Design of an Object-Oriented Turbomachinery Analysis Code: Initial Results

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Abstract

Performance prediction of turbomachines is a significant part of aircraft propulsion design. In the conceptual design stage, there is an important need to quantify compressor and turbine aerodynamic performance and develop initial geometry parameters at the 2-D level prior to more extensive Computational Fluid Dynamics (CFD) analyses. The Object-oriented Turbomachinery Analysis Code (OTAC) is being developed to perform 2-D meridional flowthrough analysis of turbomachines using an implicit formulation of the governing equations to solve for the conditions at the exit of each blade row. OTAC is designed to perform meanline or streamline calculations; for streamline analyses simple radial equilibrium is used as a governing equation to solve for spanwise property variations. While the goal for OTAC is to allow simulation of physical effects and architectural features unavailable in other existing codes, it must first prove capable of performing calculations for conventional turbomachines.

OTAC is being developed using the interpreted language features available in the Numerical Propulsion System Simulation (NPSS) code described by Claus et al (1991). Using the NPSS framework came with several distinct advantages, including access to the pre-existing NPSS thermodynamic property packages and the NPSS Newton-Raphson solver. The remaining objects necessary for OTAC were written in the NPSS framework interpreted language. These new objects form the core of OTAC and are the BladeRow, BladeSegment, TransitionSection, Expander, Reducer, and OTACstart Elements. The BladeRow and BladeSegment consumed the initial bulk of the development effort and required determining the equations applicable to flow through turbomachinery blade rows given specific assumptions about the nature of that flow. Once these objects were completed, OTAC was tested and found to agree with existing solutions from other codes; these tests included various meanline and streamline comparisons of axial compressors and turbines at design and off-design conditions.

Nomenclature

A	meridional area
h	fluid enthalpy
$\dot{m}$	mass flow rate
MN	fluid Mach number
P	fluid pressure
r	radius
V	velocity
α	absolute frame tangential angle
β	relative frame tangential angle
δ	deviation angle
ω	blade row angular speed
φ	slope or meridional angle
ρ	fluid density

Subscripts

a	blade row entrance calculation station
b	blade row exit calculation station
blade	blade airfoil value
design	machine design value
flow	fluid value
i	streamline or blade segment number
ideal	ideal (isentropic) condition
m	mean, meridional
rel	relative (rotor reference frame) condition
s	static condition
t	stagnation condition
total	spanwise aggregate value
θ	tangential component

Introduction

Performance prediction of turbomachines is a significant part of aircraft propulsion design. In the conceptual design stage, there is an important need to quantify compressor and turbine aerodynamic performance and develop initial geometry parameters at the 2-D level before Computational Fluid Dynamics analyses can be used to refine the component design. At NASA Glenn there are over a

dozen different computer programs used to analyze the aerodynamic performance of turbomachinery at the 2-D level; these codes are limited for several reasons. They are usually focused on either compressors or turbines, axial or centrifugal devices, design or analysis (off-design), and limited to either meanline or streamline solutions. In addition, these codes are almost exclusively written in older versions of FORTRAN, contain scant documentation, and may exist only as an executable with no source code. For this reason the Object-oriented Turbomachinery Analysis Code (OTAC) is being developed.

OTAC performs 2-D meridional flowthrough design and analysis of turbomachines using an implicit formulation of the governing equations to solve for the conditions at the exit of each blade row. OTAC works for both compressors and turbines of axial, centrifugal, and mixed design. This is possible because the governing equations with regard to fluid flow through turbomachine blade rows do not change depending on the type of device. OTAC can perform meanline or streamline calculations; for streamline analyses simple radial equilibrium is used as a governing equation to solve for spanwise property variations. OTAC is written as an object-oriented code; this type of code structure allows for more intuitive separation of code algorithms and can improve code maintainability. Another advantage of this type of code architecture is it easily allows later enhancements such as the addition of new loss correlations or secondary flow effects. OTAC is also capable of simulating unconventional systems or effects such as counter-rotating turbine blade rows.

