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SHOCK WAVE BOUNDARY LAYER INTERACTION INVESTIGATION: CONTROL BY ROD VORTEX GENERATORS AND THEIR APPLICATION ON HELICOPTER ROTOR BLADES

F. Tejero E., P. Doerffer, P. Flaszyński

The Szewalski Institute of Fluid-Flow Machinery
Polish Academy of Sciences
Fiszera 14, 80-231 Gdańsk, Poland
{fernando, doerffer, pflaszyn}@imp.gda.pl

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Abstract. *The paper describes the numerical simulations of a new passive flow control device (Rod Vortex Generator - RVG) and the possibilities to induce streamwise vortices for controlling of a shock wave boundary layer interaction. Firstly, a row of rods were placed at the lower wall of a curved wall nozzle with negative pressure gradient. The lower wall is designed in order to mimic similar flow conditions as for wings or helicopter rotor blades. The severe flow conditions (M = 1.43) result in a strong reverse flow which is controlled by the proposed vortex generators. On the other hand, the application of RVGs on helicopter rotor blades was analyzed. In the case of forward flight conditions, flow separation is usually present at the advancing side due to shock wave boundary layer interaction while dynamic stall appears at the retreating side. The numerical results of the flow past the AH-1G helicopter rotor blade were validated against flight test data and the flow separation on the advancing side was reduced by the proposed technology improving the aerodynamic performance (ratio thrust / torque).*

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1 INTRODUCTION

Nowadays it is required to design devices of the highest efficiency leading to minimum emissions. For this reason, flow control devices are becoming more popular over the last years. For example, for energy consuming applications (e.g. rotorcrafts), the use of a proper flow control system might reduce the fuel consumption, thus limiting the CO_2 emissions.

The main feature of the aerodynamic of a helicopter is the unsteadiness of the flow due to the rotating parts (i.e. main and tail rotors). There have been several investigations concerning the flow separation reduction at the rear of the helicopter fuselage (non-rotating) which is the major component of the parasitic drag of the helicopter [1]. On the other hand, several flow control devices might be suitable at the rotating parts of the helicopter. It is important to remark that in forward flight conditions, the forward velocity is added to the blade's rotating velocity on the advancing side ($0^\circ < \psi < 180^\circ$), while the forward velocity is subtracted from the blade rotation on the retreating side ($180^\circ < \psi < 360^\circ$). This unsteadiness of the flow passing the rotor blade leads with compressibility effects on the advancing side due to severe Mach number and dynamic stall on the retreating side caused by high inflow angles. For this reason, a list of different flow control devices suitable for the rotating parts of the helicopter have been identified: vortex generators, gurney flaps, movable flaps, synthetic jets, surface suction, passive porous surfaces, riblets, etc. Working principle of each device, with the main benefits for rotorcraft application was recently published by Kenning *et al.* [2].

This paper presents the numerical investigation of separation reduction on helicopter rotor blades by Rod Vortex Generators (RVGs). As a previous step, a basic configuration of a curved wall nozzle with a strong shock wave ($M = 1.43$) which induces flow separation was studied. The application of RVGs induced streamwise vortices, limiting the reverse flow. Besides, their implementation on a wing configuration suggested that the ratio lift/drag was also possible to improve with this passive system [3]. RVGs are capable to induce streamwise vortices which enforce an exchange of momentum in the direction normal to the wall. High-momentum is transferred to the low-momentum area close to the wall, becoming fuller the boundary layer profile at the low-momentum area (separation control). Several parameters play an important role in the effectiveness of RVGs: diameter (ϕ), height (h), and pitch (Θ) and skew (a) angles, see Fig. 1. For all simulations presented in this paper, the RVGs were designed according to the boundary layer thickness (δ) of each case. According to previous investigations, the rods were designed with the following parameters: $\phi = 0.5\cdot\delta$ and $h = 0.25\cdot\delta$. In the case of pitch and skew angles, it was concluded during an optimization investigation that the strongest streamwise vortices are created for 30° and 45°, respectively.

