FORTRAN PROGRAM FOR PREDICTING OFF-DESIGN PERFORMANCE OF RADIAL-INFLOW TURBINES

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The FORTRAN IV program uses a one-dimensional solution of flow conditions through the turbine along the mean streamline. The program inputs needed are the design-point requirements and turbine geometry. The output includes performance and velocity-diagram parameters over a range of speed and pressure ratio. Computed performance is compared with the experimental data from two radial-inflow turbines and with the performance calculated by a previous computer program. The flow equations, program listing, and input and output for a sample problem are given.
A FORTRAN IV program for calculating off-design performance of a radial-inflow turbine is presented. The program uses a one-dimensional solution of flow conditions through the turbine along the mean streamline. The loss model accounts for stator, rotor, incidence, and exit losses. Other program features include consideration of stator and rotor trailing-edge blockage and computation of performance to limiting loading. Overall turbine geometry and design-point values of efficiency, pressure ratio, and mass flow are needed as input information. The output includes performance and velocity-diagram parameters for any number of given speeds over a range of turbine pressure ratio. Included in this report are the engineering equations, the program listing, and the input information and output listing for a sample turbine problem.

The experimental performance of two radial-inflow turbines is compared with the results from the computer program presented herein and with those from a previously used program. The overall computed results from the program of this report show a marked improvement over those from the previously used program and good agreement with experimental data.

A procedure for predicting the off-design performance of a radial-inflow turbine is described in reference 1. This procedure is based on a one-dimensional solution to determine the flow conditions through the turbine along the mean streamline. The FORTRAN IV computer program for this procedure is given in reference 2. This program uses turbine geometry and design-point performance as input and computes the performance and velocity-diagram parameters over a range of speed and pressure ratio. The results from this program, however, did not correlate as well as desired.
with the experimental results of some subsequently tested turbines.

The basic loss-model assumptions used in this program were reexamined to see if alternative assumptions would yield a better correlation with experimental data. Accordingly, the computer program described in reference 2 was modified. In addition, new features were added to the program to account for trailing-edge blockage and to compute the conditions for pressure ratios at or beyond stator and/or rotor choke. These features give more flexibility to the program and offer a greater range for off-design turbine analysis.

This report presents the modified FORTRAN IV program which computes overall performance for a radial-inflow turbine. The revised loss assumptions and new program features are described. Also included in the report are the engineering equations, the program listing, and a complete description of input and output including a sample turbine problem. The performance of two radial-inflow turbines (refs. 3 and 4) was computed by using the program of this report and that of reference 2. The performance predicted by each program is compared with experimental data for the two turbines.

**METHOD OF ANALYSIS**

A one-dimensional solution of flow conditions through the turbine along the mean streamline is the basis for this analysis. Two independent variables are assumed for each calculated performance point. A value of rotor-inlet-tip speed \( U_3 \) is chosen, and for each speed a range of stator-exit critical-velocity ratios \( \frac{V}{V_{cr}} \) is assumed. Symbols are defined in appendix A, and a typical turbine with station nomenclature is shown in figure 1. The equations used in the program are given in appendix B. The computer uses these equations in essentially the order listed.

There are two modes of operation for this program - the design mode and the off-design performance mode. Before the off-design performance mode can be used, two loss determinants, the stator total-pressure ratio \( \frac{p_1'}{p_0'} \) and the rotor loss coefficient \( K \), must be known. In the design mode the program automatically determines these loss determinants at the design point by means of a search routine. By repeated iterations the computer finds a pair of values for \( \frac{p_1'}{p_0'} \) and \( K \) which satisfy the input design values of mass flow rate, efficiency, and pressure ratio. These values of \( \frac{p_1'}{p_0'} \) and \( K \) are then used in the off-design performance mode. If desired, the values of \( \frac{p_1'}{p_0'} \) and \( K \) can be determined from the user's own loss procedures and used in the off-design performance mode. The off-design performance mode computes all performance parameters over the entire range of rotor speeds and stator-exit velocity ratios requested.
Turbine Losses

The results from the computer program of reference 2 did not correlate well with the experimental results from the turbine tests of references 3 to 6. The three main losses were (1) a stator loss, (2) an incidence loss, and (3) a rotor loss. It was decided to reexamine and modify the models used to represent these losses to see if a better correlation could be obtained.

Stator loss. - In reference 1 the loss in kinetic energy across the stator is proportional to the average kinetic energy in the blade row and is represented by the equation

\[ L_S = \frac{V_{1, id}^2 - V_1^2}{2gJ} = K_S \frac{V_0^2 + V_1^2}{2gJ} \]  

The stator loss coefficient \( K_S \) is determined from design-point performance and then is assumed to be constant for the off-design calculations.

In order to check this assumption, stator loss coefficients were calculated from unpublished data obtained with the turbines of references 3 to 6. All four of these turbines had static-pressure taps located just inside the stator trailing edge. Therefore, stator performance could be calculated by using these static-pressure data along with the design stator-exit blade angle and the measured values of mass flow rate, stator-exit area, and total temperature. The calculated stator loss coefficients are given as a function of stator-exit critical-velocity ratio in figure 2. As shown, the stator loss coefficient decreases significantly with increasing velocity ratio over the range of data. Thus, the assumption of a constant stator loss coefficient, as made in reference 1, does not seem to be valid.

Another way to express stator loss is as the ratio of stator-exit to turbine-inlet total pressure. Figure 3 shows the variation of stator-exit to turbine-inlet total-pressure ratio with stator-exit velocity ratio as obtained from the data of references 3 to 6. The stator total-pressure ratio for each turbine was fairly constant over the range of velocity ratio tested. Total-pressure-ratio level ranged from about 0.98 to 0.99 for most of the data. This examination and analysis indicated that a constant stator total-pressure ratio would be a better model for the stator loss, and thus it was incorporated into the program.

Incidence loss. - Minimum incidence loss does not occur at zero incidence angle with respect to the rotor blade, but at some optimum flow angle \( \varphi \) (fig. 4). The calculation of the optimum flow angle follows the method of Stanitz (ref. 7). This method was used in reference 2 and is described in appendix B as equations (B8a) to (B8d). The flow angle at the rotor inlet is \( \beta_3 \), and the incidence angle is defined as
\[ i_3 = \beta_3 - \varphi \]  

In reference 2 the incidence loss is assumed to be the component of relative velocity normal to the angle \( \varphi \):

\[ L_{IN} = \frac{W_3^2 \sin^2 i_3}{2gJ} \]  

In the program of this report, different variations in loss with positive and negative incidence were used, and equation (3) was changed to

\[ L_{IN} = \frac{W_3^2 \sin^n i_3}{2gJ} \]  

(3a)

A value of 2 was used for the exponent \( n \) for negative incidence. However, for positive incidence, a value of 3 for the exponent \( n \) gave a better correlation with experimental data.

**Rotor loss.** - In reference 1 the viscous loss in the rotor is assumed to be proportional to the average kinetic energy in the blade row as calculated from the equation

\[ L_R = \frac{W_{4, id}^2 - W_4^2}{2gJ} = K \left( \frac{W_3^2 + W_4^2}{2gJ} \right) \]  

(4)

At high pressure ratios the level of rotor inlet velocity \( W_3 \) seemed to have an excessive influence on the loss. Using the component of velocity in the direction of the optimum flow angle gave a better correlation with experimental data. In the present program, therefore, the rotor loss was calculated as

\[ L_R = \frac{W_{4, id}^2 - W_4^2}{2gJ} = K \left( \frac{W_3^2 \cos^2 i + W_4^2}{2gJ} \right) \]  

(4a)

The value of \( K \) was approximately 0.3 for all the turbines examined in this report.
Trailing-Edge Blockage

In order to account for the effect of stator trailing-edge blockage, the analysis of reference 1 assumes a variable station where the flow from the stator is assumed to occupy the entire cylindrical flow area. Trailing-edge blockage at the rotor exit is not taken into account.

The analysis of this report accounts for trailing-edge blockage at both the stator and rotor exits. The effect of blockage for each blade row is specified in terms of the ratio of the flow area just inside to that just outside the blade trailing edge. Figure 5 shows the blade-row trailing-edge region, specifically the areas used in the blockage calculation. Both angular momentum and continuity are conserved when the conditions at these stations are calculated.

Stator and Rotor Choke

The program of reference 2 did not compute turbine performance at or beyond the stator and rotor choking points. The program of this report allows turbine performance to be computed at the stator and rotor choking points and at pressure ratios beyond choking to rotor blade limiting loading. The stator choke point is where \((V/V_{cr})_1 = 1.0\), which is the point of maximum flow per unit area. For values of \((V/V_{cr})_1\) greater than 1.0, a new stator-exit flow angle \(\alpha_1\) is computed from the area required to pass the choking mass flow rate.

In order to find the rotor choking point, an iteration is required to determine the value of \((V/V_{cr})_1\) that maximizes flow per unit area at the rotor exit. Conditions upstream of the rotor exit are then held fixed. As the velocity ratio \((W/W_{cr})_4\) is increased beyond the choking value, the exit flow angle \(\beta_4\) is adjusted to pass the choking mass flow. The program is terminated at or close to blade limiting loading, where \((W_x/W_{cr})_4 = 1.0\).

COMPARISON OF COMPUTED AND EXPERIMENTAL RESULTS

This section compares the experimental results obtained with two radial-inflow turbines to the results obtained by the analytical procedures described in reference 2 and this report. The two radial-inflow turbines are those of references 3 and 4. The results of the comparison are presented in terms of mass flow rate and total and static efficiency variations with pressure ratio and speed.
Mass Flow Rate

Calculated and experimental variations of mass flow rate with turbine total-to-static-pressure ratio for various speeds are compared in figure 6(a) for the reference 3 turbine and in figure 6(b) for the reference 4 turbine. The data for the reference 4 turbine are unpublished air data, which were used herein because they covered a wider range of pressure ratios than the published argon data. For both turbines, the off-design values of mass flow rate computed by using the program of this report showed a significantly better correlation with the experimental data, especially at higher pressure ratios and lower speeds, than did the values computed by the program of reference 2. The poorest correlation between the computed and experimental values was in the region near choked flow (fig. 6(b)). In this region, the maximum deviation between computed and experimental mass flow rates was reduced from about 9 percent (program of ref. 2) to about $3\frac{1}{2}$ percent by using the program of this report.

Total Efficiency

Calculated and experimental variations of total efficiency with blade-jet speed ratio for a number of speeds are compared in figure 7(a) for the reference 3 turbine and in figure 7(b) for the reference 4 turbine. In figure 7(a) the 90- and 110-percent speed lines are not shown in order to avoid overlapping of data. The off-design values of total efficiency computed by using the program of this report showed a significantly better correlation with the experimental data, especially in the case of the reference 4 turbine, than did the values computed by the program of reference 2. As shown in figure 7(b), the maximum deviation between computed and experimental total efficiencies was reduced from about 10 percent (program of ref. 2) to essentially zero by using the program of this report.

Static Efficiency

Calculated and experimental variations of static efficiency with blade-jet speed ratio for a number of speeds are compared in figure 8(a) for the reference 3 turbine and in figure 8(b) for the reference 4 turbine. Except for blade-jet speed ratios higher than the design value, the efficiencies computed by the program of reference 2 for all speeds were generally about 2 percentage points lower than experimental values for both turbines. The efficiencies computed by the program of this report over the same range of blade-jet speed ratio generally were within 1 percentage point of the experimental values.
The overall improvement in the correlation of calculated values of mass flow rate and efficiency with experimental data indicates that the turbine loss assumptions used in this report provide a better model than those used in reference 2.

