Effect of Passive Air Jet Vortex Generator on NACA 0012 Performance

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Abstract

A numerical study of air jet vortex generator (AJVG) to delay or suppress flow separation is presented in this paper. Many researchers agree with the effectiveness of AJVG on airfoils for low Mach numbers (up to M=0.3-0.4). When the Mach number is increased, some publications [1] also claim a very effective influence of AJVG but some [2] claim that the aerodynamic response is reduced. Numerical results show how it is possible to create streamwise vortices which change the properties of the flow in the boundary layer improving the aerodynamic performance at high Mach numbers.

1. Introduction

Nowadays it is necessary to design devices of the highest efficiency leading to minimum emissions. In the aeronautics, and more specifically for helicopter rotor blades, there are several methods of flow control to improve aerodynamic performance such as the use of vortex generators or gurney flaps. There is a big effort put by many researchers to integrate these devices in a flow control strategy to improve the global performance of the devices. Vortex generators are designed to create vortex structures in streamwise direction enforcing an exchange of momentum in the direction normal to the wall, namely taking the momentum from outer region and transferring it to the low momentum region adjacent to the wall. As a result, the boundary layer profiles become fuller in the low momentum areas close to the wall and less full in the outer part of the boundary layer. This phenomenon makes the flow more stable in this critical area and flow separation can be delayed or even eliminated. There are two designs for vortex generators: vane vortex generators (VVGs), which induce vortex structures thanks to the installation of a thin strip on the surface normal to the wall, which were proposed in the 50's by Taylor [4]. Other type is air jet vortex generator (AJVGs), proposed in the beginning of the 60's by Wallis [5,6] and was implemented as an array of small orifices placed in a line transverse to the flow direction which produce longitudinal vortices by the mixing between the jet blow from each orifice and the free stream flow. The main advantage of AJVGs in respect to VVGs is that there is no a parasite drag due to the way of inducing vortex structures in the main flow and that they may be easily switched off. Design the optimum AJVG is not an easy task because there are several parameters which are related and play an important role in the intensity of the vortex. These are diameter of the orifice, spacing between AJVGs, pitch and skew angles. Several experiments with this technology have been performed during last years in the wind tunnel at the Instytut Maszyn Przepływowych [7] where the optimum dimension were studied and analyzed for getting the strongest vorticity in streamwise direction. The main conclusions of the experimental and numerical study of this technology were that the diameter of the orifice (Φ_{AJVG}) should be 10-20% of the boundary layer thickness, the spacing (L) between AJVGs should be ten times the diameter of the orifice and the strongest vorticity is obtained with 65˚ for skew angle and 30˚ for pitch angle for supersonic flows [11-12].

An aerodynamic study of a NACA 0012 airfoil with AJVG is showed in the present paper. Mach number was set to 0.8 and $Re=9\cdot10^6$ because high supersonic areas appear with strong shock waves which induce flow separation. The angle of attack is increased to get more severe conditions and stronger reverse flow. Comparison of polar graphs for both configurations (with and without flow control technique) shows how this technology can improve the aerodynamic response for transonic conditions. Some literature [2] conclude that this technique works for low Mach number (up to M=0.3-0.4) in which lift and drag coefficient can be improved. For these flow regimes, there is a delay of flow separation which leads to the increase of the critical angle of attack. Other publications [8] have studied how this technology can change the properties of the flow in the boundary layer and delay flow separation for high Mach number and consequently improve the aerodynamic effectiveness too. The chance of this technology to work properly for high velocities is showed in this paper, which is useful for example for helicopter rotor blades. Thus, this flow control technique can be applied and used in the design of the next generation of aircrafts.

2. Computational domain and numerical method

According to the preliminary results of the Instytut Maszyn Przepływowych, the NACA 0012 model with AJVG was created with a diameter of the orifice equal to 1.5 mm because the boundary layer thickness for the flow conditions studied in the paper is 10 mm and consequently the spacing between AJVGs was set to 15mm to get a ratio $L/\Phi_{AJVG}=10$. Skew and pitch angles were 65˚ and 30˚ respectively as it is recommended in literature [3].

