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Assessment of RANS and DES methods for realistic automotive models

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ABSTRACT

This paper presents a comprehensive investigation of RANS and DES models for the Ahmed car body and a realistic automotive vehicle; the DrivAer model. A variety of RANS models, from the 1-equation Spalart Allmaras model to a low-Reynolds number Reynolds Stress model have shown an inability to consistently correctly capture the flow field for both the Ahmed car body and DrivAer model, with the under-prediction of the turbulence in the initial separated shear layer found as a key deficiency. It has been shown that the use of a hybrid RANS-LES model (in this case, Detached Eddy Simulation) offers an advantage over RANS models in terms of the force coefficients, and general flow field for both the Ahmed car body and the DrivAer model. However, for both cases even at the finest mesh level hybrid RANS-LES methods still exhibited inaccuracies. Suggestions are made on possible improvements, in particular on the use of embedded LES with synthetic turbulence generation. Finally the computational cost of each approach is compared, which shows that whilst hybrid RANS-LES offer a clear benefit over RANS models for automotive relevant flows they do so at a much increased cost.

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1. Introduction

Computational Fluid Dynamics (CFD) has become one the main design tools for the external aerodynamic design of modern day vehicles. The computational resources necessary for these simulations has become more affordable, and commercial software is now sophisticated enough to handle the often complex geometries that are common in automotive design. For typical automotive configurations a separated wake flow exists behind the car body, which has a major impact on the drag and fuel efficiency of the vehicle. Whilst there are other important areas around and within the car, the ability of a CFD simulation to capture this recirculation region is largely a function of the predictive capability of the turbulence model. For this work, a comparison is made between Reynolds Averaged Navier–Stokes (RANS) models (at both eddy-viscosity and second-moment closure levels) and hybrid RANS-LES methods (for this work, Detached Eddy Simulation (DES)). RANS methods assume that the entire spectrum of turbulence can be modelled by a set of transport equations which arise from decomposing the turbulence into a mean and fluctuating component around this mean. The result of this decomposition is an additional term in the Navier–Stokes equation, named the Reynolds Stress tensor. This term requires additional modelling to close the set of equations. Whilst this approach has a certain level of empiricism, it is also based on key physical mechanisms observed in canonical flows, and thus aim to model the turbulence at a much lower cost than higher fidelity methods such as Large Eddy Simulation (LES). Hybrid RANS-LES methods attempt to provide a compromise between accuracy and computational expense by only using LES in regions of flow which are challenging to RANS models (such as separated flow) but then use RANS models elsewhere. Compared to a wall-resolved LES this results in a significant saving of computational resources.

Until recently, most validation work for turbulence models in the automotive sector was confined to simple automotive models such as the Ahmed car body [1,2] or MIRA/SAE Reference bodies. These bodies resemble a car in terms of their broad aerodynamic features, but miss some of the features of a complete automotive model. Whilst different turbulence models have been evaluated on full-car models, these are often internal studies that cannot be published for confidentiality reasons, and cannot be verified by other groups because of the control on geometry and experimental data.

This work aims to assess the capability of the current state of the art RANS and hybrid RANS-LES models (in this work, DES) for automotive relevant test cases. The desired outcome is to provide industrial users with the information to make informed choices of whether to use RANS or hybrid RANS-LES approaches, both in terms of their accuracy and computational expense.

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In this paper the Ahmed car body, a well established automotive test case that combines geometric simplicity with a comprehensive set of experimental data and prior numerical simulations is firstly studied to provide information on the performance of both RANS and hybrid RANS-LES models. Finally, a realistic car model is evaluated to assess whether the conclusions from the Ahmed car hold true for a complete vehicle and also to assess the predictive capability of these different turbulence modelling approaches for a realistic car model. For this we evaluate the DrivAer automotive model [3,4], a recent effort by TUM and Audi/BMW to produce an open-source car model based closely on realistic complete car geometries with openly available experimental data. The ultimate aim of this paper is to bring together both academic and industrial type studies to make conclusions that can be relevant to the automotive industry.

This paper is structured as follows. Section 2 outlines the turbulence models and approaches used in this study, including information on the validation procedure for the hybrid RANS-LES models. Section 3 provides information the two test cases studied in this paper, including information on the computational grid, boundary condition and numerical schemes in use. In Section 4 the results for the two test cases are presented, using both RANS and hybrid RANS-LES methods. In this section, there is also an analysis of the computational expense of each approach as well as discussion on possible improvements. Finally Section 5 provides the main conclusions from this work and suggestions for further work.