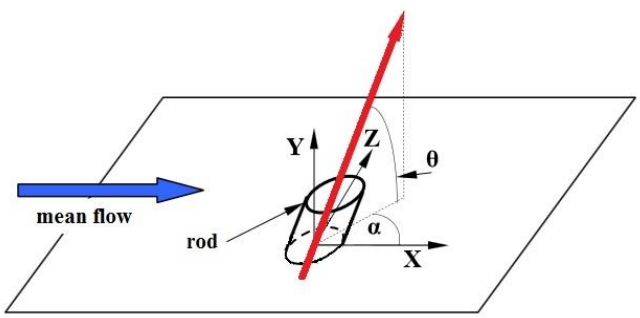

Figure 1. Schematic view of the Rod Vortex Generators

2 PHYSICAL AND NUMERICAL MODELLING

The numerical investigation was carried out with the FLOWer solver from DLR [4]. It is a modern, block-structured, aviation oriented, cell-centered code with different turbulent models closures. The ROT version of the code allows the usage of the chimera overlapping grids technique [5] and moving meshes. This approach allows to easily create grids for complex configurations (e.g. rotor blades). Besides, the implementation of RVGs on the rotor blade is solved with a single grid (RVG grid) which is added to the reference chimera set-up. Due to the capabilities of separation prediction, the two equations, low-Reynolds $k-w$ turbulence model LEA (Linear Explicit Algebraic Stress Model) [6] was chosen. The numerical algorithm uses a finite-volume, central scheme of 2nd order for the spatial discretization. The same explicit, Runge-Kutta method (CFL = 2.5) of time integration, was used for the steady simulations of the curved wall nozzle, as for the internal iterations of the implicit dual-time-stepping scheme of 2nd order applied for the helicopter rotor blade in forward flight conditions.

3 CURVED WALL NOZZLE

The experimental investigations of supersonic nozzles were carried out in flat and curved test sections. Previously, both nozzles were investigated within the UFAST project (Unsteady Effects in Shock Wave Induced Separation) [7] providing the largest available database concerning unsteady shock wave boundary layer interaction. The present numerical investigation is only focused in the curved wall nozzle (negative pressure gradient which mimics flow conditions around airfoils/wings or helicopter rotor blades). Its main feature is that in the curved duct the supersonic area is generated at the convex wall. The Mach number upstream of the shock wave increases with the increasing mass flow rate in the nozzle, until it is choked.

Prediction of the flow separation, its location and reattachment lines or size of the separation bubble is very important for accurate prediction of aerodynamic performance. In the case of channel flows, the proper prediction of flow structure is highly dependent on the appropriately resolved corner flows. The CFD results were compared with the measurements gathered during UFAST project: boundary layer profiles, static pressure on the wall, oil visualization and schlieren picture.

Figure 2 presents the Mach number contour map for the curved wall nozzle. The strong shock wave at the lower wall induces flow separation.

