

NASA/TM—2014-218301



A Guide to Axial-Flow Turbine Off-Design Computer Program AXOD2

Shu-cheng S. Chen
Glenn Research Center, Cleveland, Ohio

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Fax your question to the NASA STI Information Desk at 443-757-5803
- Phone the NASA STI Information Desk at 443-757-5802
- Write to:
STI Information Desk
NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320

NASA/TM—2014-218301



A Guide to Axial-Flow Turbine Off-Design Computer Program AXOD2

Shu-cheng S. Chen
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

June 2014

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at <http://www.sti.nasa.gov>

A Guide to Axial-Flow Turbine Off-Design Computer Program AXOD2

Shu-cheng S. Chen
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

A Users' Guide for the axial flow turbine off-design computer program AXOD2 is composed. This Users' Guide is supplementary to the original Users' Manual of AXOD. Three notable contributions of AXOD2 to its predecessor AXOD, both in the context of the Guide or in the functionality of the code, are described and discussed in length. These are: 1) a rational representation of the mathematical principles applied, with concise descriptions of the formulas implemented in the actual coding. Their physical implications are addressed; 2) the creation and documentation of an 'Addendum Listing' of input namelist-parameters unique to AXOD2, that differ from or are in addition to the original input-namelist given in the Manual of AXOD. Their usages are discussed; and 3) the institution of proper stoppages of the code execution, encoding termination messaging and error messages of the execution to AXOD2. These measures are to safe-guard the integrity of the code execution, such that a failure mode encountered during a case-study would not plunge the code execution into indefinite loop, or cause a blow-out of the program execution. Details on these are discussed and illustrated in this paper. Moreover, this computer program has since been reconstructed substantially. Standard FORTRAN Language was instituted, and the code was formatted in Double Precision (REAL*8). As the result, the code is now suited for use in a local Desktop Computer Environment, is perfectly portable to any Operating System, and can be executed by any FORTRAN compiler equivalent to a FORTRAN 90/95 compiler. AXOD2 will be available through NASA Glenn Research Center (GRC) Software Repository.

1.0 Introduction

AXOD is a preliminary axial-flow turbine off-design computer program, originally developed by the General Electric Company (Ref. 1) under contract for the NASA Lewis Research Center (now the NASA Glenn Research Center (GRC)). Since its delivery to GRC, a substantial amount of modifications, upgrades, and testing were performed on this code by researchers at the GRC. These efforts are reported in References 2, 3, and 4. A formal documentation of its past evolution, with extensive demonstration of its usages in aircraft turbine off-design performance analysis, was published in Reference 2. The code was named AXOD in that reference. A theoretical analysis and discussion on its mathematical foundation and formulations, with a systematic approach for the loss-model closure and the determination of the loss factors were described in Reference 3. Subsequently, a capability extension of AXOD to include the outlet guide vane (OGV) into its acceptable turbine configurations was reported in Reference 4.

Evidently, these aforementioned works have generated a sufficient amount of interest in this computer program, that a formal update to the original Users' Manual of AXOD composted in Reference 2 became preferable. The purpose of this work is to provide an updated guide to the description and the usage of the code.

In this document, concise descriptions of the mathematics and the formulations of the code are presented. The bases of, and the underlying physics pertinent to, these formulas are discussed. An 'Addendum Listing' of the input namelist parameters is provided. These input parameters are different from or are in addition to the original input-namelist given in the Manual of AXOD. The usages of these new parameters are addressed. A complete collection of the encoded program termination-messaging and error messages, that would or could be encountered in the execution of this code are displayed and

discussed. Lastly, a sample of input file to this new code, and its outputs generated are enclosed and illustrated in the Appendices of this paper.

Moreover, this computer program has since been reconstructed substantially. The use of standard Fortran language was instituted, and the code was formatted in Double Precision (REAL*8). As the result, the code is now suited for use in a local Desktop Computer Environment, is perfectly portable to any Operating System, and can be executed by any Fortran Compiler equivalent to a Fortran-90 or Fortran-95 compiler (Fortran-77 compiler was found problematic in handling the namelist-reads, thus was deemed unsuitable for this code).

This new version of code is hereby renamed as AXOD2.

2.0 Mathematics and Formulations

The structure of code, the algorithm, the solution-seeking procedure, and the governing equations applied in AXOD2 have no difference to its predecessor AXOD. However, the bases of code construction, the principles of mathematics, the formulation of formulas and their underlying physical implications, have not been described and discussed in an orderly, rational manner in the past. In this section, the basics of AXOD2 code construction are described. The mathematical principles applied are discussed, and the formulas derived from these principles are listed in concise, detailed forms consistent with the forms encoded in AXOD2. Their physical implications are addressed.

AXOD2 is constructed with the stator and the rotor as two separate entities. Stators are envisioned in the absolute frame-of-reference, while rotors are envisioned in the relative frame-of-reference. Between the stator and the rotor, an annulus region connects the two. Solutions are processed and obtained only at the starting and the ending stations of each component: the stator, the annulus, the rotor, and the annulus that follows. The information of the component losses needed to resolve the flow at a station is obtained via loss-modeling, as was described in References 2 and 3. The annulus regions, however, are treated as if there were no losses (isentropic) in the flow domain. The switching of the frame-of-references between the stator and the rotor is executed in the annulus region. The annulus region after the stator receives the flow conditions from the stator discharge in the absolute frame, and calculates the inflow conditions, in relative frame, for the rotor inlet. The annulus after the rotor receives discharge flow conditions in the relative frame from the rotor, and calculates the inflows needed, in absolute frame, for the following stator inlet. A schematic of the turbine stage is shown in Figure 1.

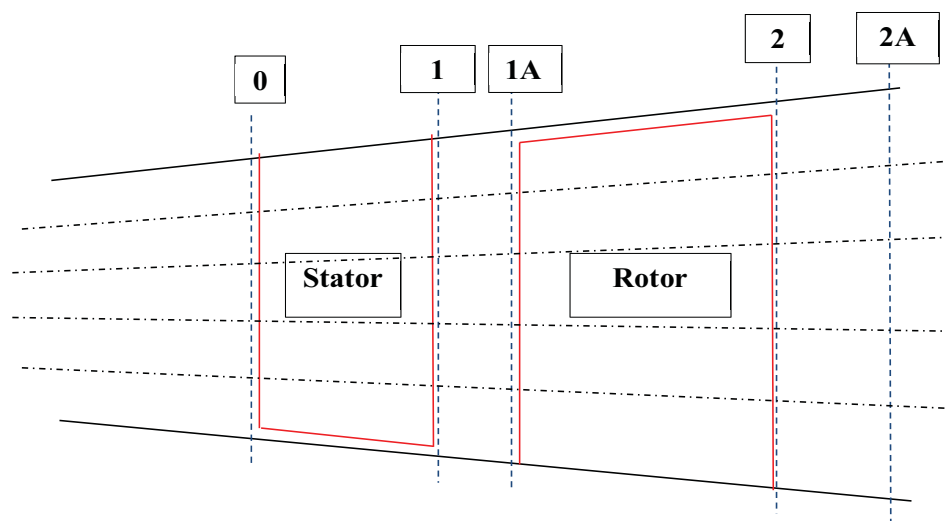


Figure 1.—A schematic of one turbine stage and the numbering of stations

In Figure 1, station 0 denotes the stator inlet, station 1 denotes the stator discharge/annulus intake; station 1A denotes the annulus exit/rotor inlet, station 2 denotes the rotor discharge/annulus intake; and station 2A is the stage exit of the annulus. The radial flow domain is subdivided into several ‘sectors’, each with an equal radius-height. A maximum of 6 sectors is permissible. The number of sectors can be either even or odd; however an odd number of sectors are preferred and recommended.

The flow of the turbine is circumferentially averaged over the ‘effective area’. At the stator inlet and the rotor inlet (stations 0 and 1A), this effective area is the blade-tip to blade-tip sector area, multiplied by the number of blade passages (i.e., the full area of the sector-annulus). At the stator discharge and the rotor discharge (stations 1 and 2), the effective area is the blade-tip to blade-tip area, subtracting the fraction contributed from the metal and viscous blockage of the blade, then multiplied by the total number of blade passages. The effective area of station 2A (the stage exit) is the full area of the annulus-exit.

In the current structure of AXOD2, a dedicated subroutine is constructed for each of the four components. Again, these are: the stator, the annulus that follows, the rotor, and the annulus that follows the rotor. The turbine can be a multi-stage turbine, and with the work of Reference 4, the last turbine stage can be simply a half-stage with the rotor been “blanked-out”, transformed into an annulus-equivalent (this technique is described in length in Ref. 4). The acceptable turbine configuration of AXOD2 includes single- or multi-stage axial flow turbines, with an optional outlet guide vane (OGV) attached.

The solution algorithm implemented in AXOD2 is a marching scheme. Computationally, flow solution is sought over the components from one discharge station to the next in sequence. In this process, all necessary inlet conditions of a component are always known from the calculation already been conducted at the discharge station of the preceding component (with the understanding that the flow conditions at the turbine inlet must be well-defined through input, to start this marching process.) Thus, the problem boils down to finding the solution at the current discharge station of interest. To obtain the flow solution at a station-of-discharge, typically a set of five first-principle (conservation) equations are solved for the set of five primary unknowns of the flow: the static pressure (P), the static temperature (T), and the three velocity components (V_x , V_u , V_r). The governing equations of the system of AXOD2 are presented and discussed herein. For clarity, these equations are cast in forms that are most consistent with the forms implemented in the coding of AXOD2. And as noted, the governing equations for the stator are cast in the absolute frame of reference; the equations for the rotor are cast in the relative frame of reference.

2.1 Mass Conservation

The equations for the mass flow rate at the discharge stations of a blade component are:

$$\omega_1 = \rho_1 * V_{x1} * A_1 * (1 - YC_{S1}) = \rho_1 * V_{m1} \cos(v_1) * A_1 * (1 - YC_{S1}) \quad (1S)$$

$$\omega_2 = \rho_2 * W_{x2} * A_2 * (1 - YC_{R2}) = \rho_2 * W_{m2} \cos(v'_2) * A_2 * (1 - YC_{R2}) \quad (1R)$$

where, ω denotes the mass flow rate through the discharge station; V_x and W_x denote, respectively, the absolute and the relative axial velocities of the flow at discharge; V_m and W_m denote, respectively, the absolute and the relative meridional flow velocities; A_1 and A_2 are the sector area of the annulus at the stator and at the rotor exit, and YC_S and YC_R are the area blockage loss factors of the stator and the rotor at discharge, respectively. The v and v' denote the meridional flow angles (streamline slope angles) of the stator and the rotor, respectively. The definition of the meridional flow angle and its implication to AXOD2 are provided later in this section.

The equation number with a ‘S’ denotes ‘stator’ in the absolute-frame; the equation number with a ‘R’ denotes ‘rotor’ in the relative-frame. This notation is applied throughout this paper. Conservation equations applied to the annulus regions are similar to those for the stators and the rotors, except that all

losses in an annulus region are zero. For example, at an annulus discharge, Equation (1S) or (1R) would apply but with the loss factor $YC = 0$.

The continuity conditions, which are the actual enforcement of the conservation of mass, applied respectively to the stators and the rotors are:

$$\sum_I \omega_{0_I} + (w_{r1} - 1) * \sum_I \omega_{0_I} = \sum_I \omega_{1_I} \quad (2S)$$

$$\sum_I \omega_{1A_I} + (w_{r2} - 1) * \sum_I \omega_{1A_I} = \sum_I \omega_{2_I} \quad (2R)$$

where, $(w_{r1} - 1)$ denotes the fraction of coolant flow injected in between stations 0 and 1, with respect to the inlet total mass flow rate of the stator at station 0; $(w_{r2} - 1)$ denotes the fraction of coolant flow injected in between stations 1A and 2, with respect to the inlet total mass flow rate of rotor at station 1A. The 'I' here is the sector-index. Notice that the continuity conditions over a blade component are enforced globally by summing up the sector mass flow rates. The total discharging flow rate is matched to the total incoming flow rate, including the coolant flow addition.