2. Turbulence models

In this paper, a variety of turbulence modelling approaches are assessed. These models represent some of the most popular RANS models as well as variants of the popular DES approach (as shown in Table 1). One of the central aims of this work is to assess the current state-of-the art RANS models against one of the most well validated and popular hybrid RANS-LES models; DES. Whilst this work cannot claim to be fully comprehensive, it represents the range of models typically found in the majority of CFD codes (both commercial and open source) and therefore provides an assessment of the current state-of-the-art RANS and DES models for automotive related flows.

The authors chose DES to represent the hybrid RANS-LES models as this is the model largely in use by the automotive industry in finite-volume solvers.

The principle behind hybrid RANS-LES methods is that a traditional wall-resolved LES is too expensive for complex high-Reynolds number flows that are influenced by near-wall effects. By applying a RANS model in the boundary layer and using LES outside of this region, the total cell count can by greatly reduced as RANS models do not require the same level of grid resolution in the boundary layer. A comprehensive review of hybrid RANS-LES methods can be found in Frohlich et al. [13], but in this study one particular method is used: DES [6]. This method has become increasingly popular due to its ease of implementation and demonstrated performance for a range of applications.

Table 1
Turbulence models used in this study.

RANS models	Hybrid RANS-LES models
Spalart Allmaras (SA) [5]	SST-DDES [6]
Realisable $k-\varepsilon$ (RKE) [7]	SST-IDDES [8]
$k-\omega$ SST (SST) [9]	SA-DDES [6]
Elliptic Blending $k-\varepsilon$ v^2-f (B-EVM) [10]	SA-IDDES [11]
Elliptic Blending Reynolds Stress Model (EB-RSM) [12]	

DES can be seen as a RANS model which performs as a LES subgrid scale model in regions where the grid is fine enough to support LES content and as a standard RANS models where the grid is not. In this study we investigate both standard DDES [6] as well as the variant, IDDES [11], which aims to improve some of the shortcomings of DDES and add a wall-modelled LES capability. Readers are advised to read the doctoral thesis of Mockett [14] for a comprehensive explanation of DES models and its variants.

2.1. Validation of DES — Decaying Isotropic Turbulence

Each DES formulation is validated using Decaying Isotropic Turbulence (DIT) to ensure the correct energy decay and validate the model constants. Whilst this is a simple, idealised test case, it is a useful first case to ensure correct levels of dissipation before moving to more complex cases. This is particularly important for commercial CFD codes which tend to have many numerical options (both default and user selectable). The solution domain of the DIT calculation is cubic with length 2π. The solution domain is meshed with three grids consisting of 32^3, 64^3 & 128^3 cubic and equidistant cells. Periodic boundary conditions are imposed in each direction. The initial velocity field is set with a suitable instance of isotropic turbulence from the Wray [15] DNS data from the AGARD database. In order to obtain the initial values for other variables such as the pressure and turbulence quantities (k & ε etc), a frozen velocity field simulation was conducted, the turbulence variables are solved, which once converged were used as initial conditions for the unsteady decay of turbulence simulation.

Calculations were performed with the commercial finite-volume code STAR-CCM+, developed by CD-Adapco. Additional simulations were conducted using the open-source finite-volume Code_Saturne [16] developed by EDF R&D.

The temporal discretisation is 2nd order, and a fully centred 2nd order scheme is used to spatially discretise the momentum convective terms unless otherwise stated. A 2nd order upwind scheme is applied to the turbulent quantities.

Fig. 1(a) & (b) shows the value of the model constant C_{DDES} (which can be seen as an equivalent to the Smagorinsky constant in LES) for each model using the 32^3, 64^3 & 128^3 grids. The C_{DDES} values were selected to give the appropriate level of dissipation for each model, although with a constant C_{DDES} value it is not possible to match the DNS data for every mesh resolution. These values agree with the calibrated values from Ashton et al. [17] as well as those observed by many partners in the EU project ATAAC (Advanced Turbulence Simulation Approaches for the Aerospace Community) [18].

Additionally, a 2nd order upwind scheme and a blended central difference scheme were used to illustrate the importance of using a numerical scheme with low numerical dissipation (Fig. 1(c)). It can be seen that using any scheme other than the fully central scheme gives too much numerical dissipation. This can lead to an over-prediction of the separation region for such cases as the 2D wall-mounted hump [17] and the Ahmed car body [19].

3. Test case descriptions

3.1. Ahmed car body

The Ahmed car body [1,2] represents a generic car geometry with a slanted back and a flat front and has been extensively tested in the literature [20–24]. While it is a much simplified version of a real car, it nevertheless provides many of flow features found in real-life cars such as the complex vortex interactions that occur in its wake and the large 3D separation region behind the car body itself. The wake behind the car body is a result of the interaction between the counter-rotating vortices produced by the slant side

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