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Resolving flow around tandem cylinders with RANS-LES hybrid methods

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1. Introduction

Turbulence modeling is one of the more challenging but useful CFD disciplines, as turbulent flow appears in a wide variety of applications. Methods based on the Reynolds-averaged Navier–Stokes (RANS) equations have proven effective for some types of problems, but lack the ability to resolve a range of turbulent length scales for some others. This can be solved by the use of large eddy simulation (LES) models, but these come with substantial additional computational demands that make them practically unusable in some cases, even on current hardware. A possible solution to this problem are hybrid RANS-LES methods, combining lower computational requirements and a wider range of resolved turbulent scales.

Detached eddy simulation (DES) hybrid RANS-LES models recently began their transition to two equation RANS models, such as the method by Strelets [5] based on Menter's Shear Stress Transport (SST) turbulence model [4]. The delayed DES (DDES) method and its variant with improved wall modeling capability (IDDES) were also proposed for the SST model by Gritskevich et al. [1]. This paper compares all of the mentioned methods with experimental data by Jenkins et al. [2, 3] on a tandem cylinder problem – a configuration formerly proposed by the AIAA Aerospace Research Center for aircraft landing gear development.

2. Mathematical model

Under the assumption that the fluid behaves according to the thermodynamic model of an ideal gas, turbulent heat flux corresponds to the Reynolds analogy, after neglecting the effects of gravity and applying Reynolds and Favre averaging, the Reynolds-Averaged Navier–Stokes equations can take the following form:

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \boldsymbol{u}) = 0, \tag{1a}$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \operatorname{div}((\rho \boldsymbol{u}) \otimes \boldsymbol{u}) = \operatorname{div} \boldsymbol{\sigma} + \operatorname{div} \boldsymbol{\tau} - \operatorname{grad} p, \tag{1b}$$

$$\frac{\partial \rho E}{\partial t} + \operatorname{div}(\rho \boldsymbol{u} H) = \operatorname{div}(\boldsymbol{\tau}\boldsymbol{u}) + \operatorname{div}\left(\frac{c_p \mu}{\mathrm{Pr}} \operatorname{grad} T\right) + \operatorname{div}\left(\boldsymbol{\sigma}\boldsymbol{u} + \left[\mu + \frac{\mu_T}{\sigma_k}\right] \operatorname{grad} k + \frac{c_p \mu_T}{\mathrm{Pr}_T} \operatorname{grad} T\right), \tag{1c}$$

where t is time, ρ represents fluid density, $\boldsymbol{u}$ denotes fluid velocity with u_1, u_2, u_3 as its components, p is pressure, E specific total energy, $H = E + p/\rho$ specific enthalpy, T represents fluid temperature, c_p is the heat capacity at constant pressure, Prandtl number and its turbulent counterpart are denoted as Pr and Pr_T, respectively, μ and μ_T are similarly dynamic laminar and eddy viscosity, σ_k is a coefficient given by a turbulence model, k represents turbulence kinetic energy, $\boldsymbol{\sigma}$ is the viscous stress tensor approximated (assuming that $\boldsymbol{S}$ is the strain tensor and $\boldsymbol{I}$ is the identity matrix) as

$$\boldsymbol{\sigma} \approx 2\mu \left(\boldsymbol{S} - \frac{1}{3}\mathrm{div}(\boldsymbol{u})\boldsymbol{I} \right) \tag{2}$$

and $\boldsymbol{\tau}$ the Reynolds stress tensor, approximated similarly to $\boldsymbol{\sigma}$ by Boussinesq approximation. To close the system, we use the equation of state

$$p = (\gamma - 1) \left[\rho E - \frac{1}{2} \rho \left(u_1^2 + u_2^2 + u_3^2 \right) \right] \tag{3}$$

and one of the turbulence models described below.

For the SST-based turbulence models, we use the 2003 variant of the SST method [4]

$$\frac{\partial \rho k}{\partial t} + \mathrm{div}\left(\rho k \boldsymbol{u}\right) = \mathrm{div}\left(\left[\mu + \sigma_k \mu_T\right] \mathrm{grad}\, k\right) + P_k - \rho k \frac{\sqrt{k}}{L_T}, \tag{4a}$$

$$\frac{\partial \rho \omega}{\partial t} + \mathrm{div}\left(\rho \omega \boldsymbol{u}\right) = \mathrm{div}\left(\left[\mu + \sigma_\omega \mu_T\right] \mathrm{grad}\, \omega\right) + \frac{C_\omega \rho}{\mu_T} P_k - \beta \rho \omega^2 + 2(1 - F_1)\mathrm{CD}, \tag{4b}$$

