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EVALUATION OF HIGH ORDER SMOOTH FILTER IN LARGE EDDY SIMULATION OF FULLY DEVELOPED TURBULENT CHANNEL FLOW WITH EXPLICIT FILTERING

Norouz M. Nouri
Saber Yekani Motlagh
Ehsan Yasari

Iran University of Science and Technology, Department of Mechanical Engineering, Tehran, Iran
e-mail: mnouri@iust.ac.ir

Explicit filtering with a smooth shape is one of approaches adopted in large eddy simulations (LES). The present work investigates the application of an explicit high order smooth (HOS) filter for the LES of a fully developed turbulent channel flow. The Crank-Nicolson scheme for time marching and second-order finite-volume schemes for spatial derivatives were implemented in this investigation. Implicit filtering, together with the Smagorinsky sub-grid scale (SGS) model, and explicit filtering, along with a HOS filter were studied in a fully turbulent channel flow. In this study, explicit HOS filtering with an explicit filter width to grid size ratio of 2.0 was in agreement with the available direct numerical simulation (DNS) data. However, the mean velocity profile in the streamwise direction was underestimated, and the turbulence intensity in the streamwise direction improved compared to other directions. Moreover, turbulence stresses were well predicted using the mixed SGS and sub-filter stress (SFS) models and applying the HOS filter as an explicit filter.

Key words: large eddy simulation, explicit filtering, implicit filtering

1. Introduction

Large eddy simulation (LES) is one of the best methods for computational modeling of turbulent flows. In contrast with the direct numerical simulation (DNS), the LES does not seek to resolve all the length scales of the flow. The LES is based on the decomposition of flow scales into a resolved sub-grid scale (SGS) where large scales are directly resolved. In this method, the SGS terms and interactions with the resolved scales are modeled. Many different methods are used to achieve the desired accuracy in the LES. The eddy viscosity-based model proposed by Smagorinsky (1963) and Germano *et al.* (1991) generally dissipates enough energy but cannot predict the stress value. The classical Smagorinsky model is obtained by applying a sharp cut-off filter and is valid only when the cut-off frequency is in the inertial sub-range of the energy spectrum. The scales in the inertial sub-range are larger than the dissipative scales and smaller than the scales that contain most of the energy (Piomelli *et al.*, 1991).

Researchers have conducted extensive studies on fully developed turbulent channel flows. Deardorff (1970) conducted the first numerical large eddy simulation of a channel flow using the Smagorinsky model and applying the central difference discretization. In the LES, discrete equations act as a low-pass filter which, by having a width equal to the cell width, produces a smooth shape in the frequency space. Therefore, there is no control on the filter shape and width. The use of a secondary filter as an explicit filter, where the shape and width are somewhat controllable, improves the performance of the solution. The widths of the explicit filter in a turbulent channel flow are 1.5 and 3 times the grid spacing. By using explicit filtering, the errors are transferred to higher wave numbers and thus, their effects on the results are small (Lund, 1997; Lund and Kaltenbach, 2003). Many methods have been proposed for explicit filtering using sharp cut-off filters. For instance, the explicit filtering of the whole velocity field at the end of each time step and the explicit filtering of the convection terms, etc. have been investigated by Tellervo (2005a,b, 2008).

Using a finite-volume method, Elhami *et al.* (2005) recently investigated a fully turbulent channel flow by means of a dynamic filtered model in which the explicit cut-off filter width was twice the grid spacing. The explicit filter shape can either be smooth or close to a sharp cut-off. Consequently, applying each of these filters will have different effects on the turbulence model (De Stefano and Vasilyev, 2002). When the explicit filter with the smooth shape is applied to the Navier-Stokes equations, the sub-filter stress (SFS) model is added to the SGS model to indicate the interactions between the small and large scales (Tellervo, 2005a,b, 2008). The scale-similarity model of Bardina *et al.*) (1980) is a well-known SFS model. To explicitly calculate the magnitude of the SFS term, the filter with a specific function is necessary.