Since one of objectives is to study the influence of the AJVG location in respects to the beginning of the separation bubble, a structured grid was generated semi-automatically with python scripts of IGG (Numeca Software). The grid topology of the clean airfoil cases is the same as for AJVG cases in order to avoid discrepancies due to the mesh. The distance from the first layer of cells to the solid wall is of the order $y^{+}=1$ because it is needed to get a high resolution in the boundary layer to solve properly the mixing between air jet and the main flow. Due to important phenomena as shock wave or flow separation taking place in the upper side of the airfoil, the grid consists in 257 x 129 x 63 nodes at the upper wall against 129 x129 x 63 at the lower wall. Overall the grid has 6 million cells and a refinement in the location of the orifice. The farfield was located 50 chords away of the airfoil because good agreement of 2D computations [9] and experimental data was proven. Figure 1 shows the grid domain for the airfoil: there is a 2D view to see the refinement of the grid in the location of the AJVG a butterfly topology for the AJVG orifice. As far as boundary conditions are concerned, the wall of the airfoil is approximated as an adiabatic surface, the farfield is modelled with the static conditions and both span-wise sides modelled as periodic conditions. An extra boundary condition has to be added when the AJVG is working. At the inlet to the AJVG hole the total conditions of the main stream are used because in presented application AJVG are considered as a passive flow control technique.

The present work has been carried out with CFD block structured Numeca code. Reynolds-averaged Navier-Stokes (RANS) with one equation turbulence model, Spalart-Allmaras, was set due to excellent speed, stability and good results obtained for similar test cases [10]. The system of differential equations is closed by a perfect gas model.

Viscosity is calculated according Sutherland’s law and Prandtl number is taken to be constant (Pr=0.7). The numerical algorithm uses a semi-discrete approach, finite volume central scheme for spatial discretisation and a CFL number of 2. In order to improve the convergence rate, a multigrid strategy of three levels has been implemented. Each simulation was run till a drop of residual of 6.5 orders of magnitude to ensure the full convergence.

