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AERODYNAMIC REDESIGNING OF AN INDUSTRIAL GAS TURBINE

Filippo Rubechini
Andrea Schneider
Andrea Arnone
"Sergio Stecco" Department of Energy Engineering
University of Florence
via di Santa Marta, 3, 50139, Firenze, Italy
Filippo.Rubechini@arnone.de.unifi.it

Federico Daccà
Claudio Canelli
Pietro Garibaldi
Ansaldo Energia
via N. Lorenzi, 8, 16152, Genova, Italy
Federico.Dacca'@aen.ansaldo.it

ABSTRACT

This paper deals with the aerodynamic redesigning of a four-stage heavy-duty gas turbine. Traditional design tools, such as through-flow methods, as well as more sophisticated tools, such as three-dimensional RANS computations, were applied in subsequent steps according to a given hierarchical criterion. Each design or analysis tool was coupled with modern optimization techniques, and the overall redesign procedure relies on a neural-network-based approach aimed at maximizing the turbine's power output while satisfying geometrical and mechanical constraints. A detailed description of the redesign procedure is provided, and the aerodynamic characteristics of the optimized geometry are discussed and compared to the original ones.

INTRODUCTION

When dealing with a turbine design, the designer must orientate himself within a multitude of available tools and methodologies. This early choice is critical, and eventually determines whether the process will succeed or fail.

The present paper presents a methodology in which such a choice was driven by a hierarchical criterion, aimed at maximizing the effectiveness of the whole process. This criterion consists in identifying, for each tool used in the redesign process, the specific characteristics that distinguish it with respect to the simpler and to the more complex ones within the process itself. Once these characteristics are identified, the conceptual boundaries of each tool can be established: it will start from a draft supplied by a simpler tool and will provide a more evolved design as the basis for the higher tool in the hierarchy.

The above criterion is founded on the belief, based on logic and confirmed by experience, that the modern and complex design and analysis tools (three-dimensional CFD) should not replace the previous ones (mean-line analysis, through-flow methods), but rather be integrated as an upper link within the overall design chain.

In the case of the present redesigning, there are two types of tools: through-flow calculations and RANS calculations. The hierarchical criterion, besides the definition of the remit of the through-flow analysis, has led to identify different optimization steps based on 3D RANS calculations, which correspond to the use of parametrizations of growing complexity of the bladings geometry. In turn, these different redesign steps were carried out exploiting optimization methods based the use of Artificial Neural Networks (ANN) (see Rubechini et al. [1]).

ANNs were used for the construction of meta-models of each constraint or objective function within an optimization. Compared to other methods, such an approach is not very efficient in terms of the total number of calculations to be performed. For example, evolutionary methods such as genetic algorithms or gradient-based methods are generally more efficient in terms of number of calculations required to reach a given optimum.

Artificial Neural Networks were chosen for two reasons. First of all, the use of meta-models allows calculations to be performed in parallel, thus potentially lowering the overall timescale of the activity. Moreover, the use of such an approach makes it easy to change the constraints and/or the objective functions during the redesign activity, as these are

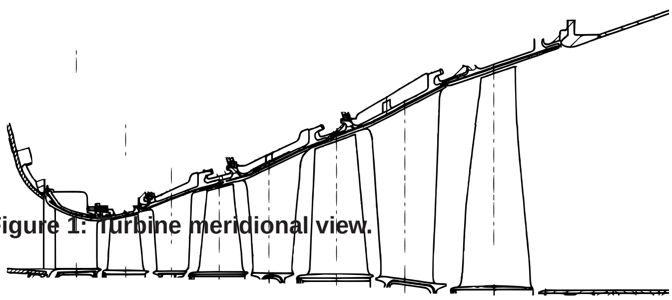


Figure 1: Turbine meridional view.

both applied downstream of the CFD computations. It is worth noticing that, in these authors experience, such a contingency is more a rule than an exception in industrial design activities.

