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AXIAL TURBINE STAGES DESIGN: 1D/2D/3D SIMULATION, EXPERIMENT, OPTIMIZATION

DESIGN OF SINGLE STAGE TEST AIR TURBINE MODELS AND VALIDATION OF 1D/2D/3D AERODYNAMIC COMPUTATION RESULTS AGAINST TEST DATA

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ABSTRACT

In recent decade, industry had started to use intensively 3D simulation in turbine flow path and its components design. At the same time, this remains a very labor- and time-consumable process that sufficiently hampers its usage, whereas unidimensional and axisymmetric analyses are still widely used in the industry practice. A comparison of the data obtained from experiments conducted on a single stage air turbine test model with the results of 1D and 2D modeling and 3D simulation using a CFD solver was performed. The results were analyzed to validate a judgement of the authors that along with 3D CFD methods the low-fidelity models can be successfully used for turbine flow path optimization with the help of DoE methods. The forthcomings and advantages of different models are also discussed.

Key words: Modeling/Experiment Data Comparison, 1D/2D/3D Analysis, Optimization.

INTRODUCTION

The validation of the computations remains a subject of meticulous attention in the industry. Some authors introduce the results of comparison of the turbine rig test data with 2D computations [1, 2]. An objective of this study was to correlate the results of 1D, 2D and 3D aerodynamic computations with the proven test data extracted from experiments on several designs of a single stage test air turbine.

It was shown that proper unidimensional and axisymmetric models based on validated empiric methods of loss computation provide an accuracy of the flow path parameters estimation sufficient for solving a bulk of practice valuable optimization problems.

The turbine multidisciplinary optimization problems are the topic of different authors' research (see, for example, the list of references presented in [3]).

It was proposed to perform optimization on parameterized geometrical 3D models of blade rows or stages utilizing the design of numerical experiment (DoE) technique [4, 6], earlier applied to optimization on 1D and 2D models. Aside from the problems of aerodynamic optimization, this permits to solve the problems of multidisciplinary optimization with regard to, for instance, strength, vibration and other limitations.

NOMENCLATURE AND GLOSSARY

$(u/C_0)_{opt}$	Optimal isentropic velocity ratio;
ξ_n%	relative loss in nozzle vane;
ξ_b %	relative loss in blade;
ξ_{ex} %	relative loss with exit velocity;
η_i%	intrinsic efficiency;
G	fluid flow rate;
ω	rotation frequency;
δ_r	tip clearance;
α_1	nozzle outlet angle;
β_2	blade outlet angle;
Co	isentropic velocity;
l	blade height;
D	diameter;
u	circumferential velocity;
NURBS	non-uniform rational B-spline;
Effective (gauging) vane/blade exit angle	$\alpha\ (\beta)_{eff}$=arcsin a/t, where a - throat; t – pitch.
Tip clearance	a clearance between blading shroud and peripheral seal fins

DESIGN, PARAMETERS OF TEST STAGES, AND PROBLEM FORMULATION

Experimental studies of the stages under consideration have been performed in 1982 and presented in [6] to validate the principles of turbine stages and cascades design and optimization described in [4] and to estimate an effect of such factors as fluid leakage in the tip clearance, the pump-up effect in near-hub zone, the negative reaction degree, etc.

First design of the stage (MI), Figure 1/left, was a prototype of IP turbine last stage of the large steam turbine with reaction at mean radius such that provided axial flow exit from the stage and had a twist by the law of free-vortex design. The second design of the stage (MII) was purposed for testing the possibility to increase a load on the stage preserving axial flow exit. At that, significant negative reaction was expected in near hub zone, which detrimental effect could be reduced to minimum by usage of specially profiled cascades with divergent passages. The twist applied in MII stage was computed by the method of optimization described in [4].
Recent papers by Moroz at al. [7, 8] provide details of the current state of that approach.

Main parameters of the stages put on trial are presented in Table 1.

Table 1. Main parameters of the test stages

Parameter	Value	
Stage design	MI	MII
Inlet pressure, Pa	117000	130000
Inlet temperature, K	373	373
Outlet pressure, Pa	100000	100000
Rotation frequency, 1/s	7311	8212
Nozzle vane mean diameter, m	0.2978	0.2978
Nozzle vane length, m	0.0822	0.0822
Blade mean diameter, m	0.2986	0.2986
Blade length, m	0.0854	0.0854
Nozzle vane outlet gauging angle near hub, deg	20	17.2
at mean radius, deg	24	17.5
at peripheral radius, deg	28	17.8
Blade outlet gauging angle near hub, deg	32	41
at mean radius, deg	29.7	26
at peripheral radius, deg	26	19

Figure 1 illustrates the sketches of the stages under study.

The test study included measurement of integral characteristics of the stage with the help of nozzle flowmeters, fluid brake, pneumatic measuring probes of full and static pressure connected to mercury and water U-tube pressure gauges. In the course of experiment, an optimal isentropic velocity ratio was determined by changing the rotor rotation frequency and subsequent traverse measurements. Flow parameters were measured in axial gaps downstream vanes and blades by means of fixed three-hole pressure probes. Instrumentation, experimental technique, and methods of test data processing used in the course of rig testing were driven by Kharkov NTU "KhPI" in-house standards [6]. Statistical estimation showed that the root-mean-square error for the curves depicted on Figure 3 formed max 0.3% from the absolute error.