Contrarily, the continuity conditions over the stations of the annulus region are:

$$\omega_1 + (w_{r1A} - 1) * \omega_1 = \omega_{1A} \quad (3a)$$

$$\omega_2 + (w_{r2A} - 1) * \omega_2 = \omega_{2A} \quad (3b)$$

The flow rates are matched locally sector by sector and no summation is applied. The $(w_{r2A} - 1)$ is the fraction of the coolant flow injected in the annulus region between stations 1 and 1A, with respect to the mass flow rate at the annulus intake (or equivalently, of the preceding stator discharge). The $(w_{r1A} - 1)$ is the fraction of coolant flow injected in the annulus region between stations 2 and 2A, with respect to the flow rate at its annulus intake (or the preceding rotor discharge).

In Equations (2S), (2R), (3a), and (3b), ω_1 and ω_2 were defined in Equations (1S) and (1R). Although not shown here, ω_0 , ω_{1A} , and ω_{2A} are defined the same way only without the blockage loss factor YC , because these three stations are the stations of the blade-component-inlet (or equivalently, the stations of the annulus-discharge; see Fig. 1 for the illustration), and the flow is treated as frictionless there.

2.2 Streamwise Momentum Conservation

The streamwise momentum balance applied in AXOD2 is not a conservation equation, but rather it is merely a modeling equation for the loss of total pressure across a blade component. This streamwise momentum loss is casted into two explicit mechanisms, with two sets of loss coefficients YA and YB .

The first loss mechanism is the stagnation region total pressure loss. The loss factors are expressed as:

$$Y_{AS} = \left[\left(\frac{P_{t0}}{P_0} \right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{P_{t01}}{P_0} \right)^{\frac{\gamma-1}{\gamma}} \right] \left/ \left(\frac{\gamma-1}{2} \right) M_0^2 \right. \quad (4S-1)$$

$$Y_{AR} = \left[\left(\frac{P'_{t1A}}{P_{1A}} \right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{P'_{t1A2}}{P_{1A}} \right)^{\frac{\gamma-1}{\gamma}} \right] \left/ \left(\frac{\gamma-1}{2} \right) M'_{1A}{}^2 \right. \quad (4R-1)$$

Here, ‘01’ represents an interim state immediately after the stator inlet state 0 and ‘1A 2’ represents the interim state immediately after the rotor inlet state of 1A. The subscript (*t*) denotes the ‘total’ quantity. The superscript (*'*) refers to the quantity in the relative frame. The γ is the ‘specific heat ratio’, and the M is the Mach number. These notations are applied consistently throughout this paper.

Noted here, the precise formulas of the stagnation region total pressure loss implemented in AXOD2 are actually in the forms of:

$$\eta_S^{opt} * (1 - Y_{A_S}) = \left\{ 1 - \left[\left(\frac{P_{t0}}{P_0} \right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{P_{t01}}{P_0} \right)^{\frac{\gamma-1}{\gamma}} \right] / \left(\frac{\gamma-1}{2} \right) M_0^2 \right\} \quad (4S-2)$$

$$\eta_R^{opt} * (1 - Y_{A_R}) = \left\{ 1 - \left[\left(\frac{P'_{t1A}}{P_{1A}} \right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{P'_{t1A2}}{P_{1A}} \right)^{\frac{\gamma-1}{\gamma}} \right] / \left(\frac{\gamma-1}{2} \right) M'_{1A}{}^2 \right\} \quad (4R-2)$$

The η_S^{opt} and the η_R^{opt} are the stagnation region total pressure recovery factors of the stator and the rotor, respectively. Since the flow Mach number operating in an aircraft turbine is mostly subsonic throughout the turbine flow path, the inlet stagnation pressure recovery factors would be unity (i.e., 1.0) in most of the turbine operations. An exception is when operating at the beyond-choke condition is required (e.g., when operated at the limit-loading condition). For that case, the stagnation pressure recovery factor at the inlet of an outlet guide vane (OGV) could be lower than one, but only slightly. For all studies conducted with AXOD2, the inlet stagnation pressure recovery factors, η_S^{opt} and η_R^{opt} , were set to unity.

The second loss mechanism specified is the blade row kinetic energy loss. The loss coefficients are expressed as:

$$1 - Y_{B_S} = \left(\frac{T_{t1} - T_1}{T_{t1}} \right) / \left(\frac{T_{t1}^{id} - T_1}{T_{t1}^{id}} \right) \quad (5S)$$

$$1 - Y_{B_R} = \left(\frac{T'_{t2} - T_2}{T'_{t2}} \right) / \left(\frac{T'_{t2}^{id} - T_2}{T'_{t2}^{id}} \right) \quad (5R)$$

The superscript (*id*) refers to the ‘ideal’ quantities, and they are defined as:

$$T_{t1}^{id} / T_1 = \left(P_{t1}^{id} / P_1 \right)^{\frac{\gamma-1}{\gamma}} = \left(\left[P_{t01} \left(\frac{T_{t1}}{T_{t0}} \right)^{\frac{\gamma}{\gamma-1}} \right] / P_1 \right)^{\frac{\gamma-1}{\gamma}} \quad (6S)$$

$$T'_{t2}^{id} / T_2 = \left(P'_{t2}^{id} / P_2 \right)^{\frac{\gamma-1}{\gamma}} = \left(\left[P'_{t1A2} \left(\frac{T'_{t2}}{T'_{t1A}} \right)^{\frac{\gamma}{\gamma-1}} \right] / P_2 \right)^{\frac{\gamma-1}{\gamma}} \quad (6R)$$

T_{11}^{id} is the ideal total temperature at the stator discharge, where the flow is assumed isentropically expanded in the stator from the interim state of ‘01’ to the state of 1; and T_{12}^{id} is the ideal relative total temperature at the rotor discharge, where the flow is assumed isentropically expanded in the rotor from the interim state ‘1A 2’ to the discharge state of 2. Rigorous derivation for the two equations is omitted here, but notice that the discharge states of the actual quantities in these equations contain the total temperature ratios of $\frac{T_{11}}{T_{10}}$ and $\frac{T'_{12}}{T'_{1A}}$, respectively for the stator and for the rotor. This is the most general expression of the isentropic relation for the expansion process described here, and is the precise form applied in the coding of AXOD2. When no coolant flow is added, $\frac{T_{11}}{T_{10}}$ of the stator would be just unity (1.0); and if the sector meanline diameters at the rotor inlet and at the discharge were identical, the ratio $\frac{T'_{12}}{T'_{1A}}$ of the rotor would also be one. However, when there is coolant flow addition, neither $\frac{T_{11}}{T_{10}}$ nor $\frac{T'_{12}}{T'_{1A}}$ should be unity, as they would be affected by the coolant temperature injected.

In Equations (5S) and (5R), T_{11} and T_1 are the actual absolute-total-temperature and the static temperature of the flow at the stator discharge; T'_{12} and T_2 are the actual relative-total-temperature and the static temperature of the flow at the rotor discharge. These quantities are obtained by solving the system equations.

Before moving on to the next conservation equation, an important point is made here. Although the streamwise momentum loss specified here consists of only two explicit mechanisms, however, solving the flow at a discharge station requires one to satisfy simultaneously the complete set of governing equations, which includes the mass conservation, the momentum conservations, and the energy conservation. Since the governing equations are inter-connected, therefore when counting the losses of streamwise total pressure (the streamwise momentum loss) across a blade-component from inlet to discharge, all three aforementioned loss factors: YA , YB , and YC (the area-blockage loss factor in the mass conservation) are contributing to the total loss. The effect of the blockage loss on momentum is implicit; it contributes the thermodynamic loss of the streamwise momentum through the changes in P (static pressure) and ρ (density). This loss is in addition to the kinetic energy loss of YB . Another important point to be stated is that all three of the loss mechanisms are contributing *visibly only* to the streamwise momentum loss (the total pressure loss). The reason for this is that no other principal conservation equations described under the present context contains loss (viscous term) of the explicit nature. This statement will be clear as we move on to the discussion of the remaining principles of conservation.

In application, the loss factors YA are correlated to the inflow incidence angles, the loss coefficients YB are correlated to a tangential blade loading factor, and the blockage loss factors YC are correlated to the discharge blade angles of the blade-component. These correlations are provided and discussed in detail in Reference 3.

Equations (4S-1) and (4R-1), Equations (5S) and (5R), and Equations (6S) and (6R) are applicable to the annulus discharge but with the loss factors (YA , YB) set to zero, because the flow in the annulus regions are treated as isentropic. The actual states-of-equation of the P_t and the T_t applicable to an annulus discharge are derived directly from the equations of the absolute frame, i.e., Equations (4S-1), (5S), and (6S) with zero loss factors. Conversion of the quantities between the absolute-frame and the relative-frame, when needed, are done in a straight forward manner following their respective definitions.

2.3 Angular Momentum Conservation

The equations for the angular momentum conservation applied over the blade-components are:

$$0 = 0 \quad (7S)$$

$$PW = [U_{1A}(W_{u1A} + U_{1A}) - U_2(W_{u2} + U_2)] / GJ \quad (7R)$$

Where, ‘ PW ’ is the specific work-extract from the rotor (PW here is a positive quantity. The ‘ $-PW$ ’ would be referred to as ‘the specific work-input’ or simply ‘the specific work’; the sign of PW in References 3 and 4 was wrongfully presented). The U_{1A} and U_2 are the tangential rotor blade velocities, and W_{u1A} and W_{u2} are the relative tangential flow velocities, at the rotor inlet (station 1A) and at the rotor discharge (station 2) respectively. The G and J are the unit conversion factors.

Equation (7R) is commonly referred to as the Euler turbomachinery equation. It is the discrete form of the angular moment-of-momentum balance attributed to the change in angular momentum of the flow, from inlet to discharge over a blade-component. It is rigorously satisfied without the inclusion of the viscous term (loss), even though the flow across the blade-component is acknowledged to be viscous. Physically, for a turbine, it represents the net specific work extracted from the flow through the interaction with the blade component. This net work-output provides both the useful work (the shaft work) and the wasteful works (frictional losses), such as tip-clearance vortices formation, windage loss on the faces of the turbine disk, and bearing and seal loss, etc. Notice that Equation (7S) is simply an identity $0=0$. This is due to the fact that no work is produced over a stator, since it is stationary with no blade speed.

The angular moment-of-momentum equation (Eq. (7R)) is a major governing equation for the design of turbomachinery, but ironically, for the off-design code such as AXOD2, this equation is in fact redundant. The reason for this is that the specific work-extract, PW , is a resultant to AXOD2, not a design-requirement, since AXOD2 is solving the direct problem, not the inverse problem as to a design code, in which ‘ PW ’ would be a given quantity assigned from input. Although still connected implicitly to the system through the energy equation, Equation (7S) or (7R) on their own does not provide a meaningful relation in solving the unknowns (i.e., P , T , V_x , V_u , and V_r). For this system of governing equations to be well-posed (i.e., to be sufficient and unique in solving the unknowns), a set of additional, supplementary conditions must be provided at the stator and at the rotor discharge, respectively. In AXOD2, this additional condition is a specified (assigned) tangential flow angle at the blade-component discharge station. This treatment is described and discussed in length in the paper of Reference 4. The so-called ‘supplementary conditions of the velocity component equations’ are defined later in this section.

In contrast, at the annulus discharge, the angular momentum conservation equations are well-defined and definitive. In the absence of the tangential blade force (no blades exist in the annulus region), they are simply given as:

$$V_{u1} * D_1 = V_{u1A} * D_{1A} \quad (7a)$$

$$V_{u2} * D_2 = V_{u2A} * D_{2A} \quad (7b)$$

where, V_u is the absolute tangential-flow-velocity, and D is the sector meanline diameter. Subscript ‘1’ refers to station 1, and subscript ‘1A’ refers to station 1A. Subscript ‘2’ refers to station 2, and subscript ‘2A’ refers to station 2A.

