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# Large-eddy simulation of the flow past a circular cylinder at sub- to super-critical Reynolds numbers

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ABSTRACT

Large-eddy simulation of turbulent flow past a circular cylinder at sub- to super-critical Reynolds numbers is performed using a high-fidelity orthogonal curvilinear grid solver. Verification studies investigate the effects of grid resolution, aspect ratio and convection scheme. Monotonic convergence is achieved in grid convergence studies. Validation studies use all available experimental benchmark data. Although the grids are relatively large and fine enough for sufficiently resolved turbulence near the cylinder, the grid uncertainties are large indicating the need for even finer grids. Large aspect ratio is required for sub-critical Reynolds number cases, whereas small aspect ratio is sufficient for critical and super-critical Reynolds number cases. All the experimental trends were predicted with reasonable accuracy, in consideration the large facility bias, age of most of the data, and differences between experimental and computational setup in particular free stream turbulence and roughness. The largest errors were for under prediction of turbulence separation.

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## 1. Introduction

Physics and simulation capability of three-dimensional (3D) unsteady separation remains a significant challenge for many fields, including marine and ocean engineering. Ships and off-shore structures suffer separations due to bluff bodies, sharp edges, appendages, wave-induced, and off-design conditions. A fundamental problem for both applications is the turbulent flow past a circular cylinder studied for many years focusing on Reynolds number (Re) effects on smooth surface separation and wake.

The following flow regimes for the turbulent flow past a circular cylinder were defined in Williamson [1], Sumer and Mutlu[39], and Schewe [2]: sub-critical for $3 \times 10^2 < Re < 2 \times 10^5$, critical for $2 \times 10^5 < Re < 3.5 \times 10^5$, super-critical for $3.5 \times 10^5 < Re < 1.5 \times 10^6$, and post-critical for $Re > 1.5 \times 10^6$. Laminar/turbulent separation, laminar separation bubble, turbulent transition, shear layer and Karman instabilities govern the nature of the flow separation for different flow regimes. In particular, the sudden drop of drag force in the critical Re regime, i.e., drag crisis phenomenon, is one of the important topics in fluid dynamics due to its complex flow physics.

For experimental studies, flow phenomena including instabilities as per flow region were explained and summarized in detail by Williamson [1]. Local pressure and skin-friction coefficients were measured at a wide range of Re from sub-critical to post-critical region and boundary layer separation and transition from laminar to turbulent was characterized by Achenbach [3]. At high Re, super-critical region, drag coefficient and vortex shedding frequency was measured and studied by Roshko [4]. Turbulent flow at critical region was studied by Bearman [5] and Farell and Blessmann [6]. Pfeil and Orth [7] studied the influence of the flow disturbances on the separation and transition of the boundary layer and measured flow transition near the laminar separation bubble for the super-critical Re. Experimental benchmark validation data are available for mostly global/integral and limited local flow variables, as summarized in Table 1.

There were many computations for flow around a circular cylinder at a wide range of Re. Most of them were focused on the low Re range and provided good results. However, there were few studies conducted at critical Re including RANS/URANS (unsteady Reynolds Averaged Navier–Stokes Simulation), DES (Detached Eddy Simulation) and LES (Large Eddy Simulation). URANS methods cannot predict the drag crisis due to its inability to predict boundary layer transition to turbulence since most studies either neglect transition modeling or use models that do not display correct trends [8–11]. For instance, Vaz et al. [8] investigated drag crisis in two/three dimensions using RANS approach. A good agreement of drag coefficient was obtained at the sub-critical region but the results were unsatisfactory at the super-critical region. Even a clear drop of drag coefficient was not found. Although the Stouhal number (St) was predicted well, this cannot guarantee accurate flow solution as pointed out by Rodi et al. [12]. Hybrid methods such as DES show some improvements over URANS, but only few studies to

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**Table 1**
Summary of experimental studies and validation variables.