FORTRAN PROGRAM

Program Input

The program input consists of two title, or heading, cards followed by the required physical data and option indicators in NAMELIST format. The information contained in columns 1 to 60 of the title cards is printed as two lines of heading on the output listing. The two title cards, even if left blank, must be the first two cards in the data package. Two additional title cards must precede each different case being run in the same data package.

The physical data and option indicators are input in data records having the NAMELIST name IN. All necessary physical data and option indicators must be inputted for the first case in the data package. For succeeding cases in the same data package, only those items being changed need be inputted.

Options. - There are three sets of options that must be specified by the input. All three are specified by the variable MODE as described in the input variable list. The first option is the choice of units, SI or U.S. customary, to be used for input and output. The particular unit to be used for each variable is included in the input variable list.

The second option is the choice of a mode of operation: either the design mode or the off-design performance mode. The design mode is used to automatically determine the stator total-pressure ratio and rotor loss coefficient that yield design flow and efficiency at the design pressure ratio. The input variable ITEST, as described in the input variable list, is used to specify whether total efficiency and total- to total-pressure ratio or static efficiency and total- to static-pressure ratio are used as the design values being matched. The off-design performance mode is used to compute the performance over the desired ranges of speed and pressure ratio.

The third option provides for the choice of long or short output for the off-design performance mode. Long output is always given for the design mode. The long output includes complete velocity-diagram information in terms of critical-velocity ratios and angles, actual and equivalent overall performance parameters, and dimensionless design parameters. The short output includes only certain of the equivalent performance and dimensionless design parameters. The exact output provided is described in the section Description of Output.

Input variables. - The input variables comprising NAMELIST IN are as follows:
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL1</td>
<td>stator-exit blade angle, $\alpha_1$, deg</td>
</tr>
<tr>
<td>A0</td>
<td>area at turbine inlet (scroll inlet), $A_0$, m$^2$; ft$^2$</td>
</tr>
<tr>
<td>A1</td>
<td>area upstream of stator exit (circumferential area inside blade trailing edge), $A_1$, m$^2$; ft$^2$</td>
</tr>
<tr>
<td>A3</td>
<td>area upstream of rotor inlet (circumferential area outside blade leading edge), $A_3$, m$^2$; ft$^2$</td>
</tr>
<tr>
<td>A5</td>
<td>area downstream of rotor exit (annular area outside blade trailing edge), $A_5$, m$^2$; ft$^2$</td>
</tr>
<tr>
<td>BL1</td>
<td>blockage factor at stator exit, ratio of area inside blade passage to area outside blade passage (fig. 5)</td>
</tr>
<tr>
<td>BL4</td>
<td>blockage factor at rotor exit, ratio of area inside blade passage to area outside blade passage (fig. 5)</td>
</tr>
<tr>
<td>B4</td>
<td>rotor-exit blade angle, $\beta_4$, deg</td>
</tr>
<tr>
<td>DELV</td>
<td>incremental value of stator-exit critical-velocity ratio $(V/V_{cr})_1$</td>
</tr>
<tr>
<td>DELY</td>
<td>incremental value of rotor-exit critical-velocity ratio $(W/W_{cr})_4$ used after rotor choke</td>
</tr>
<tr>
<td>D2</td>
<td>stator-exit diameter, $D_2$, cm; in.</td>
</tr>
<tr>
<td>D3</td>
<td>rotor-inlet diameter, $D_3$, cm; in.</td>
</tr>
<tr>
<td>ETAD</td>
<td>specified design value of static efficiency $\eta_s$ or total efficiency $\eta_t$ (see ITEST)</td>
</tr>
<tr>
<td>G</td>
<td>ratio of specific heat at constant pressure to specific heat at constant volume, $\gamma$</td>
</tr>
</tbody>
</table>
| ITEST| specifies which design values are used for PDSGN and ETAD:  
if ITEST=1, total- to static-pressure ratio $p_0^t/p_5$ and static efficiency $\eta_s$ are used  
if ITEST=2, total- to total-pressure ratio $p_0^t/p_5^t$ and total efficiency $\eta_t$ are used |
| MODE | specifies which program option is used:  
MODE=0 yields the off-design performance mode in SI units and with long output  
MODE=1 yields the off-design performance mode in SI units and with short output  
MODE=2 yields the design mode in SI units |
MODE=3 yields the off-design performance mode in U.S. customary units and with long output

MODE=4 yields the off-design performance mode in U.S. customary units and with short output

MODE=5 yields the design mode in U.S. customary units

PD stator total-pressure ratio, $p'_1/p'_0$

PDSGN specified design total- to total-pressure ratio $p'_0/p'_5$ or total- to static-pressure ratio $p'_0/p_5$ (see ITEST)

P0 inlet total pressure, $p'_0$, N/m²; psfa

R gas constant, $R$, J/(kg)(K); ft·lb/(lb)°R

T0 inlet total temperature, $T'_0$, K; °R

U3 rotor-inlet tip speed, $U_3$, m/sec; ft/sec

$U_4/U_3$ ratio of rotor-exit mean speed to rotor-inlet tip speed, $U_4/U_3$ (Rotor-exit mean speed must correspond to rotor-exit mean velocity diagram. It is recommended that this be at the area-mean radius if no better value is available.)

VMAX final value of stator-exit critical-velocity ratio $(V/V_{cr})_1$

V1 initial value of stator-exit critical-velocity ratio $(V/V_{cr})_1$

WD design value of mass flow rate, $w$, kg/sec; lb/sec

XK rotor loss coefficient, $K$

YMAX final value of rotor-exit critical-velocity ratio $(W/W_{cr})_4$

ZZ number of blades at rotor inlet

Sample input. - Input sheets with the data used in computing the performance for the reference 3 turbine (figs. 6(a), 7(a), and 8(a)) are shown in tables I and II. Selected output obtained with this input is presented and described in the next section. Table I is for the design mode. Table II is for the off-design performance mode for speeds of 100, 110, 90, 70, 50, and 30 percent of design. Each line of the input form shown in tables I and II represents one data card. The first two cards are the mandatory title cards, which can contain any desired message. The next four cards contain the turbine physical data and option indicators. The design-point quantities ETAD, PDSGN, and WD are included for the design mode (table I). The loss coefficients XK and PD determined by the design-mode calculation are included in the off-design-mode (table II) data. Additional data sets may follow the first data set, as they do in table II, and need only
include those values that differ from previous case data. As shown in table II, only the speed is changed for the next five cases.

**Description of Output**

The design-mode output for the input of table I is shown in table III. The top line of output is a program identification title that is automatically printed. The next two lines are the title card messages. The following three lines are the input variable values. The symbolism used to identify the output values is defined in terms of the engineering symbols in the list at the end of this section. Printed next are the computed values of stator total-pressure ratio and rotor loss coefficient followed by the design values of mass flow rate, efficiency, and pressure ratio.

The remainder of the output in table III is divided into two parts. In the section VELOCITIES AND ANGLES, all the absolute and relative critical-velocity ratios and angles at various stations throughout the turbine are listed for the design stator-exit critical-velocity ratio. The section OVERALL PERFORMANCE gives all the performance parameters computed by the program.

Off-design performance mode output is shown in tables IV and V. Table IV shows the long output and presents the first three points obtained by using the input of table II. Table V shows the short output that would be obtained from the first data set of table II if MODE=1. The first six lines in both tables are the same as for the design-mode output. The remainder of the output in table IV gives the velocities, angles, and overall performance in the same format as previously described for the design-mode output. In table V the output is limited to certain of the overall performance parameters useful for defining the overall performance map.

A list of the variable names as used for the output and their corresponding engineering symbols is given in the following table:
<table>
<thead>
<tr>
<th>Variable name</th>
<th>Engineering symbol</th>
<th>Variable name</th>
<th>Engineering symbol</th>
<th>Variable name</th>
<th>Engineering symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA-1</td>
<td>( \alpha_1 )</td>
<td>ETA-T</td>
<td>( \eta_t )</td>
<td>VCR)3</td>
<td>( V_{cr,3} )</td>
</tr>
<tr>
<td>ALPHA-2</td>
<td>( \alpha_2 )</td>
<td>GAMMA</td>
<td>( \gamma )</td>
<td>V/VCR)3</td>
<td>( V_{r}/V_{cr} )</td>
</tr>
<tr>
<td>ALPHA-3</td>
<td>( \alpha_3 )</td>
<td>I-3</td>
<td>( I_3 )</td>
<td>VR/VCR)3</td>
<td>( V_{r}/V_{cr} )</td>
</tr>
<tr>
<td>ALPHA-5</td>
<td>( \alpha_5 )</td>
<td>K</td>
<td>( K )</td>
<td>VU/VCR)3</td>
<td>( V_{u}/V_{cr} )</td>
</tr>
<tr>
<td>A0</td>
<td>( A_0 )</td>
<td>N</td>
<td>( N )</td>
<td>VCR)5</td>
<td>( V_{cr,5} )</td>
</tr>
<tr>
<td>A1</td>
<td>( A_1 )</td>
<td>NS</td>
<td>( N_{s} )</td>
<td>V/VCR)5</td>
<td>( V_{r}/V_{cr} )</td>
</tr>
<tr>
<td>A3</td>
<td>( A_3 )</td>
<td>N/T</td>
<td>( N/T )</td>
<td>VU/VCR)5</td>
<td>( V_{u}/V_{cr} )</td>
</tr>
<tr>
<td>A5</td>
<td>( A_5 )</td>
<td>NU</td>
<td>( \nu )</td>
<td>VX/VCR)5</td>
<td>( V_{x}/V_{cr} )</td>
</tr>
<tr>
<td>BETA-3</td>
<td>( \beta_3 )</td>
<td>PD</td>
<td>( p_1/p_0 )</td>
<td>W</td>
<td>W</td>
</tr>
<tr>
<td>BETA-4</td>
<td>( \beta_4 )</td>
<td>( (p_1/p_0)_{des} )</td>
<td>( p_0 )</td>
<td>W.F.</td>
<td>W.F.</td>
</tr>
<tr>
<td>BETA-5</td>
<td>( \beta_5 )</td>
<td>P0,</td>
<td>( p_0/p_5 )</td>
<td>WN/DEL</td>
<td>WN/DEL</td>
</tr>
<tr>
<td>BL1</td>
<td>( B_1 )</td>
<td>P0, /P5</td>
<td>( p_0/p_5 )</td>
<td>W</td>
<td>W</td>
</tr>
<tr>
<td>BL4</td>
<td>( B_4 )</td>
<td>P0, /P5,</td>
<td>( p_0/p_5 )</td>
<td>WF</td>
<td>WF</td>
</tr>
<tr>
<td>DEL-H</td>
<td>( \Delta h' )</td>
<td>R</td>
<td>( R )</td>
<td>WN/DEL</td>
<td>WN/DEL</td>
</tr>
<tr>
<td>DEL-H/T</td>
<td>( \Delta h'/T_0 )</td>
<td>TOR/P</td>
<td>( \Gamma )</td>
<td>WT/P</td>
<td>WT/P</td>
</tr>
<tr>
<td>DESIGN ETA-S</td>
<td>( \eta_{s,des} )</td>
<td>TOR/P</td>
<td>( 10^6 \Gamma/p_0 )</td>
<td>10000W ( \sqrt{T_0/p_0} )</td>
<td>144W ( \sqrt{T_0/p_0} )</td>
</tr>
<tr>
<td>DESIGN ETA-T</td>
<td>( \eta_{t,des} )</td>
<td>T0,</td>
<td>( T_0 )</td>
<td>W/WR/CRC)3</td>
<td>(W_r/W_cr)3</td>
</tr>
<tr>
<td>DESIGN P0, /P5</td>
<td>( (p_0/p_5)_{des} )</td>
<td>U3</td>
<td>( U_3 )</td>
<td>WR/CRC)3</td>
<td>(W_r/W_cr)3</td>
</tr>
<tr>
<td>DESIGN WT- FLOW</td>
<td>( \omega_{des} )</td>
<td>U4U3</td>
<td>( U_4/U_3 )</td>
<td>WU/WRCR)3</td>
<td>(W_u/W_cr)3</td>
</tr>
<tr>
<td>D3</td>
<td>( D_3 )</td>
<td>V/VCR)0</td>
<td>( V_{cr,0} )</td>
<td>WCR)4</td>
<td>(W_u/W_cr)4</td>
</tr>
<tr>
<td>EQ-DE-L-H</td>
<td>( \Delta h_{eq} )</td>
<td>V/VCR)1</td>
<td>( V_{cr,1} )</td>
<td>WX/WCR)4</td>
<td>(W_x/W_cr)4</td>
</tr>
<tr>
<td>EQ-N</td>
<td>( \omega_{eq} )</td>
<td>VR/VCR)1</td>
<td>( V_{r}/V_{cr} )</td>
<td>W/CRC)5</td>
<td>(W_x/W_cr)5</td>
</tr>
<tr>
<td>EQ-P0, /P5,</td>
<td>( (p_0/p_5)_{eq} )</td>
<td>VU/VCR)1</td>
<td>( V_{u}/V_{cr} )</td>
<td>WX/WCR)5</td>
<td>(W_x/W_cr)5</td>
</tr>
<tr>
<td>EQ-P0, /P5,</td>
<td>( (p_0/p_5)_{eq} )</td>
<td>V/VCR)2</td>
<td>( V_{cr,2} )</td>
<td>ZZ</td>
<td>ZZ</td>
</tr>
<tr>
<td>EQ-TOR</td>
<td>( \Gamma_{eq} )</td>
<td>VR/VCR)2</td>
<td>( V_{r}/V_{cr} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EQ-W</td>
<td>( \omega_{eq} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETA-S</td>
<td>( \eta_s )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Messages**

