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PARTIALLY-AVERAGED NAVIER- STOKES SIMULATIONS IN ENGINEERING FLOWS

S. Krajnovic[1*], A. Rao[1], G. Minelli[1], J. Zhang[1], B. Basara[2]
[1]Chalmers University of Technology, Dept. of Mechanics and Maritime Sciences, Gothenburg, Sweden
[2]Advanced Simulation Technology, AVL List GmbH, Graz, Austria

ABSTRACT

This paper presents the most recent applications of the Partially-Averaged Navier-Stokes equations for engineering flows together with the review of the previous work in the field. Partially-Averaged Navier Stokes (PANS) simulation has been successfully used for several different applications of flows around ground vehicles. Examples of flows studied using PANS are that of the flow around square-back Ahmed body, flow around simplified passenger vehicle influenced by crosswinds, flow around simplified intercity trains, to the influence of passive and active flow control on the reduction of the aerodynamic drag on simplified vehicles. The idea of the application of hybrid methods such as PANS is to decrease the resolution requirements that are needed in turbulence resolving simulations such as LES. The resolution requirements of LES are normally very high in the near-wall regions, and this is where the PANS method is expected to activate more turbulence modelling, and thereby decrease the computational effort. The PANS method used by the authors is based on the variable switching coefficient that regulates the amount of the turbulence modelling in the simulation. Previous studies have shown that such implementation of PANS is in line with the requirements that PANS should adapt to the computational grid. The most recent predictions range from simplified ground vehicle flow, flow around a freight train locomotive to the investigation of active flow control for trucks and ships. The new predictions show good agreement with the experimental observations.

KEY WORDS: Partially-Avraged Navier-Stokes simulations, PANS, bluff body flow, vehicle aerodynamics, hybrid RANS-LES

INTRODUCTION

Partially-Averaged Navier Stokes (PANS) [1] simulation has been successfully used for several different applications of flows around ground vehicles. Examples of flows studied using PANS are that of the flow around square-back Ahmed body [2,9], flow around simplified passenger vehicle influenced by the crosswind [3,5], flow around a rudimentary landing gear [4], flow around simplified intercity train [6] to influence of passive [7] and active flow control [8] on the reduction of the aerodynamic drag on simplified vehicles.

The general conclusion is that PANS predictions of flows around simplified vehicles is in good agreement with the experimental observations. Furthermore, the PANS method produces similar results as LES but with smaller computational effort.

The idea of the application of hybrid methods such as PANS is to decrease the resolution requirements that are needed in turbulence resolving simulation such as LES. The resolution requirements of LES are normally very high in the near-wall regions and this is where the PANS method is expected to activate more turbulence modeling, and thereby decrease the computational effort. The key feature of the PANS method is

*Corresponding Author: sinisa@chalmers.se

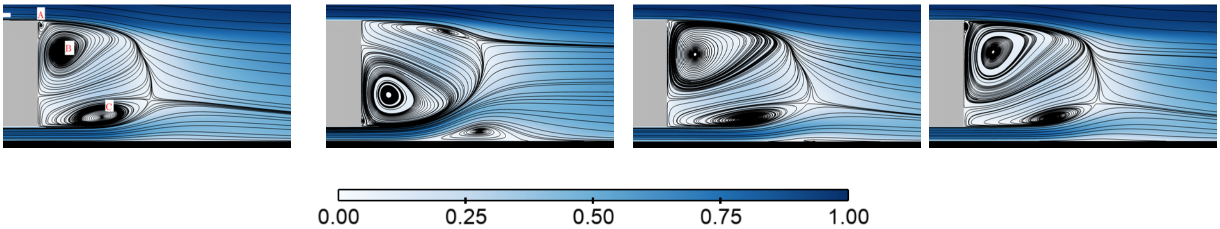
the adaptivity to existing computational grids. The PANS method used by the authors is based on the variable switching coefficient f_k that regulates the amount of the turbulence modeling in the simulation. Previous studies have shown that such implementation of PANS is in line with the requirements that PANS should adapt to the computational grid. Our experience is that the coarsening of the computational grid results in actuation of more turbulence modeling while the opposite releases more turbulence scales. This normally led to small difference in the time-averaged results when the grid refinement study is performed. Nonetheless, these results show the potential of PANS as the engineering tool for unsteady flow predictions for ground vehicles.
This paper presents recent PANS simulations including several challenging vehicle flows. We start with the well-known Ahmed body flow with slanted rear end, which is found to be difficult to predict with any technique that includes RANS modelling. The second flow presented here is that around a locomotive. The paper continues with the investigation of the flow around trucks [10]. Finally, PANS was used to study drag reduction of the flow around a ship using active flow control.