where ω represents the specific turbulence dissipation rate, L_T denotes the model length scale, P_k is a production term described in [4] and any model constant ϕ for the SST model is computed as $\phi = F_1 \phi^{k-\omega} + (1 - F_1)\phi^{k-\varepsilon}$ using

$$\begin{aligned} &\sigma_k^{k-\omega} = 0.85, \quad &&\sigma_\omega^{k-\omega} = 0.5, \quad &&\beta^{k-\omega} = 0.075, \quad &&C_\omega^{k-\omega} = 0.553, \\ &\sigma_k^{k-\varepsilon} = 1, \quad &&\sigma_\omega^{k-\varepsilon} = 0.856, \quad &&\beta^{k-\varepsilon} = 0.0828, \quad &&C_\omega^{k-\varepsilon} = 0.44. \end{aligned} \tag{5}$$

The eddy viscosity is given using the function F_2 from [4]

$$\mu_T = \frac{a_1 \rho k}{\max\left(a_1 \omega, F_2 S\right)}, \quad a_1 = 0.31. \tag{6}$$

The model length scale L_T is defined using the RANS and LES lengths

$$l_{\mathrm{RANS}} = \frac{\sqrt{k}}{\beta^* \omega}, \quad l_{\mathrm{LES}} = C_{\mathrm{DES}} \Delta, \quad \hat{l}_{\mathrm{LES}} = C_{\mathrm{DES}} \hat{\Delta} \tag{7}$$

with Δ being the the maximum length of the cell's edges and C_{DES} is a coefficient described in [5] and $\hat{\Delta}$ is its modification which also utilizes the distance from the nearest wall [1], which give the following formulations for the SST, SST-DES, SST-DDES and SST-IDDES methods:

$$\begin{aligned} L_T^{(\mathrm{RANS})} &= l_{\mathrm{RANS}}, \quad &L_T^{(\mathrm{DDES})} &= l_{\mathrm{RANS}} - f_d \max\left(0, l_{\mathrm{RANS}} - l_{\mathrm{LES}}\right), \\ L_T^{(\mathrm{DES})} &= \min\left(l_{\mathrm{RANS}}, l_{\mathrm{LES}}\right), \quad &L_T^{(\mathrm{IDDES})} &= \tilde{f}_d \left(1 + f_e\right) l_{\mathrm{RANS}} + \left(1 - \tilde{f}_d\right) \hat{l}_{\mathrm{LES}}, \end{aligned} \tag{8}$$

where f_d, $\tilde{f}_d$, f_e are functions described in [1].

3. Numerical model

The computation is done on our in-house parallel CFD software Orion. Implicit formulation of finite volume method is used, with linear reconstruction to obtain convective fluxes with the HLLC Riemann solver and diffusive fluxes are computed using the values on the diamond cell. Derivatives of the fluxes are computed analytically. Dual time stepping technique is utilized with local time stepping in the dual time.

4. Problem description

The tandem cylinder problem is given by two identical cylinders in a row, the first causing continuous vortex shedding, from which the vortex street passes to the front of the second cylinder, where the separated shear layer temporarily reattaches only to be separated again to form another vortex street. The Reynold number is 166 000, with the free stream velocity being 44 m/s. The diameter of the cylinders is $D = 0.057\,15$ m and their axes are $3.7D$ apart.

The computational grid is unstructured with 17 725 cells in each of the 30 layers in the z direction that are $0.025D$ thick. The grid satisfies the condition that the dimensionless wall distance $y^+ < 1$ for cells adjacent to the walls. The left domain boundary has the inlet boundary condition prescribed, while the right boundary is for the outlet. The cylinders are no-slip walls (with zero velocity at the surface).

5. Results

The results of the RANS-LES hybrid methods show good agreement with the experimental data by Jenkins et al. [2, 3]. The average pressure coefficients on the rear cylinder are shown in Fig. 1 and show that the SST-IDDES method matches the experimental data almost perfectly. The only difference are the values on the back of the cylinder (after separation occurs), which show some fluctuations in the computed values. This may be due to sampling in the statistical evaluation.

The difference between RANS and RANS-LES hybrid methods in computed vorticities is shown in Figs. 2 and 3. The lack of three-dimensional turbulent fluctuations in the results of the base RANS method is apparent.

