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Detached-Eddy Simulation of Flow Past Tandem Cylinders *

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Abstract: In this paper, 2 detached-eddy simulation (DES) approaches, namely SST-DES and SST-DDES are implemented, integrated in to the naoe-FOAM-SJTU solver which is developed based on the open source platform OpenFOAM. Flow past 2 cylinders in tandem arrangement is selected as the benchmark case for the validation of the SST-DES and SST-DDES approaches. The experiment was previously conducted in 2 different wind tunnels at the NASA Langley Research Center. Time-averaged flow fields and some quantities of computational results are compared with experiments. In addition, the 3D instantaneous flow structures are also given and discussed. It is shown that the current implementation of SST-DES and SST-DDES is able to resolve some characteristics for massively separated complex turbulent flows.

Key words: SST-DES; SST-DDES; flow separation; tandem cylinders
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Introduction

With the increase of computation power and advance 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 on computational costs. According to Spalart[1], LES would be applicable for industrial problems such as airborne or ground vehicles in approximately 2045. On the other hand, the Reynolds-averaged Navier-Stokes (RANS) method is able to predict boundary layers and their separation at a low cost, but not suitable for unsteady flows as it will produce too much eddy viscosity in the free shear flow region. The idea of hybrid RANS/LES method came out for its economy and efficiency. The main strategy for hybrid

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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 which, in recent years, has been widely applied to many industrial problems. According to Travin et al.[2], DES was defined as "a 3D unsteady numerical solution using a single turbulence model, which functions as a sub-grid-scale model in regions where the grid density is fine enough for a large-eddy simulation, and as a Reynolds-averaged model in regions where it is not". DES was first proposed by Spalart et al.[3] based on the one-equation S-A model[4] to address the challenge of predicting massively separated flows at high Reynolds numbers. Menter, Kuntz et al.[5-6] reported problematic 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.[5] introduced the shedding function to protect the RANS region from early transformation to the sub-grid-scale model for the shear stress transport (SST) based DES formulation to avoid early flow separation caused by GIS. Spalart el al.[7] 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 cylinder is a classic flow problem, which involves boundary layer transition, flow separation, reattachment and/or vortex shedding. Different behaviors at different Reynolds numbers make it a more complex phenomenon. Due to the abundant flow particulars, it has become a benchmark case for newly proposed numerical turbulence modeling strategies[2,8-9]. Compared with a single cylinder, flow past tandem cylinders involves more complex fluid mechanics and is more common in offshore engineering, aeroacoustics and thus become the benchmark case of the present study.

The CFD solver naoe-FOAM-SJTU is originally a unsteady Reynold-averaged Navier-Stokes (URANS) solver[10] developed based on OpenFOAM, aiming at addressing ship and ocean engineering problems[11-12]. With recent integration of the overset grid technique[13], 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.

1 Numerical approaches

1.1 Basic concepts of DES

The standard one-equation S-A model defines the turbulent length scale as the distance to closest wall d. The original DES, proposed by Spalart et al.[3], replace d with new length scale $\tilde{d}$, which is defined as

$$\tilde{d} = \min(C_{\mathrm{DES}}\Delta, d), \tag{1}$$

where, C_{DES} is a calibrated constant which functions like the Smagorinsky constant in the SGS model. Δ is based on the largest dimension of the grid cell:

$$\Delta \equiv \max(\Delta x, \Delta y, \Delta z). \tag{2}$$

The above definition is suitable for structured grids. For unstructured grids, a more common and general definition is given by the cube root of the cell volume V:

$$\Delta \equiv \sqrt[3]{V}. \tag{3}$$

It is to be noted that the grid designed for DES only differs from that for LES in the near wall boundary layer region, where the DES behaves like RANS. This is the main reason that DES needs less computation cost compared with LES.

From the definition of the original S-A DES, it can be concluded that any turbulent model with a clear definition of turbulent length scale can be modified easily to implement its DES formulation accordingly.

