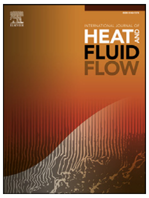
International Journal of Heat and Fluid Flow 000 (2017) 1–10

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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



Reynolds stress modelling of wake interference of two cylinders in tandem: Conventional vs. eddy-resolving closure

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ARTICLE INFO

Article history:
Available online xxx

ABSTRACT

A differential, near-wall Reynolds stress model (RSM) employed in Unsteady RANS (Reynolds-Averaged Navier–Stokes) framework, coupled with the equation governing the inverse turbulent time scale relying on the so-called 'homogeneous dissipation' rate ($\omega_h = \varepsilon_h/k$), was applied to two in-line tandem-cylinder flow configurations. The configurations differ with respect to the distance between cylinders, with the consequence of a differently characterized wake structure. The reference experimental database has been provided by Jenkins et al. (2005, 2006) and Neuhart et al. (2009). Complementary to the 'conventional' Reynolds stress model based on the Jakirlic and Hanjalic's (2002) formulation, its version sensitized appropriately to account for the turbulent unsteadiness by a selective enhancement of its production in line with the SAS (Scale-adaptive Simulation) proposal (Menter and Egorov, 2010), formulated recently by Jakirlic and Maduta (2015), was also applied. This eddy-resolving RSM formulation has been shown to be capable of returning all important mean flow and turbulence features of the configurations considered, including also the intermittent shedding behaviour of the flow in the gap between cylinders related to the long-distance case. The model's inherent capability of capturing the turbulence unsteadiness resulted consequently in the correctly predicted mean flow and turbulence fields, unlike the conventional URANS RSM model which could reasonably well return only the mean surface pressure distribution.

1. Introduction

The flow past a circular cylinder is certainly one of the most frequently investigated flow configurations in fluid mechanics research. Because of its fundamental importance (it represents a generic bluff body configuration for studying vortex dynamics, the drag and lift variation due to wake unsteadiness, etc.) and its relevance in technical applications this flow has been intensively investigated in the past, see e.g. a review of early works in Hinze (1975). Numerous experimental investigations and computational studies by means of statistical models and, more recently, direct numerical simulations (DNS; e.g., Aljure et al., 2015) and large-eddy simulations (LES) of the cylinder flows have been reported in the literature. A nice overview is given in Rodriguez et al. (2015), who performed an LES over a range of diameter-based Reynolds numbers up to $Re_D = 850000$, and in Palkin et al. (2016), who did some RANS modelling, considering both Reynolds-stress (RSM) and eddy-viscosity models (EVM), in addition to a complementary LES.

The flow past a pair of such cylinders in various arrangements – side-by-side and in-line arrangements as well as different combinations of both resembling a staggered arrangement – immersed in a cross-flow, aiming at studying the wake interference, exhibits a significant structural complexity enhancement compared to the flow past a single cylinder (Zdravkovich, 1977; Summner, 2010). Such cylinder-pair constellations are often encountered in engineering applications. Accordingly, the presently considered circular cylinders in an in-line tandem arrangement (Fig. 1) have a large practical relevance. They mimic a two-dimensional (with respect to the mean flow) simplification of a landing gear configuration of an aircraft. This represents an important source of noise during the landing/take-off operation. Accordingly, the noise issue was the main objective behind the measurement campaign conducted by Jenkins et al. (2005, 2006) and Neuhart et al. (2009). As it strongly depends on the interaction between the flow fields past cylinder components the details about the mean flow and turbulence fields were also provided experimentally. The present work focuses on the computational modelling of the latter phenomena. Two dis-

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.07.012
0142-727X/© 2017 Published by Elsevier Inc.

Please cite this article as: R. Maduta et al., Reynolds stress modelling of wake interference of two cylinders in tandem: Conventional vs. eddy-resolving closure, International Journal of Heat and Fluid Flow (2017), http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.07.012

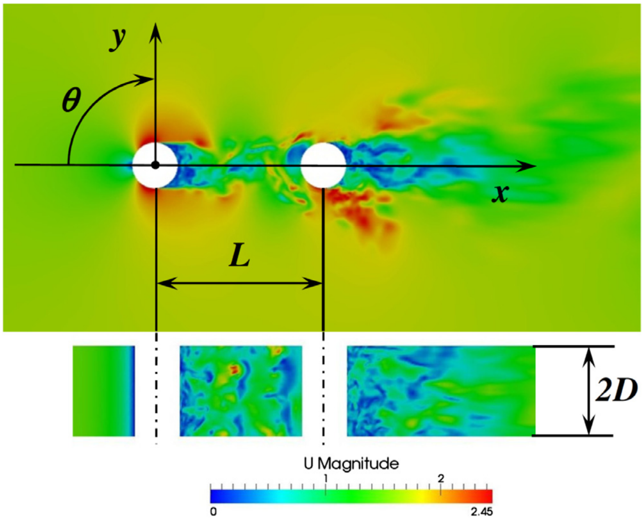

Fig. 1. Tandem cylinder configuration - the coordinate system adopted and instantaneous velocity field in the *x*-*y* plane obtained by the present eddy-resolving RSM model.