| EFD | Re ($\times 10^{-5}$) | Aspect ratio (L/D) | Tu (%) | Roughness (k/D) | Blockage (%) | Variables |
|---|---|---|---|---|---|---|
| Wieselsberger [40] | Sub-post | N/A | N/A | N/A | N/A | $C_D$ |
| Achenbach [3] | 0.6–50 | Abt 3.3 | 0.7 | Smooth | 17 | $C_D$, $\theta_s$, Cp and Cf |
| Schewe [2] | 0.2–71 | 10 | 0.4 | Smooth | 10 | $C_D$, $C_L$, $C_L^{RMS}$ and St |
| MARIN exp. [8] | Abt. 0.3–8 | Abt 18.6 | N/A | N/A | N/A | $C_D$ |
| Bearman [5] | 1–7.5 | 12 | 0.2 | Smooth | 6.5 | $C_D$, $C_L$, $-C_{pb}$ and St |
| Norberg [41] | 0.0005–2 | 2 | 0.1 | Smooth | 1 | $-C_{pb}$ |
| Shih et al. [42] | 3–80 | Abt. 8.2 | N/A | $3.0 \times 10^{-4}$ | 11 | $-C_{pb}$ |
| Szepessy and Bearman [43] | 0.08–1.4 | 6.7 | 0.05 | N/A | 7.7 | $C_L^{RMS}$ |
| West and Apelt [44] | 0.11–2.2 | 15–35 | 0.2 | Smooth | 8.2 | St |
| Roshko [45] | 0.8–4.5 | N/A | N/A | N/A | N/A | St |
| Cantwell and Coles [37] | 0.69–3.37 | >10 | <1 | Smooth | <10 | Cp and Cf |
| Bearman and Wadcock [46] | 0.025 | N/A | N/A | N/A | N/A | $\Lambda$ |
| Bruun and Davies [47] | 0.6–6 | 10 | 0.1 | Smooth | 13 | $R_{pp}$, $\Lambda$ |
| Iida et al. [48] | 0.06–1.5 | N/A | N/A | N/A | N/A | $\Lambda$ |
| Kacker et al. [49] | 0.1–3 | 8.0 | 0.4 | Smooth | 4.7 | $\Lambda$ |
| Leehey and Hanson [50] | 0.04–0.07 | 97 | 0.04 | Smooth | Open jet | $R_{pp}$, $\Lambda$ |
| Moeller [51] | 0.05–0.56 | 16/19 | 0.3 | Smooth | Open jet | $\Lambda$ |
| Novak and Tanaka [52] | 0.02 | N/A | N/A | N/A | N/A | $\Lambda$ |
| Sonneville [53] | 0.45 | 13 | 0.4 | N/A | 5.6 | $\Lambda$ |
| Szepessy [34] | 0.43 | 10 | 0.05 | Smooth | 7.7 | $\Lambda$ |
| Maekawa and Mizuno [54] | 0.37–2.8 | 3 | N/A | Smooth | 23 | $f_{SL}$ |
| Bloor [55] | 0.002–0.5 | 20–655 | 0.03 | Smooth | 5 | $f_{SL}$ |
| Kourta et al. [56] | 0.02–0.6 | 7 | 0.1 | Smooth | 3 | $f_{SL}$ |
| Okamoto et al. [57] | 0.025–0.045 | 4 | N/A | Smooth | 8 | $f_{SL}$ |
| Wei and Smith [58] | 0.012–0.11 | 14–34 | N/A | Smooth | 1–19 | $f_{SL}$ |

reach definitive conclusions [8,9,13]. Simulations with laminar and turbulent separations was performed at sub-critical and super-critical Re with DES by Travin et al. [13] and a good agreement of local pressure distribution was obtained but there was discrepancy in the skin-friction distribution at super-critical Re which implies the laminar to turbulent transition in the boundary layer from his approach. The few LES (large-eddy simulation) studies on the flow past a circular cylinder show promising results for predicting the drag crisis.