If there is no solution for a particular turbine case in the design mode, a message will be printed - "NO SOLUTION FOR THIS CASE - CHECK A1, BL1, AL1 OR B4, BL4." This will happen when the program cannot select values for the loss determinants \( p_1/p_0 \) and \( K \) that will satisfy the design input values of mass flow, efficiency, and pressure ratio.

In the off-design performance mode for conditions beyond choking to blade limiting loading, a message will be printed after the last computed performance point - "LAST CASE IS APPROXIMATE LIMITING LOADING CASE."
**MAIN PROGRAM**

**FORTRAN Variables**

The FORTRAN variables used in the main program are defined in the following table in terms of the engineering symbols, where available, or by descriptive terminology:

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Engineering symbol</th>
<th>Variable name</th>
<th>Engineering symbol</th>
<th>Variable name</th>
<th>Engineering symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>$\varphi$</td>
<td>DELHOT</td>
<td>$\Delta h'/T_0$</td>
<td>FC</td>
<td>$\cos \theta$</td>
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<tr>
<td>ALX</td>
<td>$\alpha_1$</td>
<td>DELLL</td>
<td>incremental value of $\left(\frac{W}{W_{cr}}\right)_4$</td>
<td>PP</td>
<td>integration variable</td>
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<td>AL1</td>
<td>$\alpha_1$</td>
<td>DELTA</td>
<td>$\delta$</td>
<td>FS</td>
<td>$\sin \theta$</td>
</tr>
<tr>
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<td>$\alpha_2$</td>
<td>DELV</td>
<td>incremental value of $\left(\frac{V}{V_{cr}}\right)_1$</td>
<td>F1</td>
<td>integration variable</td>
</tr>
<tr>
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<td>$\alpha_3$</td>
<td>DELV1</td>
<td>incremental value of $\left(\frac{V}{V_{cr}}\right)_1$</td>
<td>G</td>
<td>$\gamma$</td>
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<tr>
<td>AL5</td>
<td>$\alpha_5$</td>
<td>DELY</td>
<td>incremental value of $\left(\frac{W}{W_{cr}}\right)_4$</td>
<td>G1</td>
<td>$\gamma + 1$</td>
</tr>
<tr>
<td>AX</td>
<td>temporary storage</td>
<td>DELL</td>
<td>$\Delta h'_s$</td>
<td>G2</td>
<td>$\gamma - 1$</td>
</tr>
<tr>
<td>A0</td>
<td>$A_0$</td>
<td>DHIDS</td>
<td>$\Delta h'_{id,s}$</td>
<td>G3</td>
<td>$(\gamma - 1)/(\gamma + 1)$</td>
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<tr>
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<td>$A_1$</td>
<td>DHIDT</td>
<td>$\Delta h'_{id,t}$</td>
<td>G4</td>
<td>$\gamma/(\gamma + 1)$</td>
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<td>A3</td>
<td>$A_3$</td>
<td>DHTCR</td>
<td>$\Delta h'/\theta_{cr}$</td>
<td>G5</td>
<td>$\gamma/(\gamma - 1)$</td>
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<tr>
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<td>$A_5$</td>
<td>D2</td>
<td>$D_2$</td>
<td>HA</td>
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<td>$D_3$</td>
<td>HB</td>
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<td>$\epsilon$</td>
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<td>B3</td>
<td>$\beta_3$</td>
<td>EQPRS</td>
<td>$(p'<em>0/p_0)</em>{eq}$</td>
<td>IND</td>
<td>integer variable controlling logical sequence in CONTIN</td>
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<td>B4</td>
<td>$\beta_4$</td>
<td>EQPRT</td>
<td>$(p'<em>0/p_0)</em>{eq}$</td>
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<td>$\Gamma \epsilon/\delta$</td>
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<td>integer variable controlling proper input in GETK and SEEKPR</td>
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<td>CAPQ</td>
<td>$w/p_5$</td>
<td>ETAD</td>
<td>$\eta_s,des \ or \ \eta_t,des$</td>
<td>K</td>
<td>index variable</td>
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<td>CASE</td>
<td>variable for title message</td>
<td>ETAS</td>
<td>$\eta_s$</td>
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<td>index variable</td>
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<td>COSAL1</td>
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<td>$\eta_t$</td>
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<td>MODE</td>
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<td>QX</td>
<td>( (V/V_{cr})_0 )</td>
<td>VRVC2</td>
<td>( (V_x/V_{cr})_2 )</td>
</tr>
<tr>
<td>NAME</td>
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<td>( \left( \frac{T_4}{T_4'} \right)^{1/2} )</td>
<td>VRVC3</td>
<td>( (V_x/V_{cr})_3 )</td>
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<tr>
<td>NCOUNT</td>
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<td>R</td>
<td>VU3T</td>
<td>( V_{u,3, opt} )</td>
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<tr>
<td>P</td>
<td>temporary storage (pressure ratio)</td>
<td>RHOS5</td>
<td>( p_5 )</td>
<td>VU4VC3</td>
<td>( V_{u,4}/V_{cr,3} )</td>
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<tr>
<td>PD</td>
<td>((p_0/p_5')_d e s ) or ((p_0'/p_5')_d e s )</td>
<td>RHOS5P</td>
<td>( p_5' )</td>
<td>VUVC1</td>
<td>( (V_x/V_{cr})_1 )</td>
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<tr>
<td>PDSGN</td>
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<td>( \Gamma/p_0' )</td>
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<tr>
<td>P4P3ID</td>
<td>((p'/w_{cr})_4 )</td>
<td>TOR</td>
<td>( \Gamma )</td>
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<td>P4P4ID</td>
<td>((p'/w_{cr})_4 )</td>
<td>T0</td>
<td>( T_0 )</td>
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<td>((p'/w_{cr})_4 )</td>
<td>T3T3</td>
<td>( (T''/T')_3 )</td>
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<tr>
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<td>T4T3</td>
<td>( T''/T' )</td>
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<tr>
<td>P5P0G</td>
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<td>T4T4</td>
<td>( T''/T' )</td>
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<tr>
<td>P5P0P</td>
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<td>( U_3 )</td>
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<tr>
<td>P5P0PG</td>
<td>((p'/w_{cr})_4 )</td>
<td>U4U3</td>
<td>( U_4/U_3 )</td>
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<tr>
<td>P5P5</td>
<td>((p'/w_{cr})_4 )</td>
<td>VC5VC0</td>
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<tr>
<td>P5P5P</td>
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<td>VCR</td>
<td>( V_{cr,5} )</td>
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<td>V0VC0</td>
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<td>( (V_x/V_{cr})_5 )</td>
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<td></td>
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<td>WNC</td>
<td>( w_{cr} )</td>
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<td></td>
<td>WNODE</td>
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<td></td>
<td>VRVC1</td>
<td>( (V_x/V_{cr})_1 )</td>
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</tr>
</tbody>
</table>
**Program Listing**

A FORTRAN IV COMPUTER PROGRAM TO PREDICT DESIGN AND OFF-DESIGN PERFORMANCE OF A RADIAL INFLOW TURBINE

INTERNATIONAL SYSTEM OF UNITS

MODE=0, IMPLIES OFF-DESIGN PERFORMANCE MODE WITH FULL OUTPUT.

MODE=1, IMPLIES OFF-DESIGN PERFORMANCE MODE WITH SHORT OUTPUT.

MODE=2, IMPLIES DESIGN MODE TO DETERMINE THE VALUE OF K AND PD.

CUSTOMARY UNITS

MODE=3, IMPLIES OFF-DESIGN PERFORMANCE MODE WITH FULL OUTPUT.

MODE=4, IMPLIES OFF-DESIGN PERFORMANCE MODE WITH SHORT OUTPUT.

MODE=5, IMPLIES DESIGN MODE TO DETERMINE THE VALUE OF K AND PD.

