International Journal of Heat and Fluid Flow 000 (2017) 1–6

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Improving separated-flow predictions using an anisotropy-capturing subgrid-scale model

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ARTICLE INFO

Article history:
Received 3 July 2016
Revised 10 October 2016
Accepted 13 January 2017
Available online xxx

Keywords:
Large-eddy simulation
Explicit algebraic subgrid-scale model
Anisotropy-capturing subgrid-scale model

ABSTRACT

The major conclusion of this paper is that resolution requirements for large-eddy simulation (LES) of flow separation and reattachment can be significantly reduced using the anisotropy-capturing explicit algebraic subgrid-scale (SGS) stress model (EASSM) of Marstorp *et al.* (*J. Fluid Mech.*, vol. 639, 2009, pp. 403–432), instead of the conventional isotropic dynamic eddy-viscosity model (DEVM). LES of flow separation in a channel with streamwise periodic hill-shaped constrictions and spanwise homogeneity is performed at coarse resolutions for which it is observed that flow separation cannot be predicted without a SGS model and cannot be correctly predicted by the DEVM, while reasonable predictions are obtained with the EASSM. It is shown that the lower resolution requirements by the EASSM, compared to the DEVM, is not only due its nonlinear formulation, but also due to the better formulation of its eddy-viscosity part. The improvements obtained with the EASSM have previously been demonstrated using higher-order numerical solvers for channel flows. In this study, it is observed that these improvements still remain using a low-order code with significant inherent numerical dissipation.

1. Introduction

Large-eddy simulation (LES) of shear flows with isotropic subgrid-scale (SGS) models has high resolution requirements (Baggett et al., 1997), which limits its applicability to low Reynolds number flows. Resolution requirements in LES, among others, depend on how well the SGS anisotropy is captured by the SGS model. To capture the SGS anisotropy, a proper description of the structure of the SGS stress tensor needs to be achieved. Eddy-viscosity SGS models (EVM), which assume linearity between the SGS stress and strain-rate tensors, give a poor description of the SGS anisotropy, since these two tensors are often only weakly correlated (Clark et al., 1979; Liu et al., 1994). These models can predict correct mean flow statistics at moderate and fine resolutions, if the SGS anisotropy is weak and a proper mean SGS dissipation is provided.

Structural SGS models improve the geometrical representation of the modelled SGS stress tensor. The scale similarity model (Bardina et al., 1980) and mixed models, based on a combination of the scale similarity and eddy-viscosity model (Liu et al., 1994) are examples. These anisotropy-capturing SGS models give a higher correlation between the modelled and true SGS stresses than the EVM. Other structural models are based on tensorial expansions of the SGS stress tensor in terms of the strain- and rotation-rate tensors. The anisotropy-capturing explicit algebraic SGS stress model (EASSM) by Marstorp et al. (2009) is a nonlinear structural model. It has been successfully tested and analysed for LES of channel flow with and without system rotation at different Reynolds numbers (Rasam et al., 2011, 2013). It has been shown, using pseudo-spectral methods, that accurate LES predictions with the EASSM can be obtained in these cases at resolutions considerably coarser than with the isotropic dynamic EVM (DEVM, Germano et al., 1991).

Resolution requirements for LES in complex geometries using less accurate numerical methods with inherent numerical dissipation are more strict and more difficult to quantify than in simple channel flows. In Rasam et al. (2014b), as the first step towards LES of more complex flows with the EASSM, we performed LES of channel flow with periodic hill-shaped constrictions at a fine resolution and showed that the EASSM performs better than the DEVM. In this paper, we extend our previous study to considerably coarser grids and investigate the differences in the performance of the anisotropy-capturing EASSM, the isotropic DEVM and no SGS model simulations and assess the effect of resolution in these cases. For the LES we use a low-order finite volume code with inherent numerical dissipation.

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.01.005

Table 1
Summary of the current and reference simulations. The reference LES is denoted as case REF. N_x, N_y and N_z are the number of grid points in the streamwise, cross-stream and spanwise directions, respectively. Δt is the simulation time step, non-dimensionalised with the bulk velocity and hill height. Mean separation and reattachment locations are denoted as $\left(\frac{x}{h}\right)_{sep}$ and $\left(\frac{x}{h}\right)_{reat}$, respectively.

Case		$N_x \times N_y \times N_z$	SGS model	Δt	$\left(\frac{x}{h}\right)_{sep}$	$\left(\frac{x}{h}\right)_{reat}$
EASSM-1	Rasam et al. (2014b)	148 × 156 × 92	EASSM	4.0×10^{-3}	0.22	4.42
DEVM-1	Rasam et al. (2014b)	148 × 156 × 92	DEVM	4.0×10^{-3}	0.23	4.15
NSM-1	Rasam et al. (2014b)	148 × 156 × 92	–	4.0×10^{-3}	0.24	4.24
EASSM-2		128 × 156 × 80	EASSM	6.0×10^{-3}	0.26	4.15
DEVM-2		128 × 156 × 80	DEVM	6.0×10^{-3}	0.26	4.00
NSM-2		128 × 156 × 80	–	6.0×10^{-3}	0.27	3.78
EASSM-3		98 × 156 × 64	EASSM	8.0×10^{-3}	0.34	3.70
DEVM-3		98 × 156 × 64	DEVM	8.0×10^{-3}	0.47	2.83
NSM-3		98 × 156 × 64	–	8.0×10^{-3}	–	–
REF	Breuer et al. (2009)	280 × 220 × 200	DEVM	1.8×10^{-3}	0.19	4.69

The rest of the paper is organised as follows. In Section 2, the computational set up is given. The results are presented and discussed in Section 3. Effects of the nonlinear term in the EASSM formulation is given in Section 4 followed by the conclusions in Section 5.