REDESIGN DESCRIPTION

A meridional view of the turbine subjected to the present redesigning is shown in Fig. 1. The redesign procedure was divided in three steps:

- Step 1: redesign the turbine expansion line (stage enthalpy drops)
- Step 2: span-wise distributions of flow properties within each stage
- Step 3: detailed 3D airfoil shape (blade velocity distributions)

During the redesign process, several constraints of a different nature are to be considered:

- mechanical constraints
- thermal constraints
- constraints associated with heat transfer issues

The geometrical constraints are related to the required level of project retrofitability, that has to be almost complete in order to avoid complex alterations of the existing project. For this reason, the following constraints need to be satisfied, which enable the retrofitting of the new geometry in the original turbine:

- disks and casing shape (meridional flow-path) unchanged
- blade count of each blade row unchanged
- limit each blade axial size to fit the existing housing
- blades roots unchanged

As far as the thermal constraints are concerned, they were defined during a parallel heat exchange feasibility study. These constraints set some temperature limits in several parts of the meridional channel, thus affecting the expansion line design. The constraints imposed by the heat balance discipline are related to the turbine capacity. In fact, during the definition of the thermal cycle, the turbine capacity was increased by about 4%. This choice led to a reduction in the expansion ratio of the machine and to a rise in exhaust temperature. Most of these constraints were driven by marketing reasons, and concern the technology level and target markets.

As stated above, the present work is devoted to the aerodynamic aspect of turbine redesigning: the final objective consists in the definition of new airfoil profiles for each of the eight turbine blade-rows.

All the turbine blades were designed at "design point" conditions, except for the last stage. The operating point of each stage is very close to the "knee" of the characteristic curve, so that their matching point don't change in off-design conditions. The only stage that changes its behavior under off-design conditions is the fourth one. For this reason, the downstream strut was included during the calculations performed for the last stage design.

The following sections provide a detailed description of the redesigning procedure, by discussing each different redesign step.

COMPUTATIONAL PROCEDURE

Through-flow Solver

Through-flow analyses were carried out by using an in-house code for the duct flow analysis of air cooled gas turbines. It is based on the stream-wise curvature calculation: the averaged axi-symmetric flow is studied on a 2D computational grid made of two different sets of lines located in the turbine meridional plane.

The first set is made of straight lines, drawn from the hub to the casing, representing the leading edge and the trailing edge of each single blade. More straight lines can be added between two different blades in order to account for annulus effects.

The second set is made of stream-wise curved lines that are automatically placed by the code itself in order to meet a proper constant radial mass flow distribution between each couple of adjacent lines.

Besides the standard set of equations (radial equilibrium, continuity and energy conservation), many different auxiliary equations are iteratively solved to determine the real gas properties, the velocity triangles and the streamline curvature along the meridional section. At every iteration, both the flow pressure losses (profile and secondary losses) and the exit flow angles are calculated for each blade by means of simplified empirical correlations.

The code allows for the calculation of the principal averaged effects of the air cooling system on the main gas flow. Different types of cooling air injections can be added at different locations throughout the entire meridional section, representing film cooling, leading and trailing edge cooling, blade leakage and sealing. Each type of injection is characterized by different loss correlations.

RANS Solver

The multi-row, multi-block release of the TRAF code (Arnone [2]) was used in the present work. In this flow solver the unsteady, three-dimensional, Reynolds averaged Navier-Stokes equations are written in conservative form in a curvilinear, body-fitted coordinate system and solved for density, absolute momentum components, and total energy. The space discretization is based on a cell-centered finite volume scheme. Both scalar and matrix artificial dissipation models introduced by Jameson et al. [3] and Swanson and Turkel [4] are available in the code. In order to minimize the amount of artificial diffusion inside the shear layers, an eigenvalues scaling was implemented to weight these terms. The system of governing equations is advanced in time using an explicit four-stage Runge-Kutta scheme. Residual smoothing, local time-stepping, and multi-gridding are employed to speed-up convergence to the steady state solution. The solver features several turbulence closures, ranging from simple algebraic models to advanced multi-equations ones ([5], [6], [7], [8]). In the present work, the Baldwin–Lomax model was preferred for optimization runs because of its robustness, and the $k-\omega$ one for final verifications.

As far as the inlet/outlet boundary conditions are concerned, span-wise distributions of total enthalpy, total pressure and flow angles are imposed at the subsonic first row inlet, while the outgoing Riemann invariant is taken from the interior. At the subsonic last row outlet, static pressure is prescribed, and the density and the momentum components are extrapolated.

Flow injection and extraction modeling features, including a blade/flowpath film cooling model and the capability of modeling annulus wall flows, are available. Flow injections are handled by imposing mass flow rate, flow angles and stagnation temperature, the static pressure is extrapolated from the interior. Flow extractions can be imposed either by prescribing the mass flow rate or by imposing the static pressure on the extraction surface area, and in the latter case the extracted mass flow rate is a result of the computation.