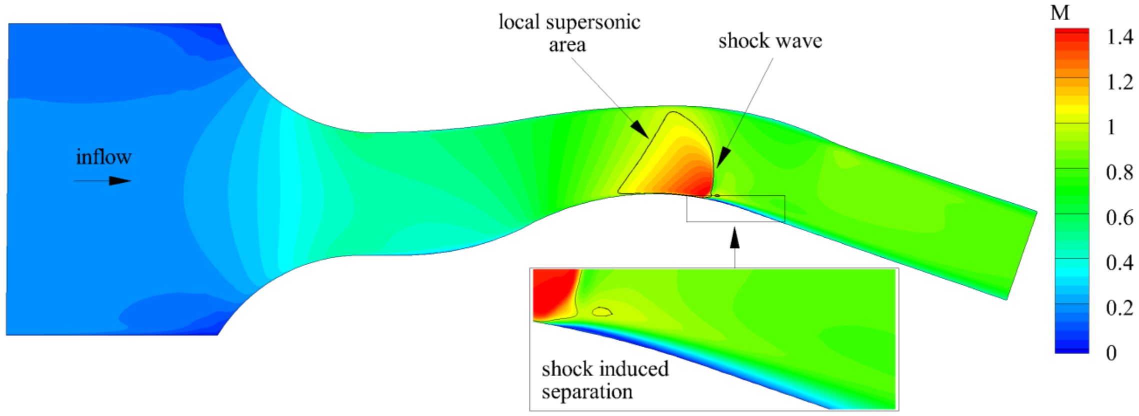

Figure 2. 2D view of the curved wall nozzle

In total, 16 RVGs are placed in spanwise direction covering the full span of the nozzle. Each rod is embedded in a rectangular box and a butterfly topology within the box is applied (see Fig. 3). The application of the RVGs increases significantly the number of mesh cells:

from $4.86 \cdot 10^6$ for the reference case to $21.7 \cdot 10^6$ for the flow control case. For all simulations the non-dimensional of the first layer of cells from the wall is of the order of $y^+ = 1$ (sufficient for resolving the laminar part of the turbulent boundary layer).

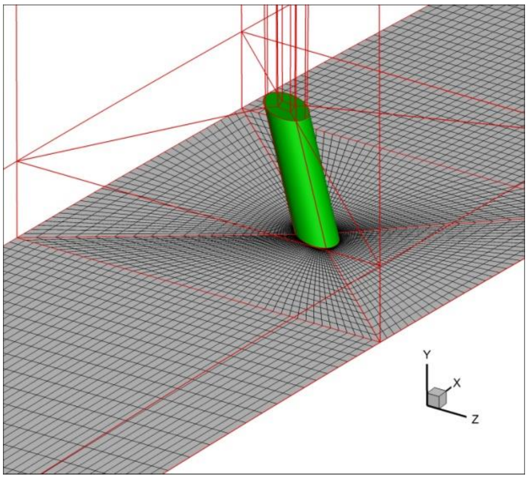

Figure 3. RVG detail and grid topology

Figure 4 presents the boundary layer comparison for the reference case at three cross sections: X = 15 mm (upstream of the flow separation), 67 mm (area of reverse flow) and 145 mm (downstream of the flow reattachment). It is noticeable that the predicted incoming boundary layer is overpredicted in reference to the measurements which results in an overprediction of the separation bubble. The separation bubble height is slightly larger in the simulation than in the experimental data. Lastly, the last cross section allows for a comparison of the boundary layer thickness for the reattached flow, showing its overestimation by the CFD simulations.