Equations (7a) and (7b) replace Equations (7S) and (7R) of the blade-components, as the angular momentum conservation equations for the annulus discharge. Equations (7a) and (7b) are definitive and self-sufficient, no supplementary assignment is needed. When the expressions of the relative frame are needed, they are converted from these equations of the absolute frame in a straight forward manner.

When the tangential flow angle is needed at the annulus discharge, it can be obtained analytically (as opposed to been assigned) by satisfying simultaneously the two equations: the mass conservation (Eqs. (3a) or (3b)), and the angular momentum conservation (Eqs. (7a) or (7b)). This derivation has some relevance to the work presented in Reference 4 and is given here:

From Equations (3a) and (1S), one can write:

$$w_{r1A} * \rho_1 * A_1 * V_{x1} * (1 - Y_{CS1}) = \rho_{1A} * A_{1A} * V_{x1A} \quad (7c)$$

And from Eq. (7a):

$$V_{u1} * D_1 = V_{u1A} * D_{1A}$$

Dividing the two, we get:

$$\frac{V_{u1A}}{V_{x1A}} = \frac{V_{u1}}{V_{x1}} * \frac{1}{w_{r1A}} * \frac{1}{(1 - Y_{CS1})} * \left(\frac{\rho_{1A}}{\rho_1} * \frac{A_{1A}}{A_1} * \frac{D_1}{D_{1A}} \right) \quad (7d)$$

Here, V_u is the absolute tangential-flow-velocity, V_x is the absolute axial-flow-velocity, ρ is density, A is the sector area of the annulus, and D is the sector meanline diameter. The w_{r1A} is the ratio of the annulus discharge mass flow rate ω_{1A} to the annulus intake mass flow rate ω_1 , seen in Eq. (3a). The Y_{CS1} is the area blockage-loss factor at station 1 (in Eq. (1S)). The $\frac{V_u}{V_x}$ above is the ‘tangent of the tangential flow angle’.

The tangential flow angle at the discharge station 2A (i.e., at the stage exit), with respect to the annulus intake of station 2, is obtained the same way analogous to the derivation shown by Eqs. (7a), (7c), and (7d). For this, one obtains,

$$\frac{V_{u2A}}{V_{x2A}} = \frac{V_{u2}}{V_{x2}} * \frac{1}{w_{r2A}} * \frac{1}{(1 - Y_{CR2})} * \left(\frac{\rho_{2A}}{\rho_2} * \frac{A_{2A}}{A_2} * \frac{D_2}{D_{2A}} \right) \quad (7e)$$

When the relative tangential flow angle is needed, it can be deduced by simply converting from the absolute tangential flow angle expressed here.

2.4 Radial Momentum Conservation

The equations of radial momentum conservation (the radial equilibrium conditions) applied in AXOD2 are:

$$\frac{G}{\rho_1} \frac{dP_1}{dr} = \frac{V_{u1}^2}{r} \quad (8S)$$

$$\frac{G}{\rho_2} \frac{dP_2}{dr} = \frac{(W_{u2} + U_2)^2}{r} \quad (8R)$$

The expression is commonly referred to as the ‘simple radial equilibrium condition’. An elaborated derivation of this equation can be found in Reference 5. P_1 and P_2 are the static pressures, ρ_1 and ρ_1 are densities, at stator discharge and at rotor discharge, respectively. V_{u1} is the absolute tangential flow velocity at a stator discharge, W_{u2} is the relative tangential flow velocity at the rotor discharge. The U_2 is the blade velocity at the rotor discharge. The r is the radial coordinate.

The radial equilibrium condition is a differential equation; it merely provides the distribution relation of P along the radial direction at a discharge station. Although extremely important for the flow solution to be physical, but no absolute magnitude of P can be obtained from this equation alone. It has to be coupled with the equation of mass conservation and solved together, until the continuity condition (Eq. (2S) or (2R)) is satisfied over the blade-component. Thus the coupling of Equations (8S) and (1S), or Equations (8R) and (1R), together constitutes only one well-posed relation for the system at the stator

discharge, or at the rotor discharge. Therefore, once again, we are facing with the problem of an ill-posed system; the flow solution is not obtainable unless a set of supplementary conditions are given at the stator exit and at the rotor exit, respectively. In AXOD2, this set of supplementary conditions is the specifications (assignments) of the meridional flow angles (streamline slope angles) at the stator and at the rotor discharge, respectively. These assignments supplement the deficiency of the need to couple the two principal equations: Equations (8S) and (1S) at the stator discharge and Equations (8R) and (1R) at the rotor discharge. This argument is also discussed in Reference 4.

In contrast, at the annulus discharge the radial equilibrium condition is not applied at all. This is because the continuity condition (the conservation of mass) at the annulus discharge is enforced locally sector-by-sector as was described by Eqs. (3a) and (3b). Thus it is self-sufficient at the annulus discharge. The coupling of mass and the radial pressure distribution is unnecessary. In AXOD2, the well-posedness of the system at the annulus discharge is ensured simply through the adaptation of the meridional flow angles (streamline slope angles) being given there (assigned; equal to the streamline slope angles at their respective annulus intakes.) The radial distribution of pressure is in fact ignored at the annulus discharge.

2.5 The Energy Conservation

The last principle of conservation is the conservation of energy. The equations implemented in AXOD2 are the followings:

$$cp_0 * T_{t0} + (w_{r1} - 1) * cp_{01}^{cool} * T_{t01}^{cool} = w_{r1} * cp_1 * T_{t1} \quad (9S)$$

$$cp_{1A} * \left[T'_{t1A} + \left(U_2^2 - U_{1A}^2 \right) / (2GJ * cp_{1A}) \right] + (w_{r2} - 1) * cp_{1A2}^{cool} * T'_{t1A2}^{cool} = w_{r2} * cp_2 * T'_{t2} \quad (9R-1)$$

Whereas in Eq. (9R-1),

$$T'_{t1A2}^{cool} = \left[T_{t1A2}^{cool} + U_2^2 / (2GJ * cp_{1A2}^{cool}) \right] \quad (9R-2)$$

In Equation (9S), T_{t0} and T_{t1} are the absolute total temperatures of the flow at the stator inlet and at its discharge, respectively. Them T_{t01}^{cool} is the absolute total temperature of the coolant injected into the stator passage, between station 0 and station 1. The $(w_{r1} - 1)$ denotes the mass fraction of the coolant flow addition, with respect to the mainstream mass flow rate at the stator inlet of station 0. The cp 's are the specific heats of the media at constant pressure. In Equation (9R-1), T'_{t1A} and T'_{t2} are the relative total temperatures of the flow at the rotor inlet and at the rotor exit, respectively. The T'_{t1A2}^{cool} is the relative total temperature of the coolant injected into the rotor passage between station 1A and station 2. The $(w_{r2} - 1)$ is the fraction of the coolant mass flow injected, with respect to the inlet mass flow rate of the rotor at station 1A. And cp 's are the specific heats of the media at constant pressure, at various locations. The U_{1A} and U_2 are the blade speeds (tangential blade velocities) at the rotor inlet and at the rotor discharge, respectively.

In Equation (9R-2), T'_{t1A2}^{cool} is the relative-total-temperature and T_{t1A2}^{cool} is the absolute-total-temperature of the coolant flow injected into the rotor passage. This equation is formulated with the argument of compatibility to the right-hand-term in Eq. (9R-1).

The energy conservation equations for the blade-components expressed here can be derived rigorously. But the processes, in particular those for the energy equation of the rotor, are quite involved. This detailed derivation is omitted here.

The energy equations for the annulus regions, including the coolant flow additions, are implemented in the manner analogous to Eq. (9S), i.e., the equation of the absolute frame. The relative total

temperature of the flow at the annulus discharge, when needed, is simply deduced out from the absolute total temperature of the flow at discharge, obtained in analogy with Eq. (9S).

Note that, the formulas given above are cast in forms consistent with the forms implemented in the coding of AXOD2, with a minor difference that the coefficients of specific heat (the cp 's) in AXOD2 are mass-averaged between the two corresponding states. This averaging is somewhat difficult to be included here without cluttering the expressions of the energy equations. Thus, the present forms of expression are adopted.

The derivation of the equations for the energy conservation presented here involves the assumptions of: 1) frictionless flow at the end-stations (i.e., the inlet and the discharge stations) of a component; 2) insulated (adiabatic) walls; and 3) the effect of the radial flow mixing in the component passage is ignored (dismissed).

2.6 Supplementary Conditions of the Velocity Component Equations

In addition to the five principal equations, a set of supplementary velocity component equations are needed.

For the stators:

$$V = \sqrt{V_m^2 + V_u^2} \quad (10a)$$

$$V_m = \sqrt{V_x^2 + V_r^2} \quad (10b)$$

$$\beta = \tan^{-1}(V_u/V_x) \quad (10c)$$

$$v = \tan^{-1}(V_r/V_x), \quad (10d)$$

and thus,

$$V_x = V_m * \cos(v) \quad (10e)$$

$$V_r = V_m * \cos(v) * \tan(v) \quad (10f)$$

And for the rotors:

$$W = \sqrt{W_m^2 + W_u^2} \quad (11a)$$

$$W_m = \sqrt{W_x^2 + W_r^2} \quad (11b)$$

$$\beta' = \tan^{-1}(W_u/W_x) \quad (11c)$$

$$v' = \tan^{-1}(W_r/W_x), \quad (11d)$$

and thus,

$$W_x = W_m * \cos(v') \quad (11e)$$

$$W_r = W_m * \cos(v') * \tan(v') \quad (11f)$$

In here, V and W are the absolute and relative total velocities of the flow, V_m and W_m are the absolute and relative meridional velocity components, V_x and W_x are the absolute and relative axial velocity components, V_u and W_u are the absolute and relative tangential velocity components, and V_r and W_r are the absolute and relative radial velocity components. The β and β' are the tangential flow angles at stator and

at rotor discharge, respectively. The ν and ν' are the meridional streamline slope angles of the stator and the rotor, respectively.

As noted previously, the β and β' and the ν and ν' are the supplementary conditions necessary for the well-posedness of the system equations. They are always assigned at the discharge stations of the stator and the rotor. The manner in which they are assigned is described in Reference 4.

In AXOD2, the flow direction is always placed onto the meridional plane, instead of the axial plane. The major velocity components used in AXOD2 are the V_m and W_m and the V_u and W_u . When V_x and W_x or V_r and W_r are needed, they are expressed in form of Equations (10e) and (11e) or (10f) and (11f), respectively.

This concludes the section of 'Mathematics and Formulations'.

Before moving on to the next subject, it is noted here that the solution processing algorithm implemented in AXOD2 is well developed but rather complex. The step-by-step solution-seeking procedure can be tracked more easily through the documentation and the code-descriptions provided in Reference 1. However, many of the detailed treatment that currently implemented in code AXOD2 are substantially different from the coding described in Reference 1. The step-by-step processing of the algorithm in solving the system equations is not included in the scope of this paper, and no attempt shall be made to describe it here. For the interested reader, to be proficient with the codes encoded in AXOD2, one has to get into it and read/check the statements line-by-line, with Reference 1 serves as a guide or overview for the understanding of the flow chart and logic of this code.

In regard to the practical application of this code, there are many validation cases performed and the results were reported comprehensively in Reference 2, 3, and 4. The procedure undertaken in the usage of the code for problem solving has also been documented, illustrated, and reported in these references. This subject will not be repeated here, interested reader is referred to these papers cited.

3.0 Addendum Listing of the Input Namelist Parameters

Through modifications and upgrades described in References 3 and 4, some of the original input parameters in code AXOD were redefined, and some new ones were added. However, care was duly taken in AXOD2 to ensure these modifications and upgrades do not interfere with or altering the original functionality of the code. A list of input parameters that differ from or are in addition to the original namelist input described in the Users' Manual of AXOD (Ref. 2) is provided herein.

1. 'KOGV' (scalar; = 0 or 1); a new parameter:

When KOGV=1, the Stator of the "KSTG" stage (the last stage) is the outlet guide vane (OGV);
the Rotor of the "KSTG" stage is blanked-out.

When KOGV=0, all stages are in the full-stage configuration.

Default is "KOGV=0".

