G Model
APOR-1151; No. of Pages 11
ARTICLE IN PRESS
Applied Ocean Research xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Applied Ocean Research
journal homepage: www.elsevier.com/locate/apor

Large eddy simulations of a circular cylinder at Reynolds numbers surrounding the drag crisis

Thomas P. Lloyd [a,b,*], Marion James [b]

[a] MARIN Academy, Maritime Research Institute Netherlands, Wageningen, The Netherlands
[b] Fluid Structure Interactions Group, Faculty of Engineering and the Environment, University of Southampton, Southampton, United Kingdom

ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form 2 October 2015
Accepted 16 November 2015
Available online xxx

Keywords:
Circular cylinder
Drag crisis
High Reynolds number
Large eddy simulation
Numerical schemes

ABSTRACT

Large eddy simulations of the flow around a circular cylinder at high Reynolds numbers are reported. Five Reynolds numbers were chosen, such that the *drag crisis* was captured. A total of 18 cases were computed to investigate the effect of gridding strategy, turbulence modelling, numerical schemes and domain width on the results. It was found that unstructured grids provide better resolution of key flow features, when a 'reasonable' grid size is to be maintained.

When using coarse grids for large eddy simulation, the effect of turbulence models and numerical schemes becomes more pronounced. The dynamic mixed Smagorinsky model was found to be superior to the Smagorinsky model, since the model coefficient is allowed to dynamically adjust based on the local flow and grid size. A blended upwind-central convection scheme was also found to provide the best accuracy, since a fully central scheme exhibits artificial wiggles, due to dispersion errors, which pollute the solution.

Mean drag, fluctuating lift Strouhal number and base pressure are compared to experiments and empirical estimates for Reynolds numbers ranging from 6.31×10^4 to 5.06×10^5. In terms of the drag coefficient, the drag crisis is well captured by the present simulations, although the other integral quantities (*rms* lift and Strouhal number) show larger discrepancies. For the lowest Reynolds number, the drag is seen to be more sensitive to the domain width than the spanwise grid spacing, while at the higher Reynolds numbers the grid resolution plays a more important role, due to the larger extent of the turbulent boundary layer.

1. Introduction

The flow around circular cylinders is of considerable interest within the areas of turbulence research and engineering analysis. Predicting cylinder forces is particularly important when aiming to reduce vortex-induced vibration, which may occur in a maritime context (in offshore risers for example). Such fluid–structure interaction scenarios have been investigated both experimentally [1] and computationally [2]. However, accurate prediction of the unsteady forces on smooth fixed circular cylinders still remains a challenge for computational methods typically used in engineering.

Cylinder flows have received a considerable amount of research attention due to the complex flow behaviour behind the cylinder, which is highly Reynolds number dependent. Reviews of the vortex-shedding behaviour of circular cylinders are provided by Williamson [3] and Norberg [4]. For Reynolds numbers (*Re*) relevant in maritime engineering, the flow exhibits two regimes, nominally separated at $\sim 2 \times 10^5$ (see [3]). For:

- $Re < 2 \times 10^5$, the wake is turbulent while the attached flow is laminar; the shear layer transitions to turbulence via Kelvin–Helmholtz instability modes, with the length of the shear layer reducing as the Reynolds number increases.
- $Re > 2 \times 10^5$, transition occurs on the cylinder surface (boundary layer becomes turbulent); the flow therefore remains attached for longer due to the locally stronger positive pressure gradient, resulting in a large reduction in drag.

It is this drag reduction, known as the *drag crisis*, which is of particular interest in engineering, as large fluctuating loads have implications for structural design and material fatigue life.

Computational studies of circular cylinders have utilised a number of turbulence modelling techniques. Rosetti et al. [5] presented a detailed verification and validation study using the unsteady Reynolds-averaged Navier–Stokes (URANS) equations for a wide range of Reynolds numbers. For two-dimensional computations, these authors found that the drag crisis was not well captured using this approach, which models all the scales of turbulence. Vaz et al.

