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Advanced Gas Turbine Concept, Design and Evaluation Methodology. Preliminary Design of Highly Loaded Low Pressure Gas Turbine of Aircraft Engine

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ABSTRACT

This article deals with the conceptual approach to optimize efficiency and power of a highly loaded gas turbine flow path design. Different problems were analyzed during low pressure turbine (LPT) preliminary design of high-bypass aircraft jet engine.

PROBLEM STATEMENT

At present, turbomachines' elements design using integrated software is developing intensively [1, 2, 3, etc.] Simplified models of computation (1D/2D) [1, 4] as well as precise full-dimensional ones [5] may be used in such systems. A comparison of aerodynamic computational results using carefully selected 1D/2D models and CFD analysis with experimental data [3, 4] is evidence of simplified calculations adequate accuracy for preliminary design.

More detail review of the integrated software for turbomachines design you can find in [5].

Gas turbine engine qualitative characteristics are determined by the concepts taken into account on early phases of engine components design [1].

Design specification requires a mandatory parameters values list and the main requirements were high efficiency value (~94 %), weight minimization, strict axial and radial dimension constraints and outlet flow angle deviation from axial direction restriction to a value less than 20 deg. Complex turbine flow path outline shape in meridional plane is the result of these facts. Several low pressure turbine designs with 6 and 7 stages were examined to ensure turbine reliability. Flow path designs in meridional plane with given axial and radial constraints is presented on Fig 1.

The LPT was designed with the help of a multidisciplinary turbomachinery design and optimization suite. It allowed for designing various turbine flow paths while meeting specification requirements.

Turbomachinery design and optimization suite gave the designer a possibility to use different tools to solve flow path design and analysis tasks. Optimization tasks formulations are very flexible. Software service functions provide convenient interface with data project, strong reliability and quick response during the design process.

Tasks used during the turbine scheme definition and their descriptions are listed below:

- Multistage preliminary flow path design is based on finding the solution of 1D problem in inverse formulation. Quasi-random search methodology is used to find optimal solution.
- Preliminary chords and relative pitch values estimation provides minimum total losses taking into account structural and modal constraints.
- Flow path design in meridional plane and stage-by-stage heat drop distributions are found with the help of searching the solution of 1D problem in direct formulation.
- Optimal blade twist and lean laws determination is made with the help of stage-by-stage axisymmetric analysis using Design of Experiment based study engine to search optimum solution on response functions.
- Planar cascades are profiled using various criteria such as minimizing the maximum profile shape curvature and minimizing profile losses
- High efficient 3D blade shapes are designed to minimize turbine weight taking into account structural and modal constraints calculated using beam theory and 3D FEM analysis.
- Final aerodynamic efficiency estimation of different designs is made with CFD simulations. Calculation results are compared with each other to find optimal design.

Initial data for the first design are reported in the Table 1.

Table 1. Initial design data

1	Design point	
1.1	LPT Inlet Total Temperature	1144.3 [K]
1.2	LPT Inlet Total Pressure	323.64 [kPa]
1.3	HPT Exit Swirl (from axial direction)	20 [deg]
1.4	LPT Rotational Speed	2020 [rpm
1.5	LPT Inlet Mass Flow	39.39 [kg/s]
1.6	LPT T-T Pressure Ratio	7.26 [-]
1.7	DH/T (cpDT/Tin)	424.7 [J/kgK]
1.8	Fuel to air ratio	0.0165
1.9	Max Tip Speed (LPT last Blade)	200 [m/s]
1.10	HPT Exit Inner Diameter	0.750 [m]
1.11	HPT Exit Outer Diameter	0.875 [m]
1.12	LPT Inlet Hub Diameter (recommended)	0.957[m]
1.13	LPT Inlet Tip Diameter (recommended)	1.097[m]
1.11	LPT Efficiency required, min	94.0% [-]
2	Geometry constraints	
2.1	Exit LPT Max Swirl Angle (from axial direction)	25 [deg]
2.2	Max LPT Length (duct included)	
2.3	LPT Outlet Tip Diameter, max	1.866[m]
2.4	TE edge diameter, min	0.7[mm]