2. Add 'cxs, cxSR, cxr, cxRS' (scalars; inches) to the input namelists:

'cxs' is the axial length of the stator vane,
'cxSR' is the axial length of the annulus of stator-rotor,
'cxr' is the axial length of the rotor blade,
'cxRS' is the axial length of the annulus of rotor-stator.

No default is assigned to 'cxs, cxSR, cxr, cxRS'.

With these user-input lengths, one can now accurately specify the axial dimensions of the turbine stages, which are used to calculate the sector slopes for the meridional flow angles (Equations 10(d) and 11(d) cited in this paper).

To engage this option of user-specified axial lengths, one needs to set "iar=0" in the namelist-input. And needs to provide the data for 'cxs, cxSR,cxr,cxRS' stage-by-stage in the input namelists.

When "iar" is not zero, the vane/blade/annulus axial lengths are determined via empirical sizing correlations cited by Glassman (Ref. 6), which are built-in to the code. These options are unchanged and are still active as they were. The original "iar=0" option (pure axial turbine), however, has been replaced.

Default for "iar" is 2 (medium aspect ratio blades).

3. Add 'ANGminS(6)' (degrees) to the input namelists;
Add 'ANGminR(6)' (degrees) to the input namelists.

'ANGminS' is a 1-D array with the dimension of sectors employed.

Default is 0.0.

It specifies the inlet stagnation region streamline deflection angle (due to flow circulation; in degrees) at each sector of the Stator.

'ANGminR' is a 1-D array with the dimension of the sectors employed.

Default is 0.0.

It specifies the inlet stagnation region streamline deflection angle (due to flow circulation; in degrees) at each sector of the Rotor.

If assigned, these parameters are given/read stage-by-stage. But with certain "SLI" options, automatic matching is made, so that only some of them are the required input. Auto-matching is conducted on these parameters according to the similarity relation cited in Reference 3.

4. Reformulated 'SETA(6)' (dimensionless) in the namelist-input;
Reformulated 'RETA(6)' (dimensionless) in the namelist-input.

'SETA' is a 1-D array with the dimension of the sectors employed.

Default is 1.0.

It specifies the value of the blade-row efficiency of the Stator (the $(1-YB_S)$ cited in Equation (5S) of this paper).

'RETA' is a 1-D array with the dimension of the sectors employed.

Default is 1.0.

It specifies the value of the blade-row efficiency of the Rotor (the $(1-YB_R)$ cited in Equation (5R) of this paper).

If assigned, these parameters are given/read stage-by-stage. But with certain "SLI" options, automatic matching is made, so that only some of them are the required input. Auto-matching is conducted on these parameters according to the similarity relation cited in Reference 3.

5. Reformulated 'SCF(6)' (dimensionless) in the namelist-input;
Reformulated 'RCF(6)' (dimensionless) in the namelist-input.

'SCF' is a 1-D array with the dimension of the sectors employed.

Default is 1.0.

It specifies the value of the blade-row area blockage factor of the Stator (the $(1-YC_S)$ cited in Equation (1S)).

‘RCF’ is a 1-D array with the dimension of the sectors employed.

Default is 1.0.

It specifies the value of the blade-row area blockage factor of the Rotor (the $(1-YC_R)$ cited in Equation (1R)).

If assigned, these parameters are given/read stage-by-stage. But with certain "SLI" options, automatic matching is made, so that only some of them are the required input. Auto-matching is conducted on these parameters according to the similarity relation cited in Reference 3.

6. Reformulated ‘SREC(6)’ (dimensionless) in the namelist-input;
Reformulated ‘RREC(6)’ (dimensionless) in the namelist-input.

‘SREC’ is a 1-D array with the dimension of the sectors employed.

Default is 1.0.

It specifies the baseline value of the stagnation region total pressure recovery factor of the Stator, cited in Equation (4S-2).

‘RREC’ is a 1-D array with the dimension of the sectors employed.

Default is 1.0.

It specifies the baseline value of the stagnation region total pressure recovery factor of the Rotor, cited in Equation (4R-2).

‘SREC’ and ‘RREC’ are the reserved parameters for the stagnation region total pressure loss, in addition to the loss contributed from the flow incidence effect. As noted in Section 2.0 of this paper, for all cases studied, the value of the stagnation region total pressure recovery factors were set at 1.0 (the default; no baseline loss of stagnation pressure at the stator or at the rotor inlet).

The usage of this option has not been explored, and can be reformulated in the code to account for the specific effect on losses, such as the shock loss or the unsteadiness loss, when necessary.

7. Add ‘STF(6)’ (dimensionless) to the input namelists;
Add ‘RTF(6)’ (dimensionless) to the input namelists (actually ‘RTF’ already exists as a namelist-input in the original code, but is redefined here).

‘STF’ is a 1-D array with the dimension of the sectors employed.

Default is 1.0.

It is an “extra loss factor” multiplied to the blade-row loss coefficient (the YB_S) of the Stator.

‘RTF’ is a 1-D array with the dimension of the sectors employed.

Default is 1.0.

It is an “extra loss factor” multiplied to the blade-row loss coefficient (the YB_R) of the Rotor.

‘STF’ and ‘RTF’ are strictly user-specified parameters, no auto-matching are made on these. When assigned, these two parameters are to be given/read sector-by-sector, and stage-by-stage. If a particular

blade row is not being given, that would mean the STF (/RTF) is 1.0 (the default) for that blade row. These factors need not be given again at the next speed-line; the same value will be automatically applied.

The similarity laws cited in Reference 3 implicitly assume the proportionality is with a constant coefficient. These “extra loss factors” are applied when the losses in a rotor or a stator are known different from the similarity relation of constant coefficient.

8. The ‘SLI’ options:

The option of ‘SLI’ determines how the following parameters are to be specified or be interpreted:

- a. Stagnation region streamline deflection angles: ANGminS, ANGminR;
- b. Blade-row efficiencies: SETA, RETA;
- c. Area blockage factors: SCF, RCF;
- d. Stagnation region total pressure recovery factors: SREC, RREC.

SLI = -1, 1 are the two original options in the code.

SLI = 0, 2, 3, 4 are the newly added auto-matching.

Default is "SLI=1" (to preserve the execution/result of the original cases).

The most practical usage is "SLI=3".

SLI = -1 : All sectors and all blade-rows need to be given/assigned.

SLI = 0 : Need input for each sector of both the first stator and the first rotor.

The remaining stators of the ensuing stages will be determined automatically based on the similarity relations with respect to the first stator;

The remaining rotors of the ensuing stages will be determined automatically based on the similarity relations with respect to the first rotor.

SLI = 1 : Need input for each sector of both the first stator and the first rotor.

The remaining stators of the ensuing stages will be assigned the value exactly identical to the value of the first stator. No similarity law is applied.

The remaining rotors of the ensuing stages will be assigned the value exactly identical to the value of the first rotor. No similarity law is applied.

SLI = 2 : Need input on the meanline sector of the stator-only for each stage.

Within each stage, the sectors will be auto-matched to the value assigned to the meanline sector, according to the similarity law; the rotor will be auto-matched to the value of the stator, again, utilizing the similarity law.

This process is conducted stage-by-stage, thus this input (on the meanline sector of the stator) needs to be provided at each stage.

SLI = 3 : Need input on the meanline sector of the first stator only.

All sectors and all blade-rows are auto-matched to the value assigned to the meanline sector of the first stator, utilizing the similarity law.

This option is the most robust option available. And it was applied to all the newly studied cases conducted with AXOD2.

SLI = 4 : Same as SLI=3, only the radial sectors of the first stator allow/require separate user input, instead of applying the similarity relation onto the sectors.

9. Modified 'PAF' (dimensionless) in the namelist-input:

When "PAF=0.": uniform, mass-averaged radial profile of the total temperature (T_t), and an entropy-averaged radial profile of the total pressure (P_t) are seen at the inlet of the ensuing stage (a complete mixing is assumed to occur at the stage exit).

When "PAF=1.": the radial profiles of the T_t and the P_t seen at the inlet of the ensuing stage remain the same as those obtained at the annulus-exit of the current stage (the stage exit-flow is completely un-mixed).

When " $0 < \text{PAF} < 1$ ": the radial profiles of both the T_t and the P_t seen at the inlet of the ensuing stage are the weighted-average between the profile of "PAF=0" and the profile of "PAF=1" (partial mixing at the stage exit is assumed).

Default is "PAF=0."

10. Add 'WAIRcool' (a scalar; dimensionless) as an input parameter.

'WAIRcool' is the water-to-air mass ratio specific for the coolant mixture. Coolant was specific to just air, it can now be the mixture of water-vapor and air.

Default is 0.

11. The options for the plot-file: iplot(3)

'iplot' is an array of dimension 3.

iplot(1) = 1: Equivalent mass flow rate (lbm/s) at the turbine inlet.
= 2: Corrected mass flow rate (lbm/s) at the turbine inlet.
= 3: The plain mass flow rate (lbm/s) at the turbine inlet.
= 4: Equivalent mass flow rate (lbm/s) at the first rotor (rotor 1) inlet.
= 5: Corrected mass flow rate (lbm/s) at the first rotor (rotor 1) inlet.
= 6: The plain mass flow rate (lbm/s) at the first rotor (rotor 1) inlet.
= 7: The overall turbine power produced (horse-power).
= 9: The overall torque (ft-lb).

iplot(2) = 1: The total efficiency (overall).
= 2: The static efficiency (overall).
= 3: A rating efficiency (overall; an efficiency which considered the kinetic energy of the exit swirling to be a loss).

iplot(3) = 1: The overall total-to-total pressure ratio.
= 2: The overall total-to-static pressure ratio.
= 3: The overall blade-jet speed ratio.

Default is "iplot = 1,1,1,"

This concludes the supplementary listing of the input namelist-parameters unique to AXOD2.

Some remarks in regarding the output from AXOD2:

A considerable amount of effort was afforded to the printouts of AXOD2. The variables deduced in the output routines (both the stage-by-stage, and the inter-stage sector-by-sector printouts) were carefully examined for their adequacy and correctness. As the result, some clarifications were made on the station-index where the variable was obtained, and some modifications were made concerning ambiguity of the definition or the deduction of a quantity on a few of the printed output. No serious error was found. A few new quantities were added to enhance the completeness of the output, where information was available but was not printed previously. These new additions however are quite apparent, and warrant no particular introduction. The original output listing provided in the Manual of AXOD (Ref. 2) remains sufficient. No update on the printout-listing is offered nor needed.

4.0 Termination Messaging and the Error Messages

The institution of proper stoppages and the messaging for the termination of code execution is also considered to be a notable contribution of AXOD2 to its predecessor. A substantial amount of effort was spent to ensure the integrity of the code execution is in a sound state. Potential failure modes are identified, and proper messages are provided before the stoppage of the code execution, which otherwise would or could plunge the code into infinite loop. A summary of these incidences and the messaging are described herein. These messages are printed in the Standard Output (unit 6) of AXOD2.

AXOD2 code-execution would terminate on two circumstances: natural termination (with full output given) and abrupt termination (with no output given). They are described herein:

4.1 Natural Termination

1. In the sweeping mode, the code terminates at the condition of last-rotor-choked, when “DELA=0” is specified in the input-namelist. The message would look like:

```
CASE 1 POINT 66
BLADE ROW 4 CHOKING-DETECTED.
PT/PS of this blade-row is 1.94570
All Re-Iterations Begin from BLADE ROW 1
PT/PS at the Starting Blade-Row is 1.66500
```

```
CASE 1 POINT 66
BLADE ROW 4 CHOKED. (CHOKE-ITERATION COMPLETE)
PT/PS of the starting blade-row is now 1.66322
PT/PS of this blade-row is now 1.94170
```

```
*** CASE 1 IS DONE ***
```

2. In the sweeping mode, the code terminates at the limit-loading condition, when “DELA>0” is specified in the input-namelist. The message would look like:

```
CASE 2 POINT 53
BLADE ROW 8 CHOKING-DETECTED.
PT/PS of this blade-row is 1.97108
All Re-Iterations Begin from BLADE ROW 1
```

PT/PS at the Starting Blade-Row is 1.36000

CASE 2 POINT 53

BLADE ROW 8 CHOKED. (CHOKE-ITERATION COMPLETE)

PT/PS of the starting blade-row is now 1.35917

PT/PS of this blade-row is now 2.08400

CASE 2 POINT 53

BLADE ROW 9 CHOKING-DETECTED.