Thus, the aim of this study is to investigate the use of an explicit HOS filter for the LES of a fully developed turbulent channel flow. The finite-volume method and PISO algorithm are utilized for the numerical simulations. The second order discretization method for convection and diffusion and the Crank-Nicolson method for time integration are used. The effects of explicit and implicit filtering on the prediction of the velocity profile, Reynolds stresses, and turbulence intensities are considered.

2. Governing equations in large eddy simulation

The closed form of the filtered Navier-Stokes equation is the fundamental governing equation for simulating the turbulent flow. The following equations are formally derived by applying a low-pass filter to the continuity and Navier-Stokes equations and separating the non-linear terms in three-dimensional forms

$$
\begin{aligned}
&\nabla \cdot \widetilde{U} = 0 \\
&\frac{\partial \widetilde{U}}{\partial t} + \nabla \cdot (\widetilde{U} \otimes \widetilde{U}) + \frac{1}{\rho}\nabla \widetilde{P} = \nabla \cdot (2\nu \widetilde{D}) - \nabla \cdot (B_{SGS})
\end{aligned} \tag{2.1}
$$

where $\widetilde{D}$ is defined as $\widetilde{D} = (\nabla\widetilde{U} + \nabla^{\top}\widetilde{U})/2$. The term $B_{SGS} = \widetilde{U \otimes U} - \widetilde{U} \otimes \widetilde{U}$ is the sub-grid scale (SGS) stress and represents the interactions between the small scales and the large ones. This term originates from the nonlinearity of the convection term $\nabla \cdot (\widetilde{U} \otimes \widetilde{U})$. Different models, including the well-known eddy viscosity Smagorinsky model (Smagorinsky, 1963), are introduced for the sub-grid term. There are two main assumptions made in the derivation of this model: (1) local energy equilibrium and (2) applying the sharp cut-off filter. By considering these assumptions, the relation for the ν_t (eddy viscosity) is obtained as follows

$$
\nu_t = (C_s \varDelta_{grid})^2 |\widetilde{D}| \tag{2.2}
$$

where C_s is the Smagorinsky coefficient, which $C_s = 0.2$ is used in this simulation, and $\varDelta_{grid} = (\varDelta_x \varDelta_y \varDelta_z)^{1/3}$ is the grid filter width. The classical Smagorinsky model with the wall damping function is used in this work for comparison.

3. Explicit filtering

In the LES, discrete equations act as a low-pass filter in which the cell size functions as the filter width resulting in a smooth shape in frequency space. This is referred to as the implicit filter. The limitations of this filter type are as follows.

There is no control on the filter shape, width, and energy spectrum. As a result, numerical errors are uncontrollable (Lund, 1997; Lund and Kaltenbach, 2003). Although most models, including Smagorinsky, are derived by applying a sharp cut-off filter (Smagorinsky, 1963), usually in practice, a smooth grid filter is utilized. Therefore, there is no consistency between the applied and the modeled filter. However, using a secondary filter as an explicit filter yields a controllable shape and width. This improves the performance of the solution.

Consequently, the numerical errors diminish, and the coherency between the LES model filter and the applied filter for the numerical simulation is improved. The shape of the explicit filter has different effects on the energy spectrum and LES turbulence modeling.

4. The effect of filter shape in frequency space on explicit filtering

In contrast to the sharp cut-off filter, the Gaussian and the top-hat filters are smooth in frequency space. For this reason, they are called smooth filters. Because the filter width is larger than the grid spacing in explicit filtering, additional stresses can be defined according to the available turbulence scales. For instance, the stresses related to scales smaller than the explicit filter width are called the sub-filter scale (SFS) stresses. The SFS stresses are divided into two components: the resolved SFS (RSFS) stresses, in which scales are between the grid filter width and the explicit filter width, and the unresolved SFS (URSFS) stresses (i.e. SGS stresses), which are more closely related to the length scale rather than to the grid spacing, Fig. 1. By applying the explicit

