FORTRAN PROGRAM FOR CALCULATING VELOCITIES IN THE MERIDIONAL PLANE OF A TURBOMACHINE

I — Centrifugal Compressor

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This program will determine the velocities in the meridional plane of a backward-swept impeller, a radial impeller, and a vaned diffuser. The velocity gradient equation with the assumption of a hub-to-shroud mean stream surface is solved along arbitrary quasi-orthogonals in the meridional plane. These quasi-orthogonals are fixed straight lines.
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SUMMARY

A FORTRAN IV computer program which calculates the velocities in the meridional plane of a centrifugal compressor is presented. This program will determine the velocities in the meridional plane of a backward-swept impeller, a radial impeller, and a vaned diffuser. The velocity gradient equation with the assumption of a hub-to-shroud mean stream surface is solved along arbitrary quasi-orthogonals in the meridional plane. These quasi-orthogonals are fixed straight lines.

The input quantities for this program consist essentially of mass flow, rotational speed, number of blades, inlet total conditions, loss in relative total pressure, hub-to-shroud profile, mean blade shape, and a normal thickness table. The output yields meridional velocities, approximate blade surface velocities, streamline coordinates, blade shape coordinates, and stream-channel normal thickness in the meridional plane. Numerical examples are included to indicate the use of the program and the results obtained.

INTRODUCTION

Recently, increased interest has been shown in high-pressure-ratio backward-swept centrifugal impeller blades. Centrifugal compressors with backswept impeller blades have the potential of achieving higher efficiencies than those with radial impeller blades. Several methods are available for designing radial-bladed compressors, but limited work has been done on backward-swept impeller blades. Reference 1 gives the method and numerical techniques used to find the flow distribution in the meridional plane of a radial-flow turbine. This method solves the velocity gradient equations with the assumption of a hub-to-shroud mean stream surface. A set of arbitrary straight lines
from hub to shroud is used instead of normals. These arbitrary straight lines are called quasi-orthogonals and they remain fixed regardless of any streamline change. This analysis, which has been used for radial-bladed centrifugal impellers, has now been programmed to include backward-swept centrifugal impeller blades.

This report presents a computer program for calculating the velocities in the meridional plane of a centrifugal compressor. This program will determine the velocities in the meridional plane of a backward-swept impeller, a radial impeller, and a vaned diffuser, as well as approximate blade surface velocities. The output of this program is arranged in a form so that it can be used as input to programs used to calculate the blade-to-blade loadings from references 2, 3, or 4.

In this report, a description of the input and output and a FORTRAN IV computer program are presented. A brief description of the method of analysis and the computer program are given. Numerical examples are included to illustrate the use of the program and the results obtained.

METHOD OF ANALYSIS

Reference 1 presents the method and gives the numerical techniques used to find the flow distribution in the meridional plane of a radial-flow turbine. The general velocity gradient equation is derived along an arbitrary quasi-orthogonal in the meridional plane with the assumption of a hub-to-shroud mean stream surface. The equations derived in appendix B of reference 1 are

\[
\frac{dW}{ds} = \left( A \frac{dr}{ds} + B \frac{dz}{ds} \right) W + C \frac{dr}{ds} + D \frac{dz}{ds} + \left( \frac{dh}{ds} - \omega \frac{dx}{ds} \right) \frac{1}{W} \tag{1}
\]

\[
A = \cos \alpha \cos^2 \beta - \frac{\sin^2 \beta}{r_c} + \sin \alpha \sin \beta \cos \beta \left( \frac{\partial}{\partial r} \right)_f \tag{2}
\]

\[
B = -\frac{\sin \alpha \cos^2 \beta}{r_c} + \sin \alpha \sin \beta \cos \beta \left( \frac{\partial}{\partial z} \right)_f
\]

\[
C = \sin \alpha \cos \beta \frac{dW_m}{dm} - 2\omega \sin \beta + r \cos \beta \left( \frac{dW_\theta}{dm} + 2\omega \sin \alpha \right) \left( \frac{\partial}{\partial r} \right)_f
\]

\[
D = \cos \alpha \cos \beta \frac{dW_m}{dm} + r \cos \beta \left( \frac{dW_\theta}{dm} + 2\omega \sin \alpha \right) \left( \frac{\partial}{\partial z} \right)_f
\]
The coordinate system and nomenclature are shown in figures 1 and 2.

In this analysis, the total enthalpy at the inlet \( h_1 \) and the prerotation at the inlet \( \lambda \), \( r_1 V_{\theta 1} \), are assumed constant. Therefore, equation (1) reduces to

\[
\frac{dW}{ds} = \left( A \frac{dr}{ds} + B \frac{dz}{ds} \right) W + C \frac{dr}{ds} + D \frac{dz}{ds} \tag{1a}
\]

Continuity must also be satisfied from hub to tip. The calculated mass flow across any fixed line from hub to tip must equal the specified mass flow. The mass flow is computed from

\[
w = N \int_0^S \rho W_n \Delta \theta \, ds \tag{3}
\]

integrating from hub to tip along a quasi-orthogonal.

The density is calculated from the isentropic flow equation with a correction for loss in total relative pressure. This equation is derived in reference 1. The density equation is
\[
\rho = \left( \frac{T}{T'} \right)^{1/(\gamma-1)} \rho_i' - \left[ \left( \frac{T}{T_i'} \right)^{\frac{T_i'}{T''}} \right]^{1/(\gamma-1)} \frac{\Delta p''}{RT_i'} \frac{T_i'}{T''}
\]

where

\[
\frac{T}{T_i'} = 1 - \frac{W^2 + 2\omega\lambda - \omega^2 r^2}{2c_p T_i'}
\]

\[
\frac{T''}{T_i'} = 1 - \frac{2\omega\lambda - \omega^2 r^2}{2c_p T_i'}
\]

and the relative total pressure loss

\[
\Delta p'' = p_i'sen - p''
\]

The change in the angular distance between blades \( \Delta \theta \) is

\[
\Delta \theta = \frac{2\pi}{N} - \frac{t\theta}{r}
\]

where tangential thickness \( t\theta \) is determined from

\[
t^2 = t_n^2 \left[ 1 + r^2 \left( \frac{\partial \theta}{\partial z} \right)^2 + r^2 \left( \frac{\partial \theta}{\partial r} \right)^2 \right]
\]

when the normal thickness \( t_n \) is specified.

From figure 2, it can be seen that the velocity normal to the quasi-orthogonal is

\[
W_n = W_m \cos(\psi - \alpha)
\]

where from figure 1

\[
W_m = W \cos \beta
\]
The flow angle $\beta$ is determined from the mean stream surface, $\theta = \theta(m)$, for each streamline, between the blades. Therefore,

$$\tan \beta = r \left( \frac{d\theta}{dm} \right)_f = r \left[ \frac{\partial \theta}{\partial r} \right]_f \sin \alpha + \left( \frac{\partial \theta}{\partial z} \right)_f \cos \alpha$$

(12)

where $\left( \frac{d\theta}{dm} \right)_f$ is the directional derivative along a streamline.

The $\partial \theta/\partial z$ and $\partial \theta/\partial r$ in equation (9) refer to the mean blade shape. The $\left( \frac{\partial \theta}{\partial z} \right)_f$ and $\left( \frac{\partial \theta}{\partial r} \right)_f$ in equations (1a) and (12) refer to the mean stream surface between the blades. The mean stream surface is assumed to deviate from the mean blade shape at a radius $r_b$ for a centrifugal machine. An approximate equation for determining $r_b$ is given by reference 5,

$$r_b = r_1 e^{-0.7t(\Delta \theta)}$$

(13)

The equation for the mean stream surface when $r \geq r_b$ is

$$\theta_f = \frac{\left( \frac{\tan \beta_o}{r_o} - \frac{\tan \beta_b}{r_b} \right)(m - m_b)^3}{3(m_o - m_b)^2} + \frac{\tan \beta_b}{r_b} (m - m_b) + \theta_b$$

(14)

The boundary conditions used to obtain equation (14) were $\beta_o$, the outlet flow angle; $\theta_b$, the angular coordinate of the mean blade shape at $r_b$; and $\left( \frac{d\theta}{dm} \right)_b$. Differentiating equation (14), we obtain

$$\left( \frac{d\theta}{dm} \right)_f = \frac{\left( \frac{\tan \beta_o}{r_o} - \frac{\tan \beta_b}{r_b} \right)(m - m_b)^2}{(m_o - m_b)^2} + \frac{\tan \beta_b}{r_b}$$

(15)

It will be noted that equation (1a) is in terms of $\left( \frac{\partial \theta}{\partial z} \right)_f$ and $\left( \frac{\partial \theta}{\partial r} \right)_f$ and that, on the mean stream surface, $\theta$ is a function of the meridional distance $m$, for each streamline. The relation between them is

$$\left( \frac{d\theta}{dm} \right)_f = \left( \frac{\partial \theta}{\partial r} \right)_f \sin \alpha + \left( \frac{\partial \theta}{\partial z} \right)_f \cos \alpha$$

(16)

5
The preceding equations are solved with the specification of a mean blade shape. The mean blade shape can be specified by two methods. The first method of specifying the mean blade shape is specifying the angular coordinate of the mean blade shape $\theta$ constant along a quasi-orthogonal. Since the quasi-orthogonal is a fixed straight line, the mean blade shape is completely specified by specifying $\theta$ as a function of the meridional distance $m$ for the hub and shroud streamlines. Therefore, $d\theta/dm$ is known, but the $\partial \theta/\partial r$ and $\partial \theta/\partial z$ have to be determined. If the directional derivative is taken in the $m$ and $s$ direction, then

$$\frac{d\theta}{dm} = \frac{\partial \theta}{\partial r} \frac{dr}{dm} + \frac{\partial \theta}{\partial z} \frac{dz}{dm} = \frac{\partial \theta}{\partial r} \sin \alpha + \frac{\partial \theta}{\partial z} \cos \alpha$$ (17a)

and

$$\frac{d\theta}{ds} = \frac{\partial \theta}{\partial r} \frac{dr}{ds} + \frac{\partial \theta}{\partial z} \frac{dz}{ds} = \frac{\partial \theta}{\partial r} \sin(\mu + \alpha) + \frac{\partial \theta}{\partial z} \cos(\mu + \alpha)$$ (17b)

With the specification of $d\theta/ds = 0$ and the geometry in figure 3, the following equations are obtained:

$$\frac{\partial \theta}{\partial z} = \frac{\cos \psi}{\cos(\psi - \alpha)} \frac{d\theta}{dm}$$ (18)

and

$$\frac{\partial \theta}{\partial r} = \frac{\sin \psi}{\cos(\psi - \alpha)} \frac{d\theta}{dm}$$ (19)

This case is used for backswept centrifugal impeller blades. This case is also used for centrifugal diffusers, but equations (13) to (15) are not used because the mean blade shape is the same as the hub-to-shroud mean stream surface.