PT/PS of this blade-row is 2.21485

All Re-Iterations Begin from BLADE ROW 1

PT/PS at the Starting Blade-Row is 1.35917

BLADE ROWS 8 AND 9 CHOKE-DETECTED

Re-Start this POINT from BLADE ROW 1

DELPR at that Blade Row Was 0.50000E-02

DELPR Will Now Be 0.10423E-02

PT/PS of the starting value is 1.35604

CASE 2 POINT 55

BLADE ROW 10 CHOKING-DETECTED.

PT/PS of this blade-row is 1.94428

All Re-Iterations Begin from BLADE ROW 1

PT/PS at the Starting Blade-Row is 1.35813

CASE 2 POINT 55

BLADE ROW 10 CHOKED. (CHOKE-ITERATION COMPLETE)

PT/PS of the starting blade-row is now 1.35760

PT/PS of this blade-row is now 2.01263

POINT 69

Limit Loading is Reached. AACCS = 1.0000

*** CASE 2 IS DONE ***

3. Also in the sweeping mode, the code terminates at the outlet-guide-vane-choke, when both "DELA>0" and "KOGV=1" are specified in the input-namelist, and the outlet guide vane (OGV) happens to be found choked. The message would look like:

CASE 3 POINT 45

BLADE ROW 8 CHOKING-DETECTED.

PT/PS of this blade-row is 1.81833

All Re-Iterations Begin from BLADE ROW 1
PT/PS at the Starting Blade-Row is 1.38800

CASE 3 POINT 45
BLADE ROW 8 CHOKED. (CHOKE-ITERATION COMPLETE)
PT/PS of the starting blade-row is now 1.38790
PT/PS of this blade-row is now 1.91344

POINT 81
The OGV is Found Partially Choked.
Upstream Flow Rate Can Not Go Through.
The Last Data Point is Contaminated.

*** CASE 3 IS DONE ***

4. In the single-point mode, when “WG” (mass flow rate at the turbine inlet) is assigned through the namelist-input, the code terminates when the solution is obtained and the output is given. The message is simply:

*** CASE 1 IS DONE ***

Definition of the limit-loading condition and the circumstance of the OGV found-choked, as indicated above, are described and discussed in length in Reference 4. Reader is referred to that paper for detail.

4.2 Abrupt Termination

The abrupt termination occurs when a failure mode is encountered during the code execution. Execution is simply stopped on the spot, error message is given, and no output is available at this incidence.

1. “WG” specified is too large for the single-point mode of execution. The message is:

CASE 1 POINT 1
BLADE ROW 4 CHOKING-DETECTED.
PT/PS of this blade-row is 1.87398
All Re-Iterations Begin from BLADE ROW 1
PT/PS at the Starting Blade-Row is 1.33839

SINGLE POINT MODE. WG = 65.0000 LBM/S
EXECUTION TERMINATED. NO OUTPUT IS GIVEN.
WG is out-of-range. Try A Smaller WG.

2. “WG” specified is too small for the single-point mode of execution. The message would be:

UNDER-FLOW in SUBROUTINE STA1.
OUTPUTS ARE MEANINGLESS at THIS CONDITION.

PROGRAM IS TERMINATED. TRY A HIGHER PTPS.

Although the instruction here is “TRY A HIGHER PTPS”, but in this incidence, the root cause is actually “WG” specified being too small, which caused the flow at station 1 to be under-developed. One should try using a larger “WG”.

3. Under-flow/reverse-flow detected. This occurs when executing in the sweeping mode and the “PTPS” value specified in the input-namelist is too small (too close to 1.) for the flow to develop in the turbine flow path. This message may look like:

```
CASE 1 POINT 1
BLADE ROW 7 CHOKING-DETECTED.
PT/PS of this blade-row is 1.00936
All Re-Iterations Begin from BLADE ROW 1
PT/PS at the Starting Blade-Row is 1.03800
```

```
CASE 1 POINT 1
BLADE ROW 7 CHOKING-DETECTED.
PT/PS of this blade-row is 1.00890
All Re-Iterations Begin from BLADE ROW 1
PT/PS at the Starting Blade-Row is 1.03600
```

```
CASE 1 POINT 1
BLADE ROW 7 CHOKING-DETECTED.
PT/PS of this blade-row is 1.00793
All Re-Iterations Begin from BLADE ROW 1
PT/PS at the Starting Blade-Row is 1.03400
```

```
CASE 1 POINT 1
BLADE ROW 7 CHOKING-DETECTED.
PT/PS of this blade-row is 1.00751
All Re-Iterations Begin from BLADE ROW 1
PT/PS at the Starting Blade-Row is 1.03200
```

```
UNDER-FLOW in SUBROUTINE STA1.
OUTPUTS ARE MEANINGLESS at THIS CONDITION.
PROGRAM IS TERMINATED. TRY A HIGHER PTPS.
```

At this incidence, the cause is indeed “PTPS” specified being too small, one should try using a larger “PTPS” to start the sweeping mode execution.

There are two other possible scenarios where an abrupt termination would occur, however neither of the two incidences has been experienced so far. Nevertheless, they are prepared in the code. These are:

4. An intermediate blade row is found alone-choked in the turbine flow path. This message would be given in MAIN of the program. In its exact Fortran statements, it writes:

```
write(6,2015) JBRC
```

```

write(9,2015) JBRC
2015 format(17x,'Blade Row ',I2,' is Found Alone-Choked.',
1      17x,'Last-Blade-Row-Choke is Not Reachable.',
1      17x,'A Design Flaw Exists in The Turbine Flow Path.',
1      17x,'PROGRAM IS TERMINATED.',/)

```

5. A two-blade-row-found-choked scenario has occurred in the turbine flow path, and “DELPR” is below the mark of 5.E-8 (near machine zero; the machine accuracy of the desktop computer used for the code development was determined to be at 1.E-8). “DELPR” is the pressure ratio incremental change (increase) in a single iterative step. This message would occur in SUBROUTINE LOOP, and in the exact Fortran statements it writes:

```

write(6,2010)IPC2,IBRC
write(9,2010)IPC2,IBRC
2010 format(17X,'Blade Rows ',I2,' and ',I2,
1      ' Are Choked Simultaneously.',
1 17x,'(DELPR < 5.E-8). A Design Flaw Exists in The Flow Path.',
1 17x,'PROGRAM IS TERMINATED.',/)

```

This completes the section of ‘Termination Messaging and The Error Messages’. And as stated in the beginning of this section, it is believed that all possible scenarios for a failure mode to occur in the code execution have been accounted for. This ensures the integrity of the code execution, that a blow-out or plunging into indefinite loop will not happen in a case study.

5.0 Concluding Remark

A Users’ Guide for the computer program AXOD2 is provided. This Users’ Guide is supplementary to the original Users’ Manual of AXOD. Three notable contributions of AXOD2 to its predecessor AXOD were described and discussed in this paper. Firstly, the governing equations of the system were listed in a concise manner, that are consistent with the forms actually encoded in AXOD2. Rational representation and the implication of the mathematical principles applied were discussed. Secondly, a documentation of the ‘Addendum Listing’ of input namelist-parameters unique to AXOD2, that are different from (redefined) or are in addition to the original input-namelist given in the Manual of AXOD was composed. The functionality and the usages of these new input parameters were addressed. And thirdly, the institution of proper stoppages of the code execution in AXOD2, with their corresponding termination messaging and/or error messages were described and displayed. Moreover, this computer program has been reconstructed substantially from its original form of AXOD. Standard Fortran Language was instituted, and the code is formatted in Double Precision (REAL*8). As the result, the code is now suited for use in a local Desktop Computer Environment, is perfectly portable to any Operating System, and can be executed by any Fortran Compiler equivalent to a Fortran-90/95 compiler. AXOD2 will be available through NASA Glenn Research Center (GRC) Software Repository.

Appendix A.—Sample Input

The sample input-file provided here is a 4 ½-stage turbine with an average stage loading factor of 4.66, designed by Pratt & Whitney Aircraft (Ref. 7) and experimentally tested in the turbine rig at NASA Glenn Research Center (Ref. 8). This case was studied with AXOD2 and reported in Reference 4. It is utilized here as a sample case. The input file reads:

```
NASA/P&W (Four and 1/2)-Stage Fan-Drive Turbine (ref. TMX-3498)
100 PERCENT SPEED (MUST GO FIRST)
&DATAIN
TTIN=518.7,PTIN=14.7,
PTPS=1.35,DELC=.002,DELL=.01,DELA=0.05,
STG=5.,SECT=5.,PCNH=5*0.2,AACS=1.0,VCTD=1.,
RG=53.35,RPM=2980.,
GAMG=5*1.4,RWG=5*1.0,
iplot=3,1,1,
SLI=3.0,IAR=0,ICYL=1,icf=1,EPR=1.0,
EXPX=4.,EXPP=3.,
STAGE=1.,ENDJOB=0.,endstg=0.,endplt=1.,
DR=15.956,15.700,15.538,15.538,15.458,
DT=19.000,19.280,19.596,20.154,20.492,
cxs =0.6,
cxSR=0.2,
cxr =0.857,
cxRS=0.286,
SDIA=5*0.,
SDEA=59.95,62.43,64.27,65.47,66.03,
RDIA=50.83,53.53,55.20,55.85,55.47,
RDEA=64.46,66.22,67.34,67.82,67.66,
SETA=5*.956,
scf=5*0.984,
ANGminS=5*3.0,
stf=5*1.0,RTF=5*1.0,
SREC=5*1.0,RREC=5*1.0,
&END

&DATAIN STAGE=2.,
RWG=5*1.0,GAMG=5*1.4,
DR=15.458,15.318,15.180,15.180,15.120,
DT=20.492,21.030,21.328,21.964,22.282,
cxs =0.992,
cxSR=0.331,
cxr =1.058,
cxRS=0.353,
SDIA=57.12,58.67,59.06,58.29,56.35,
SDEA=64.68,66.85,68.37,69.25,69.48,
RDIA=57.45,59.20,59.71,58.96,56.97,
RDEA=65.75,67.51,68.63,69.11,68.95,
endstg=0.,
&END

&DATAIN STAGE=3.,
RWG=5*1.0,GAMG=5*1.4,
DR=15.120,14.842,14.662,14.662,14.582,
DT=22.282,22.920,23.218,23.874,24.172,
cxs =1.134,
cxSR=0.378,
cxr =1.295,
cxRS=0.432,
SDIA=58.58,59.76,59.70,58.39,55.84,
```

SDEA=64.51,66.69,68.22,69.09,69.31,
RDIA=55.6,56.3,55.9,54.3,51.0,
RDEA=64.0,65.6,67.2,67.2,67.2,
endstg=0.,
&END

&DATAIN STAGE=4.,
RWG=5*1.0,GAMG=5*1.4,
DR=14.582,14.224,14.006,14.006,14.006,
DT=24.172,24.770,25.068,25.664,25.844,
cxs =1.529,
cxSR=0.510,
cxr =1.839,
cxRS=0.613,
SDIA=56.67,57.12,56.19,53.87,50.18,
SDEA=61.81,64.00,65.53,66.40,66.61,
RDIA=54.07,54.53,53.00,49.49,43.99,
RDEA=61.13,62.89,64.01,64.49,64.33,
endstg=0.,
&END

&DATAIN STAGE=5.,
RWG=5*1.0,GAMG=5*1.4,
KOGV=1,
DR=14.006,4*16.10,
DT=25.844,4*24.434
cxs =3.337,
cxSR=1.112,
cxr =0.5,
cxRS=0.5,
SDIA=53.13,52.92,51.43,48.65,44.58,
SDEA=5*0.0,
RDIA=5*0.0,
RDEA=5*0.0,
endstg=1.,endjob=0.,
&END

