Very Large Eddy Simulation of Draft Tube Flow

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Project

Part of Ph.D project

- Numerical Investigations of Unsteady Flow in Draft Tubes

Supervisor

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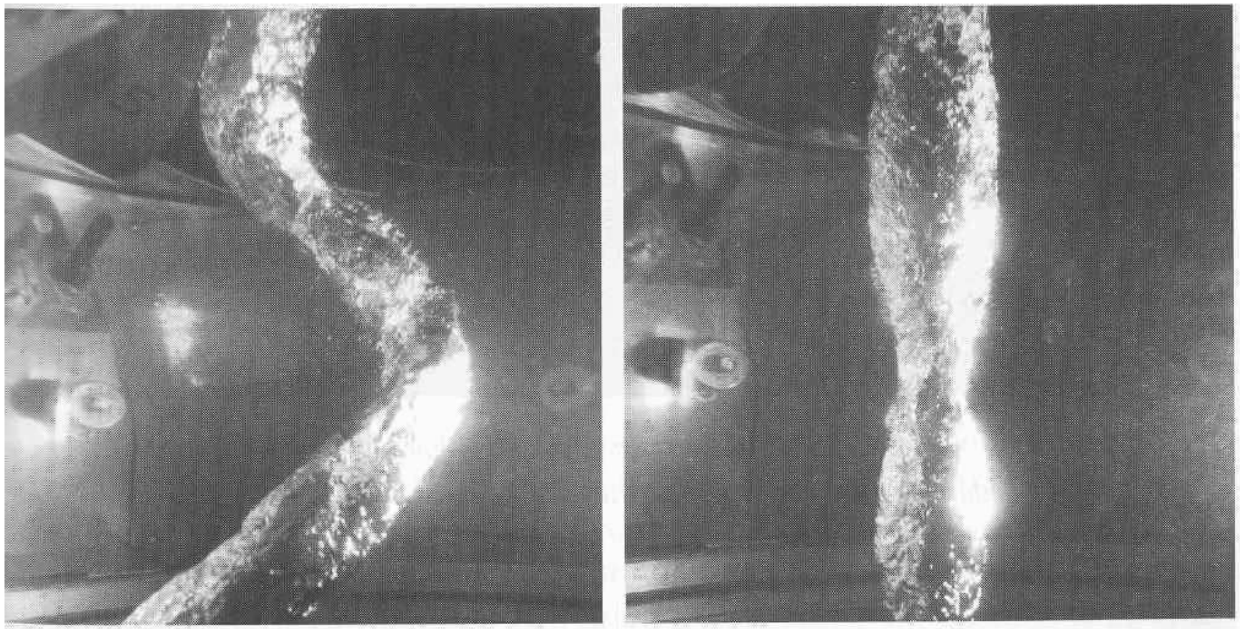
Background and motivation



When a turbine is operating at part load a swirling flow will exit the runner. This gives rise to an oscillating vortex core that cause vibrations and a decrease in efficiency.

Goals

of the present work:

- To analyse how sensitive the flow is to modeled turbulent length and time scales.

of future work:

- To improve numerical simulations of unsteady swirling flow in draft tubes.

Unsteady modeling methods - overview

LES An LES is obviously very good for predicting the most important unsteady motions of swirling flow. In LES, the energy containing eddies of the left hand side of the turbulent kinetic energy spectrum must be resolved everywhere. As the modeled turbulent length scales is assumed to be proportional to the local grid spacing, LES is not an option for the real application, because the Reynolds number of a real water turbine flow ($Re > 10^7$) is too high.

URANS The (U)RANS turbulence models are tuned to steady flow, i.e. to predict the effect of all unsteady motions. This often results in steady solutions.

