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HEAVY DUTY GAS TURBINE SIMULATION: A COMPRESSOR IGV AIRFOIL OFF-DESIGN CHARACTERIZATION

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ABSTRACT

The correct simulation of power plant behavior over a variety of operating conditions has to be extremely detailed in order to provide reliable help to the turbomachinery developers. The latter instance implies for designers and commercial personnel to be equipped with reliable calculation tools (in-house developed or commercial). In particular, Performance Analysis Codes (PACs) allow the designers to analyze different system configurations. To predict off-design behavior, these codes need to be not limited to thermodynamic analysis, but also able to perform a simplified description of each component that require a specific set of correlations. The selection of suitable correlation sets for compressor IGV airfoils could be very difficult. This paper deal with a procedure based on 2D-CFD analysis to provide a reliable evaluation of compressor IGV airfoils deviation and profile loss coefficients in a wide range of operating condition. The analysis were set up on the IGV of the Ansaldo Energia AE94.3A compressor and the developed correlations were successfully implemented in an in-house PAC called ESMS.

NOMENCLATURE

i	Flow incidence	[deg]
m	mass flow rate	[kg/s]
p	Pressure	[Pa]
R	Reaction degree	[Pa]
T	Temperature	[K]

Non dimensional groups

Ma	Mach number	$[-]$
m^*	Reduced mass flow rate $m\frac{\sqrt{T}}{p}$	$[-]$
Re	Reynolds number	$[-]$

Subscripts

g	Geometric
nom	Nominal condition
0	Total thermodynamic condition
1	blade row inlet parameter
2	blade row outlet parameter

Acronym

CAC	Cycle Analysis Code
CFD	Computational Fluid Dynamics
IGV	Inlet Guide Vane
OGV	Outlet Guide Vane
PAC	Performance Ansaldo Code

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α	Blade angle	[deg]
β	Pressure ratio	[-]
δ	Exit deviation angle ($\alpha_2 - \alpha_{2g}$)	[deg]
ε	Flow deflection angle ($\alpha_2 - \alpha_1$)	[deg]
ω	Pressure loss coefficient	[$-$]

Introduction

The energy market development in the last decade has been influenced by several driving factors. Rising of power demand, energy market liberalization and emerging environmental regulations increased the competition and the need for technology innovation of gas turbines operating in combined cycle. To meet the strict customer requirements, related to low emissions, reliability and high performance, the correct estimation of power plant behavior over a variety of operating conditions has to be extremely detailed. To do that the designers and commercial personnel must be equipped with reliable calculation tools (in-house developed or commercial) properly modified for specific needs. In particular, Cycle Analysis Codes (CACs) allow the designers to select proper energy system configurations. In this field, several new codes have been created or existing codes improved in the last years by research centers and software houses (GateCycle by GE Enter Software, GSP by USA National Aerospace Laboratory). To predict off-design behavior, these codes need to be not limited to thermodynamic analysis, but also able to perform a simplified description of each component and/or to introduce their characteristic curves. On the other side, commercial offers to the customer are defined making use of so-called performance codes, specific for each machine, based on the matching of performance maps and characteristic curves (not always available) of the main gas turbine components. Both types of approach require comparison and validation, and particularly for the performance codes, calibration is necessary by means of measurements carried out from field at different loads and ambient conditions. The coupling between the simulation cycle and the analysis of singular components becomes fundamental to provide a real picture of the GT in all typical operating conditions (base-load, partial load, star/stop cycle), from different points of view (performance, overall mass balances, temperature/pressure trends along the gas path, etc.). Partial load simulations with a modular approach have already been proposed by some authors (1; 2) and they are based on the use of performance maps furnished by the equipment manufacturer. Approach of this kind are limited to the cases where performance maps are available. To overcome this problem Facchini (3) and Carcasci (4) developed a specific code, called ESMS, based on modular approach. The code requires a geometric description of the components, which allows the characteristic parameters to be identified which can then be used in typical both design and off-design correlations (e.g., the velocity triangle at mean radius and other cascade parameters for the compressor or turbine). The reliability over a wide range of operating conditions of the used correlations assumes a crucial role on the reliability of the entire performance code. Thus, the selection of a suitable set of correlations become a fundamental task. In the literature, reliable correlations for airfoils profile losses and deviation related to both turbine/compressor blades and vanes are available (5; 6).