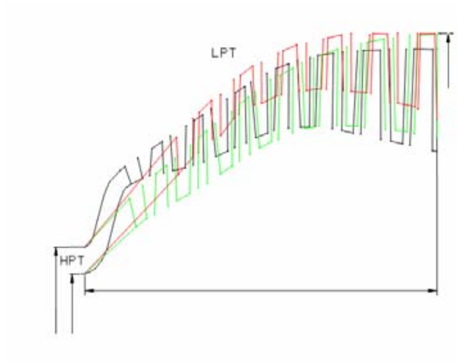

Fig 1. Different flow path designs in meridional plane with given axial and radial constraints (hub, tip diameters, max length)

DESIGN CONFIGURTIONS OVERVIEW

A lot of possible configurations have been taken into account with the required inlet geometric constraints and maximum outer casing diameter. Two variants of a flow path design with 6 and 7 stages meeting the requirements were chosen for a more detailed study (Fig. 2).

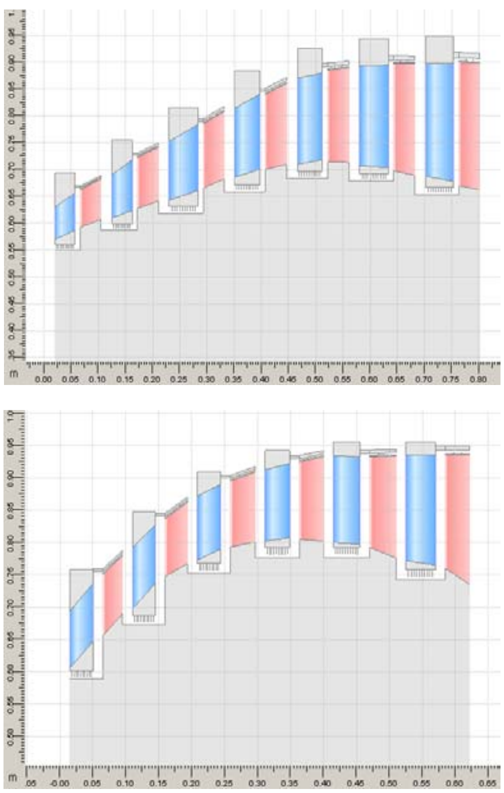

Fig 2. Top-down: 7-stage and 6-stage flow paths satisfying geometrical constraints.

As the meridional shapes are necessarily complex to provide high efficiency, a non-uniform layout of the stage heat drop is used (Fig. 3) that ensures similar efficiency level throughout stagnation parameters from one stage to another (Fig. 4). Stages with outer diameter close to design limit are the most loaded excluding the last stage. Outlet flow angle at positive hub reaction on this stage has to be close to axial direction (Fig. 5). On the intermediate stages, in order to achieve positive hub reaction on the hub, the designer assigns not axial outlet flow angle.

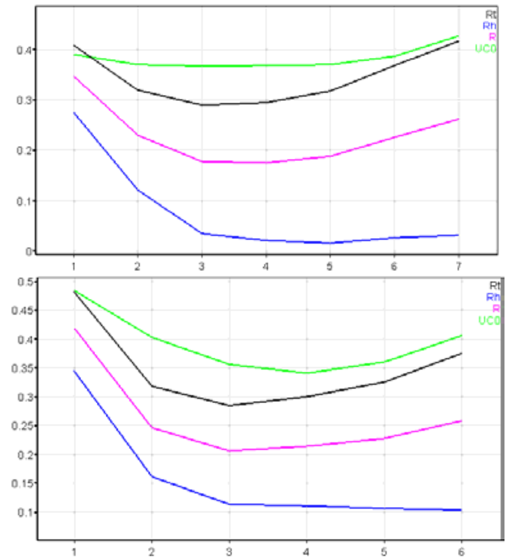

Fig 3. Top-down: stage heat drops and reactions distribution (law of circulation) of the 7-stage and 6-stage turbines.
(Rt – tip reaction, Rh – hub reaction, R – mean reaction, UC0 – u/C_0 factor).