Unsteady methods

VLES In VLES, RANS models are used. However, away from walls, where is easy (cheap) to resolve large scale structures, a filter is introduced. The modeled length and time scales are compared to what potentially can be resolved in the simulation, and, if larger, they are filtered. Contrary to LES, the non-resolved (modeled) parts of the turbulent flow may have length scales smaller than the local grid spacing. As compared to an LES, coarser grids can be used. In this study, we generalize the filtering procedure of Willems to a LRN $k-\omega$ turbulence model.

Filtering the turbulent quantities

The filter derived by Willems [a] can be generalized to yield

$$\widehat{\nu}_t = \ell_t^2/t_t = g^2\frac{k}{\omega} = g^2\nu_t,$$

where the filter function $g(\ell_t, L_t)$ is defined as

$$g = (\ell_t/L_t)^{2/3}.$$

[a] Ph.D thesis: *Numerische Simulation turbulenter Scherströmungen mit enem Zwei-Skalen Turbulenzmodell*, Rheinish-Westfälischen Technischen Hochschule, Aachen, Germany, 1996

Upper limit of the turbulent length scale

If we choose the upper limit of modeled turbulent lengthscale as

$$l_t = \min\left\{L_t,\ \alpha\left(\max\left\{\Delta,\ U\delta t\right\}\right)\right\},$$

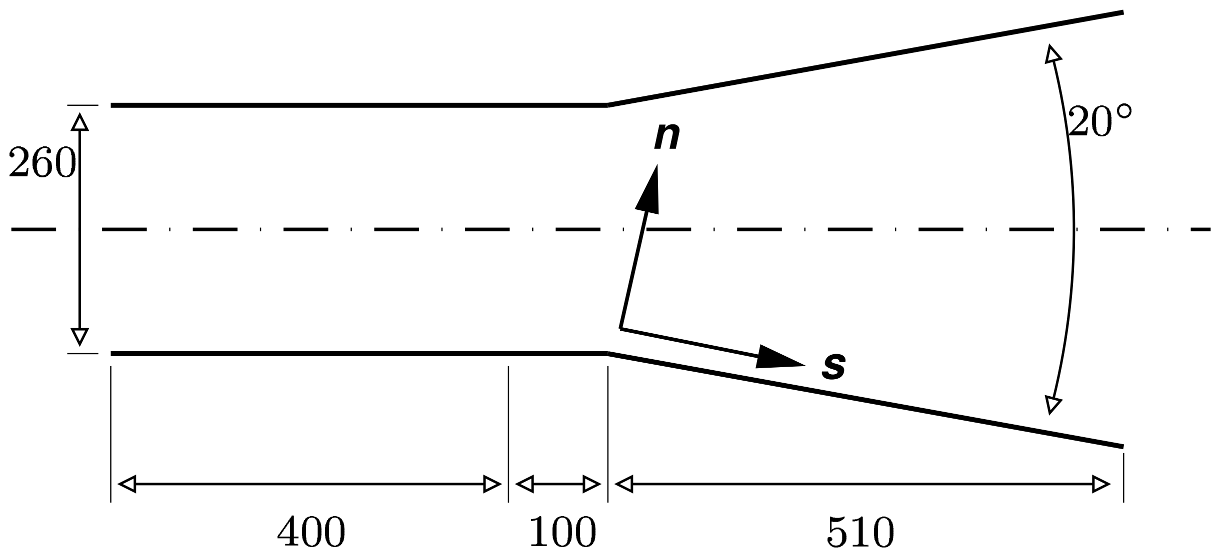
a value of $\alpha > 1$ is needed because a turbulent structure cannot be resolved on subgrid scales.

Upper limit of the turbulent length scale

The main motivation for filtering is to limit the influence of the model on the resolvable mean flow.

- Because $\hat{\nu}_t \leqslant \nu_t$, the damping influence of the eddy viscosity on the mean flow will be smaller.
- Because of the above, the solutions are expected to be more unsteady.
- And why model something that has the potential of being resolved?