* Corresponding author at: MARIN Academy, Maritime Research Institute Netherlands, Wageningen, The Netherlands. Tel.: +31 317 49 39 11.
E-mail address: t.lloyd@marin.nl (T.P. Lloyd).

0141-1187/$ – see front matter © 2015 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2015.11.009

Please cite this article in press as: Lloyd TP, James M. Large eddy simulations of a circular cylinder at Reynolds numbers surrounding the drag crisis. Applied Ocean Research (2015), http://dx.doi.org/10.1016/j.apor.2015.11.009

A	frontal area
D	cylinder diameter
C_D	drag coefficient $(2(\mathbf{F}\cdot\mathbf{e}_x)/\rho A U_0^2)$
C_L	lift coefficient $(2(\mathbf{F}\cdot\mathbf{e}_y)/\rho A U_0^2)$
C_p	pressure coefficient $(2(p-p_0)/\rho U_0^2)$
$\mathbf{e}$	unit vector
$\mathbf{F}$	force vector
p	pressure
Re	Reynolds number $(U_0 D/\nu)$
St	Strouhal number $(fD/U_0|$
t	time
t^*	normalised time (tU_0D)
U_0	reference velocity
ρ	fluid density
ν	kinematic viscosity
$\overline{()}$	filtered quantity
$()'$	fluctuating quantity
$\langle()\rangle$	mean quantity

[6] compared detached eddy simulation (DES) to URANS, but found it did not consistently provided superior predictive capabilities over some RANS models. Very high Reynolds numbers (10^6) were treated using DES in [7], yet the authors note limited success as Reynolds number increases, due to coarse grids and simplified transition modelling. Since DES typically exhibits a RANS-like behaviour in the boundary layer, the inaccuracies associated with the RANS turbulence model remain.

Large eddy simulations, in which only the small turbulence scales are modelled, have typically focussed on low Reynolds numbers where the grid resolution requirements are less demanding. There is, for example, a large body of literature concerning $Re = 3900$ [8–12]. Whilst good agreement between numerical and experimental data is typically seen, grid sizes may still be regarded as large (*e.g.* 6×10^6 cells [9]). At higher Reynolds numbers, grids with a much larger number of cells have been used. For example, at $Re = 1.4 \times 10^5$, grids contain up to 90 million unstructured cells [13,14], which are clearly prohibitive for most engineering applications where computational power is limited. Breuer [15] presented large eddy simulations at $Re = 1.4 \times 10^5$, investigating the effects of grid resolution, domain size and subgrid turbulence model. The maximum grid size used was 6.76 million cells. While the effects of subgrid turbulence model and grid density are difficult to separate in large eddy simulation (LES), this study showed significant sensitivity of the integral results to the choice of subgrid model.

In this paper we analyse the performance of LES for high Reynolds number cylinder flows, suitable for ‘engineering’ applications. The aim was to understand the impact of key modelling decisions on the accuracy of predictions, while maintaining ‘reasonable’ grid sizes. In Section 2, an overview of the computational methods used is provided. Section 3 outlines the chosen test case and set-up of the computational domain. Results are presented in three sections: Section 4 details the effects of grid refinement for both structured and unstructured grids for a single Reynolds number; Section 5 analyses the chosen numerical schemes at the same Reynolds number; and Section 6 reports the results for five Reynolds numbers from 6.31×10^4 to 5.06×10^5. Finally, discussions and conclusions are made in Sections 7 and 8.

2. Numerical models

We solved the governing equations for the unsteady flow of an incompressible fluid, which may be written as

$$\nabla \cdot \mathbf{u} = 0 \tag{1a}$$

and

$$\partial_t(\mathbf{u}) + \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u}, \tag{1b}$$

where $\mathbf{u}$ is the velocity vector, ρ the fluid density, p the pressure and ν the molecular kinematic viscosity. Since turbulent flow contains a wide range of length and time scales, the Navier–Stokes equations are extremely expensive to compute if the entire spectrum of turbulence is resolved. Therefore Eqs. (1a) and (1b) were solved in their filtered form, known as *large eddy simulation*.