1.2 The SST-DES formulation

The two-equation SST model have been proved accurate and robust for ship and ocean engineering problems[14] and thus has been selected as the base RANS model of the current DES-like methods' implementation for naoe-FOAM-SJTU. OpenFOAM's own implementation[15-16] of SST modifies the original SST model[17] by replacing vorticity Ω with strain rate S in the definition of turbulence eddy viscosity. Thus the transport equation for turbulent kinetic energy k and specific dissipation ω is given by

$$\frac{\partial k}{\partial t} + \frac{\partial(u_j k)}{\partial x_j} = \tilde{G} - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\nu + \alpha_k \nu_t)\frac{\partial k}{\partial x_j}\right], \tag{4}$$

$$\frac{\partial \omega}{\partial t} + \frac{\partial(u_j \omega)}{\partial x_j} = \gamma S^2 - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \alpha_\omega \nu_t)\frac{\partial \omega}{\partial x_j}\right] + (1 - F_1) CD_{k\omega}. \tag{5}$$

The length scale of the SST RANS model is defined as

$$l_{\text{RANS}} = \frac{\sqrt{k}}{\beta^* \omega}. \tag{6}$$

Then the dissipation term in the k-equation can be rewritten as

$$D^k_{\text{RANS}} \equiv \beta^* k\omega = k^{3/2}/l_{\text{RANS}}. \tag{7}$$

The DES formulation modifies the dissipation term by replacing calculated RANS length scale l_{RANS} with mixed length scale l_{DES}, which is defined as

$$l_{\text{DES}} = \min(C_{\text{DES}}\Delta, l_{\text{RANS}}). \tag{8}$$

Calibrated DES constant C_{DES} is blended from 2 constants using Menter's blending function F_1[18-19]:

$$C_{\text{DES}} = (1 - F_1) C^{k\text{-}\varepsilon}_{\text{DES}} + F_1 C^{k\text{-}\omega}_{\text{DES}}. \tag{9}$$

Thus the k-equation becomes

$$\frac{\partial k}{\partial t} + \frac{\partial(u_j k)}{\partial x_j} = \tilde{G} - \frac{k^{3/2}}{l_{\text{DES}}} + \frac{\partial}{\partial x_j}\left[(\nu + \alpha_k \nu_t)\frac{\partial k}{\partial x_j}\right]. \tag{10}$$

Details about the constants and coefficients in the above equations can be referred to Zhao and Wan[20].

1.3 SST-DDES formulation

DDES was proposed to address the MSD and GIS in the original DES[7]. In the SST-DDES formulation[21], the turbulent length scale is redefined as

$$l_{\mathrm{DDES}} = l_{\mathrm{RANS}} - f_{\mathrm{d}} \max(0, l_{\mathrm{RANS}} - C_{\mathrm{DES}}\Delta), \tag{11}$$

where f_{d} is the empirical blending function defined as

$$f_{\mathrm{d}} = 1 - \tanh[(C_{\mathrm{d1}} r_{\mathrm{d}})^{C_{\mathrm{d2}}}], \tag{12}$$

$$r_{\mathrm{d}} = \frac{\nu_t + \nu}{\kappa^2 d_{\mathrm{w}}^2 \sqrt{0.5(S^2 + \Omega^2)}}, \tag{13}$$

where, ν_t and ν are the eddy and molecular viscosities respectively, $\kappa = 0.41$ is the von Karman constant and d_{w} is the distance to wall. f_{d} is zero in the near wall boundary layer to deactivate the DES limiter and ensure that DES works in the RANS manner. In such a way, the RANS region is protected by a "shield" from being early translated to LES. All the constants and coefficients used in this paper are obtained from Gritskevich et al.[21].

2 Results and discussion

The experiment was performed at the Basic Aerodynamic Research Tunnel (BART) and the Quiet Flow Facility (QFF) at the NASA Langley Research Center (LaRC)[22]. It is comprised of 2 cylinders of an equal diameter D with a centroid separation distance L in the streamwise direction. 2 different centroid distances of $L/D = 1.435$ and $L/D = 3.7$ were investigated in the measurements. The present paper focuses on the former one. The measurements setup the cylinder with a diameter of $D = 0.057\ 15$ m and a span of $12.44D$. Fig. 1 shows the measurement facilities in BART.