6. Conclusions

Hybrid RANS-LES methods based on the two equation SST model showed good agreement with experimental data on the tandem cylinder problem. Even the most basic DES method was able to capture the turbulent flow better than the RANS method and the results obtained by the SST-IDDES model were the closest to the experimental data.

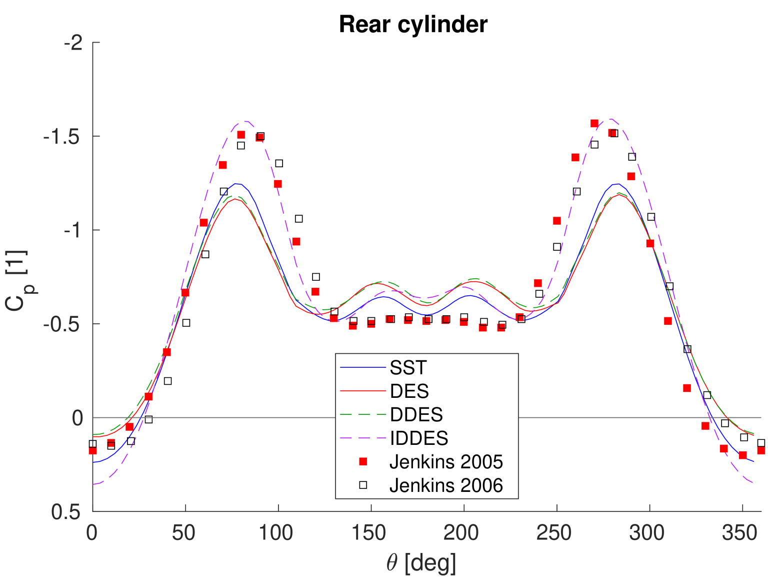

Fig. 1. Comparison of the average computed pressure coefficients on the rear (tandem) cylinder by the base RANS SST model, its RANS-LES hybrid methods and experiments [2, 3]

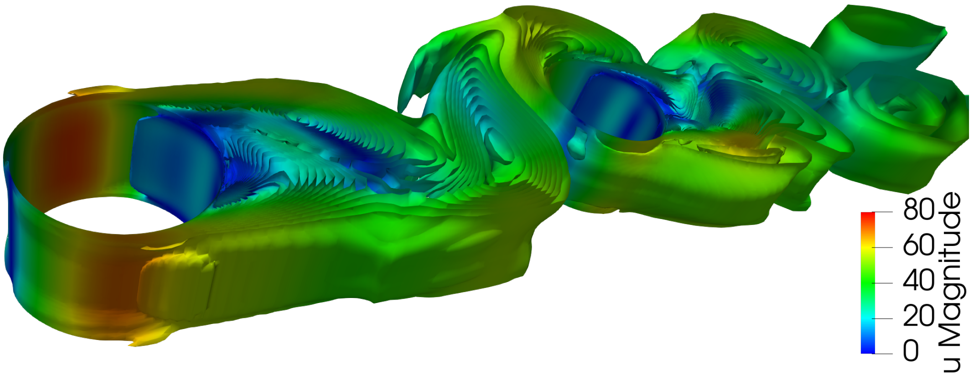

Fig. 2. Vorticity contours colored by computed velocities obtained by the RANS SST model

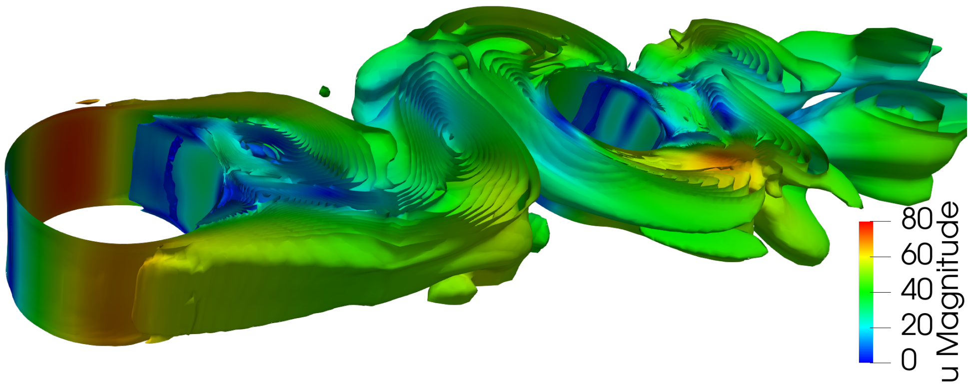

Fig. 3. Vorticity contours colored by computed velocities obtained by the DES-SST model

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