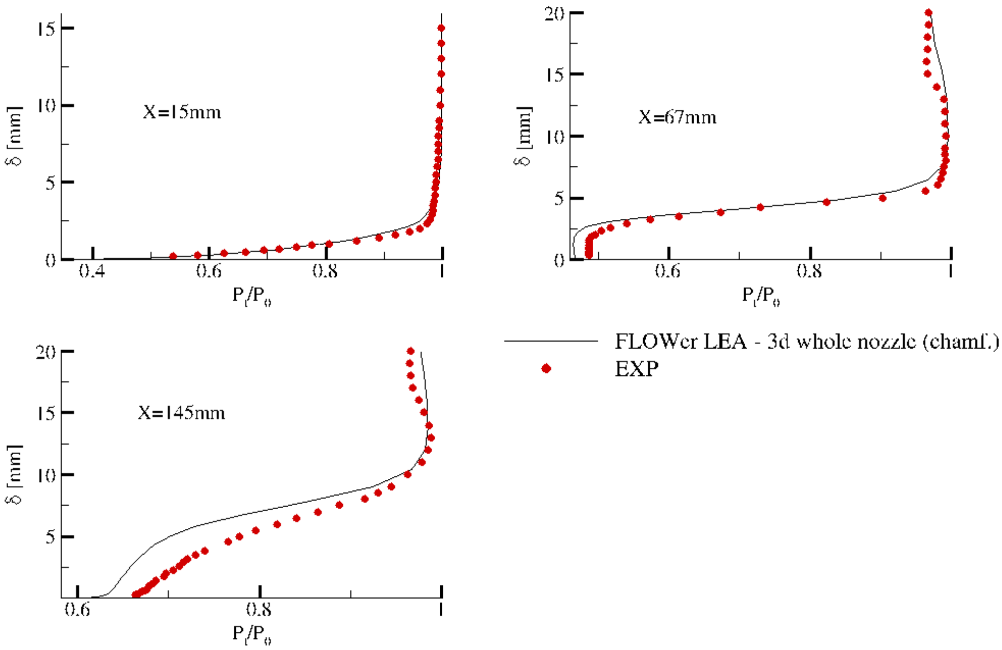

Figure 4. Boundary layer comparison – Reference case

Figure 5 presents the boundary layer comparison when the RVGs are applied. Both cross-sections are located downstream of the shock wave. It is visible that some differences of the boundary layer thickness and triple point location exist. More detailed results with different CFD solvers (Ansys – Fluent and Numeca Fine/Turbo) and turbulence models (Spalart-Allmaras and SST) can be found in [8].

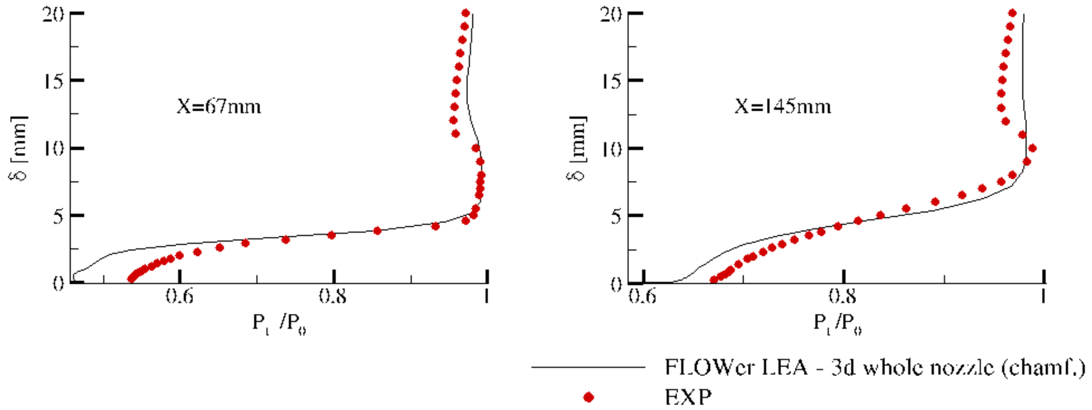

Figure 5. Boundary layer comparison – RVG case

Comparison of the separation bubbles size for the reference and flow control cases is shown in Figure 6. Although the reverse flow is not fully eliminated, the large separation bubble seen in the reference case is reduced and splitted into smaller bubbles, proving the effectiveness of this proposed passive flow control device.