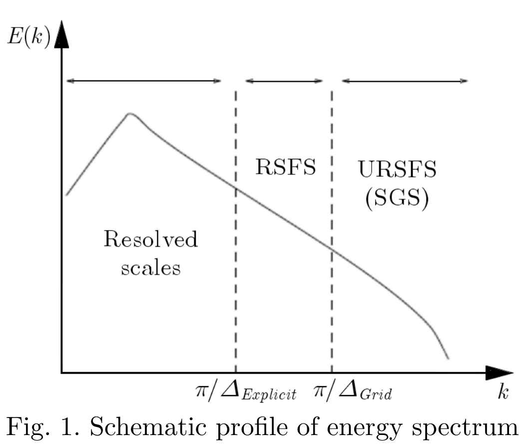

Fig. 1. Schematic profile of energy spectrum

smooth filter in frequency space, the energy spectrum can be separated into three parts. The low wave number portion is filtered and well resolved on the grid. This portion contains the velocity, which is filtered once to represent the implicit filter or discretization, and a second time, to represent an explicit smooth filter. The middle portion represents SFS motions that can theoretically be reconstructed by an inverse filter operation. However, this reconstruction is impeded by numerical errors which will increase near the cut-off frequency. The last portion contains SGS motions that cannot be resolved on the grid and must be modeled. In smooth explicit filtering, SGS modeling is not sufficient; the SFS term must be added to take into account the turbulence stresses. There is no need for this improvement when applying a sharp filter as an explicit filter. Whenever sharp filters are used, the SFS term disappears (Chow and Street, 2005; Nouri *et al.*, 2008). The main concern is that when the filter is discretized on the grid, the filter acts as a smooth filter. It follows that methods to obtain filters in a physical space with shapes close to the sharp cut-off in the frequency space must be developed (De Stefano and Vasilyev, 2002; Nouri *et al.*, 2007; Tellervo, 2008).

5. Explicit filtering with smooth filter

By filtering the Navier-Stokes equations for a second time by a smooth filter and separating the non-linear term, we obtain the closed form of the Navier-Stokes as the equation below

$$\frac{\partial \overline{\widetilde{U}}}{\partial t} + \nabla \cdot (\overline{\widetilde{U}} \otimes \overline{\widetilde{U}}) + \frac{1}{\rho} \nabla \overline{\widetilde{P}} = \nabla \cdot (2\nu \overline{\widetilde{D}}) - \nabla \cdot (B) \tag{5.1}$$

where

$$B = \overline{B}_{SGS} + B_{SFS} = (\overline{\widetilde{U \otimes U}} - \overline{\widetilde{U} \otimes \widetilde{U}}) + (\overline{\widetilde{U} \otimes \widetilde{U}} - \overline{\widetilde{U}} \otimes \overline{\widetilde{U}}) \tag{5.2}$$

($\sim$) and ($-$) represent the primary implicit and the secondary explicit filter, respectively. $\overline{B}_{SGS}$ is the sub-grid scale (SGS) stress, which must be modeled using a model such as Smagorinsky. Moreover, B_{SFS} is the sub-filter scale stress and should be reconstructed by the resolved velocity field (Tellervo, 2005b). The scale-similarity model proposed by Bardina *et al.* (1980) is defined as

$$B_{SFS} = \overline{\overline{\widetilde{U}} \otimes \overline{\widetilde{U}}} - \overline{\overline{\widetilde{U}}} \otimes \overline{\overline{\widetilde{U}}} \tag{5.3}$$

The Bardina model makes the approximation $U = \widetilde{U}$ (i.e., that the full velocity is equal to the filtered velocity) to close the SFS stress term, resulting in $B_{SFS} = \overline{\overline{\widetilde{U}} \otimes \overline{\widetilde{U}}} - \overline{\overline{\widetilde{U}}} \otimes \overline{\overline{\widetilde{U}}}$. It allows backscatter of energy from the small to the large scales, making it a desirable component of any SFS model. The model does not dissipate enough energy, however. Thus, Bardina also introduced the mixed model, which combined the Smagorinsky and the scale-similarity model. This gave much improved correlations while allowing for adequate dissipation.

In this study, a mixed model consisting of Smagorinsky's SGS model and Bardina's SFS is used for turbulence stress modeling. In the numerical algorithm, the value of sub-filter scale stress is calculated by applying the HOS filter. Moreover, the turbulence viscosity is obtained from Smagorinsky's SGS model and added to the physical viscosity.

