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INVESTIGATION OF SWEEP APPLIED TO ROTATING AXIAL CASCADES AND NUMERICAL SIMULATIONS OF FLOW

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Abstract: *This paper presents an original approach regarding the application of sweep to rotating blade cascades. The justification for swept blades is given by its consequence, i.e. a reduction of local velocity (usually from supersonic/ transonic to subsonic regimes) such that the losses due to shock waves and/or boundary layer displacement and/or followed by reattachment are minimized. As study cases were considered a cascade blade, as well as forward and backward sweep of span-wise cross sections. The RANS model was used to describe the flow and a comparative study was conducted by using four turbulence models, i.e. Spalart-Allmaras, k-ε, k-ω and Reynolds Stress RST models. The CFD analysis was done with the FLUENT solver, with the settings for 2D case, implicit equations and double precision. The convergence was monitored such that the residuals should be minimized. The results of the numerical simulations of the flow are expressed as the distributions of Mach number (in relative flow, since it is a rotational frame), static pressure, static temperature and entropy, which have been presented comparatively, for each turbulence model and sweep study case, corresponding to the design rotational speed of 275 [m/s].*

Keywords: *aerodynamics, rotating axial blade cascades, sweep, numerical simulation, CFD analysis.*
MSC2010: __________

1. INTRODUCTION

The design of the modern aircraft engines is targeted to the achievement of new standards for performance and reliability, as well as the satisfying of the environmental friendly demands, i.e. tough limits for aircraft noise and emissions level.

Among the assets of the propulsion technology that produce a quieter engine are the advanced aerodynamics together with composite fans. High speed flow at tip blade, in particular for large diameter fans, is responsible for noise and blade loss induced by the occurrence of shock waves, boundary layer separation and/ or re-attachment.

On the other hand, high blade loading enables a more compact construction of compressors and fan, and therefore weight reduction; nevertheless, the higher the blade loading, the higher the rotational speed and the velocities at tip blade. The sound level of the jet engines can be reduced by the new design of the larger fan blades; as larger fans turn slower than the smaller ones, then the velocity of air is reduced and therefore the noise is lowered. But larger fans involve larger diameters and the velocity at blade tip can be transonic up to supersonic unless the rotational speed diminishes.

The engine thrust can be increased with larger compressor pressure ratios and more stages.

By the design of highly loaded cascades, the number of the compressor stages is reduced, as well as the parts weight. The fewer the compressor stages, then fewer parts and fewer costs. On the other hand, by lowering the flow velocity at tip blade from supersonic to transonic and/or subsonic, blade loss due to shock waves, boundary layer separation and /or re-attachment can be significantly reduced.

Therefore, the use of sweep to the design of blades for the axial flow compressor and fan is advantageous for reducing noise level and blade loss, and hence performance improvement via optimized construction.

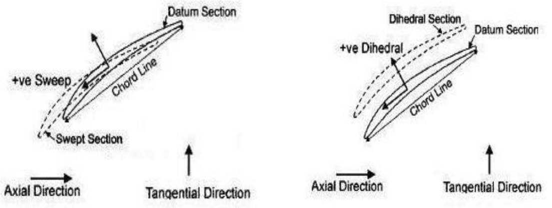
2. BASICS OF BLADE STACKING

2.1 Justification for the use of sweep to transonic cascades

Blade ***sweep*** has been used in transonic compressor design with the intent of reducing shock losses, analogous to the use of swept wings in external aerodynamic applications. Under certain circumstances it is beneficial to align the blade leading and/or trailing edges LE/ TE more closely with the local flow direction. Sweep and dihedral define the stacking line modifications (which are also referred as 3D stacking, [5]) do change the blade surface, such that the blade edges are aligned more closely to the local direction of flow. The 3D stacking is important for both ***technology manufacturing*** **reasons** (with regard to the flow of mechanical operations that allows to obtaining the blade surface) and ***functional***, since it influences the multi staged axial flow compressor's cascades through flow pattern, within blade tip areas and at off-design regimes in a higher extent. From CFD and experiment has been shown that the movement of the boundary layer at blade tip has a large influence upon the rotor flow pattern. For instance, no matter that at the design regime the reverse flow is absent (i.e. the design regime free of local stall), with the decay of the flow coefficient at off-design regimes, the tip blade area (wherein the boundary layer has been detached) becomes larger. The use of *3D stacking* has been the source of a large number of experimental and numerical investigations over recent years, and consequently it came up the need to define carefully the conventions. Considering an axis placed on the LE/ TE lines, Zero-lift airfoil axis or any other particular shape and airfoil movement, can generate the 3D stacking. In Fig. 1 are explained the sweep and dihedral movements.