Code development background

The choice of programming language in which to write a new code can be important; in the case of OTAC the decision was made to develop the code using the interpreted language features available in the Numerical Propulsion System Simulation (NPSS) code. NPSS is itself an object-oriented framework used primarily for thermodynamic cycle analysis of aircraft propulsion systems. The interpreted language of NPSS, syntactically similar to C++, and its object-oriented design allow for new computational objects to be added by developers and users. While not as robust as other object-oriented languages such as Python, coding within the NPSS framework came with several distinct advantages. The most significant advantage was the ability to use the pre-existing NPSS thermodynamic property packages and the NPSS Newton-Raphson solver. Other advantages allowed for the blade rows to be solved independently of each other and customizable output via the NPSS DataViewer object. With the decision to write OTAC within NPSS, the creation of objects specific to OTAC could proceed.

The initial set of objects necessary for the core functions of OTAC are the FlowStation, OTACstart, Expander, Reducer, BladeRow, BladeSegment, and TransitionSection. The NPSS thermodynamic packages are accessed through the NPSS FlowStation object, which assumes 1-D flow. This object was modified slightly to accommodate a 3-D flow state; this was the only modification requiring changes to the NPSS source code. The next three objects in OTAC perform simple but necessary functions. The OTACstart object allows declaration of flow properties at the entrance of the turbomachine. The Expander object divides a single fluid stream based on the desired number of streamlines. Conversely, the Reducer object aggregates a set of streams into an equivalent single flow stream. The two critical objects in OTAC are the BladeRow assembly and the BladeSegment elements contained within it. An
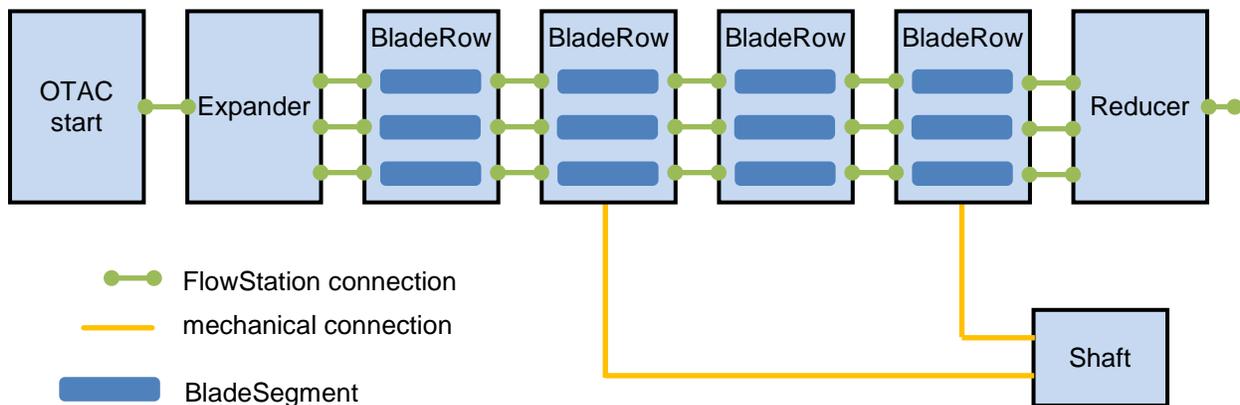

Figure 1 Object layout for a 2-stage, 3-stream OTAC example model

example of a three-stream, two-stage turbomachine model using these objects is shown in Figure 1. The Shaft object is the standard NPSS Shaft Element and provides rotational speed to any connected blade rows. Not shown in the figure is the TransitionSection object, which allows for area changes between blade rows. Finally, instances of the NPSS solver object are used to converge blade row exit properties to the appropriate solution.

The bulk of the code development effort centered around the BladeRow and BladeSegment objects. A schematic of how the BladeRow, BladeSegment, and NPSS solver interact is shown in Figure 2 for a five streamline example. Each streamline is contained within its own BladeSegment and has both an entrance and exit FlowStation, "a" and "b" respectively, containing the fluid properties. The entrance states are known and the exit states must be determined. The exit state of each BladeSegment is uniquely determined by seven independent variables (two thermodynamic state variables, three velocity state variables, a local mass flow rate or area, and a local radial location variable); for OTAC the independent variable set was chosen to be h_t, P_t, MN, α, ϕ, $\dot{m}$, and radius. By setting the meridional mass flow rate at the exit of each BladeSegment equal to its entrance value overall continuity is ensured; this also means each BladeSegment actually represents a small streamtube rather than a geometrically fixed section of the blade. Each streamtube has an outer and inner radius centered around its local streamline

radial location. For this reason the radial streamline locations for the BladeSegments must always lie between the hub and tip radii of the machine, while traditional codes permit calculations to be done at the hub and tip radii. Hub and tip calculation stations could be added, but this is unlikely to produce better results simply due to the fact that flows near the hub and casing are highly three-dimensional, the effects of which are neglected in 2-D codes.