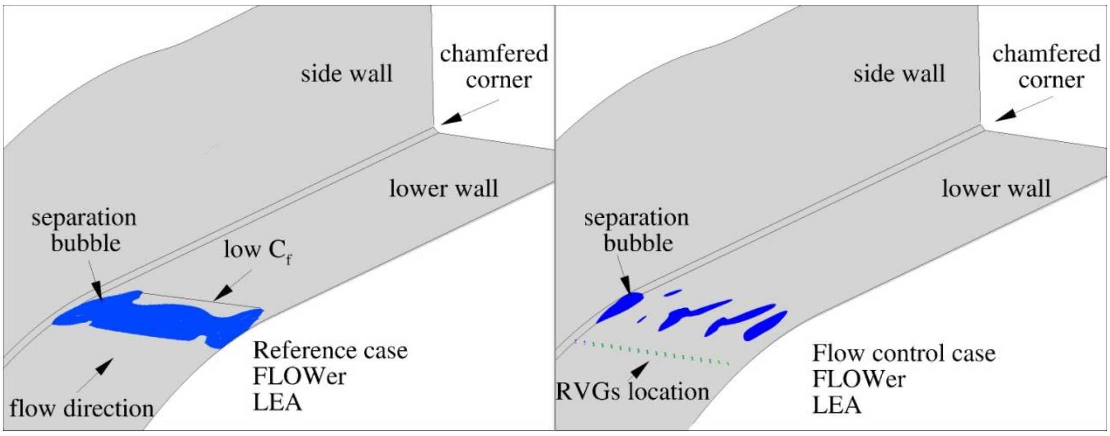

Figure 6. Separation control by RVGs on the curved wall nozzle

4 AIRFOIL CONFIGURATION

The aerodynamic enhancement by RVGs on an airfoil/wing configuration was investigated as previous step to helicopter rotor blades. For this reason, the flow around the NACA 0012 for severe conditions was studied. The Mach number was set to M = 0.8 and Reynolds number Re = $9 \cdot 10^6$. These flow conditions are representative at the advancing side of the flow passing the helicopter rotor blade in high-speed forward flight. Due to the severe inflow conditions, supersonic areas with strong shock waves induce flow separation. The angle of attack was increased to intensify the shock wave and therefore the reverse flow. The numerical validation of the reference case can be found in [3] as well as more detailed information concerning the geometry.

The onset of the reverse flow for the studied conditions is AoA = 1.4˚ (the flow is reattached) and above AoA = 2.0˚ the flow separation is strong enough to prevent the reattachment. The figure 7 presents an exemplary picture (AoA = 4.0˚) of the suction side of the airfoil with an array of four rod vortex generators. The shock wave induces flow separation at 40% of the chord. The application of RVGs leads to the increment of the skin friction downstream of the rods (due to the formation of streamwise vortices) and a delay of the separation line to 44% of the chord.

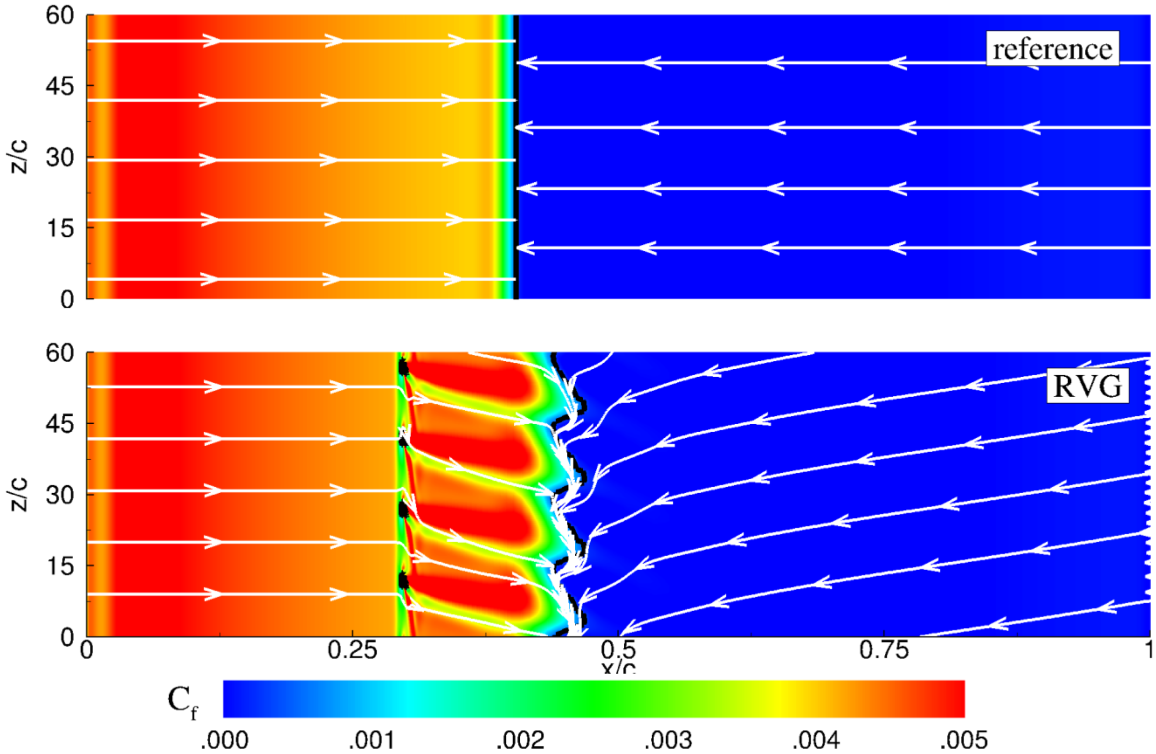

Figure 7. Friction coefficient and streamlines (M = 0.8, Re = $9{\cdot}10^6$, AoA = 4.0˚)

