A two-stage low pressure gas-turbine model for rotor-stator aerodynamic interaction investigations

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Abstract

In present paper a two stage model of low pressure gas turbine is presented which has been specially designed and constructed for studying the rotor-stator aerodynamic interaction. The model is a large scale, low speed one and allows for detailed measurement of velocity and pressure fields employing the most suitable and advanced experimental techniques. The special design allows for easy change of operating point and main geometric parameters (axial gaps and clocking between bladings) thus making the model a powerful and flexible test rig for stationary and rotating annular cascades. All the model characteristics are described together with the design procedure and philosophy.

Introduction

Low pressure stages of gas turbines have large effect on the whole engine performance and, at the same time, they also have strong influence on the overall cost. Therefore, performance increase and weight reduction of LP stages are of great interest. From this point of view, an important limit is represented by cruise operating conditions where the Reynolds number is low resulting in performance deterioration.

It is well known that the aerodynamic rotor-stator interaction may have a positive effect on the LP stages performance at low Reynolds number (e.g. Schroeder, 1991, Schulte and Hodson, 1998); the physical reason of this – i.e. the effect of upstream generated wakes on the blade boundary layer transition – is also known that reliable numerical models for predicting this phenomenon are not available.

For these reasons a national research project funded by the Italian government is presently ongoing. Within the framework of this project the Universities of Cagliari, Firenze, and Genova have designed and constructed a low pressure, two stage gas turbine model specially devoted to the study of the rotor–stator interaction. The model design philosophy and characteristics are presented in this paper.

Turbine architecture

The model, sketched in fig. 1, is a large scale, low speed, two-stage axial flow turbine; it is representative of low pressure gas turbine stages and its overall dimensions are 3766 mm x 2170 mm x 2269 mm (length x width x height). The working fluid is atmospheric air fed by a centrifugal fan mounted downstream of the turbine model. To obtain repetitive flow conditions as well as to vary the operating point, the turbine is provided with a variable stagger centripetal distributor producing pre-swirled flow at the first stage inlet.

The turbine is braked by means of a 40 kW D.C. reversible electrical motor and the fan is driven by a 60 kW variable speed electronically controlled electrical motor. The desired operating point is obtained acting simultaneously on the electrical motors rotational speed and on the guide vane stagger angle. Mean flow characteristics are monitored by means of aerodynamic probes mounted upstream of the first stator. The first stage inlet turbulence level may be changed by means of screens mounted upstream of the first stator. In case particular flow conditions at the turbine inlet are required an additional rotating wheel, equipped with cylindrical bars, can be added with modification of the first stator wheel.

The turbine model has been specially designed to study the aerodynamic rotor-stator interaction in LP turbines. The main lines of the model design are the following: the most interesting parameters, both geometric and fluid dynamic ones, must be easily changed within the aeronautical application typical range and measurements must be easily taken by means of the most advanced experimental techniques. Beyond the ease in instrumentating the model, for resolution needs, a large scale turbine model is recommended. Furthermore the required power and the overall facility encumbrance are constraints which may become prohibitive.Therefore, to leave more freedom to the design, it has been decided to properly reproduce the interesting fluid dynamic phenomena and to renounce to design a “true” low pressure stage (i.e. Mach number is low and blade aspect ratio is moderate). In such a way the required power has been limited to reasonable values.