Both the dihedral & sweep have been introduced and used for the rotor 3D blade design into the core compressors for the Rolls-Royce Trent family engines and Joint Engine Alliance of the GE & PW for the GP7000 series.

According to Gallimore [9-10], Neubert and Weingold [13], Golub, Rawls and Russell [11], theory would suggest that the reduction in shock losses would be achieved by either positive or negative sweep, but tests of various transonic rotors demonstrate the advantage of positive sweep in achieving both improved efficiency and flow range.



(a)- sweep (b)- dihedral

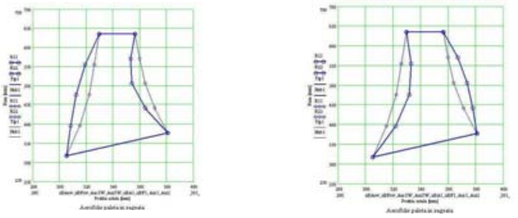
Fig. 1- Basic stacking line modifications, [5]

Near the hub the *positive sweep* reduces the region of low axial velocity towards the TE while the ***negative sweep*** causes a separation to occur. The positive sweep near the hub moves the front part of the suction surface into a higher-pressure region, which reduces the effective incidence and peak velocity along the airfoil chord at the expense of increasing the blade force near the trailing edge. A similar trend is observed near the rotor tip while the opposite trend is observed at mid-height. ***Positively swept*** end-wall sections increase the leading edge blade force and reduce the trailing edge blade force near mid-height. The ***negative sweep*** leads to the creating of favorable conditions for boundary layer separation. The ***positive dihedral*** reduces the hub corner and tip clearance losses, leading to a fuller velocity profile near the end-walls, but at the expense of increasing the losses near the mid-height region. The use of *positive dihedral* has been calculated to be beneficial for both fixed and free ends of blades. It provides a method of introducing a rapid reduction in blade force local to the end-walls and alleviates high suction surface deceleration rates in these regions at the expense of increased blade force at mid-span.

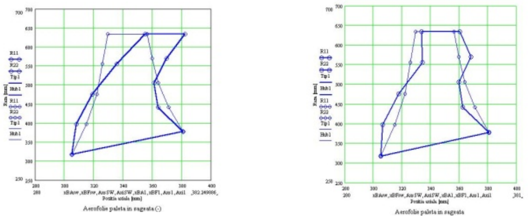
2.2 Swept blade constructions and study cases

Blade loss and noise level are significantly lowered by using the airfoil sweep into 3D line stacking, since the velocity at tip blade is reduced, which means construction optimization for performance improvement.

With respect to the aircraft's flight direction and the air velocity at inlet, the sweep movements are **Forward *FWD* Sweep** (i.e. ***positive sweep***) and **Backward *BCK* Sweep** (i.e. ***negative sweep***), as indicated in fig. 1. With referrence to the axial flow compressor blade, there are 5 significant blade spanwise sections, equally distanced located, as follows: blade hub **B**, midspan **M**, blade tip V, and BM – at bottom half midspan, MV – at top half midspan. Constructions of positive and negative swept blades with respect to the study case rotor blade and swept rotor blade are compared in fig. 2.



(a)- forward sweep (b)- backward sweep



(c)- combination of FWD & BCK sweep (d)- combination of FWD & BCK sweep

Fig. 2- Constructions of swept blades, [1]

Note that the solutions obtained by the author after applng various sweep angles at different blade span-wise cross sections, are very similar with actual fan blade constructions; e.g. fig. 2-c is likewise the fan blade of the *GE Unducted Fan UDF* engine, and fig. 2-d features the fan blades of the *PW&GE GP7200*, *GEnX* and *RR Trent 1000* engines.