Gas Modelling

As discussed in some depth for a similar application by Rubechini et al. [9], the evolving gas mixture undergoes significant variations in its properties not only because of the large temperature variations, but also because the gas composition varies with the fuel/air ratio as cooling air is added. In the present case more than 10% of pure cooling air is added to the inlet mass flow, thus causing a reduction of the fuel/air ratio from inlet to outlet. Therefore, the variation of the gas properties along the turbine flowpath is due to the combined effects of temperature drop and change in gas composition. In the present case, as well as for most gas turbines, the negligible variation of the gas constant R allows us to model the gas mixture as an ideal gas (i.e. thermally perfect), whose equation of state is given by $pv = RT$. On the other hand, the specific heat c_p and the specific heat ratio γ undergo significant variations. The calorically imperfect behavior of the gas mixture is accounted for by adopting a real-gas model, in which the gas is treated as thermally ideal, and c_p varies as a function of local temperature and fuel/air ratio.

Parameterization

The three-dimensional blade geometry is handled by using an in-house developed parameterization. Airfoils are represented by means of B-splines, two distinct curves for suction and pressure sides. The coordinates of the control points are expressed in terms of normalized curvilinear abscissa and distance from a construction curve, in the chord-wise and normal-like directions respectively (see Fig. 2). Such a construction curve represents the airfoil's back-bone, and can be regarded as a pseudo-camber line. In turn, the pseudo-camber line is defined by a B-spline with 3, 4 or 5 control points.

The capability to handle the camber line, the suction and the pressure sides separately proves very useful during optimization. For example, it can be exploited to reduce the number of degrees of freedom during an optimization, by moving only the control points of the pseudo camber line, while maintaining a good control on the characteristics of the airfoil (blade angles, stagger angle, chord length).

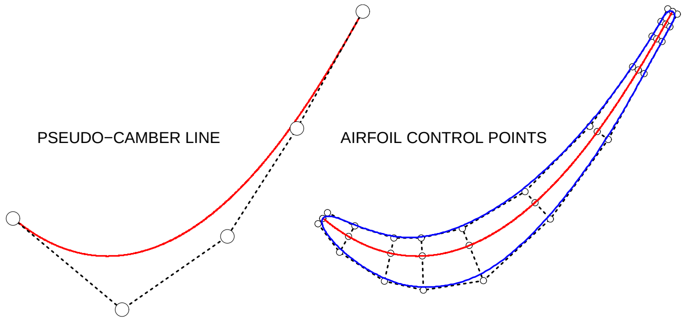


Figure 2: Airfoil parameterization.

The span-wise distributions of all airfoil parameters are again represented using B-splines, whose number of control points is chosen by the designer according to the complexity of the three-dimesional airfoil to be described.

Structural Analysis

An important aspect to be considered during the redesign is represented by the structural problem. Accounting for structural limitations is essential for final design purposes, and may guide the designer in choosing a given solution among several aerodynamic optima by eliminating those geometries that don't meet structural requirements. To this end, the open-source, 3D structural finite element solver CalculiX ([10]) was included in the optimization procedure. In the present redesigning, both the static and the dynamic behaviors of each geometry were checked by running a FEM analysis downstream of the CFD one.

Optimization

Each optimization described in this paper has been carried out by means of the following procedure. The first action consists in defining each geometric parameter subjected to optimization, together with its range of variation. This defines the design space. Then, the design space is populated using a quasi-random sequence, and the corresponding geometries are calculated. For each objective function and constraint, a response surface is generated using artificial neural networks, and a Montecarlo method is used to find a set of optimum solutions on the response surface. Finally, the optimum set is verified by CFD calculations, and a solution is chosen by the designer.

The response surface approach is often referred to as meta-model technique, since it provides a "model of the model" (Kleijnen [11]). Artificial neural networks were chosen as a well-known approach to fit a wide class of objective functions ([12], [13]). Sobol's method was used to generate a quasi-random sequence of training data. With respect to a random sampling, the Sobol sequence provides a better coverage over the design space under investigation. A feed-forward network with two hidden layers was used. As far as the training is concerned, a gradient-based back-propagation method was employed. In order to improve the generalization ability, a hybrid network made of multiple trained neural networks was used (Rai [14]). Effective hybridization can be accomplished by choosing a different architecture, a different training set and a different initialization of weight vectors during the training process. The generalization ability of the network was evaluated by computing the prediction error over an independent validation dataset.