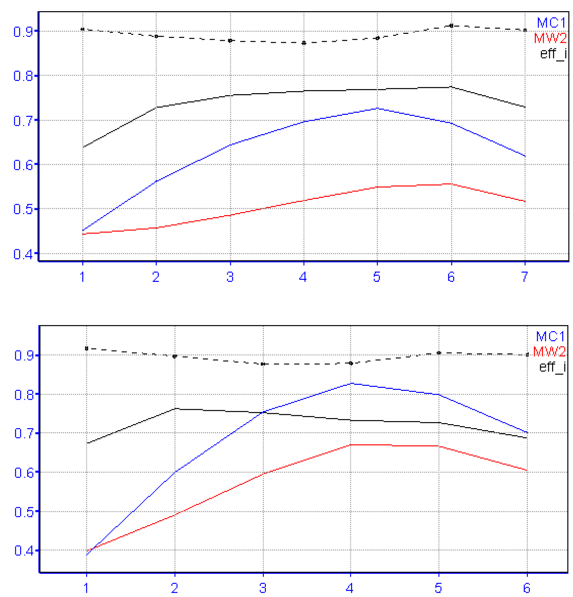

Fig 4. Top-down: 7-stage and 6-stage turbine Mach numbers and efficiency distribution on static and stagnation parameters.
(MC1 – nozzle outlet absolute velocity Mach number, MW2 – blade outlet relative velocity Mach number; eff_i – total-to-static stage internal efficiency).

After 1D meanline calculation, a stage-by-stage 2D (axisymmetric) calculation was performed to determine twist laws of blades which provides the highest efficiency. Required mass flow was determined by the changing of nozzle outlet angle on the mean diameter at specified stage inlet temperature and pressure and stage outlet static pressure.

The greatest deviations from the law of circulation are observed in the last stages and also in the first stages of the 6-stage design where to secure positive hub reaction the nozzle lean is used. Last stages parameters of the considered designs are presented in Fig. 6.

The efficiency of the examined designs as a whole is comparable. The 6-stage design has less length and weight but it is difficult for designing because of large lean of the first stages. The 7-stage flow path is smoother and its blades have a simpler shape.

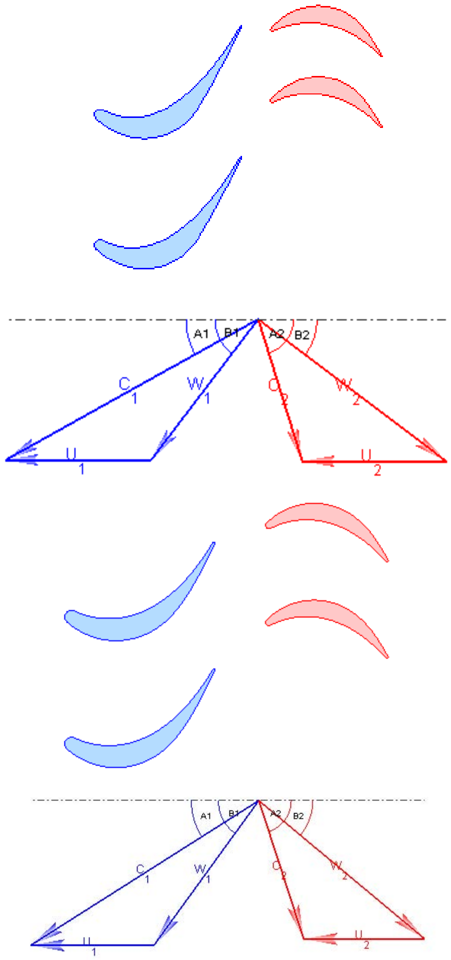

Fig 5. Top-down: 7-stage and 6-stage turbines profiles and velocity triangles on the mean diameter of the last stage.

Considered designs, as can be seen from 3D FEM analysis are subject to stress level noticeably less than permissible that allows for blading that is extremely light. But it is important to bear in mind that since the optimal cascades pitches (0.7…0.8) have to be observed, the number of blades in crowns are increased, thusly making the design process and wheel manufacturing more complicated.