**DIMENSION NAME(10), CASE(10)**

**NAMELIST IN/ G, P0, T0, A0, A1, A3, A5, D3, AL1, B4, BL1, BL4, PD, PSDGN, IT, T**

**1U3, U4U3, R, V1, DELV, VMAX, XK, WD, ZZ, MODE, PD, ETA, DEL, YMAX, D2**

**SUBR(X,G)={(1-(G-1.))/(G+1.))**

**READ(5,100) (NAME(I), I=1,10)**

**READ(5,100) (CASE(I), I=1,10)**

**READ(5,IN)**

**WRITE(6,200) NAME, CASE**

**WRITE(6,400) G, P0, A1, AL1, B4, PD, R, T0, A3, BL1, BL4, XK, D3, A0, A5, U3,
IF(MODE .EQ. 1 .OR. MODE .EQ. 4) WRITE(6,666)
DELV1 = DELV
ALX = AL1
B4X = B4
T = 01745329
TOL = .0001
AL1 = T*AL1
B4 = T*B4
COSAL1 = COS(AL1)
SINAL1 = SIN(AL1)
COSB4 = COS(B4)
SINB4 = SIN(B4)
XJ = 778.029
GR = 32.1741
IT = 1
J = 1
K = 1
L = 1
M = 1
N = 1
VX = 0.
XDEL = .1
G1 = G+1.
G2 = G-1.
G3 = G2/G1
G4 = G/G1
G5 = G/G2

BEGIN STATOR ANALYSIS

IF(MODE .EQ. 3 .OR. MODE .EQ. 4 .OR. MODE .EQ. 5) GO TO 2
VCR = SQRT(2.*G4*R*T0)
PVCR = PO*SQRT(2.*G4/R/T0)
GO TO 3
2 VCR = SQRT(2.*G4*GR*R*T0)
PVCR = PO*SQRT(2.*G4*GR/R/T0)
3 VLVCL = V1
9 CONTINUE
IF(VLVCL .GT. 1.) GO TO 15
NCOUNT = 0
IF(MODE .EQ. 0 .OR. MODE .EQ. 1 .OR. MODE .EQ. 3 .OR. MODE .EQ. 4) GO TO 10
PD = 1.0
4 K = 1
SS = WD/PVCR/AL/COSAL1/PD
VLVC1 = .5
5 X = VLVCL
F = SUBR(X,G) -SS
FP = (F+SS)/X-2.*X*X/G1*(1.-G3*X*X)**(1./G2-1.)
VLVC1 = X-F/FP
IF(ABS((VLVC1-X)/VLVC1) .LT. TOL) GO TO 10
GO TO 5
15 VK = 1.
PVK = SUBR(VK,G)
WK = COS(ALX*T)*PVK*AL*PVCR*PD
PV1 = SUBR(VLVC1,G)
COSAL1 = WK/(PV1*PV1*PVCR)
AL1 = ACOS(COSAL1)
SINAL1 = SIN(AL1)
GO TO 13
10 PV1=SUBR(V1VC1,G)
   W1=PV1*A1*PVCR*COSAL1*PD
   VOVCO=V1VC1/6*
   QX=PV1*A1/AO*COSAL1*PD
12 X= VOVCO
   F=SUBR(X,G) -QX
   FP= (F+QX)/X-2.0**X/G1*(1.0-G3**X)**(1.0/G2-1.0)
   VOVCO= X-F/FP
   IF(ABS((VOVCO-X)/V1VC1)*LT*TOL) GO TO 13
   GO TO 12
13 VUVC1=V1VC1*SINAL1
   VRVC1=V1VC1*COSAL1
   VUVC2=VUVC1
   STATOR EXIT CONDITIONS
   Q=PV1*COSAL1 *BL1
   X=V1VC1/3*
61 F=(1.0-G3*(X*X+VUVC2**2))**(1.0/G2)*X-Q
   F1=(F+Q)/X
   FP=-2.0**X/G1*F1**(1.0/G2-1.0)+F1
   X1=X-F/FP
   IF(ABS((X1-X)/X1)-TOL) 62.62.63
63 X=X1
   GO TO 61
62 VRVC2=X
   V2VC2=SQRT(VRVC2**2+VUVC2**2)
   PV2=SUBR(V2VC2,G)
   COSAL2=VRVC2/V2VC2
   AL2=ACOS(COSAL2)
   SINAL2=SIN(AL2)
   FREE STREAM SPACE CONDITIONS
   VUVC3=VUVC2*D2/D3
   Q= PV2*COSAL2*D2/D3
   X=VUVC3/5*
22 F=(1.0-G3*(X*X+VUVC3**2))**(1.0/G2)*X-Q
   F1=(F+Q)/X
   FP=-2.0**X/G1*F1**(1.0/G2-1.0)+F1
   X1=X-F/FP
   IF(ABS((X1-X)/X1)-TOL) 20,20,21
21 X=X1
   GO TO 22
20 V3VC3=SQRT(VUVC3**2+X*X)
   COSAL3=X/V3VC3
   AL3=ACOS(COSAL3)
   SINAL3=SIN(AL3)
   VRVC3=X
   ROTOR INLET CONDITIONS
   T3T3=(1.0-G3*(2.0*U3*VUVC3/VCR-(U3/VCR)**2))
   WCVC3=SQRT(T3T3)
   WUVC3=VUVC3-U3/VCR
   WUWC3=WUVC3/WCVC3
   W3VC3=SQRT(WUVC3**2+VRVC3**2)
   W3WC3=W3VC3/WCVC3
   WRWC3=SQRT(W3WC3**2-WUWC3**2)
   P3P3=T3T3**(G5)
   PWVC3=T3T3**((G1/2)*G2)
   SINC=WUWC3/W3WC3
\[ B3 = \arcsin(\sin B3) \]
\[ \cos B3 = \cos(B3) \]
\[ V3TU3 = 1 - 1.98/ZZ \]
\[ VU3T = V3TU3 \cdot U3 \]
\[ WU3T = VU3T - U3 \]
\[ AB = \arctan((WU3T/VCR)/VRVC3) \]
\[ X3 = B3 - AB \]
\[ FS = \arcsin(X3) \]
\[ FC = \cos(X3) \]
\[ WC3 = WVVC3 \cdot \cos \theta \]
\[ T4T3 = 1 - G3 \cdot (U3/WCR3) \cdot 2 \cdot (1 - U4U3) \cdot 2 \]
\[ W3WC4 = \sqrt{T4T3} \]
\[ PW4PW3 = T4T3 \cdot (1 - G3/2) \]
\[ PW3 = \text{SUBR}(W3WC3, 0) \]
\[ YGIV = PW3 \cdot (A3/A5 \cdot BL4) \cdot (\cos B3/\cos B4) \cdot PW4PW3 \]
\[ \text{IF}(\text{MODE} = 2 \text{ OR } \text{MODE} = 5) \text{ X3 = } 1 \]

**ROTOR ANALYSIS**

- **Y = 0.3**

31 \text{IND} = 1

32 \text{NCOUNT} = \text{NCOUNT} + 1

33 \text{CX} = W3WC4 \cdot 2 \cdot (XX \cdot FC \cdot 2 + FS \cdot 2)

34 \text{AX} = XX \cdot FC \cdot 2 + FS \cdot 2

35 \text{N} = 2

36 \text{GO TO 9}

80 \text{IF}(\text{MODE} = 2 \text{ OR } \text{MODE} = 5) \text{ GO TO 82}

85 \text{CONTINUE}

89 \text{W4WC4} = Y

90 \text{PW4} = \text{SUBR}(Y, G)

91 \text{P4P4ID} = YGIV/PW4

92 \text{PW4 = PVRCPD*PWVC3*PW4PW3*P4P4ID}

93 \text{CONTINUE}

94 \text{W4WC4 = W4WC4*\sin B4}

95 \text{WXWC4 = W4WC4*\cos B4}

96 \text{HA = WXWC4}

97 \text{IF}(\text{HA} \geq 1) \text{ GO TO 56}

98 \text{Q = PW4*COS B4*BL4}

99 \text{X = W4WC4/3}
70 \( F = (1.0 - G3 \times (X \times X + WUWC4 \times X)) \times (1.0 / G2) \times X - Q \)
\( F1 = (F + Q) / X \)
\( FP = -2.0 \times X / G1 \times F1 \times (2.0 - G) \times X + F1 \)
\( X1 = X - F / FP \)
\( \text{IF(ABS((X1-X)/X1)<TOL)} \) \( \text{71,71,72} \)
72 \( X = X1 \)
\( \text{GO TO 70} \)

**ROTOR EXIT CONDITIONS**

71 \( W5WC5 = X \)
\( W5WC5 = X \times X + WUWC4 \times 2 \)
\( W5WC5 = \text{SQRT}(W5WC5) \)
\( \text{SIN85} = WUWC4 / W5WC5 \)
\( \text{VUWC4} = 1.0 / WCVC3 \times U4U3 \times U3 / VCR / WC4WC3 + WUWC4 \)
\( VUWC5 = VUWC4 \)
\( V5WC5 = VUWC5 \times 2 + X \times X \)
\( V5WC5 = \text{SQRT}(V5WC5) \)
\( T4T4 = 1.0 + G3 \times (VUWC4 \times VUWC4 - WUWC4 \times WUWC4) \)
\( Q1 = \text{SQRT}(T4T4) \)
\( VXVC5 = W5WC5 / Q1 \)
\( VUVC5 = VUWC5 / Q1 \)
\( V5VC5 = V5WC5 / Q1 \)
\( \text{AL5} = 1.0 / T \times \text{ASIN}(V5VC5 / V5VC5) \)
\( BS5 = 1.0 / T \times \text{ASIN}(\text{SIN85}) \)
\( WUWC5 = WUWC4 \)
\( VUC4VC3 = WUWC4 \times WC4WC3 \times WCVC3 + U4U3 \times U3 / VCR \)
\( T5T0 = 1.0 - 2.0 \times G3 / VCR \times (U3 \times VUVC3 - U4U3 \times U3 \times VU4VC3) \)
\( T5 = T0 \times T5T0 \)
\( VCR5 = VCR \times \text{SQRT}(T5T0) \)
\( P5P5 = T4T4 \times (G5) \)
\( P4P3ID = T4T3 \times (G5) \)
\( P5P0 = PD \times P3P3 \times P4P3ID \times P4P4ID \times P5P5 \)
\( P5 = PD \times P5P0 \)
\( P5P5P = (1.0 - G3 \times (V5VC5 \times 2)) \times (G5) \)
\( P5P0P = P5P0 \times P5P5P \)
\( VC5VC0 = (VCR5 / VCR) \times VCR5 \)
\( P5P0G = P5P0 \times (G2 / G) \)
\( P5P0PG = P5P0P \times (G2 / G) \)
\( Z = 1.0 / P5P0 \)
\( Z1 = 1.0 / P5P0P \)
\( H1 = 1.0 / VC5VC0 \)
\( \text{ETAS} = H1 / (1.0 - P5P0PG) \)
\( \text{ETAT} = H1 / (1.0 - P5P0G) \)

**AUTOMATIC DETERMINATION OF XK AND PD**

\( \text{IF(MODE} \times \text{EQ} \times O \times \text{OR} \times \text{MODE} \times \text{EQ} \times 1 \times \text{OR} \times \text{MODE} \times \text{EQ} \times 3 \times \text{OR} \times \text{MODE} \times \text{EQ} \times 4) \) \( \text{GO TO 40} \)
\( \text{ET} = \text{ETAS} \)
\( \text{IF(IATESTEQ} \times 2) \) \( \text{ET} = \text{ETAT} \)
\( \text{IF(K \times \text{EQ} \times 5) \) \( \text{GO TO 30} \)
\( \text{CALL GETK(XK,ET,ETAD,K)} \)
\( \text{IF((ETAD-ET) \times GT \times 1) \) \( \text{GO TO 90} \)
\( \text{GO TO 31} \)
30 \( \text{PR = Z1} \)
\( \text{IF(IATESTEQ} \times 2) \) \( \text{PR} = Z \)
\( \text{IF(L \times \text{EQ} \times 5) \) \( \text{GO TO 40} \)
\( \text{CALL SEEKPR(PDSGN,PR,PD,L)} \)
\( \text{GO TO 4} \)
**EXTRA OUTPUT CALCULATIONS**

**C**

40 CONTINUE

IF (MODE.EQ.3 .OR. MODE.EQ.4 .OR. MODE.EQ.5) GO TO 41

**C**

THETCR = G4*R*T0/48247.36

STHETA = SQRT(THETCR)

DELTA = P0/101325.0

XNOTH = 100.*U3/3.*14159/D3/STHETA

XN = XNOTH*STHETA

DHTCR = H1*48247.36/G3

DELH = DHTCR*THETCR

DHIDS = (1.*P5POPG)*G5*R*T0

DHIDT = (1.*P5POG)*G5*R*T0

EQPRS = 1./((1.*DHIDS/289484.2/THETCR)**3.5)

EQPRT = 1./((1.*DHIDT/289484.2/THETCR)**3.5)

XNU = U3/SQRT(2.*DHIDS)

WTOP = W1**100.*2**SQRT(T0)/PO

TOR = DELH**W1**9.549274/XN

TOP = TOR**1.*E+06/PO

ELAM = DELH/U3**2

RHO5P = P5PO*PO/VCR5**22**G4

P = DELH*W1/1000.