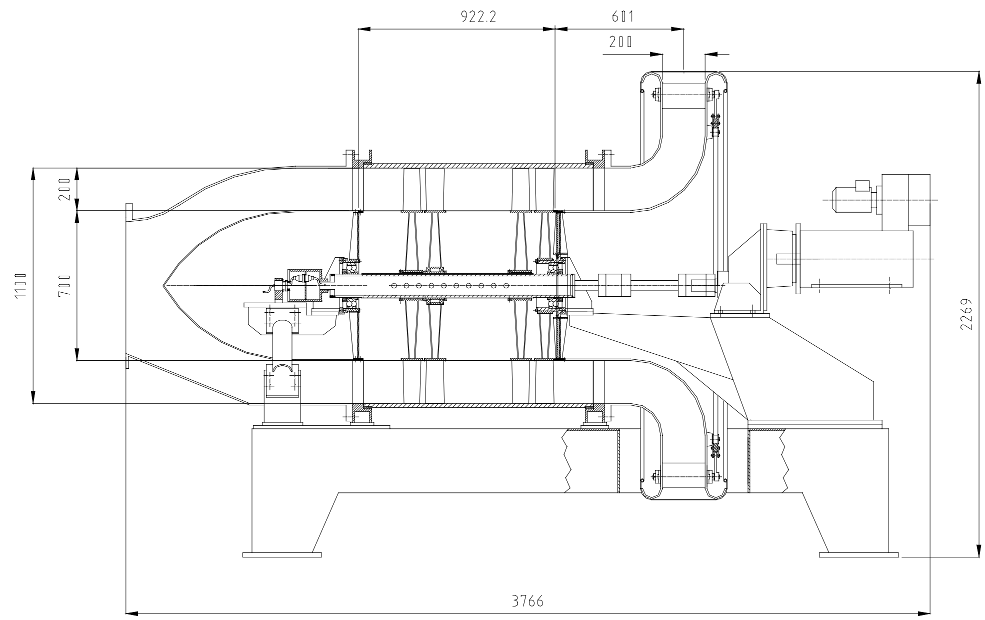

Figure 1. Turbine model.

To comply with these requirements shroud and stators have been made independent to each other: similarly to the rotor blades, also the stator ones are fixed on wheels. These are freely mounted on the shaft and the shroud has no structural function; equilibrium to rotation is obtained by means of metal bars crossing slots in the bottom part of the shroud. Thus, the first stator angular position and the axial positions of the rotors and of the second stator may be varied resulting in variation of both clocking and gapping.

The shroud is made of *Plexiglas*; its upstream part is connected to the centripetal distributor and the downstream part is connected to the discharge channel. *Polidur* bearings allow for independent rotation of the shroud. A long longitudinal opening, which may be filled with modular caps or with an optical glass window, allows for stationay probes insertion within the stators and for LDV measurements respectively.

Axial and radial positioning of the probes is realized by means of a two axis traversing system mounted on the shroud while angular positioning is obtained by means of the shroud rotation system; all movements are computer controlled with minimum steps of 10 μm.

The instantaneous angular position of the shaft is continuously measured by means of an incremental encoder; for rotating probes, transmission of data to the stationary system is obtained by means of a 36-channels, low noise, slip-ring device. The turbine shaft is hollow thus allowing cables from the rotating probes to reach the slip rings. The shaft will also be provided with pneumatic connections in such a way to be used for flow visualisations and to allow for studying flow emission from both rotor and stator blades.

These solutions allow for employing many different experimental techniques: stationary aerodynamic probes and hot wire anemometry, surface mounted (stationary and rotating) hot film anemometer, laser Doppler anemometry, flush mounted miniature pressure transducers (stationary and rotating), flow visualisations.

Flow conditions and turbine geometry

The meridional channel mean radius is 450 mm and the blade height and chord are 200 mm and 120 mm respectively; the bladings may be axially moved within a maximum length of 925 mm. The chord based Reynolds number may be varied up to 300000, corresponding to an outlet isentropic Mach number of 0.113. In these conditions the estimated flow rate is 11.8 kg/s with a total pressure drop per stage of about 1200 Pa and an overall ideal power of about 24 kW (12 kW per stage). Both rotor and stator bladings have 30 blades, resulting in a reduced frequency of 1.282 at the nominal rotational speed of 450 r/min. The complete turbine characteristics at nominal operating conditions are reported in table 1.

Centripetal inlet guide vane			
Inlet diameter	D_{in}	=	1900 mm
Blade height	b	=	200 mm
Inlet total conditions	T_{to}/p_{to}	=	atmospherical
Turbine stage			
Mean diameter	D_m	=	900 mm
Blade height	l	=	200 mm
Blade chord (at midspan)	c	=	120 mm
Pitch to chord ratio (at midspan)	t/c	=	0.785
Blade stagger angle	γ	=	30.8°
Blade numbers	$z_{stat} = z_{rot}$	=	30
Design flow angles at midspan: stator inlet rotor inlet rotor outlet	 α_o α_1/β_1 α_2/β_2	 = = =	 -37.7° 63.2°/37.7° -37.7°/-63.2°
Rotational speed	n	=	450 r/min
Chord based Reynolds number	Re_c	=	300000
Isentropic outlet Mach number	$M_{1is} = M_{2relis}$	=	0.113
Flow coefficient	$\varphi = v_{ax}/u$	=	0.827
Load coefficient	$\psi = 2\Delta p_t/\rho u^2$	=	4.540
Zweifel coefficient	$Z = 2t/c_{ax} \cos\beta_2/\cos\beta_1 \sin(\beta_1-\beta_2)=$		1.055
Reduced frequency	$\nu = z_{rot}nc_{ax}/60v_{ax}=$		1.282

Table 1. Turbine model characteristics.