Figure 8 presents the effect of the RVGs on the normal force (C_n), drag (C_d) and pitching moment (C_m) coefficient. Below AoA = 1.4˚ for the polar graphs of the flow control device, no data is shown since the flow is fully attached to the profile, therefore it cannot be expected a positive effect of the RVGs. With increasing angles of attack, the reverse flow is stronger and the positive effect on terms of C_n appears. Besides, the stall angle of the airfoil is increased by 2.0˚ with the flow control system. The increment of C_n results in a drag penalty which is acceptable if the ratio C_n / C_d is compared. For the same drag, the application of the RVGs provides a higher C_n (better aerodynamic performance). Only a slight difference appears for high angles of attack when the C_m is compared. Therefore, it can be concluded that the application of RVGs on airfoils lead with a separation control which is related to the aerodynamic enhancement presented here.

5 HELICOPTER ROTOR BLADE IN FORWARD FLIGHT

The application of the passive rod vortex generators on the helicopter rotor blades was investigated for two different states of flight: hover and forward flight. In the case of hover conditions, the model helicopter rotor blade of Caradonna – Tung [9] was chosen due to the availability of experimental data for severe conditions which induced flow separation and could be controlled by the proposed flow control system. For validation purposes, the transonic case with a tip Mach number of 0.87, collective angle equal to 8˚ and tip Reynolds number of $3.9 \cdot 10^6$ was chosen. A review of previous RANS simulations for this severe test case reveals a significant scatter with the measurements [10, 11]. The implementation of 14 RVGs at the tip of the blade lead to a separation control and aerodynamic enhancement (thrust coefficient was increased by 2.2% with a power consumption penalty of 1.2%) [12, 13].

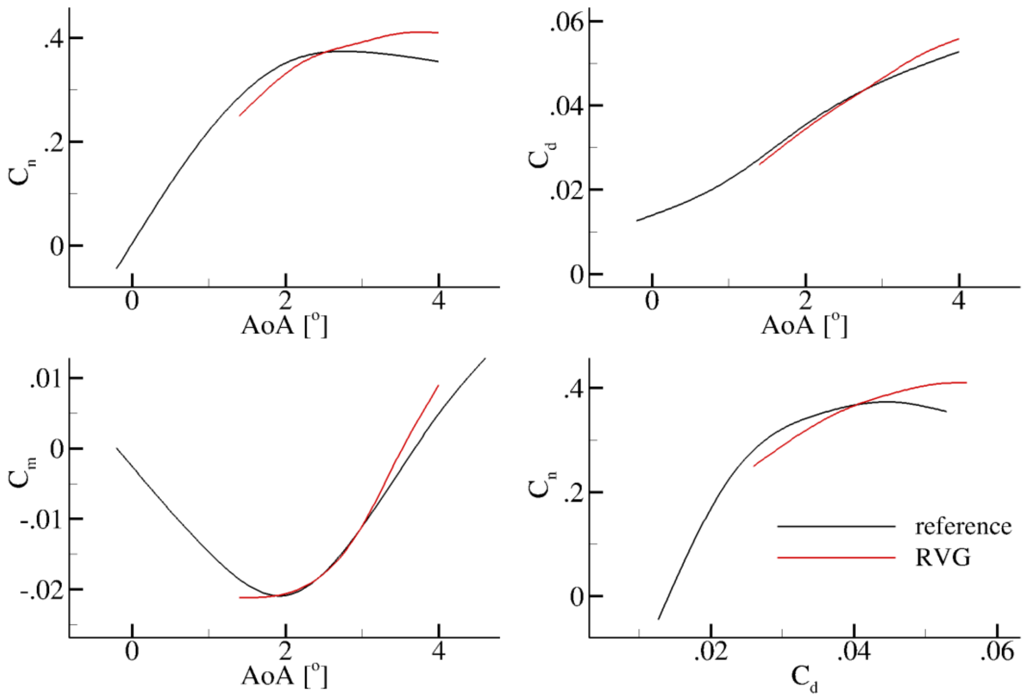

Figure 8. Comparison of C_n, C_d and C_m ($M = 0.8$, $Re = 9 \cdot 10^6$, AoA = 4.0˚)

