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Laminar separation bubbles on the transitional flow around airfoils

Burbujas de separación laminar en flujo en transición alrededor de perfiles aerodinámicos

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Abstract

The purpose of this work is to apply the γ-Re_θ turbulence model, which is one of the numerical methods of shear stress transport (SST) applicable to transient flow, to examine if it shows the expected laminar separation cells or *bubbles*. This condition is key in the way to guarantee that the numerical modeling of lift and drag forces in aerodynamic profiles is more faithful to corresponding experimental data. For this, several two-dimensional simulations implemented with OpenFOAM, a well-known Finite Volume Method (FVM) package, were carried out for a Reynolds number range between $1x10^4$ and $5x10^5$, with the airfoils NACA0012, SG6043 and S826, in which the laminar separation bubbles usually form. Numerical results of lift and drag coefficients show correct prediction of experimental results and error is reduced by 3% when compared to other simulations. In particular, adequate performance of the model is observed for regions close to or greater than the angle of attack for which the aerodynamic profile stalls. On the other hand, the geometric footprint of the flow simulated with this γ-Re_θ transition SST model shows great improvement compared to previous studies regarding the formation of laminar separation bubbles, which in turn means better performance when calculating lift and drag coefficients. It is also concluded that laminar separation occurs in the three studied airfoils, being symmetric or asymmetric profiles.

Key words: Airfoil performance; Turbulence model; Transitional flow; Finite Volume Method; Laminar separation bubble; Reynolds number; Intermittency.

Resumen

El objetivo en este trabajo es comprobar si el uso del modelo de turbulencia γ-Re_θ, que es parte de la familia de métodos numéricos de transporte de esfuerzo cortante (SST) aplicable a flujo transitorio, muestra las burbujas de separación laminar. Esta condición es clave en la ruta a garantizar que el modelado numérico de coeficientes de sustentación y arrastre en perfiles aerodinámicos sean más fieles a datos experimentales correspondientes. Para ello se llevaron a cabo varias simulaciones bidimensionales del flujo alrededor de los perfiles S826, SG6043 y NACA0012, implementadas en el paquete de método de volúmenes finitos OpenFAOM, en un ámbito de número de Reynolds entre $1x10^4$ y $5x10^5$, en el que es esperable la formación de burbujas de separación laminar. Los resultados numéricos de coeficientes de sustentación y arrastre, muestran una correcta predicción de los resultados experimentales y se reduce en un 3% el error ponderado promedio respecto a simulaciones de referencia. En particular, se observa un adecuado desempeño del modelo para regiones cercanas o superiores al ángulo de ataque para el cual el perfil aerodinámico entra en condición de pérdida aerodinámica. Por otra parte, la huella geométrica del flujo simulado con este modelo SST de transición γ-Re_θ, muestra una notable mejoría respecto a estudios previos en cuanto a la formación de las burbujas de separación laminar, lo que se asocia con su superioridad en el cálculo de los coeficientes de sustentación y arrastre. Se concluye también que la separación laminar ocurre en los tres perfiles estudiados, siendo algunos simétricos y otros asimétricos.

Palabras claves: Desempeño aerodinámico; Modelo de turbulencia; Flujo en transición; Método de volumen finito; Burbuja de separación laminar; Número de Reynolds, Intermitencia.

