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Assessment of turbulence models for the simulation of turbulent flows past bluff bodies

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ABSTRACT

The accuracy of a recently developed one-equation turbulence model in predicting complex flows with massive separation is assessed against the well-known Spalart Allmaras (SA) and the k-ω-SST-Scale Adaptive Simulation (SAS) models. The unsteady 3-D flow past a square cylinder at $Re = 2.2 \times 10^4$, as well as a 3-D flow over a wall-mounted cube at $Re = 4.0 \times 10^4$ are computed and compared to available experimental data. The recently developed model is capable of resolving turbulent flow structures, thereby predicting all major unsteady phenomena with a marked improvement over other Reynolds average Navier–Stokes (RANS) models. The computational time required by the model in comparison to that required by Large Eddy Simulation (LES) renders it a suitable candidate for simulating 3D unsteady complex engineering flows such as building aerodynamics with reasonable accuracy.

1. Introduction

Flows past bluff bodies, which are encountered in various engineering applications, possess complex phenomena that involve multiple flow separation and reattachment points, small and large-scale turbulent structures, and unsteady vortex shedding. There is a need to accurately and efficiently predict flow structures associated with bluff bodies from an applied wind engineering perspective. In building aerodynamics for instance, prediction of wind forces and the pressure distribution, pollution dispersion, as well as wake structures are of crucial importance.

Historically, statistical turbulence models have had difficulties in accurately predicting the complex flow phenomena such as the ones mentioned above (Rodi, 1997). Large Eddy Simulation (LES) has proven to be more suitable for resolving large-scale turbulent structures as it requires modeling of the energy transfer to scales in the inertial range. However, LES requires larger simulation time, higher mesh resolution, and smaller time-step size rendering this approach more costly compared to the Unsteady Reynolds averaged Navier–Stokes (URANS). Although recent advances in computers and computational algorithms made LES more feasible to adopt in recent decades, research has gone a long way towards improving the computational accuracy of turbulence models. Recently, Menter and Egorov (2005) developed the Scale-Resolving Simulation (SRS) concept that is based on the inclusion of the second derivative of velocity in a two-equation turbulence closure. This in turn enables the model to adjust to resolved turbulent structures rather than dissipating them as RANS models do, an ability of the model referred to as Scale-Adaptive Simulation (SAS). This ability allows the formation of a turbulent spectrum for a given spatial and temporal resolution. In addition, adjusting the model's length-scale to resolved turbulent structures is achieved by reducing the eddy viscosity levels to those of the LES values. With any decrease in temporal resolution or increase in time step, the SAS model shifts smoothly from an LES model through successive declining stages of scale-resolving mode back to an URANS. In such a situation, the URANS model compensates for the non-resolved portion of the spectrum, thereby exhibiting a behavior similar to the Detached Eddy Simulation (DES). With a further decrease in temporal resolution, to an extent where the SAS model cannot adjust to resolved structures, the model reverts back to URANS mode. It is worth to mention that at such large time steps, the LES model produces inaccurate results (Menter and Egorov, 2005) whereas the URANS serves as a backbone for the SAS model. Following the methodology developed by Menter (1997) in which Bradshaw's hypothesis, i.e., a constant turbulent structure parameter $|-\overline{uv}|/k$, is used to transform two-equation closures to single-equation models, (Elkhoury, 2011, 2008, 2007, 2015) developed several versions of these models all of which included a second derivative of velocity, mainly the von Kármán length scale, allowing the model to operate in a scale resolving mode.

Models with SRS capabilities function best in globally unstable flows with large separation regions that are usually associated

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Nomenclature

A_1	turbulence-model closure coefficients
C_f	skin-friction coefficient
C_p	skin-friction coefficient
$a_1, C_1, C_2, C_3, C_4, C_5, C_s, C_\mu$	turbulence-model closure coefficients
d	wall distance, m
$D(\ )/Dt$	material derivative
D_1, D_2	turbulence-model wall-damping functions
E_{BB}	Baldwin–Barth destruction term, m^2/s^2
E_{dest}	turbulence-model destruction term, m^2/s^2
$E_{diff/dest}$	turbulence-model diffusion/destruction term, m^2/s^2
$E_{1\text{-}k\text{-}\varepsilon}$	destruction term based on one-equation k-ε model, m^2/s^2
E_p	limiter based on turbulence production, m^2/s^2
f_p	turbulence-model production limiter
F_1, F_2	blending functions
I	turbulence intensity
k	turbulence kinetic energy m^2/s^2
l	length-scale, m
l_r	reattachment length-scale, m
L_{vk}	von Kármán length-scale, m
L	mixing length scale, m
Re	Reynolds number
r	destruction-to-production ratio
S,Ω	strain-rate magnitude, vorticity magnitude s^{-1}
St	Strouhal number
u,v,w	Cartesian velocity components, m/s
U_o	reference velocity components, m/s
U_b	bulk velocity components, m/s
x_r	reattachment length, m
Δ	grid spacing, m
ν	kinematic viscosity, m^2/s
u^+	dimensionless velocity scale
y^+	dimensionless, sublayer-scaled distance
$\beta_{i,1}$, $\beta_{i,2}$, β^*	turbulence-model closure coefficients
$\tilde{\Delta}t$	non-dimensional time step
Δt	time step, s
ε	turbulence dissipation rate, m^2/s^3
ω	specific dissipation rate, 1/s
Ω_{cv}	cell volume, m^3
k	von Kármán constant
$\tilde{\nu}_T, \nu_T$	kinematic eddy viscosity, m^2/s
$\sigma_v, \sigma_k, \sigma_\epsilon, \sigma_{k1}, \sigma_{\omega 1}, \sigma_{k2}, \sigma_{\omega 2}$	turbulent diffusion coefficient