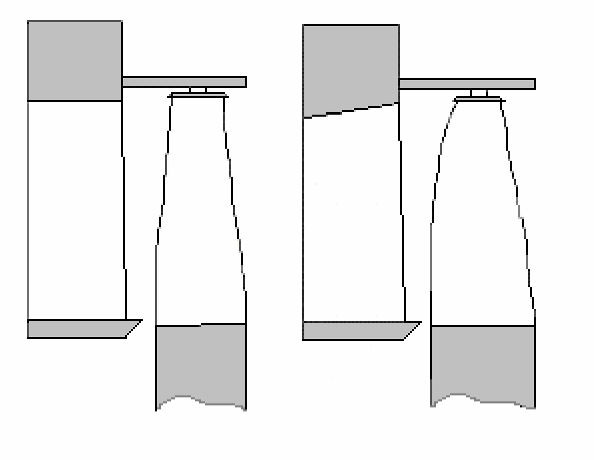


Figure 1. Sketches of MI (left) and MII (right) stage design

Numerical studies included the following analyses:

- unidimensional (1D) and axisymmetric (2D) stage computations with *AxSTREAM*^{TM} software;
- nozzle vane/blade re-engineering with *AxSTREAM* and subsequent blade export to external mesher for preparation for further 3D aerodynamic analysis;
- 3D CFD analyses with CFX-5.7;
- computed and test data comparison;
- analysis of validity of different complexity computations for stage characteristics prediction and for practical application in stage performance optimization.

UNIDIMENSIONAL AND AXISYMMETRIC COMPUTATIONS

In addition to the stage integral characteristics, axisymmetric computations provide the flow parameters distribution in axial gaps along radius. At this, a method of loss components estimation along radius is a subject of importance. In this study we used Craig and Cox method for profile and secondary losses analysis. The secondary losses were concentrated at the blade tip by a special algorithm. The secondary loss was calculated for each station along the blade height fitting a local profile loss magnitude. Then, the secondary losses were concentrated at the tip and the hub under the parabolic law following the sum of secondary losses and the sum of local profile losses parity.

Additionally, a loss from leakage in the tip clearance was also accounted for.

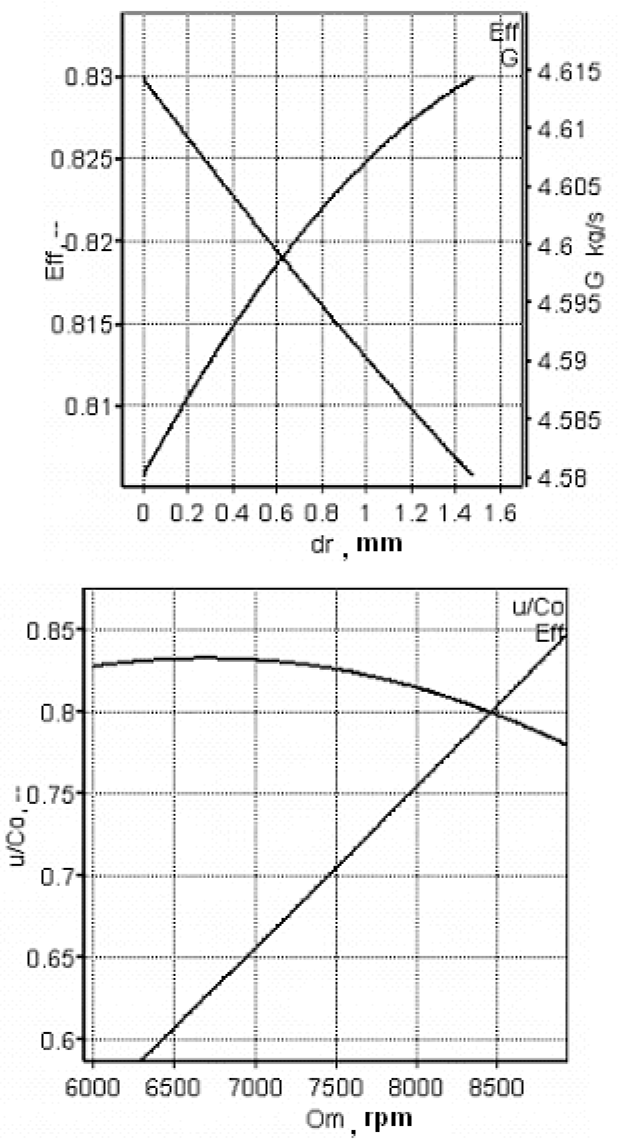


Figure 2. Stage MI efficiency and flow rate computed with regard to the value of tip clearance (top); stage MI efficiency and isentropic velocity ratio computed dependently on rotation frequency (bottom)

The stages were designed for optimal 0.63 and 0.55 u/Co ratios at minimal radial clearances. The radial clearance increase entails certain variation of the optimum u/Co ratio.