Testcase

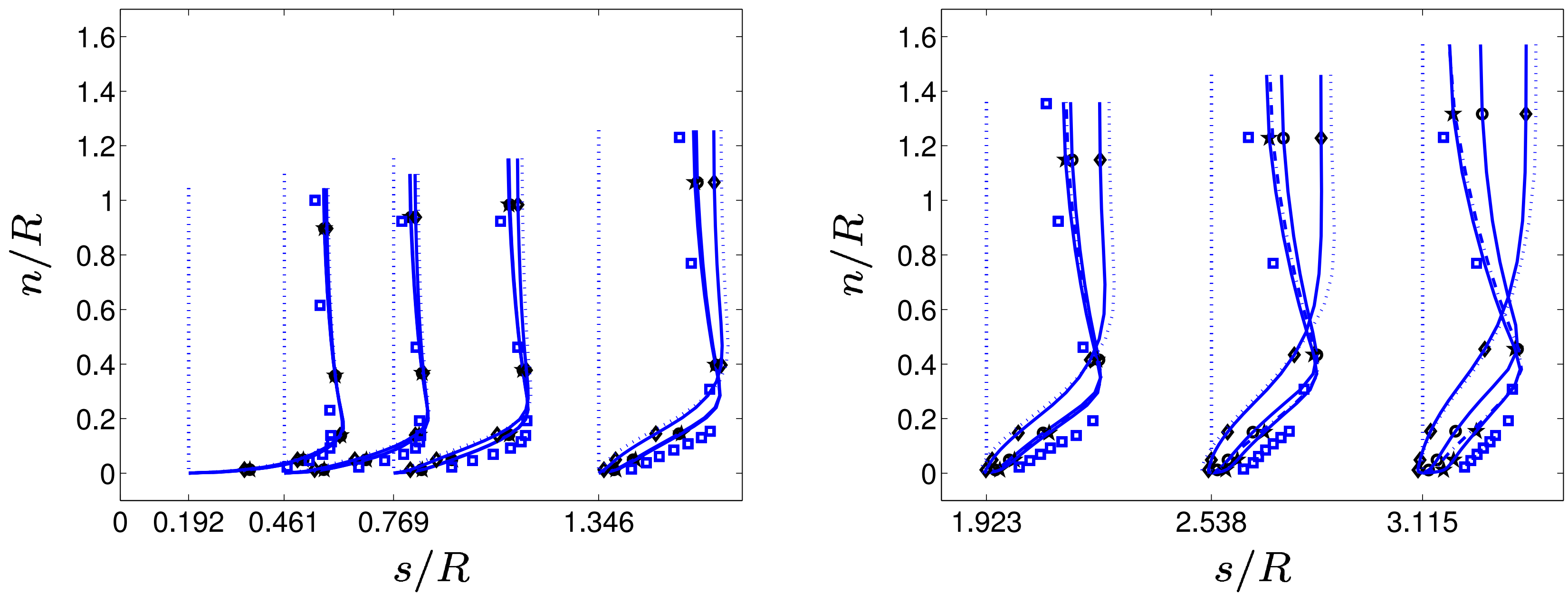


Unsteady RANS/VLES of swirling flow through a diffuser, $Re = 202,000$.

- Isolate the most important physics.
- Investigate the filtering approach using different values of α on two different grids (1,000,000 and 2,500,000 nodes)

