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Modeling Surface Riblets Skin Friction Reduction Effect with the Use of Computational Fluid Dynamics

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Towards the minimization of fuel consumption and aicraft emissions reduction, many disruptive technologies have been proposed in aviation industry regarding the improvement of aircraft aerodynamic performance. Among others, these technologies involve innovative passive and active flow control methodologies and techniques. A passive flow control methodology which is studied in the current work is the implementation of riblets, which are inspired by shark skin morphology, on a NACA 0012 airfoil. The main purpose of riblets is to alter the boundary layer characteristics near the wall region in such a way that the total skin friction decreases, resulting in an overall drag reduction of the aircraft with a straightforward impact on fuel consumption and thus emissions. The riblets are implemented in the Reynolds Averaged Navier Stokes equations with appropriate source terms in the turbulent dissipation transport equation. Two turbulence models are used, the k-ω SST linear eddy viscosity model and the Baseline Reynolds Stress model which also uses the transport equation of the specific rate of turbulence dissipation (ω). The computational results are compared with available experimental data of NACA 0012 with surface riblets attached. Drag and skin friction coefficients are presented for various angles of attack and the maximum potential benefit from riblet use is evaluated regarding aerodynamic performance and consequently reduction of emissions and fuel consumption.

1. Introduction

In recent years, significant resources have been allocated in reseach relating to CO_2 emissions and fuel consumption reduction in the aviation industy. An import area of such research is the flow control techniques that can contribute towards drag reduction in aerial vehicles, such as passenger airliners, Unmanned Aerial Vehicles (UAVs) and cargo aircrafts. The total drag breakdown of an aerial vehicle during cruise conditions indicates that a significant portion of it, is due to skin friction (about 40-50 %) (Robert, 1992). This makes skin friction drag reduction especially appealing to designers, for it can directly affect the aerial vehicle's emissions and fuel consumption. To achieve that, different strategies have been considered, regaring either the laminar-turbulent boundary layer transition control, or the minimization of the viscous drag component in fully turbulent conditions. Regarding the latter, specially designed micro-grooved materials (riblets) that can be applied on the aircraft external surfaces show great promise. Various riblet geometries have been studied in the past, with results for flat plates giving a maximum total drag reduction of about 8-10 %. The optimum riblet geometry depends on a number of parameters (Figure 1 (a)), i.e. riblet spacing s, riblet height h and the Reynolds number. Non-dimensional parameters have been used by Walsh and Linderman (1984) in order to define the correlation between the drag reduction and the Reynolds number. These parameters of riblet dimensions are expressed in wall units, as shown in Eq(1), where v is the kinematic viscosity and u^* is the friction velocity.

$$L^+ = \frac{L \cdot u^*}{v} \tag{1}$$

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Even though, the non dimensional riblet spacing parameter (s^+) is most widely used in literature for the evaluation of riblets, a considerable scattering (~40 %) occurs for the optimum value of s^+, when riblets of different shapes are examined (García-Mayoral and Jimenez, 2011). In their work García-Mayoral and Jimenez (2011), proposed the use of the square root of the groove cross section, l_g^+, to overcome this issue. The main advantage of using l_g^+ over s^+, is that the optimum value of it has a variation of about only 10 %. Catalano et. al. (2018) calculated that the optimal l_g^+ mean value is equal to 10.5, as is shown in Figure 1 (b).