Optimization routines allowed designing 6-stage turbine flow path (See Fig 2) with aerodynamic and geometric characteristics shown below (Fig. 6).

Table 2. Integral characteristics of 6-stage flowpath

	Parameters	**Units**	**Pessimistic loss estimation**	**Optimistic loss estimation**
N_c	capacity	MW	18.38	18.74
η_i	internal total-to-static efficiency	-	0.890	0.908
η_i^*	internal total-to-total efficiency	-	0.928	0.946
G	mass flow rate at outlet	kg/s	39.39	39.39

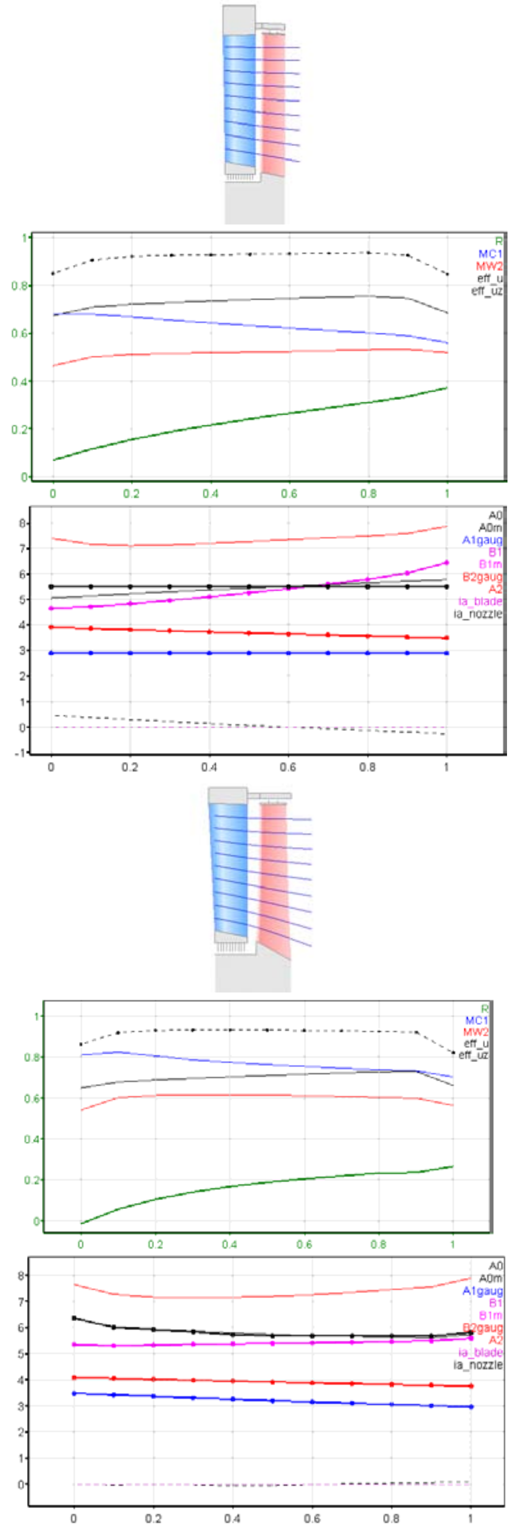

Fig 6. Top-down: 7-stage and 6-stage turbines streamlines and thermodynamic parameters and last stages angles distribution. (R – reaction, MC1 – nozzle outlet absolute velocity Mach number, MW2 – blade outlet relative velocity Mach number, eff_u – total-to-static stage peripheral efficiency, eff_uz –total-to-total stage peripheral efficiency; A0 - nozzle inlet absolute flow angle, A0m - nozzle inlet metal angle, A1gaug - nozzle gauging angle, B1 - blade inlet relative flow angle, B1m - blade inlet metal angle, B2gaug - blade gauging angle, A2 - blade outlet absolute flow angle, ia_blade – blade incidence angle, ia_nozzle – nozzle incidence angle).