Bi-stable behaviour in the wake of a heavy vehicle.

Recent experiments [11] in the wake of a simplified heavy vehicle has shown that the flow topology in the near wake of an integrated tractor-trailer (or more commonly known as the Ground Transportation System – GTS) remains invariant over a large range of Reynolds numbers. This allows numerical techniques such as LES and PANS to accurately compute the flow. The GTS model is a classic bluff body, with an elliptical rounded nose, a slender body and a squareback base. In the experimental investigations, asymmetrical flow topology is observed in the longitudinal or vertical midplane of the body, while a pair of counter-rotating vortices are observed in the lateral midplane in the wake. In the vertical midplane, the flow field is characterised by a tiny vortex close to the base (A), adjoining a large triangular shaped vortex (B) and a smaller vortex (C) on the opposite side of vortex (B). Flow predictions using RANS fails to predict this asymmetrical flow topology, with a pair of symmetric vortices in both the lateral and the vertical midplanes [12][13].

The flow field is investigated using both LES and PANS at Re_W= 2.7 x 10^4 to compare directly with the experimental simulations of [11], where Re_W is the Reynolds number based on the width of the GTS. The GTS is placed at a height of 0.14H, as in the original studies of [14][15]. For this study, two hexahedral mesh consisting of ~ 8 and 11 million elements are used. The boundaries of the computational domain are located at sufficiently far distances resulting in a blockage ratio of less than 1%. A time-step of 7.5 x 10^{-4} s is used to ensure low CFL number. The averaging of the flow field is carried out afer one flow passage through the domain, for five flow passes. Four cases are investigated, primarily with the change in the differencing scheme employed for the momentum equations: Case1 - LES using 95% central differencing scheme (CDS), Case2 - PANS with AVL SMART (Sharp and Monotonic Algorithm for Realistic Transport), Case3 - PANS with 95% CDS and Case4 - PANS with 95% CDS. While cases Shown in figure 1 are the the contours of the time-averaged velocities for the four cases in the near wake. While the LES simulations of Case1 predicts a flow topology which is anti-symmetric to that observed in the experiments of [11] and [15], Case2 with PANS – AVL SMART, predicts a right flow topology similar to the experiments, along with a ground vortex being observed which is approximately equal to the gap height. In Cases 3 and 4, the CDS schemes for the momentum equations produces a flow topology similar to the LES, but the wake is significantly stretched in the streamwise direction. With an increase in the spatial resolution in Case 4, the size of vortex C reduces and the vortex A is clearly observed. The shape of the separatrix is also different to Case 2, with the ground vortex providing a more uniform curvature. The flow in the near wake of a GTS model can exhibit bi-stable behaviour. It may be noted that the height-to-width ratio of the GTS (1.392) is similar to the width-to-height ratio of a squareback Ahmed body (1.35), where bi-stable flow is observed in the lateral midplane [16][17].

Shown in figure 2 (a) and 2(d) are the contours of the pressure coefficient on the base for Case1 and Case2, respectively, which are in the two flow states. Lower pressure is observed when vortex B is closer to the base, which is further supported by images 2(b) and 2(e), which show the slanted torus of the pressure coefficient. In Case1, the bottom of the torus is farther away from the base, while in Case 2, it is closer. Figure 2(e) also shows that the ground vortex spans approximately 50% of the width of the base. Shown in figures 2(c) and 2(f) are the isosurfaces of the normal stresses in the streamwise direction $< u_x'^{*2} >$. These images show that the largest amount of stress occurs along the sides of the GTS and the region associated with vortex C. Figure 2(f) also shows the stresses associated with the ground vortex.