The second method of specifying the mean blade shape is specifying $\theta$ as a function of the axial distance $z$. This case is used for radial-element centrifugal impellers. Therefore, $\partial \theta/\partial r = 0$ and

$$\frac{d\theta}{dm} = \frac{\partial \theta}{\partial z} \cos \alpha$$ (20)
However, when slip occurs, that is, when the mean stream surface deviates from the mean blade shape, \( (\frac{d\theta}{dm})_f \) is known from equation (15). It is assumed that the mean stream surface deviates from the mean blade shape only in the radial direction. Therefore, \( \frac{\partial \theta}{\partial z} \) is known (mean blade shape), and

\[
\left( \frac{\partial \theta}{\partial r} \right)_f = \frac{\frac{d\theta}{dm}_f - \frac{\partial \theta}{\partial z} \cos \alpha}{\sin \alpha}
\]

(21)

The numerical techniques and procedures used for the solution of equations (1a), (2), and (3) are given in reference 1.

**DESCRIPTION OF INPUT**

A description of the input for the FORTRAN IV computer program QUAC is given in this section. The input quantities consist essentially of mass flow, rotational speed, number of blades, specific-heat ratio, inlet total temperature and density, gas constant, loss in total relative pressure, hub-to-shroud profile, mean blade shape, and a normal thickness table. Since the program does not use any constants which depend on the system of units being used, any consistent set of units may be used. In the following input, each item has units specified in both the SI and U.S. customary systems.
The input format is shown in table I. The first card is a title card and this card must be put in. The input variables are:

- **MX**: number of quasi-orthogonals
- **KMX**: number of streamlines
- **MR**: number of r-values of TN in the thickness table
- **MZ**: number of z-values of TN in the thickness table
- **W**: rotational speed, rad/sec
- **WT**: mass flow, kg/sec; slugs/sec
- **XN**: number of full blades
- **GAM**: specific-heat ratio
- **AR**: gas constant, J/(kg)(K); (ft)(lbf)/(slug)(°R)
- **TYPE**: integer; used as a code to indicate how arrays WA, Z, R, and DN are given initially; the integer values are
  - 0: These quantities will be calculated by the program.
  - 1: Quantities just computed for previous case will be used for next case. (Used only when more than one case is calculated on single computer run.)
- **MT**: number of z-coordinates in ZT array
- **SRW**: integer that will cause the program to print out certain values; used for debugging purposes; the integer values are
  - 0: value when not debugging; usual case
  - 13: SPLINE
  - 16: SPLINT
  - 21: RUUT
- **MXBL**: quasi-orthogonal number where blade starts
- **TEMP**: inlet total temperature, \( T'_i \), K; °R
- **ALM**: inlet prerotation, \( \lambda \), \( m^2/sec; ft^2/sec \)
- **RHO**: inlet total density, \( \rho'_i \), kg/m³; slugs/ft³
- **PLOSS**: loss in relative total pressure, \( \Delta p'' \), N/m²; lb/ft²
ANGR streamline rotation angle, deg (The streamlines are rotated so that the slope of the program's cubic spline curve is not too large. Good results are obtained from the cubic spline if the absolute value of the slope is not greater than 1. Recommended angles are as follows: for an impeller, 45°; for a diffuser, 90°; and for an axial-flow compressor, 0°.)

KSTH determines the number of times the streamlines are smoothed for each iteration (For example, if KSTH = 0, no smoothing occurs. This is the usual case (KSTH = 0).)

NPRT output control that determines which streamlines are printed out (For example, if NPRT = 1, every streamline is printed out; and if NPRT = 5, every fifth streamline is printed out.)

ITER number of iterations to be performed after ERROR is less than TOLER or after ERROR has started to increase (If ITER = 0, data will be printed for every iteration; if ITER > 0, data will be printed only for the final iteration. Normally ITER = 1, but for a first-run set ITER = 0 and check the first few iterations to see if the data were put in properly.)

KD determines compressor type (For a backward-swept impeller, KD = 0; for a diffuser and an axial-flow compressor, KD = 1; for a radial element impeller, KD = 2.)

SFACT blade multiplier to allow for splitter blades (For the case with no splitters, SFACT = 1.0; and for the case with splitters, SFACT = 2.0.)

ZSPLIT z-coordinate where splitter blade begins, m; ft (If there are no splitters, ZSPLIT > ZH(MX).)

BETO outlet flow angle, \( \beta_0 \), deg

CORFAC ratio of streamline correction used to calculated streamline correction (CORFAC affects the stability of the solution. If too large a value is used, the new streamlines are less smooth than the previous ones. If a computation is based on this set of streamlines, the calculated streamline correction becomes erratic. Therefore, it is important that the streamline correction used give a smooth streamline for the next iteration. A value of 0.1 is recommended.)

SSN last quasi-orthogonal where smoothing is desired (For no smoothing, SSN = 0.)

ZS array of z-coordinates on shroud of hub-to-shroud profile located at quasi-orthogonal positions (see fig. 4), m; ft
ZH array of z-coordinates on hub of hub-to-shroud profile located at quasi-orthogonal positions (see fig. 4), m; ft

RS array of r-coordinates on shroud corresponding to ZS (see fig. 4), m; ft

RH array of r-coordinates on hub corresponding to ZH (see fig. 4), m; ft

THTA array of θ-coordinates (mean blade shape), rad (When KD = 0 and KD = 1, θ is constant along a quasi-orthogonal and must correspond to the ZS, ZH, RS, and RH arrays. When KD = 2, θ is a function of axial distance z and must correspond to the ZT array.)

ZT array of z-coordinates corresponding to the THTA array, m; ft (Only used when KD = 2.)

TN array of thicknesses normal to the mean blade shape, tn, m; ft (This array has z-values of thickness going across and r-values of thickness going down the table. Values of thicknesses and corresponding z- and r-coordinates should extend beyond all boundaries of hub-to-shroud profile so that valid interpolation can be done in the program.)

XZ array of z-coordinates for thickness table (TN), m; ft (The z-coordinates increase going across the table for a given r-coordinate.)

XR array of r-coordinates for thickness table (TN), m; ft (The r-coordinates increase going down the table for a given z-coordinate.)
INSTRUCTIONS FOR PREPARING INPUT

Theta Constant Along a Quasi-Orthogonal

After the hub-to-shroud profile has been specified (fig. 5), the mean blade shape is determined. The angular coordinate of the mean blade shape \( \theta \) is specified as a function of the meridional distance \( m \) for the hub and the shroud, as shown in figure 6. Values of \( \theta \) that are spaced to give good results from a cubic spline used in the program are selected. For a given value of \( \theta \), the meridional distances are determined for the hub and shroud from figure 6. These meridional distances are then converted to the proper \( z \)- and \( r \)-coordinates. Therefore, the \( z \)- and \( r \)-coordinates for the end points of a quasi-orthogonal have been determined. These are the quantities \( \theta \), \( r_s \), \( z_s \), \( r_h \), and \( z_h \) that are put in the program. The maximum number of quasi-orthogonal allowed is 21.

Theta Not Constant Along a Quasi-Orthogonal

This case is used for a radial impeller. The quasi-orthogonals are arbitrarily selected on the hub-to-shroud profile. They should be selected so that the program's
cubic spline curve will fit them smoothly. The mean blade shape is determined by specifying \( \theta \) as a function of the axial distance \( z \), as shown in the third numerical example (p. 18). MT is the number of \( \theta \)-values used. It should, also, be noted that KD = 2 for this case.

**Smoothing of Streamlines**

If the streamlines are not smooth, a smoothing routine can be used. KSTH is the number of times the streamlines are smoothed, and SSN is the last quasi-orthogonal where smoothing occurs. For an impeller, the streamline smoothing can take place only in the area shown in figure 7. It cannot take place in the other region because of the methods used. A recommended value for KSTH for smoothing is 4.

Another method of smoothing the streamlines is to put quasi-orthogonals upstream of the impeller. The mean blade shape is extended into this region with the requirement of a negligible blade loading. These upstream quasi-orthogonals will allow a smoother transition into the impeller. For this case, MXBL is set equal to the quasi-orthogonal number where the blade starts. The first numerical example (p. 14) uses both these techniques.
DESRIPTION OF OUTPUT

An example of the output from the program is shown in table II. This output is in U.S. customary units. Each section of the output has been numbered to correspond to the following description:

(1) The first output of the program is the input.

(2) Output 2 gives the stagnation speed of sound at the inlet in meters per second (ft/sec); the radius at which the mean stream surface deviates from the mean blade shape (RB) in meters (ft); and a list of the number of iterations required to obtain a solution with the corresponding maximum streamline change in meters (ft).

(3) Output 3 gives some of the important quantities used in the calculation procedure which are also useful for debugging purposes. This output is given for every streamline printed out. Streamline 1 is at the hub and streamline 21 is at the shroud. The number of streamlines printed out is controlled by the input parameter NPRT. Items listed are

- \( \alpha \): angle between meridional streamline and \( z \)-axis, deg
- \( \rho \): curvature of meridional streamline, \( m^{-1}; \ ft^{-1} \)
- \( r \): meridional distance, \( m; \ ft \)
- \( \beta \): flow angle, \( \beta \), deg
- \( T \): tangential blade thickness, \( m; \ ft \)
- \( A \): eq. (2)
- \( B \): eq. (2)
- \( C \): eq. (2)
- \( D \): eq. (2)

(4) Output 4 gives the velocities and pressure for every streamline printed out. Items listed are

- \( z \): z-coordinate, \( m; \ ft \)
- \( r \): r-coordinate, \( m; \ ft \)
- \( \omega \): relative velocity on mean stream surface, \( m/sec; \ ft/sec \)
- \( \text{PRESS} \): static pressure, \( N/m^2; \ lb/ft^2 \)
- \( \text{WTR} \): suction-surface velocity, \( m/sec; \ ft/sec \)
- \( \text{WL} \): pressure-surface velocity, \( m/sec; \ ft/sec \)
- \( T T R E L \): total relative temperature, \( K; \ ^\circ R \)
(5) Output 5 gives the stream-channel coordinates and the blade shape coordinates for the hub, mean, and shroud. Only the shroud information is shown here. This information is used to determine the blade-to-blade loading from reference 2, 3, or 4. The M ARRAY, R ARRAY, and the stream-channel normal thicknesses in the meridional plane are in meters (ft); and the THETA ARRAY, the angular coordinates of the blade shape, is in radians.

STGR  angular distance from center of trailing-edge circle of blade to center of leading-edge circle of blade, rad
RI    leading-edge radius, m; ft
RO    trailing-edge radius, m; ft

For the case with splitters, the following additional output is given:

MLER  distance from leading edge of blade to leading edge of splitter, m; ft
STGRS angular distance from center of trailing-edge circle of splitter to center of leading-edge circle of splitter, rad
RI    leading-edge radius of splitter, m; ft
RO    trailing-edge radius of splitter, m; ft
BETAS flow angle at leading edge of splitter, deg

(6) Output 6 gives the inlet flow angle for the hub, mean, and tip, in degrees. These angles are calculated inside the blade passage.