GO TO 43

41 THETCR = G4*R*T0/16141.4357

STHETA = SQRT(THETCR)

DELTA = P0/2116.22

XNOTH = 720.*U3/3.*14159/D3/STHETA

XN = XNOTH*STHETA

DHTCR = H1*16141.4357/G3/XJ

DELH = DHTCR*THETCR

DHIDS = (1.*P5POPG)*G5*R*T0/XJ

DHIDT = (1.*P5POG)*G5*R*T0/XJ

EQPRS = 1./((1.*DHIDS/124*4808/THETCR)**3.5)

EQPRT = 1./((1.*DHIDT/124*4808/THETCR)**3.5)

XNU = U3/SQRT(2.*GR*XJ*DHIDS)

WTOP = W1**SQRT(T0)**144./PO

TOR = DELH**W1**1.*12164E-05/XN

TOP = TOR**144./PO

ELAM = DELH**GR*XJ/U3**2

RHO5P = P5PO*PO**2.*GR**G4/VCR5**2

P = DELH**W1**XJ/550.

43 PRS = 1./EQPRS

EPS = (GL/2.)*((G5)**7395945/G)

WTHODE = W1**STHETA**EPS/DELTA

EQTOR = TOR**EPS/DELTA

WNODE = WTHODE*XNOTH

DELHOT = DELH/T0

XNOT = XN**SQRT(T0)

RHO5RT = P5P5P**2*(1./G)

RHO5 = RHO5RT*RHO5P

CAPQ = W1/RHO5

SCAPQ = SQRT(CAPQ)

IF (MODE.EQ.3 .OR. MODE.EQ.4 .OR. MODE.EQ.5) GO TO 42

XNS = XN**10472**SCAPQ/(DHIDT**2**75)

GO TO 45

42 XNS = XN**SCAPQ/(XJ*DHIDT)**2**75

45 CONTINUE
C
C
COMPLETE WRITE OUT
C
IF(IT=EQ.3) GO TO 44
AL1=AL1/T
AL2=AL2/T
XI3 = XI3/T
AL3=AL3/T
B3=B3/T
B4=B4/T
44 CONTINUE
IF(MODE=EQ.1 OR MODE=EQ.4) WRITE(6,505) V1VC1, XNS, PRS, XNU, ETAT,
IETAS, DHTCR, WTHODE, EQPRS, EQPRT
IF(MODE=EQ.0 OR MODE=EQ.3) GO TO 46
IF(MODE=EQ.1 OR MODE=EQ.4) GO TO 48
WRITE(6,509) PD*XK*WD
IF(ITEST.EQ.1) WRITE(6,525) ETAD, PDSGN
IF(ITEST.EQ.2) WRITE(6,526) ETAD, PDSGN
46 CONTINUE
WRITE(6,501) WTHODE, EQPRS, Z1, WTOP, W1, DHTCR, ETAS, XNU, DELHOT, DELH,
IXNOTH, ETAT, XNS, XNOT, ELAM, EQTOR, EQPRT, Z, TOP, TOR, XN, P, WTHODE, T5, P5
IF(MODE=EQ.2 OR MODE=EQ.5) GO TO 51
48 CONTINUE
IF(WXWC4.EQ.1) GO TO 59
IF(J.EQ.2) GO TO 57
IF(IT.GE.2) GO TO 55
AL1=AL1*X*T
B4=B4*X*T
V1VC1=V1VC1+DELV
IF(V1VC1.GT.VMAX) GO TO 51
GO TO 9
51 AL1=ALX
DELV= DELV1
B4= B4X
GO TO 1
55 IT=3
GIV=Y*GIV*COS(B4*X*T)
Y= Y+DELY
IF(Y.GT.YMAX) GO TO 51
53 W4WC4= Y
PW4= SUBR(Y*G)
AX= XK*Y*Y+CX
BX= 1-G3*Y*Y
P4P4ID= (1-G3*(AX/BX))**G5
COSB4=GIV/(PW4*P4P4ID)
B4= ACOS(COSB4)
B4= -B4
COSB4= COS(B4)
SINB4= SIN(B4)
B4= B4/T
IF(J.EQ.2) GO TO 58
GO TO 85
56 IF(J.EQ.2) GO TO 57
Y= Y-DELY
DELY= DELY/5.
J= 2
57 Y= Y+DELY
GO TO 53
58 HB = W4WC4*COSB4
IF(ABS((HB-HA)/HA) LT .02) GO TO 59
DELL = DELL/2.
GO TO 85
59 WRITE(6,600)
GO TO 51
90 WRITE(6,300)
GO TO 1
STOP
C    FORMAT STATEMENTS
C    ERROR MESSAGE NUMBER 1
100 FORMAT(10A6)
200 FORMAT(11H1,35X,43HNASA RADIAL INFLOW TURBINE COMPUTER PROGRAM/
         124X*10A6/24X*10A6)
300 FORMAT(/1OXt54HNO SOLUTION FOR THIS CASE - CHECK A1,BL1,AL1 OR B4,
         1BL4)
400 FORMAT(7HK GAMMAs2X*G13o5*7H PO*2X*G13.5*6H A1*2X*G13.5;*
         12X*7HALPHA-1,2X,G13.5,7H BETA-4,2X,G13.5,5H PD,2X,G13.5/
         27H R,2X,G13.5,7H TO,2X,G13.5,6H A3,2X*G13.5,2X*
         37H BL1*2X,G13.5,57H BL4*2X,G13.5,57H Kc,2X,G13.5 /
         47H D3,2X,G13.5,7H A0,2X,G13.5,6H A5,2X,G13.5,2X,
500 FORMAT(/5OXt15HVELOCITIES AND ANGLES/
         112H V/VCR)
         11X*G13.5,1X,11HALPHA-1 ,G13.5,1X,11HW/VCR)3 ,
         AG13.5,1X*11HW/WCR)4 *G13.5,1X*11HW/WCR)5 ,G13.5/
         212H VU/VCR)1  G13.5,1X,11HALPHA-2 ,G13.5,1X,11HVU/VCR)3 ;
         AG13.5,1X,11HW/WCR)4 *G13.5,1X,11HVU/VCR)5 ,G13.5/
         312H VR/VCR)1  G13.5,1X,11HALPHA-3 ,G13.5,1X,11HVR/WCR)3 ,
         AG13.5,1X,11HW/WCR)4 *G13.5,1X,11HVR/WCR)5 ,G13.5/
         412H V/CVR)1  G13.5,1X,11HBETA-3 ,G13.5,1X,11HW/VCR)3 ;
         AG13.5,1X,11HBETA-4 ,G13.5,1X,11HVU/VCR)5 ,G13.5/
         512H V/CVR)2  G13.5,1X,11HI-3 ,G13.5,1X,11HW/VCR)3 ;
         AG13.5,1X,11HBETA-5 ,G13.5,1X,11HVU/VCR)5 ,G13.5/
         62H VR/VCR)12 G13.5,1X,11HWCR)3 ,G13.5,1X,11HWR/WCR)3 ,
         AG13.5,1X,11HWCR)15 G13.5,1X,11HALPHA-5 ,G13.5)
501 FORMAT(/50X,21HV VELOCITIES AND ANGLES/
         112H V/VCR)1  G13.5,1X,11HALPHA-1 ,G13.5,1X,11HW/VCR)3 ,
         AG13.5,1X*11HW/WCR)4 *G13.5,1X*11HW/WCR)5 ,G13.5/
         212H VU/VCR)1  G13.5,1X,11HALPHA-2 ,G13.5,1X,11HVU/VCR)3 ;
         AG13.5,1X,11HW/WCR)4 *G13.5,1X,11HVU/VCR)5 ,G13.5/
         312H VR/VCR)1  G13.5,1X,11HALPHA-3 ,G13.5,1X,11HVR/WCR)3 ,
         AG13.5,1X,11HW/WCR)4 *G13.5,1X,11HVR/WCR)5 ,G13.5/
         412H V/CVR)1  G13.5,1X,11HBETA-3 ,G13.5,1X,11HW/VCR)3 ;
         AG13.5,1X,11HBETA-4 ,G13.5,1X,11HVU/VCR)5 ,G13.5/
         512H V/CVR)2  G13.5,1X,11HI-3 ,G13.5,1X,11HW/VCR)3 ;
         AG13.5,1X,11HBETA-5 ,G13.5,1X,11HVU/VCR)5 ,G13.5/
         612H VR/VCR)12 G13.5,1X,11HWCR)3 ,G13.5,1X,11HWR/WCR)3 ;
         AG13.5,1X,11HWCR)15 G13.5,1X,11HALPHA-5 ,G13.5)
505 FORMAT(10G13.5)
509 FORMAT(13X,2HP0,G15.6/14X,1HK,G15.6/1X,14HDESIGN WT-FLOW,G15.6)
525 FORMAT(3X,12HDESIGN ETA-S ,G15.6/2X,13HDESIGN PO,*5,G15.6)
526 FORMAT(3X,12HDESIGN ETA-T ,G15.6/1X,14HDESIGN PO,*5,G15.6)
600 FORMAT(/1OX,41LAST CASE IS APPROXIMATE LIMITING LOADING)
666 FORMAT(/1HK VIWC1.8X*2HNS.11X*9HEQ-P0,*4X*2HNU.11X*4HETAT.9X,
         14HETAS.9X,5HDHTCR,8X,6HWTIODE,7X,9HEQ-P0,*P5,4X,10HEQ-P0,*P5,)
2040 FORMAT(/10X,44HNO SOLUTION COULD BE FOUND IN 100 ITERATIONS)
2050 FORMAT(/10X,69HITERATION PROCEDURE HAD TO BE RESTARTED TO AVOID NEG
         1ATIVE TEMPERATURE/15X,67HRESTART PROCEDURE WAS ABORTED AFTER 1000
         2TOTAL NUMBER OF ITERATIONS)
Subroutine GETK (XK, ETA, ETAD, K)

Subroutine GETK varies the value of the loss coefficient \( K \) by false positioning until the design value of efficiency is met.

