International Journal of Heat and Fluid Flow 54 (2015) 28–38

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Hybrid turbulence model simulations of hemisphere-cylinder geometry

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ARTICLE INFO

Article history:
Received 28 August 2014
Received in revised form 6 April 2015
Accepted 28 April 2015
Available online 14 May 2015

Keywords:
Three-dimensional separation
Computational fluid dynamics
Leeward vortices
Hybrid turbulence model
Reynolds number scaling

ABSTRACT

When low aspect ratio geometries such as submarines, torpedoes, or missiles are operated at large angles of attack three-dimensional separation will occur on the leeward side. Separation incurs losses and can result in undesirable unsteady forces. An improved understanding of three-dimensional separation is desirable as it may open the door to new methods for the control or prevention of separation. Numerical simulations of three-dimensional separation can provide detailed insight into instability mechanisms and the resultant flow structures. For most technical applications the Reynolds numbers are too high for direct numerical simulations and lower-fidelity approaches such as hybrid turbulence models become attractive. In this paper a hybrid turbulence model blending strategy is employed that adjusts the model contribution according to the local grid resolution. The strategy is validated for two-dimensional plane channel flow at $Re_\tau = 395$ and 2000. The model is then employed for simulations of a hemisphere-cylinder geometry at 10° and 30° angle of attack. The simulations demonstrate satisfactory model performance over a wide range of Reynolds numbers ($5 \times 10^4 < Re_D < 5 \times 10^5$). A nose separation bubble is captured for the lower Reynolds numbers and leeward vortices are observed for 30° angle of attack regardless of Reynolds number.

1. Introduction

Separation for low aspect ratio geometries such as submarines, torpedoes, or missiles is always three-dimensional (3-D). Coherent structures can arise as a consequence of hydrodynamic instabilities. The instability mechanisms and the resultant structures are 3-D and their interaction with each other is highly complex. The accurate prediction of the nonlinear evolution and dynamical interactions of these structures is of crucial importance as they can strongly influence the global mean flow behavior (which in turn affects performance) and exert unsteady aerodynamic forces. An improved understanding of the flow physics governing 3-D separation in general, and the dynamics of the flow structures in particular, is desirable as this may lead to successful separation control strategies.

Already the mean flow topology of 3-D separated flow regions is very complicated. The skin-friction line pattern, which is characterized by singular points and lines of separation (and attachment) which connect these singular points, provides a description of the flow topology (Lighthill, 1963; Tobak and Peake, 1982) (Fig. 1). "Nodes" are points where skin-friction lines converge (separation) or from which they diverge (attachment). Nodes about which skin-friction lines spiral are known as "focal points". They form the roots of vortices that are often referred to as "horn vortices". Points where "opposing" skin-friction lines meet and then spread outward sideways are called "saddle points". Three-dimensional separation is indicated by the convergence of skin-friction lines onto a particular limiting skin-friction line, the line of separation. At this line the streamlines are forced away from the surface.

Numerical simulations of 3-D separation can provide detailed insight into instability mechanisms and the resultant flow structures. However for flows of practical relevance the Reynolds numbers are often too high to be easily accessible by Direct Numerical Simulations (DNS). For simulations to become feasible the small scales have to be modeled. The lowest grid resolution requirement and lowest computational cost are incurred by Reynolds-Averaged Navier–Stokes (RANS) calculations. However, for bluff body flows as considered here, that exhibit considerable separation, unsteadiness, and energetic large-scale structures, steady RANS calculations are often not a good choice. An alternative to RANS is Large-Eddy Simulation (LES), which, for massively separated flows, is generally more accurate, but also computationally more expensive. The LES grid needs to be sufficiently fine to resolve a significant part of the turbulent wavenumber spectrum. Although the resolution requirement is not as stringent as for DNS, the required near-wall grid resolution is considerably higher than for RANS and increases with Reynolds number. In this context, hybrid

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2015.04.007
0142-727X/

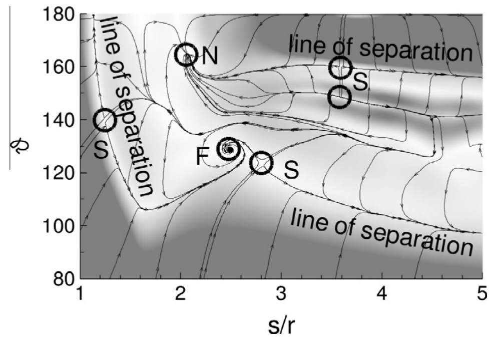

Fig. 1. Hemisphere-cylinder at $Re = 5 \times 10^3$ and $\alpha = 30^\circ$. Skin-friction coefficient, $0 < c_f < 0.013$, and skin-friction lines. F: Focus, N: node, and S: saddle point.

RANS/LES strategies which combine the advantages of RANS and LES are being developed. Speziale (1997, 1998) was among the first to propose a hybrid turbulence modeling approach that combines the advantages of RANS, LES, and DNS.