tinct tandem-cylinder configurations characterized by different in-between spacing were considered: $L = 3.7\ D$ (long-distance case) and $L = 1.435\ D$ (short-distance case). The corresponding Reynolds number, based on the cylinder diameter D ($D = 0.05715$ m) and velocity of the oncoming flow ($U_{inlet} = 44$ m/s), and the Mach number are $Re_D = 166000$ and $Ma = 0.1285$, respectively. According to Zdravkovich (1997) this Reynolds number corresponds to the very end of the subcritical range ($Re_D = 1000 - 200000$) with laminar-to-turbulent transition taking nominally place in the separated shear layer. The tandem-cylinder case represents a technical configuration in which the interaction between two bluff bodies influences to the largest extent the flow field in its entirety. Depending on the distance between cylinders strong structural changes could be observed. According to Zdravkovich (1985) the distance $L/D = 3.7$ relates to the so-called bistable case corresponding to a configuration in which the flow structure at/behind the first cylinder switches from the continuous shedding, resembling the well-known von Karman vortex street, to a continuously separated shear layer reattaching temporarily at the front side of the rear cylinder (the time-averaged flow pattern is characterized by a free-reattachment point between cylinders); behind the second cylinder a continuous vortex street develops (Fig. 2a). Unlike the long-distance case, in the short distance configuration ($L/D = 1.435$) the cylinders are that close to each other resembling one long obstacle for the oncoming flow. Accordingly, the wall boundary layer separating quasi-stationary from the front cylinder transforms into a shear layer which reattaches at the rear cylinder (Fig. 2b). The flow in the wake behind the downstream cylinder exhibits a continuous shedding behaviour. These descriptions reveal the flow structure past the large-distance case being more challenging for turbulence models due to the bistable (intermittent) behavior. It has been experimentally demonstrated in the longer distance case ($L/D = 3.7$), when comparing the flow structures past downstream cylinder with both a tripped and a non-tripped boundary layer, that the flow separating from the upstream cylinder wasn't strongly disturbed to be treated as fully turbulent in the latter case. This represents a difficulty for the computational model validation by reference to the experimental data, since predicting the location of the laminar to turbulent transition is fairly uncertain. Therefore, the dataset corresponding to the tripped front cylinder and thus fully turbulent approach was recommended to be used for the reference. The boundary layer tripping has no effect in the configuration with the short in-between spacing. Unlike the case with the longer in-between gap, exhibiting a symmetrical pressure distribution at both cylinders with characteristic negative peaks corresponding to the locations with strongest flow acceleration ($\theta = 90^o$ and $\theta = 270^o$), the shorter distance configuration is characterized by an asymmetrical wall pressure development at the downstream cylinder. It is interesting to note that the above-mentioned asymmetrically arranged peaks change their magnitude depending on the experimental campaign.

The afore-described flow features make the tandem cylinder configuration particularly challenging for the computational modelling. The LES-relevant scale-resolving flow simulation methods, which gained increasing popularity in recent years, are especially suitable for capturing the highly unsteady wake regions. Accordingly, numerous computational studies and workshops on collaborative turbulence models validation are reported in the literature. We mention here only some computational activities referring to the experimental campaign by Jenkins et al. (2005, 2006) and Neuhart et al. (2009). Especially interesting are the computational workshops reporting about comparative assessment of different scale-resolving turbulence closure models, Lockard (2011), Schwamborn and Strelets (2012; see also Garbaruk et al., 2012). Keeping in mind the fact that appropriate capturing of the fluctuating turbulence represents an essential prerequisite for the correct reproduction of the sound pressure, only LES and relevant variable-resolution hybrid LES/RANS computational schemes have been tested, all showing high potential in dealing with the high unsteadiness level of the separated shear layers and complex recirculation regions. The predictive performance of differently modified RANS-based models employed to describe the sub-scale turbulence within the IDDES- (Improved Delayed Detached-Eddy Simulation, Shur et al., 2008 and Spalart, 2009), SAS- (Scale-Adaptive Simulation, Menter and Egorov, 2010) and FSM-relevant (FSM: Flow-Simulation Methodology, Speziale, 1998) scale-resolving methods was the subject of recent computational studies of the large-spacing tandem cylinder case ($L/D = 3.7$) by Garbaruk et al. (2014) and Weinmann et al. (2014). Appropriately extended 1-equation (SA: Spalart and Almaras, 1994) and 2-equation $k - \omega - SST$ (Menter, 1994) RANS models, as well as ω-quantity-based EARSM (Explicit Algebraic Reynolds Stress Model) model (Weinmann et al., 2014), were utilized. The best overall agreement with the experimental database was obtained by the IDDES-SA (Garbaruk et al., 2014), IDDES-SST and FSM-SST (Weinmann et al., 2014) model schemes, with the latter scheme introducing a novel variable-resolution function expressed in terms of appropriate ratios of both characteristic length scales, the Kolmogorov and RANS-relevant turbulent ones, to the grid-spacing. Gopalan and Jaiman (2015) simulated the tandem cylinder case over a range of in-between spacings encompassing all characteristic shedding regimes observed experimentally by using a hybrid LES/RANS procedure employing appropriately-incorporated linear and non-linear versions of the Menter's $k - \omega - SST$ model as the background RANS model. As already indicated, the conventional RANS models, despite being employed in the unsteady framework, are due to their Reynolds averaging procedure incapable of adequately capturing the flow physics dominated by the organized, large-scale coherent structures with a broader spectrum. Accordingly, these models were not frequently applied in the past for computing the tandem cylinder flow configurations. Still, the work of Khorrami et al. (2007), who performed two-dimensional unsteady computations by employing the $k - \omega - SST$ RANS model, deserves to be mentioned. The results obtained for the larger in-between cylinder spacing reveal typically a shorter recirculation zone behind the first cylinder and a largely overpredicted size of the flow reversal region behind the downstream cylinder, in large contrast to the experimental evidence. On the other hand, these

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