Introduction

The Navier Stokes equations are the equations that describe the motion of a macroscopic viscous fluid. They are widely known and their development for certain types of flow is conventionally proposed in basic books on fluid mechanics [1]. One of their most challenging features is that, in general, they do not have an analytical solution, so a numerical approximation is key to their application in cases of particular interest. However, the direct numerical solution of these equations for general flow cases has an impractical computational cost, so multiple approximations are applied to solve them indirectly. A frequent technique is to use a turbulence model, such as the Reynolds Averaged Navier Stokes (RANS) [2], which simplifies the equations, but adds additional terms without adding additional equations. This situation, known as the turbulence lock problem [3], requires applying some particular formulation to the case to obtain as many equations as unknowns. For example, for the aerodynamic profiles of small-scale wind turbine blades, the k-ω SST (Shear Stress Transport) [4] and k-ε RNG (Renormalization Group) [5] models have been used. In particular, the k-ω SST model is suitable for high Reynolds numbers, which is a condition in which no separation occurs, as it is far from the transition region. Accordingly, [6] these models do not give adequate results in turbulent cases, as they do not correctly calculate the boundary layer separation point. For the case of Reynolds numbers (Re) below $5x10^5$, the flow over the upper face of the blades is mainly laminar and the formation of laminar separation bubbles occurs, resulting in a loss of aerodynamic performance, in the particular case of small scale wind turbines [7]. It is relevant to clarify that in any case it is a single phase flow, the separation bubbles are regions of the flow where the boundary layer is detached and flow recirculation occurs, but no distinct phase is generated in that region [8]. These bubbles are dependent on the Reynolds number, the airfoil curve and the pressure distribution; for Re = $1x10^5$ the bubble is longer and affects the flow drastically [9].

In the case of real operating conditions of wind turbines, turbulence in the flow can favour the detachment of the boundary layer and therefore be an element that generates laminar separation bubbles. The effect of turbulence on the efficiency of wind turbines is widely documented in the literature [10], for example in [11] it is mentioned that wind turbines are not designed for high turbulence flows. However, turbulence can also, in some cases, reduce the formation of these bubbles, so it is reported that an increase in turbulence can positively impact energy production [12], [13] and [14].

According to [9], [15] and [16] the SST γ-Re_θ transition model reproduces the behaviour of the flow under the conditions where laminar separation bubbles are generated. In the case of [8] an analysis is performed for Re = 10^5 with a transition model, studying airfoils having irregularities at the leading edge. It is found that the irregularities affect the formation of the laminar separation bubbles, but have a negligible effect on the lift force.

In a study with another fluid, water in this case, the γ-Re_θ transition model is also used to simulate the transition from laminar to turbulent flow, under conditions of Re = $7x10^5$, over the blades of a propeller. This research concludes that the transition model accurately reproduces the experimental results, in particular the position and shape of the boundary layer, and thus of the laminar separation bubble [17].

The γ-Re_θ model has even been tested to simulate the flow of airfoils with high Reynolds numbers, between 3 $x10^6$ and $6x10^6$, where it has been shown that the applicability under these conditions depends on the critical angle of attack of the airfoil and that the model predicts with a high deviation the static pressure values in the areas precisely where the transition from laminar to turbulent occurs [18].

Other approaches to determine the points where the transition between laminar and turbulent flow occurs can also be found in the literature, such as the e^N method presented in [19].

The aim of this work is to apply the transition SST model γ-Re_θ, to the modelling of a flow around three airfoils, namely NACA0012, SG6034 and S826, at conditions of $1x10^4 < Re < 5x10^5$ which is where laminar separation bubbles usually form. It is intended to observe the laminar separation bubble in the simulation, with the hypothesis that, if the model shows it, then the drag and lift coefficient results will have adequate agreement with the experimental results available in the literature.

Materials and methods

Mathematical model

In this work, the transition γ-Re_θ SST model described in [15] and [20] will be used, which has four transport equations and is based on the k-ω SST model. The first transport equation is for k which is the turbulent kinetic energy.

$$\frac{\partial \rho \mathrm{k}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \mathrm{k}) = \nabla \cdot \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla \mathrm{k} \right) + \gamma P_k - D_k \max(\gamma, 0.1)$$

Where ρ is the density, U is the fluid velocity, μ is the dynamic viscosity, μ_t is the dynamic turbulent viscosity, σ_k is a constant, P_k is the turbulent kinetic energy production and D_k is the turbulent kinetic energy dissipation. The value of the constants and the definition of each term can be found in [15].