The process occurring across the blade row is assumed to be steady, circumferentially uniform, and adiabatic. The applicable equations presented by Jones (2014) are summarized here with the effects of slope and streamline curvature neglected. The exit state of each BladeSegment must meet the following criteria:

$$\dot{m}_b = \dot{m}_a \tag{1}$$

$$h_{t_b} - h_{t_a} = \omega\left(r_b V_{\theta_b} - r_a V_{\theta_a}\right) \tag{2}$$

$$P_{t_b} = P_{t\ ideal_b} - \Delta P_{t\ loss} \tag{3}$$

$$\beta_{flow_b} = \beta_{blade_b} + \delta \tag{4}$$

Also, the outer radius of each streamtube must coincide with the inner radius of the streamtube directly above it while the aggregate mean radius of all the streamtubes must equal the machine design mean radius value:
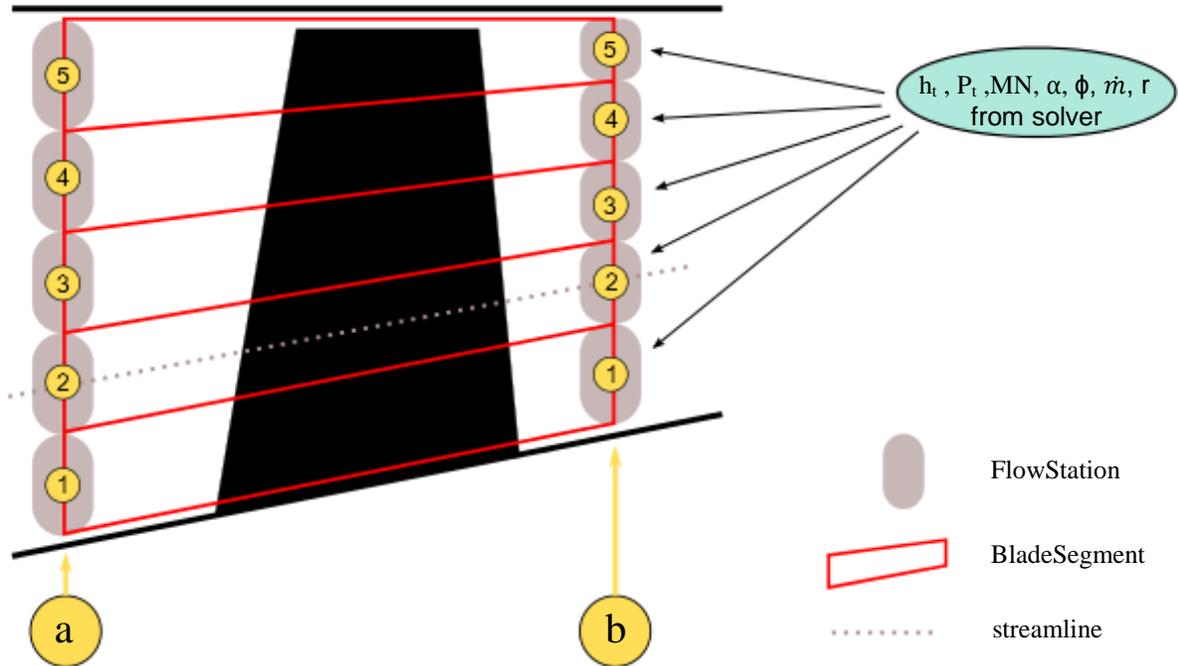
$$r_{inner_{i+1}} = r_{outer_i} \tag{5}$$

