IMPACT OF DYNAMIC SUBGRID SCALE MODELING IN DDES SIMULATION OF MASSIVELY SEPARATED FLOWS

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Massively separated flow is of great interest in academic researches of turbulence for its highly frequent appearance in industry applications such as deep sea platforms. For the balance of accuracy and economy, hybrid RANS/LES combines the advantages of RANS and LES by simulating the near wall flow region with RANS and the separated flow region with LES. It stands to reason that hybrid RANS/LES methods become an ideal choice to predict massively separated flows in current engineering applications. Detached-eddy simulation (DES) is one of the mostly used hybrid RANS/LES method due to its simplicity in formulation and adaptation in complex geometry. However, one of the most serious problem faced by DES is the modeled stress depletion (MSD) problem. MSD occurs when the grid is fine enough for activating LES branch of DES but not fine enough to resolve the turbulence fluctuations internal to boundary layers. Delayed detached-eddy simulation (DDES) is the remedied version of detached-eddy simulation (DES) by optimizing the character turbulence length scale to protect the RANS region from being prematurely switched into LES region. But DDES should be hardly declared as perfect, and there still remains a rather large space for the improvement of DDES. Since the investigation of improving LES is going on by many scholars at the same time, it is a natural idea to introduce the research achievement of LES into DDES for better performance. One of the most remarkable concept in LES modeling is the dynamic model. Recently, a few researches of deriving the dynamic version of DDES, in which the model constant is dynamically determined, have been carried out by Z.Yin, et al[1] and He, et al[2] independently.

The main purpose of this paper is to study the impact that how dynamic procedure can influence the performance of DDES in simulating massively separated flow around bluff-bodies which is a research hotspot in ocean engineering. Since the concept of dynamic DDES is quite brandnew and very few relevant researches have been carried out, it is very meaningful to examine the capability of dynamic DDES model to be industrial. In the current work, flow around a square cylinder at Reynold number Re =22000 is simulated. Here the two-equation SST model are operated in RANS mode both in DDES and dynamic DDES models.

The main idea of DES is redefining the turbulence length scale which is contained in the dissipative term of the turbulence kinetic energy transport equation. The turbulence length scale defined in the SST-DES model[3] is as follows:

$$L_{DES} = \min(L_{RANS}, L_{LES}) \tag{1}$$

where $L_{RANS} = \sqrt{k}/(C_\mu \omega)$ is the RANS turbulence length scale, and $L_{LES} = C_{DES}\Delta$ is the LES length scale, i.e. local grid scale.

To protect RANS region from being invaded by LES region, DDES modified the character turbulence length scale by introducing the delay function. The delay function proposed by Spalart[4] takes the form:

$$f_d = 1 - \tanh((8r_d)^3) \tag{2}$$

where $r_d = \frac{\nu_t + \nu}{\sqrt{u_{ij}u_{ij}}\kappa^2 d^2}$ is the delay factor. In the near wall boundary layer, f_d is equal to 0. While in the separated region far from wall, f_d approaches 1. The RANS turbulence length scale of DDES version is defined as

$$L_{DDES} = L_{RANS} - f_d \max(0, L_{RANS} - L_{LES}) \tag{3}$$

One can see that L_{DDES} is promised to be L_{RANS} in the boundary layer where is supposed to be covered by RANS region.

The dynamic k-equation subgrid LES model proposed by Kim, et al[5] can be chosen as the chief source, which is as follows:

$$\frac{\partial \rho k}{\partial t} + \nabla\cdot(\rho U k) = \nabla\cdot\left[\left(\mu + \frac{\mu t}{\sigma_{K3}}\right)\nabla k\right] + P_k - \frac{\rho k^3}{\Delta/C_e} \tag{4}$$