In the turbulent kinetic energy transport equation, the P_k

term is multiplied by the intermittency γ, which represents the percentage of time in which turbulent fluctuations are present in the boundary layer. If the intermittency is zero, the boundary layer is laminar, if it is 1 the boundary layer is turbulent and in the range 0 to 1 it is transition. This partly gives the name to the model used. In the same equation the turbulent kinetic energy dissipation term is multiplied by the maximum between 0.1 and the value of the intermittency. This puts a lower limit of 10% of the dissipation value in the k-ω SST model.

The second transport equation ω which is the specific rate of kinetic energy dissipation.

$$\frac{\partial \rho\omega}{\partial t} + \nabla\cdot(\rho\mathbf{U}\omega) = \nabla\cdot\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla\omega\right) + \frac{\xi}{\upsilon_t}P_k - \beta\rho\omega^2 + 2(1-\mathrm{F}_1)\frac{\rho\sigma_\omega{}^2}{\omega}\nabla k{:}\nabla\omega$$

Where is the turbulent kinematic viscosity and the model constants are the terms ξ, β and . In the transport equation of the specific rate of kinetic energy dissipation there is a mixing function (F_1) which defines in the SST k-ω model whether the k-ω (for the region near the wall) or the k-ω (for the region near the free stream) model is used.

In addition to the above two equations, which are very similar to those of the k-ω SST model, there is a transport equation for intermittency in the γ-Re_θ transition SST model:

$$\frac{\partial \rho\gamma}{\partial t} + \nabla\cdot(\rho\mathbf{U}\gamma) = \nabla\cdot\left(\left(\mu + \frac{\mu_t}{\sigma_\gamma}\right)\nabla\gamma\right) + P_\gamma - D_\gamma$$

Where the definition of the intermittency production P_γ and the intermittent kinetic energy dissipation D, as well as the value of the constant γ can be found in [15].

Additionally, there is an equation for Re_θ which represents the point where the intermittency starts to increase:

$$Re_\theta = \frac{\rho U\theta}{\mu}$$

where y is the coordinate perpendicular to the surface over which the fluid flows and the subscript infinity denotes the values in the free stream of the fluid.

$$\theta = \int_0^\infty \frac{\rho U}{\rho_\infty U_\infty}\left(1 - \frac{U}{U_\infty}\right)dy$$

Boundary for airfoils under study

The simulation is carried out in the OpenFOAM program, in which a two-dimensional computational domain is established with a length of fifteen times the chord between the flow inlet and the airfoil, as well as between the airfoil and the top and bottom edges. For the outgoing boundary, twenty times the size of the chord between the profile and the outgoing boundary is used, as bounded in [16]. The only difference is that in the case of the simulation presented in this research, the computational domain is rectangular and in the reference it is C-type, but in both cases the edges of the domain are far enough away from the profile to interfere with the results.

The boundary conditions are: fixed inlet velocity (11.5 m/s for the case of Re = 10^5) and zero pressure gradient in the rest of the boundary. To determine the minimum time that each simulation must be run, several tests are carried out and it is determined that, with 4000 s of simulation, the flow stabilises and the solution is independent of the simulation time. It is worth noting here that the simulation time depends on the available computational capacity, so that a modern computer can simulate 4000 s of flow in a much shorter real time.

Additionally, the input conditions shown in Table 1 are imposed, where a value of IT = 0.2% is adopted to make the results comparable with [16], where the same value is used. In Table 1 the angle of attack step is 2°.

Table 1: Input constants in the computational model.