In the IGV, there is an expansion of air, so from a thermodynamical point of view, the IGV operates as a turbine nozzle but it is normally shaped as a compressor airfoil. Due to this evidence, both the usual correlations developed for compressor and turbine airfoils could lead to significant errors if applied to the IGV. Due to the lack of suitable set of correlations for the compressor IGV provided in the literature, the authors perform a fast and reliable procedure,based on 2D-CFD analysis, for the estimation of IGV airfoil performance in terms of profile loss coefficients and deviation.

Despite the procedure is here implemented for an IGV, it could be easily applied to any kind of airfoil in order to develop a reliable correlations library for the entire machine.

This paper is focused on the analysis of the IGV of the Ansaldo Energia AE94.3A compressor and the developed correlations were successfully implemented in the in-house code Algor, the Ansaldo Energia customized version code ESMS.

AE94.3A Gas Turbine

AE94.3A family runs as an advanced F-class gas turbine model series on the market, representing the latest generation Ansaldo technology gas turbine range.

AE94.3A range is a single-casing, single-shaft gas turbines having a disc-type rotor held up with a pre-stressed central tie-rod. Rotor discs are splinted together by radial facial serrations named as Hirth-couplings, which connect adjacent discs permitting the transmission of turbine torque to the compressor.

This rotor configuration provides great stiffness with a relatively low weight and permits the rotor parts to be bathed in air from all sides, which prevent thermal stresses and rotor distortion during load changes and rapid starts up. The rotor is supported by two bearings, located outside the pressurized region. This ensures excellent running qualities and constant proper alignment. The front bearing casing is fixed to a ring that rests on two supports by means of radial struts guiding the airflow entering the compressor. A rigid one-piece cylinder, comprised in the exhaust casing, supports the turbine bearing. A lever system permits to vary the pitch of the first row of compressor vanes in order to adjust the mass flow of inlet air to the needs of start-up, shutdown and part-load operation.

AE94.3A compressor (fig.1) is a 15-stage axial flow, with one IGV and one OGV row. It has a capability of about 640 kg/s mass flow rate at ISO conditions with a pressure ratio of 17.7. Five bleeding mass flow are extracted from the compressor in order to deliver cooling air to the turbine blades. The AE94.3A

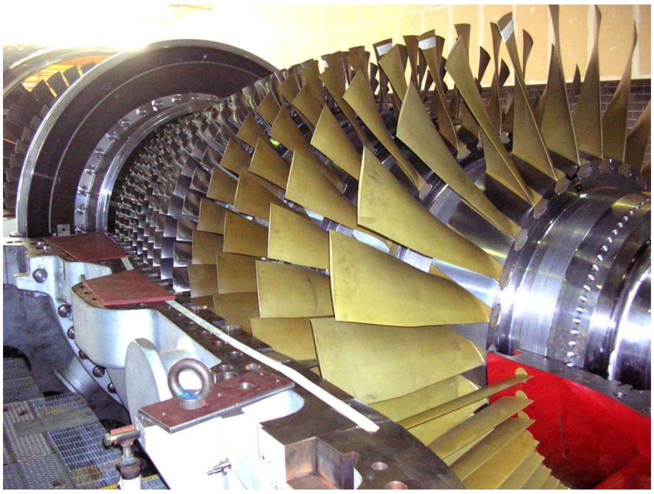

Figure 1. The AE94.3A Compressor.

compressor blades have 3D second generation controlled diffusion airfoils (CDA) that represent an optimal solution to meet requirements of low profile losses and wide operating ranges, increasing the compressor efficiency. IGV row is characterized by 51 blades in steel-chrome alloy, coated with a hardening material. The different operating conditions of the machine require a variation up to 40 degrees in the IGV stagger angle, from the start-up to the base-load condition.