On the other hand, the numerical model for the AH-1G helicopter rotor blade in forward flight was validated against the flight test data gathered during the Tip Aerodynamics and Acoustics Test (TAAT)[14]. The AH-1G is a two person, single-engine, 2-bladed, teetering rotor with a 540 symmetrical airfoil section and a linear twist of -10˚ from the shaft to the tip. During the TAAT test different forward speeds were investigated and reported. The numerical model for three different markers (low-[15, 16], medium- and high-speed) was recently published in [17, 18] where it is also possible to find a detailed description of the geometrical model applied (chimera overlapping grids technique). Only the high-speed case reveals significant flow separation which might be controlled by the proposed flow control system. The reverse flow is caused by the severe flow conditions passing the rotor blade: tip Mach number of 0.63 and advance ratio equal to 0.38. Figure 9 presents the change of normal force coefficient (C_n) with the azimuthal position at the cross section r/R = 0.99 for different speed markers. The agreement with flight test data is acceptable despite of the numerical model simplifications (e.g. the influence of the fuselage is neglected and the blades are considered as rigid).

The rod vortex generators were designed according to the previous investigations (nozzle flows and airfoils) and the flow properties (boundary layer thickness) present at the advancing side. The application of this passive flow control device on helicopter rotor blades in high-speed forward flight leads with two different behaviors. Firstly, the shock wave boundary layer interaction at the advancing side is controlled which is reflected in an enhancement of the normal force coefficient. Secondly, the dynamic stall present at the retreating side is not controlled by the RVGs due to the flow is separated already from the leading edge (rods are located in the reverse flow area and streamwise vortices are not created).

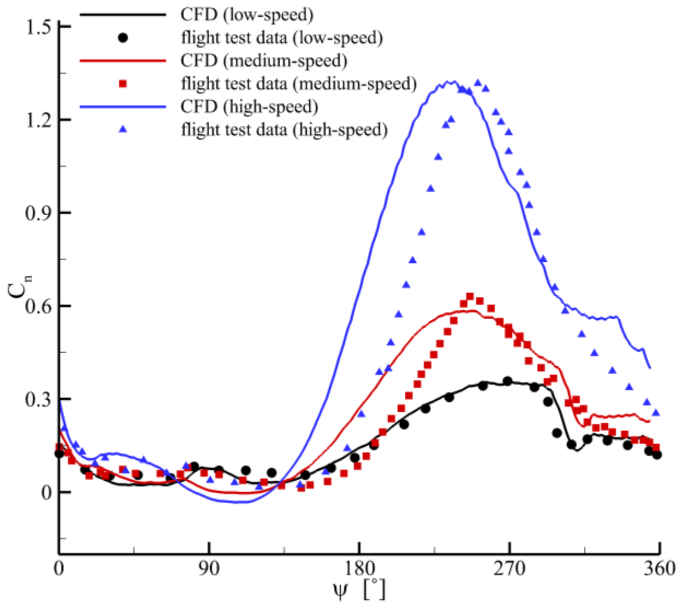

Figure 9. Instantaneous normal force coefficient C_n at r/R = 0.99 [17]

Figure 10 presents the rotor disk colored with the difference of the normal force coefficient (C_n) of the flow control configuration respect the reference case [18]. It is noticeable how the majority of the disk is colored with green (value of 0) due to the local influence of the rods in the global performance. Only their effects are present between the inner and outer rods with red color (positive effect) on the advancing side and blue color (negative effect) on the retreating side. The other azimuthal positions show a positive effect due to the low skin friction present for these positions.