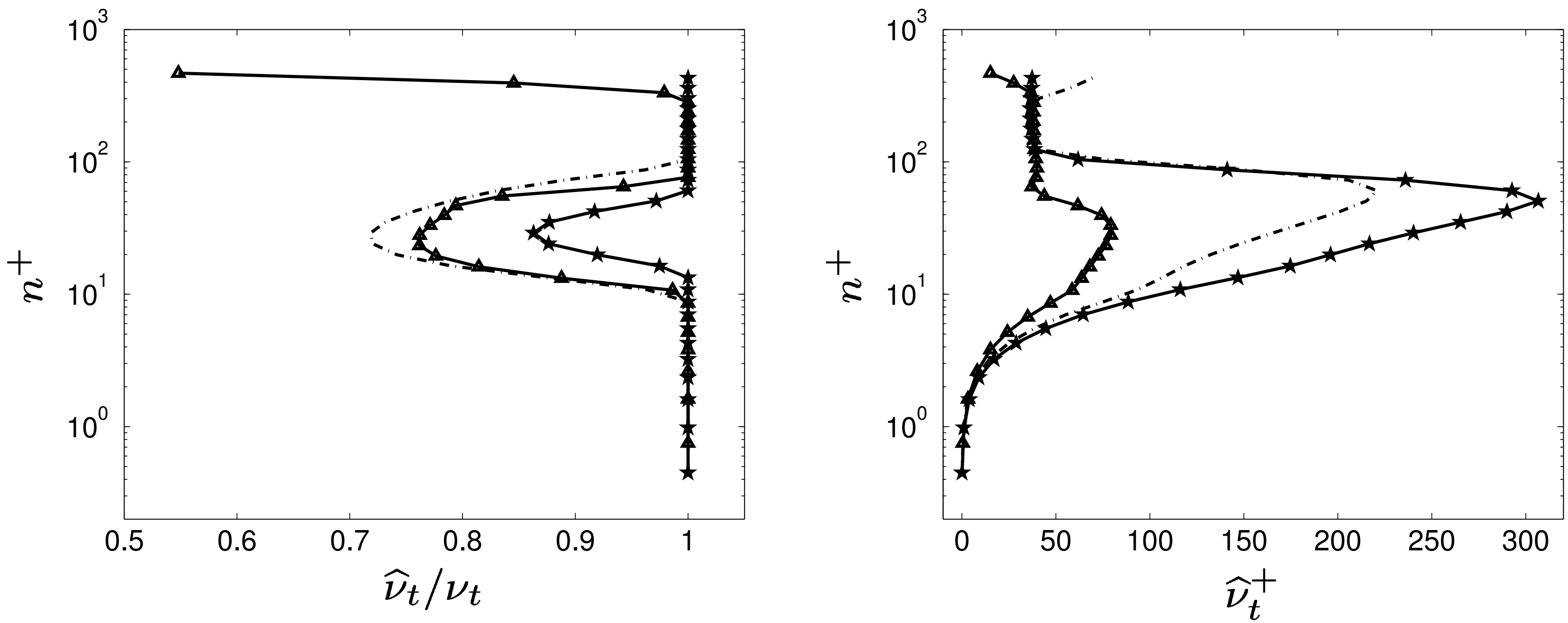
Experimental data courtesy of P. D. Clausen, Australia (available in the ERCOFTAC database)

lime-averaged streamwise velocity



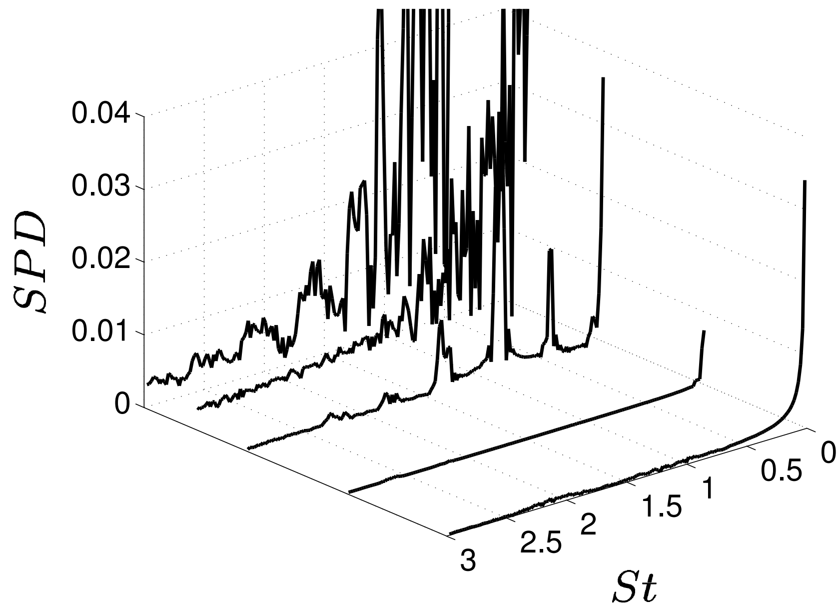
Evolution of streamwise velocity. The results are obtained by varying the filter width for the Wilcox (1988) LRN $k-\omega$ turbulence model. [○]: $\alpha = \infty$. [$\star$]: $\alpha = 4$. [$\cdot -$]: $\alpha = 3$. [$\Diamond$]: $\alpha = 2.5$. [$\cdot\cdot$]: $\alpha = 2$. [$\Box$]: Experiments. The best results are obtained with $\alpha = 3$ or 4. However, using $\alpha = 4$ results in loss of unsteady data.