Variable	Symbol	Value	Units
Reynolds number	Re	$1x10^5$	-
Angle of Attack	AoA	[0 – 14]	°
Turbulence intensity	IT	0.2	%
Density	r	1.18	kg/m^3
Chord	c	0.1	m
Kinematic viscosity	μ	$1.1516x10^{-5}$	m^2/s

Within the computational domain the airfoil of interest is placed, in this case three airfoils are studied, namely, the S826 which is also used in [16] and it is with respect to which the results obtained are compared; then the airfoils SG6043 and NACA0012, in which it is known that laminar separation occurs according to [17]. In the case of the three profiles, the no-slip condition is imposed on the entire contour. Subsequently, a triangular meshing is performed in the computational domain and refined in a stepwise manner by manipulating the element size factor, in order to ensure that the simulation is mesh-independent. This is illustrated in Figure 1 for the S826 airfoil, with an angle of attack of 8°; where it was found that from 106 elements the response variable, the lift coefficient in this case, varies by less than 0.3 % in a sustained manner, when comparing the actual value with that obtained by increasing the number of elements by 10^5 times. We then proceeded to work with a 10^6-element mesh for the rest of the simulations.

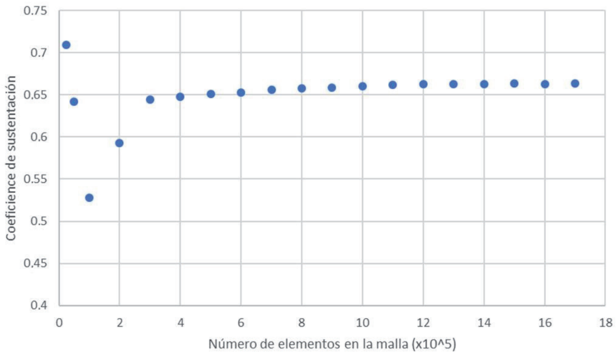

Figure 1: Study of mesh independence in the S826 airfoil.

It is important to highlight that in Open FOAM the pre-existing libraries have been used with the SST γ-Re_θ transition model, in addition, from the same program it is possible to obtain the results of the lift and drag coefficients for each simulation.

Results and discussion

Lift and drag coefficients for profile S826

The results of the simulation performed in this work are compared with those available in the literature in Lin and Sarlak [16], where the S826 airfoil for Re = $1x10^5$ is simulated with OpenFOAM and tested experimentally at DTU (Technical University of Denmark). The specific characteristics of the experimental values used in the comparison correspond to a chord length of 0.1 m; a blade length of 0.5 m; a wind speed of 15 m/s, a sampling frequency of 125 Hz and a sampling time of 10 s for each angle of attack. Figure 2 presents the results for the lift coefficient while Figure 3 shows the results for the drag coefficient. In these comparative curves only the results obtained with the γ-Re_θ transition SST model are shown, as it is the focus of interest of this research. In addition, experimental results are presented for validation purposes. However, simulations with other turbulence models have been performed in [16], which are beyond the scope of this research.

It can be seen in Figure 2 how both simulations have a consistent behaviour to the experimental data, especially at low angles of attack, below 6°. A feature of the SST transition γ-Re_θ model is that the angle of attack at which the aerodynamic stall occurs is correctly predicted. Particularly for the 12° angle of attack, both the reference simulation of [16] and the present one tend to overestimate the lift coefficient, but in the simulation presented in this research, using the SST transition γ-Re_θ model implemented in OpenFOAM, the overestimation is smaller and the results are closer to the experimental values.

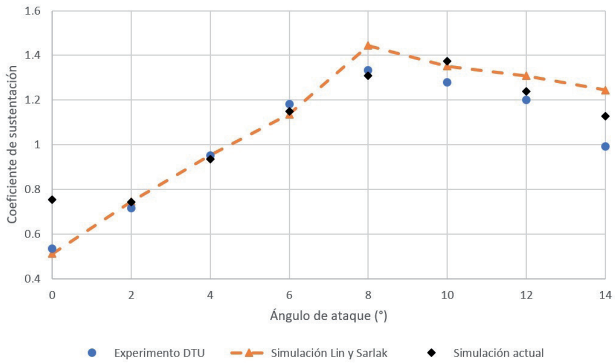

Figure 2: Results for the lift coefficient of the S826 airfoil.