Figure 2 Objects used in the BladeRow assembly

$$r_{m\,total} = r_{m\,design} \qquad (6)$$

Lastly, the radial change in properties from streamline to streamline must satisfy radial equilibrium while the aggregate area of all the streamtubes must equal the machine design area value:

$$\frac{\Delta P_s}{\Delta r} = \rho_i \frac{V_{\theta_i}^2}{r_i} \qquad (7)$$

$$A_{total} = A_{design} \qquad (8)$$

Finite differences are used to estimate the derivative in the radial equilibrium equation. In the event of a meanline simulation, equations 5 and 7 do not apply. Also, in practice the form of equation 4 is altered at design to permit either a direct or indirect design approach (e.g., desired pressure ratio as an input rather than desired design exit blade angle). The BladeRow object is responsible for tracking radial property variations from BladeSegment to BladeSegment (ΔP and Δr in equation 7) as well as the BladeSegments' aggregate mean radius and area. The NPSS solver varies the exit state of each BladeSegment via the independent variables mentioned above to produce a solution for the entire BladeRow that satisfies the above equations.

Blade row losses

Losses in turbomachinery blade rows are estimated using empirical correlations of a non-dimensional pressure loss parameter, typically defined as

$$loss\ parameter \equiv \frac{P_{t,rel\ ideal_b} - P_{t,rel_b}}{P_{t,rel_a} - P_{s_a}}$$

for compressors and

$$loss\ parameter \equiv \frac{P_{t,rel_a} - P_{t,rel_b}}{P_{t,rel_b} - P_{s_b}}$$

for turbines. These loss parameters are used to predict the magnitude of various loss mechanisms that occur in compressor and turbine blade rows.

In OTAC, each BladeSegment has a loss parameter representing the loss across that BladeSegment; the value of the loss parameter is determined by a LossModel object. Any number of LossModel objects may be attached to the BladeSegment, as shown in Figure 3. The structure of the LossModel object is intentionally general; the only restriction is that it must return a value for the loss parameter. The loss across the BladeSegment is the sum of all its attached LossModel objects' loss parameters. The advantage of this approach is the simulation flexibility offered to the user. For example, one blade segment may have a single LossModel object representing the total loss; another blade segment may have a series of LossModel objects, each representing an individual loss mechanism such as profile loss, endwall loss, or shock loss. Similarly, one blade row may have a profile loss correlation applicable for a specific airfoil type, while another blade row may use a different specification for its profile loss. Finally, users may create their own custom LossModel objects incorporating their own knowledge and proprietary experience. It is expected that as OTAC is developed, a suite of loss correlations will be available that reflects those found in the open literature.

Validation tests

At this point a series of model simulations were created to compare results from OTAC against several other codes to serve as a validation. Specifically, the objective of these tests was to verify OTAC's capability to simulate both compressors and turbines, to run at design and off-design conditions, and to run both meanline and streamline options. In addition, these tests would confirm if the NPSS solver could consistently converge to correct solutions when presented with model simulations using roughly a dozen streamlines and loss correlations representative of modern practice.
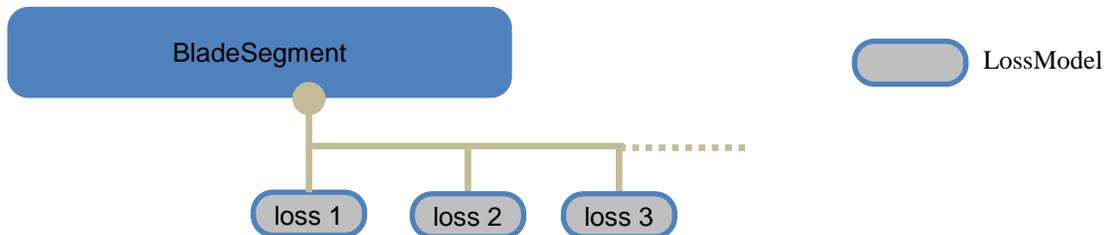
Figure 3 Schematic of a BladeSegment with attached losses; each LossModel object encapsulates a specific loss correlation and returns a value for loss parameter