NUMERICAL EXAMPLES

To indicate the use of the program and the results obtained, three numerical examples are given. The first example is a backward-swept centrifugal compressor rotor, the second is a centrifugal compressor diffuser, and the third is the input for a radial compressor. All examples are in U.S. customary units.

Backward-Swept Centrifugal Compressor

This compressor has a 6-to-1 pressure ratio. The hub-to-shroud profile of the impeller is shown in figure 8. The mean blade shape is given in figure 9, where \( \theta \) is specified as a function of the meridional distance \( m \) for the hub and shroud. The quasi-
Figure 8. Hub-to-shroud profile of backswep impeller.

Figure 9. Mean blade shape of backswep impeller.
orthogonals shown in figure 8 depend on the mean blade shape in figure 9 because \( \theta \) is constant along a quasi-orthogonal. It will be noted that in this example three quasi-orthogonals were put upstream of the impeller. This was done to allow a smooth flow transition into the impeller because of the low inlet hub-to-tip radius ratio and the high rpm. Streamline smoothing was also used. MXBL was set equal to 4, SSN set equal to 8.0, and KSTH set equal to 4. The input for this case is given in table III. The mean stream surface relative velocities are plotted in figure 10 for the hub, mean, and shroud streamlines. The velocity change near the impeller inlet was due to the blade blockage.

![Figure 10](image-url)

Figure 10. - Relative velocities in meridional plane of backswept impeller.

The blade shape coordinates and the stream-channel normal thickness needed for calculating the blade loading from reference 2, 3, or 4 are given in table IV for the mean streamline. These results are also obtained for the hub and shroud streamlines, but they are not shown here.

**Diffuser**

A flat-vaned diffuser for a centrifugal compressor was designed to have a linear static-pressure gradient from inlet to outlet. The meridional profile is shown in figure 11. The angular coordinate of mean blade shape \( \theta \) is given as a function of the me-
Figure 11. Hub-to-shroud profile of compressor diffuser.

Figure 12. Mean blade shape for compressor diffuser.
ridional distance \( m \) in figure 12. The quasi-orthogonals shown in figure 11 depend on the mean blade shape in figure 12 because \( \theta \) is constant along a quasi-orthogonal. The input for this case is given in table V. The mean stream surface velocities and the approximate blade surface velocities are plotted in figure 13 for the hub, mean, and shroud streamlines. The blade shape coordinates and the stream-channel normal thickness needed for calculating the blade loading from reference 2, 3, or 4 are given in table VI for the mean streamline.

**Radial Impeller**

This example is used to indicate the different input required. A hub-to-shroud profile is given in figure 14. The quasi-orthogonals for the profile shown are arbitrary and do not depend on the mean blade shape; that is, \( \theta \) is not constant along a quasi-
orthogonal. The mean blade shape is put in as a function of the axial distance \( z \), as shown in figure 15. Sample input is shown in table VII. The output obtained is the same as in the other examples.

**PROGRAM DESCRIPTION**

**Main Program QUAC**

The main program QUAC contains all the equations given in the method of analysis and makes the majority of the calculations. It will be noted that \( K \) is used for the streamline number and \( I \) is used for the quasi-orthogonal number. QUAC calls the subroutines RUUT, SMOOTH, INTGRL, CONTIN, SPLDER, SPLINE, LININT, and SPLINT to perform various functions such as smoothing, finding roots, integration, interpolation, and use of a cubic spline curve to determine derivatives. These subroutines, excluding RUUT and SMOOTH, are described in reference 1. A brief description of each is given herein.

The program variables for QUAC are

- \( A \) temporary storage
- \( AB \) temporary storage
AC temporary storage
AD temporary storage
AE meridional length from leading edge
AL \( \alpha \)
ALM see input
AMLER MLER (see output)
ANGR see input
AR see input
B temporary storage
BA total weight flow between hub and \( K^{th} \) streamline
BETA \( \beta \)
BETAD \( \beta_L \)
BETAS see output
BETAT \( \beta_T \)
BETOH exit blade angle at hub
BETOM exit blade angle at mean
BETOT exit blade angle at tip
C temporary storage
CAL \( \cos \alpha \)
CBETA \( \cos \beta \)
CI stagnation speed of sound at inlet
CORFAC see input
COSBD \( \cos \beta_L \)
COSBT \( \cos \beta_T \)
CP \( c_p \)
CURV \( 1/r_c \)
DELBTA \( \beta_T - \beta_L \)
DELTA calculated streamline correction
DENSTY  \( \rho \)
DN distance along quasi-orthogonal from hub
DRDM \( \frac{d}{dm} (r \omega + W \sin \beta) r \Delta \theta \)
DTDMB \( (d \theta/dm)_b \)
DTDMS \( d \theta/dm \) at splitter leading edge
DTDR \( \partial \theta/\partial r \)
DTDZ \( \partial \theta/\partial z \)
DWMDM \( dW_m/dm \)
DWTDN \( dW_\theta/dm \)
E temporary storage
ERROR maximum calculated streamline correction for present iteration
ERROR1 \( \text{ERROR from previous iteration} \)
EXPOX \( 1/(\gamma - 1) \)
G temporary storage
GAM \( \gamma \)
HR increment along quasi-orthogonal in \( r \)-direction
HZ increment along quasi-orthogonal in \( z \)-direction
I subscript to indicate number of quasi-orthogonal
IND code number for use by subroutine CONTIN
INF set equal to 1, when \((ZH - ZS) = 0\)
ITER see output
K subscript used to indicate streamline number
KD see input
KMX see input
KMXM1 \( KMX - 1 \)
KSTH see input
MR see input
MT see input
MX see input

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MZ     see input
N      MXBL
N1     N + 1
N2     MX - 1
NPRT   see input
PLOSS  see input
PRS    p
PSI    ψ
R      r
RB     r_b
RC     1/r_c
REXIT  average exit radius
RH     see input
RHO    ρ'_i
RI     leading-edge radius
RIS    leading-edge radius of splitter
RO     trailing-edge radius
RS     see input
RSPLIT r-coordinate at leading edge of splitter
RUNO   run number
SA     A, eq. (2)
SAL    sin α
SB     C, eq. (2)
SBETA  sin β
SC     β, eq. (2)
SD     D, eq. (2)
SFACT  see input
SLA    average distance between streamlines on a quasi-orthogonal
SM     distance from inlet along a meridional streamline
SM1 meridional distance from first quasi-orthogonal to quasi-orthogonal that is before point where stream surface deviates from blade surface

SM2 meridional distance from first quasi-orthogonal to a quasi-orthogonal that is after point where stream surface deviates from blade surface

SMF fractional meridional distance

SMEXIT meridional distance from first quasi-orthogonal to trailing edge of blade

SMRB meridional distance from first quasi-orthogonal to point where mean stream surface deviates from mean blade shape

SRW see input

SSN see input

STGR see output

T \( t_n \) (interpolated value)

TANBB \( \tan \beta_b \)

TANS \( \tan \beta_s \), at leading edge of splitter

TEMP \( T'_i \)

THTAB \( \theta_b \)

THTAF \( \theta_f \)

THTAS \( \theta_s \)

THH mean blade shape \( \theta \)-coordinate at hub

THHC temporary storage

THH1 blade shape, \( \theta \)-coordinate at hub on surface 1

THH2 \( \theta \)-coordinate at hub on blade surface 2

THM \( \theta \)-coordinate of mean blade shape at mean

THMC temporary storage

THM1 \( \theta \)-coordinate at mean on blade surface 1

THM2 \( \theta \)-coordinate at mean on blade surface 2

THS \( \theta \)-coordinate of mean blade shape at shroud

THSC temporary storage

THSI \( \theta \)-coordinate at shroud on blade surface 1

THS2 \( \theta \)-coordinate at shroud on blade surface 2
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN</td>
<td>see input</td>
</tr>
<tr>
<td>TOLER</td>
<td>iteration tolerance</td>
</tr>
<tr>
<td>TSPLIT</td>
<td>normal blade thickness at leading edge of splitter</td>
</tr>
<tr>
<td>TPP1P</td>
<td>T''/T'_1</td>
</tr>
<tr>
<td>TTREL</td>
<td>see output</td>
</tr>
<tr>
<td>TT</td>
<td>t_0</td>
</tr>
<tr>
<td>TYPE</td>
<td>see input</td>
</tr>
<tr>
<td>T1P</td>
<td>T/T'_1</td>
</tr>
<tr>
<td>W</td>
<td>ω</td>
</tr>
<tr>
<td>WA</td>
<td>W</td>
</tr>
<tr>
<td>WAS</td>
<td>W*, eq. (13) of ref. 1</td>
</tr>
<tr>
<td>WASS</td>
<td>W**, eq. (13) of ref. 1</td>
</tr>
<tr>
<td>WT</td>
<td>total mass flow</td>
</tr>
<tr>
<td>WTFL</td>
<td>calculated total mass between hub and K^{th} streamline</td>
</tr>
<tr>
<td>WTHRU</td>
<td>W_n</td>
</tr>
<tr>
<td>WTR</td>
<td>W_t, eq. (10) of ref. 1 (suction-surface velocity)</td>
</tr>
<tr>
<td>WL</td>
<td>pressure-surface velocity</td>
</tr>
<tr>
<td>XN</td>
<td>see input</td>
</tr>
<tr>
<td>XR</td>
<td>see input</td>
</tr>
<tr>
<td>XZ</td>
<td>see input</td>
</tr>
<tr>
<td>YA</td>
<td>average weight flow per unit length crossing a quasi-orthogonal</td>
</tr>
<tr>
<td>YH</td>
<td>temporary storage</td>
</tr>
<tr>
<td>YM</td>
<td>temporary storage</td>
</tr>
<tr>
<td>YS</td>
<td>temporary storage</td>
</tr>
<tr>
<td>Z</td>
<td>z</td>
</tr>
<tr>
<td>ZEXIT</td>
<td>average z-coordinate at exit</td>
</tr>
<tr>
<td>ZH</td>
<td>see input</td>
</tr>
<tr>
<td>ZS</td>
<td>see input</td>
</tr>
<tr>
<td>ZSPLIT</td>
<td>see input</td>
</tr>
<tr>
<td>ZT</td>
<td>see input</td>
</tr>
</tbody>
</table>

24
Subroutine RUUT

Subroutine RUUT finds the root between two given points. It is used to find the meridional distance where the mean stream surface deviates from the mean blade shape when the radius at which this occurs is given. If the root cannot be found within the tolerance, a message is printed out and the input arguments are listed. If there is trouble in finding a root, set SRW = 21 in the input and all the input to the subroutine will be printed out.

The calling sequence for RUUT is

\[
\text{CALL RUUT} (SM1, SM2, RB, SMRB, SM(1,K), R(1,K), MX)
\]

where

- **SM1** meridional distance of quasi-orthogonal before point desired (input)
- **SM2** meridional distance of quasi-orthogonal after point desired (input)
- **RB** radius at point desired (input)
- **SMRB** desired meridional distance (output)
- **SM(1,K)** array of m-coordinates (input)
- **R(1,K)** array of r-coordinates (input)
- **MX** number of r-coordinates (input)

Subroutine SMOOTH

Subroutine SMOOTH smoothes the streamlines to obtain a better numerical solution. It uses the hub streamline as the base streamline for the smoothing operation.

