Detached Eddy Simulation of a Flow over a Backward-Facing Step

Seong Hoon Kim,a Young In Kim,a Chun Tae Park,a Jae Kwang Seo,b
a SMART Design Group, KAERI, Deokjin-dong, Yuseong-gu, Daejeon, 305-353, Korea, shkim822@kaeri.re.kr e.kr
b Power Reactor Development Center, KAERI, Deokjin-dong, Yuseong-gu, Daejeon, 305-353, Korea,

1. Introduction

Turbulence models are essential ingredients for a successful flow field simulation. The turbulence models that have been generally adopted for the industry are based on the eddy viscosity assumption such as the standard k-ε model, the Spalart-Allmaras model and Wilcox's k-ω model. The Boussinesq approximation, which is the linear relationship between the strain rate and the Reynolds stress, has been known to have a limitation when additional effects such as curvature, buoyancy and rotation are added to the flowfield. To overcome these shortcomings, more sophisticated turbulence models such as the Reynolds Stress Model and the Algebraic Stress Model has been developed by many researchers.

Even though the complexity of models is increased, it is difficult to overcome an inherent defect coming from an averaging process. The averaging process in the model development is required to determine the averaged effect of turbulence to the mean flow field. The defect comes from the fact that the averaging is conducted over a full range of turbulence length scales and removes the direct effect of unsteady large eddy motions. Direct Numerical Simulation (DNS) takes an opposite approach, in which it solves all turbulence scales down to the smallest scale using very fine grids. But, this method has a serious problem for an industrial usage. The simulation cost is enormous and because of that, the possible range of the Reynolds number is limited to be very low. Large Eddy Simulation (LES) that models only small scales of turbulence has been a candidate for filling the gap between DNS and RANS. Unfortunately, LES also has a limitation of the possible Reynolds number.

The detached eddy simulation (DES) is a hybrid method between RANS and LES. The grid requirement near boundary is a main obstacle for an LES usage. DES uses RANS near the wall and LES outside of it.

The backward-facing step flow is simulated to show the DES capability. The near wall models of DES are the SST-kω model and the Spalart-Allmaras model. DES results are compared with RANS results.

2. Methods and Results

2.1 Detached-Eddy Simulation

DES was suggested by Spalart [1] and it has been developed by other researchers [2-4]. The initial method is based on the Spalart-Allmaras one equation turbulence model (DES-SA). The turbulence length scale that is related to the production and the dissipation of turbulent viscosity is changed into the following form.

$$\tilde{d} \equiv \min(d, C_{DES}\Delta) \qquad (1)$$

In doing so, $\tilde{d} = d$ in the near-wall region where RANS is solved, and $\tilde{d} = C_{DES}\Delta$ outside of it where LES is solved. In eq. (1), Δ is the maximum length of a cell, although Δ is a cell volume based value in LES. By defining Δ in this way, DES can suppress LES near wall region.

When DES adopts the SST-kω model as a RANS model (DES-SST-kω), it modifies the dissipation term of the k-equation in the SST-kω model as follows:

$$Y_k = \rho\beta^* k\omega f_{\beta^*} \qquad (2)$$

$$f_{\beta^*} = \max\left(\frac{L_t}{C_{DES}\Delta}, 1\right) \qquad (3)$$

2.2 Computational Grid and Method

Vogel and Eaton [5] conducted an experiment for the flow over a backward-facing step. They measured the temperature and flow fields. In this simulation the heat transfer phenomena is not considered.

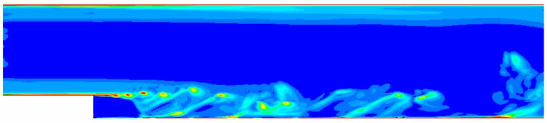
The simulation is conducted by FLUENT, a commercial computational fluid dynamics code. This code provides DES as one of the turbulence models. A converged solution with RANS is used as an initial condition. The inlet and outlet boundary condition of DES is the same to that of RANS. The boundary condition of z-direction is assigned to be symmetric.