Subscripts

cl	centerline
i,j,k	Cartesian vector and tensor notation indices
inf	freestream
T	turbulent

with bluff bodies. Both of the currently considered test cases fall under this category. For a wall-mounted cube, LES of flow was carried out with considerable success (Shah, 1998; Rodi, 1997). Steady state RANS simulations with different versions of the k-ε model (Rodi, 1997; Lakehal and Rodi, 1997; Iaccarino et al., 2003) however, showed poor agreement as these models were not able to capture the complex flow structure near the cube. On the contrary, global flow features and characteristics like the converging–diverging horseshoe vortex, separation length in front and downstream of the cube were reasonably predicted with minor differences by Iaccarino et al. (2003) when applying URANS simulation using the v^2-f model. RANS simulations of the flow past a square cylinder with various version of the k-ε model was calculated by Bosch (1995). Franke and Rodi (1993) used a Reynolds Stress Model (RSM) with wall functions while an Explicit Algebraic Stress Model (EASM) was utilized by Schmidt et al. (1999) to predict the flow past the square cylinder, however, with marginal success. Although Iaccarino et al. (2003) reported a slightly better circulation length, only LES (Rodi, 1997) and DES (Schmidt and Thiele, 2002) were barely capable of predicting acceptable results.

For models to be able to predict flow patterns associated with complex layouts, it is important that they be first validated for test cases with basic geometries. The recently proposed model (Elkhoury, 2015), referred to hereafter as the "One-Eq.-SAS model", has not been validated for complex flows with massive separation. Thus, the main objective of the present work is to assess the One-Eq.-SAS model against the well-known SA (Spalart and Allmaras, 1992) and k-ω SST–SAS (Menter and Egorov, 2010) turbulence models for flows over a surface- mounted cube and past a square cylinder. All three models are carefully assessed through a comparison of velocity profiles, wall limiting streamlines, large-scale turbulent structures, and drag coefficients against available experimental data.

2. Turbulence modeling

2.1. The SA turbulence model

The SA turbulence model was developed and calibrated based on physical arguments in boundary layers and free-shear flows. The model has gained special interest in external aerodynamics and is considered among the mature and well verified models. Excluding the transition term, the SA model can be written as

$$\frac{D\tilde{\nu}_T}{Dt} = c_{b1}\tilde{\Omega}\tilde{\nu}_T + \frac{\partial}{\partial x_j}\left(\frac{(\tilde{\nu}_T+\tilde{\nu})}{\sigma}\frac{\partial\tilde{\nu}_T}{\partial x_j}\right) + c_{b2}\left(\frac{\partial\tilde{\nu}_T}{\partial x_j}\right)^2 - c_{w1}f_w\left(\frac{\tilde{\nu}_T}{d}\right)^2 \quad (1)$$

The modified magnitude of vorticity is given by

$$\tilde{\Omega} = \Omega + \frac{\tilde{\nu}_T}{\kappa^2 d^2}f_{v2} \quad (2)$$

The closure coefficients and damping functions are as follows:

$$g = r + c_{w2}(r^6 - r), \qquad c_{w1} = \frac{c_{b1}}{\kappa^2} + \frac{(1+c_{b2})}{\sigma} \quad (3)$$

$$f_{v2} = 1 - \frac{\chi}{1+\chi f_{v1}}, \quad \chi = \frac{\tilde{\nu}_T}{\nu}, \quad f_{v1} = \frac{\chi^3}{c_{v1}^3 + \chi^3} \quad (4)$$

$$f_w = g\left[\frac{1+c_{w3}^6}{g^6 + c_{w3}^6}\right]^{1/6}, \quad r = \frac{\tilde{\nu}_T}{\tilde{\Omega}\kappa^2 d^2} \quad (5)$$

$$c_{b1} = 0.1355, \quad c_{b2} = 0.622, \quad c_{v1} = 7.1, \quad c_{w1} = 0.3, \quad \sigma = 2/3 \quad (6)$$

And the damped eddy viscosity is given by

$$\nu_T = \tilde{\nu}_T f_{v1} \quad (7)$$

2.2. The k-ω-SST–SAS turbulence model

The SAS is a concept that enables RANS models to operate in a SRS mode. This was achieved by including the von Kármán Length scale L_{vk} in the turbulence scale equation, giving it the capability of