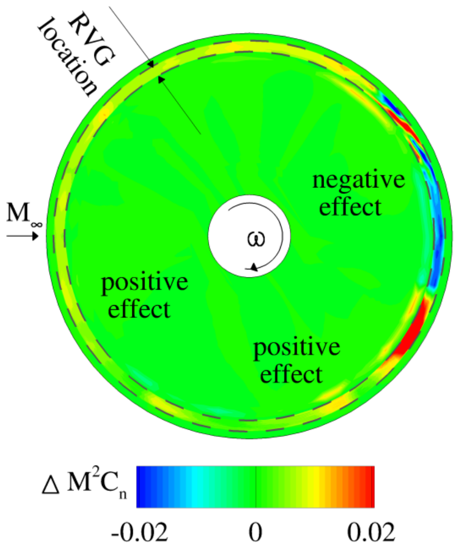

Figure 10. Normal force coefficient difference (flow control - reference) for the AH-1G helicopter rotor blade in high-speed forward flight

The flow separation induced by the strong shock wave is controlled by the proposed flow control device (see fig. 11). As shown at the selected cross-section and azimuthal positions for which reversed flow exists in case of the reference case, the flow is attached to the blade surface for the RVG configuration.

The positive effect of the RVGs on the advancing side leads with an increment of the thrust coefficient by 2.6% with a power consumption penalty of 1.1%.

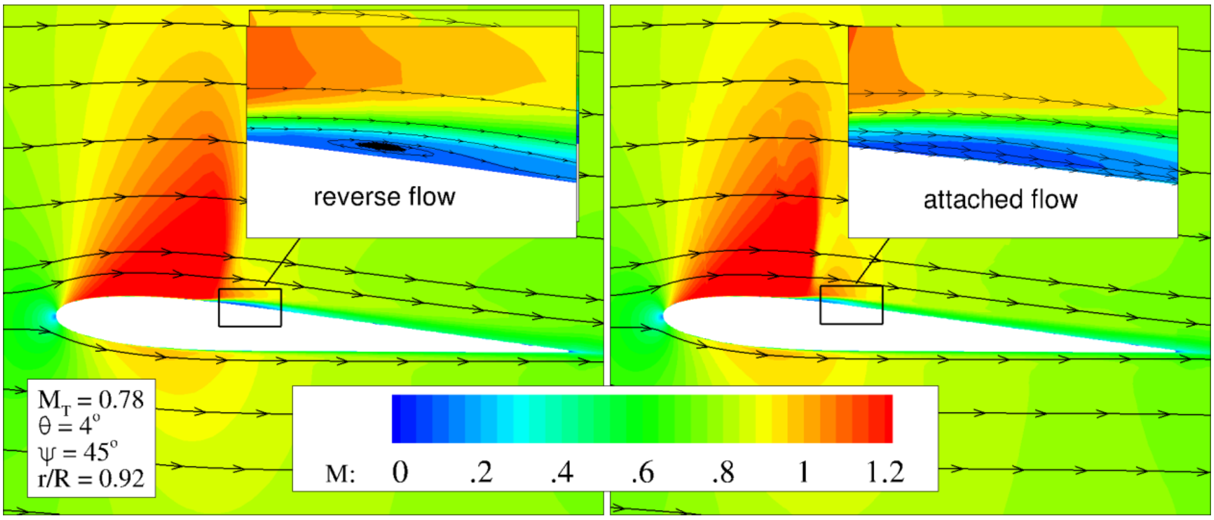

Figure 11. Contour map of Mach number at r/R = 0.92

6 CONCLUSIONS

The paper presents the numerical investigation of a passive flow control device (Rod Vortex Generators - RVGs) and the application on helicopter rotor blades. First of all, the flow separation control was investigated in more simple configurations as channel flows or airfoils. In both cases, the flow separation was reduced by means of streamwise vortices. Besides, the possibilities of aerodynamic enhancement on airfoils were studied with success.

The numerical simulations confirmed that the application of RVGs on helicopter rotor blades leads with a separation control which is reflected in an increment of thrust coefficient with a minor power consumption penalty.

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