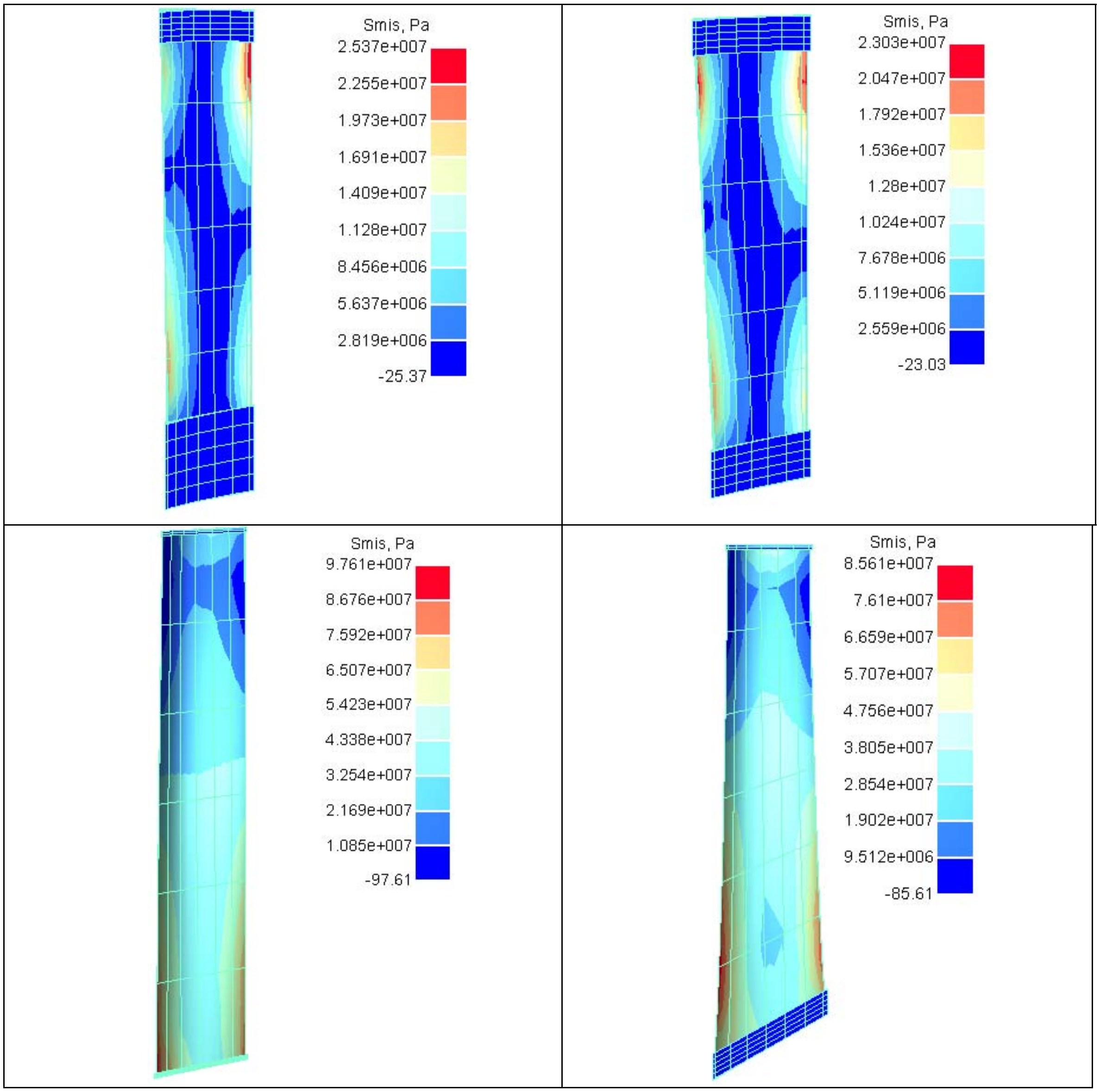

Fig 7. Von Mises stress in nozzles (from top) and blades (bellow) of 7-stage (on the left) and 6-stage (on the right) turbines.