At midspan the stage is symmetric and the MTU T106 blade profile has been employed (β_1 = -37.7°, β_2 = 63.2°, angles measured from axial direction) for which extensive investigations exist (e.g. Hoheisel et al., 1990; Acton and Fottner, 1997); at nominal conditions a Zweifel coefficient of 1.055 results. The two stages are repetitive and the stator has prismatic blades radially stacked on the trailing edge. The rotor has twisted blades specially designed in such a way to obtain an outlet flow similar to the one generated by the centripetal distributor at the first stage inlet so that nearly repetitive stages are obtained. Particular care has also been put in obtaining a highly loaded stage at midspan (where the aerodynamic interaction plays a fundamental role and the study will focus on) without extensive separations at both stator and rotor tips where solidity is lower. The design procedure of the rotor blade is summarized in the following.

First, a simplified radial equilibrium calculation has been performed to estimate the main stage characteristics and to verify blade twisting which could cause practical problems in making measurements close to the blade surface. For this reason prismatic blades have finally been adopted for the stator where most of measurements will be taken. Twisted blades have been accepted for the rotor to fit better with the stator outcoming flow. The relative flow angle distribution at the rotor inlet has been derived from the stator constant angle while at the rotor exit, to obtain a repetitive stage, a free vortex distribution has been imposed which is the same as the one generated by the centripetal distributor at nominal conditions. In such a way a non zero incidence at radii different from midspan results on the stator blades of both stages. To verify its effect, Navier-Stokes computations of the stage incoming flow have been performed showing that at the endwalls, where the highest incidence is expected, the relative flow angle difference with respect to midspan is limited to few degrees due to the combined effects of the free vortex decay and flow blockage.

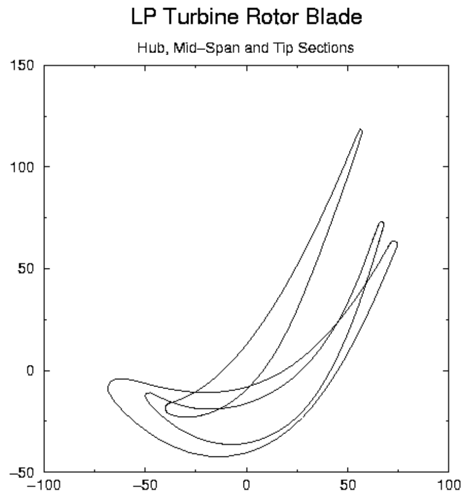

Figure 2. Stacked rotor blade section.

The rotor blade has been designed by specifying three cylindrical sections: one near the hub, one at midspan, and one near the tip. Such sections are shown, in their stacking position, in fig. 2. As previously mentioned, the T106 profile has been used for the midspan section in order to obtain a symmetric configuration in this section. The hub and tip airfoils have been designed in the present work and consist of Bezier curve segments. The airfoil design procedure allows the designer to interactively modify the control points of each Bezier segment in order to obtain a smooth passage contraction from inlet to throat and the desired shape of the blade pressure distribution. A sample tip profile and its control points are shown in fig. 3.

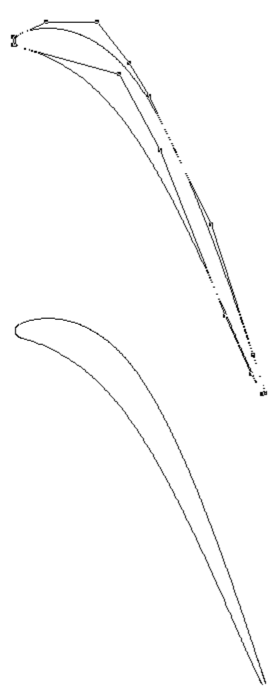

Figure 3. Sample of blade section design procedure.

Each blade section has been checked by using a quasi-3D, blade-to-blade, viscous procedure. The numerical procedure used for such an analysis is a Navier-Stokes solver for turbomachinery flows (Arnone and Pacciani, 1996).

The quasi-3D, Reynolds Averaged Navier Stokes equations are solved for conservative variables (density, absolute momentum components, and total energy) by means of a time dependent approach. The artificial compressibility concept (Chorin, 1967) is used to handle low Mach number flows. Radius and streamtube thickness variations along the considered blade-to-blade surface can be taken into account.