Asymmetric behavior of the upstream cylinder was observed in the measurements. Lockard et al.[23] performed numerical simulation with different angles of attacks (α) ranging from 0.0° to 1.5° in 0.5° increments and the results show that $\alpha = 0.5°$ gives the best result with measurements. It is therefore chosen as the case for the present study. Fig. 2 illustrates the schematic of the models and the coordinate system. The Reynolds number based on the cylinder diameter is 1.66×10^5.

Fig. 1 The BART measurement configuration

Given the insensitivity of DES-like methods to spanwise length[24], the computational domain is reduced to a span of $2\pi D$ in order to save computation cost. The computational domain extends to $-10 < x/D < 20$, $-10 < y/D < 10$, $-\pi < z/D < \pi$, as shown in fig. 3. The boundary conditions are set as follow: freestream velocity for inlet, fixed pressure for outlet, symmetry for the rest.

The unstructured polyhedral grid is generated by blockMesh, topoSet, refineMesh and snappyHexMesh utilities provided by OpenFOAM. The grid generating process is briefly introduced below.

1) An initial hexahedral background mesh is generated by blockMesh.

2) Refine the mesh in the specific region by the combination of topoSet and refineMesh.

A set of cells in the specific region (usually a box) are selected with topoSet and stored in a cell set. RefineMesh is able to subdivide the cell set in one of the binary space partitioning (BSP) tree, quadtree or octree behaviors.

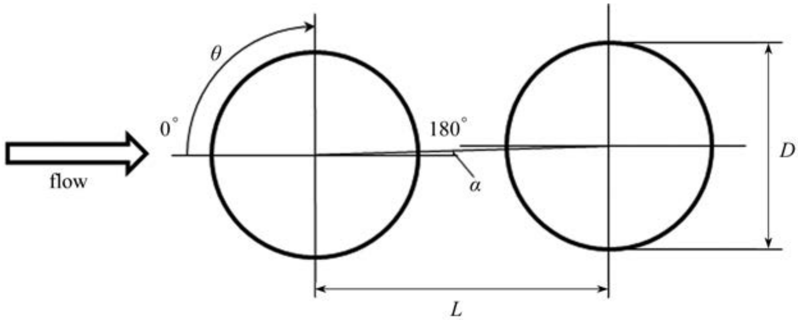


Fig. 2 Schematic of tandem cylinders with the angle of attack

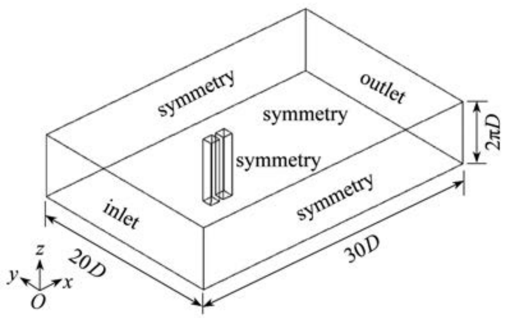


Fig. 3 The computational domain and boundary conditions

3) Repeat 2) for several times to refine the grid to desirable resolution.

4) Snappy the grid based on the cylinder geometries and add the boundary layer grid with snappyHexMesh.

The grid size for the initial background mesh is $0.5D$ in the x- and y- direction, $0.098D$ in the z- direction (spanwise). The near wall grid size out of the boundary layer is $0.007\,812\,5D$ in the x- and y- direction, $0.024\,5D$ in z- direction. y^+ of the first layer is approximately 1. Fig. 4 illustrates the computational 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 with the 2nd-order implicit scheme, the convection term is discretized by means of linear-upwind stabilized transport (LUST), which blends linear upwind and linear schemes to make solution more robust.