The efficiency and the flow rate diagrams built from the *AxSTREAM*'s axisymmetric solver with respect to the value of the tip clearance applying a Box-Behnken four-dimension design of experiment can serve as the illustration, Figure 2. In spite of the fact that 1D analysis provides the similar dependencies, an accuracy of those dependencies at small stage aspect ratio D/l is significantly lower than one provided by 2D computations due to very approximate estimation of the pressure at the peripheral diameter.

It is worth to note that it is far more difficult to perform similar computations on 3D models since such operations require non-trivial modification of the mesh on any change of the clearance dimension.

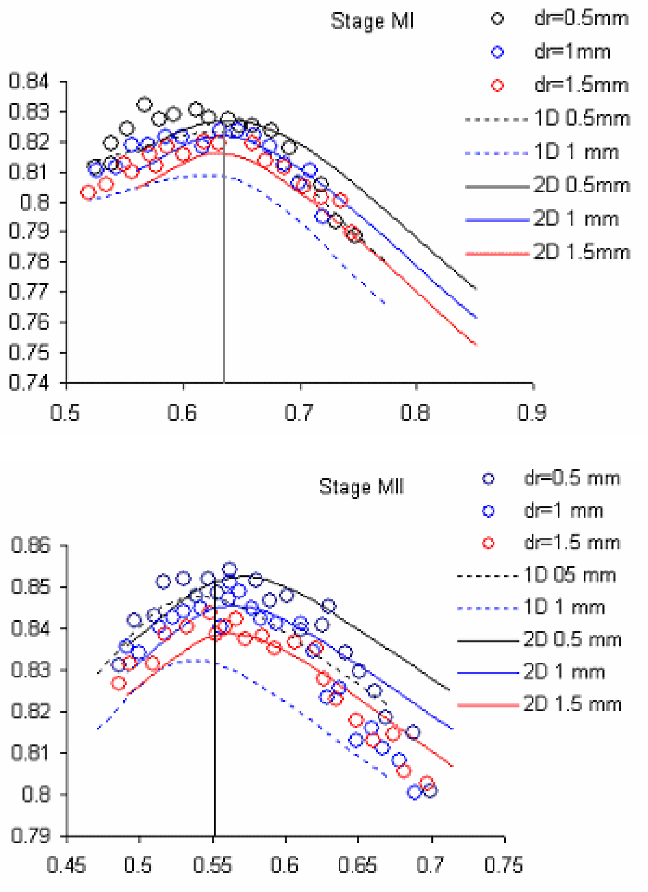


Figure 3. Stage MI (top) and stage MII (bottom) efficiency vs u/Co ratio at various dimensions of tip clearance.

Circles – test data; curves – results of 1D and 2D computations with *AxSTREAM*; vertical lines – design points.

Figure 3 demonstrates comparative diagrams of extracted from tests and computed efficiency vs rotation frequency for MI and MII stages at various dimensions of the tip clearance.

This comparison confirms the fact that computations performed with 2D model provide the reliable results over a wide interval of operational conditions and geometrical parameters variation. The results of 1D computation are in certain disagreement with the rig test data. This disagreement can be explained by applying the twist law different from the free-vortex design that causes heightened static pressure at the intercascade gap periphery.

BLADES REVERSE ENGINEERING

Since the experiment had been carried 23 year ago, it is natural that 3D models of the test stage blades had not existed. To facilitate airfoil 3D geometry for CFD modeling, the airfoils were reverse-engineered. The airfoil shapes used in the CFD model did not precisely correspond with the original used for the rig testing. At the same time, in the course of the blades re-engineering, a set of control variables was observed including relative pitch, inlet metal angle, outlet gauging angle, radii of leading and trailing edges. Smoothness of the profile configuration and favorable shape of the interblade passages were attained with the help of streamline and profile boundary layer calculations combined with profile loss estimation. Therefore, it may be argued that the re-engineered cascades are on a par with the original ones in efficiency and shouldn't bring on a noticeable increase of the losses against the test data in the calculations, which take into account the profile configuration.

The blades that were used in the test turbine stage are the subjects of particular interest from several points of view. First of all, the nozzle vane cascades are assembled from the profiles supplied with the trailing edge extension. This is characterized by heightened strength properties at reasonably high efficiency and low sensitivity to inlet flow angle variation. Then, the specially profiled cascades with divergent channels in a hub zone capable to provide -10% to 30% hub reaction at moderate loss of 4% to 6% were used that permitted to increase stage loading, preserving optimum reaction at mean radius. As it was described in [3], such types of the cascade feature a heightened sensitivity to the flow angle yaw from nominal value. Profiling was carried out with known chords, sections area, inlet and effective outlet cascade angles.

The airfoil geometry is generated on planar design sections with sections arranged along the blade height following a selected rule. A turbine designer may choose an approach for profiling, when the sections are profiled along the direction of streamlines. The authors chose another approach, which is quite simple in realization and provides the reliable results. According to that method, the airfoil centroids are placed upon a radial line. Then, a skeleton generated from the sections is covered with a surface that is a NURBS. In a process of planar sections construction, a technique of the profile shape optimization on geometrical criterion (minimum of maximum curvature) and on aerodynamic criterion (minimum of profile loss) was applied. During profiling, we obtained an exit flow angle equal the effective angle by changing the profile configuration in a zone of skew section to provide a fluid flow rate required for 3D aerodynamic analysis. To control velocity distribution along the airfoil contour and compute cascade exit flow angle and profile loss, a potential streamline with approximate regard of compressibility as well as mixed boundary layer at the profile were computed. The samples of the stage MI planar sections and airfoils are presented in Figure 4.