REDESIGN STEP 1: STAGE PRESSURE DROPS

The first step of the redesign is aimed at defining a new expansion line, that is a new distribution of pressure drops, which would constitute an aerodynamic optimum. As a matter of fact, the original expansion line was designed in such a manner that an important part of the total enthalpy drop was disposed of through the first stage. In particular, the original design is characterized by a concentrated loading across the first stage that accounts for over the 50% of the whole turbine pressure drop. Such a configuration was required because of the outdated blade cooling

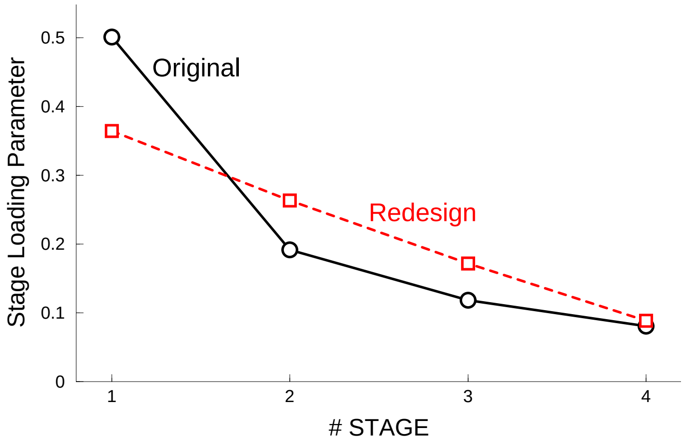


Figure 3: Original and redesigned stage pressure drops.

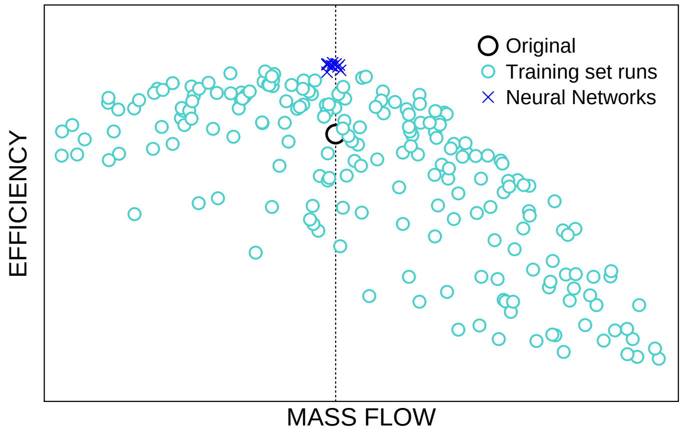


Figure 4: Optimization cloud for a single objective function. Computed and ANN suggested solutions.

technology implemented: in order to meet the thermo-mechanical constraints, the mean flow temperature had to be greatly reduced across the first stage. This type of irregular distribution clearly penalizes the aerodynamic efficiency of the entire expansion line, resulting in high Mach levels in the first stage blades. During the optimization process, reasonable assumptions about a possible upgrade of the blade cooling technology are taken into account; such an upgrade has to be performed alongside the blade aerodynamic redesign. Once the hypothesis of technology upgrade is accepted, most of the severe thermo-mechanical constraints can be removed, and a concrete optimization of the overall aerodynamic efficiency can be achieved thanks to a redistribution of the stage loading. The expansion line resulting from the first step of the optimization is consequently more uniform and the first stage loading is significantly reduced.

From a theoretical point of view, the choice of the optimum drops distribution could be made on the basis of simple 1D design criteria, or obtained from a mean-line analysis. However, since in this case we are about to modify an existing machine, the actual geometry was a convenient starting point for an optimization campaign based on CFD calculations. At the same time, among the many types of computational models of various degree of complexity, through-flow calculations were selected for this first redesign step. As a matter of fact, on the basis of the previous experience of these authors, such a tool is considered a convenient choice for the present purpose, because it is a good compromise between speed and accuracy. Moreover, through-flow analysis allows investigation of important geometrical changes in the bladings without actually specifying the new airfoil shape, which is still unknown in this step.

In light of the above considerations, this first redesign step was carried out by performing through-flow calculations, aimed at defining a re-twist of the existing bladings. The target, or objective function, was the maximum total-to-static efficiency of the overall turbine (i.e. maximum specific power output). The blade twist is defined by the span-wise stagger angle distribution of the airfoil sections describing the blade itself. For each of the eight blade-rows, the airfoil sections were allowed to be re-staggered according to a prescribed span-wise distribution. Specifically, the blade twist was parameterized by means of a B-spline with three control points. The span-wise position of each control point was kept constant, thus leading to 3 degrees of freedom for each blade-row (stagger angles at a given span), and hence to a total of 24 degrees of freedom for the overall turbine.

