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Benchmark for Detached-Eddy Simulation of Flow Past Tandem Cylinders

Weiwen ZHAO, Decheng WAN*
State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China
** Corresponding author: dcwan@sjtu.edu.cnn*

Abstract
In this paper, flow past two circular cylinders in tandem arrangement has been selected as the benchmark case for SST-DES and SST-DDES approaches. The numerical simulations are performed using the naoe-FOAM-SJTU solver which is developed based on the open source platform OpenFOAM. Time-averaged flow fields and some quantities of computational results are compared with measurements conducted at two different wind tunnels at NASA Langley Research Center. In addition, the 3D instantaneous flow structures are also given. It is shown that the current implementation of SST-DES and SST-DDES is able to handle complex turbulent flows.

Keyword: *SST-DES; SST-DDES; flow separation; tandem cylinders*

1. Introduction

With the increasing of computation power and advancing of turbulence modeling methodologies, Computational Fluid Dynamics (CFD) is developing rapidly in recent years. While accurate prediction of complex turbulent flows remains a great challenge for engineering problems. One of the bottleneck of Large-Eddy Simulation (LES) for industrial application is the resolution of local eddy energy in boundary layers. The thinner boundary layers for high Reynolds number flows make it more difficult to predict wall bounded flows for LES by increasing the demand of computational demand. According to Spalart [1], LES would be applicable for industrial problems such as airborne or ground vehicle in approximately 2045. On the other hand, Reynolds Averaged-Navier Stokes (RANS) is able to predict boundary layers and their separation in a low cost, but not for unsteady flows as it will product to much eddy viscosity. The idea of hybrid RANS/LES methods came out for its economy and efficiency. The main strategy for hybrid RANS/LES methods is to model boundary layers in RANS behavior and to resolve scales in sub-grid scale (SGS) behavior. One of the mostly well-known approaches is the Detached-Eddy Simulation (DES) which, in recent years, has been widely used in many industrial problems. DES was first proposed by Spalart [2] to address the prediction of massively separated flows at high Reynolds numbers. Menter and Kuntz [3,4] reported problem behavior on the original DES formulation for the unphysical separation caused by the inappropriate near wall grid distribution. The phenomenon is termed Grid-Induced Separation (GIS) as the separation depends on the grid spacing but not flow physics. Menter et al. [3] introduced shedding function for RANS region from the Sheared Stress Transport (SST) based DES formulation to avoid early flow separation caused by GIS. Spalart el al. [5] confirmed GIS was caused by Modeled-stress depletion (MSD) and introduced Delayed-DES (DDES) which provided a more generic formulation of the shedding function.

Flow past a circular cylinder is a classic flow problem, which involves boundary layer transition, flow separation, reattachment and/or vortex shedding. Different behaviors under different Reynolds numbers make it a more complex phenomenon. It has become a benchmark case for new proposed numerical turbulence modeling strategies [6–8]. Compared to single cylinder, flow past tandem circular cylinders involves more complex fluid mechanics and is more common in offshore engineering, aeroacoustics.

The CFD solver naoe-FOAM-SJTU is originally a URANS solver [9] developed based on OpenFOAM, aiming at addressing ship and ocean engineering problems [10,11]. With recently integrating of overset grid technique [12], naoe-FOAM-SJTU is able to handle various kinds of complex ship and ocean engineering flow problems. This study experimentally implements the DES-like method into naoe-FOAM-SJTU in order to extend the capability of addressing massively separated flows.

2. Numerical approaches

2.1 The SST-DES formulation

The SST-DES was developed based on the original two-equation SST turbulence model [13]. The modified version of SST model in OpenFOAM [14,15] replaces vorticity Ω by strain rate S in the definition of turbulence eddy viscosity. The transport equation for turbulent kinetic energy k and the specific dissipation ω is given by

$$\frac{\partial k}{\partial t}+\frac{\partial (u_j k)}{\partial x_j}=\tilde{G}-\beta^* k\omega+\frac{\partial}{\partial x_j}\left[\left(\nu+\alpha_k \nu_t\right)\frac{\partial k}{\partial x_j}\right] \quad (1)$$

$$\frac{\partial \omega}{\partial t}+\frac{\partial (u_j \omega)}{\partial x_j}=\gamma S^2-\beta\omega^2+\frac{\partial}{\partial x_j}\left[\left(\nu+\alpha_\omega \nu_t\right)\frac{\partial \omega}{\partial x_j}\right]+\left(1-F_1\right)CD_{k\omega} \quad (2)$$

