	0.6695
1.0000	0.5775	0.6781
1.0500	0.5834	0.6842
1.1000	0.5866	0.6877
1.1500	0.5872	0.6887
1.2000	0.5848	0.6869
1.2500	0.5797	0.6824
1.3000	0.5713	0.6748
1.3500	0.5599	0.6642
1.4000	0.5447	0.6502
1.4500	0.5262	0.6328
1.5000	0.5035	0.6114
1.5500	0.4769	0.5862
1.6000	0.4454	0.5564
1.6500	0.4094	0.5223
1.7000	0.3677	0.4827
1.7500	0.3207	0.4381
1.8000	0.2670	0.3869
1.8500	0.2068	0.3298
1.9000	0.1387	0.2649
1.9500	0.0625	0.1926
2.0000	-0.0230	0.1112
2.0041	-0.0305	0.1041
2.0412	0.0371	0.0371

BLADE SECTION COORDINATES (ROTATED) AT X = 13.0000

GAMMA	TI	L(SP)	L-BAR	AREA	IMIN	ILLCG	PHLCG	I(LL)	PHL
-0.6150	0.0981	1.0074	1.0433	0.2187	0.2804E-02	0.2816E-02	0.9571E-03	0.1845E-01	0.6196E-01
TM	TO	H(SP)	H-BAR	BETA	IMAX	IHHCG		I(HH)	
0.1000	0.0940	0.3001	0.2673	0.7062	0.8047E-01	0.8046E-01		0.3185	

L(IC)	L(MC)	L(TC)	L(OC)	L(IP)	L(MP)	L(TP)	L(OP)	L(IS)	L(MS)	L(TS)	L(OS)	L(CG)
0.0491	1.0396	1.0396	2.0335	0.0748	1.0401	1.0401	2.0074	0.0233	1.0391	1.0391	2.0596	1.0425
H(IC)	H(MC)	H(TC)	H(OC)	H(IP)	H(MP)	H(TP)	H(OP)	H(IS)	H(MS)	H(TS)	H(OS)	H(CG)
0.0491	0.3893	0.3893	0.0470	0.0073	0.3394	0.3394	0.0079	0.0908	0.4394	0.4394	0.0861	0.2657

L	HP	HS
0.	0.0491	0.0491
0.0491	-0.0112	0.1086
0.0500	-0.0106	0.1092
0.1000	0.0248	0.1420
0.1500	0.0577	0.1726
0.2000	0.0885	0.2014
0.2500	0.1172	0.2282
0.3000	0.1439	0.2533
0.3500	0.1687	0.2766
0.4000	0.1917	0.2983
0.4500	0.2128	0.3183
0.5000	0.2323	0.3367
0.5500	0.2500	0.3535
0.6000	0.2661	0.3688
0.6500	0.2806	0.3826
0.7000	0.2935	0.3949
0.7500	0.3048	0.4057
0.8000	0.3145	0.4150
0.8500	0.3226	0.4229
0.9000	0.3292	0.4293
0.9500	0.3343	0.4342
1.0000	0.3378	0.4377
1.0500	0.3397	0.4397
1.1000	0.3400	0.4402
1.1500	0.3387	0.4391
1.2000	0.3357	0.4365
1.2500	0.3312	0.4323
1.3000	0.3248	0.4265
1.3500	0.3168	0.4191
1.4000	0.3070	0.4099
1.4500	0.2953	0.3989
1.5000	0.2816	0.3861
1.5500	0.2660	0.3715
1.6000	0.2482	0.3548
1.6500	0.2283	0.3362
1.7000	0.2060	0.3152
1.7500	0.1813	0.2921
1.8000	0.1539	0.2664
1.8500	0.1238	0.2382
1.9000	0.0905	0.2071
1.9500	0.0546	0.1736
2.0000	0.0141	0.1359
2.0335	-0.0148	0.1089
2.0805	0.0470	0.0470

BLADE SECTION COORDINATES (ROTATED) AT X = 15.0000

GAMMA	TI	L(SP)	L-BAR	AREA	IMIN	ILLCG	PHLCG	I(LL)	PHL
-0.0103	0.1000	0.9784	1.0487	0.2133	0.1176E-02	0.1176E-02	0.5622E-04	0.8585E-02	0.4175E-01
TM	TO	H(SP)	H-BAR	BETA	IMAX	IHHCG		I(HH)	
0.1000	0.0999	0.2549	0.1864	0.4202E-01	0.7782E-01	0.7782E-01		0.3124	