Particular care has been taken in the definition of the tip section where the Zweifel coefficient turned out to be quite high (about 1.2). Due to the low value of the chord Reyolds number, the low solidity of the rotor tip section was expected to produce a flow prone to separation. In such conditions, boundary layer transition is known to play an important role on the onset and extension of separation bubbles on the suction side of the blade (Schulte and Hodson, 1998). Algebraic transition criteria, based on the ones developed by Abu-Ghannam and Shaw (1980), and Mayle (1991), were used, in conjunction with a mixing length turbulence model, to predict transition since this early stage of the design. Typical results of the quasi-3D analysis are shown in figure 4 and 5, where the pressure coefficient and skin friction distributions of the tip section are reported. The pressure coefficient of figure 4 is non-dimensionalized with respect to the outlet dynamic pressure.

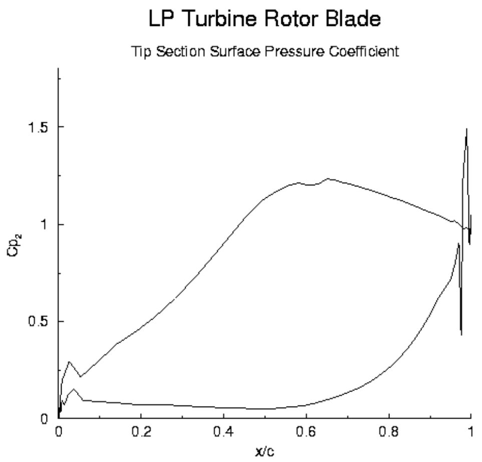

Figure 4. Pressure coefficient at rotor tip.

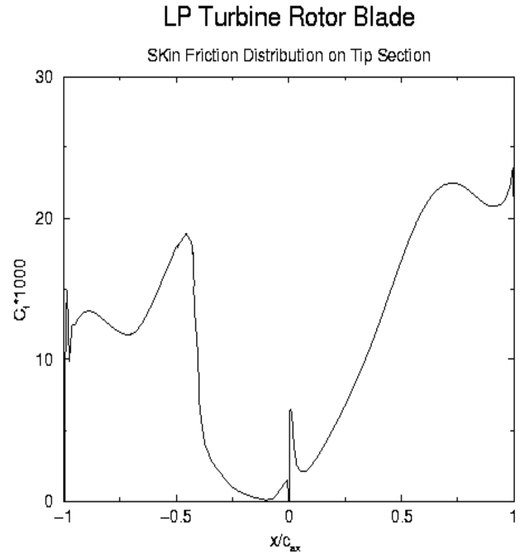

Figure 5. Skin friction coefficient at rotor tip.

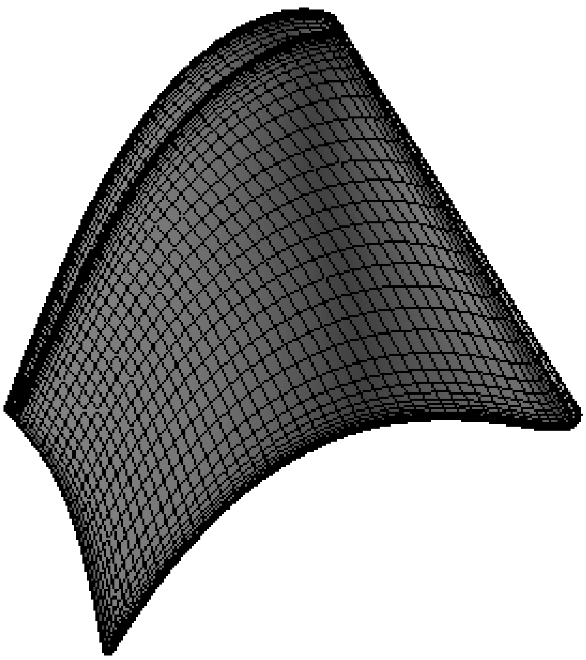

Figure 6. 3D view of the blade.

