Introduction to the 2nd workshop on CFD Uncertainty Analysis

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The subject of this workshop is CFD Uncertainty Analysis. Most of the people having come together here are well aware of the primary elements of such analysis. Nevertheless we like to reiterate the main lines, to point out once more why uncertainty analysis is needed and to explain why we have set up this meeting.

The organisers of this workshop work in the field of ship hydrodynamics. In those circles one can regularly hear the term "numerical towing tank" mentioned. There is even a yearly event called the Numerical Towing Tank Symposium (NuTTS).

The term "numerical towing tank" at least suggests that there is – or that we are quickly progressing towards - a numerical alternative for the physical towing tank, the traditional experimental facility in ship research. Attractive colourful presentations of the numerical results serve as advertisement, by which managers and decision makers are influenced.

It is easy to proclaim that numerical flow simulation is a good alternative to model testing. Yet one wonders how ship owners or the chief design officers at ship yards and navies, who typically order model tests to model basins, could accept this without some confidence in the reliability of the results. So a kind of quality assessment is needed. Here our subject comes in: CFD Uncertainty Analysis tries to figure out what the quality of numerical flow predictions actually is.

Before we embark on explaining the role of this workshop in the search for quality assessment procedures, let us consider briefly common practices. Take the proceedings of any CFD related symposium and you will find that most paper contributors are satisfied with a comparison of their numerical results with corresponding experimental data, of course typically showing that the computed data are close to the experimental data. Look here, they seem to say, we can numerically simulate what has been measured!

We are not going to dispute the usefulness and necessity of comparison between numerical and experimental data, but if you start to consider quality assessment carefully such comparison soon turns out to be too big a jump: the effects of numerical and modeling errors are undistinguishable. With numerical errors we mean the collective result of discretisation, iterative and round-off errors; with modeling errors the deficiencies caused by the mathematical model not being completely adequate to represent the physical flow problem. The effects could well be opposite; it would be not the first case to find that a numerical solution on a finer grid shows greater deviations from the experimental data than the one on a coarse grid!

Except for mixing up things in such a comparison, there arises also the question: how could one prove quality in a case where no corresponding experiments are available? If in such circumstances the question is posed: "Do these numerical results require a redesign of my ship hull or can I get away with the current version?", it really matters how much (justified) confidence you have in the results.

A better route towards quantification of the uncertainty in the results of numerical flow simulations has been laid out more than ten years ago. It starts with a clear distinction between studying numerical errors (verification) and modeling errors (validation).

Two years ago the first Lisbon workshop took place. We chose to focus on verification, to set it clearly apart from validation. So the participants were asked to estimate the uncertainty of their numerical results for two test cases, the flow over a hill (Ercoftac C-18) and the flow over a backward-facing step (Ercoftac C-30). Although experimental data for both problems are available, they were ignored. The sole purpose was: how good is the numerical prediction. What happens if the grid is further refined than what you normally would do? Does the observed order of convergence in a grid refinement study comply with the presumed theoretical order? Grids were provided, so that all participants used the same grids.

What came out? Two example results are shown in Figures 1 and 2. Figure 1 featuring a local quantity, the pressure at a certain location in the flow over the hill; figure 2 a global quantity, viz. the friction force on the bottom wall in the flow over the backward-facing step. Participants were left free in choosing a method for uncertainty estimation.

Let us first consider Figure 1. These results were obtained by the participants with the Spalart-Allmaras turbulence model on two different grid sets. Now if different persons solve the same equation set on the same grid one would expect them to produce the same result. Clearly this is not the case. Furthermore, even if they are not exactly the same, one would hope to see the error bars, indicating the numerical uncertainty, to have an overlap region. Alas, the hope turned out idle.

For an integral quantity like the friction force on the bottom in the backward-facing step flow (Figure 2) the outcome is evidently better. The variation in the data supplied is less, while in this plot three different types of grid are involved. Even so, the results of the uncertainty analysis are not completely satisfactory.

When discussing these results at the workshop, we concluded that they do not necessarily mean that the estimation of the error bands is too optimistic if one goes for 95% confidence. This is because we realized that it had not been ascertained that the participants were indeed solving the same mathematical problem. To say that all solved the RANS equations with the SA models does not prove that all code implementations were completely correct and the same boundary conditions used. Notably in turbulence model implementations it is well known that CFD practitioners tend to create their own versions of a model, with slight adjustment of coefficients, of limiter settings or otherwise. In short: we had overlooked to consider code verification. Verification must be split into two activities: code verification and calculation verification; and must be carried out in that order.