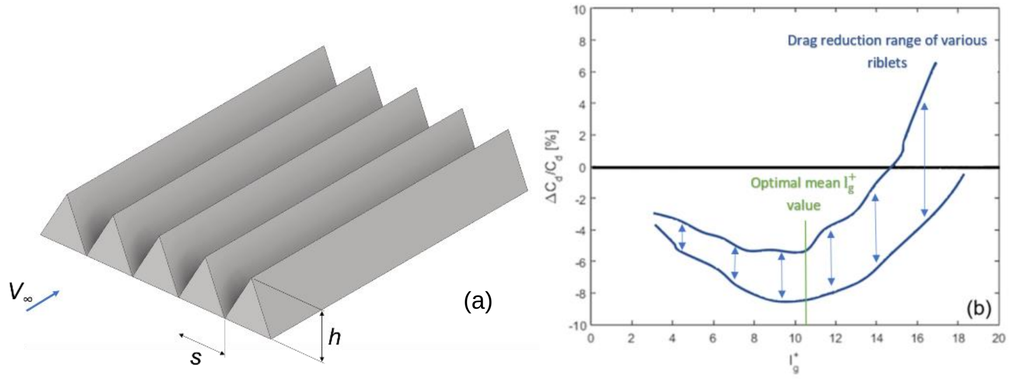

Figure 1: (a) V-groove riblet basic dimensions (b) Drag reduction as a function of the square root of groove cross section l_g^+ for various types of riblets

With the average size of riblets being in the order of 100 μm, a major issue is the difficulty to model them, using Computational Fluid Dynamics (CFD) methods. In order to accurately model the flow around riblets, Large Eddy Simulations (LES) are required, a methodology that is able to model the small eddies (time and space scales) over the riblet surface and hence predict with accuracy the skin friction reduction. However, a fine computational grid and as a sequence large computational resources are required when considering more complex geometries other than flat plates. To investigate riblets on complex geometries of engineering interest at high Reynolds numbers, such as a full scale aircraft, LES methodologies are not a useful rapid computational tool for an engineer. A solution to that was proposed by Catalano et. al. (2018), who used a specific boundary condition that is able to model the riblet effect on the flow, with the use of Reynolds Averaged Navier-Stokes (RANS) equations, and validated it by applying it to typical regional airliners CFD computations. In their work they considered 4 different cases, namely a flat plate, a transonic airfoil, a low speed airfoil and a regional aircraft configuration, with the Reynolds and Mach numbers ranging from 10^6 to 3×10^6 and 0.1 to 0.76, respectively. On all cases the k-ω SST turbulence model was applied.
In the present work, the boundary condition of Catalano et. al. (2018) is implemented on a symmetrical airfoil, commonly used in aircrafts and UAVs. The methodology is also extended to a Reynolds Stress omega based turbulence model of higher accuracy and the results are compared with available literature experimental data.

2. Tools and Methods

2.1 RANS boundary condition

The effect of riblets in RANS computations is modelled as a singular roughness problem by using an appropriate boundary condition for the specific turbulence dissipation ω. Originaly, Saffman (1970) proposed the following wall boundary condition for the k-ω turbulence models:

$$\omega = \frac{\rho \cdot u^{*2}}{\mu} \cdot S_R \tag{2}$$

For rough walls, Wilcox (2008) originally computed the value of S_R from experimental results, thus making the ω depend of the nature of the wall. Catalano et. al. (2018) proposed the use of Eq(3) which is only a function of the square root of the groove cross section l_g^+.

$$S_R = \frac{C_1}{\left(l_g^+ - C_2\right)^{2n} + C_3} \tag{3}$$

Where $C_1 = 2.5\times10^8$, $C_2 = 10.5$, $C_3 = 10^{-3}$ and n=3.

For the evaluation of the applied boundary condition, a preliminary CFD analysis on a 2D case is performed. The NACA 0012 airfoil is selected, for it has been both extensively studied computationaly and experimentaly, and is also widely used in aeronautical applications, e.g. in empennages of airliners and UAVs (Panagiotou et. al., 2016). Two turbulence models are employed, the two-equation Shear Stress Transport model (SST) k-ω of Menter (1994), which is commonly used in aeronautical applications (Christodoulou et. al., 2019) and the Baseline Reynolds Stress Model (BSL-RSM), which is an ω based RSM model that adopts a blending function for modeling the transport of the turbulent dissipation (as SST model) which was successfully used for the unsteady flow modelling of compressor blades, Vlahostergios (2018).