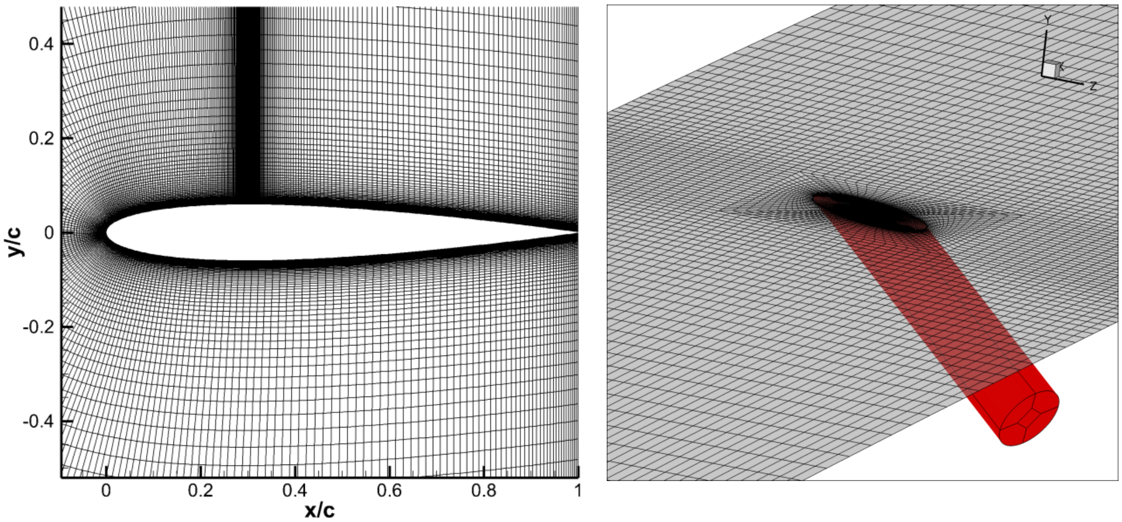


Figure 1. NACA 0012 computational domain

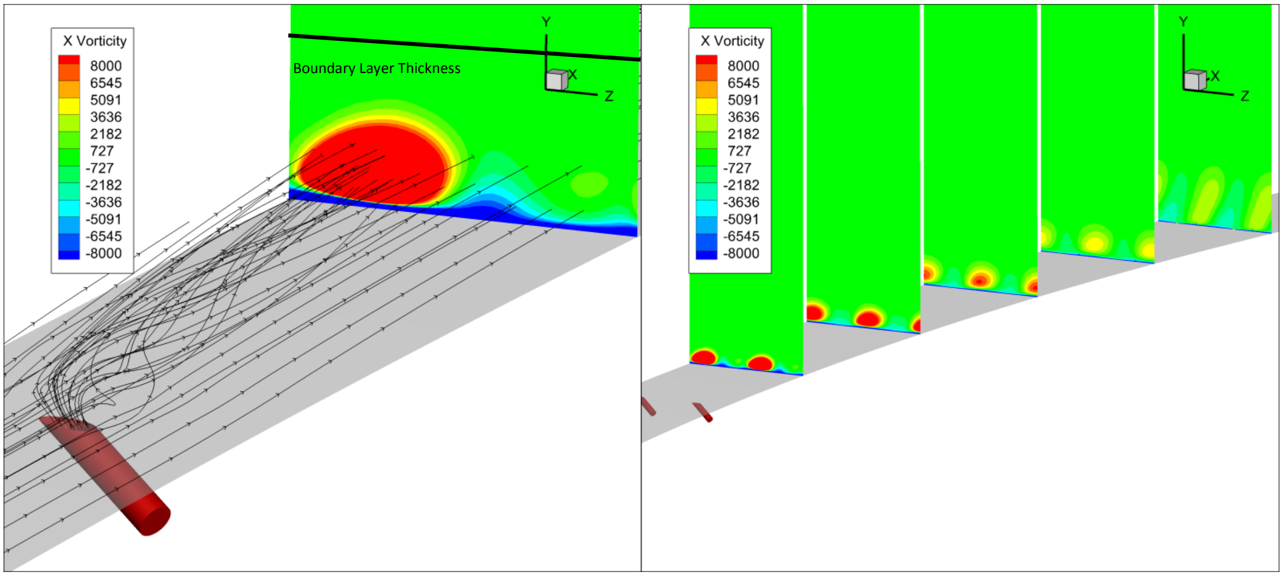
3. Numerical results and discussion

For given flow conditions, shock wave moves upstream when the angle of attack is increased and flow separation follows the shock wave. Five AoAs are studied in the present paper: 1.4˚, 2.2˚, 3˚, 3.5˚ and 4˚ in which the location of the flow separation appears at x/c=0.57, x/c=0.545, x/c=0.48, x/c=0.45 and x/c=0.4 respectively. This shift of the detachment point implies the study of the AJVG orifice location in respect to the shock wave and how it influences the flow separation and the aerodynamic performance. Table 1 summarizes the positions of the AJVG for the different angles simulated. It is really important to optimize the distance between the orifice and the detachment point. It should be neither very close, because there is not enough space to develop stable structure which can modify the properties of the boundary, nor very far, because the area covered with the maximum vorticity is decreased which makes that the aerodynamic performance reduces.

