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Partially-averaged Navier–Stokes simulations of two bluff body flows

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ABSTRACT

The paper discusses the PANS model in the framework of engineering applications of bluff body flows. Comparisons with the resolving LES technique and URANS of a three dimensional bluff body flow are made for a better understanding of the behavior of PANS model in these flows. Several implementation issues of PANS such as f_k variable in space and time, the influence of the inlet boundary conditions and discretization scheme are discussed. The reference comparison with LES and URANS displays the differences between the methods in the complex interaction between the resolved and the modeled coherent flow scales. The PANS model is compared with competing techniques of LES, DES and RANS for challenging flow around a generic vehicle at yaw. The remaining problems and the possible directions in the improvement of the PANS model are discussed.

1. Introduction

Bluff body flows are characterized by regions of separated flow where unsteadiness governs the flow dynamics. For predictions of these flows, the traditional Reynolds-averaged Navier–Stokes (RANS) statistical modeling was found to produce inaccurate results. The key problem of the steady RANS model for bluff body flows can be found in its inability to model a broad spectrum of turbulent scales.

The introduction of hybrid methods in bluff body aerodynamics is motivated by deficiencies in predictions of methods that rely on the resolution of turbulence such as DNS and LES and the traditional RANS simulations that heavily rely on turbulence modeling. The former methods require computation resources that are currently unavailable while the latter is not capable of predicting unsteady bluff body flows. There are several directions in hybrid RANS/LES modeling, and a review of the methods can be found in [1]. These models combine resolution of parts of the coherent structure motion with RANS turbulence modeling. The switch between the two is often done in a zonal way, such as in detached eddy simulation (DES) and hybrid RANS/LES where the near-wall flow is modeled using RANS while the outer flow is resolved with LES. The appropriate hybrid technique must be capable of dealing with different regions of bluff body flows from the growth of the boundary layer to the separation and formation of shear layers and wakes. DES is the most successful hybrid method to have received wide spread use in the research community and industry. The DES technique has been shown to be successful in several bluff body flows and seems to be rather well understood [2]. The main characteristic of DES is that, by definition, it behaves as URANS near the wall (normally in the boundary layer) and as LES away from the wall. The advantage that the near-wall flow is difficult to resolve with LES is

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treated in RANS mode and the flow away from the wall e.g. the separated wake flow where LES is a good modeling choice, is treated in the LES mode. Another advantage of DES is that it is easy to understand the behavior of the method in different flow regions except perhaps in the gray area between the RANS and the LES. The zonal approach of DES is not only an advantage. As most of the boundary layer is modeled using RANS, important flow dynamics of the boundary layer can be lost. The outer region treated in the LES mode does not require as fine a computational grid as the near-wall flow when simulated using LES. However, even the flow of the outer region will be dependent on the grid resolution because the LES length scale is a function of the grid size. Since no RANS turbulence modeling is permitted in the outer flow region, the prediction of the flow is very dependent on the computational grid used. Partially-averaged Navier–Stokes (PANS) is a method proposed by [3] as a bridging technique between RANS and DNS. The switch in PANS is continuous and based on the ratios of unresolved to total kinetic energy (f_k) and the ratio of the unresolved to total dissipation (f_ε). These parameters are used to modify the RANS model coefficients so that the required resolution of the coherent-structure motion is obtained. The advantage of PANS in bluff body aerodynamics is in its non-zonal formulation. Ideally the PANS will adapt to the existing computational grid resolving the flow scales that can be resolved by the grid and complementing with RANS turbulence modeling where needed. A typical PANS simulation will produce the unresolved-to-total ratio of the turbulent kinetic energy that varies in the regions of separated flow as will be later seen in Fig. 4. This allows for flexibility in the method as RANS modeling can provide sufficient levels of Reynolds stresses when the grid is not adequate to resolve the turbulence.

The PANS technique has been used for several different bluff body flows including flows around cubes, pyramids [4], cylinders [5], simplified vehicles [6–8] and airplane landing gear. The method has also been applied to passive [9,10] and active flow control of bluff body flows [11]. All these studies have been performed by the first author and his colleagues and they have always focused on the performance of PANS for one particular flow. Most of the studies produced flow predictions in good agreement with experimental data, and the results were always better than LES results using identical computational grids. Some of the predictions, such as that around a rudimentary landing gear, shows very impressive results with good agreement with the experimental data and also show that the model can adapt to the existing grid. The second observation is as important as the accuracy of the prediction in an engineering approach where the user cannot afford a parametric study of the grid for good PANS prediction.

This paper presents an overview and insight into the use of PANS simulations for bluff body flows. For the first time, we are not only looking at the resulting predictions of the flows but also on the modeling and numerical building blocks of the method. The review is done in a critical way with the aim to expose the strength and the weaknesses of the technique. Furthermore, it aims to increase our knowledge about how PANS behaves compared with other methods (such as LES, DES or URANS).

1.1. PANS equations

The PANS equations [12] read:

$$\frac{\partial U_i}{\partial t} + U_j\frac{\partial U_i}{\partial x_j} + \frac{\partial \tau(V_i, V_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 U_i}{\partial x_j \partial x_j}$$

Here a turbulent velocity V_i field is decomposed into two parts by an arbitrary filter as $V_i = U_i + u_i$. $\tau(V_i, V_j) = -2\nu_u S_{ij} + 2/3k_u\delta_{ij}$ where k_u and ε_u are the unresolved turbulent kinetic energy, and the dissipation and the eddy viscosity of unresolved scales is given by [3] as

$$\nu_u = C_\mu \frac{k_u^2}{\varepsilon_u}$$

The resolved stress tensor is given by

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$$

The model equations for the unresolved kinetic energy k_u and the unresolved dissipation ε_u are required to close the system of equation given previously. These equations as derived by [12] are:

$$\frac{\partial k_u}{\partial t} + U_j\frac{\partial k_u}{\partial x_j} = P_u - \varepsilon_u + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_u}{\sigma_{ku}}\right)\frac{\partial k_u}{\partial x_j}\right]$$

$$\frac{\partial \varepsilon_u}{\partial t} + U_j\frac{\partial \varepsilon_u}{\partial x_j} = C_{\varepsilon 1}P_u\frac{\varepsilon_u}{k_u} - C^*_{\varepsilon 2}\frac{\varepsilon_u^2}{k_u} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_u}{\sigma_{\varepsilon_u}}\right)\frac{\partial \varepsilon_u}{\partial x_j}\right] \quad (1)$$

Here, P_u and ε_u are the production and the dissipation rate of unresolved turbulent kinetic energy

$$P_u = -\tau(V_i, V_k)\frac{\partial U_i}{\partial x_k}$$

The model coefficients are

$$C^*_{\varepsilon 2} = C_{\varepsilon_1} + \frac{f_k}{f_\varepsilon}(C_{\varepsilon_2} - C_{\varepsilon_1}); \quad \sigma_{k_u} = \sigma_k\frac{f_k^2}{f_\varepsilon}; \quad \sigma_{\varepsilon_u} = \sigma_\varepsilon\frac{f_k^2}{f_\varepsilon}$$