Numerical simulation of the flow around a circular cylinder at Reynolds number Re = 3900 by means of the PANS model

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Abstract. The paper presents a study of various versions of PANS approach for turbulence simulation using a flow around a cylinder at Reynolds number Re = 3900 as an example. The considered models were implemented in the in-house CFD package. The influence of the method of determining the parameter \( f_k \) on the flow behind the cylinder was studied. The first method assumed a constant value of \( f_k \). In the second method, the \( f_k \) value depended on the local computational mesh scale and the shear scale.

1. Introduction

Recently, second-generation URANS methods have been developed, in particular, the Partially Averaged Navier-Stokes (PANS) model is proposed in [1]. The advantage of this approach is that the physical resolution of the flow structures turns out to be independent of the grid spacing, and with sufficient grid detail, the PANS solution will allow resolving the most important energy-carrying vortex structures. The eddy viscosity model is used to close the unresolved fluctuations. Within this approach, the width of the averaging filter is controlled by the ratio of the simulated turbulent energy to the total kinetic energy \( f_k \). Depending on the value of \( f_k \), there is a seamless transition from RANS at \( f_k = 1 \) to DNS at \( f_k = 0 \). The model parameter \( f_k \) determines the ratio of the simulated to the total turbulent energy and, thus, sets the boundary between the resolved and simulated turbulent scales. At \( f_k = 1 \), the equations of the turbulence model transform into the URANS equations. At \( f_k < 1 \), the dissipative term of the turbulence dissipation equation is modified, which leads to a decrease in the simulated turbulence energy and, as a consequence, to a decrease in turbulent viscosity and, accordingly, the generation of smaller-scale eddies. The \( f_k \) parameter can be adaptive, varying depending on the ratio of the grid scale to the shear scale of the flow. The PANS model based on the RANS k-\( \omega \) SST model with the adaptive parameter \( f_k \) was implemented in the SigmaFlow computational fluid dynamics software developed at the Institute of Thermophysics SB RAS and the Department of Thermophysics of the Siberian Federal University.

2. Numerical model

The flow around a circular cylinder in a transverse fluid flow was considered as an example of an external separated flow. The studies were based on the works of [2] and [3]. The channel was \( 20D \) wide and \( 20D \) long, where \( D \) is the cylinder diameter (0.1 m). The distance from the entrance to the axis of the cylinder was \( 5D \), and the length of the cylinder was \( 3D \). At the input, a uniform distribution of the velocity normal to the input was set. The Reynolds number was Re = 3900. At the output, the
mass conservation and non-reflective boundary conditions were used. Symmetry conditions were set on the lateral, upper and lower boundaries.

The computational meshes were built according to the octo-tree principle, in which detailing is carried out by dividing a square cell into 4 equal parts. The meshes were refined around the cylinder and in the wake area. Near the cylinder, a wall layer was distinguished with a thickening towards the cylinder wall. The transition between the boundary layer and the surrounding mesh was carried out using hexahedral cells. The coarse mesh consisted of 1.65\times10^6 cells and the fine one consisted of 3.3\times10^6 cells (figure 1).

Four turbulence models were considered: URANS based on the \(k-\omega\) SST model [4], dynamic LES, and two versions of the PANS approach based on the \(k-\omega\) SST model. The first version of the PANS method used a constant value of parameter \(f_k = 0.25\) in the whole computational domain [2]. The second version (PANS-D) used switching of parameter \(f_k\) depending on the local shear scale of the flow. The dependence of \(f_k\) on the flow was based on the following estimate:

\[
\text{Re}_{L} \frac{\Delta \left( \frac{\partial U}{\partial y} \right)}{v_{\text{eff}}} \frac{\Delta^2 |S|}{V + V_t} f_k = \frac{k_{\text{mod}}}{k_{\text{tot}}} \frac{\Delta}{L_S} \left( \frac{V + V_t}{0.3|S|} \right)^{1/2},
\]

from here we get a formula for \(f_k\) [5]:

\[
f_k = \frac{k_{\text{mod}}}{k} \geq \frac{1}{\sqrt{c_\mu}} \left( \frac{\Delta}{L_S} \right)^{2/3} f_k = C_1 \left( \frac{\Delta}{L_S} \right)^{2/3}.
\]

**Figure 1.** Computational meshes: (a) coarse mesh, (b) fine mesh.
3. Results

As we can see from Fig. 2, the parameter is $f_k < 1$ in the wake region and it reaches a minimum in the recirculation zone behind the cylinder, which means a partial resolution of turbulent eddies in this region. In the boundary layer $f_k = 1$, i.e. PANS is switched to the RANS $k$-$\omega$ SST model. In this case, the PANS model shows the results of calculating the flow behind the cylinder, which are close to the results of URANS (figure 3). Due to dissipativity of the $k$-$\omega$ SST model, the boundary layer on the cylinder is calculated incorrectly, which is showed by a high level of the modeled turbulence kinetic energy near the cylinder (figure 3c). At a constant value of $f_k = 0.25$, the level of turbulent pulsations near the cylinder is low in the entire computational domain, and the resolvable turbulent pulsations are close to the LES results. In this case, the averaged fields of the velocity and pressure for the PANS method are close to the results of LES and experiment (figure 3a, b). The URANS method resolves the largest-scale coherent structures (figure 4a), while the PANS and LES methods resolve much more scales of the vortex structures (figure 4b, c). For all the models, refining the mesh leads to increasing the length of the recirculation zone behind the cylinder and improving the pressure distribution on the cylinder (figure 5).

![Figure 2. The $f_k$ parameter near the cylinder.](image)

![Figure 3. Results on the coarse mesh: (a) longitudinal velocity along the axis behind the cylinder, (b) pressure coefficient on the cylinder surface, (c) modelled turbulence kinetic energy along the axis behind the cylinder, (d) resolved turbulence kinetic energy along the axis behind the cylinder.](images)
Figure 4. Vortices behind the cylinder visualized by $q$-criteria: (a) URANS, (b) PANS $f_k = \text{const}$, (c) PANS-D, (d) LES.

Figure 5. Comparison of the coarse (red lines) and fine (blue lines) meshes: (a) longitudinal velocity along the axis behind the cylinder, (b) pressure coefficient on the cylinder surface.
4. Conclusions

Hybrid RANS/LES models demonstrate promising capabilities, such as an excellent predictive ability on coarse meshes (as compared to LES). However, many open questions and unresolved problems remain. Hybrid models often reproduce unsteady spatial flow even for the simplest attached flows, which are perfectly calculated by RANS models. What is really necessary is to preserve a stationary solution for stationary flows, but activate a nonstationary solution when a strong instability is detected. The PANS is one of the hybrid methods that allows flexible control of the level of resolution of turbulent pulsations. The main idea discussed in this paper is the ability to locally tune the $f_k$ parameter in the PANS model to obtain a flow-sensible method. For this, the PANS model with a variable value of the $f_k$ parameter was implemented in the in-house CFD code SigmaFlow. As the studies have shown, the calculation results are significantly dependent on the used base ("subgrid") model and grid resolution, and this requires further detailed research.

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