70 PERCENT SPEED
&DATAIN STAGE=1.0,PTPS=1.45,
RPM=2086.0,ENDSTG=0.0 &END
&DATAIN STAGE=2. &END
&DATAIN STAGE=3. &END
&DATAIN STAGE=4. &END
&DATAIN STAGE=5.,VCTD=-1.,ENDSTG=1.,endjob=0. &END

120 PERCENT SPEED
&DATAIN STAGE=1.0,PTPS=1.3,
RPM=3576.0,ENDSTG=0.0 &END
&DATAIN STAGE=2. &END
&DATAIN STAGE=3. &END
&DATAIN STAGE=4. &END
&DATAIN STAGE=5.,VCTD=-1.,ENDSTG=1.,ENDJOB=1. &END

Appendix B.—Sample Output

The purpose of this output listing is to provide the reader with an impression in regarding the type and the amounts of data extracted from this code, and perhaps also provide a means for users to confirm the authenticity of the code they acquired. The printout listed here contains both the stage-by-stage printout (five stages altogether), and the inter-stage sector-by-sector printout (only the Stage 1 printout is given here to save the space). Note also that only the Case 1, Point 1 results are printed, the remaining Points and Cases are omitted. And, the printout of Standard Options (the echoing of the input options chosen, printed before the actual output is given) is also omitted. The output would look like:

```

NASA TURBINE CODE AXOD2

1   NASA/P&W (Four and 1/2)-Stage Fan-Drive Turbine (ref. TMX-3498)
    100 PERCENT SPEED (MUST GO FIRST)

                                CASE 1. 1
                                STAGE PERFORMANCE

    STAGE 1   STAGE 2   STAGE 3   STAGE 4   STAGE 5   STAGE 6   STAGE 7   STAGE 8
    TT 0      518.7     480.3     447.1     423.6     409.5
    PT 0      14.700    10.778    8.010     6.458     5.622
    WG 0      12.681    12.681    12.681    12.681    12.681
    DEL H     9.214     7.970     5.640     3.390     0.000
    WRT/P     19.647    25.785    33.476    40.416    45.640
    DH/T     0.01776   0.01659   0.01261   0.00800   0.00000
    N/RT     130.845    135.975    140.935    144.793    0.000
    ETA TT    0.87243    0.85036   0.88083   0.85951   0.00000
    ETA TS    0.62994    0.68533   0.77928   0.78243   0.00000
    ETA AT    0.68504    0.73438   0.83823   0.85614   0.00000
    PT0/PS1   1.350     1.296     1.188     1.101     1.028
    PT0/PS2   1.561     1.455     1.279     1.165     1.037
    PT0/PTBAR 1.364     1.346     1.240     1.149     1.010
    PTR1A/PS2 1.344     1.245     1.135     1.076     1.027
    TTR1A/TT0 0.96240    0.96317   0.97019   0.98031   1.00000
    TTBAR/TT0 0.92597    0.93085   0.94743   0.96665   1.00000
    PS 1      10.887     8.302     6.742     5.852     5.421
    TTR 1A    499.2     462.6     433.8     415.2     409.5
    PTR 1A    12.640     9.206     7.091     5.940     5.568
    PS 2      9.416     7.406     6.263     5.541     5.422
    TTR 2     499.4     462.9     434.1     415.6     409.5
    PTR 2     12.657     9.219     7.106     5.961     5.568
    TT 2A     480.1     447.0     423.5     409.2     409.5
    PT 2A     10.753     7.996     6.449     5.616     5.568
    TTBAR 2A  480.3     447.1     423.6     409.5     409.5
    PTBAR 2A  10.778     8.010     6.458     5.622     5.566
    UP/VI     0.26902    0.31375   0.41264   0.54953   0.00000
    UR/VI     0.23607    0.25866   0.31669   0.39097   0.00000
    W.F. P    4.35210    3.48096   2.28838   1.29549   0.00000
    W.F. R    5.65164    5.12159   3.88500   2.55929   0.00000
    RX P      0.31191    0.29314   0.29222   0.35184   -0.00631
    RX R      0.22516    0.11563   -0.01386   -0.04760   -0.01139
    REACT P   0.46496    0.38062   0.34313   0.39371   0.00000
    REACT R   0.37441    0.14597   -0.05097   -0.09617   0.00000
    ALPHA 0   0.000     58.386    55.002    40.012    8.493
    I STATOR  3.000     5.621     1.574    -10.745   -41.062
    ALF 1     64.186    68.216    68.115    65.490    0.000
    BET 1A    56.431    57.544    49.984    26.512    0.000
    I ROTOR   6.880     4.219    -0.192   -21.551    0.000
    BET 2     67.164    68.501    67.129    63.960    0.000
    ALF 2A    58.386    55.002    40.012    8.493    0.000
    DBET P    123.595    126.046   117.113    90.472    0.000
    DBET R    117.935    122.565   117.465   104.737    0.000
    M 1       0.65289    0.58976   0.47807   0.35846   0.19583
    M1 RT     0.71772    0.68735   0.58885   0.46414   0.20454
    MR 1A     0.44547    0.37502   0.26007   0.15786   0.19583
    MR1A RT   0.53832    0.51286   0.42182   0.31038   0.20454
    MR 2      0.63415    0.54024   0.40994   0.31246   0.19494
    MR2 TIP   0.61745    0.54040   0.43539   0.35560   0.18403
    E/TH CR   9.214     8.607     6.543     4.152     0.000
    N/RTH CR  2980.0    3096.8    3209.8    3297.6     0.0
    WRTHCRE/D 12.678    16.639    21.601    26.079    29.451
    RPM       2980.0    2980.0    2980.0    2980.0     0.0
    MF 2A     0.22233    0.18561   0.15196   0.13441   0.19494

```

M 2A 0.42414 0.32362 0.19841 0.13591 0.19494

OVERALL PERFORMANCE

W.F. P	2.76278	W.F. R	4.39622	DEL H	26.21400	WNE/60D	629.646	TORQUE	828.694
WRT/P	19.64674	N/RT	130.845	DH/T	0.05054	N/RTH CR	2979.978	TOR/P	56.37376
PT0/PT2	2.64112	PT0/PS2	2.71114	PT/PAT2	2.64024	E/TH CR	26.21361	EQ TOR	2166.15792
ETA TT	0.86917	ETA TS	0.84939	ETA TTRP	0.86917	HP	470.204	U/VIS	0.15671
PT/T EQ	2.64112	PT/S EQ	2.71114						
+				WG 0	12.6809	EQ WGO	12.67753	PT0/PS1	1.35000

1 NASA/P&W (Four and 1/2)-Stage Fan-Drive Turbine (ref. TMX-3498)
100 PERCENT SPEED (MUST GO FIRST)

CASE 1. 1
INTER-STAGE PERFORMANCE

STA 0	STATOR INLET		STAGE 1				
DIAM 0	15.956	16.260	16.869	17.478	18.087	18.696	19.000
SLOPE 0		-4.54	-1.99	0.57	3.13	5.67	
WG 0		2.536	2.536	2.536	2.536	2.536	
TT 0	518.7	518.7	518.7	518.7	518.7	518.7	518.7
PT 0	14.700	14.700	14.700	14.700	14.700	14.700	14.700
ALPHA 0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
I STA 0	2.350	2.481	2.745	2.978	3.152	3.235	3.276
V 0	295.948	295.948	295.948	295.948	295.948	295.948	295.948
VU 0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VZ 0	295.948	295.948	295.948	295.948	295.948	295.948	295.948
TS 0	511.4	511.4	511.4	511.4	511.4	511.4	511.4
PS 0	13.990	13.990	13.990	13.990	13.990	13.990	13.990
DENS 0	0.07384	0.07384	0.07384	0.07384	0.07384	0.07384	0.07384
M 0	0.26696	0.26696	0.26696	0.26696	0.26696	0.26696	0.26696

STA 1	STATOR EXIT						
DIAM 1	15.700	16.058	16.774	17.490	18.206	18.922	19.280
SLOPE 1		-3.89	0.53	4.94	9.29	13.54	
WG 1		2.758	2.618	2.501	2.421	2.382	
TT 1	518.7	518.7	518.7	518.7	518.7	518.7	518.7
ALF 1	58.623	59.892	62.428	64.186	65.182	65.424	65.545
DALF	58.623	59.892	62.428	64.186	65.182	65.424	65.545
V 1	763.107	750.130	724.174	699.706	677.670	657.255	647.048
VU 1	652.416	648.920	641.929	629.881	615.083	597.713	589.027
VZ 1	396.843	376.293	335.194	304.693	284.445	273.356	267.812
TS 1	470.3	471.9	475.1	478.0	480.5	482.7	483.9
PS 1	10.294	10.415	10.659	10.887	11.091	11.281	11.376
DENS 1	0.05909	0.05958	0.06056	0.06148	0.06231	0.06307	0.06346
M 1	0.71777	0.70444	0.67778	0.65289	0.63066	0.61022	0.60001
ZWI INC	0.9172	0.9016	0.8703	0.8478	0.8391	0.8474	0.8516
ETASC	0.9653	0.9633	0.9594	0.9560	0.9535	0.9523	0.9517

STATOR FORCES							
AVG DIA	15.828	16.159	16.822	17.484	18.146	18.809	19.140
FTAN/IN	-171.7	-166.9	-157.3	-147.9	-140.2	-134.4	-131.5
			F TAN	-247.5			
FAX/IN	165.4	166.8	169.6	169.2	166.8	160.4	157.2
			F AX	275.5			
F DRUM	-77.3						-106.7

STA 1A	ROTOR INLET		STAGE 1				
DIAM 1A	15.538	15.944	16.755	17.567	18.379	19.190	19.596
SLOP 1A		-3.89	0.53	4.94	9.29	13.54	
WG 1A		2.758	2.618	2.501	2.421	2.382	
TTR 1A	499.9	499.7	499.3	499.2	499.2	499.4	499.5
PTR 1A	12.686	12.672	12.646	12.640	12.651	12.680	12.695
BET 1A	52.500	53.476	55.428	56.431	56.445	55.360	54.817
I ROTOR	7.701	7.513	7.137	6.880	6.646	6.308	6.139

R 1A	575.036	555.315	515.872	478.506	444.391	413.054	397.385
RU 1A	456.996	446.256	424.777	398.702	370.336	339.835	324.585
MR 1A	0.53956	0.52028	0.48174	0.44547	0.41258	0.38253	0.36750
U 1A	202.036	207.312	217.865	228.418	238.971	249.524	254.801
STA 2	ROTOR EXIT						
DIAM 2	15.538	16.000	16.923	17.846	18.769	19.692	20.154
SLOPE 2		-0.11	3.71	7.49	11.21	14.84	
WG 2		2.579	2.505	2.478	2.509	2.610	
BET 2	63.601	64.459	66.175	67.164	67.430	66.967	66.736
DBET	116.101	117.935	121.603	123.595	123.875	122.327	121.553
R 2	706.926	698.391	681.320	668.349	659.200	654.136	651.604
RU 2	633.583	630.142	623.258	615.961	608.713	601.988	598.626
MR 2	0.67356	0.66485	0.64742	0.63415	0.62475	0.61943	0.61677
U 2	202.036	208.038	220.042	232.046	244.050	256.054	262.056
RX	0.23580	0.25100	0.28139	0.31191	0.34045	0.36833	0.38227
DEL H	8.811	8.919	9.136	9.280	9.370	9.412	9.432
PSI	2.69044	2.58882	2.38559	2.19153	2.01108	1.84373	1.76005
ETA TT	0.86694	0.86810	0.87040	0.87239	0.87525	0.87984	0.88213
ETA TS	0.56830	0.58295	0.61226	0.63602	0.65541	0.67078	0.67846
ETA AT	0.63521	0.64597	0.66748	0.68718	0.70602	0.72449	0.73373
ZWI INC	1.3999	1.3660	1.2983	1.2554	1.2408	1.2543	1.2611
ETARC	0.9328	0.9296	0.9232	0.9187	0.9167	0.9176	0.9180
	ROTOR FORCES						
AVG DIA	15.538	15.972	16.839	17.706	18.574	19.441	19.875
FTAN/IN	204.4	198.8	187.5	179.2	174.7	174.3	174.2
			F TAN	397.2			
FAX/IN	67.8	74.8	83.3	92.8	102.8	112.8	116.1
			F AX	201.9			
F DRUM	0.0						-183.6
STA 2A	STAGE EXIT			STAGE 1			
DIAM 2A	15.458	15.961	16.968	17.975	18.982	19.989	20.492
SLOP 2A		-0.11	3.71	7.49	11.21	14.84	
WG 2A		2.579	2.505	2.478	2.509	2.610	
PT 2A	10.910	10.873	10.799	10.753	10.730	10.733	10.734
TT 2A	482.0	481.6	480.7	480.1	479.7	479.5	479.4
V 2A	520.163	504.631	473.567	447.584	426.539	410.890	403.066
VU 2A	433.602	423.114	402.138	381.160	360.578	340.808	330.923
ALF 2A	56.407	56.978	58.121	58.386	57.710	56.041	55.206
MF 2A	0.27351	0.26146	0.23736	0.22233	0.21566	0.21703	0.21771
M 2A	0.49495	0.47978	0.44944	0.42414	0.40370	0.38852	0.38093
VZ 2A	287.454	275.003	250.101	234.624	227.857	229.523	230.355
TS 2A	459.5	460.4	462.0	463.4	464.5	465.4	465.9
PS 2A	9.232	9.288	9.402	9.502	9.591	9.672	9.713
DENS 2A	0.05423	0.05446	0.05493	0.05534	0.05572	0.05609	0.05627