Fig. 3 shows the comparison between the original stage pressure drops and the ones obtained at the end of this redesign step. The stage loading parameter is calculated as the relative pressure drop for each stage and is representative of the main gas flow expansion line along the meridional path of the turbine.

An example of the typical optimization cloud is shown in Fig. 4. Open circles represent the results of each computed geometry, whereas crosses are associated to optimum geometries eventually suggested by neural networks. These optimum geometries typically describe a Pareto front when plotted against the different objective functions, hence the choice of the final optimum solution is not unique and always implies some arbitrariness from the designer.

REDESIGN STEP 2: SPAN-WISE DISTRIBUTIONS

As discussed in the previous section, the average stage drops were frozen as a result of the first redesign step. With these average drops as a constraint, the second step is aimed at defining the span-wise distribution of the flow properties. This redesign step can be conceived again as an optimization campaign, in which the objective function is represented by the turbine's efficiency, while the mass flow, the stage drops and the structural limitations are imposed as constraints. More in detail, the second redesign step consisted of a stage-by-stage optimization of the airfoil camber lines by means of three-dimensional viscous analysis. The thickness distributions of the original airfoils were "mounted" on the new camber lines from the previous step, which correspond to the re-stagger suggested by the through-flow calculations.

For each blade, the camber line was parameterized at three different span-wise positions (hub, mid-span and tip) by means of a B-spline with three control points . As a result, we have a total of 9 degrees of freedom for each blade.

In order to restrict the number of design parameters, or degrees of freedom of the optimization, each turbine stage was subjected to a ded-

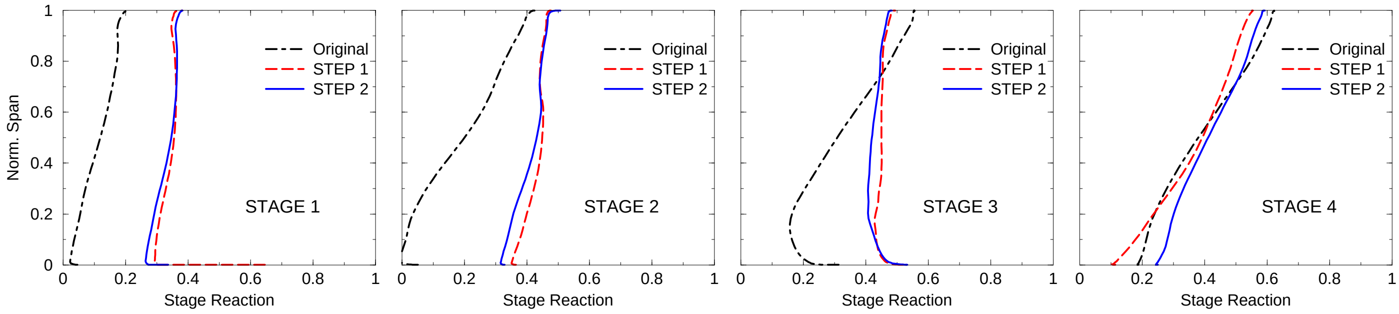
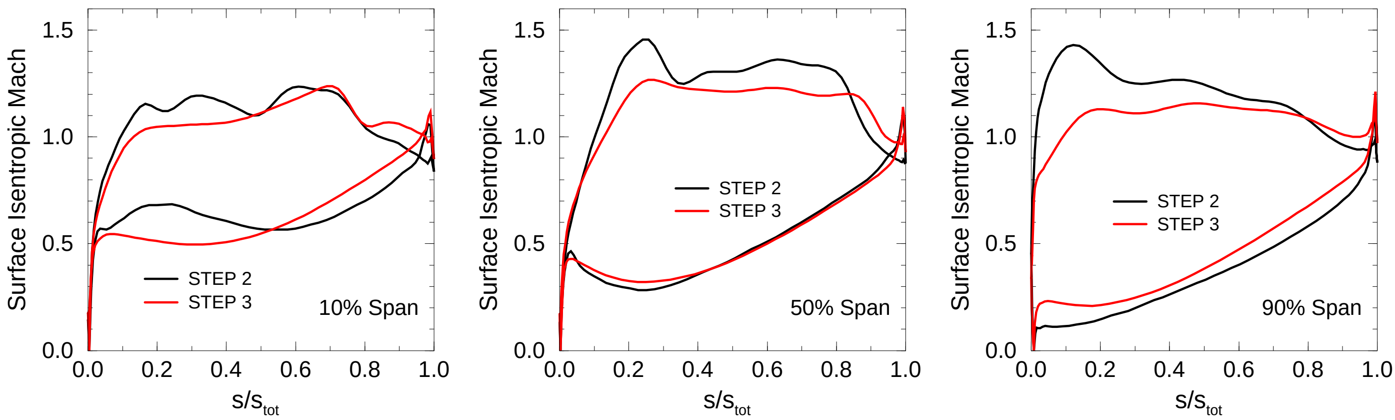


Figure 5: Degree of reaction for each stage. Comparison between original, redesign Step 1 and redesign Step2.