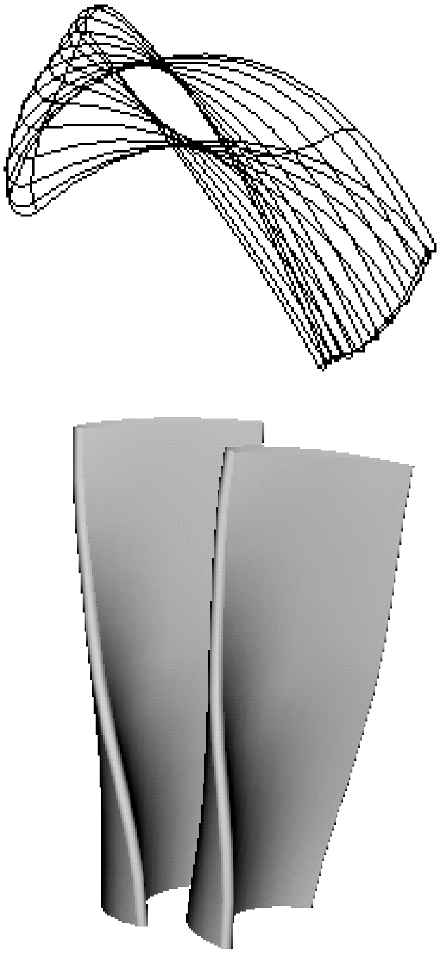


Figure 4. Stage MI planar sections and airfoil re-engineered with *AxSTREAM*

The blade geometrical models built in the way described above can be exported in IGES or some other formats that are readable for the meshers of commercial CFD packages such as Fluent, CFX, etc.

This method of blade geometrical modeling can be also applied to the blade parameterization when solving its shape optimization problems.

3D AERODYNAMIC COMPUTATIONS

The flow boundary conditions for the CFD model were aligned with the peak velocity ratio, minimum radial clearance, and no disk cavity leakage flow. The leakage over the rotor tips was also not accounted for in the model. The stage efficiency (static and total) and pitch averaged parameters were determined using the CFD post-processing tool.

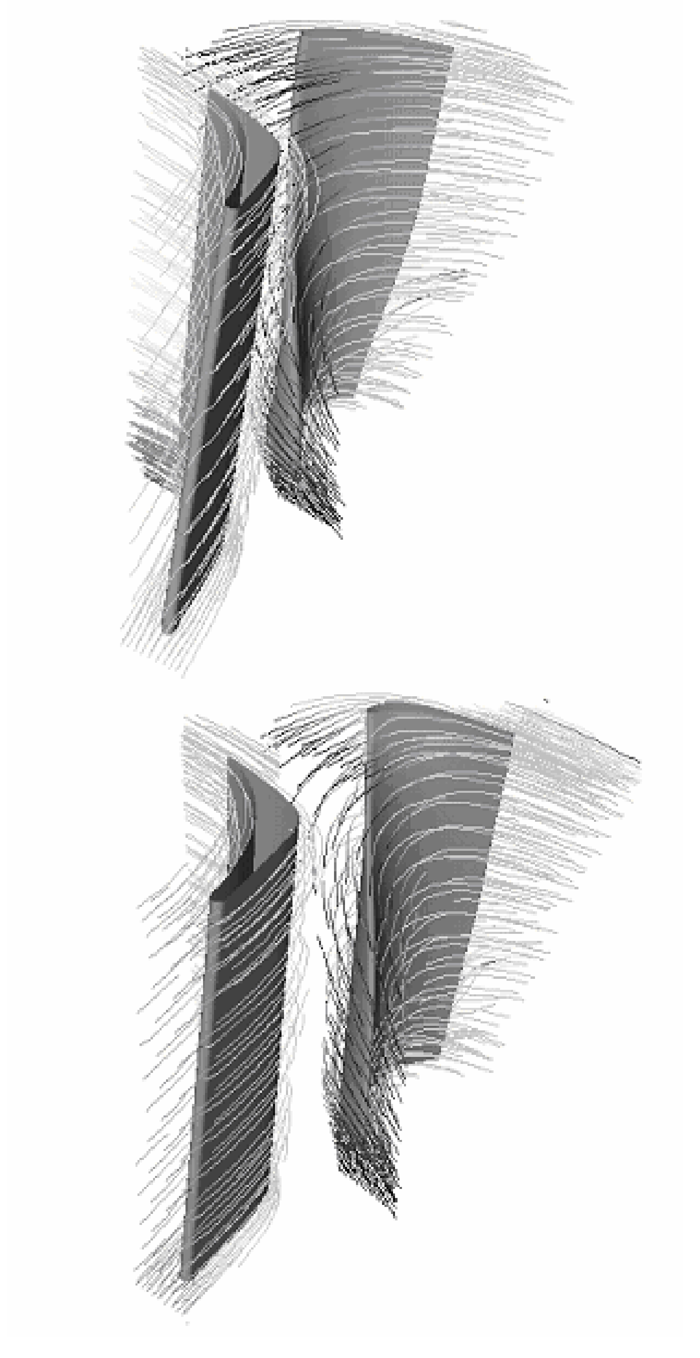


Figure 5. Geometrical models and velocity contours in MI (top) and MII (bottom) flow paths prepared for export to CFX 5.7