Table3. Stage parameters of 6-stage flowpath

Stage number	1	2	3	4	5	6
α_0 – nozzle inlet metal angle in abs frame, deg	90	76.3	60.82	51.4	46.6	56.7
α_{1gaug} - nozzle outlet gauging angle, deg	29	7	18	19.7	25.1	33.
β_{1m} – blade inlet metal angle, deg	66.5	40.1	34.1	31.4	40.6	56.7
β_{2gaug} – blade outlet gauging angle, deg	30	26	24	25	31	39
α_2 – flow angle in abs. frame downstream rotor, deg	76.3	60.8	51.4	46.6	56.7	71.6
D_2/l – mean diameter to blade height ratio	16.3	18.1	15.8	13.3	10.8	8.3
u/C_0 – isentropic velocity ratio	0.51	0.42	0.38	0.34	0.36	0.40
c_z/u – flow factor	0.7	0.7	0.7	0.8	1.0	1.1
H_T – stage load factor	1.5	2.4	2.8	3.3	2.9	2.3

SOME PRACTICAL ISSUES

The authors found these results to be very interesting from Avio Group from various points of view. While SoftInWay was carrying ahead its design work, an alternative design for two 7 stages configurations for the some cycle was initiated. The 7 stages choice was done for these two modules on the basis of a preliminary optimization that excluded the 6 stages possibility for high loads reasons.

But this solution was taken based on a preliminary optimization in which the choice of parameters was not optimal. As a matter of fact the original model did not have the capability to test an inlet duct as was the case one implemented in the SoftInWay solution. This is probably the most interesting technical choice in the Axstream code solution and it was obtained thanks to the possibility to change a large number of parameters together, without prejudices that take to do some preliminary design choise by default. This is one of the strength points of the code especially for innovative design solutions.

This possibility is fundamental in the modern aerodynamic design to obtain challenging objectives like the ones asked today to designers in order to jump over old design criteria in finding innovative design solutions. In figure 8 a comparison between the three design solutions is reported.

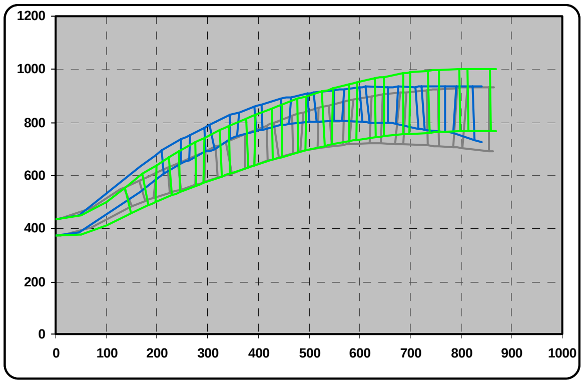

Fig 8. Meridional comparison sketch between the three analysed configurations.

The first design solution proposed by Avio, grey in figure, is a 7 stage configuration with low rotational velocity due to low radii and with low power split on the first stages. This solution takes to a high angular average deflections (about 115 deg) and low performance not able to achieve the requested values for about 1 percentage point.

For this reason Avio has tested the 7 stage green design in the figure. This configuration, thanks to bigger radii can achieve better module performance like the ones requested by the cycle but with a weight increase of about 30% with respect to the original solution. This configuration has also the disadvantage of requiring a redesign of components after the low pressure module changing the outlet maximum radius. With these results it seemed that the initial requirements could not be satisfied.

The final solution has, due to the good preliminary optimization work, some innovations able to solve weight problems, respect geometric constraints and to gain the needed efficiency. The long aggressive inlet duct choice is able to take the first stages at bigger diameters with the capability to have greater power on the first stages and this is a preferred solution that can reduce the average angle deflection of about five degrees and to work in a good efficiency zone on the Smith diagram (see figure 9).

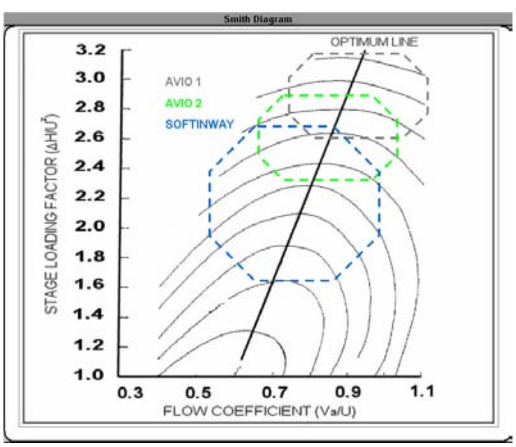

Fig 9. Smith diagram for the three analyzed configurations.