A LES study was performed at a Re in the subcritical region, but very close to critical region, by Breuer [14]. In his study, SGS (sub-grid scale stress) model and aspect ratio effects were examined and good agreement was obtained, especially in the near wake although his grid refinement did not show much improvement. Another LES study was conducted at the supercritical region with a wall-modeled boundary layer by Catalano et al. [15]. In their study, the skin-friction had a similar discrepancy as Travin et al. [13]'s results due to the inadequately modeled boundary layer. Recently, a LES study at the critical region was performed by Ono and Tamura [16] showed good agreement for the super-critical Re but lacked other regimes; the flow structures included the laminar separation bubble but separation angle was under-predicted. Studies roughly showed trends of St, but pressure and shear stress distributions were limited. James and Lloyd [17] predicted the drag crises while Lee and Yang [18] suggested that capability but lacked super-critical results. Kim and Mohan [19] showed good agreement for the sub-and super-critical Re but lacked critical results. Current LES only sparsely covers Re regimes up to the super-critical Re, use small AR especially at the sub-critical Re, use relatively coarse grids for the boundary layer, and do not make full use of the available experimental benchmark validation data.

Momentum and energy conserving convection schemes such as central difference schemes are optimum for LES as with sufficient grid quality and resolution enable fully resolved turbulence up to the grid cutoff frequency, whereas non-conserving schemes display numerical dissipation well before the grid cutoff frequency [20]. However, central difference schemes are unstable on greatly stretched grids; thus, LES for single-phase complex geometries uses momentum conservative third order Quick and 5th order WENO upwind schemes, which are able to capture an acceptable range of the energy cascade [20]. LES for two-phase flows has the additional difficulty of stability across the interface for conservative convection schemes; therefore, non-conservative schemes have been used in particular in the precursory research for surface-piercing cylinder flow by Suh et al. [21] and Koo et al. [22] for sub-critical and sub- to super-critical Re, respectively. The sub-critical Re results were satisfactory however the critical and super critical were not since the deep flow did not display the correct single-phase trends.

The objective herein is verification, validation and analysis of physics for high fidelity LES of single-phase cylinder flow for sub-critical and super-critical Re in conjunction with the ITTC OEC Workshop on VIV and Wave Run-up held in Nantes, France October 17–18, 2013. The approach uses an orthogonal curvilinear grid flow solver, CFDShip-Iowa V6.2, quantitative verification and verification, sensitivity studies for AR, grid and convection schemes, assessment of LES quality, validation using all available experimental data.

## 2. Computational methods

In the LES approach, the Navier–Stokes equations are spatially filtered so that the large, energy carrying eddies are resolved and the small-scale, dissipative eddies are modeled by a SGS model. After applying the filtering operation and the SGS model, the Navier–Stokes equations for the incompressible viscous flow with constant density and viscosity can be written as:

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}\bar{\mathbf{u}}) = -\nabla \bar{p} + \nabla \cdot [(\nu + \nu_t)(\nabla \bar{\mathbf{u}} + (\nabla \bar{\mathbf{u}})^T)], \quad (1)$$

$$\nabla \cdot \bar{\mathbf{u}} = 0, \quad (2)$$

where $t$ is the time, $\mathbf{u}$ is the velocity vector, $p$ is the pressure, the bar on a variable $\bar{\ }$ denotes the filtering operation, $\nu$ is the kinematic viscosity, and superscript $T$ represents the transpose operation. The turbulent eddy viscosity $\nu_t$ is defined as

$$\nu_t = C\Delta^2|\bar{\mathbf{S}}| \quad (3)$$

where $\Delta$ is the filter length (the implicit top-hat filter in this study), $|\bar{\mathbf{S}}| = \sqrt{2\bar{\mathbf{S}} \cdot \bar{\mathbf{S}}}$ with the filtered strain rate tensor $\bar{\mathbf{S}} = \frac{1}{2}[\nabla \bar{\mathbf{u}} + (\nabla \bar{\mathbf{u}})^T]$, and the coefficient $C$ is to be determined by the SGS model to

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