6. Derivation of HOS filter

The expansion of the multi-dimensional velocity series at the point $x_j = (x, y, z)$ is written as

$$\widetilde{U}_i(x'_j) = \widetilde{U}_i(x_j) + (x'_k - x_k)\frac{\partial \widetilde{U}_i(x_j)}{\partial x_k} + \frac{1}{2}(x'_k - x_k)(x'_l - x_l)\frac{\partial^2 \widetilde{U}_i(x_j)}{\partial x_k \partial x_l} + \dots \tag{6.1}$$

and the smooth Gaussian filter function is defined as

$$\begin{aligned} &G(x - x'', y - y'', z - z'', \Delta_x, \Delta_y, \Delta_z) \\ &\quad = \Big(\sqrt{\frac{6}{\pi}}\Big)^{\frac{3}{2}} \frac{1}{\Delta_x \Delta_y \Delta_z} \exp\Big(-\frac{6(x - x'')}{\Delta_x^2} - \frac{6(y - y'')}{\Delta_y^2} - \frac{6(z - z'')}{\Delta_z^2}\Big) \end{aligned} \tag{6.2}$$

Using the following convolution integration

$$\overline{\widetilde{U}}(x, y, z) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} G(x - x', y - y', z - z')\widetilde{U}(x', y', z')\, dx'\, dy'\, dz' \tag{6.3}$$

the high order smooth filter for the smooth Gaussian filter is achieved as

$$\begin{aligned} \overline{\widetilde{U}}(x, y, z) &\approx \widetilde{U}_i - \frac{\Delta^2}{24}\nabla^2 \widetilde{U}_i + \frac{\Delta^4}{1152}\Big(\frac{\partial^4 \widetilde{U}_i}{\partial x^4} + \frac{\partial^4 \widetilde{U}_i}{\partial y^4} + \frac{\partial^4 \widetilde{U}_i}{\partial z^4}\Big) \\ &\quad + \frac{5\Delta^4}{1728}\Big(\frac{\partial^4 \widetilde{U}_i}{\partial x^2 \partial y^2} + \frac{\partial^4 \widetilde{U}_i}{\partial y^2 \partial z^2} + \frac{\partial^4 \widetilde{U}_i}{\partial z^2 \partial x^2}\Big) + O(\Delta^6) \end{aligned} \tag{6.4}$$

In this work, we consider four terms of the equation (10) as a HOS filter.

7. Numerical considerations in flow simulation

The present study uses the second-order central difference scheme for the diffusion term, the interpolation of the convection term on the collocating grid, and the finite-volume PISO algorithm. For time integration, the Crank-Nicolson method is performed. The main steps of the numerical procedure of the PISO algorithm along with explicit filtering are defined as follows:

1. Numerical calculations begin by discretizing and solving the linearized Navier-Stokes equation considering a specific pressure field and assuming definite flux to obtain the mean velocity (i.e. prediction process).
2. Next, the Poisson equation of pressure is used to achieve a corrected pressure field. The terms of this equation are also discretized with the second-order central difference method.
3. The velocity field is also corrected by using the pressure field obtained from Step 2. Steps 2 and 3 can be iterated several times.
4. The value of sub-filter scale stress $B_{SFS} = \overline{\overline{\widetilde{U}} \otimes \overline{\widetilde{U}}} - \overline{\overline{\widetilde{U}}} \otimes \overline{\overline{\widetilde{U}}}$ is calculated by applying the HOS filter. This step is the equivalent of smooth explicit filtering.
5. The turbulence viscosity (ν_t) is obtained and added to the physical viscosity.