The computational domain is defined by 24 H × 5 H × 1 H. H is the step height. The first 4 H is an upstream of the step. Outside of the near-wall region DES is LES, so it requires the same grid resolution as LES does. In the near-wall region, DES turns into RANS, such as the Spalart-Allmaras model and the SST-kω model. Keeping it in mind, we constructed a computational grid to be consistent with the grid requirements for each models. The first grid off the wall is less than 1 in the wall unit, and the grid stretching in every direction is less than 1.2. The maximum grid spacing in the normal and streamwise direction is 0.1 H. The grid spacing is constant, 0.05 H, in the spanwise direction. The total number of the final grid is over 1.8 million. The time step is decided in such a way that the CFL number in most of the computational domain is less than 1.

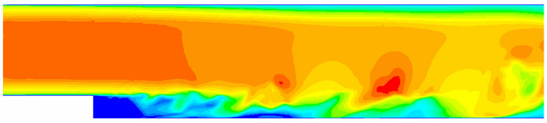
2.3 Results

Figure 1 shows an instantaneous vorticity and a velocity magnitude of a cross section in the z-direction. In the same figure, the mean velocity magnitude is shown at the same cross section. Vortices are generated from the tip of the step and they move to the downstream. In the case of LES vortices exists in the boundary layer upstream of the tip, but in this approach there is no visible vortex in the same region. Because the large eddy generated at the tip and its effect on the downstream region is our main interest, the boundary layer is solved by RANS and, by doing so the required number of grid points is reduced by an order of magnitude with respect to LES.

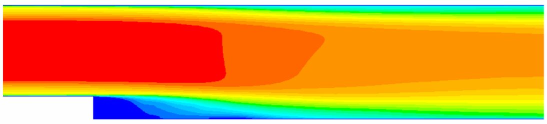
Figure 2 shows the relative length scale, which is, for example, $d - C_{DES}\Delta$ in DES-SA, at the symmetric plane. In this figure, the red region solves LES and the other colored region solves RANS. The figures of the relative length scale of each DES model are different. This is caused from the way of determining turbulence length scale. The Spalart-Allmaras model determines it by the distance from the wall, so in DES-SA the boundary between LES and RANS is fixed during the simulation. On the other hand, the SST-kω model obtains it by calculating from the turbulence quantities, so in DES-SST-kω the boundary keeps moving during the simulation. Sometimes RANS is activated far from the wall in DES-SST-kω. This unwanted activation happens



(a) Instantaneous Vorticity Magnitude (DES-SST-kω)



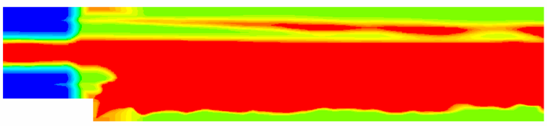
(b) Instantaneous Velocity Magnitude (DES-SST-kω)



(c) Mean Velocity Magnitude (DES-SST-kω)

Figure 1. Simulation results

(a) Relative Length Scale (DES-SA)



(b) Relative Length Scale (DES-SST-kω)

Figure 2. Comparison of the relative length Scale obtained by DES-SA and DES-SST-kω simulations

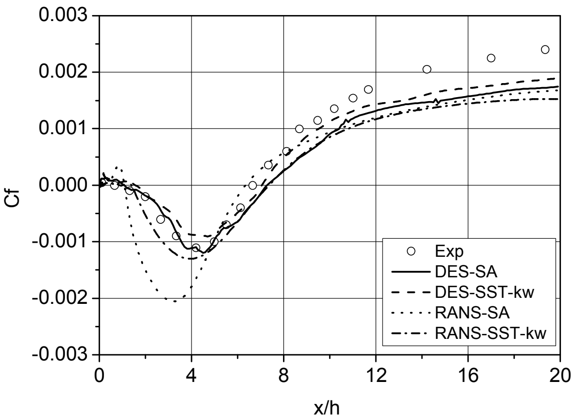


Figure 3. Comparison of the skin friction coefficients

due to not using the wall distance to determine the turbulence length scale.

Figure 3 shows the comparison of the skin friction coefficients predicted by DES and RANS. The predictions by DES are far better than the ones by RANS. DES-SA and DES-SST-kω show the closest estimate in the recirculation region and the redevelopment region respectively. It seems that the large eddy structure captured by the LES part of DES is one of the reasons that DES is better than RANS.

3. Conclusion

DES, a RANS/LES hybrid method, was conducted for a backward-facing step flow. This method predicted a closer behavior of the skin friction coefficient when compared to the experiment than RANS does.

During the simulation, we found that the grid generation is important to conduct DES successfully. To implement DES correctly, the requirements of grid and timestep are investigated more thoroughly.

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