The first validation was of a single rotating compressor blade row as a design condition. Results from OTAC were compared against output from a 13-stream analysis of the fan rotor of the Energy Efficient Engine (E[3]) presented by Halle and Michael (1981). For this test a radial distribution of non-dimensional loss parameter matching the values in the report was input since OTAC had no loss correlations at that time. The results from the 13-stream OTAC model deviated from the E[3] report, particularly for the meridional velocity component shown by the grey line in Figure 4. OTAC currently assumes simple radial equilibrium while the E[3] solution accounts for streamline curvature and other effects. The blue lines in Figure 4 show that the
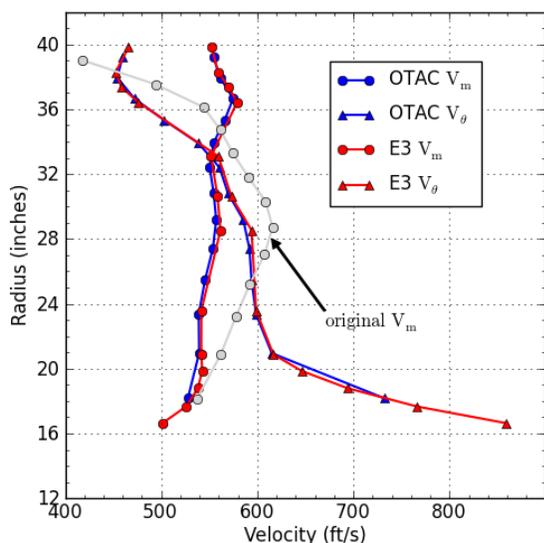
Figure 4 Comparison between OTAC and E[3] report values of velocity components for a single fan rotor

OTAC results could be made to closely match those from the E[3] report if a tuning factor was added to the OTAC radial equilibrium equation. Nevertheless, because of this discrepancy it was decided that future tests would compare OTAC against data which also assumed simple radial equilibrium.

For this next test an OTAC model was compared against output from Richard Hearsey's turbomachinery design and analysis code, HT0300. As an option, the solution from HT0300 can be required to neglect the effects of streamline curvature and slope (Hearsey, 2011) so this would be the closest possible comparison with the assumptions in OTAC. The test simulation consisted of an inlet guide vane (IGV) followed by a rotor. The results shown in Figure 5 show identical spanwise velocity
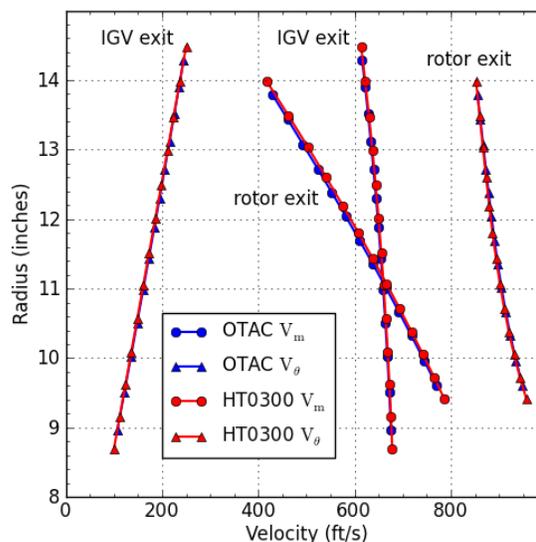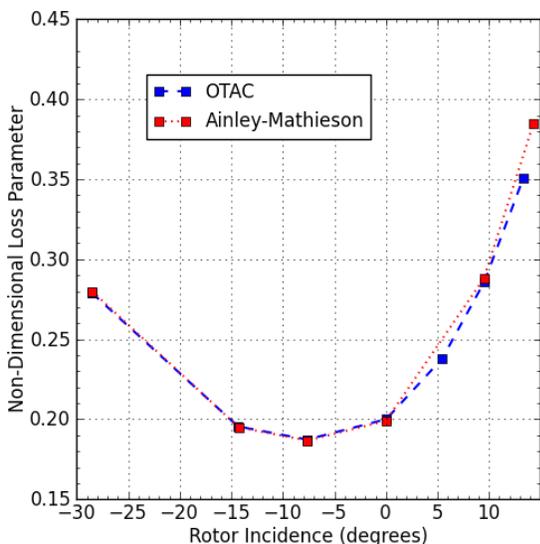

Figure 5 Comparison between OTAC and HT0300 calculated values of velocity components for an IGV followed by a rotor

distributions between OTAC and HT0300, validating the OTAC equation set for on-design calculations.