This design solution allows to respect the required performances and to gain an additional saving in terms of weight of approximately 15% on the first Avio configuration.

For the performances validation, and comparisons between the three designs, the CFD TRAFMS code has been used. This work has generally shown an optimal correspondence between preliminary results supplied by SoftInWay code and the ones of such analysis (see figures 10-11-12).

At the moment subsequent optimization of the configuration with a 3D detailed redesign is in development to ultimately improve the predicted performances with High lift, SWC and 3D profiling concepts.

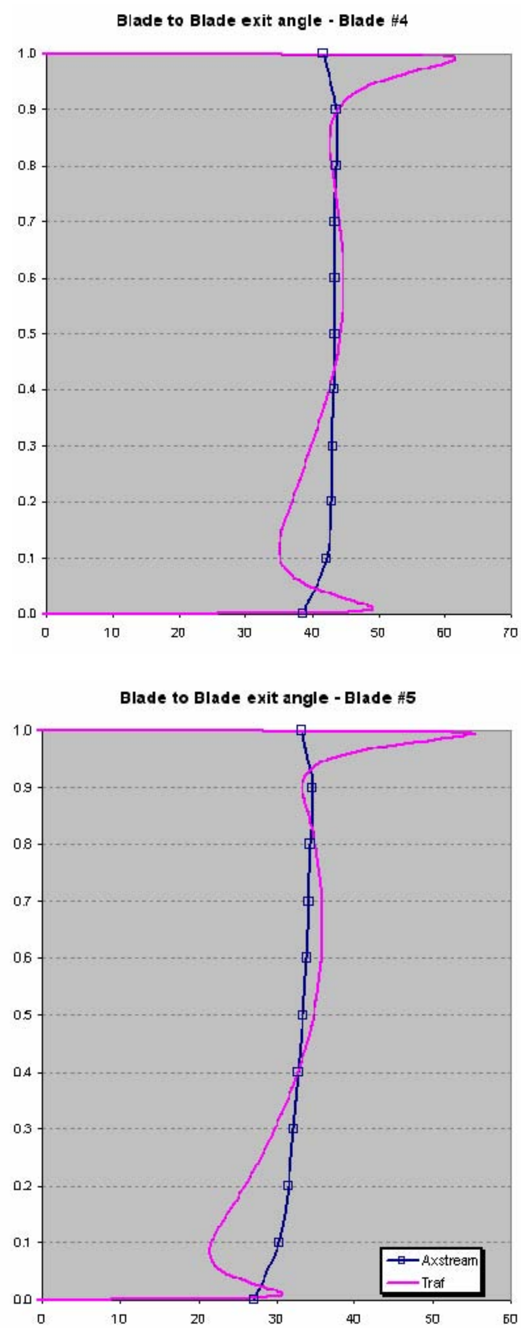

Fig 10. CFD vs Softinway comparisons. Blade to blade exit angles from Blade #4 - #5.