	AoA=1.4	AoA=2.2	AoA=3	AoA=3.5	AoA=4
AJVG_x/c=0.3	Yes	Yes	Yes	Yes	Yes
AJVG_x/c=0.4	Yes	Yes	Yes	Yes	No
AJVG_x/c=0.5	Yes	No	No	No	No

Table 1. Location of AJVG for different angles of attack

Since the air jet is blown with certain skew and pitch angles in respect to the main flow, twisted and spiraled structures appear forming high vorticity areas which modify the boundary layer and influence the flow separation (Figure 2). It is clearly visible how the vorticity is dissipated in space: near the orifice the values of vorticity are high and cover a big area in span direction and when the flow is travelling downstream, not only the values of maximum vorticity are dramatically reduced but also the area involved. The last cross section of the fig.2b is in the beginning of the separation and it can be noticed how the vorticity is lifted by the separation bubble.



(a) (b)

Figure 2. Air jet streamlines and vorticity contours

In Figure 3 it is shown how the maximum value of vorticity develops downstream of the AJVG for different locations of the orifice and angles of attack. Each figure has a vertical line which points the beginning of separation. From this figures, it can be observed the asymptotic character of the vorticity in the beginning of the development of the vortex structures and how it reaches a constant value after certain streamwise distance. This is the key issue in the optimization of the location of the orifice enough space is needed to create a stable structure before arriving at the detachment point. As it will be explained below, it is better in terms of aerodynamic performance to have the orifice relative far from the separation bubble than placing the orifice very close to the bubble where there is not enough space to fully develop a streamwise vortex. The best effect would be to increase lift (L) and reduce drag (D) giving the maximum ratio L/D. This technology is able to increase lift because it is modifying the boundary layer and reduce separation but unfortunately there is a drag penalty. The overall goal is to increase L/D. Table 2 summarizes the aerodynamic coefficients for all the cases studied in the paper. The first angle of attack showed in fig.3 is AoA=1.4˚ in which three locations of the orifice were simulated. When the AJVG is placed at x/c=0.3, there is enough space to develop stable structures and from x/c=0.45 until the separation point the value of maximum vorticity is constant, after that point, it can be noticed how the value of vorticity drops due to interaction between the air jet and the separation bubble. When the orifice is located at x/c=0.4, there is also enough space to develop stable structures. Since the constant value of vorticity has been achieved just before the detachment point, there is no space to dissipate vorticity in spanwise direction and the ratio L/D is higher for this configuration than for x/c=0.3. The AJVG at x/c=0.5 gives the worst L/D ratio because the orifice is so close to the bubble that stable structures are not fully created.

The next angle of attack studied was AoA=2.2˚ and the conclusions were the same as the previous angle: both configuration (orifice at x/c=0.3 and x/c=0.4) are sufficiently far in respect to the detachment point and the highest L/D ratio is for x/c=0.4. Increasing the AoA causes that the separation point moves upstream and as result the location of the AJVG at x/c=0.4 is not good anymore in terms of aerodynamics coefficients for the other AoA studied (3˚, 3.5˚ and 4˚). For the last angle of attack (AoA=4˚) and orifice place at x/c=0.3, fig.3 shows how the maximum vorticity does not reach a constant value before the detachment point, there is not enough space to form stable structures. It can be concluded that for all AoA the orifice should be placed at x/c=0.3 where there is a reasonable good efficiency for low and high angles of attack.

It has been showed that there is no optimum location of the AJVG for certain flow conditions. Depending on the angle of attack, the orifice should be placed in different locations to get the best C_L/C_D ratio. One important feature of the AJVG is the possibility of switching it on and off when needed. Therefore different AJVG holes could be installed in the airfoil and flow control could be obtained by the activation of these AJVG which are the best suited for the particular shock location.