In the preceding tests the stagnation pressure losses were calculated using set values of the non-dimensional loss parameter. The next tests required altering the loss parameter from a prescribed input to one that is calculated using an established loss correlation. The difficulty of this task was considerably increased in the author's opinion due to the lack of adequate documentation in the public literature. As these correlations are of necessity empirical in nature, the need to explicitly declare the angular sign convention for both static and moving blade rows is essential. Likewise, since the loss correlations have historically come from static blade row testing, clear distinction between relative frame parameters and absolute frame parameters is critical. Finally, since errors in documentation do exist, a worked example solution is of extreme value. The axial turbine blade row loss model of Ainley and Mathieson (1957) met this criteria and was implemented as a loss correlation in OTAC.
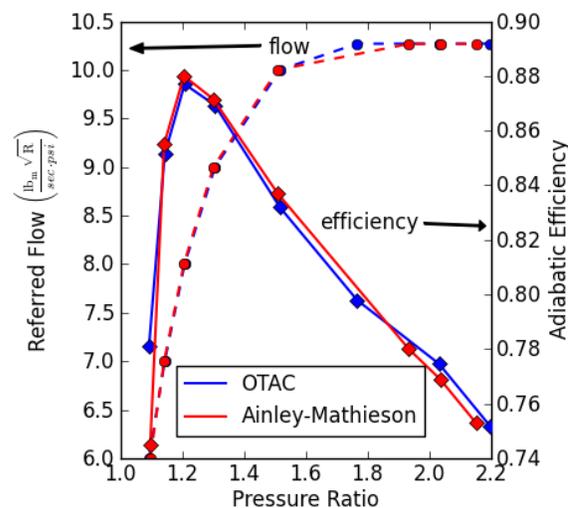
The single-stage meanline turbine example presented by Ainley and Mathieson was modeled in OTAC. Input variation of stage entrance mass flow affects rotor incidence angle, with the resulting rotor loss parameter shown in Figure 6. The loss parameter for the vane is effectively constant in this case, and the OTAC value matched that of the example. The OTAC simulation could only be run to a maximum rotor incidence of 13.5 degrees compared to Ainley

Figure 6 Comparison between OTAC and Ainley-Mathieson loss models as a function of rotor incidence

Figure 7 Comparison between OTAC and Ainley-Mathieson mass flow and efficiency characteristics for a single-stage turbine meanline calculation

and Mathieson's 14.3 due to the vane mass flow choking limit being reached. Figure 7 compares the flow and efficiency characteristics of the OTAC simulation against Ainley and Mathieson's example, verifying both OTAC's meanline off-design capability and its handling of losses.

With the Ainley-Mathieson loss model as a guide, another turbine loss model based on the work of Kacker and Okappu (1982) was written in OTAC; this loss model was implemented by Hendricks (2014) as part of work on the Variable Speed Power Turbine project. A 5-stage low pressure turbine (LPT) model was created with losses predicted using this loss correlation. The OTAC model contains nine streamlines and is compared against a similar HT0300 5-stage LPT analysis with eleven streamlines. Note that the turbine loss parameter was re-defined to account for potential changes in streamline radius across the blade row by using pressures based on rothalpy as explained by Cumpsty (1989) and Japikse and Baines (1994). The losses