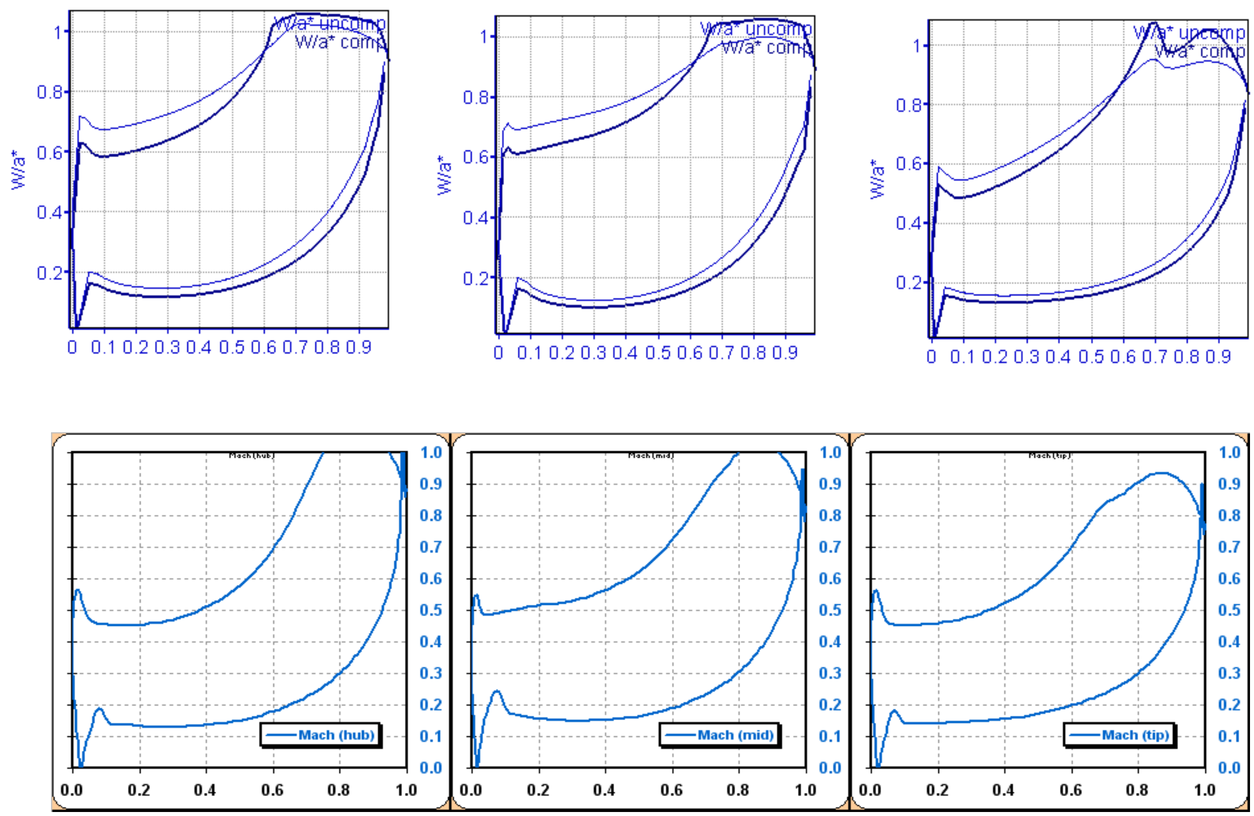

Fig 11. CFD (from below) vs SoftInWay (from above) comparisons of isentropic Mach numbers on Blade #4.
(W-downstream relative velocity; a*-critical velocity; (un)comp – (un)compressible flow results).

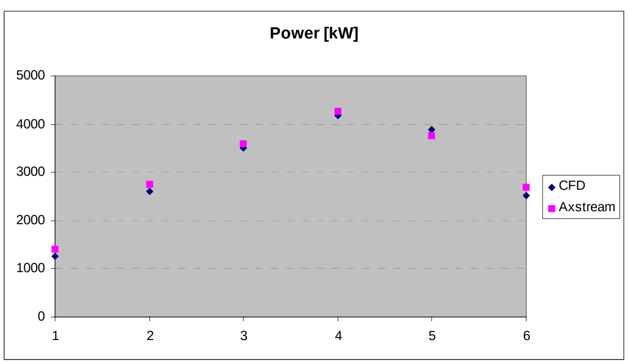

Fig 12. CFD vs SoftInWay comparisons. Power on the various stages.

SUMMARY

Modern day flow path design and optimization tools provide designers with new and powerful capabilities to analyze, compare and weight numerous design solutions based on myriad of variables.

While no design may be optimally "perfect" those capabilities the gas turbine communities now possess give them the opportunity to approach the design process in a whole new manners just as described in the title of this paper, "Advanced Gas Turbine Concept, Design and Evaluation Methodology"

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