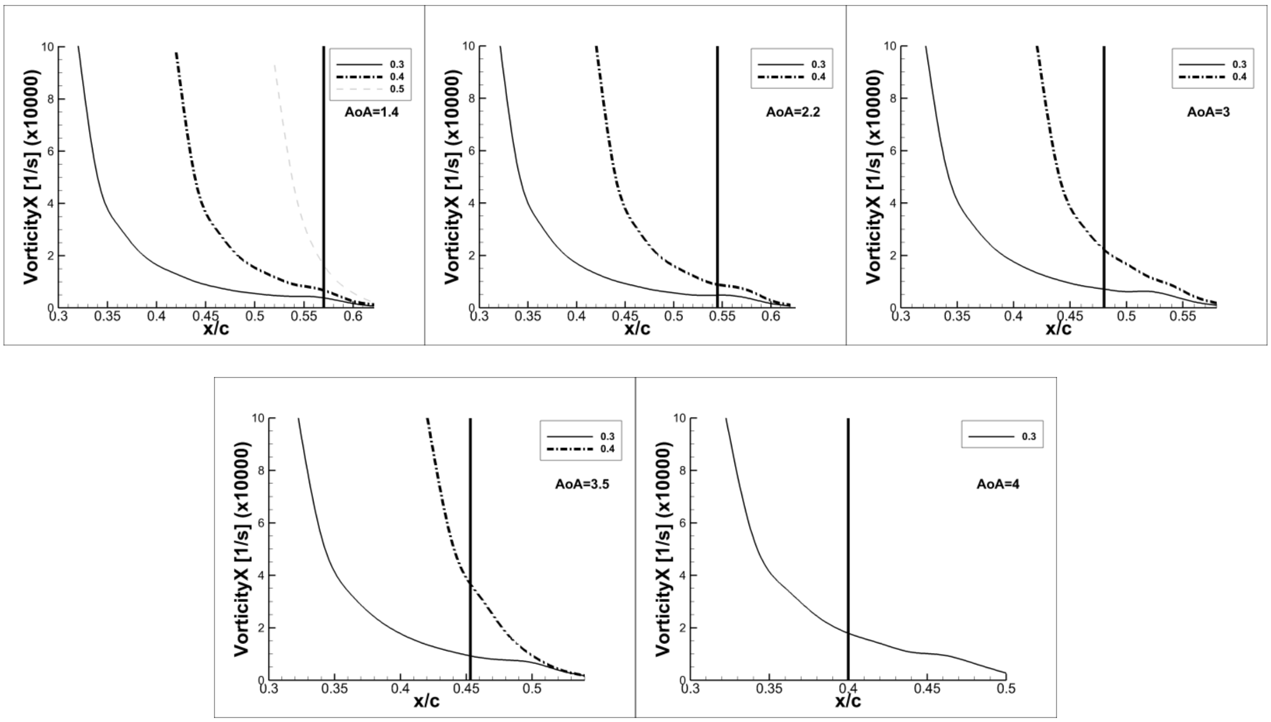


Figure 3. Development in space of maximum vorticity

	AoA=1.4	AoA=2.2	AoA=3	AoA=3.5	AoA=4
CLEAN	C_L=0.2852 C_D=0.02744 C_L/C_D=10.394	C_L=0.3604 C_D=0.03787 C_L/C_D=9.517	C_L=0.3782 C_D=0.04575 C_L/C_D=8.267	C_L=0.3719 C_D=0.04967 C_L/C_D=7.487	C_L=0.3623 C_D=0.05327 C_L/C_D=6.801
AJVG_x/c=0.3	C_L=0.2636 C_D=0.02623 C_L/C_D=10.050	C_L=0.3678 C_D=0.03823 C_L/C_D=9.621	C_L=0.4085 C_D=0.04762 C_L/C_D=8.578	C_L=0.4172 C_D=0.05281 C_L/C_D=7.900	C_L=0.4193 C_D=0.05750 C_L/C_D=7.292
AJVG_x/c=0.4	C_L=0.267836 C_D=0.02637 C_L/C_D=10.157	C_L=0.3757 C_D=0.03866 C_L/C_D=9.718	C_L=0.4171 C_D=0.04921 C_L/C_D=8.476	C_L=0.4083 C_D=0.05240 C_L/C_D=7.792	-
AJVG_x/c=0.5	C_L=0.2709 C_D=0.02759 C_L/C_D=9.819	-	-	-	-