2.2 Grid independency studies and computational details

To verify that the size of the computational grid is not affecting the results of the CFD analyses, a grid independency study is performed for both turbulence models at 12 ° angle of attack (AOA). The non-dimensional coefficients of total and viscous drag, as well as skin friction are monitored, and a 80,000 elements computational grid is selected, for which the monitors first become constant with increased grid size (Figure 2). For all the cases y^+ was less than unity in order to ensure the proper integration of the transport equations inside the whole boundary layer regions. The grid consists of both structured and unstructured regions, with emphasis given in the area close to the airfoil (25 structured-like cells in the normal to the wall direction), where the boundary layer is developing. The grid generation is performed on the commercial BETA ANSA pre-processing software (v19.1.0). All cases are solved on the ANSYS Fluent software (Release 18.2), using a pressure based solver. The SIMPLE scheme is employed for the pressure-velocity coupling and a second order spatial discretization scheme for all the equations that are solved. The boundary conditions of the transport dissipation equation for the riblet effect is integrated to the overall solution procedure in Fluent with an appropriate user defined function (UDF subroutine).

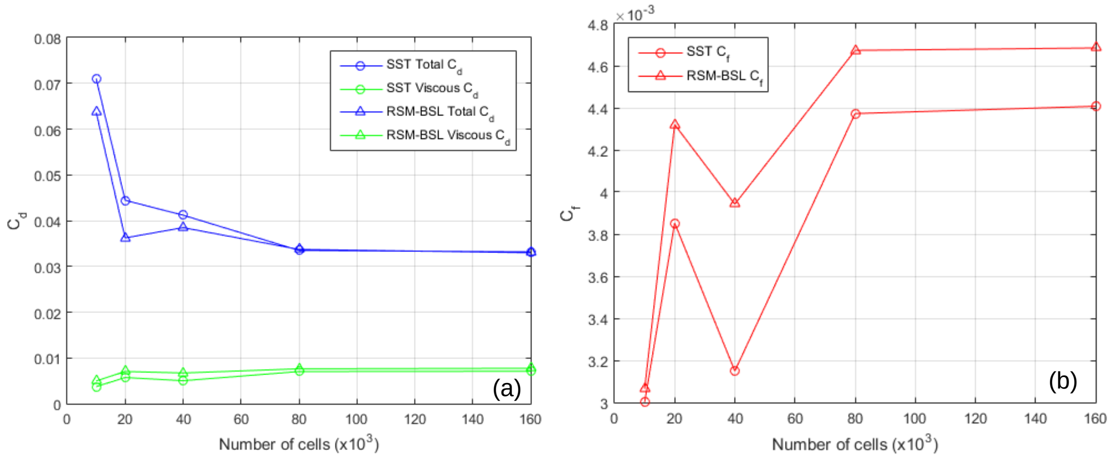

Figure 2: Variation of the (a) total and viscous drag and (b) friction coefficients with the computational grid size

2.3 Validation of RANS modeling

A validation of the riblet computational modeling tecnique, that is examined in the present work, is performed with comparison with experimental data from Sundaram et. al. (1996) and Subashchandar et. al. (1995). Specifically, a NACA 0012 airfoil is modeled at the flow conditions presented in Table 1. In the works of Sundaram et. al. (1996) and Subashchandar et. al. (1995) symmetric V-groove riblets (height equal to spacing) from 3M company are used with two different riblet heights, namely 0.076 mm and 0.152 mm. The riblets are applied on both the pressure and sunction sides of the airfoil, in a surface ranging from 12 to 96 % of the chord length, and the airfoil is examined in a range of AOA from 0 to 12 degress with a 2 degree interval.

Table 1: NACA 0012 modeling flow conditions.