The dissipation term in k-equation can be rewritten as

$$D^k_{RANS}=\beta^* k\omega = k^{3/2}/l_{RANS} \quad (3)$$

where, l_{RANS} is the turbulent length scale calculated from RANS models. The DES variation modified the dissipation term by replacing the calculated RANS length scale l_{RANS} with a mixed length scale l_{DES}, which is defined as

$$l_{DES}=\min(C_{DES}\Delta, l_{RANS}) \quad (4)$$

in which, C_{DES} is the calibrated DES constant blending from two constants using Menter's blending function F_1 [16]

$$C_{DES}=(1-F_1)C^{k-\varepsilon}_{DES}+F_1 C^{k-\omega}_{DES} \quad (5)$$

and Δ is the filtered length scale in SGS model. Thus the k-equation becomes

$$\frac{\partial k}{\partial t}+\frac{\partial (u_j k)}{\partial x_j}=\tilde{G}-\frac{k^{3/2}}{l_{DES}}+\frac{\partial}{\partial x_j}\left[\left(\nu+\alpha_k \nu_t\right)\frac{\partial k}{\partial x_j}\right] \quad (6)$$

Details about the constants in equations can be referred to Zhao and Wan [17].

2.2 The SST-DDES formulation

DDES was proposed to address the MSD and GIS in the original DES [5]. In the SST-DDES formulation [18], the turbulent length scale is redefined as

$$l_{DDES}=l_{RANS}-f_d\max(0, l_{RANS}-C_{DES}\Delta) \quad (7)$$

where f_d is empiric blending function defined as

$$f_d=1-\tanh\left[(C_{d1}r_d)^{C_{d2}}\right] \quad (8)$$

$$r_d=\frac{\nu_t+\nu}{k^2 d_w^2\sqrt{0.5(S^2+\Omega^2)}} \quad (9)$$

All the constants and coefficients in this paper are obtained from Gritskevich et al. [18].

3. Results and Discussion

The experiments were performed at Basic Aerodynamic Research Tunnel (BART) and Quiet

Flow Facility (QFF) at NASA Langley Research Center (LaRC) [19]. Two different centroid distances $L/D = 1.435$ and $L/D = 3.7$ were investigated in the measurements, where D is the diameter and L is the distance between the cylinder centroids. While the present paper focused on the former one. The measurements setup the circular cylinder with a diameter $D = 0.05715m$ and span $12.4D$ and $16D$. Considering the insensitivity of DES-like methods to spanwise length [20], the computational domain is reduced to span $2\pi D$ in order to save computation cost. Asymmetric behavior of the upstream cylinder is observed in the measurements, Lockard et al. [19] performed numerical simulation with different angle of attack (AoA) ranging from 0.0° to 1.5° in 0.5° increments and the results show that AoA=0.5° gives the best result with measurements. It is therefore chosen as the case of the current study. The Reynolds number based on cylinder diameter is 1.66×10^5.

The unstructured polyhedral grid is generated by *blockMesh*, *topoSet* and *refineMesh* utilities provided by OpenFOAM. The grid generating process will be briefly introduced below. The initial hexahedral background mesh is generated by *blockMesh*. The *topoSet* then selects a set of cells which are inside a box region and stores them in a *cellSet*. Then *refineMesh* refines the cells in the *cellSet* by splitting hexahedral cells. Note that *refineMesh* can split cells in arbitrary directions in 3D Cartisian coordinates system. It therefore offers more flexibility than *snappyHexMesh*, which is another grid generating tools provided by OpenFOAM and can only offer an octree-based mesh refinement. The computational domain extends to $-10 < x/D < 20$, $-10 < y/D < 10$, $-\pi < z/D < \pi$. The grid size for background mesh is 0.5*D*. The near wall grid size out of boundary layer is 0.0078125*D*. The y+ of the first layer is approximately 1. The spanwise grid size is 0.098*D*. Fig. 1 illustrates the grid of the tandem cylinders. The total cell element number is approximately 4.47×10^6. The simulation time step is set to $0.01D/U_\infty$. The temporal term is discretized using second order implicit scheme, convection term is discretized by Linear-Upwind Stabilized Transport (LUST), which blends linear upwind and linear schemes to make solution more robust.

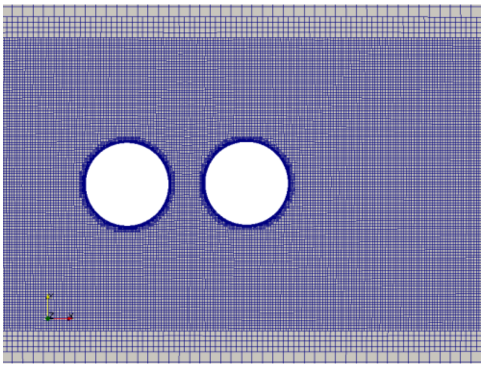
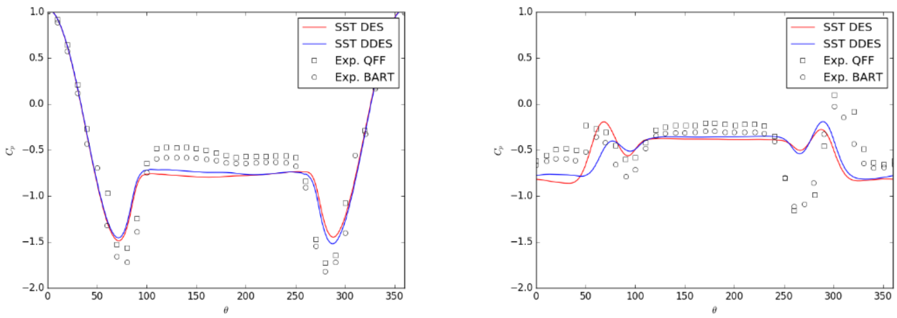