calculated in the HT0300 analysis and the OTAC implementation of Kacker-Okapuu did not agree exactly, but were similar enough to allow for comparison. Figure 8 shows the spanwise meridional and tangential velocity distributions at the exit of the fourth stage vane and rotor, where differences between OTAC and HT0300 were greatest due to the propagated effects of the different loss values. Nevertheless, very good agreement is obtained. As a further validation, the fourth stage analysis was re-done in OTAC using the same stage entrance conditions and radial loss distribution as the HT0300 model. The OTAC results then precisely matched the HT0300 results within numerical tolerance. Finally, the OTAC model was run off-design over a range of speeds and flows to generate a performance map. While there is no corresponding comparison data, the OTAC results shown in Figures 9a and 9b display the expected trends and lend confidence to the OTAC validation of off-design capability for streamline analyses.
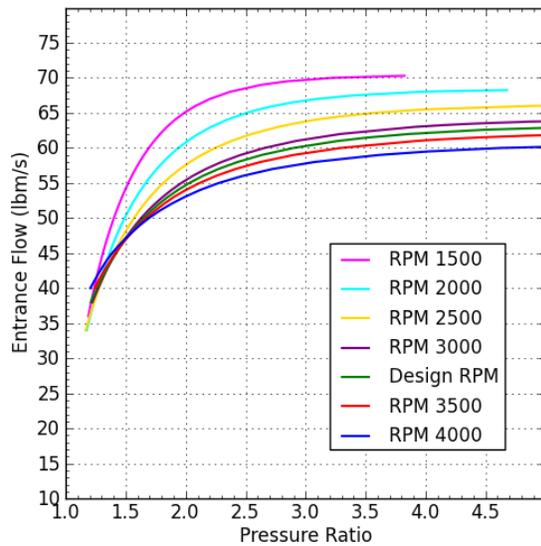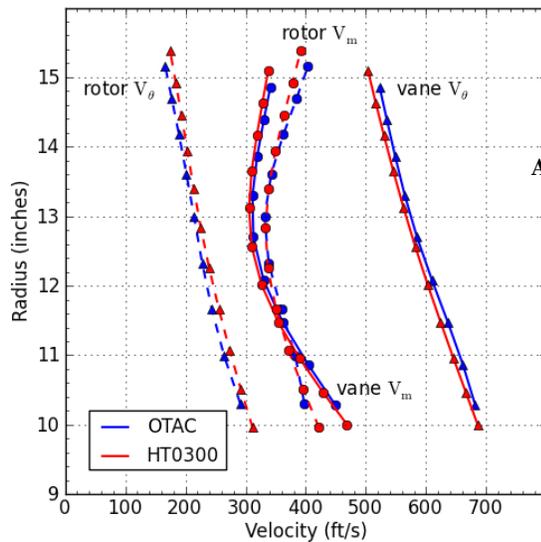
a) mass flow characteristics
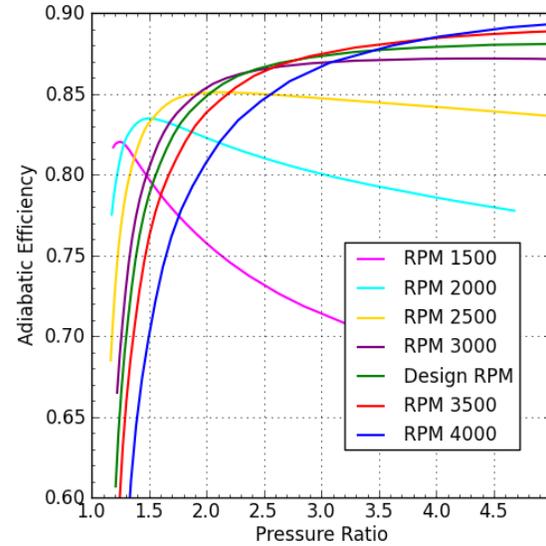
b) efficiency characteristics

Figure 9 Performance of a 5-stage low pressure turbine calculated by OTAC using 9 streamlines

During OTAC's development several attempts were made to implement a loss model representative of compressor blade rows. Loss correlations and minimum loss incidence calculations based on methods presented by Aungier (2003) were implemented in OTAC. Unfortunately the reference does not contain any applicable example calculations so there is no explicit basis for comparison with any OTAC results. Nevertheless, a two-stage fan model was created and run over a range of speeds and flows to generate a performance map, shown in Figure 10.

The maximum flow for any speed was determined by the point at which OTAC failed to converge; this occurred as one or more blade rows approached choke. As the blade rows approached the minimum flow the loss correlations become suspect as the blade row enters stall. An upper limit on stall-side profile loss was enforced to facilitate converged solutions, and the stall point was chosen as the point at which this loss limit was reached. The map characteristics closely resemble those of actual fan designs. In a separate effort, Denney (2014) used OTAC to model the NACA 5-stage compressor using the same Aungier loss correlations; the results compared favorably to the actual test data.

Figure 8 Comparison between OTAC and HT0300 calculated velocity components for the fourth stage of a five-stage LPT

Some additional verification tests have also been made using OTAC to simulate non-axial devices. A test model successfully replicated a meanline, design point centrifugal impeller calculation by Saravanamuttoo et al (2009). Another model of an impeller with a diffuser has been made and compared to an example calculation by Japikse & Baines (1994); results are given in Table 1. The difference in impeller exit flow angle is due to the assumed sign convention. More information than was provided in the example is necessary to determine the reason why the diffuser exit flow angle is different, but the author believes it could be a calculation error in the text caused by inadvertently ignoring the given diffuser exit area and assuming the meridional velocity at the diffuser exit is equal to that at the impeller exit. This is a common assumption in blade row calculations where exit area is not explicitly given. In this case when the calculation is re-done in OTAC assuming a constant meridional velocity, a diffuser exit flow angle of 50.94 degrees is obtained which exactly matches that of the example. However, this exit state does not then satisfy the given diffuser exit area.