Chord length	Freestream velocity	AOA	Reynolds number
0.6 m	30 m/s	0 – 12 deg	10^6

In order to accurately model the effect of the riblets on the airfoil, the boundary condition is applied separately on the pressure and sunction side. The average wall shear stress on each side is used to calculate the appropriate l_g^+ value that corresponds to the riblets height, h. For the symmetric V-groove riblets the relation between l_g^+, s^+ and h^+ is given by Eq(4).

$$s^+=h^+=\sqrt{2}\, l_g^+ \tag{4}$$

In Figure 3, the modeling of the two riblet heights is compared with the available experimental data. For both the k-ω SST and the BSL-RSM turbulence models, the riblet implementation through the UDF provides an overall benefit to the total drag reduction with the BSL-RSM calculating 2 % higher values. However, there is an overprediction of the drag coefficient absolute values in comparison to the experiments for both models. This is related to the linear relation regarding the eddy viscosity model formulation of the SST, and the linear pressure strain correlation of the BSL-RSM model. In order to take into consideration the boundary layer transitional characteristics that are present for the examined Reynolds number, it is suggested by the authors the use of a transitional turbulence model or a RSM model with non-linear relations for the Reynolds stresses dumping, due to pressure diffusion, near the walls. However, further research is needed in order to quantify and assess the effect and validity or the recalibration of the proposed riblet-effect boundary condition for turbulence models that are designed for modeling boundary layers with transitional characteristic.
The drag reduction due to the riblets is similar for both the CFD computations and the experiments, with a constant offset in the C_d of about 0.001. The k-ω SST model predicts a slightly smaller drag reduction compared to the BSL-RSM of 0.4 % and 0.2 % for the riblets with h=0.152 mm and h=0.076 mm respectively.

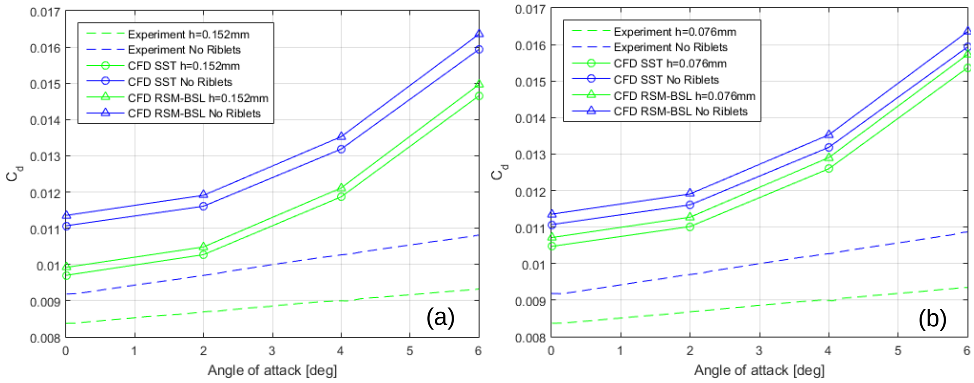

Figure 3: Comparison of C_d reduction between CFD results and experimental data (Sundaram et. al., 1996) for riblet height (a) h=0.152mm and (b) h=0.076mm

3. Results and discussion

The specific turbulence dissipation boundary condition is used to investigate the potential for drag reduction on a symmetrical airfoil, e.g. the NACA 0012. An l_g^+ sensitivity analysis is performed, on the airfoil at a 0 degree AOA, and the optimal value of 10.5 is confirmed, as Catalano et. al. (2018) proposed for a flat plate.
On both airfoils an optimum riblet size (based on l_g^+) is applied for different AOA. This corresponds to a different riblet size for each angle, and airfoil side (pressure or sunction), since the optimum l_g value, and hence h, depends on the wall shear stress as demonstrated in Eq(1). In Figure 4 the maximum improvement potential of the NACA airfoil is presented.