The slopes of the quasi-orthogonals are

\[
m_I = \frac{y_{SI} - y_{hI}}{x_{SI} - x_{hI}}
\]

and the streamline slopes are

\[
m_K = \frac{y_{I+1} - y_{I-1}}{x_{I+1} - x_{I-1}}
\]

(22)

(23)

25
where $K$ is the streamline number and $I$ is the quasi-orthogonal number. The $x$-$y$ coordinates of an intersection can now be determined. From analytical geometry,

$$
\left(x_I\right)_I = \frac{(y_{I-1} - m_K x_{I-1}) - (y_I - m_K x_I)}{m_I - m_K}
$$

(24)

The smoothed $x$-coordinate is

$$
\left(x_I\right)_I = \left(\frac{x_I}{D}\right) + x_I
$$

(25)

where $D$ is the smoothing factor. The smoothed $y$-coordinate is

$$
y_I = y_I + m_I \left(\frac{x_I}{D}\right)
$$

(26)

When $m_I = 0$, the following equations are used:

$$
\left(y_I\right)_I = m_K (x_I - x_{I-1}) + y_{I-1}
$$

(27)

$$
\left(y_I\right)_I = \frac{(y_I - y_I)}{D} + y_I
$$

(28)

and

$$
\left(x_I\right)_I = x_I
$$

(29)

When $m_K = 0$,

$$
\left(y_I\right)_I = m_I (x_{I-1} - x_{h_I}) + y_{h_I}
$$

$$
\left(y_I\right)_I = \frac{(y_I - y_I)}{D} + y_I
$$

(30)
and

\[
(x_1)_I = \left(\frac{(x_1)_I - x_I}{D}\right) + x_I
\]

(31)

The value of $D$ is 2 for all quasi-orthogonals except for the last three, where smoothing occurs. The values of $D$ for these three are 2.6667, 4.0, and 8.0, respectively. This was done so that there would not be any discontinuities when only certain sections of the streamlines are smoothed.

The calling sequence for SMOOTH is

\[
\text{CALL SMOOTH}(Z(1, K), R(1, K), ZH, RH, AB, SSN, INF)
\]

where

- $Z(1, K)$: z-coordinate of streamline
- $R(1, K)$: r-coordinate of streamline
- $ZH$: z-coordinate of hub streamline
- $RH$: r-coordinate of hub streamline
- $AB$: slope of quasi-orthogonals, $m_I$
- $SSN$: last quasi-orthogonal where smoothing is desired
- $INF$: indicator for quasi-orthogonals with a slope of infinity

The program variables are

- $D$: smoothing factor
- $SLOPE$: slope of quasi-orthogonals, $m_I$
- $SLOPE1$: streamline slope, $m_K$
- $X$: z-coordinate of streamlines
- $XH$: z-coordinate of hub streamline
- $X1$: z-coordinate of smoothed streamline
- $Y$: r-coordinate of streamlines
- $YH$: r-coordinate of hub streamline
- $Y1$: r-coordinate of smoothed streamline
Other Subroutines

Subroutines INTGRL, CONTIN, SPLDER, SPLINE, LININT, and SPLINT are described in reference 1. INTGRL is used for numerical integration. CONTIN is used to determine the hub velocity for the next continuity iteration. SPLDER is used to determine the values of the derivatives at the specified interpolated points. SPLINE is used to determine the first and second derivatives. If there is a problem with the SPLINE subroutine, set SRW = 13 in the input and the input and output of the SPLINE subroutine will be printed out. LININT is used to determine the interpolated values of the normal blade thickness from the given thickness table. SPLINT is used for interpolation. The input and output data for SPLINT will be printed out if SRW = 16.

PROGRAM LISTING

```c
C CALCULATION OF VELOCITY AND PRESSURE DISTRIBUTION IN A CYTRIFUGAL COMPRESSOR
C
C
COMMON SRW

DIMENSION AL(21,21), BETA(21,21), CAL(21,21), CBETA(21,21), INF(21),
1 CURV(21,22), DN3(21,21), P3S(21,21), R(21,21), Z(21,21), SM(21,21),
2 SA(21,21), SP(21,21), SD(21,21), SAL(21,21), SBETA(21,21),
3 TNI(21,21), TT(21,21), WA(21,21), WTR(21,21), TREL(21,21), WL(21,21),
4 DIMENSION AB(22), AC(22), AD(22), BA(21), DELTA(21), DRM(21), AF(22),
5 YM(21), DTOM(21), DWM(21), DTOM(21), RH(21), RS(21), ZH(21), ZS(21),
6 THETA(21), WFL(21), XR(21), XT(21), XZ(21), ETAI(3), AA(3), THETA(21),
7 DIMENSION THH(21), THM(21), THS(21), THH1(21), THH2(21), THM1(21),
8 ITH(21), THS1(21), THS2(21), DTRZ(21), DTRD(21), ZT(21),
9 Y2A(21), YF2(21), YS(21), TI(3), TO(3)

INTEGER RUNO, TYPE, SRW, HUB, SHROUD
RUNC=0

READ (5,1001)
WRITE (6,1049)
WRITE (6,1001)
READ (5,1010) MX, KM, MR, MZ, W, WT, XN, GAM, AR
ITAC = 1
RUNC=RUNC+1
WRITE (6,1020) RUNO
WRITE (6,1007)
WRITE (6,1011) MX, KM, MR, MZ, W, WT, XN, GAM, AR
READ (5,1010) TYPE, MT, SRW, MXR, TEMP, ALM, RHO, PLOSS, ANGR
WRITE (6,1008)
WRITE (6,1011) TYPE, MT, SRW, MXR, TEMP, ALM, RHO, PLOSS, ANGR
READ (5,1010) KSTH, NFR, ITER, KD, SFAC, ZSPLIT, RETO, CORFAC, SSN
WRITE (6,1009)
WRITE (5,1011) KSTH, NFR, ITER, KD, SFAC, ZSPLIT, RETO, CORFAC, SSN
ITER = ITER + 1
READ (5,1030) (ZS(I), I=1, MX)
WRITE (6,1029)
WRITE (6,1028) (ZS(I), I=1, MX)
READ (5,1030) (ZH(I), I=1, MX)
```
UTCLER = WT/100000.
TCLER = (RS(1)-RH(1))/5000.
IF(RS(1)<0.E-10) TOLER = (ZH(1)-ZS(1))/5000.
DC 110 K=1,KMX
11C SM(I,K)=C.
BA(I)=0.
DC 120 K=2,KMX
12C BA(K) = DLAT(K-1)*WT/FLOAT(KMX-1)
DC 130 I=1,KMX
13C DN(I,1)=C.
ANGR = ANGR/57.29577
145 CONTINUE
CI = SQRT(GAM*AR*TEMP)
WRITE(6,1049)
WRITE(6,1050) CI
KMXY1 = KMXY-1
CP = AR*GAM/(GAM-1.0)
EXPCH = 1./(GAM-1.0)
BETC = BETO/57.29577
ZEXIT = (ZS(MX)+ZH(MX))/2.
REXIT = (RS(MX)+RH(MX))/2.
IF ( KD.EQ. 1 ) GO TO 149
CALL LININT(ZEXIT,REXIT,XZ,XR,TN,21,21,T)
RR = REXIT*EXP(-.71*(2.*3.14159/(XN*SFAC)-T/REXIT))
WRITE (6,1027) RR
149
ERRCR = 100000.
C
C BEGINNING OF LOOP FOR ITERATIONS
15C IF(ITER.EQ.0) WRITE (6,1060) ITNO
C
IF(ITER.EQ.0) WRITE (6,1070)
ERRCR1 = ERRCR
ERRCR = 0.
C
C START CALCULATION OF PARAMETERS
C
DC 180 K=1,KMX
DC 180 I=2,MX
SM(I,K) = SM(I-1,K)+SQR((Z(I,K)-Z(I-1,K))**2+(R(I,K)-R(I-1,K))**2)
1 2)
180 CONTINUE
DC 230 K=1,KMX
DC 160 I=1,MX
AP(I) = Z(I,K)*COS(ANGR) + R(I,K)*SIN(ANGR)
AC(I) = R(I,K)*COS(ANGR) - Z(I,K)*SIN(ANGR)
CALL SPLINE(AP,AC,MX,AL(I,K),CURV(I,K))
DC 170 I=1,MX
CURV(I,K) = CURV(I,K)/(1.0+AL(I,K)**2)**1.5
AL(I,K) = ATAN(AL(I,K)) + ANGR
CALL S(1,K) = COS(AL(I,K))
17C SAL(I,K) = SIN(AL(I,K))
IF ( KD.EQ. 2 ) GC TO 171
CALL SPLINE(SM1,I,K),THTA ,MX,DTDM,AC
GC TC 172
171 CALL SPLCER(ZT,THTA,MT,Z(1,K),MX,DTDZ)
172 DC 204 I =1,MX
T = 0.
THTAF(I) = THTA(I)
IF(I.GE.MXR) CALL LININT(ZS(I,K),R(I,K),XZ,XR,TN,21,21,T)
IF (ZS(I,K).GE.ZH(I)) GO TO 202
PSI = ATAN((RS(I)-RH(I))/(7S(I)-ZH(I)))+1.5708
GC TC 203
202 PS1 = ATAN1((ZH(I)-ZS(I))/(RS(I)-RH(I)))
203 IF ( KD.EQ. 2 ) DTDM(I) = DTDZ(I)+CAL(I,K)
IF ( KD.EQ. 2 ) DTRD(I) = 0.0
IF (OK.NE. 2 ) DTZD(I) = COS(P1)/COS(P1 - AL(I,K))*DTDM(I)
IF (OK.NE. 2 ) DTD(I) = SIN(P1)/COS(P1 - AL(I,K))*DTDM(I)
204 T(I,K) = T+SQRT(1.0+R(I,K)**2*(DTD(I)**2+TDZD(I)**2))
IF (OK.EQ. 1) GO TO 207
DC 205 I = 1,MX
IF (RI(K).GT. RP) GO TO 206
C CONTINUE
206 SM1 = SM1-1,K
SM2 = SM2-1,K
CALL RUUT(SM1,SM2,RP,SMRB,SM1(K),R(I,K),MX)
IF (OK.EQ. 2 ) CALL SPLINT(ZT,THTA,MT,Z(1,K),MX,THTAF)
CALL SPLINT(SM1(K),THTAF,MX,SMRB,1,THTAB)
CALL SPLINE (SM(1,K),THTAF,MX,SMRB,I,DTDMB)
TANRB = RB*DTDMB
SMEXIT = SM(MX,I)
DC 201 I = I,MX
IF (R(I,K) .LT. RB) GO TO 201
THTAF(I) = THTAB + (SM(I,K)-SMRB)**3*(TAN(RETO)/REXIT-TANRB/RB)/
1.3*Q*(SMEXIT-SMRB)**2 + (SM(I,K)-SMRB)* TANRB/RB
DTCR(I) = (THTAF(I)-THTAB)*CAL(I,K))/SAL(I,K)
GC TC 201
200 DTCR(I) = 0.0
201 CONTINUE
207 DC 220 I = 1,MX
BETA(I,K) = ATAN(R(I,K)*DTDM(I))
SBETA(I,K) = SIN(BETA(I,K))
CBETA(I,K) = COS(BETA(I,K))
AR(I) = WA(I,K)*CBETA(I,K)
22C AC(I) = WA(I,K)*SBETA(I,K)
CALL SPLINE(SM(I,K),AR,MX,DWDM,AD)
CALL SPLINE(SM(I,K),AC,MX,DWDM,AD)
IF ((ITER.LE.0 .AND. (MOD(K-1, NPRT).NE.0)) )WRITE (6,IC80) K
DC 23C I = 1,MX
SA(I,K) = CBETA(I,K)**2*CAL(I,K)*CURV(I,K)-SBETA(I,K)**2/R(I,K)
1.*SA(I,K)*CBETA(I,K)*SBETA(I,K)*DTDR(I)
SR(I,K) = SAL(I,K)*CBETA(I,K)*DWDM(I)-2.0*SBETA(I,K) +DTDR(I)
1.*SR(I,K)*CBETA(I,K)*(CWTDM(I)**2+2.*SA(I,K))
SC(I,K) = -CBETA(I,K)**2*SA(I,K)*CURV(I,K)
1.*SC(I,K)*CBETA(I,K)*SBETA(I,K)*DTDR(I)
SD(I,K) = SAI(K)*CBETA(I,K)*DWDM(I)+DTDZ(I)
1.*SR(I,K)*CBETA(I,K)*(CWTDM(I)**2+2.*SA(I,K))
IF ((ITER.GT.0 .OR. (MOD(K-1, NPRT).NE.0)) )GO TO 230
A = AL(I,K)*57.29577
B = SM(I,K)
E = T(I,K)
G = BETA(I,K)*57.29577
WRITE (6,IC90) A, CURV(I,K), B, E, SA(I,K), SR(I,K), SC(I,K), SD(I,K)
23C CONTINUE
C EAC CF LCNPS - PARAMETER CALCULATION
C CALCULATE BLADE SURFACE VELOCITIES (AFTER CONVERGENCE)
C
IF (ITER.GE.0) GO TO 260
DC 25C K = 1,KMX
CALL SPLINE (SM(1,K),TT(1,K),MX,DELRTA,AC)
A = XN
DC 240 I = 1,MX
24C AB(I) = (R(I,K)*W+WA(I,K)*SBETA(I,K))*(6.283186*R(I,K)/A- TT(I,K))
CALL SPLINE (SM(1,K),AR,MX,ADRM,AC)
IF (SFAC. LE. 1.0) GO TO 245
A = SFAC*XN
DC 244 I = 1,MX
244 AB(I) = (R(I,K)*W+WA(I,K)*SBETA(I,K))*(6.283186*R(I,K)/A- TT(I,K))
CALL SPLINE (SM(1,K),AR,MX,ADM,AC)
24C DC 250 I = 1,MX
BETAC = BETA(I,K)-DELRTA(I)/2.
BETAT = BETAAD+DELRTA(I)
CSSPC = COS(BETAC)
CCSPPT = COS(BETAT)
IF (Z(I,K).GT.ZSPLIT) DRR(I) = AD(I)
END OF BLADE SURFACE VELOCITY CALCULATIONS