8. Fully developed turbulent channel flow

In the present paper, implicit and explicit filtering were applied. Based on the friction velocity and the channel half-width, the Reynolds number Re_τ equals 180. This value is equivalent to $\mathrm{Re} = 2800$, based on the average velocity. The computational domain is $4\pi\delta \times 2\delta \times 4\pi\delta/3$; δ is the channel half-width; and the x, y and z are the streamwise, wall-normal, and spanwise directions, respectively. Four mesh resolutions are performed for this simulation which are 30^3, 40^3, 50^3 and 65^3. Non dimensional streamwise velocity profiles for different mesh resolution are shown in Fig. 2. The results have shown that there are no significant differences between 65^3 and 50^3. Therefore, the resolution of 65^3 is selected for all the runs. The grid spacing in wall coordinates in the x and z directions are $\varDelta x^+ = \varDelta x u_\tau/\upsilon \approx 35$, $\varDelta z^+ = \varDelta z u_\tau/\upsilon \approx 12$. A non-uniform mesh generated with the hyperbolic tangent distribution $y_j = 0.01(1 - \tanh(\gamma(1 - 2j/N_y))/\tanh\lambda)$ was used in

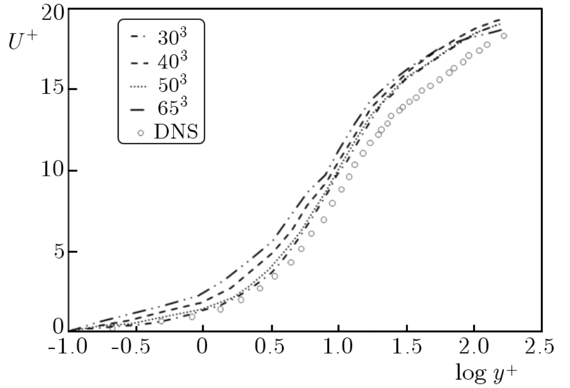

Fig. 2. Non-dimensional streamwise velocity profiles for different mesh resolution

the wall-normal direction, where N_y is the number of whole grids in the y direction, and γ is the mesh distribution factor, which is associated with the ratio of the last grid cell size in the channel centerline to the first grid cell size by $\cosh^3\gamma/\sinh\gamma$. The first mesh point away from the wall occurred at $y^+ = \Delta x u_\tau/v \approx 0.49$, and the maximum spacing at the centerline of the channel was 13.8 wall units. The initial flow field was set at 20% turbulence intensity along with a mean velocity of 15.63 in the streamwise direction. To maintain a fixed mass flow rate in each time step, a constant pressure gradient was added to the Navier-Stokes equation as a definite term. Periodic boundary conditions were applied in the streamwise and spanwise directions; no slip condition was considered at the solid walls.

9. Results

Figure 3 shows the dimensionless mean streamwise velocity profile for the implicit filter (Smagorinsky model), and for the explicit filter applying the HOS filter (mixed model). As seen in this figure, the results improve when using the mixed model. Compared to implicit filtering, the mean velocity profile was underestimated. The results were compared to the DNS results obtained by Kim *et al.* (1987).

The shear stress on the wall was the one of the effective parameters in the near-wall region. This shear stress was obtained via the slope of the velocity field near the wall. To compare the implicit and the explicit HOS filters, the magnitude and error of non-dimensional stress on the wall, which is called the skin friction factor, are compared in Table 1.

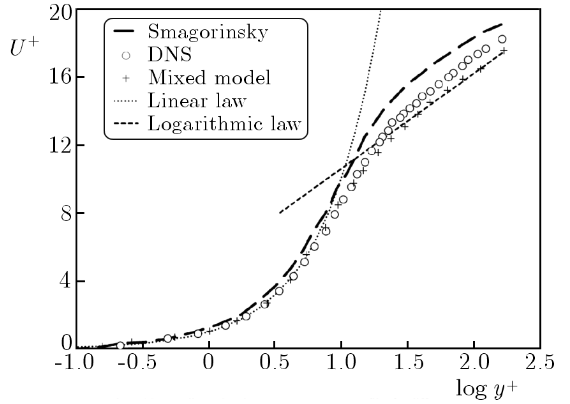

Fig. 3. Non-dimensional mean streamwise velocity obtained by the mixed model compared with Kim's DNS (Kim *et al.*, 1987) and the Smagorinsky model

Table 1. Magnitude and maximum error of skin friction factor for different filtering methods