Several versions of computational meshes and turbulence models were considered in the course of 3D CFD study. When tuning the model parameters, it seemed to us that the solver reacts inadequately to the minor changes in the grid, in the profile shape, and in the outlet flow angle in the skew section region, showing difficult-to-explain growth of the flow rate (over 5%) in comparison with the test data and the results of 1D/2D computations. This phenomenon becomes especially evident for diffuser and impulse types of the cascade. Some correction of the outlet metal angle in the course of sections profiling was a single mean to dispose of that annoying problem. It should be noted that even preliminary evaluation of 1D analysis results helped to avoid essential errors in 3D CFD simulation.

Table 2 demonstrates integrated parameters of the stages. The blade sketches and the computed velocity contours in the flow path are shown in Figure 5.

Table 2. Results of 3D analysis of the stages

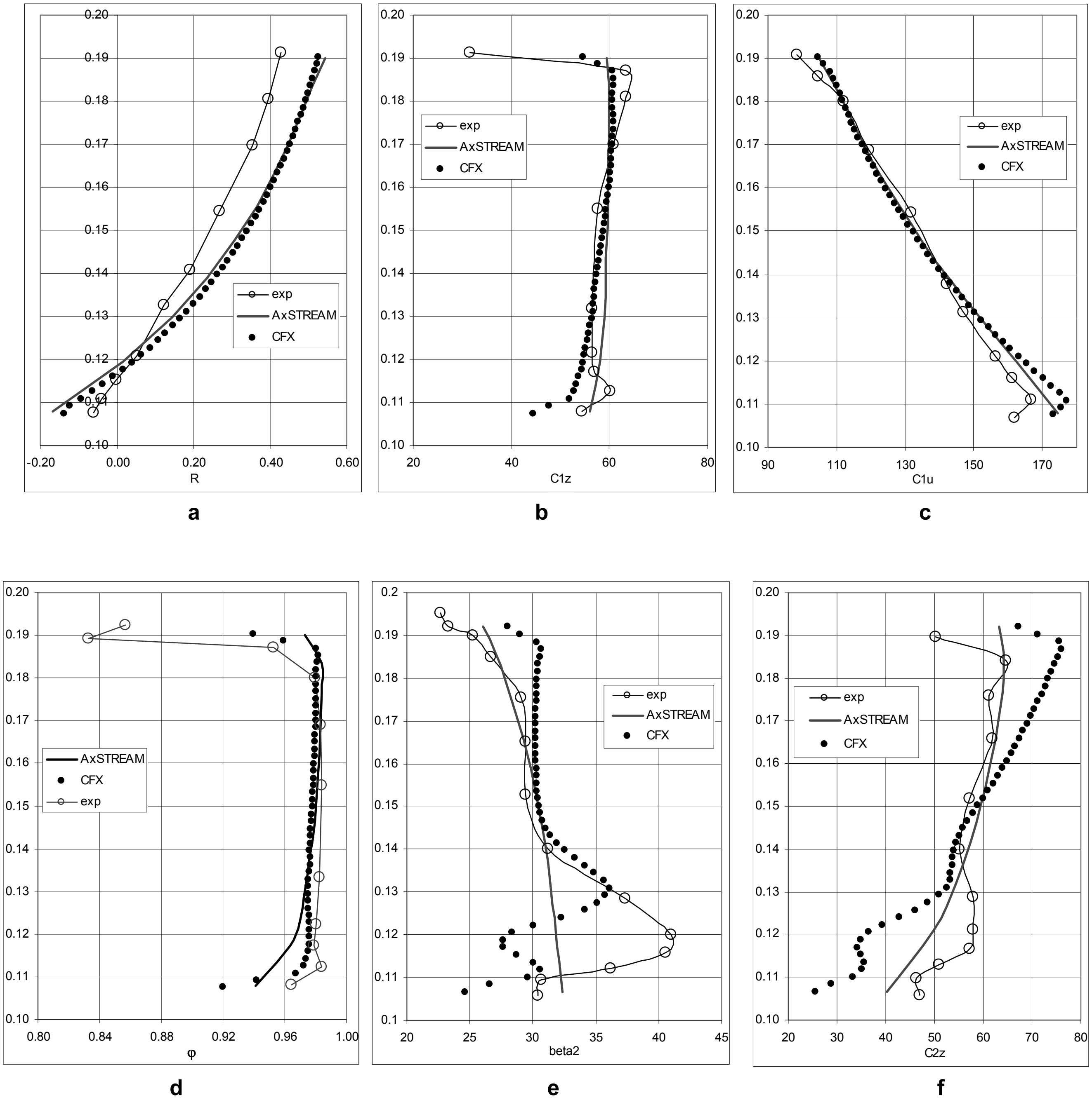
Parameter	Value	
Stage:	MI	MII
Number of finite elements :		
For nozzle vane:	144140	144140
for blade:	130500	136800
total:	274640	280940
Turbulence model:	SST	SST
Time for computation, h:	7	14
Number of iterations:	252	478
Time per iteration, s *):	101	104
Convergence criterion:	1.0e-6 RMS	1.0e-6 RMS

*) the computations were performed on a computer with configuration: P4-2.8 GHz HT, RAM 1GB, OC MS Windows 2000 Pro.

