APPLICATION OF THE CONCEPTS NREC AGILE ENGINEERING DESIGN SYSTEM TO STEAM TURBINES

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ABSTRACT

This paper describes the application of the Agile Engineering Design System®[1] to steam turbines. The step-by-step evolution of steam path design is discussed, from initial conceptual studies to final detailed blade designs. An advanced meanline analysis serves as the foundation for flow path sizing, performance estimation, and optimization. Several validation cases are presented to illustrate the prediction capabilities for a variety of steam turbine configurations. Other components of the design system provide blade shaping and stacking functions and interactive flow analysis for optimizing the blade profiles and steam path layout.

1. AGILE ENGINEERING DESIGN SYSTEM

The Agile Engineering Design System is a complementary suite of turbomachinery design tools developed by Concepts NREC (see Japikse [1]). Experience, test data, and theoretical concepts are combined to aid in the complete design, analysis, and manufacture of various types of turbomachinery, such as pumps, compressors, and turbines.

The following description illustrates how the Agile Engineering Design System is used to process the step-by-step evolution of steam turbine design, from preliminary evaluations to final blade designs. Before beginning the actual design process, it is first necessary to establish turbine operating conditions, physical size limitations, and structural requirements.

2. MEANLINE DESIGN (AXIAL™[2])

The meanline flow analysis serves as the foundation for steam path preliminary design and performance estimation. Concepts NREC has developed AXIAL, an improved meanline approach for axial turbomachinery using a reduced-order through-flow approach that balances all conservation properties from hub-to-tip and inlet-to-exit of each blade row. Dubitsky [2] describes the essential features of this program, including a comparison of predictions with test data. AXIAL has demonstrated a high level of prediction accuracy for steam turbine stages at both design point and far off design operation. Steam property calculations are possible for a wide range of conditions, from superheat to saturation conditions using the ASME library. AXIAL considers two major types of loss occurrence:

a. kinetic energy losses (or total pressure losses) generated by the blading, and
b. specific power losses that reduce shaft output power but do not generate an increase in entropy, such as some components of partial admission loss, disk friction, and wetness losses.

The following considerations have been added specifically for steam turbines: moisture losses, moisture removal, partial admission losses, flow inductions or extractions, and lashing wire losses. These capabilities enable one to model virtually any type of steam turbine

[1] Agile Engineering Design System is a Registered Trademark of Concepts ETI, Inc.
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construction, including velocity-compound (Curtis) stages, both impulse and reaction blading, convergent-divergent supersonic nozzles, and low-pressure condensing stages.

2-1. Blade Loss System

The blade loss system is based upon the combined correlations of several highly respected investigators: Ainley and Mathieson [3], Dunham and Came [4], Kacker and Okapuu [5], and Moustapha, Kacker, and Tremblay [6]. In traditional fashion, individual blade loss components are assessed for profile, secondary leakage, trailing edge, and shock losses. This loss system may be user-customized by: scaling individual loss components or overwriting specific loss model coefficients, prescribing span-wise loss and deviation profiles (hub/mean/tip), or introducing new loss models with user-defined scripts (requires Concepts NREC support). The loss system also includes special treatment of loss and deviation for choking flow in transonic domain to predict convergent and convergent-divergent passages.

The exit flow angle calculation is based on the Ainley and Mathieson correlation. It also includes the adjustments for supersonic flow and over- and under-turning due to secondary flows. An alternative model is available, which is based on correlations for discharge flow coefficient and computes deviation from continuity equation downstream throat location.

2-2. Moisture Losses and Moisture Removal

All multiphase computations are done assuming thermodynamic equilibrium flow conditions, (i.e., fully homogenous flow). Moisture losses are calculated as a simple stage power loss that is directly proportional to the average steam wetness in the component. The correction factor in this proportionality is typically between 0.6 and 1.0. Validation testing of AXIAL (to date) indicates that this simple correlation provides a good match to overall turbine performance data. More complex relationships can be added in a user-customized system.