The ESMS code

The ESMS tool was originally developed by Carcasci et. al (4); the reader is referred to previous papers (4; 7; 3) for a complete description of the modular approach used. The modular simulation code is able to create a new power plant configuration, without creating a new source program. The code is also able to handle any combination of input data. The power plant configuration is defined by connecting a number of elementary components representing different unit operations such as compressors, pumps, combustion chambers, splitters, mixers, etc. Thus, each component is defined as a black box capable of simulating a given chemical and thermodynamic transformation.

As stressed above Design and Off-Design Analysis Partial load simulations with a modular approach have already been proposed by some authors (1; 2) but their codes are based on the use of characteristic curves furnished by the equipment manufacturer. This kind of approach is inadequate for studying plants for which characteristic curves are not available. The method used in this code allows simplified component simulation resulting in a better description of cycle behavior and a better understanding of manufacturer provided information. For off-design performance evaluation, the unit description becomes more complex and it requires a more detailed design approach. The off-design study requires a geometric description of the component ((4; 3)), which allows the evaluation of the characteristic parameters to be used in typical off-design correlations (e.g., the velocity triangle at mean radius and other cascade parameters for the compressor or turbine). Thus, the off-design study is based on fixed geometry (obtained by the design study), and there is a reduction in the number of input data.

Correlation definition procedure

Present contribution concerns with a DoE (Design of Experiments) analysis methodology. The row operating conditions is defined setting the IGV stagger angle, the isentropic cascade exit Mach number and the inlet Reynolds number and the performance of the airfoil (i.e. the loss coefficient and the row deviation) were evaluated by the use of a 2D CFD code.
Despite, in principle, 3D analysis could provide a more precise evaluation of both flow deviation and loss coefficient, 2D calculations were performed for their favorable impact on the computational costs. The impact of 3D analysis on correlation quality will be addressed in the future. The midspan IGV airfoil section was selected for the analysis presented here. To include all the AE94.3A IGV airfoils operating conditions, suitable ranges of non-dimensional parameters were defined (table 1). Regarding the off-design space covering, a full factorial off-design operating points distribution was considered and, further more, a design clustering close to the nominal one was performed. A total of 550 CFD calculations was performed. Running on a modern CPU the CFD procedure takes 24 hours approx in all.
In order to implement the CFD data within the ESMS code, a suitable correlation form must be defined. Due to the large amount of numerical data and due to the fact that the provided correlations are strictly suitable to the Vx3.A2 IGV arifoils only, the typically expressions reported by several author in the literature (5) are not so useful. Leveraging the ESMS code capability to read external subroutine, the correlations were expressed in form of radial basis functions and implemented in FORTRAN subroutines.

Table 1. Tested operative conditions

Parameters	
α	$10^\circ \div -50^\circ$
Re	$1.5 \cdot 10^6 \div 3.5 \cdot 10^6$
Ma	$0.1 \div 0.6$

2D CFD Calculations

The CFD code used for all calculations presented in this work is the well know *Traf2D*. The *Traf2D* code is a two-dimensional viscous-inviscid solver developed by Andrea Arnone during a project involving ICASE (NASA Langley), ICOMP (NASA Lewis) and DE (Department of Energy Engineering of University of Florence). The code was designed for cascade flow prediction and include several techniques to achieve computational efficiency and accuracy. Details in the numerical procedure can be found in the references section (8; 9). The used release of the code implements the Baldwin-Lomax turbulence model for the turbulence closure. The numerical grids was obtained using both *Tom* and *Jerry* codes (8; 9) and the mesh generation parameters were selected through the authors experience. As example, the grid used for the nominal design case is shown in figure 2. The CFD analysis boundary conditions were given in terms of such non-dimensional parameters that is: the IGV angle, the isentropic cascade exit Mach number and the inlet Reynolds number defined as in the nomenclature.