Figure 3 shows that the simulation and experimental results are difficult to distinguish for angles of attack less than and equal to 6°. In the case of an angle of attack of 8°, the simulation of this study gives a result closer to the experimental one, with respect to the reference simulation. For angles greater than or equal to 10° the trend of the results is better captured by the current simulation; although with a difference of up to 50% for the case of 14° angle of attack, with respect to the experimental results. The underestimation of the drag coefficient shown for angles of attack of 12° or more is very common due to the effect of laminar separation bubbles. The average weighted percentage error of the simulation presented here, with respect to the experimental data of the drag coefficient, is 11%; in the case of the reference simulation of [16] the error is 14%.

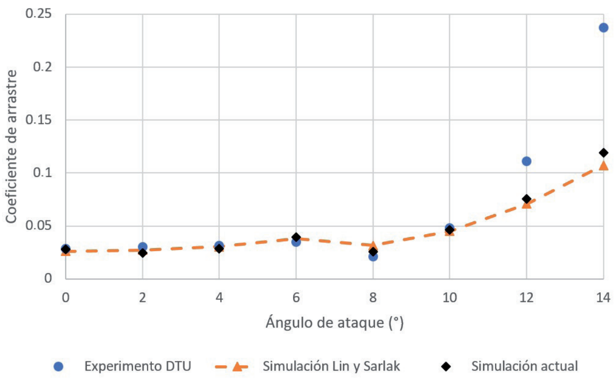

Figure 3: Results for the drag coefficient of profile S826.

Laminar separation bubbles in profiles SG6043 and NACA0012

In order to visualise the effect of different turbulence models in terms of capturing laminar separation bubbles in the flow, the result for the velocity field around an SG6043 profile, of special interest for small-scale wind turbines, is presented below [21]. Figure 4 shows the results of the k-ω SST model and Figure 5 the results of the γ-Re_θ transition SST model. In both cases with Re = 10^4 (to broaden the range of Reynolds numbers under investigation) and an angle of attack of 15° (so defined to show the phenomenon only). Although the flow separation is distinguishable in both images, the γ-Re_θ transition SST model in Figure 5 shows an improved capture of the flow behaviour, as the separation bubbles are more easily distinguishable and therefore the flow along the whole profile is better presented.

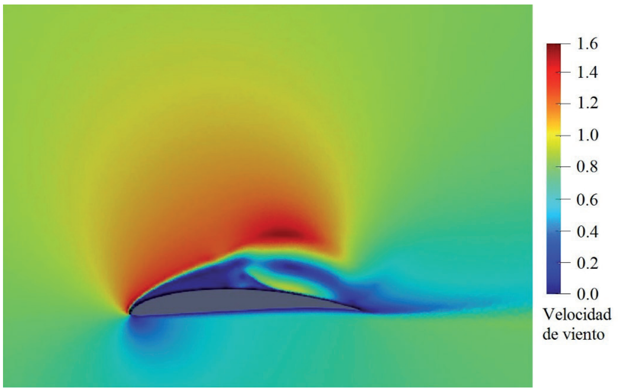

Figure 4: Velocity field in profile SG6043 with the k-ω SST model.

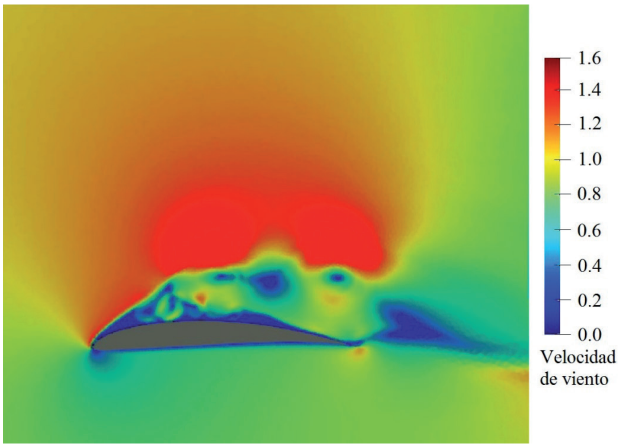

Figure 5: Velocity field in profile SG6043 with the transition SST model γ-Re_θ.