(a) (b) (c) (d)

Figure 1: Visualisation of the contours of the normalised velocity in the vertical midplane of the GTS overlaid with streamlines. (a) Case1, (b) Case2, (c) Case3, and (d) Case4. Flow is from left to right in these images.

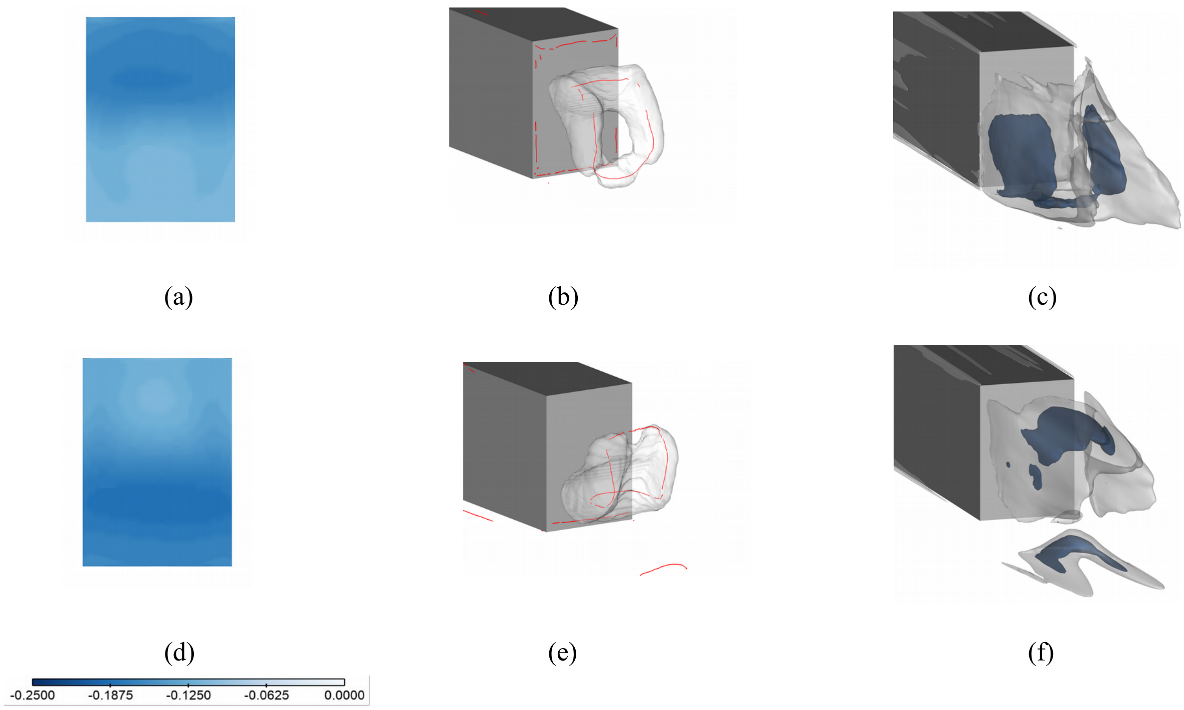


Figure 2: Top row: Case1; Bottom row : Case2. (a) and (d) Visualisation of the contours of the pressure coefficient on the base of the GTS. (b) and (e) translucent isosurfaces of the pressure coefficient (-0.2) and the vortex cores are indicted by red lines. (c) and (f) Isosurfaces of the normal stresses $< u_x'^{*2} >$. White = 0.0375, Blue = 0.02.

Thus, the wake of the GTS can take either of the two flow states, and the two flow states are by numerically reproduced by varying the numerical schemes. While PANS with AVL SMART predicts a flow topology similar to the experiments, using central differencing schemes, tend to predict an elongated wake and requiring additional spatial resolution. The differences between the two flow states have now been identified based on the pressure contours and isosurfaces of the normal stresses.

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