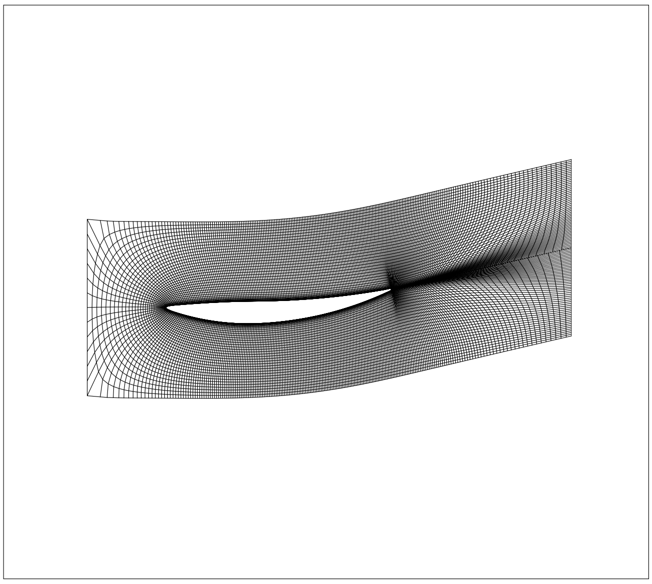

Figure 2. Computational mesh: IGV angle equal to 0.

The results were postprocessed as follow:

Flow deviation

$$\delta = \alpha_2 - \alpha_{2g} \tag{1}$$

Loss coefficient

$$\omega = \frac{p_{01} - p_{02}}{p_{02} - p_2} \tag{2}$$

Results

Flow deviation

The flow deviation over the IGV Stagger angle at design Mach and design Reynolds number is shown in figure 3.

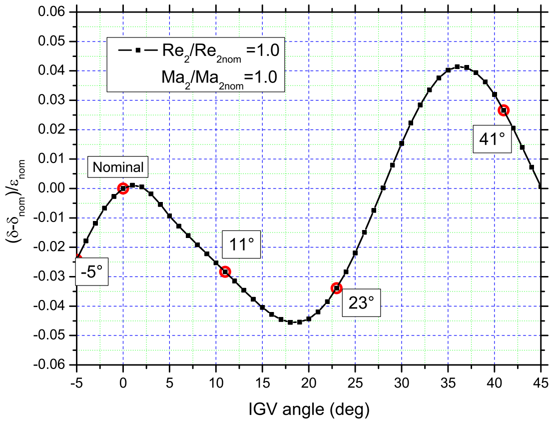

Figure 3. Flow deviation over IGV Stagger angle: Ma and Re in design conditions

Contrary to the predictions obtained by the use of the typical correlations available in the literature, the flow deviation trend evaluated by CFD is higly non-monotonic. This evidence could be motivated as follow. Starting from the nominal conditions, the increase of the Stagger angle leads to a decrease of flow deviation as the increase of the blade solidity leads to a contraction of the fluid vein. The flow deviation decreases up to no separation on the blade suction side occur. For IGV Stagger angles higher

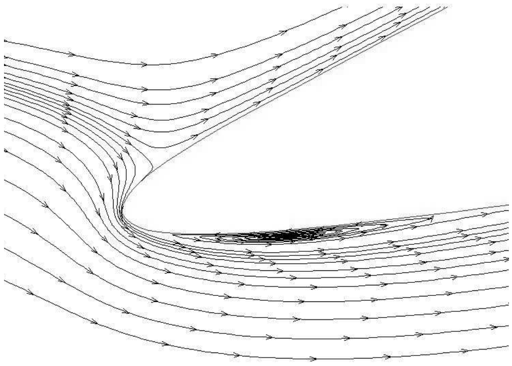

Figure 4. Streamlines IGV angle = 23°

than 18° a separation bubble takes place on the blade suction side (figure 4) and the flow deviation increase. In case of Stagger angles higher than 36° the fluid vane contraction operated by both the increased blade solidity and the presence of a wide separation bubble (figure 5) becomes prominent and the flow deviation decrease. Despite its behavior, the variation of the flow deviation over the IGV Stagger angle is quite low (about 1°). Figure 6 shows the effect of both Reynolds and Mach number on the flow deviation. From that figure emerge that, accordingly with the literature (5; 10; 6), the flow deviation is just affected by the Mach number.