The span-wise distributions of the sweep angle $\chi[^\circ]$ for each case are listed in Table 1.

Table 1 Values of the sweep angle $\chi[^\circ]$

Blade cross section	B Bottom	BM	M Midspan	MV	V Top
Case #1	0	5	7	5	0
Case #2	0	-5	-7	-5	0
Case #3	0	5	2	-7	-18
Case #4	0	6	3	-6	-3

3. MATHEMATICAL SUPPORT

3.1 Flow model

The Reynolds Averaged Navier-Stokes RANS equations system (1) has been used for modeling the main flow.

$$\begin{cases} \dfrac{\partial U}{\partial t} + \nabla F = Q \\ \\ \dfrac{\partial T}{\partial t} + \nabla G = S \end{cases} \tag{1}$$

The vectors U (2) and T (3) contain the conservative variables:

$$U = \begin{bmatrix} \rho \\ \rho V \\ \rho E \end{bmatrix} \tag{2}$$

The turbulent kynetic energy k and the turbulent dissipation ε define the vector T.

$$T = \begin{bmatrix} \rho k \\ \rho \varepsilon \end{bmatrix} \tag{3}$$

The flux vector F (4):

$$F = \begin{bmatrix} \rho V \\ \rho V \otimes V + p\bar{\bar{I}} - \bar{\bar{\tau}}^t \\ \rho H V - \rho(\alpha_t + \alpha)\nabla T - \bar{\bar{\tau}} V \end{bmatrix} \tag{4}$$

The source vector Q (5):

$$Q = \begin{bmatrix} 0 \\ \rho f \\ \rho f V + q_v \end{bmatrix} \tag{5}$$

The source term S (6):

$$S = \begin{bmatrix} S_k \\ S_\varepsilon \end{bmatrix} \tag{6}$$

The viscous flux G (7):

$$G = \begin{bmatrix} \rho k V - \left(\mu + \dfrac{\mu_t}{\sigma_k}\right)\nabla k \\ \rho k \varepsilon - \left(\mu + \dfrac{\mu_t}{\sigma_k}\right)\nabla k \end{bmatrix} \tag{7}$$

The RANS model, unllike the Navier-Stokes model, contains within the expression of the flux F (4) the tensor of the total stresses $\bar{\bar{\tau}}^t$ (8) and the effective viscosity μ_{ef} (9), which replaces the molecular viscosity μ.

$$\bar{\bar{\tau}}^t = 2(\mu + \mu_t)\bar{\bar{d}} - \frac{2}{3}(\mu + \mu_t)\nabla V \bar{\bar{I}} \tag{8}$$

$$\mu_{ef} = \mu + \mu_t \tag{9}$$

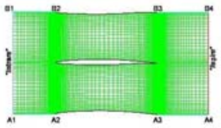
More details about the RANS model and CFD techniques are provided in the papers of Fletcher [3], Chung [4], Hirsch [5], Berbente [6] and others [7, 8].

3.2 Turbulence models

In purpose of closing the equations system, one has to include a turbulence model also; for a thorough analysis, there have been considered four turbulence models: Spalart-Allmaras, $k-\epsilon$, $k-\omega$ and RST model.

4. NUMERICAL RESULTS

In this paper a 2D study has been carried out; there has been considered the reference blade [1], defined by NACA 65(20)10 airfoils, customized blade span-wisely for the specific conditions of a rotating cascade.



(a)- no sweep effect

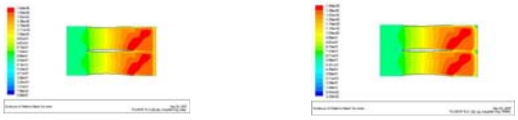
(b)- forward sweep (c)- backward sweep

Fig. 3 Computational grid

The airfoil at mid-span has been considered for the 2D study, as well as the boundary conditions and other limitations due to the neighboring cascades and the given geometry of a multi-staged axial-compressor, [1].