Table 2. Aerodynamic coefficients for NACA0012, M=0.8, Re=$9\cdot10^6$

It can be said that air jet vortex generators work properly for certain flow conditions because there is an increase of C_L. Such statement may be misleading and the direct comparison should be considered of the lift for the same drag or vice versa (C_L against C_D plot). Figure 4 shows the polars of the clean airfoil and AJVG at x/c=0.3 that is where the best aerodynamic coefficients are achieved. The onset of separation is at 1.4˚ and therefore for lower angles no big improvement can be expected. For higher angles, flow separations starts to appear and consequently there is a positive effect of the AJVG in terms of lift but with a drag penalty. Moreover, it is visible how the stall angle is delayed when AJVGs are working. C_L-C_D plot shows how for low drag the lift is higher when the flow control technique is applied. On the other hand, when the drag increases, the lift starts to decay for the clean case while lift is still growing for the AJVG case.

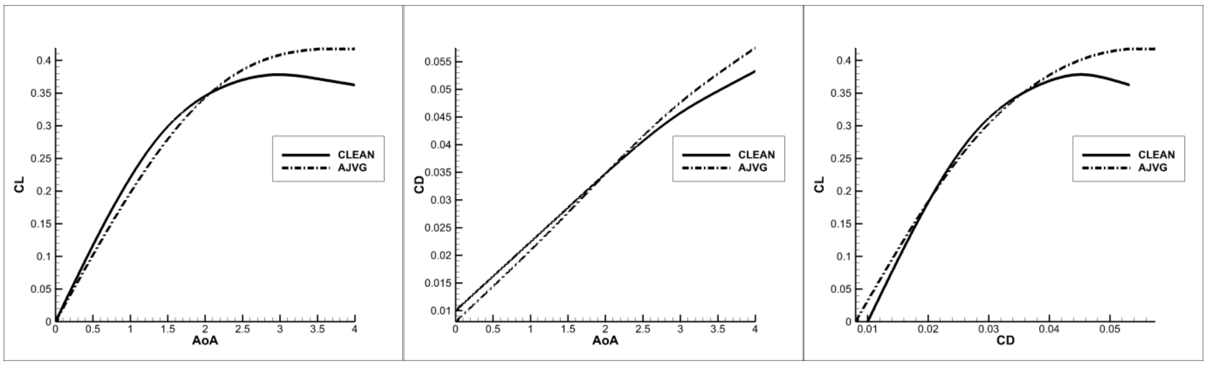


Figure 4. Comparison of polars for AJVG and clean airfoil

Numerical simulations show how the aerodynamic coefficients can be improved with the proposed flow control technique for transonic conditions with local supersonic areas against some publications which claim that the aerodynamic response of the airfoil decreases significantly for high Mach numbers. That experimental study [2] of NACA0012 showed excellent results for low speed cases and poor for high speed ones. The authors of the present papers believe that the main problem of these high speed velocity experiments was the implementation of AJVG. For higher AoA the air supply opening was not aligned with the stagnation point reducing significantly the air supply for AJVG. Numerical simulations allow to overcome such problems.

4. Conclusion and remarks

The numerical simulation of a flow control technique shows how the creation of streamwise vortices in the boundary layer can positively affect the flow with separation and therefore to get a better aerodynamic performance of the airfoil. The several simulations showed in the paper confirm that the optimization of the flow control device is needed. Key parameters as skew and pitch angle, diameter of the orifice and spacing between them have been kept constant according to previous studies in the wind tunnel and only the chordwise location of the orifice has been studied.

Computational results confirm that AJVG work better for severe conditions (high AoA) in which the flow separation appears. For high angles of attack, not only lift force is increased with this technique but also the stall angle is delayed. On the other hand, although lift decreases for low angles of attack, the drag has the same tendency and therefore this flow control technique can be applied in some application in which lift is not as important as drag. Moreover, authors have proven the effectiveness of this passive flow control method for high Mach numbers.

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