- **XK**: rotor loss coefficient, \( K \)
- **ETA**: computed value of efficiency from main program
- **ETAD**: design value of \( \eta_t \) or \( \eta_s \)
- **K**: indicator used in method of false positioning

```plaintext
SUBROUTINE GETK(XK, ETA, ETAD, K)
GO TO (100, 101, K)
100 XK1 = XK
   DIF1 = ETA - ETAD
   K = 2
   XK = XK + .005
   RETURN
101 XK2 = XK
   DIF2 = ETA - ETAD
   IF(DIF2*DIF1) = 104, 103, 102
102 XK1 = XK2
   XK = XK + .005
   DIF1 = DIF2
   RETURN
103 XK = XK2
   K = 5
   RETURN
104 XK = -(XK2 - XK1)/(DIF2 - DIF1)*DIF1 + XK1
   K = 5
   RETURN
END
```

Subroutine SEEKPR (PDSGN, PR, PD, L)

Subroutine SEEKPR varies the value of the stator total-pressure ratio \( \frac{p_1'}{p_0'} \) by false positioning until all design specifications are met.

- **PDSGN**: design value of \( \frac{p_0}{p_5} \) or \( \frac{p_0}{p_5} \)
- **PR**: computed value of turbine pressure ratio from main program
- **PD**: value of stator total-pressure ratio \( \frac{p_1'}{p_0'} \)
- **L**: indicator used in method of false positioning

22
Subroutine SEEKPR (PDSGN, PR, PD, L)
GO TO (10, 11, 11)

10 PDI = PD
   DIF1 = PR - PDSGN
   L = 2
   PD = PD -.005
   RETURN

11 PD2 = PD
   DIF2 = PR - PDSGN
   IF (DIF2 * DIF1) 14, 13, 12

12 PD1 = PD2
   PD = PD - .005
   DIF1 = DIF2
   RETURN

13 PD = PD2
   L = 5
   RETURN

14 PD = -(PD2 - PD1)/(DIF2 - DIF1) * DIF1 + PD1
   L = 5
   RETURN
END

Subroutine CONTIN (XEST, YCALC, IND, JZ, YGIV, XDEL)

Subroutine CONTIN is a curve-fitting routine which is described in detail in reference 8. It is used to determine the rotor-exit velocity ratio value needed to satisfy continuity at the rotor exit.

XEST value of estimated velocity Y

YCALC mass flow parameter based on estimated velocity

IND index to control next iteration in CONTIN and to indicate when a choked-flow solution has been found

JZ index variable

YGIV input mass flow parameter

XDEL maximum permitted change in estimated velocity Y per iteration

SUBROUTINE CONTIN(XEST, YCALC, IND, JZ, YGIV, XDEL)
C
C--CONTIN CALCULATES AN ESTIMATE OF THE RELATIVE FLOW VELOCITY
C--FOR USE IN THE VELOCITY GRADIENT EQUATION
C
DIMENSION X(3), Y(3)
NCALL = NCALL + 1
IF (IND NE 1 AND NCALL GT 100) GO TO 160
GO TO (10, 30, 40, 50, 60, 110, 150) * IND
C--FIRST CALL
10 NCALL = 1
   XORIG = XEST
   IF (YCALC = GT = YGIV AND JZ = EQ = 1) GO TO 20
   IND = 2
   Y(1) = YCALC
   X(1) = 0.
   XEST = XEST + XDEL
   RETURN
20 IND = 3
   Y(3) = YCALC
   X(3) = 0.
   XEST = XEST - XDEL
   RETURN
C--SECOND CALL
30 IND = 4
   Y(2) = YCALC
   X(2) = XEST - XORIG
   XEST = XEST + XDEL
   RETURN
40 IND = 5
   Y(2) = YCALC
   X(2) = XEST - XORIG
   XEST = XEST - XDEL
   RETURN
C--THIRD OR LATER CALL - FIND SUBSONIC OR SUPERSONIC SOLUTION
50 Y(3) = YCALC
   X(3) = XEST - XORIG
   GO TO 70
60 Y(1) = YCALC
   X(1) = XEST - XORIG
   IF (YGIV = LT = AMINI(Y(1), Y(2), Y(3))) GO TO (120, 130), JZ
   IND = 6
   CALL PABC(X, Y, APA, BPB, CPC)
   DISCR = BPB**2 - 4.0*APA*(CPC - YGIV)
   IF (DISCR = LT = 0.) GO TO 140
   IF (ABS(400.0*APA*(CPC - YGIV)) = LE = BPB**2) GO TO 90
   XEST = -BPB - SIGN(SQRT(DISCR))*APA
   IF (JZ = EQ = 1 AND APA = GT = 0.0 AND Y(3) = GT = Y(1)) XEST = -BPB -
   1.0 SQRT(DISCR)
   IF (JZ = EQ = 2 AND APA = LT = 0.) XEST = -BPB - SQRT(DISCR)
   XEST = XEST / 2.0 / APA
   GO TO 100
90 IF (JZ = EQ = 2 AND BPB = GT = 0.) GO TO 130
   ACB2 = APA / BPB *(CPC - YGIV) / BPB
   IF (ABS(ACB2) = LE = 1.0 - 8.0) ACB2 = 0.
   XEST = -(CPC - YGIV) / BPB *(1.0 + ACB2 + 2.0*ACB2**2)
100 IF (XEST = GT = X(3)) GO TO 130
   IF (XEST = LT = X(1)) GO TO 120
   XEST = XEST + XORIG
   RETURN
C--FOURTH OR LATER CALL - NOT CHOKED
110 IF (XEST - XORIG = GT = X(3)) GO TO 130
   IF (XEST - XORIG = LT = X(1)) GO TO 120
   Y(2) = YCALC
   X(2) = XEST - XORIG
   GO TO 70
C--THIRD OR LATER CALL - SOLUTION EXISTS, C--BUT RIGHT OR LEFT SHIFT REQUIRED
120 IND = 5

24
Subroutine PABC (X, Y, A, B, C)

Subroutine PABC calculates the coefficients A, B, and C of the parabola
\[ y = Ax^2 + Bx + C \] passing through three given X, Y points supplied by subroutine CONTIN.
SUBROUTINE PARC(X,Y,A,B,C)

C--PARC CALCULATES COEFFICIENTS A, B, C OF THE PARABOLA
C--Y=A*X**2+B*X+C, PASSING THROUGH THE GIVEN X,Y POINTS
C

DIMENSION X(3), Y(3)
C1 = X(3)-X(1)
C2 = (Y(2)-Y(1))/(X(2)-X(1))
A = (C1*C2-Y(3)+Y(1))/C1/(X(2)-X(3))
B = C2-(X(1)+X(2))*A
C = Y(1)-X(1)*B-X(1)**2*A
RETURN
END

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 17, 1975,
505-04.
APPENDIX A

SYMBOLS

A  area, \( m^2; ft^2 \)
B  blockage factor
\( C_1 \) dimensional constant, 200; \( 720/\pi \)
\( C_2 \) dimensional constant, 1; \( 360/\pi \)
\( C_3 \) dimensional constant, 1000; 550
D  diameter, cm; in.
g  conversion constant, 1; \( 32.1741 \text{ ft/sec}^2 \)
\( \Delta h' \) specific turbine work, J/kg; Btu/lb
\( \Delta h'_{id,s} \) ideal turbine work based on inlet-total- to exit-static-pressure ratio, J/kg; Btu/lb
\( \Delta h'_{id,t} \) ideal turbine work based on inlet-total- to exit-total-pressure ratio, J/kg; Btu/lb
i  incidence angle, deg
J  mechanical equivalent of heat, 1; \( 778.029 \text{ ft-lb/Btu} \)
K  rotor loss coefficient, dimensionless
\( K_S \) stator loss coefficient, dimensionless (ref. 1)
L  kinetic energy loss, J/kg; Btu/lb
N  turbine speed, rad/sec; rpm
\( N_s \) specific speed, dimensionless; rpm \( (\text{ft}^{3/4})/\text{sec}^{1/2} \)
n incidence loss exponent
P  power, kW; hp
p  pressure, \( N/m^2; \text{ psfa} \)
R  gas constant, J/(kg)(K); \( (\text{ft-lb})/(\text{lb})(^\circ\text{R}) \)
T  absolute temperature, K; \( ^\circ\text{R} \)
U  blade speed, m/sec; ft/sec
V  absolute velocity of gas, m/sec; ft/sec
W  gas velocity relative to rotor, m/sec; ft/sec
WF  work factor, eq. (B38)
w  mass flow rate, kg/sec; lb/sec
ZZ  number of rotor blades at rotor inlet
α  absolute gas angle (angle between absolute velocity vector and meridional plane, positive when tangential velocity component is in direction of wheel velocity), deg
β  relative gas angle (angle between velocity vector relative to wheel and meridional plane, same sign convention as for α), deg
Γ  torque, N-m; in.-lb
γ  ratio of specific heat at constant pressure to specific heat at constant volume
δ  ratio of turbine inlet total pressure to U.S. standard atmospheric pressure, eq. (B22)
ε  function of γ used in relating parameters to those using air inlet conditions at U.S. standard sea-level conditions, eq. (B23)
\( \eta_s \)  efficiency based on ratio of inlet total to exit static pressure
\( \eta_t \)  efficiency based on ratio of inlet total to exit total pressure
\( \theta_{cr} \)  squared ratio of critical velocity at turbine inlet to critical velocity at U.S. standard atmospheric temperature, eq. (B21)
ν  blade-jet speed ratio, eq. (B37)
ρ  gas density, kg/m³; lb/ft³
φ  optimum rotor flow angle, deg

Subscripts:
cr  condition corresponding to \( V/V_{cr} = 1 \)
des  design
eq  air equivalent (U.S. standard sea level) values
id  ideal
IN  incidence
max  maximum
opt  optimum
R  rotor
r  radial component

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S    stator
u    tangential component, positive when in direction of wheel velocity
x    meridional component, component in plane containing axis of rotation
0    station at turbine inlet
1    station immediately upstream of stator exit
2    station immediately downstream of stator exit
3    station immediately upstream of rotor inlet
4    station immediately upstream of rotor exit
5    station immediately downstream of rotor exit

Superscripts:
'    absolute total state
''   total state relative to rotor

*    U.S. standard sea-level air conditions (temperature, 288.15 K (518.67° R);
     pressure, 101325 N/m² (2116.22 psfa), specific-heat ratio, 1.4; gas constant, 
     287.04 J/(kg)(K) (53.35 (ft-lb)/(lb)(°R))

The analytical procedure involves a step-by-step solution of the flow conditions through the turbine along a mean line. Thus, at the rotor exit, the flow conditions and velocity diagrams are those at the mean radius, which could be a flow mean or an area mean. The two independent variables that are fixed for any given calculation point are the rotor-inlet-tip speed ratio $\left(\frac{U}{V_{cr}}\right)_3$ and the stator-exit critical-velocity ratio $\left(\frac{V}{V_{cr}}\right)_1$. The analytical procedure and the equations used are outlined in the following paragraphs.

Stator Analysis

The total temperature is assumed to be constant for the first four stations. Thus,

$$V_{cr,0} = V_{cr,1} = V_{cr,2} = V_{cr,3}$$

The mass flow per unit area is expressed as

$$\frac{\rho V}{\rho'V_{cr}} = \frac{V}{V_{cr}} \left[1 - \frac{\gamma - 1}{\gamma + 1} \left(\frac{V}{V_{cr}}\right)^2\right]^{1/(\gamma - 1)}$$

For an input value of $p_1'/p_0'$ and the assumed value of $\left(\frac{V}{V_{cr}}\right)_1$, the continuity relation at station 0 is

$$\left(\frac{\rho V}{\rho'V_{cr}}\right)_0 = \frac{p_1'}{p_0'} \left(\frac{\rho V}{\rho'V_{cr}}\right)_1 \frac{A_1}{A_0} \cos \alpha_1$$

Equation (B1) is substituted into equation (B2), which can then be solved iteratively for $\left(\frac{V}{V_{cr}}\right)_0$. 