There is an extremely simple and powerful method for code verification: the Method of Manufactured Solutions (MMS). Indeed, the method is as simple as it is fruitful. “Make” a solution by analytical functions; insert it in the governing equations and find the unbalance for each equation; add the resulting source terms to the equations so that your model becomes a model for the defined analytical solution; solve the equations including the source terms and evaluate the error with respect to the analytical solution. From a grid refinement study the order of convergence can be verified.

Now we are again here in Lisbon. Like in the first edition, the subject is CFD Uncertainty Analysis. And we try to quantify the uncertainty of the predictions of the same test case as two years ago: the flow over a backward-facing step. But the other test case in this workshop is a Manufactured Solution, which has been constructed to do code verification for RANS solvers. Where we clearly separated verification from validation in the first edition of this workshop, now we can also deal separately with code verification and calculation verification.

Let us see whether we can do better than last time.

Cp at ***x=2.5h, y=0.25h***

C_p		Grid	Set	C_p	U	C_p -U	C_p +U
1	INSEAN	401x401	A	-0.4680	0.00880	-0.47680	-0.45920
2	INSEAN	401x401	B	-0.4700	0.02240	-0.49240	-0.44760
3	NRMI	401x401	A	-0.4688	0.00915	-0.47798	-0.45968
4	NRMI	401x401	B	-0.4720	0.00249	-0.47449	-0.46951
5	ECN	401x401	A	-0.4585	0.01016	-0.46870	-0.44838
6	ECN	401x401	B	-0.4571	0.00836	-0.46541	-0.44869
7	BSHC	361x361	A	---	---	---	---
8	IST/MARIN A	401x401	A	-0.4570	0.00325*	-0.46029	-0.45379
9	IST/MARIN A	201x201	A	-0.4561	0.01009	-0.46620	-0.44602
10	IST/MARIN A	401x401	B	-0.4592	0.00918*	-0.46833	-0.44998
11	IST/MARIN A	201x201	B	-0.4561	0.00173	-0.45783	-0.45436
12	IST/MARIN B	281x281	A	-0.4627	0.00217	-0.46484	-0.46050
13	IST/MARIN B	281x281	B	-0.4642	0.00622	-0.47042	-0.45798

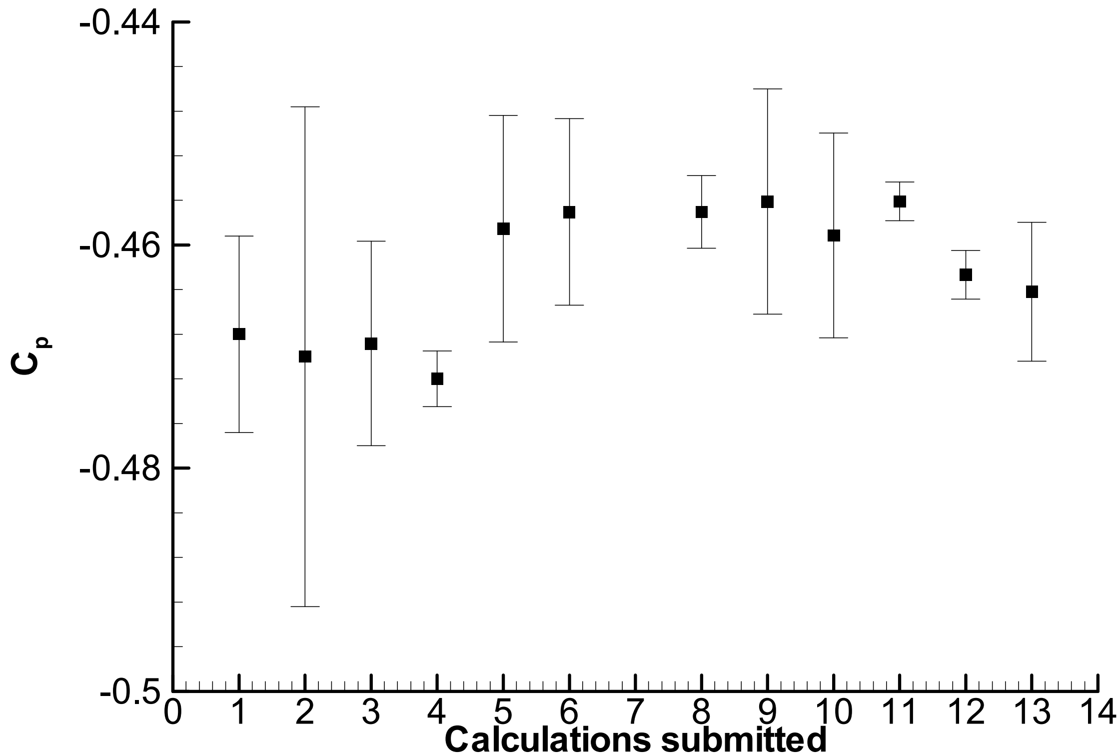

Figure 1: Pressure at x=2.5 h and y=0.25h in the flow over a hill (ERCOFTAC C-18)