Appendix C.—Sample Plot File

The following is the plot file generated. Two parts are created in each plot file. For this example, they are: pressure ratio (PR) versus efficiency (EFF), and PR versus mass flow rate (FLOW). But other choices are available, for example, power output (HP), or torque (TORQ) can replace “FLOW”. The options of plot, ‘iplot(3)’, given in Section 3.0 of this paper control the combination.

```

269          TURBINE EFFICIENCY VS. PR, RPM, AND AREA
AREA      1          1.00
SPED      3          70.0      100.0      120.0
PR      88      2.3421      2.3521      2.3623      2.3726      2.3831      2.3937      2.4044
PR      88      2.4154      2.4265      2.4377      2.4492      2.4608      2.4727      2.4848
PR      88      2.4970      2.5095      2.5223      2.5353      2.5485      2.5621      2.5759
PR      88      2.5900      2.6044      2.6193      2.6344      2.6500      2.6659      2.6823
PR      88      2.6991      2.7165      2.7343      2.7528      2.7718      2.7916      2.8120
PR      88      2.8332      2.8553      2.8783      2.9023      2.9275      2.9539      2.9818
PR      88      3.0112      3.0424      3.0757      3.1114      3.1498      3.1916      3.2373
PR      88      3.2879      3.3446      3.4092      3.4846      3.5750      3.6890      3.8441
PR      88      4.0892      4.7206      5.0386      5.8059      5.8403      5.8735      5.9057
PR      88      5.9371      5.9677      5.9975      6.0267      6.0551      6.0828      6.1099
PR      88      6.1362      6.1617      6.1863      6.2098      6.2327      6.2551      6.2769
PR      88      6.2982      6.3189      6.3390      6.3585      6.3773      6.3954      6.4129
PR      88      6.4298      6.4461      6.4620      6.4776
EFF      88      0.81295      0.81254      0.81214      0.81173      0.81132      0.81090      0.81049
EFF      88      0.81007      0.80964      0.80922      0.80879      0.80835      0.80792      0.80747
EFF      88      0.80703      0.80658      0.80612      0.80567      0.80520      0.80473      0.80426
EFF      88      0.80378      0.80329      0.80280      0.80230      0.80179      0.80128      0.80076
EFF      88      0.80023      0.79969      0.79914      0.79858      0.79801      0.79742      0.79683
EFF      88      0.79622      0.79559      0.79495      0.79430      0.79362      0.79292      0.79219
EFF      88      0.79144      0.79067      0.78985      0.78900      0.78810      0.78715      0.78614
EFF      88      0.78505      0.78387      0.78258      0.78113      0.77947      0.77749      0.77499
EFF      88      0.77143      0.76389      0.76074      0.75377      0.75336      0.75294      0.75251
EFF      88      0.75205      0.75157      0.75107      0.75056      0.75003      0.74949      0.74894
EFF      88      0.74839      0.74784      0.74731      0.74680      0.74630      0.74578      0.74526
EFF      88      0.74473      0.74421      0.74369      0.74317      0.74266      0.74216      0.74166
EFF      88      0.74118      0.74070      0.74022      0.73973
PR      89      2.6411      2.6598      2.6787      2.6981      2.7178      2.7379      2.7584
PR      89      2.7793      2.8007      2.8225      2.8449      2.8677      2.8911      2.9151
PR      89      2.9397      2.9649      2.9908      3.0175      3.0449      3.0731      3.1022
PR      89      3.1323      3.1633      3.1955      3.2288      3.2633      3.2993      3.3367
PR      89      3.3757      3.4165      3.4593      3.5042      3.5516      3.6017      3.6548
PR      89      3.7113      3.7719      3.8369      3.9073      3.9840      4.0683      4.1620
PR      89      4.2672      4.3877      4.5287      4.6986      4.9139      5.2104      5.7124
PR      89      6.5416      6.5943      6.6448      6.6934      6.7403      6.7856      6.8296
PR      89      6.8722      6.9138      6.9543      6.9939      7.0326      7.0706      7.1079
PR      89      7.1446      7.1805      7.2157      7.2503      7.2840      7.3169      7.3489
PR      89      7.3798      7.4101      7.4398      7.4689      7.4972      7.5248      7.5515
PR      89      7.5773      7.6023      7.6262      7.6493      7.6717      7.6935      7.7147
PR      89      7.7353      7.7553      7.7747      7.7934      7.8114
EFF      89      0.86917      0.86917      0.86917      0.86916      0.86915      0.86914      0.86913
EFF      89      0.86911      0.86909      0.86907      0.86905      0.86903      0.86900      0.86897
EFF      89      0.86893      0.86890      0.86886      0.86881      0.86877      0.86872      0.86867
EFF      89      0.86861      0.86855      0.86849      0.86842      0.86834      0.86826      0.86818
EFF      89      0.86808      0.86798      0.86787      0.86776      0.86763      0.86749      0.86734
EFF      89      0.86718      0.86700      0.86680      0.86658      0.86634      0.86607      0.86576
EFF      89      0.86540      0.86499      0.86450      0.86390      0.86312      0.86202      0.86005
EFF      89      0.85595      0.85557      0.85520      0.85482      0.85443      0.85402      0.85360
EFF      89      0.85315      0.85269      0.85219      0.85167      0.85113      0.85056      0.84996
EFF      89      0.84934      0.84871      0.84805      0.84739      0.84672      0.84605      0.84538
EFF      89      0.84473      0.84406      0.84339      0.84271      0.84203      0.84135      0.84068
EFF      89      0.84002      0.83937      0.83875      0.83813      0.83752      0.83690      0.83629

```

EFF	89	0.83569	0.83508	0.83449	0.83390	0.83332		
PR	81	2.7314	2.7564	2.7820	2.8081	2.8349	2.8623	2.8903
PR	81	2.9191	2.9486	2.9788	3.0099	3.0418	3.0747	3.1085
PR	81	3.1434	3.1794	3.2165	3.2548	3.2945	3.3356	3.3783
PR	81	3.4226	3.4688	3.5169	3.5671	3.6197	3.6748	3.7328
PR	81	3.7939	3.8586	3.9273	4.0004	4.0787	4.1629	4.2541
PR	81	4.3535	4.4629	4.5843	4.7213	4.8783	5.0622	5.2856
PR	81	5.5720	5.9802	7.0350	7.1029	7.1681	7.2309	7.2914
PR	81	7.3496	7.4058	7.4603	7.5131	7.5645	7.6146	7.6635
PR	81	7.7114	7.7584	7.8045	7.8499	7.8946	7.9388	7.9823
PR	81	8.0253	8.0676	8.1093	8.1501	8.1901	8.2292	8.2671
PR	81	8.3044	8.3410	8.3768	8.4117	8.4458	8.4789	8.5108
PR	81	8.5417	8.5714	8.6003	8.6236			
EFF	81	0.87251	0.87296	0.87340	0.87383	0.87425	0.87466	0.87507
EFF	81	0.87548	0.87587	0.87627	0.87665	0.87704	0.87742	0.87780
EFF	81	0.87818	0.87855	0.87892	0.87930	0.87967	0.88004	0.88042
EFF	81	0.88080	0.88118	0.88156	0.88194	0.88234	0.88273	0.88313
EFF	81	0.88354	0.88395	0.88438	0.88480	0.88524	0.88569	0.88616
EFF	81	0.88662	0.88710	0.88758	0.88808	0.88858	0.88907	0.88955
EFF	81	0.88999	0.89028	0.88884	0.88855	0.88825	0.88793	0.88760
EFF	81	0.88726	0.88691	0.88654	0.88615	0.88574	0.88530	0.88482
EFF	81	0.88432	0.88379	0.88322	0.88262	0.88198	0.88131	0.88061
EFF	81	0.87988	0.87913	0.87836	0.87758	0.87679	0.87601	0.87524
EFF	81	0.87446	0.87367	0.87288	0.87209	0.87130	0.87053	0.86977
EFF	81	0.86903	0.86831	0.86759	0.86687			

EOT

270

TURBINE FLOW FUNCTION VS. PR, RPM, AND AREA

AREA	1	1.00						
SPED	3	70.0	100.0	120.0				
PR	88	2.3421	2.3521	2.3623	2.3726	2.3831	2.3937	2.4044
PR	88	2.4154	2.4265	2.4377	2.4492	2.4608	2.4727	2.4848
PR	88	2.4970	2.5095	2.5223	2.5353	2.5485	2.5621	2.5759
PR	88	2.5900	2.6044	2.6193	2.6344	2.6500	2.6659	2.6823
PR	88	2.6991	2.7165	2.7343	2.7528	2.7718	2.7916	2.8120
PR	88	2.8332	2.8553	2.8783	2.9023	2.9275	2.9539	2.9818
PR	88	3.0112	3.0424	3.0757	3.1114	3.1498	3.1916	3.2373
PR	88	3.2879	3.3446	3.4092	3.4846	3.5750	3.6890	3.8441
PR	88	4.0892	4.7206	5.0386	5.8059	5.8403	5.8735	5.9057
PR	88	5.9371	5.9677	5.9975	6.0267	6.0551	6.0828	6.1099
PR	88	6.1362	6.1617	6.1863	6.2098	6.2327	6.2551	6.2769
PR	88	6.2982	6.3189	6.3390	6.3585	6.3773	6.3954	6.4129
PR	88	6.4298	6.4461	6.4620	6.4776			
FLOW	88	13.3185	13.3283	13.3380	13.3477	13.3572	13.3667	13.3760
FLOW	88	13.3853	13.3944	13.4035	13.4125	13.4214	13.4302	13.4389
FLOW	88	13.4475	13.4561	13.4645	13.4729	13.4812	13.4894	13.4975
FLOW	88	13.5056	13.5135	13.5214	13.5292	13.5369	13.5445	13.5521
FLOW	88	13.5596	13.5670	13.5743	13.5816	13.5887	13.5958	13.6029
FLOW	88	13.6098	13.6167	13.6235	13.6303	13.6369	13.6435	13.6500
FLOW	88	13.6565	13.6629	13.6692	13.6755	13.6816	13.6878	13.6938
FLOW	88	13.6998	13.7057	13.7116	13.7174	13.7231	13.7288	13.7344
FLOW	88	13.7399	13.7454	13.7463	13.7468	13.7468	13.7468	13.7468
FLOW	88	13.7468	13.7468	13.7468	13.7468	13.7468	13.7468	13.7468
FLOW	88	13.7468	13.7468	13.7468	13.7468	13.7468	13.7468	13.7468
FLOW	88	13.7468	13.7468	13.7468	13.7468	13.7468	13.7468	13.7468
PR	89	2.6411	2.6598	2.6787	2.6981	2.7178	2.7379	2.7584
PR	89	2.7793	2.8007	2.8225	2.8449	2.8677	2.8911	2.9151
PR	89	2.9397	2.9649	2.9908	3.0175	3.0449	3.0731	3.1022
PR	89	3.1323	3.1633	3.1955	3.2288	3.2633	3.2993	3.3367
PR	89	3.3757	3.4165	3.4593	3.5042	3.5516	3.6017	3.6548
PR	89	3.7113	3.7719	3.8369	3.9073	3.9840	4.0683	4.1620
PR	89	4.2672	4.3877	4.5287	4.6986	4.9139	5.2104	5.7124
PR	89	6.5416	6.5943	6.6448	6.6934	6.7403	6.7856	6.8296