(a) Near HUB **(b) MID-SPAN** **(c) Near SHROUD**

Figure 6: Surface isentropic Mach distributions. Comparison between redesign Step 2 and 3.

icated campaign. However, the inlet/outlet boundary conditions for the computation of each single stage are unknown, as they depend on the actual geometry generated by the parameterization. On one hand, the aerodynamic design should be carried out in a multi-stage environment, in order to account for the actual operating conditions of each stage as they result from the matching with the neighbouring stages. On the other hand, using the complete multi-stage model throughout the optimization of each stage would require an impractical computational effort, incompatible with the project schedule. Therefore, the computational domain for the redesign of a given stage included five blade-rows: one row upstream, the stage to be redesigned, and one stage downstream of it.

The total-to-total efficiency of the stage to be re-designed was selected as the objective function, with the exception of the last stage, for which the total-to-static efficiency was considered. In fact, the fourth stage has to discharge the flow as much in the axial direction as possible for maximum power output.

Fig. 5 shows the modification of the span-wise reaction starting from the original turbine stages, at the end of the first and of the second redesign steps.

REDESIGN STEP 3: AIRFOIL DESIGN

The objective of the last redesign step is the definition of the final airfoil shape or, equivalently, the detailed blade velocity distributions. For each blade-row, the geometrical changes under investigation concern the span-wise distribution of airfoil shape parameters, described above in the parameterization section. At a given span-wise position, the airfoil shape is modified by moving both the camber line and the airfoil control points, and, in addition to that, airfoils of stator baldes are allowed to move along axial and tangential directions to account for three-dimensional stacking effects.

The third redesign step was undertaken using 3D, single-row RANS calculations. For the single-row calculations to continue to be representative of the actual multi-row environment, the preservation of the matching with the contiguous blade-rows is of primary importance. This requires that the optimized geometry faithfully reproduce the radial distributions determined in Step 2, at both the inlet and the outlet boundaries. The imposition of the standard boundary conditions (inlet total pressure and temperature, inlet flow angles, static pressure at outlet) is not sufficient to ensure such a matching, and additional constraints must be introduced. In particular, the complete matching can be

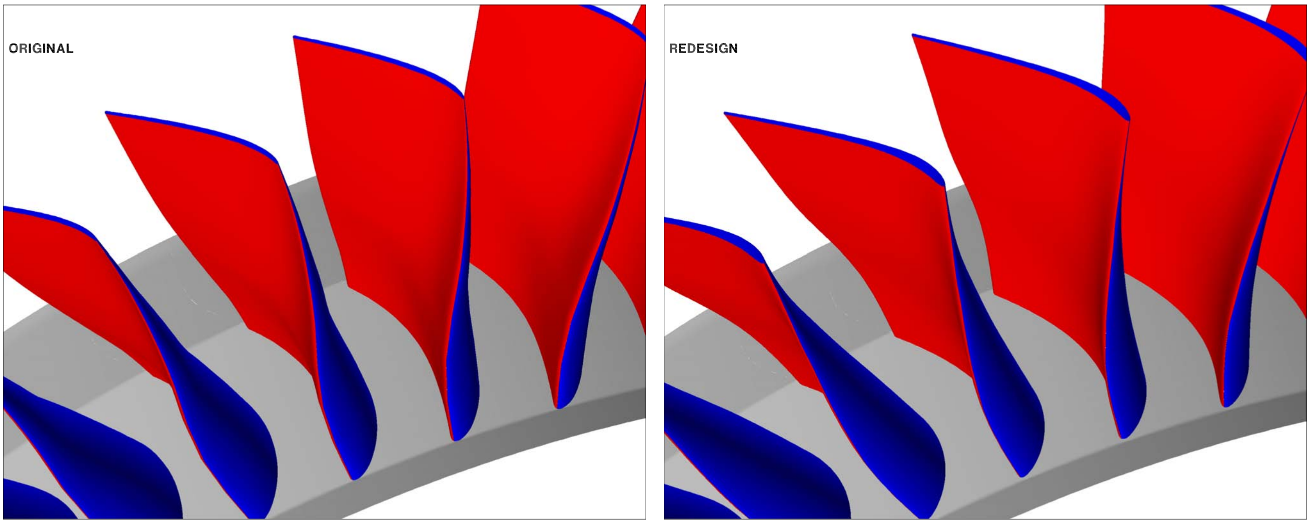


Figure 7: Turbine fourth rotor (TB4). Comparison between original and redesign.