L(IC)	L(MC)	L(TC)	L(OC)	L(IP)	L(MP)	L(TP)	L(OP)	L(IS)	L(MS)	L(TS)	L(OS)	L(CG)
0.0500	1.0499	1.0499	2.0498	0.0703	1.0499	1.0499	2.0294	0.0296	1.0498	1.0498	2.0701	1.0481
H(IC)	H(MC)	H(TC)	H(OC)	H(IP)	H(MP)	H(TP)	H(OP)	H(IS)	H(MS)	H(TS)	H(OS)	H(CG)
0.0500	0.2628	0.2628	0.0499	0.0043	0.2128	0.2128	0.0043	0.0957	0.3128	0.3128	0.0956	0.1853

L	HP	HS
0.	0.0500	0.0500
0.0500	-0.0048	0.1046
0.0500	-0.0048	0.1046
0.1000	0.0173	0.1257
0.1500	0.0381	0.1455
0.2000	0.0576	0.1641
0.2500	0.0758	0.1816
0.3000	0.0928	0.1978
0.3500	0.1086	0.2129
0.4000	0.1232	0.2269
0.4500	0.1367	0.2398
0.5000	0.1490	0.2516
0.5500	0.1602	0.2623
0.6000	0.1703	0.2720
0.6500	0.1792	0.2806
0.7000	0.1871	0.2882
0.7500	0.1940	0.2947
0.8000	0.1997	0.3002
0.8500	0.2044	0.3048
0.9000	0.2081	0.3083
0.9500	0.2107	0.3108
1.0000	0.2123	0.3123
1.0500	0.2128	0.3128
1.1000	0.2123	0.3123
1.1500	0.2108	0.3109
1.2000	0.2082	0.3084
1.2500	0.2045	0.3049
1.3000	0.1999	0.3004
1.3500	0.1941	0.2949
1.4000	0.1873	0.2884
1.4500	0.1794	0.2808
1.5000	0.1705	0.2722
1.5500	0.1604	0.2625
1.6000	0.1492	0.2518
1.6500	0.1369	0.2400
1.7000	0.1234	0.2271
1.7500	0.1088	0.2131
1.8000	0.0930	0.1980
1.8500	0.0759	0.1817
1.9000	0.0576	0.1642
1.9500	0.0381	0.1456
2.0000	0.0172	0.1256
2.0498	-0.0049	0.1046
2.0997	0.0499	0.0499

BLADE SECTION COORDINATES (ROTATED) AT X = 18.0000

GAMMA	TI	L(SP)	L-BAR	AREA	IMIN	ILLCG	PHLCG		I(LL)	PHL		
0.1340	0.0999	0.9275	1.0494	0.2076	0.2755E-03	0.2758E-03	-0.1358E-03		0.2136E-02	0.2049E-01		
TM	TO	H(SP)	H-BAR	BETA	IMAX	IHHCG			I(HH)			
0.1000	0.1000	0.2170	0.0946	-0.1052	0.7426E-01	0.7426E-01			0.3029			
L(IC)	L(MC)	L(TC)	L(OC)	L(IP)	L(MP)	L(TP)	L(OP)	L(IS)	L(MS)	L(TS)	L(OS)	L(CG)
0.0500	1.0518	1.0518	2.0542	0.0572	1.0517	1.0517	2.0479	0.0427	1.0519	1.0519	2.0606	1.0493
H(IC)	H(MC)	H(TC)	H(OC)	H(IP)	H(MP)	H(TP)	H(OP)	H(IS)	H(MS)	H(TS)	H(OS)	H(CG)
0.0500	0.1195	0.1195	0.0500	0.0005	0.0695	0.0695	0.0004	0.0994	0.1695	0.1695	0.0996	0.0947