START CALCULATION OF WEIGHT FLOW VS. DISTANCE FROM HUB

DC 370 I=1, KMX
INC=1
DC 270 K=1, KMX
AC(K)=DN(I,K)
GC TC 29C
WA(I,1)=.5*WA(I,1)
DC 30 C K=2, KMX
J=K-1
HR=R(I,J)-R(I,K)
HZ=Z(I,J)-Z(I,K)
WAS = WA(I,J)*.1+SA(I,J)*HR+SC(I,J)*HZ +SB(I,J)*HR+SD(I,J)*HZ
WASS = WA(I,J)+WAS*(SA(I,K)*HR+SC(I,K)*HZ)+SB(I,K)*HR+SD(I,K)*HZ

WA(I,K)=(WAS+WASS)/2.

DC 340 C K=1, KMX
TIP= 1-(WA(I,K)**2+2.*W*ALM-(W*R(I,K)**2))/2./CP/TEMP
IF(TIP LT .0) GO TO 280
TPPIP= 1-(2.*W*ALM-(W*R(I,K)**2))/2./CP/TEMP
TREL(I,K)= TPPIP*TEMP
SMF = 0.*C
IF(I*GE.*XBL) SMF = (SM(I,K)-SM(MXBL,K))/(SM(MX,K)-SM(MXBL,K))
DENSTY=TIP**EXPN*RHO-(TIP/TPPIP)**EXPN*PLOSS/AR/TPPIP/TEMP**SMF
PRS(I,K)=DENSTY*AR*TIP*TEMP
IF(ZS(I,GE.*ZH(I))) GC TO 320
PSI = ATAN((RS(I)-RH(I))/(ZS(I)-ZH(I)))+1.5708
GC TC 33C

PSI=ATAN((ZS(I)-ZS(I))/(RS(I)-RH(I)))

WTHRU=WA(I,K)*C.beta(I,K)*COS(PSI-AL(I,K))

A=SA
IF(Z(I,K).LT.*ZSPLIT) A=SFAC*XN
C = 6.*282186*R(I,K)-A**TT(I,K)
AD(K)=DENSTY*WTHRUC
CALL INTCREL(AC(I,K),AD(I,K),KMX,WTFL(1))
YA(I)= WTHFL(KMX)/DN(I,KMX)
YH(I)= AD(I)
KM = (KMX+1)/2
YM(I)= AD(KM)
YS(I)= AD(KMX)
IF(APS(WT-WTHFL(KMX)).LE.-WTOLER) GO TO 350
CALL CONTIN (WA(I,1),WTFL(KMX),IND,1,WT)
IF(IND.NE.6) GO TO 290

CALL SPLINT (WTFL,AC,KMX,BA,KMX,AB)
DC 360 K=1, KMX
DELTA=ABS(AB(K)-CN(I,K))
DN(I,K)=(1.-CORFAC)*CN(I,K)+CORFAC*AR(K)
IF(DELTA.GT.*ERROR)ERROR=DELTA
CCCONTINUE

END CF LCOP - WEIGHT FLOW CALCULATION

CALCULATE STREAMLINE COORDINATES FOR NEXT ITERATION

DC 380 K=2, KMXM1
DC 39C I=1, KMX
7(I,K)=DN(I,K)/DN(I,KMXM1*(ZS(I)-ZH(I)))*ZH(I)
3EC R(I,K)=DN(I,K)/DN(I,KMX)*(RS(I)-RH(I))+RH(I)
   IF (KSTH.EQ.0) GC TO 383
   DC 381 I=1,MX
   INF(I) = 0
   IF(ZS(I).EQ.ZH(I)) GC TO 3805
   A(I) = (RS(I)-RH(I))/(ZS(I)-ZH(I))
   GC TC 381
3805 INF(I) = 1
381 CONTINUE
   DC 382 K=2,KMXM1
   DC 382 J=1,KSTH
382 CALL SMCTH (Z(I,K),R(I,K),ZH,RH,AR,SSN,INF)
383 IF (ERROR.GE.ERROR1).OR.(ERROR.LE.TOLER)) ITER=ITER-1
   IF(ITER.GT.0) GO TO 410
   WRITE (6,1100)
   DC 400 K=1,KMX,NPRT
   WRITE (6,1080) K
   DC 390 I=1,MX
   AB(I) = Z(I,K)*CCS(ANGR) + R(I,K)*SIN(ANGR)
390   AC(I) = R(I,K)*COS(ANGR) - Z(I,K)*SIN(ANGR)
   CALL SPLINE (AB,AC,MX,AD,CURV(I,K))
   DC 400 I=1,MX
   CURV(I,K)=CURV(I,K)/(1.+AD(I)**2)**1.5
   R= 7 (I,K)
   N= R(I,K)
40C WRITE (6,1110) R,D,WA(I,K),PRS(I,K),WTR(I,K),WL(I,K),TTREL(I,K)
   WRITE (6,1130)
41C A=ERROR
   WRITE (6,1120) ITNO,A
   ITNC=ITNC+1
   IF (ITER.GE.0) GO TO 150
   N = MXRL
   DC 419 J=1,3
   K = 1
   IF (J.EQ.2) K = (KMX+1)/2
   IF (J.EQ.3) K = KMX
   IF (KC.EQ.2 ) GO TO 417
   CALL SPLINE (SM(I,K),THTA ,MX,DTDM,AC)
   GC TC 41F
417 CALL SPLKER(ZT,THTA,MT,Z(I,K),MX,DTDZ)
   DTCM(MX)= CAL(MX,K)*CTDZ(MX)
418 IF (J.EQ.1 ) CETCM = ATAN(R(MX,K)*DTDM(MX))
   IF (J.EQ.2 ) CETCM = ATAN(R(MX,K)*DTDM(MX))
   IF (J.EQ.3 ) CETCM = ATAN(R(MX,K)*DTDM(MX))
   CALL LINT (Z(MX,K),R(MX,K),XZ,XR,TN,21,21,TO(J))
419 CALL LINT (Z(N,K),R(N,K),XZ,XR,TN,21,21,TI(J))
   K = (KMX+1)/2
   DC 440 I=1,MX
   SLA = DN(I,KMX)/FLOAT(KMX-1)
   IF(ZS(I).GE.ZH(I)) GC TO 420
   PSI = ATAN((RS(I)-RH(I))/(ZS(I)-ZH(I)))+1.5708
   GC TC 43C
42C PSI = ATAN((ZH(I)-ZS(I))/(RS(I)-RH(I)))
430 AB(I) = YA(I)*SLA*COS(PSI-AL(I,1))/YH(I)
   AC(I) = YA(I)*SLA*COS(PSI-AL(I,KMX))/YM(I)
440 AC(I) = YA(I)*SLA*COS(PSI-AL(I,KMX))/YS(I)
   IF (KTH.LE.2) GO TO 442
   DC 441 I=1,MX
   THH(I) = THTA(I)
   THW(I) = THTA(I)
441 THS(I) = THTA(I)
   GC TC 442
CALL SPLINT(ZT,THTA,MT,Z(1,1),MX,THH)
CALL SPLINT(ZT,THTA,MT,Z(1,K),MX,THM)
CALL SPLINT(ZT,THTA,MT,Z(1,KM),MX,THS)