2. Computational setup

2.1. Numerical method

Code_Saturne 3.1 (http://www.code-saturne.org), an unstructured collocated finite volume solver for incompressible flows (Archambeau et al., 2004), is used for the simulations as in Rasam et al. (2014b). A conservative form of the incompressible Navier–Stokes equations is solved by the code using a second-order central differencing in space and a second-order Crank–Nicolson scheme in time. The pressure-velocity coupling is based on a SIMPLEC algorithm with Rhie–Chow interpolation.

2.2. Geometry and grid

The flow is periodic in the streamwise direction and the domain extends from one hill top to the other with a domain length $9h$, where h is the hill height. The hill size in the streamwise direction is $3.86h$. The spanwise direction is homogeneous with a width of $4.5h$ and the channel height in the unconstricted part is $3.035h$. The top wall is flat. A no-slip condition is used at the bottom and top walls. The Reynolds number, based on the bulk velocity at the hill crest and the hill height, is $Re_b = 10595$. x, y and z correspond to the streamwise, wall-normal and spanwise direction, respectively. For a further discussion of the test case we refer to Rasam et al. (2014b).

Nearly orthogonal curvilinear grids in the x-y plane with clustering of the grid points near the upper and lower walls, to ensure that the first grid point is at $y^+ < 1$ in wall units, are used in the simulations. The grid in the streamwise direction is slightly clustered on the windward side of the hill. The distribution of the grid points in the spanwise direction is uniform.

LES is performed at three different resolutions with the EASSM, DEVM and without a SGS model (NSM). A summary of the simulation parameters as well as those of the reference well-resolved LES (called REF) using the DEVM (Breuer et al., 2009) is given in Table 1. The resolution in wall units, for the first near-wall cell, in case REF in the streamwise direction, Δ_x^+ is less than 25 and in the spanwise direction, Δ_z^+ is less than 30. The grids used in this study have Δ_x^+ less than 40, 50 and 70 and Δ_z^+ less than 60, 70 and 90 for the finest to the coarsest ones, using the viscous length scale from case REF.

2.3. Explicit algebraic SGS stress model (EASSM)

The EASSM consists of an eddy-viscosity and a nonlinear part with the following formulation

$$\tau_{ij} = \frac{2}{3}K^{SGS}\delta_{ij} + \beta_1 K^{SGS}\widetilde{S}^*_{ij} + \beta_4 K^{SGS}(\widetilde{S}^*_{ik}\widetilde{\Omega}^*_{kj} - \widetilde{\Omega}^*_{ik}\widetilde{S}^*_{kj}), \quad (1)$$

where K^{SGS} is the SGS kinetic energy and $\widetilde{S}^*_{ij}$ and $\widetilde{\Omega}^*_{ij}$ are normalised resolved strain- and rotation-rate tensors. The coefficients β_1 and β_4 are given as

$$\beta_1 = \frac{9}{4}c_1\beta_4, \quad \beta_4 = -\frac{33}{20}\frac{1}{[(9c_1/4)^2 + 2\widetilde{\Omega}^*_{ij}\widetilde{\Omega}^*_{ij}]}, \quad (2)$$

where c_1 is a model coefficient. For details regarding the model derivation and coefficients see Marstorp et al. (2009) and Rasam et al. (2014a). The Yoshizawa model (Yoshizawa, 1986) is used for K^{SGS} as

$$K^{SGS} = c\,\widetilde{\Delta}^2|\widetilde{S}|^2, \quad |\widetilde{S}| = \sqrt{2\widetilde{S}_{ij}\widetilde{S}_{ij}}, \quad (3)$$

where the model coefficient c is dynamically determined using the Germano identity. It is locally averaged over the neighbouring cells for stability. Test filtering is carried out with a top-hat filter (local averaging over the cells sharing a common face) with a length scale, $\widehat{\widetilde{\Delta}} = 2\widetilde{\Delta}$, where $\widetilde{\Delta} = \sqrt[3]{\Omega}$ and Ω is the volume of a computational cell.

2.4. Dynamic eddy-viscosity model (DEVM)

The DEVM (Germano et al., 1991) has the following formulation

$$\tau_{ij} - \frac{2}{3}K^{SGS}\delta_{ij} = -2c_s\widetilde{\Delta}^2|\widetilde{S}|\widetilde{S}_{ij}, \quad (4)$$

where c_s is computed dynamically using the Germano identity with the least-square approximation (Lilly, 1992). Test filtering is carried out with a top-hat filter with a length scale $\widehat{\widetilde{\Delta}} = 3\widetilde{\Delta}$.

3. Results and discussion

3.1. Streamlines of the mean flow

Flow separation and reattachment are the key features of the periodic hill flow. To discuss these features, streamlines of the mean flow for all cases are shown in Fig. 1a–c together with the contour plot of the mean resolved shear stress $\langle u'v' \rangle$ at the finest resolution. The instantaneous separation and reattachment points have a high spatial variation in time, but the mean flow separates near the top of the hill and reattaches further downstream and a recirculation bubble is formed between these two points. The

Please cite this article as: A. Rasam et al., Improving separated-flow predictions using an anisotropy-capturing subgrid-scale model, International Journal of Heat and Fluid Flow (2017), http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.01.005