Lastly, a radial inflow turbine model with argon as a working fluid has been compared against output from the RTD code by Glassman (1976). The results show overall agreement, but direct comparison is difficult because RTD differentiates between conditions at the inside and outside of the rotor exit trailing edge, while OTAC assumes circumferential uniformity. All of these design comparisons are encouraging but streamline and off-design capability of OTAC for non-axial devices has yet to be fully tested.

Conclusions and future work

The results of the above tests verify OTAC's core feature set. Simulations using OTAC included compressor and turbine blade rows and stages at design and off-design conditions. Both meanline and streamline capability was verified and several loss correlations have been implemented. OTAC allows users to develop their own loss correlations if desired. Considerable work remains to realize the code's full potential. The BladeRow and BladeSegment objects have been written to take into account the effects of blockage, but no blockage model has yet been implemented. Another desired requirement is the ability to account for the effects of cooling flow extraction or addition. Currently OTAC will fail to converge with input mass flows close to or beyond choking conditions; a method must be found to enable converged solutions near choke and choked solutions up to turbine limit load. Finally, while OTAC currently neglects streamline curvature effects

it may be possible to add this capability; in this case the E^3 comparison of Figure 4 will be revisited.

impeller exit	OTAC	Japikse
Pt, psi	31.17	31.17
Tt, R	653.5	653.7
Vm, ft/s	342.4	342.4
Vθ, ft/s	843.8	843.8
β flow, degrees	19.04	-19.04
α flow, degrees	67.91	67.91
slip factor	0.8772	0.8772
diffuser exit		
Pt, psi	30.04	30.04
Ps, psi	26.71	26.64
α flow, deg	55.99	50.94

Table 1 Comparison between OTAC and Japikse & Baines centrifugal compressor calculation

References

Ainley, D.G. & Mathieson, G.C.R., 1957, "A Method of Performance Estimation for Axial-Flow Turbines", R. & M. No. 2974.

Aungier, R.H., 2003, "Axial-Flow Compressors: a Strategy for Aerodynamic Design and Analysis", The American Society of Mechanical Engineers, ASME Press, New York.

Claus, R.W., Evans, A.L., Lytle, J.K. & Nichols, L.D., 1991, "Numerical Propulsion System Simulation", Computing Systems in Engineering, Vol. 2, No. 4, pp 357-364.

Cumpsty, N.A., 1989, "Compressor Aerodynamics", Krieger Publishing Company, Florida.

Denney, R., Kestner, B. & Mavris, D.N., 2014, "Compressor Modeling and Simulation Using Object-Oriented Turbomachinery Analysis Code (OTAC)", AIAA 2014-3927.

Glassman, A.J., 1976, "Computer Program for Design Analysis of Radial-Inflow Turbines", NASA TN D-8164.

Halle, J.E. & Michael, C.J., 1981, "Energy Efficient Engine Fan Component Detailed Design Report", NASA-CR-165466.

Hearsey, R.M., 2011, "Program HT0300 Versions 2.356 & 2.357 User's Manual", June 2011.

Hendricks, E.S., Jones, S.M. & Gray, J.S., 2014, "Design Optimization of a Variable-Speed Power Turbine", AIAA-2014-3445.

Japikse, D. & Baines, N.C., 1994, "Introduction to Turbomachinery", Concepts ETI, Inc. and Oxford University Press, Vermont.

Jones, S.M., 2014, "Development of an Object-Oriented Turbomachinery Analysis Code Within the NPSS Framework, NASA TM-2014-216621.

Kacker, S.C. & Okapuu, U., 1982, "A Mean Line Prediction Method for Axial Flow Turbine Efficiency", Journal of Engineering for Power, January 1982, Vol. 104, pp 111-119.

Saravanamuttoo, H.I.H., Rogers, G.F.C., Cohen, H. & Straznicky, P.V., 2009, "Gas Turbine Theory", Pearson Education Limited, England.