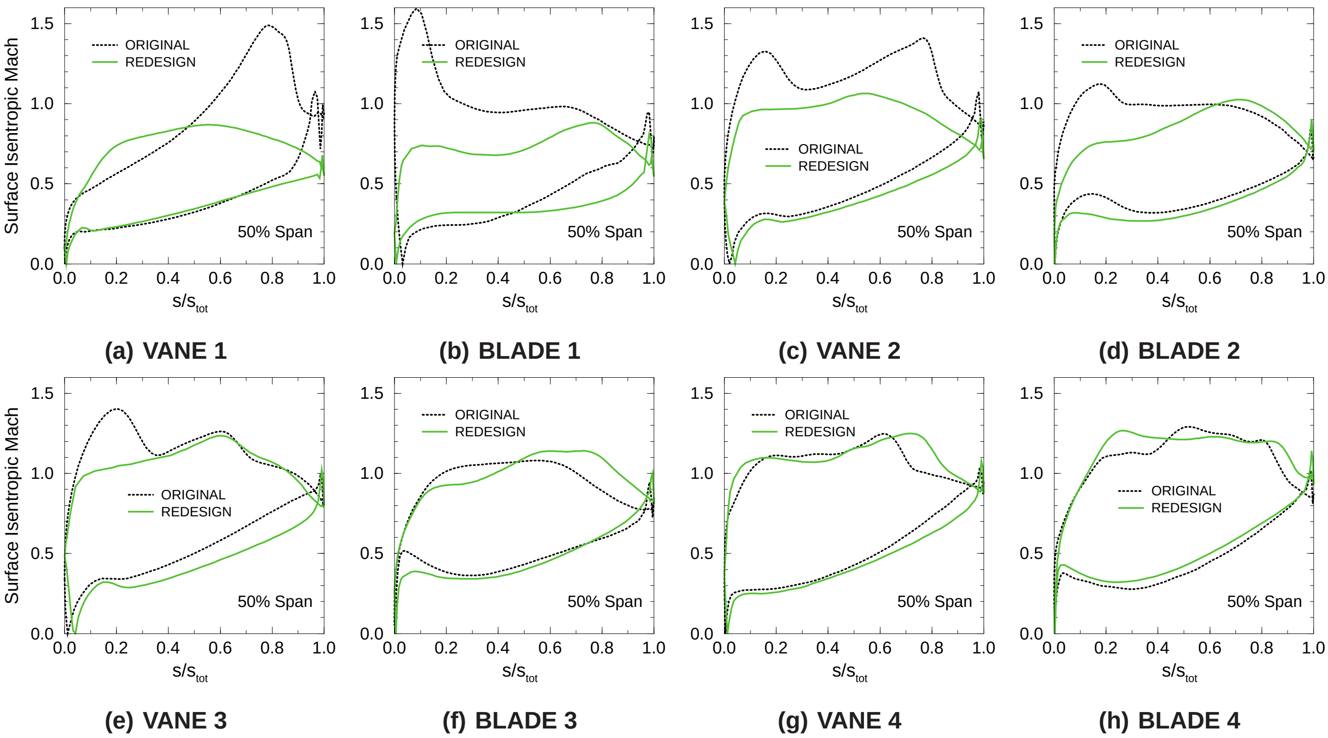


Figure 8: Surface isentropic Mach distributions on each blade at mid-span. Comparison between original and redesign.

achieved by ensuring, in addition to the standard boundary conditions, that the radial distribution of inlet static pressure and outlet flow angle are also respected.

The number of geometric parameters needed to effectively describe an airfoil is high, so the optimization campaigns of this final step are characterized by more degrees of freedom than the previous ones. However, single-row calculations are computationally less expensive, thus allowing to carry out more calculations. Optimizations at this third redesign step were characterized by an average number of degrees of freedom of about 30, and required thousands of calculations for each blade-row. Anyway, each single calculation took about 10 minutes.

