Turbulence Modelling of the Prolate Spheroid

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Motivation

This study aims to increase the understanding of turbulence modelling for separating bluff body flows. These types of flows have relevance in numerous engineering disciplines, where their accurate prediction is of essence for cost-efficient, safe designs. To provide a proper assessment of a set of selected model's suitability for this type of flow, the procedures in ASME (2009) is adopted. The test case is the 6:1 prolate spheroid at $45°$ incidence at $Re = 16000$. The simulations are to be validated against preliminary results of a DNS study by my supervisor and his colleagues.

- Perform a V&V study in accordance with ASME (2009) for a set of RANS, hybrid and LES turbulence models.
- Identify critical physical aspects of the flow that needs to be captured to ensure qualitative similarity to the DNS results. Provide recommendations for appropriate turbulence modelling of the studied flow configuration and similar flows.

Methods

Apart from recent history, the only tractable approaches to bluff body flows were a combination of theoretical and experimental fluid mechanics (EFD). However, there are some important limitations to EFD related to blockage and scale effects. Many of the limitations of EFD can be circumvented with computational fluid dynamics(CFD). In CFD, a mathematical model, resembling the physics, is solved numerically to simulate the flow in an approximate fashion. For marine applications, this model consists of the incompressible Navier-Stokes equations coupled with some turbulence model.

In this study, the CFD software OpenFOAM, utilizing the FVM method, has been used to simulate the fluid flow. In essence, this has constituted to a set of filtered equations alongside a set of turbulence models. Below the different models are listed. These models are based on a literature survey on turbulence modelling of bluff body flows.

RANS Models: $k-\omega\ SST, k-\omega\ SSTLM$

Hybrid Models: $k-\omega\ SST\ SAS, k-\omega\ DES$

LES Models: Smagorinsky, WALE

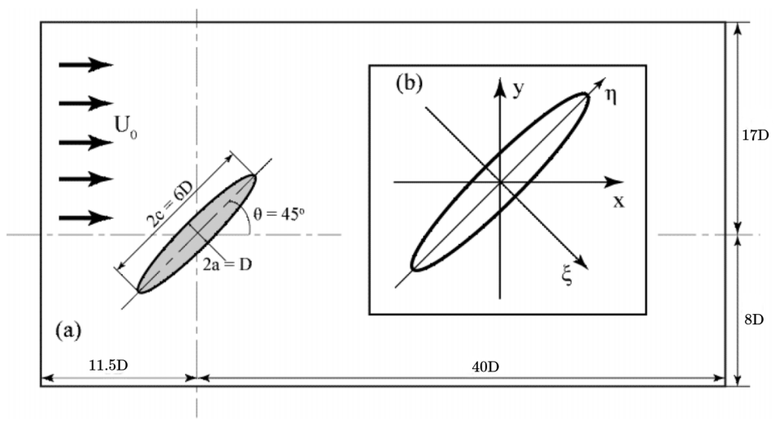

Figure 1: Domain in $x-y$ plane.

Nomenclature

- **V&V**: Verification and Validation
- **Re**: Reynolds number
- **RANS**: Reynolds-Averaged Navier-Stokes
- **LES**: Large-eddy simulation
- **DNS**: Direct numerical simulation
- **SRS**: Scale-Resolving simulation

Conclusions and future wo

A V & V study have been performed successfully for RANS and hybrid models for the 6:1 prolate spheroid. These models were shown unsuitable to model this flow, but note the stabilization of the hybrid models. The LES models are able to capture the asymmetry of the flow, but are very sensitive to numerical settings. In a follow-up study, it is assumed that improvements in methodology (cf. thesis), would have yielded stable results for all models. This new study should include anisotropic hybrid models and LES models. WALE is a particular interesting model as it is able to model wall-bounded laminar flows.

It is assumed that the wake needs to be resolved with a SRS mode to capture the unsteady wake, triggering the instability. Further, turbulence anisotropy is of major importance at a moderate Reynolds number as seen in this study.

References

ASME (2009), *Standard for verification and validation in computational fluid dynamics and heat transfer*, American Society of Mechanical Engineers, New York, NY.

Results & Recommendations

The DNS results are characterized by a moderately unsteady asymmetric wake. This is depicted in Figure 2. The asymmetry is substantial and amounts to as much as 84% of the drag force on average.