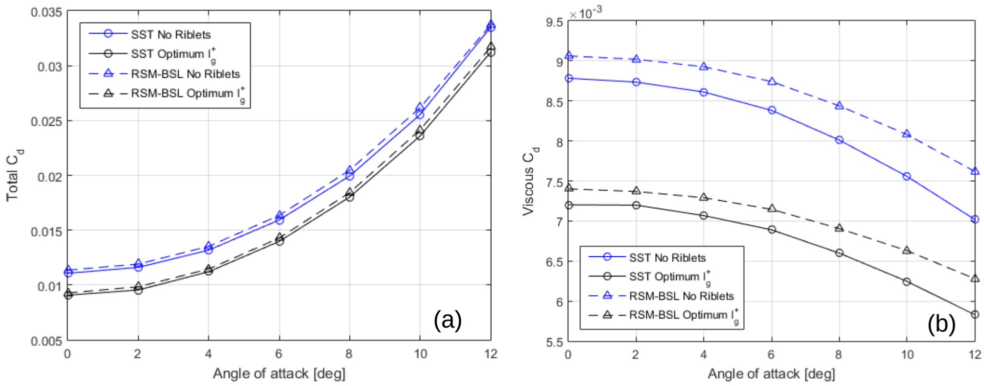

Figure 4: Comparison of (a) total and (b) viscous drag coefficients for a NACA 0012 airfoil with and without optimal riblet sizing (l_g^+=10.5) for two turbulence models

The k-ω SST model predicts a possible total drag reduction between 9.5-18 % for 0-8 degrees AOA. The maximum total drag reduction seems to diminish with increase in AOA, and drops to about 6 % in the 10-12 deg range. The BSL-RSM model predicts a constant 0.3 % greater total drag reduction than the SST in all angles. Meanwhile, the viscous drag component reduction, is at an almost constant percentage for the SST model (17-18 %), compared to which the BSL-RSM model has a 0.2 % positive offset. In Figure 5, vectors of the velocity magnitude are plotted on the sunction side of the airfoil, in the area near the trailing edge, at a 10 deg AOA. It can be seen, that the velocity gradient for the BSL-RSM model with respect to the wall distance (highleted in the encircled area) is larger than the SST, leading to an increased shear stress value and consequently to an increased drag calculation.

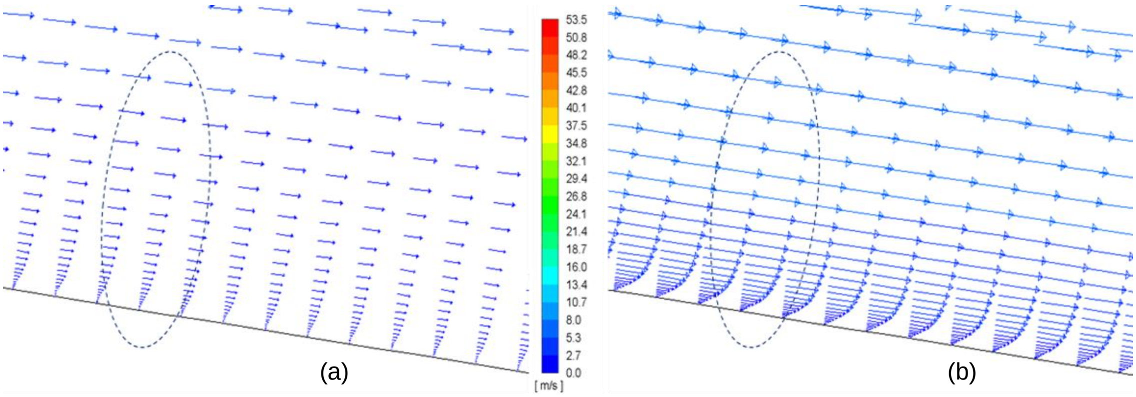

Figure 5: Velocity magnitude at the NACA 0012 trailing edge area at 10 deg angle of attack, using (a) the k-ω SST and (b) BSL-RSM turbulence models.

In Figure 6 the skin friction coefficient along the airfoil length is presented for the cases with optimal riblets and with no riblets at all, for the k-ω SST model at 6 and 12 deg angles of attack.