Where we can define the LES length scale

$$L_{LES} = C_k \Delta \tag{5}$$

and the subgird eddy viscosity is read as

$$\mu_{sgs} = L_{LES}\sqrt{k} \tag{6}$$

In the dynamic subgird k-equation LES model, the model coefficients C_k and C_e are dynamically determined during computation as

$$C_k = \frac{1}{2}\frac{L_{ij}\cdot M_{ij}}{M_{ij}\cdot M_{ij}} \tag{7}$$

where

$$L_{ij} = \widehat{\overline{U_i}\overline{U_j}} - \widehat{\overline{U_i}}\widehat{\overline{U_j}} \quad (8)$$

$$M_{ij} = -2\Delta\sqrt{K}\widehat{\overline{S_{ij}}} \quad (9)$$

Back to DDES model, the LES subgrid length scale L_{LES} is defined in eq (5). Apparently, one can substitute it with the L_{LES} of the dynamic subgird k-equation LES model which is described above and dynamic DDES is obtained. What should be noticed is that the coefficient C_e is unused in the derivation of dynamic DDES in this paper. It is for the reason that C_e is responsible for the construction of the dissipation term in the dynamic k-equation LES model, while the dissipation term of DDES is explicitly constructed by the form of ω-transport equation. Hence, it is unnecessary to reconstruct the dissipation term of DDES using the form which is defined in the dynamic subgrid LES model. For more details of dynamic DDES model, one can read the paper[2] for reference.

All the computations presented in this paper is carried out on the open source platform OpenFOAM. The Naiver-Stokes equations are discretized by using a cell-centered finite-volume method based on block-structured grids. The implicit Euler scheme is adopted to discretize the unsteady time integration. The convective term is discretized by linear TVD scheme with a limiter, while the diffusive term is discretized by Gauss linear conservation scheme. The coupled velocity and pressure is dealt by applying the PIMPLE algorithm.

The diameter of the square cylinder is set to be D = 0.01m, and the height is set to be 4D. The origin of coordinates is set at the center of the square cylinder. The length of the computational domain in the flow direction is arranged as 36D, while 20D is set for the vertical direction. This form of domain arrangement is to ensure the full characteristics of flow past a square cylinder can be completely captured.

According to the physics feature of the computation domain, the boundary is marked as the inlet, the outlet, the sides, the bottom and the top. The surface of the cylinder is considered as a no-slip wall. At the inlet boundary, a uniform incoming flow with velocity equal to the free stream velocity $U_\infty = 2.2m \cdot s^{-1}$ is defined. At the outlet boundary, the pressure gradient is set equal to 0. The rest of the boundaries is defined as symmetry boundary, assuming that the height of the cylinder is infinite.

As can be seen in Figure 1, Structured mesh generation is chosen in this case because of the simple geometry of the cylinder. the mesh domain of $5D$ around the cylinder is generated with the O block grids. While the rest of mesh domain is generated with orthogonal hexahedral grids. The thickness of the first grid near the wall of the cylinder is set as $\Delta = 0.005D$ with time step being $0.003\mathrm{D}/U_\infty$ to ensure that $y^+ \leq 1$. The grid nodes distributed in the span-wise direction is set to be $n_Z = 80$.

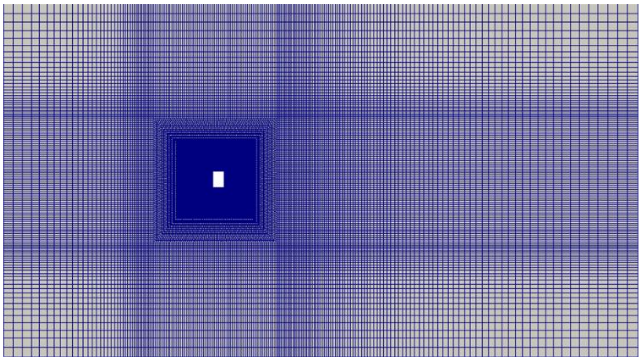


Figure 1: Computation Mesh

Some typical values of the overall flow parameters such as the drag coefficient C_d and the period of shedding S_t are presented together with experimental values[5] and LES predictions[6] in Table 1. The total averaged time is about 100 periods of vortex shedding, which is considered to be long enough for the average operations. Compared with the experiments data, one can see that the overall flow parameters predicted by both DDES and dynamic DDES are admirably accuracy. It means that the dynamic procedure can barely improve the performance of DDES in predicting time averaged overall parameters. This observation is also obtained by Carine, et al[7] when studying the impact of the dynamic procedure in the performance of VMS subgrid LES model.