Hybrid RANS/LES simulations of configurations involving flow separation from smooth surfaces (such as submarine hulls) are challenging because the separation location is not fixed by a geometric discontinuity (such as a step). Several researchers have carried out hybrid simulations for bluff geometries and in the following a short overview of simulations for circular cylinders and a sphere are discussed. The circular cylinder is an attractive candidate for such investigations because of the immense available reference data in the literature (e.g., Williamson (1996)). As the Reynolds number for the circular cylinder is increased beyond $Re \approx 300{,}000$ the boundary layer transitions to turbulence before separation. As a result separation is delayed, the wake becomes narrower, and the drag coefficient drops rapidly from about 0.5 to 0.2 (“drag crisis”).

Travin et al. (1999) carried out Detached Eddy Simulations (DES) of a cylinder with laminar (Re = 50,000, 140,000) and turbulent separation (Re = 140,000, 3×10^6). For the cases with turbulent separation the boundary layer was tripped. Good agreement was observed for the shedding frequency and the mean drag as well as the pressure, and skin friction distributions. The downstream extent of the recirculation region was about twice as long as in the experiment, the Reynolds stresses were about 30% off compared to the experiment, and the results were found to be grid dependent. Nevertheless, the DES meanflow results were in much better agreement with the experiment than reference results obtained from unsteady RANS (URANS) calculations.

Elmiligui et al. (2010) employed a two-equation k–ε model with RANS/LES transition function (dependent on grid spacing and turbulence length scale) and a modified Partially Averaged Navier–Stokes (PANS) model (Girimaji et al., 2003) for simulating the flow around a steady and rotating circular cylinder. For a steady cylinder case with turbulent separation (Re = 140,000, high free-stream turbulence) accurate predictions of the drag coefficient and the Strouhal number were obtained with URANS calculations (based on the k–ε model). For a case with laminar separation (Re = 50,000) the hybrid turbulence models outperformed the URANS models.

Belme et al. (2010) employed Variational Multiscale LES (VMS-LES) and hybrid RANS/LES (based on VMS-LES) for simulating the flow past a circular cylinder at Reynolds numbers between 20,000 and 500,000. The wake and drag predictions were in good agreement with experimental data. Moussaed et al. (2014) employed the same hybrid model for simulating the flow over a circular cylinder at Reynolds numbers between $Re = 1.4 \times 10^5$ and 6.7×10^5. The model was in RANS mode in the attached boundary layer and switched to LES mode in the separated boundary layer and wake. The mean pressure distribution over the cylinder was in reasonable agreement with reference data. The solution was found to be only weakly affected by the grid resolution.

You and Kwon (2010) carried out URANS and hybrid RANS/LES simulations of a circular cylinder for $Re = 3.6 \times 10^6$. For the latter, both the DES and the Scale Adapted Simulation (Menter and Egorov, 2005) model were employed. In all instances the cylinder suction peak was slightly underpredicted compared to the experiment. The Reynolds normal stresses (and turbulent kinetic energy) obtained with the different turbulence models were noticeably different.

Constantinescu and Squires (2003) employed LES and DES for investigating a sphere at Re = 10,000. For this Reynolds number the flow separates laminar and the wake is turbulent. The computed drag coefficient, Strouhal number, separation location, and skin friction distributions were in good agreement with experimental data. Compared to results for a second-order-accurate discretizaton, results for a fifth-order-accurate upwind discretization showed a more pronounced dependence on the turbulence model coefficients. This is in agreement with Margolin and Rider (2002) who showed that the numerical diffusion of certain lower-order upwind schemes can mimick the subgrid stress.

For the results presented in this paper, a hybrid turbulence model was employed that adjusts the model contribution locally according to the ratio of turbulence length scale and grid resolution. The model was tested for two-dimensional plane channel flow at $Re_\tau = 395$ and 2000. The plane turbulent channel flow is a common test case for hybrid LES/RANS models (e.g., Batten et al. (2004), Travin et al. (2006), Temmermann et al. (2005)).

Following the model validation, simulations were carried out for a hemisphere-cylinder geometry at 10° and 30° angle of attack. These simulations serve two purposes: They demonstrate the model performance over a wide range of Reynolds numbers ($5 \times 10^4 < Re_D < 5 \times 10^5$) and they reveal how the mean flow topology changes with Reynolds number. Earlier research indicates considerable 3-D flow separation for the hemisphere-cylinder at angle of attack (Bippes, 1986; Wang and Hsieh, 1992; Hsieh and Wang, 1996; Hoang et al., 1997, 1999; Ying et al., 1987; Gross et al., 2013). At low-Reynolds number conditions and for large angles of attack, a separation bubble forms on the fore-body. In addition, the cross-flow causes the boundary layers to separate, roll up, and form a pair of streamwise vortices on the leeward side of the body (leeward vortices). Three types of separation lines are common for hemisphere-cylinders: The bow separation line and the primary and secondary separation lines. The latter two are associated with the leeward vortices. At small angles of attack, foci terminate the bow separation line and horn vortices are present. At larger angles of attack, the leeward vortices appear to connect in the bow separation bubble and form a horseshoe vortex (Hsieh and Wang, 1996).

The paper is organized as follows: First the turbulence modeling is explained. Then details regarding the grid resolution and boundary conditions are discussed. The hemisphere-cylinder simulations constitute the main body of the paper and, together with the turbulence model validation, are presented in Section 3. Finally a short summary and conclusions are provided.

2. Methodology

2.1. Navier–Stokes code

A research computational fluid dynamics (CFD) code that was developed in our laboratory (Gross and Fasel, 2008, 2010) was employed for the present investigations. The compressible