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The mass flow rate is then computed as

\[ w = \frac{p'_1}{p'_0 \left( \frac{\rho V}{\rho' V_{cr}} \right)} \left( \rho' V_{cr} \right)_0 A_1 \cos \alpha_1 \]  

(B3)

where \( (\rho' V_{cr})_0 \) is evaluated from the known inlet conditions of \( p'_0 \) and \( T'_0 \) by using

\[ \rho' = \frac{p'}{R T'} \]

and

\[ V_{cr} = \sqrt{\frac{2 \gamma}{\gamma + 1}} g R T' \]

For values of \( V/V_{cr} \) greater than 1.0, the choking value of mass flow rate is used to calculate a new stator-exit flow angle:

\[ \cos \alpha_1 = \frac{w_{cr}}{\frac{p'_1}{p'_0} \left( \frac{\rho V}{\rho' V_{cr}} \right)_0 \left( \rho' V_{cr} \right)_0 A_1} \]  

(B4a)

At station 1 the geometry of the velocity diagram gives

\[ \left( \frac{V_u}{V_{cr}} \right)_1 = \left( \frac{V}{V_{cr}} \right)_1 \sin \alpha_1 \]  

(B4b)

\[ \left( \frac{V_r}{V_{cr}} \right)_1 = \left( \frac{V}{V_{cr}} \right)_1 \cos \alpha_1 \]  

(B4c)

Station 2 conditions are determined by assuming that \( (\rho' V_{cr})_1 = (\rho' V_{cr})_2 \) and since \( D_2 = D_1 \), \( (V_u/V_{cr})_1 = (V_u/V_{cr})_2 \). The continuity relation between stations 1 and 2 is written as
\[
\left( \frac{\rho V}{\rho'V_{cr}} \right) B_1 \cos \alpha_1 = \left( \frac{\rho V}{\rho'V_{cr}} \right) \cos \alpha_2
\]  
(B5a)

where

\[
B_1 = \frac{A_1}{A_2}
\]  
(B5b)

and

\[
\left( \frac{\rho V}{\rho'V_{cr}} \right) \cos \alpha_2 = \left\{ 1 - \frac{\gamma - 1}{\gamma + 1} \left[ \frac{V_r}{V_{cr}} \right]^2 + \left( \frac{V_u}{V_{cr}} \right)^2 \right\}^{1/(\gamma - 1)} \frac{V_r}{V_{cr}}
\]  
(B5c)

The geometry of the velocity diagram gives

\[
\left( \frac{V}{V_{cr}} \right) \left\{ \frac{V_r}{V_{cr}} \right\}^2 + \left( \frac{V_u}{V_{cr}} \right)^2 \right\}^{1/2}
\]  
(B5d)

and

\[
\alpha_2 = \cos^{-1} \frac{\frac{V_r}{V_{cr}}}{\left( \frac{V}{V_{cr}} \right)}
\]  
(B5e)

Equations (B5a) to (B5e) are solved iteratively to determine \((V_r/V_{cr})_2\), \((V/V_{cr})_2\), and \(\alpha_2\).

The conditions at station 3 are determined by assuming that

\[(\rho'V_{cr})_2 = (\rho'V_{cr})_3\]
and
\[
\frac{V_u}{V_{cr/3}} = \frac{V_u}{V_{cr/2}} \frac{D_2}{D_3} \quad (B6a)
\]

The continuity relation between stations 2 and 3 is given as
\[
\frac{\rho V}{\rho' V_{cr/2}} \frac{D_2}{D_3} \cos \alpha_2 = \frac{\rho V}{\rho' V_{cr/3}} \cos \alpha_3 \quad (B6b)
\]

where
\[
\frac{\rho V}{\rho' V_{cr/3}} \cos \alpha_3 = \left\{1 - \frac{\gamma - 1}{\gamma + 1} \left[\left(\frac{V_r}{V_{cr}}\right)_3^2 + \left(\frac{V_u}{V_{cr}}\right)_3^2\right]\right\}^{1/(\gamma - 1)} \quad (B6c)
\]

From the geometry of the velocity diagrams,
\[
\frac{V}{V_{cr/3}} = \left[\left(\frac{V_r}{V_{cr}}\right)_3^2 + \left(\frac{V_u}{V_{cr}}\right)_3^2\right]^{1/2} \quad (B6d)
\]

and
\[
\alpha_3 = \cos^{-1} \frac{V_r}{V_{cr/3}} \quad (B6e)
\]

Equations (B6a) to (B6e) are solved iteratively to determine \(V_r/V_{cr}\), \(V/V_{cr}\), and \(\alpha_3\).
Rotor Analysis

The relations between relative and absolute parameters at the rotor inlet are given by the following four equations:

\[
\left( \frac{T''}{T'} \right)_3 = \left\{ 1 - \frac{\gamma - 1}{\gamma + 1} \left[ \frac{2U_3 V_{u,3}}{V_{cr,3}^2} - \left( \frac{U}{V_{cr,3}} \right)^2 \right] \right\} \tag{B7a}
\]

\[
\frac{p''_3}{p'_3} = \left( \frac{T''}{T'} \right)_3^{\gamma/(\gamma - 1)} \tag{B7b}
\]

\[
\left( \frac{W_{cr}}{V_{cr}} \right)_3 = \left( \frac{T''}{T'} \right)_3^{1/2} \tag{B7c}
\]

\[
\left( \frac{\rho' W_{cr}}{\rho' V_{cr}} \right)_3 = \left( \frac{T''}{T'} \right)_3^{(\gamma + 1)/2(\gamma - 1)} \tag{B7d}
\]

The velocity-diagram geometry gives

\[
\left( \frac{W_u}{W_{cr}} \right)_3 = \left[ \left( \frac{V_u}{V_{cr}} \right)_3 - \left( \frac{U}{V_{cr}} \right)_3 \right] \left( \frac{V_{cr}}{W_{cr}} \right)_3 \tag{B7e}
\]

\[
\left( \frac{W}{W_{cr}} \right)_3 = \left[ \left( \frac{W_u}{V_{cr}} \right)_3^2 + \left( \frac{V_r}{V_{cr}} \right)_3^2 \right]^{1/2} \left( \frac{V_{cr}}{W_{cr}} \right)_3 \tag{B7f}
\]

\[
\left( \frac{W_r}{W_{cr}} \right)_3 = \left[ \left( \frac{W}{W_{cr}} \right)_3^2 - \left( \frac{W_u}{W_{cr}} \right)_3^2 \right]^{1/2} \tag{B7g}
\]
The optimum rotor-inlet flow angle $\varphi$ is calculated as follows:

$$\beta_3 = \sin^{-1} \left( \frac{W_u}{W_{cr3}} \right)$$

(B7h)

Since the rotor mean radius decreases from inlet to exit, there is a relative total-temperature drop expressible by the following equation:

$$\frac{T_{3}''}{T_{3}'} = 1 - \frac{1}{\gamma + 1} \left( \frac{U_4}{W_{cr3}} \right)^2 \left[ 1 - \left( \frac{U_4}{U_3} \right)^2 \right]$$

(B10a)

This allows the following rotor-exit parameters to be calculated:
The rotor-exit conditions are calculated by using the continuity equation between stations 3 and 4

\[
\left( \rho Ax \right)_3 = \left( \rho Ax \right)_4
\]

which is written as

\[
\left( \frac{\rho W}{\rho''W_{cr}} \right)_4 = \frac{\left( \frac{\rho W}{\rho''W_{cr}} \right)_3 A_3 \cos \beta_3}{\left( \frac{\rho''W_{cr}}{\rho''W_{cr}} \right)_4 A_4 \cos \beta_4}
\]

(B11)

where \( A_4 = B_4 A_5 \).

Everything on the right side of equation (B11) is known except \( p''/p''_{id} \), which is the relative total pressure recovery for the rotor. It can be expressed as follows:

\[
\frac{p''}{p''_{id}} = 1 - \left\{ \frac{\gamma - 1}{\gamma + 1} \left[ \frac{K \left( \frac{W}{W_{cr}} \right)_4^2}{\left( \frac{W_3}{W_{cr, 4}} \right)^2 (K \cos^2 \Theta_3 + \sin^2 \Theta_3)} \right]^{\gamma/(\gamma-1)} \right\}
\]

(B12)
Equation (B1) is substituted, in terms of relative quantities, into equation (B11). And the values of \( \left( \frac{W}{W_{cr}} \right)_4 \) and \( \frac{p_4'''}{p_4', id} \) are determined by an iteration procedure with equations (B11) and (B12). After the rotor choke point, conditions upstream of the rotor exit are held fixed. As the velocity ratio \( \left( \frac{W}{W_{cr}} \right)_4 \) is increased beyond the choking value, the exit flow angle \( \beta_4 \) is adjusted by the following equation:

\[
\cos \beta_4 = -\frac{\left( \frac{\rho W}{\rho''' W_{cr}} \right)_{\frac{A_3}{A_4}} \cos \beta_3}{\frac{p_4'''}{p_4', id} \left( \frac{\rho''' W_{cr}}{\rho''' W_{cr}} \right)_{\frac{A_3}{A_4}}} 
\]

(B13a)

The velocity-diagram geometry gives

\[
\left( \frac{W_u}{W_{cr}} \right)_4 = \left( \frac{W}{W_{cr}} \right)_4 \sin \beta_4 
\]

(B13b)

\[
\left( \frac{W_x}{W_{cr}} \right)_4 = \left( \frac{W}{W_{cr}} \right)_4 \cos \beta_4 
\]

(B13c)

Station 5 conditions are determined by assuming that \( \left( \rho''' W_{cr} \right)_4 = \left( \rho''' W_{cr} \right)_5 \) and \( \left( \frac{W_u}{W_{cr}} \right)_4 = \left( \frac{W_u}{W_{cr}} \right)_5 \). The continuity relation between stations 4 and 5 is given as

\[
\left( \frac{\rho W}{\rho''' W_{cr}} \right)_4 B_4 \cos \beta_4 = \left( \frac{\rho W}{\rho''' W_{cr}} \right)_5 \cos \beta_5 
\]

(B14a)

where

\[
B_4 = \frac{A_4}{A_5} 
\]

(B14b)

and

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\[
\left( \frac{\rho W}{\rho'' W_{cr}} \right) \cos \beta_5 = \left\{ 1 - \frac{\gamma - 1}{\gamma + 1} \left[ \left( \frac{W_x}{W_{cr}} \right)^2 + \left( \frac{W_u}{W_{cr}} \right)^2 \right] \right\}^{1/(\gamma - 1)} \left( \frac{W_x}{W_{cr}} \right) \tag{B14c}
\]

The geometry of the velocity diagram gives

\[
\left( \frac{W}{W_{cr}} \right) = \left[ \left( \frac{W_u}{W_{cr}} \right)^2 + \left( \frac{W_x}{W_{cr}} \right)^2 \right]^{1/2} \tag{B14d}
\]

\[
\beta_5 = \sin^{-1} \left( \frac{\frac{W_u}{W_{cr}}}{\frac{W}{W_{cr}} \frac{5}} \right) \tag{B14e}
\]

Equations (B14a) to (B14e) are solved iteratively to determine the values of \( \left( \frac{W_x}{W_{cr}} \right)_5 \), \( \left( \frac{W}{W_{cr}} \right)_5 \), and \( \beta_5 \).