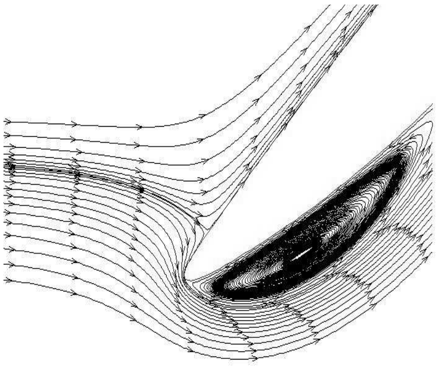

Figure 5. Streamlines IGV angle = 41°

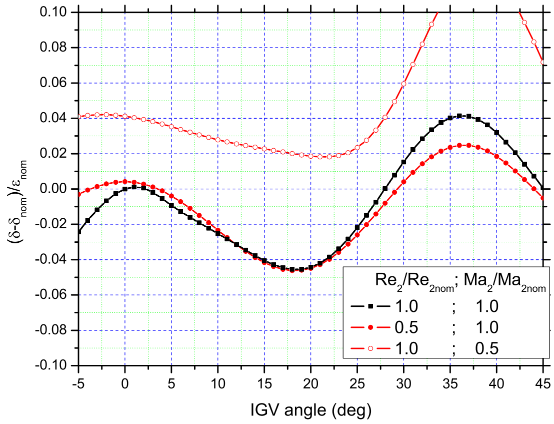

Figure 6. Flow deviation over IGV Stagger angle

Loss coefficient

The pressure loss coefficient over the IGV Stagger angle at design Mach and design Reynolds number is shown in figure 7.

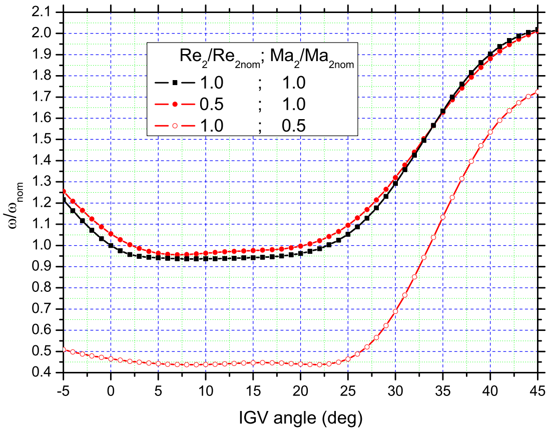

Figure 7. Pressure loss coefficient over IGV Stagger angle

As the Staggered angle increase from the design condition the pressure loss decrease slightly. This decrease is related to the evidence that in case of IGV angle equal to 0°, the coming flow approach the blade leading edge with negative incidence (figure 8). The pressure loss coefficient seems to be not affected for IGV Stagger angle within the range from 5° to 20°. For IGV angle

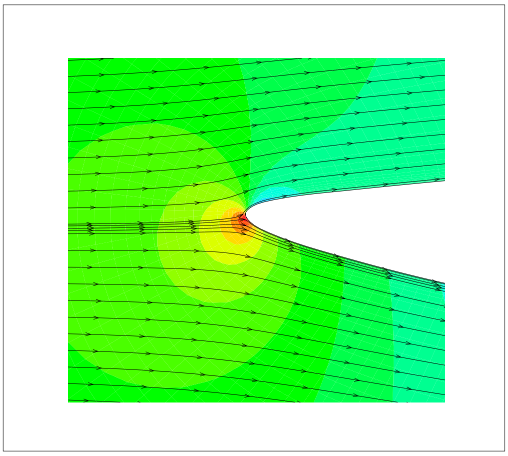

Figure 8. Streamlines over pressure contour plot: IGV angle equal to 0°

higher then 20° the separation bubble described above explanes the sharp increase of the pressure loss coefficient shown in figure 7. As for the flow deviation, the Reynolds number does not affect the pressure loss coefficient.

Correlation Implementation within ESMS

In this section the AE94.3A compressor performance over a wide range of operating condition evaluated by the in-house ESMS code is presented.

Compressor characteristic curves

Figure 9 shows the characteristic curves obtained in case of IGV angle equal to 0° and 10°. The predictions obtained by the use of the new correlation set are compared with those obtained using the Anley correlations (10; 6) and with some experimental data. For each characteristic curve both the Mach and the Reynolds number do not change so much (i.e. significant changes both in Mach and Reynolds number occur only changing the IGV Stagger angle). In such way, the discrepancies between the ESMS predictions and the experimental data in case of IGV angle equal to 0° are not related to the used IGV correlations but they are related to the compressor stage modeling (4). The last statement is remarked by the evidence that the two correlation set used for the IGV characterization provide the same results.

