On the Simulation of Statistically Unsteady Flows with the RANS Equations

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Modeling and Simulation (MS) has become an essential part of Engineering. One of the branches of MS that is routinely used is Computational Fluid Dynamics (CFD), that can address a wide variety of flows including different types of physical phenomena. One of the challenges of CFD is the accurate simulation of turbulent flows that occur in many practical applications. Currently, it is possible to simulate turbulent flows solving numerically mass conservation and momentum balance (Navier-Stokes equations) without any extra modeling (Direct Numerical Simulation, DNS). However, the requirements to perform such simulations in complex geometries at high Reynolds numbers are unaffordable. Therefore, many engineering applications are still based on the solution of the Reynolds-Averaged Navier-Stokes (RANS) equations that require the definition of mean flow quantities and the averaging of the continuity and momentum equations. These two steps of the derivation of the RANS equations generates extra terms in the momentum equations, the so-called Reynolds stresses, that require a turbulence model for their determination.

Most RANS turbulence models available in the open literature have been developed for statistically steady flows, see for example Wilcox [?], i.e. time-averaging is applied to the flow variables and to the continuity and momentum equations. The extra diffusion provided by the Reynolds stress tensor is supposed to provide enough diffusion to damp all turbulence fluctuations and enable the calculation of a mean steady flow.

In external flows around bodies of arbitrary shape, statistically steady flows require streamlined shapes aligned with the incoming flow, i.e. boundary-layers that do not exhibit significant flow separation. For bluff bodies or large angles of incidence in streamlines bodies, wide wakes are generated due to massive flow separation and vortex shedding will occur. In such conditions, time-averaging is not a reasonable option for the definition of the mean flow, because time variations generated by the vortex shedding phenomena will be considered turbulence fluctuations. In these statistically unsteady flows, the derivation of the RANS equations is based on ensemble averaging and so the time derivatives of the mean flow quantities are not zero, which is usually referred to as (U)nsteady RANS. As for the statistically steady flows, the role of the Reynolds stresses is to damp the turbulence fluctuations and allow the determination of the mean flow. However, there is no guarantee that turbulence models developed for time-averaged RANS will also be appropriate for statistically unsteady flows.

In this paper, we present simulations for the flow around a circular cylinder at Reynolds numbers ranging from sub-critical (transition in the near-wake) to super-critical (transition on the cylinder upstream of separation) performed with different turbulence models, including eddy-viscosity, explicit algebraic Reynolds Stress and Reynolds Stress models. These flows are used to discuss two of the main challenges of the simulation of statistically unsteady flows with the RANS equations:

- How to assess if the turbulence model is providing the required diffusion to damp turbulence fluctuations.
- How to quantify modeling errors of the RANS solutions.

In the first topic we also address the role of the numerical error in the outcome of the simulations.

Keywords: Computational Fluid Dynamics, RANS, Statistically Unsteady flows.

References

[1] Wilcox D.C., Turbulence Modelling for CFD, 2nd ed., DCW Industries, 2006.