RI = T1(1)/2.
THC = THH(N)*RI*TAN(BETA(N+1))/R(N+1)
RC = T0(1)/2.
TH1(MX) = THH(MX) - RI*TAN(BETA(MX))/R(MX,1) - THHC
TH2(MX) = THH(MX) - RI*TAN(BETA(MX))/R(MX,1) - THHC
RI = T1(2)/2.
THC = THH(N)*RI*TAN(BETA(N,K))/R(N,K)
RC = T0(2)/2.
TH1(MX) = THH(MX) - RI*TAN(BETA(MX))/R(MX,K) - THMC
TH2(MX) = THH(MX) - RI*TAN(BETA(MX))/R(MX,K) - THMC
RI = T1(3)/2.
THC = THS(N)*RI*TAN(BETA(N,KM))/R(N,KM)
RC = T0(3)/2.
TH1(MX) = THS(MX) - RI*TAN(BETA(MX))/R(MX,KM) - THSC
TH2(MX) = THH(MX) - RI*TAN(BETA(MX))/R(MX,KM) - THSC

DC 449 I=1, MXBL
THH(I) = 0.0
THM(I) = 0.0
THS(I) = 0.0
THP(I) = 0.0

THS2(I) = 0.0
N1 = N+1
N2 = MX-1

DC 450 I=N1,N2
TH1(I) = THH(I)*
THM(I) = THH(I)*
THS1(I) = THS(I)*
THS2(I) = THS(I)*
THH(I) = TTI(I,1)/2./R(I,1) - THHC
THM(I) = TTI(I,K)/2./R(I,K) - THMC
THS1(I) = TTI(I,KMX) /2./R(I,KMX) - THSC
THS2(I) = TTI(I,KMX) /2./R(I,KMX) - THSC

WRITE(6,1200)
WRITE(6,1239)
WRITE(6,1251)

DC 451 I=1, MX
AE(I) = SM(I,1) - SM(MXBL,1)
WRITE(6,1230)(AE(I),I=1,MX)
WRITE(6,1249)
WRITE(6,1230)( R(I,1),I=1,MX)
WRITE(6,1240)
WRITE(6,1230)( AB(I),I=1,MX)
WRITE(6,1250)
WRITE(6,1251)
WRITE(6,1230)(AE(I),I=1,MX)
WRITE(6,1252)
WRITE(6,1230)(THH(I),I=1,MX)
WRITE(6,1253)
WRITE(6,1230)(THH(I),I=1,MX)
RI = T1(1)/2.
RC = T0(1)/2.

STGR = THH(MX)
WRITE(6,1254) STGR, RI, RO
IF (Z(MX,1),LT, ZSPLIT) GO TO 453
CALL SPLINT(Z(1,1),SM(1,1),MX,ZSPLIT,1,AMLER)
CALL SPLINT(SM(1,K),R(1,1),MX,AMLER,1,RSPPT)
CALL SPLINT(SM(1,KM),THH,MX,AMLER,1,THSAS)
CALL SPLCER(SM(1,1),THH,MX,AMLER,1,DTMOS)
CALL LININT(ZSPLIT,RSPPT,XZ,XR,TN,21,21,TSMOS)
TASS = RSPPT*DTMOS
RIS = TSPLIT/2.0
STGRS = THM1(MX)-RIS*TANS/RSPLIT-THTAS +THMC
AMLER=AMLER-SM(MXBL,1)
BETAS = ATAN(TANS)
BETAS = BETAS*57.29577
WRITE(6,1255) AMLER,STGRS,RIS,RO,BETAS
WRITE(6,1201)
WRITE(6,1239)
WRITE(6,1251)
DC 454 I=1,MX
AE(I) = SM(I,K)-SM(MXBL,K)
WRITE(6,1230)(AE(I),I=1,MX)
WRITE(6,1249)
WRITE(6,1230)( R(I,K),I=1,MX)
WRITE(6,1240)
WRITE(6,1230)( AC(I),I=1,MX)
WRITE(6,1250)
WRITE(6,1251)
WRITE(6,1230)(AE(I),I=1,MX)
WRITE(6,1252)
WRITE(6,1230)(THM1(I),I=1,MX)
WRITE(6,1253)
WRITE(6,1230)(THM2(I),I=1,MX)
RI = TI(2)/2.
RC = TO(2)/2.
STCR = THM1(MX)
WRITE(6,1254) STCR,RI,RO
IF (Z(MX,K).LT.ZSPLIT) GO TO 456
CALL SPLINT (Z(1,K),SM(1,K),MX,ZSPLIT,1,AMLER)
CALL SPLINT (SM(1,K),R(1,K),MX,AMLER,1,RSPLIT)
CALL SPLINT (SM(1,K),THM1,MX,AMLER,1,THTAS)
CALL SPLINT (SM(1,K),THM2,MX,AMLER,1,DTDM)
CALL LININT(ZSPLIT,RSPLIT,XZ,XR,TN,21,21,TSPLIT)
TANS = RSPLIT*TDMS
RIS = TSPLIT/2.0
STGRS = THM1(MX)-RIS*TANS/RSPLIT-THTAS +THMC
AMLER=AMLER-SM(MXBL,K)
BETAS = ATAN(TANS)
BETAS = BETAS*57.29577
WRITE(6,1255) AMLER,STGRS,RIS,RO,BETAS
WRITE(6,1202)
WRITE(6,1239)
WRITE(6,1251)
DC 457 I=1,MX
AE(I) = SM(I,KMX)-SM(MXBL,KMX)
WRITE(6,1230)(AE(I),I=1,MX)
WRITE(6,1249)
WRITE(6,1230)( R(I,KMX),I=1,MX)
WRITE(6,1240)
WRITE(6,1230)( AC(I),I=1,MX)
WRITE(6,1250)
WRITE(6,1251)
WRITE(6,1230)(AE(I),I=1,MX)
WRITE(6,1252)
WRITE(6,1230)(THS1(I),I=1,MX)
WRITE(6,1253)
WRITE(6,1230)(THS2(I),I=1,MX)
PI = TI(2)/2.
RC = TO(2)/2.
STCR = THS1(MX)
WRITE(6,1254) STCR,RI,RO
IF (Z(MX,KMX).LT.ZSPLIT) GO TO 459
CALL SPLINT (Z(1,KMX),SM(1,KMX),MX,ZSPLIT,1,AMLER)
CALL SPLINT (SM(1,KMX),R(1,KMX),MX,AMLER,1,RSLPT)
CALL SPLINT (S(1,KMX),THS,MX,AMLER,1,THTAS)
CALL SPLCR(S(1,KMX),THS,MX,AMLER,1,DTDMS)
CALL LININT(ZSPLIT,RSLPT,XZ,XR,TN,21,21,TSLPT)
TANS = RSLPT*TDMS
RIS = TSLPT/2.0
STGRS = THS1(MX)-RIS*TANS/RSLPT-THTAS+THSC
AMLER=AMLER-S(MXBL,KMX)
RETAS = ATAN(TANS)
 RETAS = RETAS*57.29577
WRITE(6,1255) AMLER,STGRS,RIS,RO,BETAS

459 DO 460 J=1,3
I = MXBL
   IF(J.EQ.2) K=(KMX+1)/2
   IF(J.EQ.3) K=KMX
   TIP = 1.-(WA(I,K)**2+2.*W*ALM-(W*R(I,K))**2)/2./CP/TEMP
   DENSTY = TIP**EXPON*RHOC
   C = 6.283186*R(I,K)-XNN*TT(I,K)
   WIDTH = AB(MXBL)
   IF(J.EQ.2) WIDTH = ACH(MXBL)
   IF(J.EQ.3) WIDTH = ACH(MXBL)
   WM = RA(2)/DENSTY/C/WIDTH
   WTHETA = ALM/R(I,K)-W*W(I,K)
   RETAI(J) = ATAN(WTHETA/WM)
   AA(J) = RETAI(J)*57.29577

46C CONTINUE
WRITE (6,1170) AA
GC TC 10
I01C FORMAT (415,6F10.4)
I02C FORMAT (EHORUN NO.13,10X,25HINPUT DATA CARD LISTING )
I03C FORMAT (7F10.4)
I04C FORMAT (10X24HRCD CARDS FOR DN,WA,Z,R )
I05C FORMAT (26HK STAG SPEED OF SOUND AT INLET = ,F9.2)
I06C FORMAT (///5X13HITERATION NO.13)
I07C FORMAT (1H 6X5HALPHA9X5HRC 9X5HBETA 9X5HTT 9X5HSA 9
1X5HSC 9X5HSD )
I08C FORMAT (2X10HSTREAMLINE13)
I09C FORMAT (5F14.6)
I10C FORMAT (1H1L9X5H 215X5H K 15X5HWA 15X5HPSRS14X3HWTR14X3HWL
114X6HTREL )
I11C FORMAT (6F19.6,F18.6)
I12C FORMAT (18H ITERATION NO. 13,10X,24HMAX. STREAMLINE CHANGE = ,
IF10.6)
I13C FORMAT (1HJ)
I16C FORMAT (12F11.4)
I17C FORMAT (///1H1L,10X,20HINLET ANGLES - HUR,F7.2,8H, MEANF7.2,10H
1, SHRCDF7.2)
I0C1 FORMAT(RCH
I 1)
I007 FORMAT(1H0,3X,2HMX,2X,3HKMX,3X,2HMR,3X,2HMZ,6X,1HW,14X,2HWT,
113X,2XHN,12X,3HGAM,12X,2HAR)
I008 FORMAT(1H0,1X,4HTYPF,1X,4H MT ,2X,3HSRW,1X,4HMXBL,5X,4HTEMP,
111X,3HALK,12X,3HRHC,12X,5HPLCSS,9X,4HANGR)
I009 FORMAT(1H0,1X,4HXSTH,1X,4HNPRT,1X,4HITER,1X,4H KD ,4X,5HFACT,
19X,6FZSPLIT,10X,4HBETO,11X,6F4CORFAC,9X,3HSSN)
I011 FORMAT (415,6G15.5)
I027 FORMAT(1H0,4HRB = ,F8.5)
I028 FORMAT (7G15.5)
I025 FORMAT(1H0,5X,8HZS ARRAY)
I031 FORMAT(1H0,5X,8HZH ARRAY)
$IBFC RUIT   DECK

SUBROUTINE RUIT(A,B,Y,X,SM,R,MX)

