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NUMERICAL STUDY OF TURBULENT FLOW AROUND A GENERIC AIRSHIP AT HIGH ANGLE OF ATTACK

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ABSTRACT

This article presents a numerical study of turbulent flow around a generic three-dimensional prolate spheroid with a 20° angle of attack. The Reynolds number we use is a moderate one $Re = 4 \times 10^4$. In this work we compare three different turbulence models : the RANS $k - \varepsilon$, the LES Smagorinsky and the VMS-LES. The numerical code makes use of a mixed FE/FV formulation based on tetrahedra. A Roe's scheme is employed in conjunction with two MUSCL schemes of different precisions.

INTRODUCTION

This study is within the scope of an airship development program. The airships in question are ones of large dimension ($\approx 300\,m$ long), used for air freight. They are intended to carry up to 250 tons of merchandise and expected to be an economical means of transport, requiring less expensive ground infrastructures in comparison with traditional aircrafts. They should also be subject to less statutory restrictions (e.g.: noise regulation . . .). The development of these airships is still in its beginnings on the contrary to the moderately sized ones, which were subject to greater development and exploitation (essentially for advertising and air monitoring purposes).

This work is about the air flow around a flying airship, especially in the case of a non-zero angle of attack, which occurs in the presence of a lateral wind. In regards to the dimensions and velocity of the airship, the flow is fully turbulent, but it is only weakly compressible.

In order to carry out a generic numerical study, and to be able to make experimental comparisons in a future work, we studied the flow around the prolate spheroid $6:1$, which is close to the actual form of an airship. This geometrical form was studied experimentally by Chesnakas and Simpson [1], they mesured flow turbulent quantities around a prolate spheroid of $L = 1.37\,m$ m in length, within a flow of $Re = 4.2 \times 10^6$. At high angle of attack, the prolate spheroid geometrical form represents a numerical challenge, since the flow separation location is not related to any particular geometrical feature. There have been several previous numerical studies that have assessed turbulence models [2, 3], by using this geometrical form as well as the previously mentioned Reynolds number.

The accurate computation of air flow at this Re requires the usage of very fine meshes, especially in the case of Large Eddy Simulation (LES). In the present work, we compare several numerical methods, so, we use a lower Reynolds number ($Re = 4 \times 10^4$) to achieve all the computations within a reasonable period of time while using a moderately-sized mesh.

NUMERICAL APPROACH

Navier-Stokes solver: Compressible and three-dimensional Navier-Stokes equations are solved for a Newtonian fluid flow, using unstructured meshes containing tetrahedra [4]. Spatial discretization is based on a mixed Finite Elements/Finite Volumes formulation [5]. The diffusive terms are treated by a P1-Galerkin FE method, while the convective ones are approximated by a FV upwind Roe's scheme [6] that is extended by a MUSCL (Monotone Upwind Schemes for Conservation Laws) linear reconstruction technique [7, 8], two varieties of which are compared in this study [9]:

- A (V4) scheme whose numerical viscosity is made up of fourth-order derivatives. This scheme is at least of second-order accuracy.
- A (V6) low diffusion scheme that is stabilized by a numerical viscosity containing sixth-order derivatives. This scheme is at least of third-order accuracy.

Time advancing is assured by a second order implicit scheme with three time levels. The solver is preconditioned by a low-Mach Turkel preconditioner, which is useful for such a weakly compressible flow. The code is also parallel. It makes use of non-overlapping domain decomposition.

Turbulence models: Three different turbulence modelings were used in this study, from classical RANS to VMS-LES.

RANS: The Reynolds Averaged Navier-Stokes (RANS) two-equations statistical models are designed to provide steady mean flow fields. They generally rely on Boussinesq turbulent viscosity. But this viscosity may be too large and may damp important steady and unsteady vortical flow structures. Non-equilibrium flows, like those arising close to leading edge at a high angle of attack, are generally not accurately modeled. We use a standard two-equation $k-\varepsilon$ model [5].

LES: Large Eddy Simulation (LES) models are based on the spatial filtering of the Navier-Stokes equations with respect to suitable filter width. Only the large scales, which correspond to the filtered flow variables, are directly simulated. As for the unresolved subgrid scales, a modeling is introduced which takes into account their effect on the large scales. In this study, the well known Smagorinsky model is used [9].

VMS-LES: Unlike the classical LES approach, the Variational MultiScale LES (VMS-LES) model is not based on the spatial filtering of the Navier-Stokes equations, but on the variational projection of these equations over a space of coarse scales, as well as over a space of fine scales [10]. The VMS-LES method separates the scales *a priori*, that is before the simulation is started. Furthermore, the VMS-LES method models the effects of the unresolved scales, but only in the equations governing the fine scales, and not in the equations governing the whole resolved scales, like the LES method does. Thus, with the VMS-LES model, a lesser amount of numerical viscosity is introduced into the solver.