The relations between absolute and relative parameters at the rotor exit are given by

\[
\left( \frac{T'}{T''} \right)_4 = \left( \frac{T'}{T''} \right)_5 = 1 - \frac{\gamma - 1}{\gamma + 1} \left( \frac{W_u}{W_{cr}} \right)^2 + \frac{\gamma - 1}{\gamma + 1} \left( \frac{V_u}{W_{cr}} \right)^2 \tag{B15a}
\]

where

\[
\left( \frac{V_u}{W_{cr}} \right)_4 = \left( \frac{W_u}{W_{cr}} \right)_4 + \left( \frac{U_4}{V_{cr, 3}} \right) \left( \frac{W_{cr, 3}}{W_{cr, 4}} \right) \left( \frac{W_{cr, 3}}{W_{cr, 4}} \right) \tag{B15b}
\]

\[
\left( \frac{p'}{p''} \right)_5 = \left( \frac{T'}{T''} \right)_5^{\gamma/(\gamma - 1)} \tag{B15c}
\]
and

\[
\left( \frac{V_{cr}}{W_{cr/5}} \right) = \left( \frac{T'}{T''} \right)_{5}^{1/2}
\]  

(B15d)

With the assumption that \( V_u/W_{cr} \) = \( V_u/W_{cr} \) \(_4\) and \( W_x/W_{cr} \) = \( V_x/W_{cr} \) \(_5\), the geometry of the velocity diagram gives

\[
\left( \frac{V_x}{V_{cr/5}} \right) = \left( \frac{W_x}{W_{cr/5}} \right) \left( \frac{W_{cr}}{V_{cr/5}} \right)
\]  

(B16a)

\[
\left( \frac{V_u}{V_{cr/5}} \right) = \left( \frac{V_u}{W_{cr/5}} \right) \left( \frac{W_{cr}}{V_{cr/5}} \right)
\]  

(B16b)

\[
\left( \frac{V}{V_{cr/5}} \right) = \left[ \left( \frac{V_x}{V_{cr/5}} \right)^2 + \left( \frac{V_u}{V_{cr/5}} \right)^2 \right]^{1/2}
\]  

(B16c)

\[
\alpha_5 = \sin^{-1} \left( \frac{V_u}{V_{cr/5}} \right)
\]  

(B16d)

Overall Turbine Performance

The turbine overall total-temperature ratio is given by

\[
\frac{T_5'}{T_0'} = 1 - 2 \left( \frac{\gamma - 1}{\gamma + 1} \right) \left( \frac{U_3 V_u, 3 - U_4 V_u, 4}{V_{cr, 3}^2} \right)
\]  

(B17a)
where

\[
\frac{V_{u,4}}{V_{cr,3}} = \left(\frac{W_u}{W_{cr}}\right)^4 \left(\frac{W_{cr,4}}{W_{cr,3}}\right) \left(\frac{W_{cr}}{V_{cr,3}}\right) + \left(\frac{U_4}{V_{cr,3}}\right)
\]  

(B17b)

and the critical velocity at the turbine exit is

\[
V_{cr,5} = \left(\frac{T_{5}'}{T_{0}'}\right)^{1/2} V_{cr,0}
\]

(B17c)

The overall turbine total- to total-pressure ratio is given by the equation

\[
\frac{p_5'}{p_0'} = \left(\frac{p_1'}{p_0'}\right) \left(\frac{p_3'}{p_0'}\right)^3 \left(\frac{p_4'_{id}}{p_0'}\right) \left(\frac{p_4''}{p_0'}\right) \left(\frac{p'}{p''_5}\right)
\]

(B18)

The total- to static-pressure ratio at the turbine exit is obtained from

\[
\left(\frac{p}{p'}\right) = \left[1 - \frac{\gamma - 1}{\gamma + 1} \left(\frac{V}{V_{cr,5}}\right)^2\right]^{\gamma/(\gamma-1)}
\]

(B19a)

The overall turbine total- to static-pressure ratio is then

\[
\frac{p_5}{p_0} = \left(\frac{p_5'}{p_0'}\right) \left(\frac{p}{p'}\right) \left(\frac{p'}{p''_5}\right)
\]

(B19b)

The turbine total and static efficiencies are obtained from

\[
\eta_t = \frac{1 - \frac{T_5'}{T_0'}}{1 - \left(\frac{p_5'}{p_0'}\right)^{\gamma - 1}/\gamma}
\]

(B20a)

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The following equations define the additional performance parameters which appear in the output listing:

\[ \eta_s = \frac{1 - \frac{T'_5}{T'_0}}{1 - \left(\frac{p_5}{p'_0}\right)^{(\gamma-1)/\gamma}} \]  \hspace{1cm} (B20b)

\[ \theta = \frac{\gamma - \frac{RT'_0}{\gamma + 1}}{\left(\frac{\gamma - RT'_0}{\gamma + 1}\right)^*} \]  \hspace{1cm} (B21)

\[ \delta = \frac{p'_0}{p'^*} \]  \hspace{1cm} (B22)

\[ \epsilon = \frac{0.7395945}{\gamma} \left(\frac{\gamma + 1}{2}\right)^{(\gamma-1)/\gamma} \]  \hspace{1cm} (B23)

\[ N_{eq} = \frac{C_1 U_3}{D_3 (\theta')^{1/2}} \]  \hspace{1cm} (B24)

\[ \Delta h'_{eq} = \left(\frac{\gamma}{\gamma - 1}\right) R \frac{T'_0}{\theta} \left(1 - \frac{T'_5}{T'_0}\right) \]  \hspace{1cm} (B25)

\[ w_{eq} = \frac{w(\theta')^{1/2}\epsilon}{\delta} \]  \hspace{1cm} (B26)

\[ \Gamma_{eq} = \frac{C_2 J w \Delta h'}{N} \frac{\epsilon}{\delta} \]  \hspace{1cm} (B27)

\[ (wN)_{eq} = \frac{wN\epsilon}{\delta} \]  \hspace{1cm} (B28)
\[ \Delta h_{id, s} = \left[ 1 - \left( \frac{p_5}{p_0} \right)^{(\gamma - 1)/\gamma} \right] \frac{\gamma}{\gamma - 1} \frac{RT_0}{\gamma} \quad (B29) \]

\[ \Delta h_{id, t} = \left[ 1 - \left( \frac{p_5}{p_0} \right)^{(\gamma - 1)/\gamma} \right] \frac{\gamma}{\gamma - 1} \frac{RT_0}{\gamma} \quad (B30) \]

\[ \frac{\left( \frac{p_0}{p_5} \right)}{p_5} = \left[ 1 - \left( \frac{\gamma - 1}{\gamma RT} \right)^* \frac{J \Delta h_{id, s}}{\theta_{cr}} \right]^{-\gamma/((\gamma - 1)} \quad (B31) \]

\[ \frac{\left( \frac{p_0}{p_5} \right)}{p_5} = \left[ 1 - \left( \frac{\gamma - 1}{\gamma RT} \right)^* \frac{J \Delta h_{id, t}}{\theta_{cr}} \right]^{-\gamma/((\gamma - 1)} \quad (B32) \]

\[ \left( \frac{p_5}{p_0} \right)_{eq} = \frac{1}{\left( \frac{p_0}{p_5} \right)_{eq}} \quad (B33) \]

\[ \Delta h' = \Delta h_{eq} \theta_{cr} \quad (B34) \]

\[ N = N_{eq}(\theta_{cr})^{1/2} \quad (B35) \]

\[ \Gamma' = \Gamma_{eq} \delta \quad (B36) \]

\[ \nu = \frac{U_3}{(2gJ \Delta h_{id, s})^{1/2}} \quad (B37) \]

\[ \frac{WF}{U_3^2} = gJ \Delta h' \quad (B38) \]

\[ P = \frac{\Delta h' wJ}{C_3} \quad (B39) \]
\[
\frac{WT}{P} = \frac{w(T'_0)^{1/2}}{p_0} \\
\frac{DEL-H}{T} = \frac{\Delta h'}{T'_0} \\
\frac{N}{T} = \frac{N}{(T'_0)^{1/2}} \\
\frac{TOR}{P} = \frac{T}{p'_0} \\
T'_5 = T'_0 \left( \frac{T'_5}{T'_0} \right) \\
p'_5 = p'_0 \left( \frac{p'_5}{p'_0} \right) \\
\rho'_5 = \frac{p'_5}{RT'_5} \\
\rho_5 = \rho'_5 \left( \frac{p}{p'_5} \right)^{1/\gamma} \\
N_s = \frac{N \left( \frac{w}{\rho_5} \right)^{1/2}}{(J \Delta h'_{id, t})^{0.75}}
\]
REFERENCES


### TABLE I. - SAMPLE INPUT FOR DESIGN MODE

<table>
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<tr>
<th>STATEMENT NUMBER</th>
<th>FORTRAN STATEMENT</th>
</tr>
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<tbody>
<tr>
<td>1 2 3 5</td>
<td>12.62-CM DIA TURBINE</td>
</tr>
<tr>
<td>4</td>
<td>100 PERCENT SPEED</td>
</tr>
<tr>
<td>5</td>
<td>$\sin P_0 = 172368.9, T_0 = 1144.44, A_0 = 0.120176, A_1 = 0.038008, A_3 = 0.039789, A_5 = 0.044543, A_{L1} = 72.47, B_4 = 56.86, U_3 = 237.9524, U_4 U_3 = 567765, R = 99.1976, G = 1.6667, B_{L1} = 95168, B_{L4} = 93718, Z_2 = 22, \alpha = 0.5, V_{1L} = 0.30, D_{V_{max}} = 0.80, D_{E} = 0.05, D_{V_{max}} = 1.40, D_{3} = 12.6238, D_{2} = 12.9997, \text{MODE} = 2, \alpha = 0.913, P_{DSGN} = 1.74, I_{Test} = 2, W_{D} = 133.879. $</td>
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### TABLE II - SAMPLE INPUT FOR OFF-DESIGN PERFORMANCE MODE

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</tr>
<tr>
<td>2</td>
<td>100 PERCENT SPEED</td>
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</tr>
<tr>
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<tr>
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<td>3</td>
<td>110 PERCENT SPEED</td>
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NASA-C-836 (REV. 0-4L-591)


**TABLE III. - OUTPUT FOR DESIGN MODE**

NASA RADIAL INFLOW TURBINE COMPUTER PROGRAM
12 x 62-CM DIA TURBINE
100 PERCENT SPEED

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**VELOCITIES AND ANGLES**

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### TABLE V. - SHORT OUTPUT FOR OFF-DESIGN PERFORMANCE MODE

**NASA RADIAL INFLOW TURBINE COMPUTER PROGRAM**

**12x62-CM DIA TURBINE**

**100 PERCENT SPEED**

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**LAST CASE IS APPROXIMATE LIMITING LOADING**
Figure 1. - Turbine stator and rotor.

Figure 2. - Variation of stator loss coefficient with stator-exit critical-velocity ratio for design speed.
Figure 3. Variation of stator total-pressure ratio with stator-exit critical-velocity ratio for design speed.

Figure 4. Rotor blade incidence nomenclature.

Figure 5. Trailing-edge blockage for a typical blade row.
Figure 6. Comparison of calculated and experimental mass flow rates.
Figure 8. Comparison of calculated and experimental static efficiencies.
Figure 7. Comparison of calculated and experimental total efficiencies.
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