To enhance the blade sensitivity to wake-induced transition, the hub and tip sections have been designed to be aft loaded. At the tip, where the solidity is low, it was found that increasing the adverse pressure gradient on the suction side would result in the inceptionand rapid growth of a separation bubble downstream the throat section. To limit such undesired phenomenon, the blade loading has been gradually displaced backward, from hub to casing, by raising the sections stagger angle. Such circumstance resulted in the highly twisted blade, as can be deduced from figure 2. This also allows a radially inward optical access required to perform LDV measurements in the suction side boundary layer. Therefore, as shown in fig. 2, a three dimensional stacking of the three sections has then been adopted. The resulting three-dimensional shape of the blade is clearly appreciable in fig. 6. A three-dimensional, steady, viscous analysis of the rotor blade has been carried out to assess the impact of three-dimensional effects and secondary flow. Particularly, such an analysis was mainly aimed at checking the flow characteristics at mid-span. We wanted reduced three-dimensional effects in this region, in order to have a flow structure which resembles the one obtained from a two dimensional computation of the T106 cascade. Inlet conditions for such calculation were taken from a three-dimensional viscous analysis of the inlet duct. A three-dimensional, steady, viscous, analysis of the rotor blade has been carried out to assess the impact of three-dimensional effects and secondary flow. Particularly, such an analysis was mainly aimed at checking the flow characteristics at mid-span. We wanted reduced three-dimensional effects in this region, in order to have a flow structure which resembles the one obtained from a two dimensional computation of the T106 cascade. Inlet conditions for such calculation were taken from a three-dimensional viscous analysis of the inlet duct.

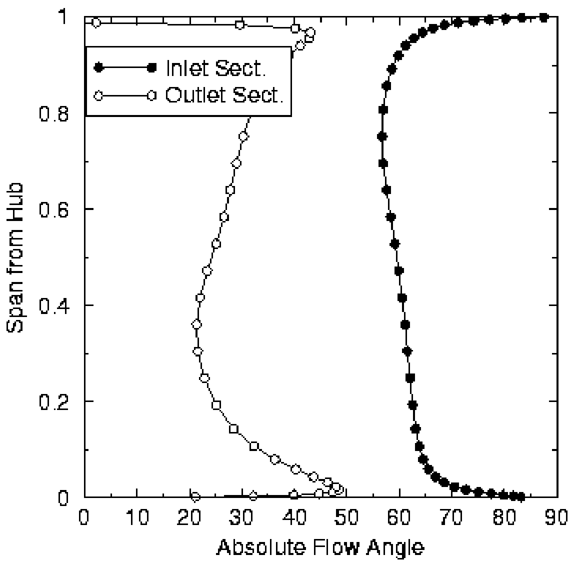

Figure 7. Absolute flow angle at rotor inlet and outlet.

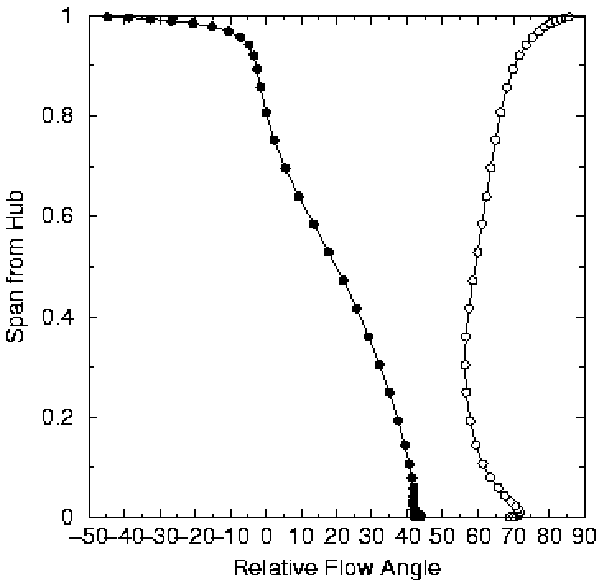

Figure 8. Relative flow angle at rotor inlet and outlet.

Figures 7 and 8 show inlet and outlet radial distributions of absolute and relative flow angles respectively. As can be appreciated, the effects of secondary flows are confined near the endwalls and affects no more than 10÷20 % of the blade span. No relevant distorsions are present along the remaining part of the blade height and the predicted flow structure was considered acceptable for our purposes.

Figure 9 shows blade surface pressure coefficient distributions at three fractions of the rotor blade span. The inlet flow angle appears correctly matched by the inlet blade angle, resulting in a nearly zero incidence value along the whole blade height. A constant acceleration along the suction side of the blade, from inlet to throat, can be appreciated for all the three reported pressure coefficient distributions.

Finally, axial velocity contours near the suction side of the rotor blade are reported in fig. 10. A flow structure typical of the *High-Lift* design concept can be appreciated. Boundary layer thickening effects, without the presence of extensive separations, are observable on the blade surface downstream the throat section.