COMPARISON OF EXPERIMENTAL AND COMPUTED DATA

Comparisons of the 2D model, 3D model, and test data are shown as radial distributions on Figures 6 and 7 and average parameters in Table 3. At the nozzle exit the results show the 2D and 3D predictions are in agreement with the test data. At the blade exit the 2D and 3D predictions deviate from the test data near the hub region. The hub region contains a zone of separated flow caused by the divergent airfoil design section, this effect is not captured by the prediction models.

2D solver that operates with only cascade outlet gauging angle provided more smooth flow parameters variation after the working wheel and demonstrates more close proximity to the test data (Figures 6f, 7f). At the same time, 3D solver tried to determine the cascade actual exit angle, which features quite intricate configuration resulting from, besides all other factors, availability of flow separation zones at the blade ends. As Figures 6f and 7f show, a better convergence of computed and test kinematic characteristics is still desirable even taking into account not very high accuracy of measurements ahead of rotating blade row.



a b c

d e f

Figure 6. Computation vs experiment (comparison for stage MI)
Flow parameters distribution along nozzle vane and blade height:
a - reaction;
b – axial velocity component after nozzle vane;
c – tangential velocity component after nozzle vane;
d – nozzle vane velocity coefficient;
e – blade exit flow angle in relative motion;
f - axial velocity component after blade;