Friction resistance of the bottom wall

$(C_F)_b$		Grid	Set	$(C_F)_b$	U	$(C_F)_b$-U	$(C_F)_b$ +U
1	INSEAN	241x241	A	0.0259	0.00031	0.02559	0.02621
2	INSEAN	241x241	B	0.0269	0.00080	0.02610	0.02770
3	INSEAN	241x241	C	0.0265	0.00045	0.02605	0.02695
4	NRMI	241x241	B	0.0258	0.00045	0.02538	0.02628
5	NRMI	241x241	C	0.0265	0.00003	0.02646	0.02652
6	ECN	241x241	A	0.0267	0.00845	0.01824	0.03514
7	ECN	241x241	B	0.0284	0.00598	0.02246	0.03443
8	ECN	241x241	C	0.0271	0.00796	0.01916	0.03508
9	WVU 7 grids	241x241	B	0.0264	0.00210	0.02430	0.02850
10	WVU 4 grids	241x241	B	0.0264	0.00200	0.02441	0.02841
11	IST/MARIN A	241x241	A	0.0260	0.00038	0.02565	0.02642
12	IST/MARIN A	241x241	B	0.0258	0.00047	0.02538	0.02632
13	IST/MARIN A	241x241	C	0.0261	0.00042	0.02565	0.02649
14	IST/MARIN B	241x241	A	0.0267	0.00026	0.02641	0.02693
15	IST/MARIN B	241x241	B	0.0272	0.00060	0.02662	0.02782
16	IST/MARIN B	241x241	C	0.0285	0.00354	0.02492	0.03200

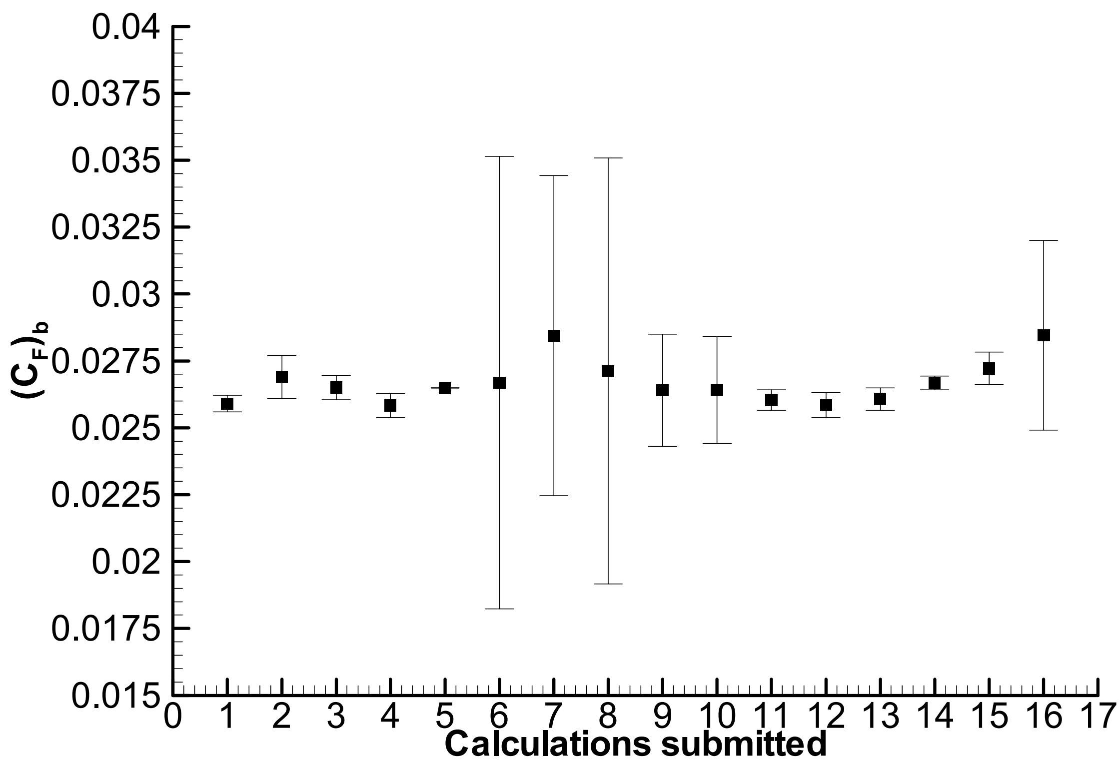

Figure 2: Friction force on the bottom boundary in the backward-facing step flow (ERCOFTAC C-30)