Filter function g^2 and eddy-viscosity



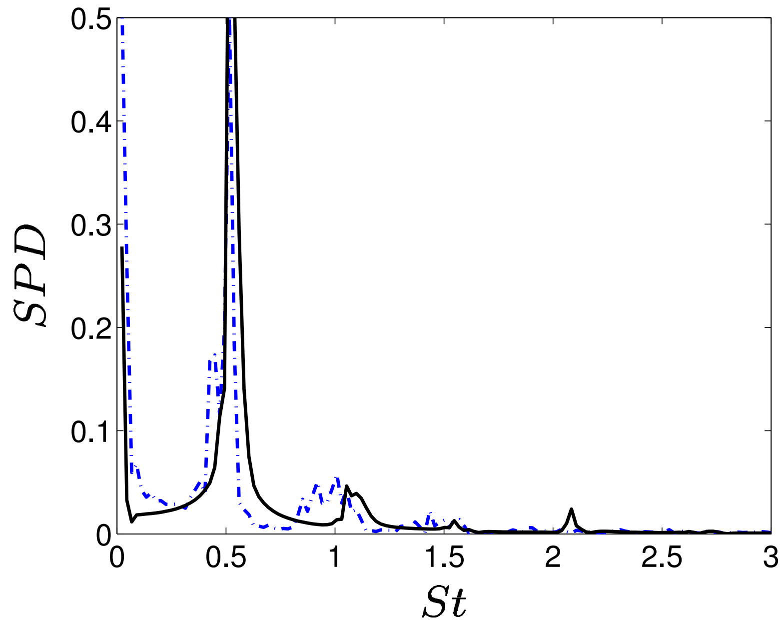
Wall-normal distribution of the filter function (left) and $\widehat{\nu}_t^+$ (right) obtained from different filter widths and different grids. [$\cdot-$]: $\alpha = 3$, Grid A. [$\star$]: $\alpha = 4$, Grid A. [$\triangle$]: $\alpha = 3$, Grid B. The data are taken near the exit of the diffuser at $s/R = 3.115$. The wall-normal distance to the centerline is approximately 470 plus units. Only every second grid point is represented by a marker in the results from Grid B.