The difference between the two models is that the transition model is able to more accurately model the separation and bubble formation. It is for this reason that the results of the lift and drag coefficients in the airfoil at small angles of attack were similar in Figures 2 and 3. The difference is crucial when approaching the angle of attack at which it enters the separation zone. In these cases, the error of the transition model is smaller and that separation moment can be simulated, whereas the SST model underestimates the lift along the airfoil, so that the simulated pressure is incorrect over the entire separation zone. In addition, the drag coefficient is underestimated by the non-transition model because it does not adequately capture the vortices in the wake, which are known to be responsible for the distortion in the fluid pressure field, which causes the drag to increase.

Additionally, a similar case is presented in Figure 6, for the well-known symmetric profile NACA0012, with Re = 5x10^5 and an angle of attack of 15°. It is possible to observe a bubble near the leading edge and detachment of the boundary layer towards the middle of the profile. This would place it in an aerodynamic stall condition.

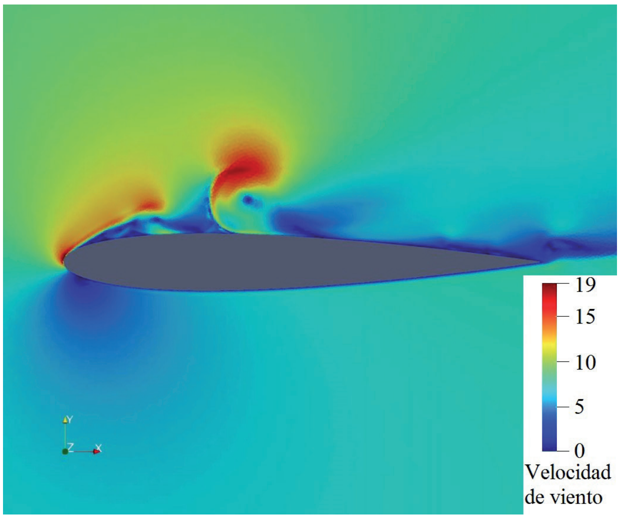

Figure 6: Velocity field in the NACA0012 profile with the γ-Re_θ transition SST model.

The results obtained indicate, for the particular profiles and conditions of this study, that the γ-Re_θ transition SST model is able to capture the phenomenon of laminar separation bubbles for Reynolds numbers between 1x10^4 and 5x10^5.

Conclusions

After implementing in OpenFOAM the γ-Re_θ transition SST model and performing several simulations, it is possible to conclude the following:

- The turbulence model that contemplates the transition through intermittency is able to reproduce the experimental results, with an average weighted percentage error up to 3% lower. In the case of the lift coefficient, with a smaller error than in the case of the drag coefficient.

- The SST γ-Re_θ transition model offers advantages mainly for angles close to or above the angle at which the airfoil enters the stall condition, for the cases analysed in this research.

- For the same flow condition, both the k-ω SST model and the transition γ-Re_θ SST model allow to visualise the flow separation, in the case of the model with transition the bubbles are much clearer than in the model without transition. Therefore, the pressure field is better simulated, since the lift and drag values are more faithful to the experimental ones.

- The laminar separation bubble phenomenon occurs in the three profiles studied, namely the symmetric profile NACA0012 and the asymmetric profiles S826 and SG6043, for Reynolds numbers between 1x10^4 and 5x10^5, under the particular conditions of this research.

With the results obtained in this research, it is possible to continue with the line of research related to the performance of airfoils in transition flow, adding variants in the airfoils, which allow improving their aerodynamic performance in the particular Reynolds conditions between $1x10^4$ and $5x10^5$.

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