The RANS models were unable to capture the instability triggering the flow asymmetry. I.e., its time-averaging damps out the small temporal scales required to develop the asymmetry. Thus, the models predicted a flow symmetric about the meridional plane and a steady wake.

The hybrid simulations faced issues with numerical stability due to the unbounded of central differencing. Following stabilization, the hybrid models predicted a symmetric flow, but an unsteady wake. Thus, the models were in SRS mode in the wake.

The LES models faced the same issues with stability as the hybrid models. However, following stabilization, the Smagorinsky model was able to model an asymmetric wake (cf. Figure 3). This was less severe than the DNS wake and the average sideway force amounted to 79 % of the DNS result.

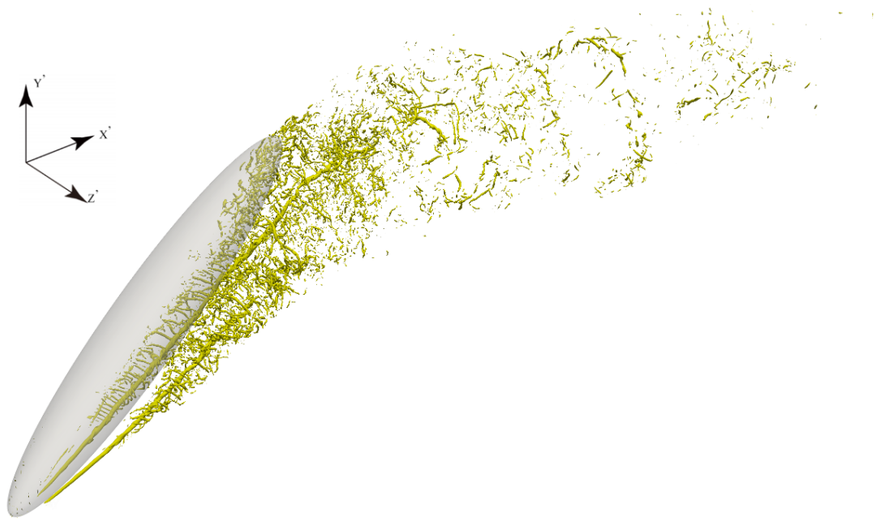

Figure 2: DNS Topology by λ_2 - structures.

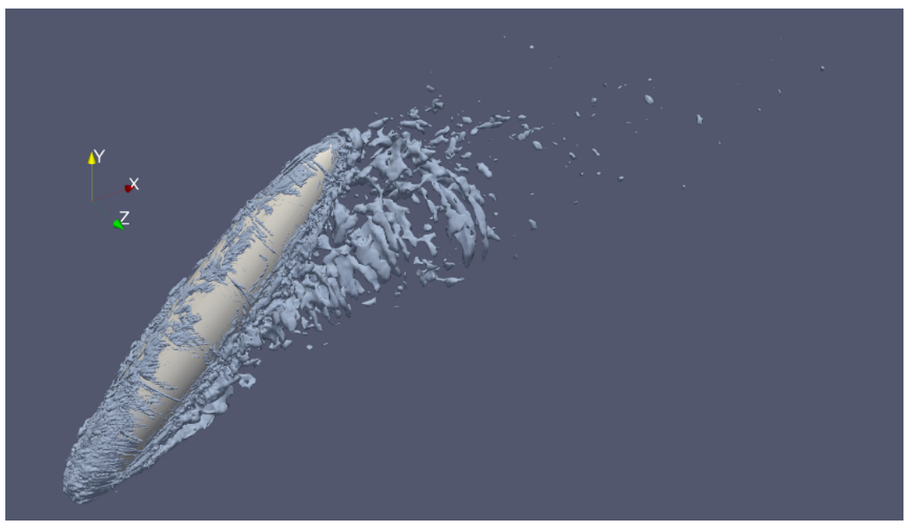

Figure 3: Smagorinsky Topology by λ_2 - structures.

From the stabilized results and results prior to stabilization, it is assumed that wake asymmetry and near body turbulence anisotropy are essential properties of the flow that needs to be captured accurately to predict the flow asymmetry. Without the former, the wake instability, causing wake oscialltions are not triggered. Due to the characteristics of the flow (curved, laminar-turbulent transition) and the LES results, turbulence anisotropy is deemed important. I.e., this yields stronger oscillations, which is seen as necessary to establish the wake asymmetry. Accordingly, LES and hybrid models with anisotropic RANS modes are believed to be sutiable turbulence models of this flow.