Condensing steam turbines that operate far below the saturation line are usually constructed with some type of moisture removal devices in the low-pressure stages. Moisture removal (i.e., water separation) is beneficial from both a performance and mechanical (i.e., erosion) standpoint. AXIAL can estimate the performance benefits of three types of moisture removal devices: (1) leading edge grooves, (2) trailing edge suction slots (stationary blades), or (3) casing outer wall cavities that act as water catchers. In addition to specifying the location of the moisture removal device, the AXIAL models consider the amount of dry steam extracted, as well as the effects of large droplet fraction.

2-3. Partial Admission Losses

Another type of power loss (or "parasitic" loss) that is common in steam turbines is that of partial admission. This loss occurs when nozzles are only provided to cover a portion of the circumference. This practice allows for an increased nozzle and bucket height that improves both performance and manufacturability. For an inlet stage, each partial admission segment is typically connected to a control valve to enable start-up and part load operation. Partial admission losses result from two different sources: (1) rotor blade pumping loss (or windage loss) in the inactive passages, and (2) scavenging or end-of-sector loss as the blades fill and empty when passing into and out of the active sector.

AXIAL provides several different modeling options for calculating these partial admission losses. The Frolov [7] correlation was found to provide particularly good results during validation studies. In addition to these two loss sources, AXIAL also estimates the end-of-sector leakage flow, which is the circumferential leakage flow that bypasses the active flow segment by leaking out of the axial gap between blade rows. This leakage can be significant for partial admission stages that have some pressure drop (reaction) across the rotor.

2-4. Lashing Wire Loss

Lashing wires (or "lacing" wires) are typically required in tall, unshrouded blade rows to provide additional damping for blade vibration. AXIAL uses a momentum-based method to convert a lashing wire drag calculation into a corresponding velocity decrement. The reduced velocity is then converted into total pressure and entropy losses.

2-5. Steam Turbine Validation Cases

AXIAL has been validated against a wide variety of turbine applications and operating conditions, including partial admission, wet steam, and multiple-choked blade rows. In all cases, default loss models are used without any special corrections or assumptions. Table 1 provides a summary of validation results for the four steam turbine cases described below. These cases cover a large portion of typical steam turbine operation in terms of blade height, velocity ratio, pressure ratio, and steam quality. Dubitsky [2] provides additional test comparisons for partial admission, supersonic conditions, and drilled and reamed nozzles.

- Case 1: 44% partial-admission Curtis stage designed and laboratory tested by Elliott Company; choked inlet nozzle and transonic first rotating row.
- Case 2: 17-stage turbine-generator unit designed and field-tested by Elliott Company; extraction flows, lashing wire, and wet steam operation.
- Case 3: 4-stage geothermal steam turbine; all stages operating below the saturation line with choked flow and high moisture losses.
- Case 4: 780 mm last stage of condensing steam turbine for power generation; transonic/supersonic operation with high moisture losses. Data from Simou [8].

TABLE 1. SUMMARY OF STEAM TURBINE VALIDATIONS

Case 1	Velocity Ratio	Efficiency Difference*		
		With Seals	Without Seals	
	0.125	-1.0%	-2.2%	
	0.151	-0.1%	-1.4%	
	0.175	-0.5%	-0.7%	
	0.201	-0.9%	+0.0%	
	0.225	-0.3%	+1.4%	
	0.250	+1.2%	+3.7%	
Case 2	Units	Test	Axial	Difference
Inlet Flow	Kg/sec	25.2	24.51	-2.7%
Shaft Power	kW	23,449	23,054	-1.7%
Steam Rate	Kg/kW-hr	3.87	3.83	-1.1%
Case 3	Units	Test	Axial	Difference
Inlet Flow	Kg/sec	26.71	26.67	-0.2%
Shaft Power	kW	10,364	10,372	+0.1%
Efficiency		Proprietary	Proprietary	-0.4%
Case 4	Units	Test	Axial	Difference
Leaving Loss, $\frac{1}{2} C_2^2$	kJ/kg	55	56	+1.9%
Efficiency	(t-t / t-s)	78% / 55%	76% / 57%	-2.6%
* AXIAL efficiency (t-s) / test efficiency (t-s)				

3. BLADE DESIGN & ANALYSIS (AXCENT™[3])

After completing the steam path preliminary design with AXIAL, the design details are then passed to the AxCent design system to begin 3D geometry construction and higher order analysis. This system integrates various blade shaping and stacking tools with interactive flow analyses that allow one to optimize the blade profiles in an iterative process.