Method	Kim's DNS data [7]	Smagorinsky implicit filter	Mixed model (HOS filter)
$C_{f,wall}$	8.18E-3	7.99E-3	8.14E-3
Error $C_{f,wall}$ [%]	–	2.33	0.04

The results obtained from the explicit filter were better than those from the implicit filter. Moreover, it is evident that the smooth filter accurately predicted the near-wall velocity slope. Numerical simulation for turbulence intensity in the streamwise direction comparing with Kim's DNS (Kim *et al.*, 1987) and the Smagorinsky model is shown in Fig. 4. Using the sub-filter model together with the sub-grid model improved the results, though the difference was obvious. This difference was due to the dissipative property of the Smagorinsky model. Figures 5 and 6 show the turbulence intensity profiles in the wall-normal and spanwise directions, respectively. It is evident that the mixed model influences turbulence intensity most significantly in the streamwise direction.

The peak value of the turbulence intensity profiles was one of the parameters related to the buffer layer. Table 2 presents the non-dimensional maximum error and magnitude of the peak value of the streamwise turbulence intensity for the DNS and different filtering methods.

The deviation of the peak value of turbulence intensity from the real value was improved by applying explicit filtering. Moreover, the peak value of the

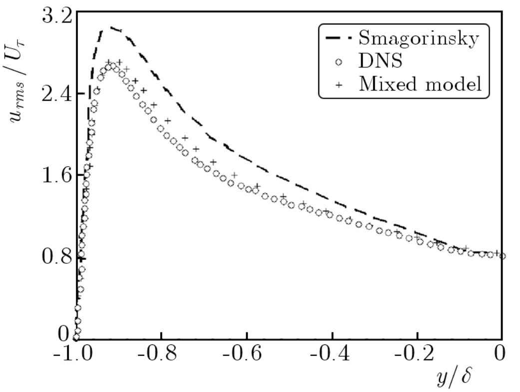

Fig. 4. Streamwise turbulence intensities for the mixed model, Kim *et al.* (1987) DNS model, and the Smagorinsky model

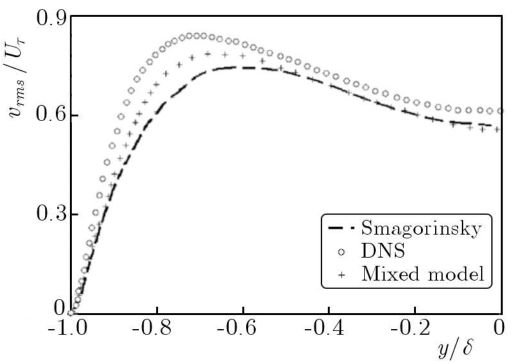

Fig. 5. Wall-normal turbulence intensities for the mixed model compared with Kim *et al.* (1987) DNS model, and the Smagorinsky model

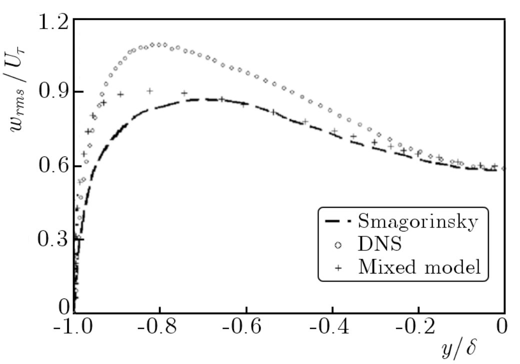

Fig. 6. Spanwise turbulence intensities for the mixed model, Kim *et al.* (1987) DNS model, and the Smagorinsky model

Table 2. Non-dimensional maximum error and magnitude of pick values of streamwise turbulence intensity for DNS and different filtering methods

Method	Kim's DNS data [7]	Smagorinsky implicit filter	Mixed model (HOS filter)
Pick valu of u_{rms}/U_τ	2.68	3.04	2.74
Error [%]	–	13.432	2.23

turbulence intensity, in $y^+ \simeq 10$, was closest to the real value when the mixed model and the HOS filter were used.