Table 1: Overall flow parameters of the flow past a square cylinder

Data Source	C_d	**St**	l_r/D
DDES	2.40	0.126	1.14
dynamic DDES	2.38	0.128	1.10
Experiment[5]	2.35	0.135	-
LES[6]	2.18	0.130	1.07

The distribution of normalized mean horizontal velocity in the centerline of the wake compared with the experiment value is shown in Figure 2. It can be seen that the prediction of both these two model is quite close in the near wall regime where RANS model is supposed to be activated. While dynamic DDES shows better congruency with experiment data than DDES in regime $2 \leq x/D \leq 6$. It could be speculated that dynamic DDES resolves more abundant turbulence motions than DDES, i,e the dynamic procedure helps DDES to reach wider range of turbulence scales. This deduction is supported by the distribution of horizontal velocity fluctuations in the centerline which is shown in Figure 5. It can be seen that the horizontal velocity fluctuations predicted by dynamic DDES is apparently smaller than DDES, as a result of more turbulence motion resolved by dynamic DDES. Moreover, as can be seen in Figure 6, dynamic DDES is also thought to be better than DDES in predicting the distribution of vertical velocity fluctuations in regime $2 \leq x/D \leq 6$ which is mentioned above.

The distribution of mean horizontal velocity and mean vertical velocity is also shown in Figure 3-4. It could be seen that the predictions of dynamic DDES and DDES are both quite close to the experiment data. While in the regime y/D >=1.5 away from the wall, dynamic DDES shows slightly superior than DDES in predicting the mean vertical velocity. It has been reported by Matthieu, et al[8] that the predictions of mean velocity at section x/D=1 by RANS and DDES is nearly the same. Hence, it is not surprising that dynamic DDES shows barely improvement of DDES.