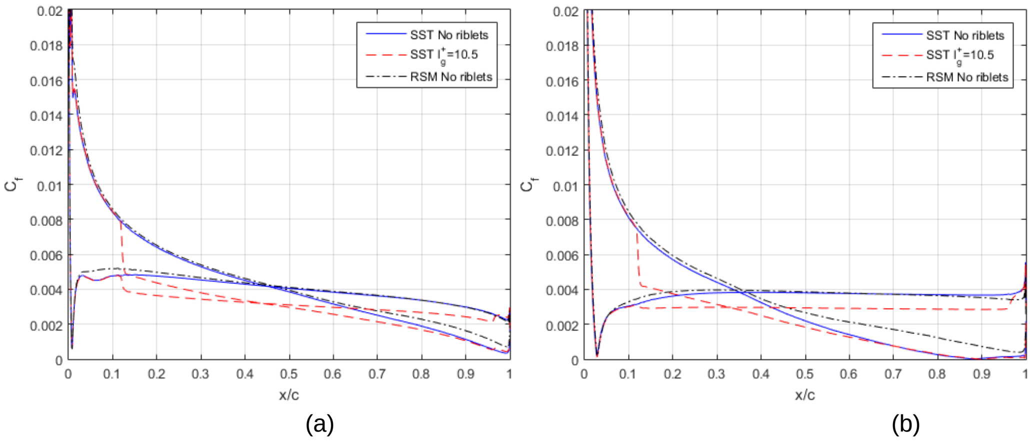

Figure 6: Comparison the computed skin friction coefficient with and without optimal riblets around the NACA airfoil at (a) 6 deg and (b) 12 deg angles of attack

It can be noted that for the riblet case a sudden skin friction reduction occurs at 12 % of the chord, corresponding to the initial application point of the ω boundary condition. On the sunction side of the airfoil, the reduced C_f value gradually converges towards the no riblet value near the trailing edge, though this happens at an earlier x/c at the 12 ° angle. Meanwhile on the pressure side the C_f reduction is held relatively constant along the airfoil length. This variation of skin friction, on both sides of the airfoil, indicates a negative correlation between riblet effectiveness and adverse pressure gradients. Also, from Figure 6, the different skin friction coefficient distribution between the k-ω SST and BSL-RSM can be examined. The RSM model predicts a higher skin friction on both the pressure and suction side of the airfoil, and especially in the trailing edge area of the latter. Hence, the higher drag value of the RSM computations can be attributed, to this difference between the two models' prediction of wall shear stresses.

4. Conclusions

In the present study, the effectiveness of a boundary condition for riblet modeling in RANS computations has been investigated. The NACA 0012 airfoil is examined at a chord based Reynolds number of 10^6 and AOA up to 12 °. CFD computations, using the two equation k-ω SST and the BSL-RSM turbulence models, are assessed and compared against experimental data. Both turbulence models tend to overpredict the drag value, while the drag reduction due to riblets is in relative agreement with the experiments. The maximum drag reduction potential in various AOA, from riblet use is determined. The maximum viscous drag reduction is estimated about 17 %. Additionally, a comparison is made between the computed skin friction difference of the two turbulence models. The implemented boundary condition for the specific turbulence dissipation shows great potential in modeling the effect of riblets on complex geometries. The major advantage of this method lies in its implementation in RANS equations, allowing relatively quick computations. As a result, the impact of the use of riblets on specific locations on an aircraft surfaces can be investigated and their geometry depending on the local flow conditions can be determined. This has a straightforward impact to the prediction of the fuel saving and the emissions reduction due to the overall skin friction drag reduction. Based on the findings of the current work, the boundary condition will be implemented in more complex aerodynamic surfaces (i.e. UAVs) together with other flow control methodologies. The results of the investigations will be compared with higher fidelity CFD methods, such as Large Eddy Simulations (LES) or Detached Eddy Simulations (DES). Morover, other types of engineering applications that can utilize riblets will also be investigated with the present method, such as wind turbines, turbomachinery compressor blades and fluid transport processes with increased friction losses.

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