C   RCCT FINDS A ROOT FOR (FX-Y) IN THE INTERVAL (A,B)
C
C
COMMON SRW
INTEGER SRW
DIMENSION SM(21),R(21)
TOLERY = Y/50000.
IF (SRW.EQ.21) WRITE(6,1000) A,B,Y,TOLERY
X1 = A
CALL SPLINT (SM,R,MX,X1,1,FX1)
IF (SRW.EQ.21) WRITE(6,1010) X1,FX1
X2 = B
DC 3C I=1,15
   X = (X1+X2)/2.
   CALL SPLINT (SM,R,MX,X1,1,FX1)
   IF (SRW.EQ.21) WRITE(6,1010) X,FX
   IF (((FX1-Y)*(FX-Y),GT.0.) GO TO 20
   X2 = X
   X1 = X
   FX1 = FX
   20 CONTINUE
   IF (ABS(Y-FX).LT.TOLERY) RETURN
   WRITE (6,1020) A,B,Y,FX,X
   RETURN
C
C
1000 FORMAT(12H1INPUT ARGUMENTS FOR ROOT -- A =G13.5,3X,3HB =,G13.5,  
       3X,3HY =,G13.5,3X,8HTOLERY =, G13.5/16X,1HX,17X,2HFX)
1010 FORMAT(8X,G16.5,G16.5)
1020 FORMAT(21HROOT CUT OF TOLERANCE,2X,3HA =,G16.5,2X,3HB =,G16.5,2X,  
       13HY =,G16.5,2X,4HFX =,G16.5,2X,3HX =,G16.5)
EN
$\text{IBFTC SMCCTH DECK}$

```
$\text{SUBROUTINE SMOOTH (X,Y,XH,YH,SLOPE,SSN,INF)}$
$\text{DIMENSION X(21),Y(21),XH(21),YH(21),X1(21),Y1(21),INF(21)},$
$\text{ISLOPE(21)}$
NS = SSN
N1=NS-1
DC 10 I =2,N1
D=0.0
IF(I.EQ.(NS-1)) D=8.0
IF(I.EQ.(NS-2)) D=4.0
IF(I.EQ.(NS-3)) D=2.6667
IF(X(I+1).EQ.X(I-1)) GO TO 5
$\text{SLCPE1} = (Y(I+1)-Y(I-1))/(X(I+1)-X(I-1))$
IF (INF(I).EQ. 1 ) GO TO 6
X1(I) = ((Y(I-1)-SLCPE1*X(I-1))-(YH(I)-SLCPE(I)*XH(I)))/(SLOPE(I)
1-SLCPE1)
X1(I)=(X1(I)-X(I))/C)+X(I)
Y1(I) = YH(I)+SLOPE(I)*(X1(I)-XH(I))
GC TC 10

C SLOPE1 = INFINITY
5 Y1(I) =SLOPE(I)*(X(I-1)-XH(I))+YH(I)
Y1(I)=((Y1(I)-Y(I))/C)+Y(I)
X1(I)=(X(I-1)-X(I))/D)+X(I)
GC TC 10

C SLOPE = INFINITY
6 Y1(I) = SLCPE1*(X(I)-X(I-1))+Y(I-1)
Y1(I)=((Y1(I)-Y(I))/C)+Y(I)
X1(I) = X(I)
10 CONTINUE
DC 2C I =2,N1
Y(I) = X1(I)
20 Y(I) = Y1(I)
RETURN
END$
```

$\text{IBFTC INTGRL DECK}$

```
$\text{SUBROUTINE INTGRL (X,Y,N,SUM)}$
$\text{DIMENSION X(50),Y(50),S(50),A(50),B(50),C(50),F(50),W(50),SB(50)},$
$\text{IG(50),EM(50),SUM(50)}$
COMMON SRW
INTEGER SRW
DC 1C I=2,N
1C S(I)=X(I)-X(I-1)
NC=N-1
DC 20 I=2,NC
A(I)=S(I)/6.0
B(I)=(S(I)+S(I+1))/3.0
C(I)=S(I+1)/6.0
2C F(I)=(Y(I+1)-Y(I))/S(I+1)-(Y(I)-Y(I-1))/S(I)
A(N)=-.5
B(N)=1.0
P(N)=1.0
C(1)=-.5
```
F(1)=C.0
F(N)=C.0
W(I)=P(I)
SB(I)=C(I)/W(I)
G(I)=0.0
DC 3 C I=2,N
W(I)=P(I)-A(I)*SP(I-1)
SP(I)=C(I)/W(I)
\[ G(I) = (F(I) - A(I)) * G(I-1) / W(I) \]
EM(A)=G(A)
DC 40 I=2,N
K=N+I-1
\[ EM(K) = G(K) - SR(K) * EM(K+1) \]
SUM(I)=C.0
DC 50 K=2,N
\[ SUM(K) = SUM(K-1) + S(K) * (Y(K)+Y(K-1))/2.0 - S(K) * 3*(EM(K)+EM(K-1))/2 \]
140 C
IF(ISRW.EQ.17) WRITE(6,1000) N,(X(I),Y(I),SUM(I),EM(I),I=1,N)
RETURN
100 C FORMAT (17H1 NO. OF POINTS =13/10*5HX 15X5HY 15X5HSUM
1 13x10+2ND DERIV.)/(4E20.8))
END

$18FTC CONTIN DECK

SUPRCUTI E CONTIN (WA,WTFL,IND,I,WT)
DIMENSION SPEED(3),WEIGHT(3)
135 GC TC (140,150,210,270,370),IND
14C SPEED(1) = WA
WEIGHT(1) = WTFL
DELTA = WT/WTFL-WA-WA
IF(ABS(DELTA).GT.100.) DELTA = SIGN(100.,DELTA)
WA = DELTA+WA
INC = 2
RETURN
15C IF ((WTFL-WEIGHT(1))/(WA-SPEED(1))) 180,180,160
16C SPEED(2) = WA
DELTA = (WT-WTFL)/(WTFL-WEIGHT(1))*(WA-SPEED(1))
IF(ABS(DELTA).GT.100.) DELTA = SIGN(100.,DELTA)
WA = DELTA+WA
166 SPEED(1) = SPEED(2)
WEIGHT(1) = WTFL
RETURN
17C WRITE (6,1000) 1,WTFL
INC = 6
RETURN
18C INC = 3
IF (WTFL.GE.WT) GO TO 140
IF (SPEED(1)-WA) 190,200,200
19C SPEED(2) = SPEED(1)
SPEED(1) = 2.0*SPEED(1)-WA
SPEED(3) = WA
WEIGHT(2) = WEIGHT(1)
WEIGHT(3) = WTFL
WA = SPEED(1)
RETURN
39
20C SPEED(2) = WA
SPEED(3) = SPEED(1)
SPEED(1) = 2.0*WA-SPEED(1)
WEIGHT(2) = WTFL
WEIGHT(3) = WEIGHT(1)
WA = SPEED(1)
RETURN
21C WEIGHT(1) = WTFL
IF (WTFL.GE.WT) GO TO 140
IF (WEIGHT(1)-WEIGHT(2)) 230,380,220
22C WEIGHT(3) = WEIGHT(2)
WEIGHT(2) = WEIGHT(1)
SPEED(3) = SPEED(2)
SPEED(2) = SPEED(1)
SPEED(1) = 2.0*SPEED(2)-SPEED(3)
WA = SPEED(1)
RETURN
23C IF (SPEED(3)-SPEED(1)-10.0) 170,170,240
24C INC = 4
25C WA = (SPEED(1)+SPEED(2))/2.0
RETURN
26C WA = (SPEED(3)+SPEED(2))/2.0
RETURN
27C IF (SPEED(3)-SPEED(1)-10.0) 170,170,280
28C IF (WTFL-WEIGHT(2)) 320,350,290
29C IF (WA-SPEED(2)) 310,300,300
30C SPEEC(1) = SPEED(2)
SPEED(2) = WA
WEIGHT(1) = WEIGHT(2)
WEIGHT(2) = WTFL
GC TC 245
31C SPEED(3) = SPEED(2)
SPEED(2) = WA
WEIGHT(3) = WEIGHT(2)
WEIGHT(2) = WTFL
GC TC 245
32C IF (WA-SPEED(2)) 340,330,330
33C WEIGHT(3) = WTFL
SPEED(3) = WA
GC TC 245
34C WEIGHT(1) = WTFL
SPEED(1) = WA
GC TC 245
35C INC = 5
IF (WA-SPEED(2)) 380,360,360
36C SPEEC(1) = SPEED(2)
WEIGHT(1) = WEIGHT(2)
SPEED(2) = (SPEEC(1)+SPEEC(3))/2.0
WA = SPEED(2)
RETURN
37C INC = 4
WEIGHT(2) = WTFL
WA = (SPEEC(1)+SPEEC(2))/2.0
RETURN
38C INC = 5
39C WEIGHT(3) = WEIGHT(2)
SPEEC(3) = SPEEC(2)
SPEEC(2) = (SPEEC(1)+SPEEC(3))/2.
WA = SPEEC(2)
RETURN
10CC FFORMAT (/12H FIXED LINE 12,12H, MAX WT = F10.6)
END
$IBFTC SPLDER DECK

SUBROUTINE SPLDER(X,Y,N,Z,MAX,DYDX)
DIMENSION X(50),Y(50),S(50),A(50),B(50),C(50),F(50),W(50),SB(50),
IG(50),EM(50),Z(50),DYDX(50)
DC 1C I=2,N
1C S[I]=X(I)-X(I-1)
NC=K-1
DC 20 I=2,NC
A(I)=S(I)/6.0
B(I)=(S(I)+S(I+1))/3.0
C(I)=S(I+1)/6.0
2C F(I)=(Y(I+1)-Y(I))/S(I+1)-(Y(I)-Y(I-1))/S(I)
A(N)=-.5
B(I)=1.0
B(N)=1.0
C(I)=-.5
F(I)=C.0
F(N)=C.0
W(I)=B(I)
SB(I)=C(I)/W(I)
G(I)=0.0
DC 3C I=2,N
W(I)=B(I)-A(I)*SB(I-1)
SB(I)=C(I)/W(I)
3C G(I)=(F(I)-A(I)*G(I-1))/W(I)
EM(N)=G(N)
DC 4C I=2,N
K=N+1-I
4C EM(K)=G(K)-SB(K)*EM(K+1)
DC 9C I=1,MAX
K=2
IF(Z(I)-Y(I)) 60,70,70
6C WRITE (6,1000)Z(I)
100C FORMAT (17H OUT OF BLADE Z =F10.6)
GC TC 85
65 WRITE (6,1000)Z(I)
K=N
GC TC 85
7C IF(Z(I)-Y(K)) 85,85,80
8C K=K+1
IF(K-N) 70,70,65
85 DYDX(I)=-EM(K-1)*(X(K)-Z(I))*2/2.0/S(K)+EM(K)*(X(K-1)-Z(I))*2/2.0/S(K)
10/S(K)+(Y(K)-Y(K-1))/S(K)-(EM(K)-EM(K-1))*S(K)/6.0
9C CONTINUE
10C RETURN
ENC

$IBFTC SPLINE DECK

SUBROUTINE SPLINE(X,Y,N,SLOPE,EM)
DIMENSION X(50),Y(50),S(50),A(50),B(50),C(50),F(50),W(50),SB(50),
IG(50),EM(50),SLOPE(50)
COMMON C
INTEGER C
DC 1C I=2,N
S(I) = X(I) - X(I-1)
NC = N - 1
DC 2C I = 2, N
\Delta(I) = S(I) / 6
B(I) = (S(I) + S(I+1)) / 3
C(I) = S(I+1) / 6