L	HP	HS
0.	0.0500	0.0500
0.0500	-0.0006	0.1005
0.0500	-0.0006	0.1005
0.1000	0.0067	0.1077
0.1500	0.0136	0.1145
0.2000	0.0201	0.1209
0.2500	0.0261	0.1269
0.3000	0.0317	0.1324
0.3500	0.0370	0.1376
0.4000	0.0418	0.1424
0.4500	0.0462	0.1467
0.5000	0.0502	0.1507
0.5500	0.0539	0.1543
0.6000	0.0571	0.1575
0.6500	0.0600	0.1603
0.7000	0.0625	0.1628
0.7500	0.0646	0.1648
0.8000	0.0663	0.1665
0.8500	0.0677	0.1678
0.9000	0.0687	0.1688
0.9500	0.0693	0.1694
1.0000	0.0696	0.1696
1.0500	0.0695	0.1695
1.1000	0.0691	0.1691
1.1500	0.0683	0.1683
1.2000	0.0672	0.1671
1.2500	0.0657	0.1656
1.3000	0.0639	0.1638
1.3500	0.0617	0.1617
1.4000	0.0593	0.1592
1.4500	0.0565	0.1565
1.5000	0.0534	0.1534
1.5500	0.0500	0.1500
1.6000	0.0462	0.1463
1.6500	0.0422	0.1424
1.7000	0.0379	0.1381
1.7500	0.0333	0.1336
1.8000	0.0284	0.1287
1.8500	0.0232	0.1237
1.9000	0.0178	0.1183
1.9500	0.0122	0.1128
2.0000	0.0063	0.1070
2.0500	0.0001	0.1009
2.0542	-0.0004	0.1004
2.1043	0.0500	0.0500

BLADE SECTION COORDINATES (ROTATED) AT X = 19.5000

GAMMA	TI	L(SP)	L-BAR	AREA	IMIN	ILLCG	PHLCG	I(LL)	PHL
0.6883	0.0999	0.9084	1.0534	0.2079	0.1762E-03	0.1829E-03	-0.7037E-03	0.6261E-03	0.9409E-02
TM	TO	H(SP)	H-BAR	BETA	IMAX	IHHCG		I(HH)	
0.1000	0.0992	0.1961	0.0462	-0.5393	0.7494E-01	0.7494E-01		0.3056	

L(IC)	L(MC)	L(TC)	L(OC)	L(IP)	L(MP)	L(TP)	L(OP)	L(IS)	L(MS)	L(TS)	L(OS)	L(CG)
0.0500	1.0561	1.0561	2.0673	0.0511	1.0555	1.0555	2.0698	0.0488	1.0567	1.0567	2.0649	1.0548
H(IC)	H(MC)	H(TC)	H(OC)	H(IP)	H(MP)	H(TP)	H(OP)	H(IS)	H(MS)	H(TS)	H(OS)	H(CG)
0.0500	0.0457	0.0457	0.0496	0.0000	-0.0043	-0.0043	0.0001	0.0999	0.0957	0.0957	0.0991	0.0462

L	HP	HS
0.	0.0500	0.0500
0.0500	-0.0000	0.0999
0.0500	-0.0000	0.0999
0.1000	0.0013	0.1013
0.1500	0.0023	0.1025
0.2000	0.0032	0.1035
0.2500	0.0040	0.1043
0.3000	0.0045	0.1049
0.3500	0.0048	0.1053
0.4000	0.0050	0.1055
0.4500	0.0050	0.1056
0.5000	0.0049	0.1054
0.5500	0.0046	0.1052
0.6000	0.0042	0.1048
0.6500	0.0036	0.1042
0.7000	0.0030	0.1035
0.7500	0.0022	0.1027
0.8000	0.0013	0.1018
0.8500	0.0003	0.1007
0.9000	-0.0007	0.0996
0.9500	-0.0018	0.0984
1.0000	-0.0030	0.0972
1.0500	-0.0042	0.0959
1.1000	-0.0054	0.0945
1.1500	-0.0066	0.0932
1.2000	-0.0078	0.0919
1.2500	-0.0089	0.0907
1.3000	-0.0100	0.0895
1.3500	-0.0110	0.0884
1.4000	-0.0119	0.0875
1.4500	-0.0127	0.0866
1.5000	-0.0134	0.0859
1.5500	-0.0138	0.0854
1.6000	-0.0140	0.0852
1.6500	-0.0141	0.0851
1.7000	-0.0138	0.0854
1.7500	-0.0133	0.0859
1.8000	-0.0123	0.0869
1.8500	-0.0111	0.0881
1.9000	-0.0094	0.0899
1.9500	-0.0073	0.0920
2.0000	-0.0046	0.0947
2.0500	-0.0014	0.0980
2.0673	-0.0001	0.0993
2.1169	0.0496	0.0496

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