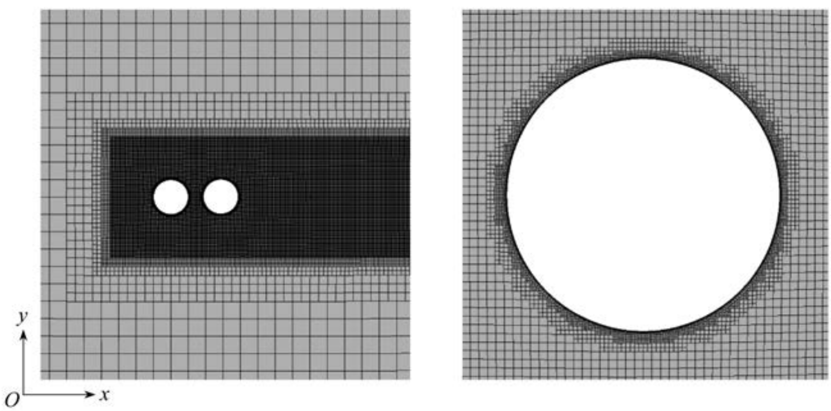


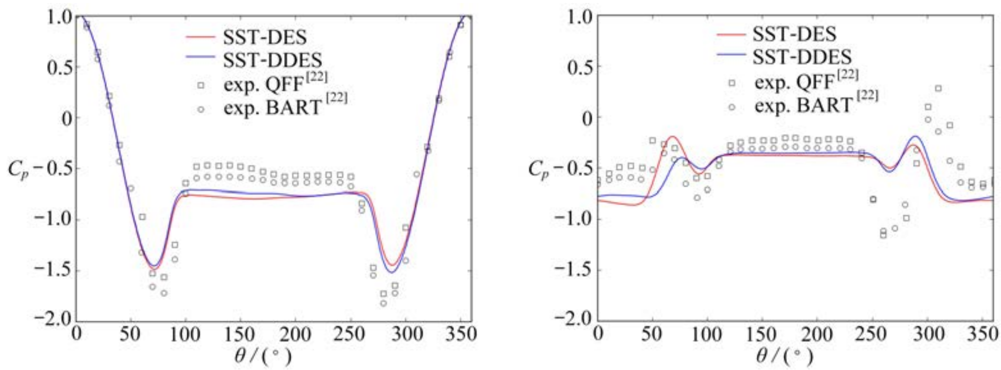
Fig. 4 The global (left) and local (right) computational meshes

Fig. 5 shows statistical mean surface pressure coefficient C_p around 2 cylinders. C_p is defined as

$$C_p = \frac{p - p_\infty}{0.5U_\infty^2}, \tag{14}$$

where, p_∞ and U_∞ are pressure at the outlet and velocity at the inlet respectively.

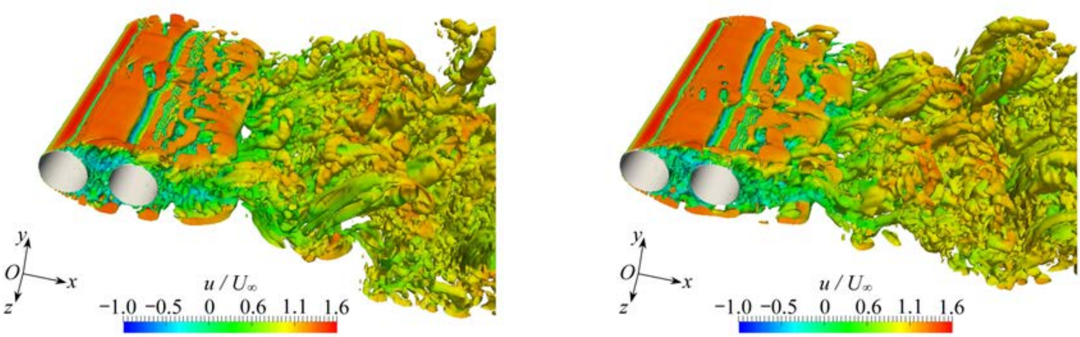
The figure reveals that the differences between SST-DES and SST-DDES are slight. In fig. 5(a), both SST-DES and SST-DDES underpredict the pressure on the upstream cylinder. We believe it is due to the low resolution of the spatial discretization scheme for the finite volume polyhedral mesh. The underpredicted pressure on the front cylinder has great impact on the rear cylinder, as shown in fig. 5(b). The pressure at the rear cylinder stagnation point ($\theta = 0°$) is consistent with that at point at $\theta = 180°$ from the front cylinder in fig. 5(a), indicating the rear cylinder is in the recirculation region of the front cylinder.