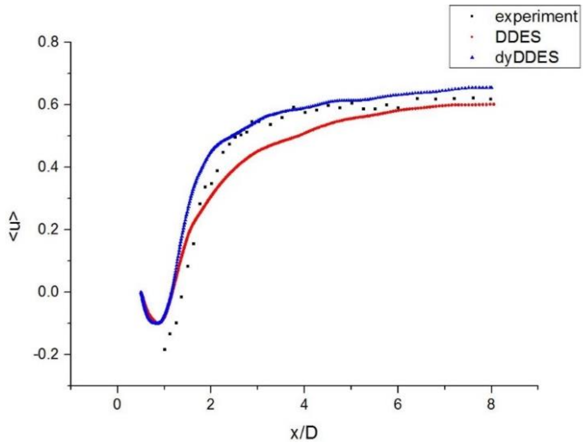


Figure 2: Mean horizontal velocity in the centerline

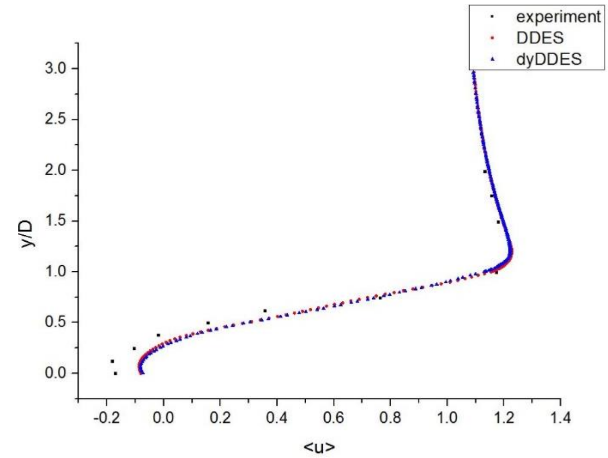


Figure 3: Mean horizontal velocity at x/D=1

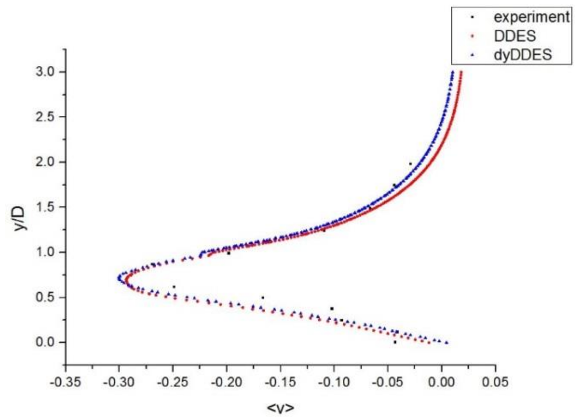


Figure 4: Mean vertical velocity at x/D=1

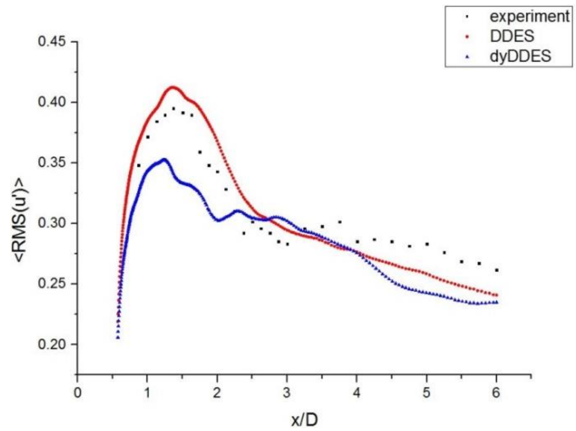


Figure 5: Horizontal velocity fluctuations in the centerline

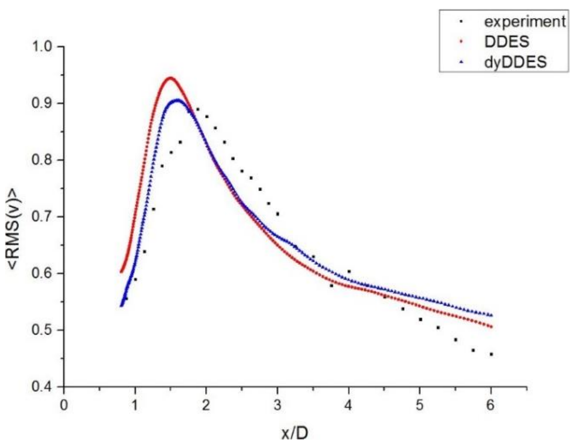
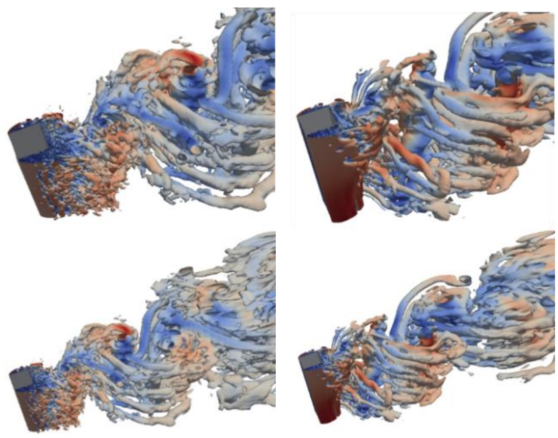


Figure 6: Vertical velocity fluctuations in the centerline



(a) Dynamic DDES (b) DDES

Figure 7: Iso-surface of the Q-criterion

Figure 7 depicts the instantaneous flow structures predicted by SST-SAS and SST-DDES. The visualization of the vortices is realized by displaying the iso-surface of the *Q*-criterion recommended by Hunt[9]. Surprisingly, dynamic DDES apparently catches much finer vorticity structures than DDES, especially in the transition region. It can be seen that the transition predicted by DDES is a bit later and rougher than dynamic DDES, whose performance is rather close to LES. From this figure one can clearly observe that dynamic DDES indeed resolves more abundant turbulence motions than DDES by visualization.

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