F(I) = (Y(I+1) - Y(I)) / S(I+1) - (Y(I) - Y(I-1)) / S(I)
A(N) = -.5
B(I) = 1
B(N) = 1
C(I) = -.5
F(I) = 0
F(N) = 0
W(I) = E(I)
SB(I) = C(I) / W(I)
G(I) = C
DC 3C I = 2, N
W(I) = E(I) - 4(I) * SB(I-1)
SB(I) = C(I) / W(I)

G(I) = (F(I) - \Delta(I) * G(I-1)) / W(I)
E(N) = G(N)
DC 40 I = 2, N
K = A + 1

E(K) = G(K) - SB(K) * E(K+1)
SLOPE(I) = S(2) / 6. * (2. * EM(1) + EM(2)) + (Y(2) - Y(1)) / S(2)
D50 = I = 2, N

SLOPE(I) = S(I) / 6. * (2. * EM(I) + EM(I-1)) + (Y(I) - Y(I-1)) / S(I)
IF (C.EQ.13) WRITE (6, 100) N, (X(I), Y(I), SLOPE(I), EM(I), I = 1, N)

FORMAT (2X15HNO. OF POINTS = I3/10X5HX 15X5HY 15X5HSLOPE15X5H1EM /
RETURN
ENDC

$IBUTIC LININT DECK

SUBROUTINE LININT(X1, Y1, X, Y, TN, MX, MY, F)
CCMCA K
DIMENSION X(MX), Y(MY), TN(MX, MY)
DC 1C J3 = 1, MX
1C IF (X1.LT.X(J3)) GO TO 20
J3 = MX
2C DC 3C J4 = 1, MY
3C IF (Y1.LT.Y(J4)) GO TO 40
J4 = MY
4C J1 = J3 - 1
J2 = J4 - 1
EPS1 = (X1 - X(J1)) / (X(J3) - X(J1))
EPS2 = (Y1 - Y(J2)) / (Y(J4) - Y(J2))
EPS3 = 1 - EPS1
EPS4 = 1 - EPS2
F = TN(J1, J2) * EPS3 * EPS4 + TN(J3, J2) * EPS1 * EPS4 + TN(J1, J4) * EPS2 * EPS3 +
TN(J3, J4) * EPS1 * EPS2
IF (K.EQ.14) WRITE (6, 1) X1, Y1, F, J1, J2, EPS1, EPS2
1C FORMAT (6H LININT3F10.5, 2I3, 2F10.5)
K = C
RETURN
ENDC
$IRFTC SPLINT DECK$

SUBROUTINE SPLINT (X,N,MAX,YINT)
DIMENSION X(50),Y(50),S(50),A(50),B(50),C(50),F(50),W(50),SB(50),
IG(50),EM(50),Z(50),YINT(50)
COMMON Q
INTEGER J

1C S(I)=X(I)-X(I-1)
NC=N-1
DC 2C I=2,NC
A(I)=S(I)/6.0
B(I)=(S(I)+S(I+1))/3.0
C(I)=S(I+1)/6.0
2C F(I)=(Y(I+1)-Y(I))/S(I+1)-(Y(I)-Y(I-1))/S(I)
A(N)=-.5
B(N)=1.0
C(N)=0.0
F(N)=0.0
W(I)=B(I)
SB(I)=C(I)/W(I)
G(I)=0.0
DC 3C I=2,N
W(I)=W(I)-A(I)*SB(I-1)
SB(I)=C(I)/W(I)
3C G(I)=(F(I)-A(I)*G(I-1))/W(I)
DC 4C I=2,N
K=A+1-I
4C EM(K)=G(K)-SB(K)*EM(K+1)
DC 9C I=1,MAX
K=2
IF(Z(I)-X(I)) 60,50,70
5C YINT(I)=Y(I)
GC TC 90
6C IF(Z(I)>X(N)) 100,75,80
IF(Z(I)>X(N)) WRITE (6,1000)Z(I)
GC TC 85
100C FORMAT (17F OUT OF RANGE Z =F10.6)
65 IF(Z(I) .GT. X(N)) WRITE (6,1000)Z(I)
K=N
GC TC 85
7C IF(Z(I)-X(K)) 85,75,80
75 YINT(I)=Y(K)
GC TC 90
8C K=K+1
GC TC 85
85 YINT(I) = EM(K-1)*(X(K)-Z(I))/S(K)+EM(K)*(Z(I)-X(K-1))/S(K)+EM(K-1)
1/S(K)+(Y(K)/S(K)-EM(K)*S(K)/6.0)*(Z(I)-X(K-1))+(Y(K-1)/S(K)-EM(K-1)
2*S(K)/6.0)*(X(K)-Z(I))
9C CONTINUE
EM(N)=S(N)
Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 16, 1971,
132-15.
APPENDIX - SYMBOLS

A  coefficient, eq. (2)
B  coefficient, eq. (2)
C  coefficient, eq. (2)

\( c_p \)  specific heat, \( J/(kg)(K) \); \( (ft)(lbf)/(slug)(^\circ R) \)
D  coefficient, eq. (2)

h  enthalpy, \( J/kg \); \( (ft)(lbf)/slug \)
m  meridional streamline distance, m; ft

N  number of blades

\( \Delta p'' \)  loss in relative total pressure, \( N/m^2 \); \( lb/ft^2 \)
R  gas constant, \( J/(kg)(K) \); \( (ft)(lbf)/(slug)(^\circ R) \)
r  radius from axis of rotation, m; ft

\( r_c \)  radius of curvature of a meridional streamline, m; ft
s  distance along a quasi-orthogonal, m; ft
T  temperature, \( K, ^\circ R \)

\( t_n \)  blade thickness normal to mean blade shape, m; ft

\( t_\theta \)  blade thickness in tangential direction, m; ft
V  absolute velocity, m/sec; ft/sec
W  relative velocity, m/sec; ft/sec
w  mass flow, kg/sec; slugs/sec
z  axial distance, m; ft

\( \alpha \)  angle between meridional streamline and \( z \)-axis, rad
\( \beta \)  angle between relative velocity and meridional plane, rad

\( \gamma \)  ratio of specific heats

\( \theta \)  angular coordinate, rad

\( \lambda \)  inlet prerotation, \( m^2/sec \); \( ft^2/sec \)
\( \rho \)  density, \( kg/m^3 \); slugs/ft^3

\( \psi \)  angle between quasi-orthogonal and radial direction, rad

\( \omega \)  rotational speed, rad/sec
Subscripts:

b  point at which mean stream surface deviates from mean blade shape
f  flow
h  hub
i  inlet
isen  isentropic
l  leading surface
m  direction of meridional streamline
n  normal direction
o  outlet
s  shroud
t  trailing surface
θ  tangential direction

Superscripts:

'  absolute total conditions
''  relative total conditions
REFERENCES


### TABLE 1: INPUT FORM FOR QUAC

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- MX: Title
- KMX: Type
- MR: Input
- MZ: Card
- W: Card
- WT: Card
- TN: Array
- ARRAY: XT
- XT: ARRAY
- XR: ARRAY

**Legend:**
- MX: Title
- KMX: Type
- MR: Input
- MZ: Card
- W: Card
- WT: Card
- TN: Array
- ARRAY: XT
- XT: ARRAY
- XR: ARRAY

**Notes:**
- MX: Title
- KMX: Type
- MR: Input
- MZ: Card
- W: Card
- WT: Card
- TN: Array
- ARRAY: XT
- XT: ARRAY
- XR: ARRAY
### TABLE II. - SAMPLE OUTPUT

**INPUT DATA CARD LISTING**

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**PLACE THICKNESS TABLE**

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**STAG. SPEED CF SOUNC AT INLET = 1116.36**

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**TABLE II. - Concluded. SAMPLE OUTPUT**

**STREAM-CHANNEL COORDINATES**

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**STREAM-CHANNEL NORMAL THICKNESS**

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**PLANE CCORDINATES**

**M ARRAY**

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**THETA ARRAY BLADE SURFACE 1**

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**STGR = -1.733525**

**SPLITTERS**

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**INLET ANGLES - HUB -30.70, MEAN -53.79, SHROUD -60.9%**
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**TYPE** | RT | SHW | MML | TEMP | AMM | BTH | PLOS | ANNGT |
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**ZH ARRAY**

|       | -.07543 | .05 | -.025 | 0 | .010167 | .95409 | .12043 |

**HS ARRAY**

|       | .14125 | .14125 | .14125 | .14125 | .14125 | .14125 | .14320 |

**HII ARRAY**

|       | .04257 | .04257 | .04257 | .04257 | .04257 | .04257 | .06044 |

**THTA ARRAY**

|       | 1.0629 | .6977 | .338 | 0 | -.125 | .500 | .960 |

**ZT ARRAY** (II KD 2, ZT ARRAY USED), THTA = (ZT). MT = No. of.

|       |       |       |       |       |       |       |       |

**TN ARRAY**

|       | .00416 | .00500 | .00433 | .00530 | .00750 | .00750 | .00750 |

**XK ARRAY**

|       | .000033 | .04723 | .09445 | .1417 | .18333 | .20833 |

**XH ARRAY**

|       | .04167 | .09126 | .14125 | .20833 | .25417 |       |
TABLE IV. - STREAM-CHANNEL AND BLADE COORDINATES FOR BACKSWEPT IMPELLER

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**TABLE V. - INPUT FOR QUAC FOR FLAT-VANE DIFFUSER**

| 2S ARRAY |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 0.00598 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .01046 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 2H ARRAY |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 0.02527 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .02123 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 2S ARRAY |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .1917 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .2417 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 2H ARRAY |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .1917 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .2417 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| THTA ARRAY |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 0 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .3122 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| ZT ARRAY | (IF KD | 2, ZT ARRAY USED, THTA = (ZT), MT = No, of,) |     |     |     |     |     |     |     |     |     |     |     |
| 0 |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .0025 |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .0035 |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .0045 |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .0055 |     |     |     |     |     |     |     |     |     |     |     |     |     |

| ZA ARRAY |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 0 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| .0050 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| ZR MRT |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 1.0a |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 400 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 200 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 200 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 200 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 200 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

| 200 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

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### TABLE VI. - STREAM-CHANNEL AND BLADE COORDINATES FOR DIFFUSER

**MEAN**

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<thead>
<tr>
<th>STREAM-CHANNEL COORDINATES</th>
<th>M ARRAY</th>
<th>R ARRAY</th>
<th>STREAM-CHANNEL NORMAL THICKNESS</th>
<th>R ARRAY</th>
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<td>STREAM-CHANNEL COORDINATES</td>
<td>M ARRAY</td>
<td>R ARRAY</td>
<td>STREAM-CHANNEL NORMAL THICKNESS</td>
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**BLADE COORDINATES**

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**Notes:**
- All coordinates are in meters.
- The normal thickness values are in millimeters.
- The stream-channel and blade coordinates are given in scientific notation.
### Table VII - Input for QUAC for Radial Impeller

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NASA-Langley, 1972 — 1 E-6592
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