Summary of Workshop Discussion

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The results of the Workshop were generally considered as gratifyingly consistent. They provided also a favorable evaluation for all three approaches to Uncertainty Estimation, (GCI based on grid triplets, least squares version of the GCI and Error Equation method). This was true

- even though some of the apparent super-convergence results (observed p greater than formal p) were used, rather than the more conservative approach of limiting p to formal order in the GCI formula;
- even though many of the grid convergence tests displayed oscillatory convergence in local values.

As expected, functional values like base pressure or integrated friction behaved better than local quantities.

Accuracy verification is important and should receive more attention, but still meets considerable resistance. These days – also in this workshop – we see quite some practical problems in the application of Richardson extrapolation, which is the most popular method of accuracy verification. The GCI was conceived for 3, or at least 2 grids, but in many applications more grids turn out to be necessary for reliable uncertainty estimates. The least-squares version of the GCI can be useful then. Although the requirement of more than three grids may seem to be demanding, it is often possible to use the solution on one grid as a starting point for the solution on the next grid. So after all the extra effort may not be too heavy. To strengthen the role of uncertainty analysis, it was suggested to all participants to get Uncertainty Analysis incorporated into the Quality Assurance procedures of the institute/university.

Fluid dynamics is difficult! Besides, comparison is difficult. We must first "distinguish apples from oranges". For example, the comparison of error bars in the results of this workshop must be considered with care. As long as we have not verified the CFD-codes involved (e.g. by the method of manufactured solutions) non-overlap of error bars does not automatically mean that safety factors have been too optimistic. Also, it is widely recognized that different codes using nominally the same turbulence model can differ in detailed implementation enough that the continuum answers differ. Furhermore, there are small modeling differences, like for example the pressure handling at a solid wall, that make the comparison of error bars obtained with different codes misleading even if the same grids are used in both codes.

The observed order of grid convergence can be quite different from the theoretical order. This was experienced by all participants of the workshop. So it is relevant in uncertainty estimation procedures to address cases of $p<0$ or $p>p_{theor}$.

Evaluation of uncertainty estimators must continue. In that respect it should be recalled that the goal is: success in 95 out of 100 cases, so incidental failures are allowed. Common sense in the choice of safety factors is allowed and even recommendable.

It was noted and agreed that oscillatory convergence does not indicate that the CFD solutions are necessarily inaccurate, even though it may make Uncertainty Estimation more problematical. In any case, oscillatory convergence is a property of the CFD solutions on the grid sequence, not of the Uncertainty Estimation method, and participants were urged to not "shoot the messenger." Oscillatory convergence clearly needs further attention. It was argued that even a model for such a situation might be developed instead of simply adopting a conservative error estimate if it occurs.

Alternatives to Richardson extrapolation for uncertainty estimation – such as the Error Transport Equation technique developed and used by the ECN group - are highly welcomed. The results presented here are encouraging. The applicability in 3D problems is still to be demonstrated. It was observed that the error bars of ECN results exclude a safety factor.

Iterative convergence errors have not been a topic at this workshop. Yet it has some practical interest to study the effects of incomplete convergence on the results of an uncertainty analysis.

For possible future workshops on the subject of uncertainty analysis, it was recommended to let the solution verification be preceded by code verification via the method of manufactured solutions. A lesson from this workshop is also that boundary conditions must be completely specified; just the inlet conditions are insufficient.

Since most participants are from the field of ship hydrodynamics, the ITTC was seen as an important body to stimulate and extend the use of uncertainty analysis. It was observed, however, that the current guidelines in the ITTC Quality Manual are inadequate. It was argued that at this stage of development the ITTC should give a recipe for uniform reporting of grid studies rather than allowing several subjective choices. If now someone claims to have followed the ITTC guidelines it is far from clear what he has done.

The workshop was generally considered as fruitful and a follow-up would be appreciated. One possibility for such a follow-up is a mini-symposium in connection with the ECCOMAS Conference in 2006 in the Netherlands.