Wall Law: In the above simulations, the flow domain is extended only up to a wall boundary located at a small distance from the surface of the prolate. In the evaluation of the viscous fluxes, the wall shear stress is computed from the non-linear Reichardt's law [5].

RESULTS

Test-case description: The flow around the $L = 1.37\,m$ long prolate has the following far-field characteristics: Mach number $M_\infty = 0.15$; Reynolds number $Re_L = 4 \times 10^4$; density $\rho_\infty = 1.1\,kg\,m^3$; $p_\infty = 101300\,Pa$; angle of attack $\alpha = 20°$. The laminar-turbulent transition was fixed at the position $x/L = 0.2$, where $x = 0$ is at the front extremity of the prolate.

The three-dimensional unstructured mesh used in the simulations contains approximately 160000 nodes and 950000 tetrahedra. The computational domain dimensions are $7.2\,m \times 4.8\,m \times 4.8\,m$. These dimensions have been succesfully used by the authors of previous numerical studies [2, 3]. The part of the mesh that surrounds the prolate surface is pseudo-structured, so that the heights of the adjacent elements at this surface have been fixed at below $7 \times 10^{-3} m$, which results in y^+ values that lie between 4 and 23.

Results:

First of all, we give in *Fig. 1*, a global view of the flow patterns as showed by the flow streams and Mach number distribution. When comparing the results obtained by the three turbulence models (*Fig. 2*), we notice that the low diffusion VMS-LES model captures more flow features than the two others. As an example, a secondary vortex is highlighted in the prolate wake as was observed in the experimental study of Chesnakas and Simpson [1].

In Table 1, we compare the aerodynamic coefficients C_x and C_y given by the three turbulent models using the V4 and V6 MUSCL schemes. The x axis is along the prolate axis and the y axis, which is perpendicular to it, lies in the plane formed by the x axis and the flow direction. They are respectively based on the reference surfaces $S_x = \pi(L/12)^2$ and $S_y = \pi L^2/24$. Once again we observe a significant difference between the RANS results and the LES models results. The RANS values are greater, which is certainly due to the higher amount of numerical viscosity introduced by this model. Furthermore, we do not notice any significant difference between the results given by the V4 and the V6 results. Moreover, this is true for the three turbulence models.

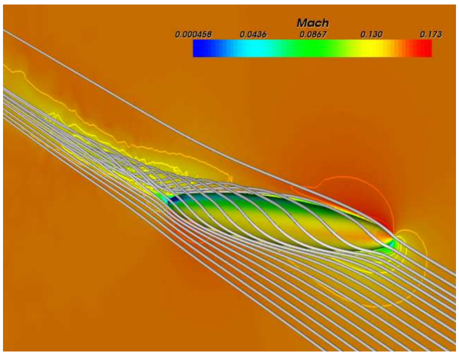

Figure 1
Trajectories and Mach number around the prolate spheroid (VMS-LES model)

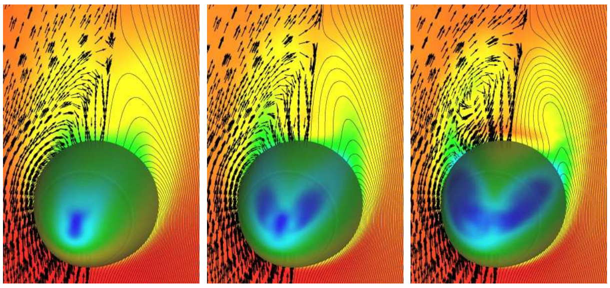

Figure 2
Velocity vectors and streamlines at the plane $x = 1.2\,m$; from left to right : RANS, LES, VMS-LES

CONCLUSION

By comparing the computed aerodynamic coefficients, we found that the RANS $k - \varepsilon$ model results were noticeably different from those of the LES and VMS-LES models and the results of the two latter were quite comparable. This is due to the high amount of numerical viscosity of the RANS model. The VMS-LES model shows some vortical structures that were not captured by the LES and RANS. In our case, the usage of the higher order MUSCL scheme (V6) did not perceptibly influence the results of the (V4) scheme.

Table 1
Aerodynamic coefficients given by the 3 turbulence models and the 2 MUSCL schemes

	C_x		C_y	
	V4	V6	V4	V6
RANS	0.1740	0.1745	0.0870	0.0861
LES	0.1295	0.1316	0.0578	0.0572
VMS-LES	0.1305	0.1313	0.0601	0.0581

KEYWORDS

Unstructured mesh, turbulence, RANS, LES, Roe's scheme, MUSCL, prolate spheroid

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