(a) The front cylinder (b) The rear cylinder

Fig. 5 Mean pressure distributions of tandem cylinders

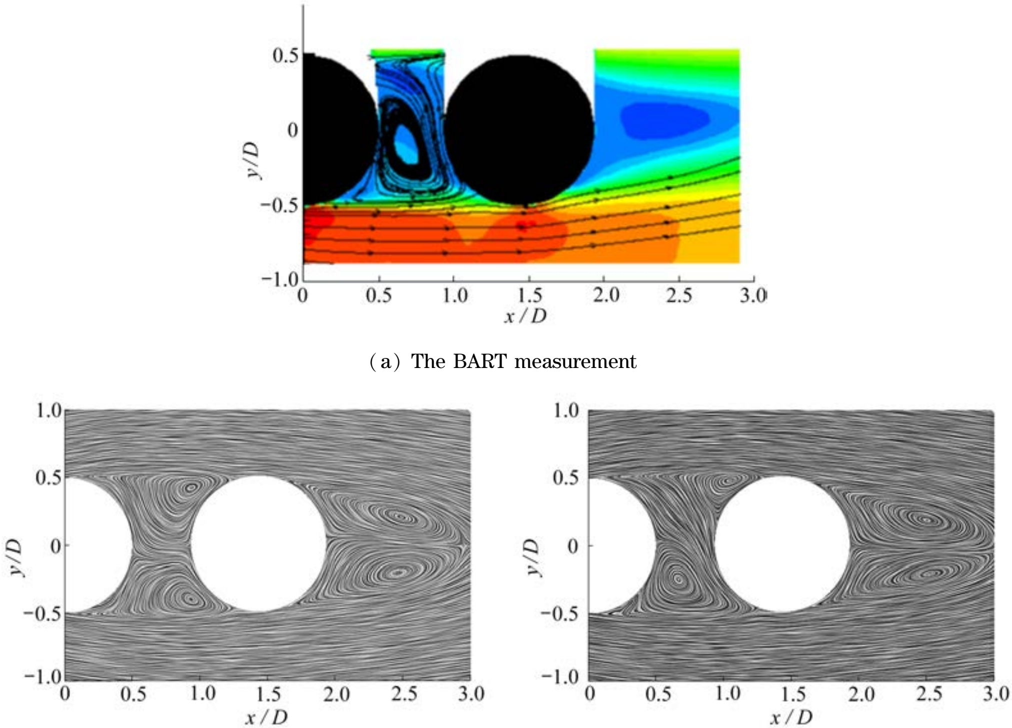
Fig. 6 shows the flow visualizations of the 2 simulations. The vorticity is represented by the 2nd invariant of the velocity gradient tensor, and colored with the non-dimensioned velocity. The von Karman vortex street is observed in the wake region. Furthermore, 3D vortical structures shed in the spanwise direction. The size of resolved eddies is consistent with the grid resolution.



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

Fig. 6 Instantaneous isosurfaces of vorticity $Q = 10$

Fig. 7 gives the streamlines of time-averaged flow. The BART experiment of particle image velocimetry (PIV) is presented in fig. 7(a). Symmetric streamlines are observed in the downstream of rear cylinder. However, the figure also reveals an asymmetric and large recirculated region in the gap between the 2 cylinders. There should be another small recirculated region in the blank area of the PIV image which is not captured by measurements. In the perspective of numerical results as shown in fig. 7(b) and (c), SST-DES failed to predict the obvious asymmetric behavior between the 2 cylinders, while SST-DDES successfully captured the pair of recirculated zones similar to those in the experiments.