There have been computed the solutions (i.e. the flow parameters) of the RANS model in association with the turbulence models, for the mid-span airfoil, without sweep effect (fig. 3-a) and with forward sweep (fig. 3-b) and backward sweep (fig. 3-c) respectively. The convergence of the solutions has been monitored for different values of the rotational speed, i.e. 0, 100, 200 and 275 [m/s].

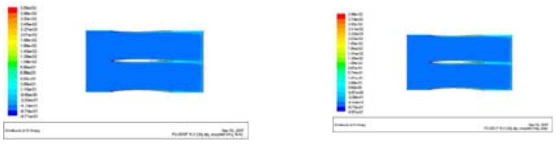
(a)- Spalart-Allmaras (b)- $k-\epsilon$



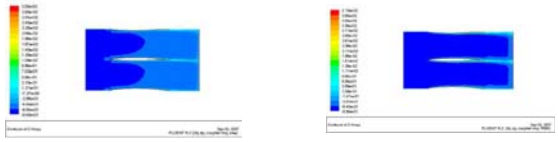
(c)- $k-\omega$ (d)- RST

Fig. 4 Mach number of the relative flow,

/ Spalart-Allmaras, $k-\epsilon$, $k-\omega$ and RST turbulence models/ no sweep effects



(a)- Spalart-Allmaras (b)- $k-\epsilon$

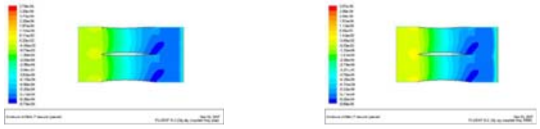


(c)- $k-\omega$ (d)- RST

Fig. 5 Entropy distributions,
/ Spalart-Allmaras, $k-\epsilon$, $k-\omega$ and RST turbulence models/ no sweep effects

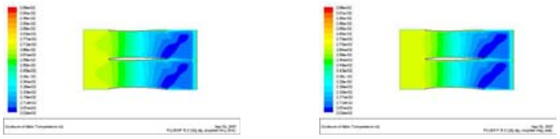
As one can notice from figs. 4-7, the numerical results and the computational accuracy are influenced in greater extent by the turbulence model. For the cascades of multistage turbomachinery, the Spalart-Allmaras model it is convenient to use due to its fast convergence velocity and it is simpler, since it is described by one equation. The $k-\epsilon$ turbulence model is rather suited to capture wall-effects, while for the main flow the other models are more accurate. The more equations used to describe the turbulence model, the greater the number of iterations to achieve a convenient computational accuracy.

(a)- Spalart-Allmaras (b)- $k-\epsilon$

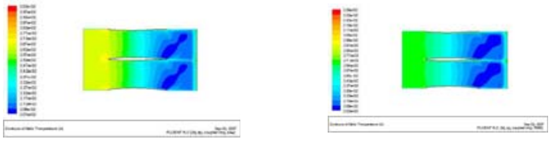


(c)- $k-\omega$ (d)- RST

Fig. 6 Pressure distributions,
/ Spalart-Allmaras, $k-\epsilon$, $k-\omega$ and RST turbulence models/ no sweep effects



(a)- Spalart-Allmaras (b)- $k-\epsilon$



(c)- $k-\omega$ (d)- RST

Fig. 7 Temperature distributions,
/ Spalart-Allmaras, $k-\epsilon$, $k-\omega$ and RST turbulence models/ no sweep effects

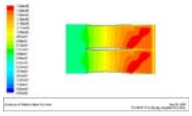
For the study case, the results obtained by using the Spalart-Allmaras SA turbulence model are in accordance with experimental data; the highest percent of recommendations that can be found in literature [14-32] points out that for the flow in (axial) cascades the Spalart-Allmaras model is the best option to describe the turbulence.