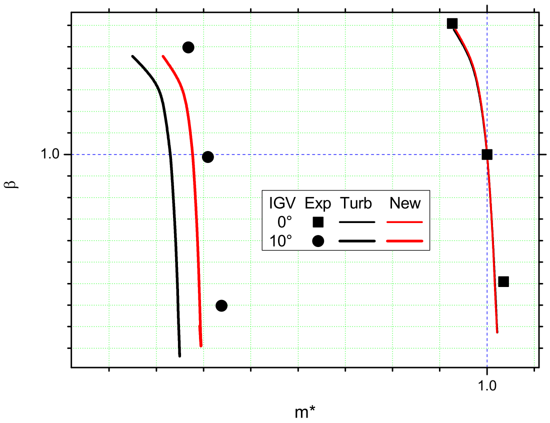

Figure 9. Characteristic curves

For higher IGV Stagger angles the new correlation set provides better results in comparison with those obtained by the use of the Anley correlations.

Running line

Figure 10 shows the compressor's running lines obtained imposing a compressor overall pressure ratio that decrease linearly with respect of the IGV angle.

That figure shows that the new correlation set provides, with respect of the Anley one, higher mass flow rates for each imposed whole compressor pressure drop. This evidence could be related to the different flow deviation evaluated by the proposed correlations. The last statement is remarked also by the figure 11 that shows the flow deviation evaluated by the compared correlations.

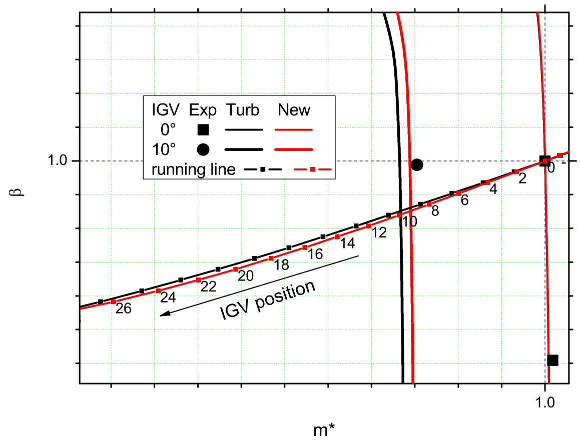

Figure 10. Running lines

Figure 12 shows that significant changes in the Mach number take place for IGV angles higher than 20°.

Finally looking at figure 13, it is possible to point out that ESMS predicts that the reaction degree of the first compressor stage becomes negative for IGV Stagger angle higher than 23°. In such conditions the first rotor operates with high negative flow incidence and the used correlations for the compressor stage performance estimation are out of their definition ranges.

Conclusion and perspectives for future work

The aim of this work is point out a simple and reliable 2D-CFD procedure to provide an evaluation of compressor IGV airfoils deviation and profile loss coefficients in a wide range of operating condition. The mentioned analysis were set up on the IGV of the Ansaldo Energia AE94.3A compressor. The developed correlations, show significant discrepancies with those published in the literature especially regarding the flow deviation. Once rearranged through radial basis functions in FORTRAN subroutines, the correlations were successfully implemented in