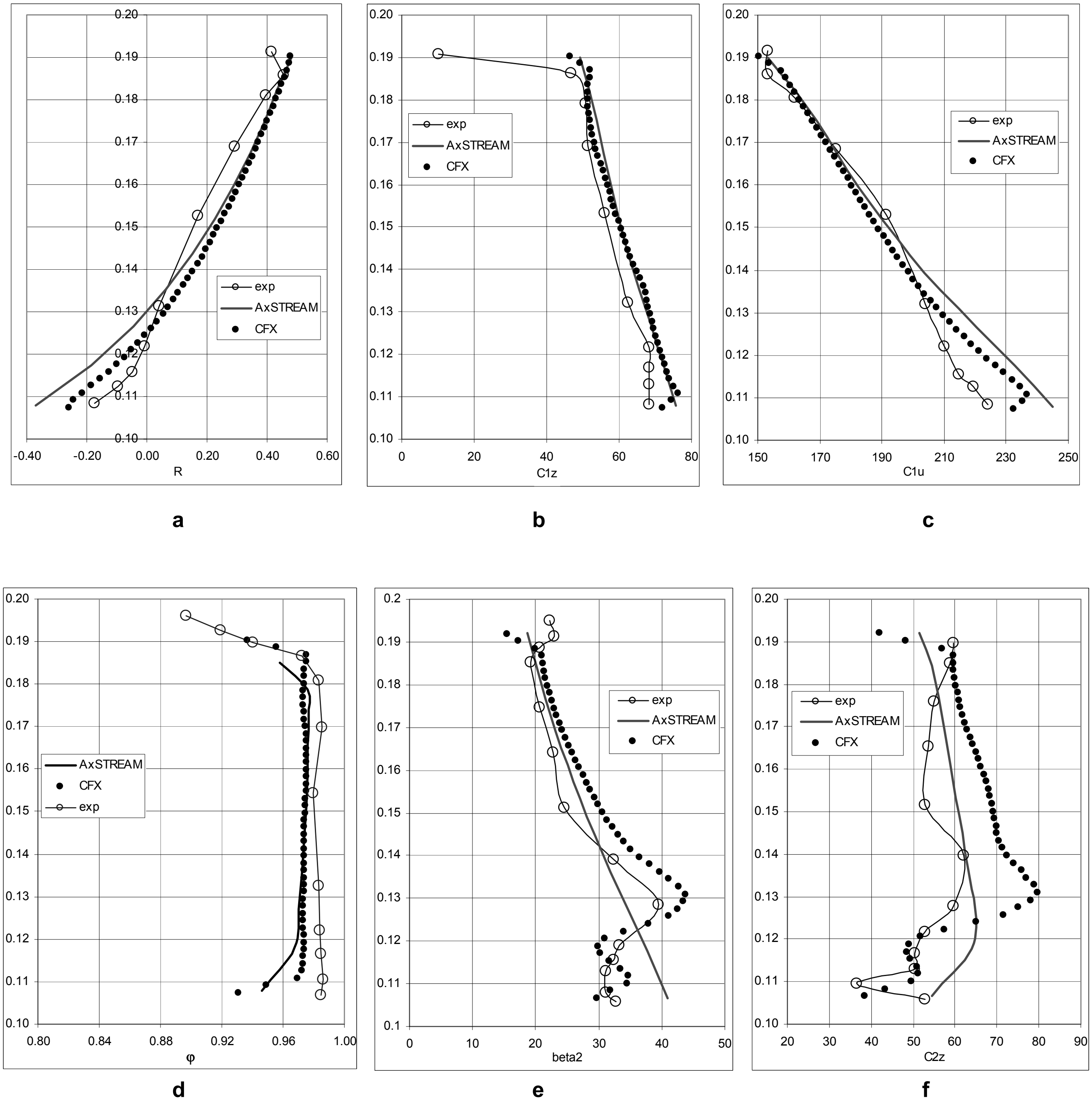


Figure 7. Computation vs experiment (comparison for stage MI).
Flow parameters distribution along nozzle vane and blade height:
a - reaction;
b – axial velocity component after nozzle vane;
c – tangential velocity component after nozzle vane;
d – nozzle vane velocity coefficient;
e – blade exit flow angle in relative motion;
f - axial velocity component after blade;

Table 3. Comparison of stages MI and MII integral parameters at minimum radial clearance

	Stage MI			**Stage MII**		
	2D AxSTREAM	**3D CFX$^{*)}$**	**Experiment**	**2D AxSTREAM**	**3D CFX$^{*)}$**	**Experiment**
$(u/C_0)_{opt}$	0.6	0.627	0.62	0.55	0.550	0.55
ξ_c%	3.5	4.0	2.7	4.9	5.2	3.1
$\xi_л$ %	2.2	2.1	2.4	2.1	3.0	4.6
$\xi_{вых}$ %	10.8	13.9	11.9	6.8	9.0	7
η_i%	82.3	80.0	83	84.9	82.8	85.3

$^{*)}$ results provided regardless to leakage in tip clearance

Generally, the results of comparison indicate the sufficient reliability of axisymmetric analysis for estimation kinematic and power parameters of the stages. However, it is uncapable to regard the local factors caused by the effects aroused at the blade ends and the flow nature variability pitchwise.

In contrast to noticeable differences in the flow kinematics computed on different types of models and extracted from experiment, the integral characteristics of the stages such as mass flow rate, efficiency, losses appeared entirely comparable, see Table 3. At that, the efficiency values determined by 2D computation have better agreement with experiment than computed on 3D model.

Our experience proves that any problem solved in 3D formulation obviating 1D and 2D analyses is fraught with a danger of gross misses in the flow rate and efficiency determination, particularly in the cases when the blade shape is defined with low accuracy due to, for example, rough measurements purposed for turbine modernization. At the same time, unidimensional and axisymmetric computations feature high reliability, high speed of operation and accuracy sufficient for conventional turbine design. In addition, those analyses allow easily regarding the gaps influence on the stage characteristics and facilitate input and output data pre- and post-processing, respectively.

3D analysis is a laborious and sophisticated analysis tool and the modeling time invested is several orders of magnitude larger than a 1D and 2D model. In addition, the designer needs to posses and maintain specialized skills for mesh generation, turbulence model selection, boundary condition application, etc.

Indeed, all forthcomings of 3D analysis is compensated by its capabilities to quantitatively count the flow nuances such as secondary effects in the cascade and flow separation, which can not be precisely regarded in the low-fidelity models, and properly reflect dependencies of the stage characteristics from geometrical and operation parameters. However, these advantages can be rationally utilized only after accumulation of a substantial skill in a certain stage type analysis or after elaborated calibration based on reliable test data.

In the present paper we didn't make our aim to discuss advances of 1D/2D computations in accuracy against 3D CFD. We rather wanted to demonstrate qualitatively the results, which can be objectively obtained from different computational methods and from rig testing.

SPECIFICS OF MULTIDISCIPLINARY OPTIMIZATION (MDO) ON DIFFERENT TYPES OF MODELS

Independently from a model selected, the flow path optimization problem formulation assumes selecting a criterion of optimality, various constraints (for functions and for intervals of independent variables variation), methods of parameterization and search for optimum solution. Usually, the problems of optimization can be solved with the help of computations in direct formulation, when blade geometry parameters are assigned and part of those parameters (defined in the course of optimization) assumed as varied ones.

1D and 2D model optimization problems don't take into account the blade shape, but consider more generalized parameters such as blade height, mean diameter, effective angle at mean radius, twist law, etc. The essence of this approach lies in response functions construction on the basis of original mathematic models and design of experiment technique. Flexibility of dependent and independent variables selection is achieved due to direct interactive access to an integrated project database, in which the magnitudes used in surrogate models creation can be easily flagged. After the computations are accomplished and the response functions are built, a search based on the method of quasi-random low-discrepancy sequences is enabled to determine an optimum geometry of the flow path. Numerous objectives solved with the approach described above indicates practical value of the low-fidelity modeling for the goals of flow path parameters optimization

Problem formulation of MDO is complicated by the necessity to integrate the fragmented solvers used for the flow, the blade strength/vibration and other computations and the modules responsible for optimization in an uniform system. The modules for control functions parameterization and tools for parameterized blades and interblade channels meshes generation belong to main non-standard components of that system. It is worth to note that the parameterization problem tightly bound to the optimization problem formulation and to the method of 3D profiling of the blade airfoil, either. As a rule, the blade airfoil optimization problem formulations extracted from publications offer to parameterize the blade airfoil using parameters that don't impact the profile section shapes, i.e. the profile stagger angle in the sections or the blade lean/sweep angles.