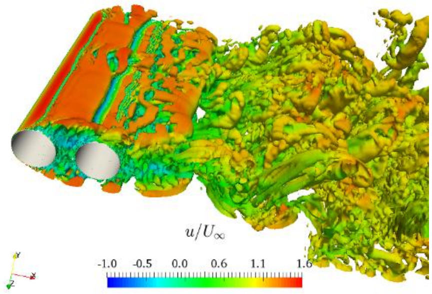
Fig.1. Computational mesh

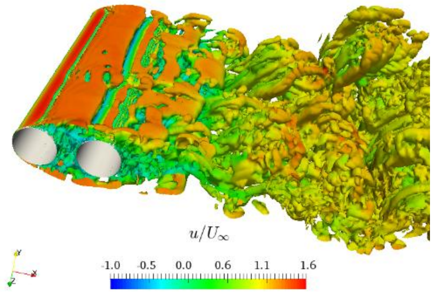
Fig. 2 shows the statistical mean pressure distribution around two cylinders. The figure reveals that the differences between SST-DES and SST-DDES are slight. In Fig. 2(a), both SST-DES and SST-DDES underpredict the pressure of the upstream cylinder. We believe it is due to the coarse grid distribution between two cylinders. A grid refinement should improve results and need to be carried out in the following work. The underpredicted pressure of the upstream cylinder has great impact on the downstream one, as shown in Fig. 2(b). The pressure at stagnation point (θ=0 deg) of the downstream cylinder is consistent with the point at θ=180 deg of the upstream one, indicating the downstream cylinder is in the recirculation region of the upstream one.



(a) Upstream cylinder (b) Downstream cylinder

Fig. 2. Mean pressure distribution of tandem cylinders

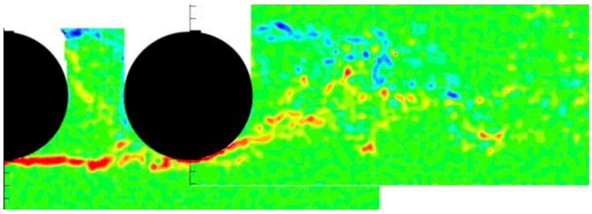




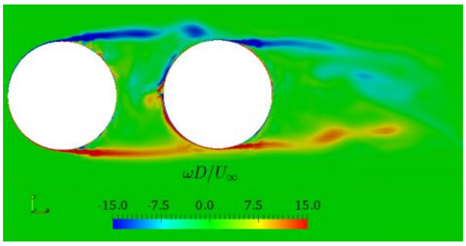
(a) SST-DES (b) SST-DDES

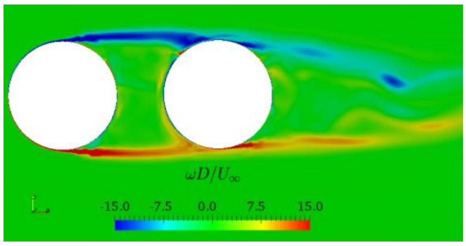
Fig. 3. Instantaneous isosurface of vorticity Q=10

Fig. 3 shows the flow visualizations of two simulations. The vorticity is represented by the second invariant of the velocity gradient tensor, and colored by the non-dimensioned flow velocity. The size of resolved vortical structures are consistent with the grid resolution. Fig. 4 shows the instantaneous spanwise vorticity contour of the tandem cylinders. Small scale vortical structures are observed in the BART experiments. This kind of small-scale structures are not captured by numerical simulations in either SST-DES or SST-DDES, which implies some kind of aspects were missing during the DES modelling. Furthermore, Fig. 4(c) shows some unphysical vorticity in the vicinity of stagnation point of the downstream cylinder in SST-DES, which is not observed in experiments and SST-DDES. Nevertheless, the shear-layer rolling up is successfully predicted by numerical simulations.



(a) BART measurement





(c) SST-DES (d) SST-DDES

Fig. 4. Spanwise vorticity contours

4. Conclusions

A benchmark running case of flow past tandem cylinders is performed to validate the SST-based DES and DDES methods. The mean pressure distribution, vortical structures in wake region and spanwise vorticities is compared to the experimental measurements. The typical aspects of the anisotropic 3D vortical structures have been successfully predicted. The simulations cannot capture all details of the flow structures. We believe further refinement would improve results. Future work may involves grid and time step sensitivity study.

Acknowledgments

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