Table 2 – The number of iterations necessary for obtaining the convergence

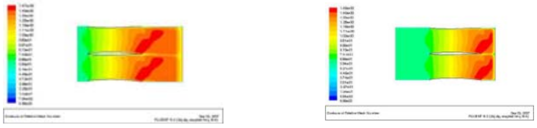
Turbu-lence model	Number of iterations		
	No-sweep	Forward sweep	Backward sweep
S-A	3160	2781	4072
$k-\epsilon$	2923	2348	4255
$k-\omega$	5115	5172	4020
RST	3308	2339	4972

In the following, there are highlighted the effects of both forward and backward sweep of the study case airfoil; a thorough computational analysis was performed, after considering four turbulence models.

The results depicted in figs. 8-11 refer to the computations carried on with the Spalart-Allmaras turbulence model.

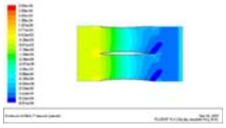


(a)- no sweep effect

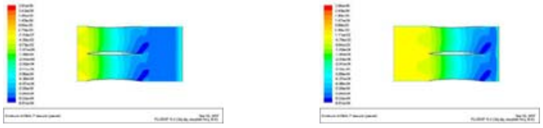


(b)- forward sweep (c)- backward sweep

Fig. 8 Effect of sweep on Mach number

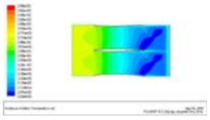


(a)- no sweep effect

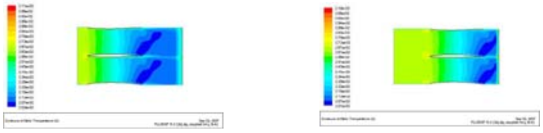


(b)- forward sweep (c)- backward sweep

Fig. 9 Effect of sweep on static pressure



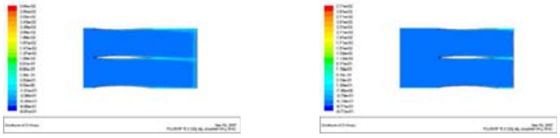
(a)- no sweep effect



(b)- forward sweep (c)- backward sweep

Fig. 10 Effect of sweep on static temperature

(a)- no sweep effect



(b)- forward sweep (c)- backward sweep

Fig. 11 Effect of sweep on entropy

5. CONCLUSIONS

This paper presents a thorough investigation regarding the application of sweep to rotating axial blade cascades.

The author develops an original approach with regard to the obtaining of swept blade constructions, as derivatives of a basic cascade blade configuration.

As study cases were considered cascade blades, with forward and backward sweep versus no-sweep configurations.

The RANS model was used to describe the flow and a comparative study was conducted by using four turbulence models, i.e. Spalart-Allmaras S-A, $k-\varepsilon$, $k-\varpi$ and Reynolds Stress RST models. The CFD analysis was done with the FLUENT solver, with the settings for 2D case, implicit equations and double precision. The convergence was monitored such that the residuals should be minimized; the number of iterations required for obtaining the convergence is listed in Table 2.

The results of the numerical simulations of the flow are expressed as the distributions of Mach number (in relative flow, since it is a rotational frame), static pressure, static temperature and entropy, which have been presented comparatively, for each turbulence model and sweep study case, corresponding to the design rotational speed of 275 [m/s]. In accordance with the experiment and literature [14-32], it came out that the Spalart-Allmaras model represents a good option for modeling the turbulence within blade cascades.

In figs. 8-11 it has been shown the effect of forward and backward sweep versus no-sweep, for the flow parameters, such as the relative Mach number, static pressure, static temperature and entropy.

Concluding remarks:

- Forward sweep allows to reduce the local velocity at blade tip and expands the area downstream the airfoil such that the losses are minimized (which is beneficial for obtaining uniform flow at the next stage cascade inlet), since the variation of the entropy is the least; thus, the optimization of blade cascades with minimum losses is enabled.
- S-A turbulence model is more suited for the CFD analysis of cascades.
- the solution is obtained faster for forward swept blade, while far much greater

number of iterations are required for backward swept blade.

- Combinations of forward and backward sweep can be used for highly loaded wide span fan blades, fig. 2-c, 2-d, [1].

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