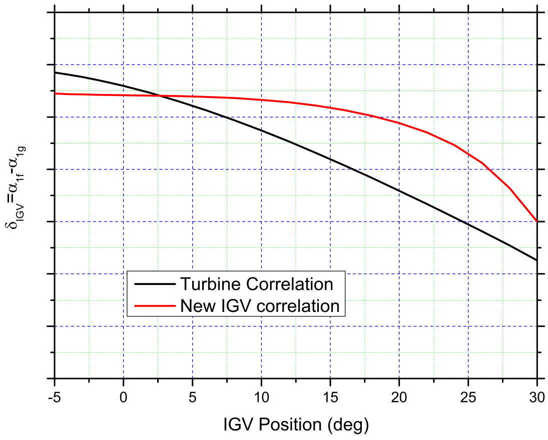

Figure 11. Flow deviation

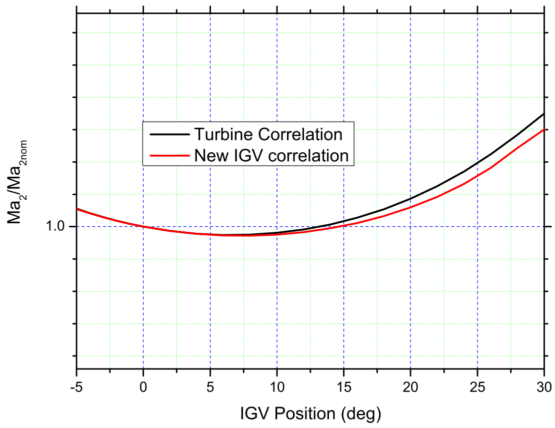

Figure 12. Mach number

a in-house PAC called ESMS. A good agreement between the predictions of the ESMS code and the available AE94.3A experimental data is finally shown. Despite some improvements are achieved using the new correlation set, the authors recognize that the correlations used for the compressor stage characterization must be revised. Notwithstanding the procedure was performed here for an IGV, it could successfully used for any king of airfoil to develop a reliable correlations library for the whole machine.

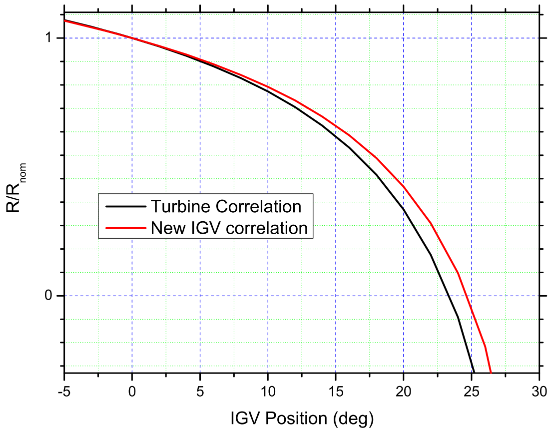

Figure 13. First rotor reaction degree

REFERENCES

[1] Perz, E., 1991. “A computer method for thermal power cycle calculation”. *ASME - J. of Engineering for Gas Turbine and Power*(Vol. 113, pp.184-189).

[2] Gay, M. E. R., and Cohn, A., 1989. “Gate: A simulation code for analysis of gas-turbine power plants”. *ASME Turbo Expo*.

[3] Facchini, B., 1993. “A simplified approach to off-design performance evaluation of single shaft heavy duty gas turbines”. *IGTI ASME Cogen Turbo Power Congress*.

[4] Carcasci, C., and Facchini, B., 1996. “A numerical method for power plant simulations”. *Journal of Energy Resources Technology*(118, pp. 36 - 43).

[5] Dixon, S., 1998. “Fluid mechanics and thermodynamics of turbomachinery”. *Butterworth-Heinemann, 4th edition*.

[6] Wei, N., 2000. “Significance of loss models in aerothermodynamic simulation for axial turbines”. *Doctoral Thesis, Dept of Energy Technology Division of Heat Power Technology, Royal Institute of Technology, Stockholm*.

[7] Carcasci, C., Facchini, B., and Marra, R., 1996. “Modular approach to off-design gas turbines simulation: New prospect for reheat applications”. *IGTI ASME Cogen Turbo Power Congress*.

[8] Ameri, A., and Arnone, A., 1991. “Three dimensional navier-stokes analysis of turbine passage heat transfer”. *AA/SAE/ASME/ASEE 27th Joint Propulsion Conference*(AIAA-91-2241).

[9] Arnone, A., Liou, M., and Povinelli, L., 1992. “Navier-stokes solution of transonic cascade flow using non-periodic c- type grids”. *Journal of Propulsion and Power*(Vol. 8, no. 2, March-April 1992, pg. 410-417).

[10] Aungier, R., 2006. “Turbine aerodynamics”. *ASME Press, New York*.