PR	89	6.8722	6.9138	6.9543	6.9939	7.0326	7.0706	7.1079
PR	89	7.1446	7.1805	7.2157	7.2503	7.2840	7.3169	7.3489
PR	89	7.3798	7.4101	7.4398	7.4689	7.4972	7.5248	7.5515
PR	89	7.5773	7.6023	7.6262	7.6493	7.6717	7.6935	7.7147
PR	89	7.7353	7.7553	7.7747	7.7934	7.8114		
FLOW	89	12.6809	12.6969	12.7128	12.7285	12.7441	12.7595	12.7748
FLOW	89	12.7899	12.8049	12.8198	12.8345	12.8490	12.8634	12.8777
FLOW	89	12.8918	12.9058	12.9196	12.9334	12.9470	12.9604	12.9737
FLOW	89	12.9869	13.0000	13.0129	13.0258	13.0384	13.0510	13.0635
FLOW	89	13.0758	13.0880	13.1001	13.1120	13.1239	13.1356	13.1472
FLOW	89	13.1588	13.1702	13.1814	13.1926	13.2037	13.2146	13.2255
FLOW	89	13.2362	13.2469	13.2574	13.2678	13.2782	13.2884	13.2985
FLOW	89	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034
FLOW	89	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034
FLOW	89	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034
FLOW	89	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034
FLOW	89	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034
FLOW	89	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034	13.3034
PR	81	2.7314	2.7564	2.7820	2.8081	2.8349	2.8623	2.8903
PR	81	2.9191	2.9486	2.9788	3.0099	3.0418	3.0747	3.1085
PR	81	3.1434	3.1794	3.2165	3.2548	3.2945	3.3356	3.3783
PR	81	3.4226	3.4688	3.5169	3.5671	3.6197	3.6748	3.7328
PR	81	3.7939	3.8586	3.9273	4.0004	4.0787	4.1629	4.2541
PR	81	4.3535	4.4629	4.5843	4.7213	4.8783	5.0622	5.2856
PR	81	5.5720	5.9802	7.0350	7.1029	7.1681	7.2309	7.2914
PR	81	7.3496	7.4058	7.4603	7.5131	7.5645	7.6146	7.6635
PR	81	7.7114	7.7584	7.8045	7.8499	7.8946	7.9388	7.9823
PR	81	8.0253	8.0676	8.1093	8.1501	8.1901	8.2292	8.2671
PR	81	8.3044	8.3410	8.3768	8.4117	8.4458	8.4789	8.5108
PR	81	8.5417	8.5714	8.6003	8.6236			
FLOW	81	12.2239	12.2445	12.2648	12.2849	12.3049	12.3246	12.3441
FLOW	81	12.3635	12.3826	12.4016	12.4204	12.4390	12.4574	12.4756
FLOW	81	12.4937	12.5115	12.5292	12.5467	12.5641	12.5813	12.5983
FLOW	81	12.6151	12.6318	12.6483	12.6647	12.6809	12.6969	12.7128
FLOW	81	12.7285	12.7441	12.7595	12.7748	12.7899	12.8049	12.8198
FLOW	81	12.8345	12.8490	12.8634	12.8777	12.8918	12.9058	12.9196
FLOW	81	12.9334	12.9470	12.9598	12.9598	12.9598	12.9598	12.9598
FLOW	81	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598
FLOW	81	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598
FLOW	81	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598
FLOW	81	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598
FLOW	81	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598
FLOW	81	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598
FLOW	81	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598	12.9598
EOT								

Appendix D.—Sample Results

The results of this sample case were published in Reference 4. They are echoed here for illustration purpose and for completeness.

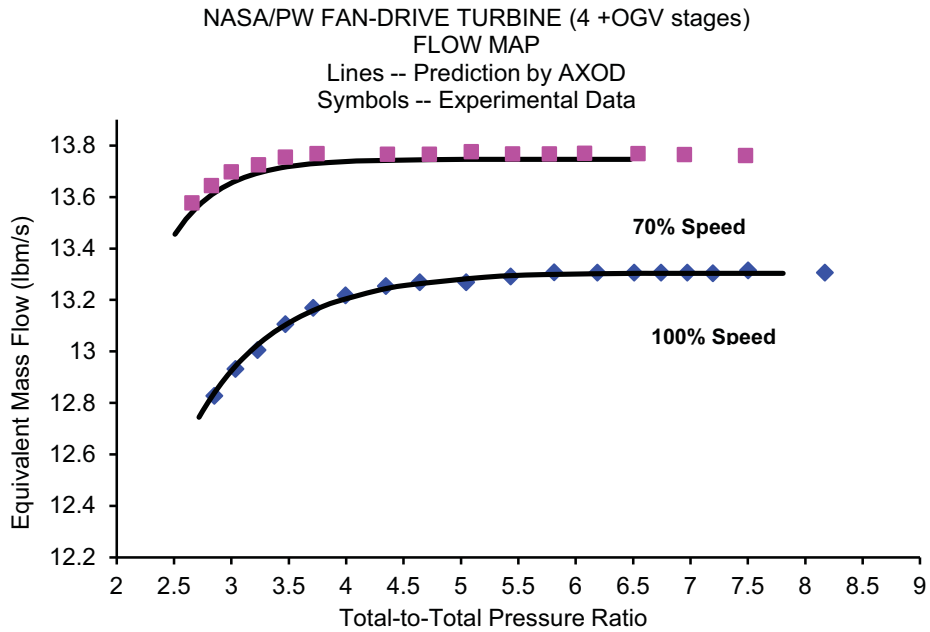


Figure 2.—Comparison of the equivalent mass flow rate (Ref. 8).

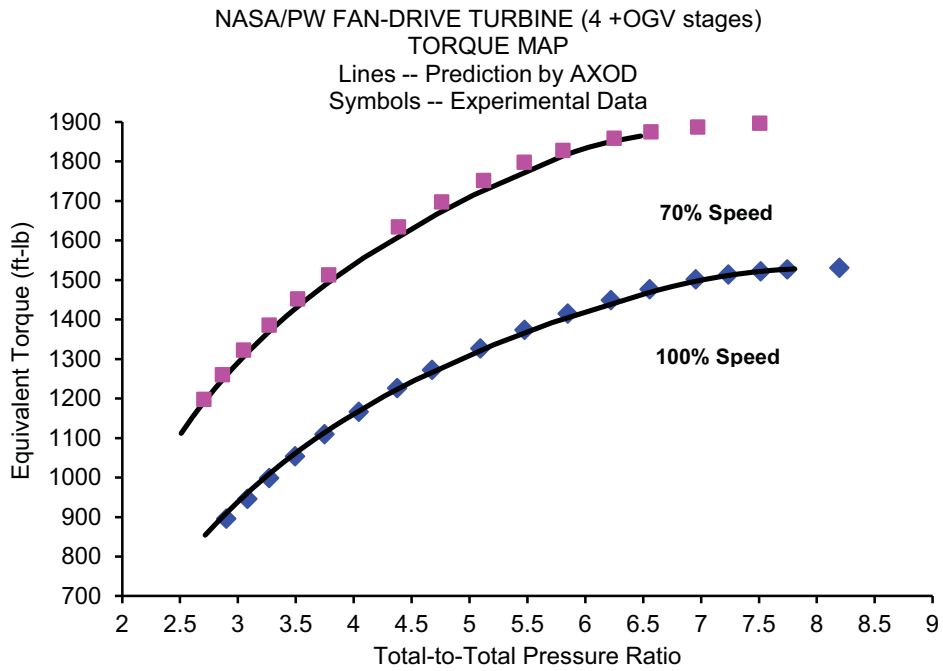


Figure 3.—Comparison of the equivalent torque (Ref. 8).

NASA/PW FAN-DRIVE TURBINE (4 +OGV stages)
EFFICIENCY MAP

Lines -- Prediction by AXOD
Symbols -- Experimental Data

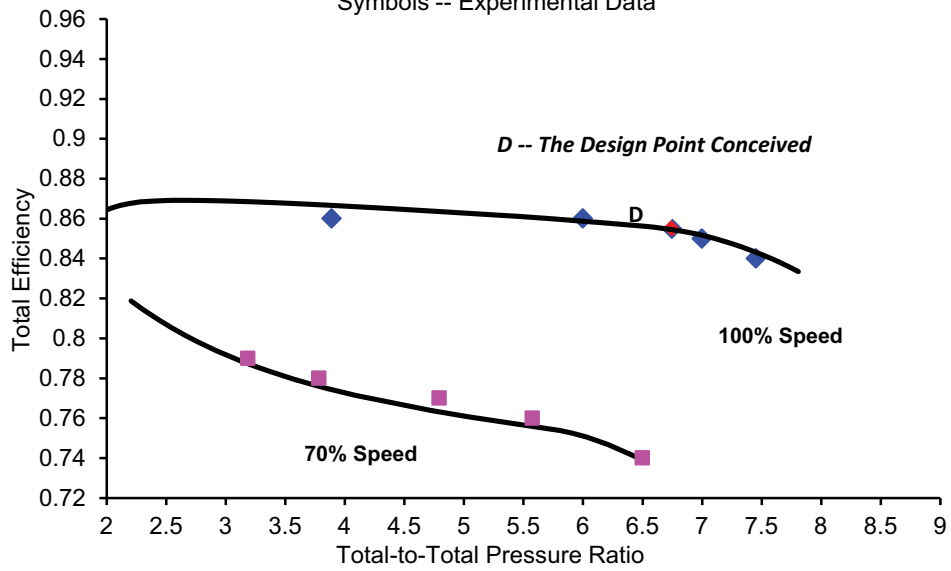


Figure 4.—Comparison of the total efficiency (Ref. 8).

References

1. Flagg, E. E., “Analytical Procedure and Computer Program for Determining the Off-design Performance of Axial Flow Turbines,” NASA CR-710, February 1967.
2. Glassman, A. J., “Modeling Improvements and User’s Manual for Axial-Flow Turbine Off-Design Computer Code AXOD,” NASA CR 195370, August 1994.
3. Chen, S. S., “Preliminary Axial Flow Turbine Design and Off-Design Performance Analysis Methods for Rotary Wing Aircraft Engines; I- Validation,” NASA/TM—2009-215651/PART1, May 2009.
4. Chen, S. S., “Capability Extension to the Turbine Off-Design Computer Program AXOD With Applications to the Highly Loaded Fan-Drive Turbines,” NASA/TM—2011-217129, July 2011.
5. Glassman, A. J., ed., Turbine Design and Application; Volume I, NASA SP-290, 1972.
6. Glassman, A. J., “Computer Code for Preliminary Sizing Analysis of Axial-Flow Turbines,” NASA CR 4430, February 1992.
7. Webster, P. F., “Design of a 4 ½-Stage Turbine with a Stage Loading Factor of 4.66 and High Specific Work Output,” NASA CR-2659, March 1976.
8. Whitney, W. J., Behning, F. P., Moffitt, T. P., and Hutz, G. M., “Cold-Air Investigation of 4 ½-Stage Turbine with Stage Loading Factor of 4.66 and High Specific Work Output; I- Overall Performance,” NASA TM X-3498, February 1977.