We used more flexible parameterization for profiling, including parameters that affect the planar sections configuration (wedge angles, edges stagger angles, profile stagger angle etc.). If design of experiment technique is used in the search for the blade shape optimum, we suppose the following algorithm of multidisciplinary optimization as most adoptable:

1. Selection of ***m*** cross-section parameters on which the profiles optimization will be performed (***m***=3…6).
2. Selection of ***n*** cross-sections, in which the parameterized profiles will be built. In practice, three sections are enough for the method of the airfoil profiling used in *AxSTREAM*.
3. Generation of design of experiment for ***m*n*** variables in the frame of assigned ranges of parameters variation with the help of a DoE tool like *AxPLAN*.
4. Blade airfoil construction by means of embedded in *AxSTREAM* module in each point of design of experiment with subsequent export of the airfoil stored in one of the standard CAD object transition format (IGES, for instance) to a mesh generation tool for further aerodynamic and strength computations.
5. Aerodynamic, structural and vibration analyses performed with corresponding solvers. At this phase of optimization, each point computation is carried out independently.
6. According to results of computations in AxPLAN, it is possible to restore the response functions (efficiency, stresses, weight, etc.) as quadratic functions and formulate and solve different tasks of the blade airfoil optimization. For example, it is possible to assign such criterions as:

- minimum of aerodynamic loss at allowable stresses and vibration constraints;
- minimum of weight strength and vibration constraints.

It is important that the quadratic models built can be stored and used for multidisciplinary analysis and optimization of the blades with similar characteristics.

CONCLUSIONS

In this study we compared single stage test air turbine aerodynamic characteristics extracted from experiment and computed with the help of 1D, 2D and 3D solvers. The paper provides the recommendations relating to most expedient usage of different models in various areas of application with regard to project quality and the resources required.

It was shown that proper unidimensional and axisymmetric models combined with proven empiric methods of loss calculation provide the accuracy of the turbine flow path computation sufficient for optimization procedures in a bulk of practice valuable cases. Comparative analysis of the experiment and simulation results indicates an untimely nature of the assertion that 3D CFD analysis is already capable to substitute physical experiments.

The paper discusses specifics of the multidisciplinary optimization problem formulations and solutions associated with usage of different types of the models. It was demonstrated how the approach realized in an integrated design software can be applied to axial turbine flow path optimization with the help of commercial packages for aerodynamic and structural 3D analyses. It was also shown that such software can be also used as an intelligence geometry parameterization tool for the goals of optimization.

REFERENCES

1. D. Corriveau, S.A. Sjolander, Experimental and numerical investigation on the performance of a family of three HP transonic turbine blades. Proceedings of ASME Turbo Expo 2004, Power for Land, Sea and Air, June 14-17, 2004 Vienna, Austria,

2. M. Pazvizna, F. Truckenmuller, C. Berlich, Heinrich Stuer. Numerical and Experimental Investigations into the Aerodynamic performance of a supersonic turbine blade profile. Proceedings of ASME Turbo Expo 2004, Power for Land, Sea and Air, June 14-17, 2004 Vienna, Austria

3. J. Turcote, J-Y. Trepanier, C. Tribes, Y. Panchenko, M. Dion and G. Plante. Integration and Multidisciplinary Design Optimization of a Simplified Gas Turbine Model Using Perl and iSIGHT. Proceedings of 10th AIAA/ISSMO Multi-disciplinary Analysis and Optimization Conference, Albany, New York, Aug. 30-1, 2004

4. A.V. Boiko, Yu.N. Govorushchenko. "The Theory of Axial Turbines Flow Path Optimal Design Basics." – Kharkov, Vischa Shkola, KhSU 1989. - 217 pp. (in Russian)

5. A.V. Boiko, Yu.N.Govorushchenko, S.V. Yershov, A.V. Rusanov and S.D. Severin. "Aerodynamic Computation and Optimal Projection of Turbomachine Flow Paths." - Kharkov, NTU "KhPI" 2002. - 356 pp. (in Russian)

6. A.V. Boiko, A.V Garkusha. "Aerodynamics of Steam and Gas Turbine Flow Path: Analysis, Research, Optimization, Design" – Kharkov, KHGPU, 1999.-360 pp. (in Russian)

7. L. Moroz, Y. Govorushchenko, L. Romanenko, P. Pagur. "Methods and Tools for Multidisciplinary Optimization of Axial Turbine Stages with Relatively Long Blades". Proceedings of Turbo Expo 2004. 14-17 June Vienna, Austria.

8. L. Moroz, Y. Govorushchenko. "Multidisciplinary Optimization of Multistage Axial Turbines Flow Path". Proceedings of 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Albany, New York, Aug. 30-1, 2004

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