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An Improved Second-Order Finite-Volume Algorithm for Detached-Eddy Simulation Based on Hybrid Grids

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Abstract. A hybrid grid based second-order finite volume algorithm has been developed for Detached-Eddy Simulation (DES) of turbulent flows. To alleviate the effect caused by the numerical dissipation of the commonly used second order upwind schemes in implementing DES with unstructured computational fluid dynamics (CFD) algorithms, an improved second-order hybrid scheme is established through modifying the dissipation term of the standard Roe's flux-difference splitting scheme and the numerical dissipation of the scheme can be self-adapted according to the DES flow field information. By Fourier analysis, the dissipative and dispersive features of the new scheme are discussed. To validate the numerical method, DES formulations based on the two most popular background turbulence models, namely, the one equation Spalart-Allmaras (SA) turbulence model and the two equation $k-\omega$ Shear Stress Transport model (SST), have been calibrated and tested with three typical numerical examples (decay of isotropic turbulence, NACA0021 airfoil at 60° incidence and 65° swept delta wing). Computational results indicate that the issue of numerical dissipation in implementing DES can be alleviated with the hybrid scheme, the resolution for turbulence structures is significantly improved and the corresponding solutions match the experimental data better. The results demonstrate the potentiality of the present DES solver for complex geometries.

AMS subject classifications: 76F99, 76M12, 65L80

Key words: Detached-Eddy simulation, second order scheme, self-adaptive dissipation, hybrid grid, finite-volume method.

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1 Introduction

Most of the flows are turbulent in nature. However, it is a great challenge to provide accurate predictions of turbulent flows. With the increasing power of digital computers, numerical simulation has gradually become a major new means for turbulence study. At present, the main methods used for numerical simulation of turbulent flows include Reynolds-Averaged Navier-Stokes (RANS) methods [1], Large-Eddy Simulation (LES), Direct Numerical Simulation (DNS) and RANS/LES hybrid algorithm. The RANS methods model the turbulent structures of all scales, and only solve the averaged equations, so they are very efficient and are widely used in industrial CFD simulations. However, when dealing with complex (e.g. high angle of attack) turbulent separated and hence vortical flows, it is usually hard for RANS methods to capture the multi-scale turbulence structures. On the other hand, DNS resolves the turbulent structures of all scales, and the governing equations are solved directly on extremely fine grids, so the cost of the computation is extremely high, and the method has been limited to simple flows and low Reynolds number cases. In LES, large eddies are resolved and the small eddies are modeled, so it is a compromise between DNS and RANS. As expected, LES is more reliable than RANS for complex turbulent flows, while the computation cost of LES is less expensive than that of DNS. Even though LES has achieved a great deal of success [2], it is also too expensive to be used in industrial applications, especially for wall-bounded turbulent flows at high Reynolds numbers, because the size of turbulent scales near the wall are roughly proportional to the distance from the wall, which means that accurate simulation requires grid nearly as fine as that in DNS. In contrast, in the near wall regions the RANS approach is known to be almost adequate in terms of computational cost, robustness and credibility [3], thus the RANS/LES hybrid algorithm with the goal of combining LES in the separated regions with models for the RANS equations in the attached boundary layers had been paid more attention in recent years, and they offer a reduced computational effort in comparison to LES while retaining much of the physical accuracy of the method [4].

The idea of RANS/LES hybrid methods began in the 1990s and noticeable progress has been reached over the past twenty years. DES is a prominent representative of these approaches and was first proposed by Spalart et al. in 1997 [5] (hereafter DES97) based on the one-equation SA turbulence model. This was followed by a more general definition of the DES length scale compatible with any RANS model proposed by Travin et al. [6], then a wide range of DES versions based on different turbulence models appeared and were successfully used in complex applications. In the original DES, the switch between RANS and LES depends on the local grid size and turbulent length scale. In some conditions, excessive tangential grid refinement will active the LES mode inside the boundary layer, while the mesh spacing is not fine enough to support resolved velocity fluctuations (i.e., LES content). This results in a reduction of the eddy viscosity and the modeled Reynolds stress without a corresponding balance by resolved turbulent content [7]. Spalart et al. had predicted this effect from the origin of DES97 and referred to it as Mod-