Figure 7 shows the profiles of the Reynolds stress component on the xy-plane. The Sub-filter scale stress predicted the turbulence stress pretty well. As seen from this Figure, explicit filtering using the mixed model had a considerable effect on the streamwise Reynolds stress. This concept was verified for the other component of the Reynolds stress.

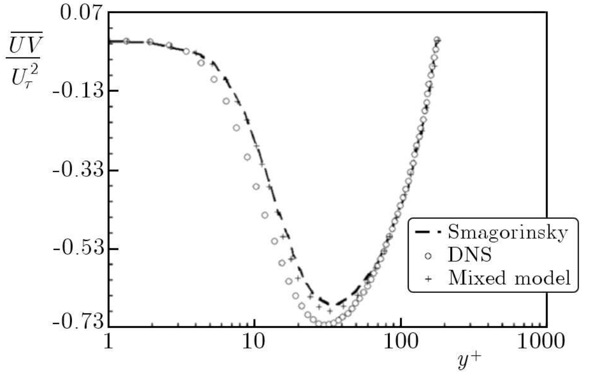

Fig. 7. Reynolds stress profiles for the mixed model, Kim *et al.* (1987) DNS model, and the Smagorinsky model

In the calculations performed in this study, the necessary time for having a solution independent of the initial condition was considered to be about $10\delta/U_\tau$. The simulation was performed using a Pentium 3.2 GHz processor. One step in the explicit filtering with the SFS model averaged 70 seconds. When implicit filtering was applied, each step took approximately 40 seconds, but the explicit filter reached the developed conditions faster than the implicit one. This difference may be explained by the fact that explicit filtering is capable of damping non-physical oscillations caused by incorrect initial conditions in conjunction with the discretization method or the turbulence modeling. Consequently, the rate of convergence increases.

10. Conclusion

In this paper, the performance of an explicit HOS filter was investigated for a fully developed turbulent channel flow as the benchmark problem. For simulations, the second-order finite-volume scheme was applied on a collocating grid system for spatial discretization. For time integration, the Crank-Nicolson method was used. The results were improved by using a mixed model along with a HOS filter; in this case, however, the mean velocity profile was underestimated. Using this approach, the turbulence intensity profiles were improved in three directions, however, the turbulence intensity in the stremwise x direction showed the maximum improvement. By considering the Reynolds stress profiles, it is obvious that the explicit filtering using the mixed model has the maximum effect. This is due to the sub-filter stresses, which are accurately predicted from the turbulence stresses.

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Ocena gładkiego filtra wysokiego rzędu przy symulacji wielkowirowej z filtrowaniem jawnym w pełni rozwiniętego turbulentnego przepływu w kanale

Streszczenie

Jawne filtrowanie typu gładkiego jest jedną z metod stosowanych w symulacjach wielkowirowych (tzw. LES). W pracy opisano zastosowanie filtra wysokiego rzędu o charakterystyce gładkiej (HOS) do symulacji wielkowirowej w pełni rozwiniętego turbulentnego przepływu w kanale. W badaniach wykorzystano metodę Cranka-Nicolsona oraz techniki przyrostów czasowych i objętości skończonych drugiego rzędu do wyznaczania pochodnych zmiennych przestrzennych. Przeanalizowano filtrowanie niejawne łącznie z podsieciowym modelem skalowym Smagorynskiego (SGS) oraz filtrowanie jawne HOS w pełni turbulentnego przepływu w kanale. W badaniach wykazano, że filtrowanie jawne za pomocą filtra HOS, którego stosunek długości do

rozmiaru siatki wynosił 2, dało zgodne wyniki z dostępnymi rezultatami bezpośrednich symulacji numerycznych (DNS). Nieco niedoszacowany okazał się średni profil prędkości w kierunku wzdłużnym przepływu, natomiast poprawiły się wyniki dotyczące intensywności turbulencji właśnie w tym kierunku w porównaniu do kierunków pozostałych. Zaobserwowano ponadto, że zastosowanie kombinacji SGS z użyciem modeli subfiltrów naprężeń (SFS) oraz HOS jako filtru jawnego pozwoliło na poprawne wyznaczenie wartości naprężeń turbulentnych.

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