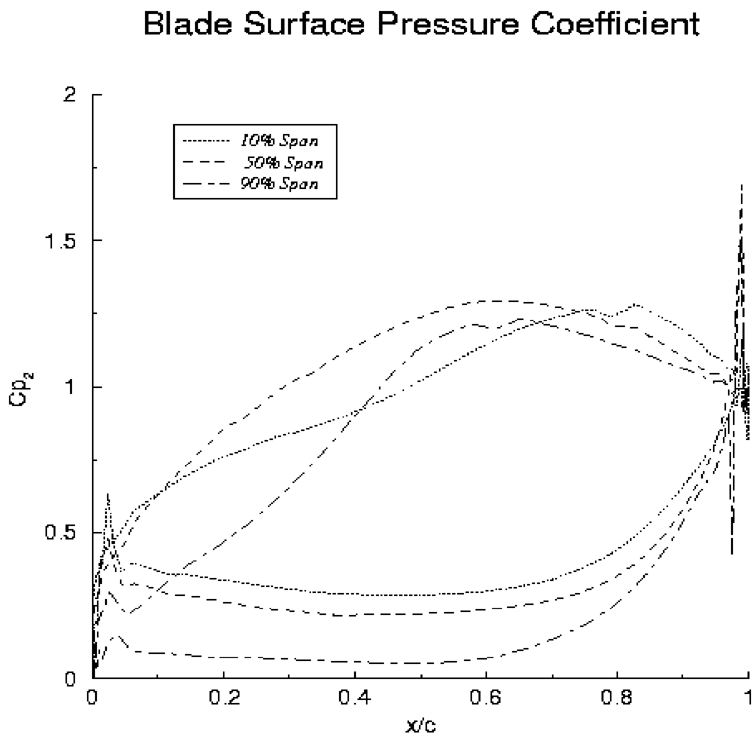

Figure 9. Rotor Blade Surface Pressure Distributions.

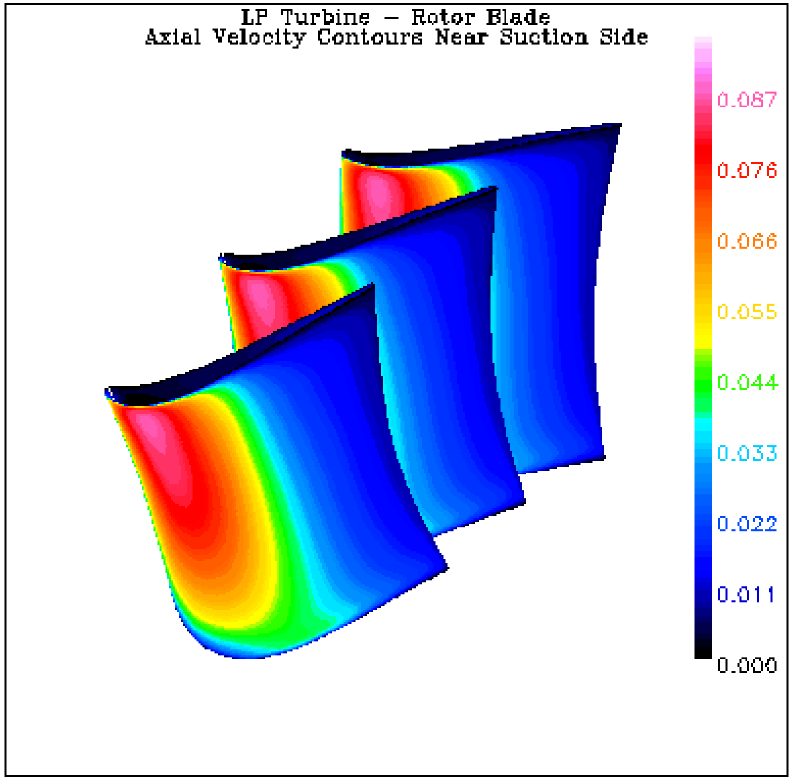

Figure 10. Axial velocity contours on rotor blades.

Conclusions

A two stage model of low pressure gas turbine has been designed and is now available in the turbomachinery laboratories of Cagliari and Genova Universities. The model is devoted to the experimental study of both rotor-stator and stage aerodynamic interactions. The design of the turbine has been carried out with the main aim of allowing for the employment of modern experimental techniques and, at the same time, to realize the most general interaction conditions by means of variation of important geometrical parameters such as axial gappings and stator clocking.

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