As far as details of the optimizations are concerned, the efficiency

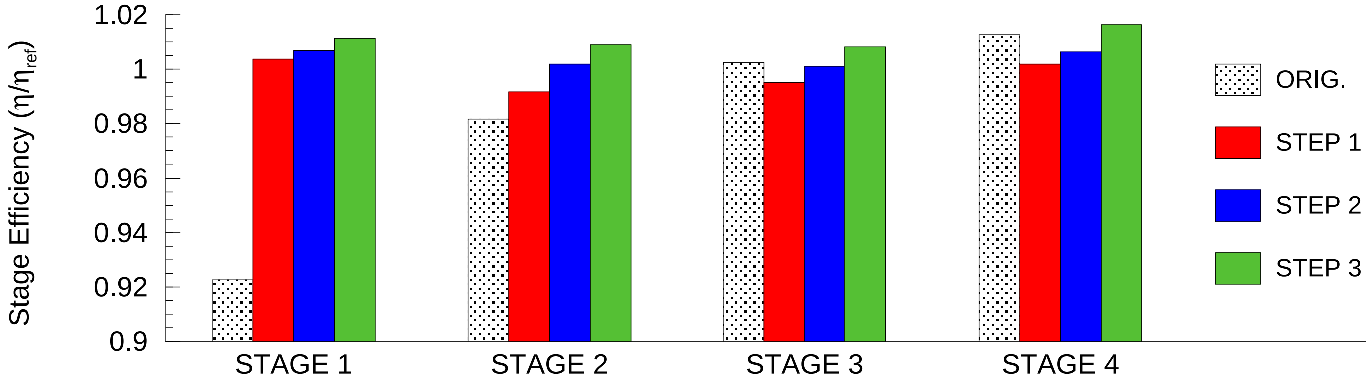


Figure 9: Stage efficiency increase at the end of each redesign step. Efficiency is divided by a reference value.

still represents the objective function, whereas the following constraints are imposed for each blade-row:

- Constancy of the mass flow
- RMS error of the inlet static pressure profile (with respect to the profile from Step 2)
- RMS error of the outlet flow angle profile (with respect to profile from Step 2)
- Structural check of the static behavior (root tensile strength)
- Structural check of the dynamic behavior (blade frequencies)

As an example of velocity distributions obtained throughout the third redesign step, Fig. 6 shows the surface isentropic Mach at three span-wise positions for the last stage rotor (TB4). The corresponding geometrical changes of the same blade are reported in Fig. 7. The overall picture of the new velocity distributions on each blade (at mid-span) is reported in Fig. 8.

CONCLUDING REMARKS

The present paper describes the aerodynamic redesigning of an Ansaldo Energia industrial gas turbine. During the redesign process, several constraints had to be imposed in order to ensure a good level of retrofitability.

The activity was conceptually divided into three steps, corresponding to different design features:

- Step 1: redesign the turbine expansion line (stage enthalpy drops)
- Step 2: span-wise distributions of flow properties within each stage
- Step 3: detailed 3D airfoil shape (blade velocity distributions)

Figure 9 illustrates the efficiency increase attributable to each step of the redesign process. It can be observed how the first stage have benefited from the new pressure drop distribution, frozen at the end of the first step. Moreover, it is worth noticing that Step 2 and 3 have brought appreciable performance benefits to all stages.

Each step was faced with different analysis tools, depending on the specific aspect under investigation. The first step was undertaken by exploiting through-flow calculations, and the blade geometries were optimized by re-twisting the original airfoils. The average stage drops were frozen at the end of this step.

The second step involved 3D multi-row calculations, and consisted of a stage by stage optimization of the airfoil camber lines. The computational domain for the redesign of a given stage included five blade-rows: one row upstream, the stage to be redesigned, and one stage downstream of it.

This third step was undertaken using 3D, single-row RANS calculations, coupled with FEM analysis for mechanical integrity checks. Each significant parameter affecting the airfoil shape was subjected to optimization, the final goal being the definition of optimum blade velocity distributions.

All the above-mentioned activities constitute a global 3D redesign procedure, in which traditional design tools as well as more sophisticated tools were applied in subsequent steps according to a given hierarchical criterion. Each design or analysis tool was coupled with modern optimization techniques, and the overall redesign procedure relied on a neural-network-based approach aimed at maximizing the turbine's power output while satisfying geometrical and mechanical constraints.

Overall, the optimization procedure proved to be an effective tool for the present redesign, and led to an estimated efficiency increase of about 2.5% with respect to the original turbine.

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