Three different types of flow analysis are integrated within the AxCent system: through-flow, blade-to-blade, and CFD. The through-flow analysis serves as the second major step of the design cycle. It is a configuration of the same 3D CFD solver in Pushbutton CFD®[4] (described below) reduced to single cell modeling in tangential direction and complemented by body force terms. This type of analysis plays a key role in distributing the radial variation of flow parameters (such as static pressure, flow turning, and work), thereby maximizing the efficiency potential. Industry standard loss and deviation models can be selected to match those used in the AXIAL analysis. Alternatively, user-defined loss and deviation models can be specified for either the meanline or through-flow solver (requires Concepts NREC support).

The third step of the design process involves the generation of 2D blade profiles (airfoils). AxCent offers a variety of parameterized approaches for constructing these 2D blade cross-sections. An improved Pritchard method, based on Japikse [1], is provided as one standardized approach. However, more arbitrary blade profiles can be developed by graphical control of Bezier curves for both the suction and pressure contours and the camber line thickness distributions. During this construction process, a table of blade section parameters can be displayed to provide immediate feedback during the contour adjustment.

The construction of 2D blade profiles is closely coupled to the blade-to-blade analysis, which is the fourth step in the design cycle. This close coupling allows one to rapidly evaluate the blade loadings (i.e., pressure distributions) and to adjust the surface curvatures for each designed blade section. The blade-to-blade solver is a 2D configuration of the same 3D CFD solver in Pushbutton CFD that is described below.

After designing all 2D cross-sections and confirming their loadings, the complete 3D blade shape can then be constructed by radially stacking the individual sections (step five of the design process). A variety of stacking options are available, including curved stacking in the tangential direction (lean or bow) or meridional direction (tilt). AxCent also has span-wise editing capability that enables one to evaluate and smooth the hub-to-tip geometry parameter distributions. The hub and tip wall contours can also be shaped by a simple manipulation of the Bezier curve control points.

A full 3D Navier-Stokes solution, called Pushbutton CFD, is an integral part of the Agile Engineering Design System and completes step six of the design cycle. Pushbutton CFD is based on an enhanced Dawes BTOB3D flow solver that has gained widespread acceptance by various organizations. Traditional CFD programs typically require large setup and processing times. However, Pushbutton CFD has been highly automated and streamlined to provide immediate feedback during blade section design iterations. Wall contouring, 3D stacking effects (i.e., lean, tilt, or bow), and injection/extraction interfaces can all be readily investigated. Integral post-processing tools enable full 3D results to be displayed on AxCent geometry, as well as 2D projections and slices through the blade passage. Anderson [9] provides more details about Pushbutton CFD and discusses its extensive validation effort.

AxCent is also capable of conducting optimization studies through a built-in interface with the iSIGHT™[5] program from Engineous Software, Inc. A generic iSIGHT simulation case can be automatically created for single blade row optimization. This case file is then modified to fit a particular task by defining iSIGHT variables, targets, constraints, scale factors, and weighting factors. Typical simulations may involve setting an optimization plan for flow path

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wall contours, 3D blade stacking (i.e., bow, lean, and tilt), or blade geometry parameters. AXIAL can also interface with iSIGHT through a generic description file. However, additional user intervention is required. In general, AXIAL can also interface with any other third-party solvers or executable files, provided that proper input/output formats are maintained.

AXISTRESS™[6] is an additional interface within AxCent that generates 3D finite element models for other commercially available stress analysis programs (such as ANSYS®[7]). Other interfaces are also available for FLUENT®[8] CFD (modeling of complex 3D flows) and CADTranslator™[9], a multi-function blade geometry translator for CAD/CAD/CAM operations.

4. SUMMARY

A successful design approach has been described for steam turbines using the Agile Engineering Design System. A reduced-order, through-flow analysis serves as the foundation for flow path sizing and performance studies. Validation cases have demonstrated this solver's ability to accurately predict steam turbine performance without any modifications to the standard loss models. Other components of the design system support blade shaping and stacking functions and interactive flow analysis for optimizing the blade profiles. A more comprehensive version of this document, including a sample design case, will be available on the Concepts NREC web site (www.conceptsnrec.com) at a future time.

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