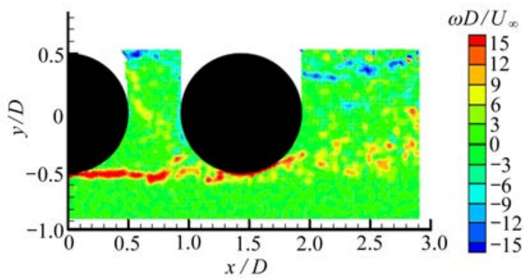
(a) The BART measurement

(b) SST-DES

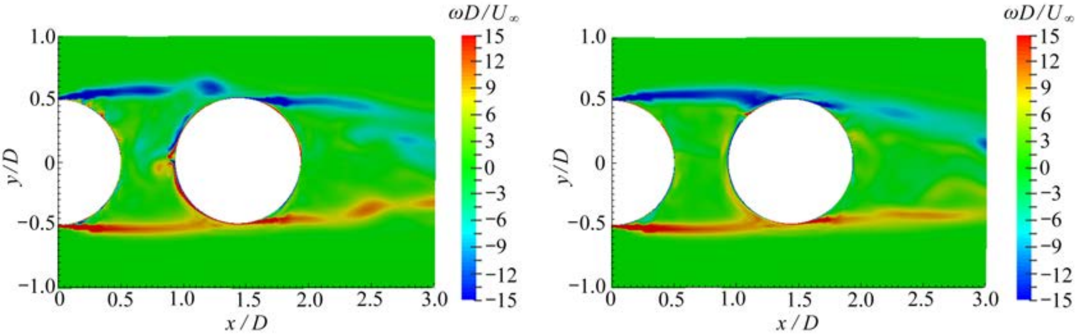
(c) SST-DDES

Fig. 7 Streamlines of the time-averaged velocity around the 2 tandem cylinders

Fig. 8 shows the instantaneous spanwise vorticity contours 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 with either SST-DES or SST-DDES, which implies some aspects were missing during the DES modelling.



(a) The BART measurement



(b) SST-DES (c) SST-DDES

Fig. 8 The instantaneous spanwise vorticity contours

Furthermore, fig. 8(b) shows some unphysical vorticity in the vicinity of the 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.

3 Conclusions

The SST-DES and SST-DDES methods are experiementally implemented, integrated to the CFD solver naoe-FOAM-SJTU. A benchmark running case of flow past tandem cylinders is performed to validate the 2 methods. The mean surface pressures are compared with the experimental measurements. The streamlines based on time-averaged flow velocity and instantaneous spanwise vorticities are compared to the PIV experiment data. The typical aspects of the anisotropic vortical structures in the 3D space have been successfully captured.

The 2 cylinders are arranged to $\alpha = 0.5°$. Both the surface pressure coefficient and streamlines show that SST-DES does not capture the asymmetric behavior as shown in the PIV data, while SST-DDES does. The futher study of spanwise vorticity shows non-physical vorticity in the vicinity of the stationary point of the rear cylinder in DES. This non-physical vortical structures do not exist in SST-DDES. We recommend using SST-DDES for the prediction of massively separated flows at high Reynolds numbers. Before the wide application of SST-DDES in naoe-FOAM-SJTU to industrial problems, an extensive study should be carried out on the time step and grid size sensitivity in the near future work.

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用 DES 分离涡方法数值模拟串列双圆柱绕流问题

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摘要： 主要开发了 SST-DES 和 SST-DDES 两种分离涡方法，并集成到基于开源代码平台 OpenFOAM 开发的 CFD 求解器 naoe-FOAM-SJTU 中.选用高 Reynolds（雷诺）数下串列双圆柱绕流问题作为标准算例来验证所开发的分离涡方法.该标准算例此前在美国国家航空航天局兰利研究中心的两个不同风洞做过物理试验.该研究将数值模拟得到的时均流场信息和一些其他物理量同物理试验结果比较，同时讨论分析了三维瞬态流场结构.结果表明该文开发的 SST-DES 和 SST-DDES 分离涡方法能够解决高 Reynolds 数下有大量流动分离的复杂流动问题.

关 键 词： SST-DES； SST-DDES； 流动分离； 串列双圆柱

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