2.1. Large eddy simulation

LES lies between direct numerical simulation (DNS) and URANS methods in terms of flow resolution. The filtered governing equations are solved, meaning the large scale turbulence is resolved on the grid, while scales smaller than the grid are modelled. These may be written as

$$\nabla \cdot \overline{\mathbf{u}} = 0 \tag{2a}$$

and

$$\partial_t(\overline{\mathbf{u}}) + \nabla \cdot (\overline{\mathbf{u}} \otimes \overline{\mathbf{u}}) = -\frac{1}{\rho}\nabla \overline{p} + \nu_{eff} \nabla^2 \overline{\mathbf{u}}, \tag{2b}$$

where overbars here denote a filtered (not a mean) quantity and $\nu_{eff} = \nu + \nu_{sgs}$ is the effective viscosity, consisting of the molecular viscosity and the subgrid scale viscosity ν_{sgs}. See [17] for a detailed background on LES. In an ideal LES, 80% of the total turbulence kinetic energy should be resolved [16]. Wall-resolved LES grids require $(\Delta x^+, y_w^+, \Delta z^+) = (50-150, <1, 15-40)$ according to [18]. Although these criteria are less onerous than DNS, a total grid cell scaling of $N_{xyz} \propto Re^{1.8}$ means that achieving a well resolved LES grid at high Reynolds number may not always be possible. In this case, the *subgrid* turbulence model used may have a larger impact on the results. Furthermore, estimating the required grid size for complex flows is difficult *a priori*.

In this paper, we compare two subgrid models. These are designed to account for the interactions between the modelled scales and the resolved flow field. Here, a brief outline of popular models is provided; Sagaut [17] describes the derivation of numerous subgrid models in more detail. The simplest subgrid model is that first derived by Smagorinsky [19], which belongs to the so-called “functional model” class. Utilising the Boussinesq hypothesis, the subgrid stress tensor is modelled as proportional to the resolved strain field, that is

$$\boldsymbol{\tau}^S - \frac{1}{3}\boldsymbol{\tau}^S \cdot \mathbf{I} = -\nu_{sgs}\overline{\mathbf{S}}. \tag{3}$$

The subgrid viscosity (equivalent to the turbulence viscosity in RANS) takes the form

$$\nu_{sgs} = (C_S\overline{\Delta})^2|\overline{\mathbf{S}}| \tag{4}$$

with $|\mathbf{S}| = (2\mathbf{S}\cdot\mathbf{S})^{1/2}$ and $\overline{\Delta}$ the grid cutoff size. The Smagorinsky constant C_S takes a value of *0.1–0.2*, depending on the flow type. An alternative approach to functional modelling is the *structural* model class, which includes those based on the *scale similarity* hypothesis. This states that the largest subgrid scales are analogous to the smallest resolved scales, thus better representing the structure of the subgrid stress tensor. This class of models better accounts for the effect of the subgrid scales on the resolved field. The subgrid tensor for the Bardina model [20] is obtained by applying a double filtering operation:

$$\boldsymbol{\tau}^B = \overline{\overline{\mathbf{u}} \otimes \overline{\mathbf{u}}} - \overline{\mathbf{u}} \otimes \overline{\mathbf{u}} \approx \overline{\overline{\overline{\mathbf{u}} \otimes \overline{\mathbf{u}}}} - \overline{\overline{\mathbf{u}}} \otimes \overline{\overline{\mathbf{u}}}. \tag{5}$$

Since the coefficient C_S is dependent on the grid resolution as well as the flow type, improvements to the subgrid model can be

Please cite this article in press as: Lloyd TP, James M. Large eddy simulations of a circular cylinder at Reynolds numbers surrounding the drag crisis. Applied Ocean Research (2015), http://dx.doi.org/10.1016/j.apor.2015.11.009