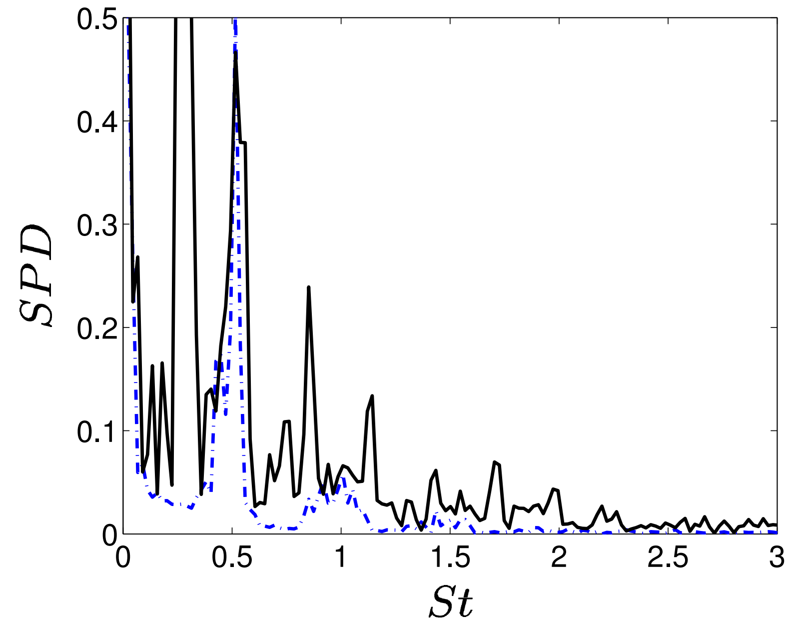
Frequencies of wall pressure



Spectral power density of the wall pressure at $s/R = 3.115$ obtained from variation of the filter width for the Wilcox $k - \omega$ model on grid A. Left to right: $\alpha = \{2,\ 2.5,\ 3,\ 4,\ \infty\}$. The densities are based on 5,000 computational time steps, which equals 1.25 s of real time. If $\alpha > 3$, all unsteadiness vanish from the flow field.

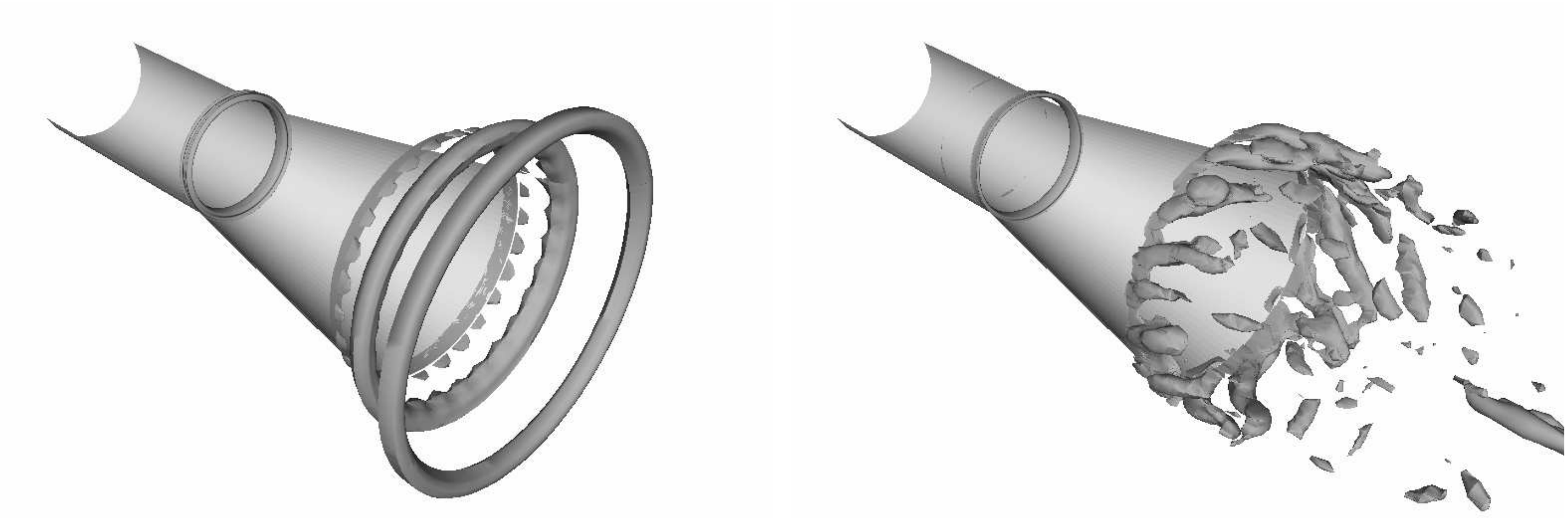
Frequencies of wall pressure near the outlet





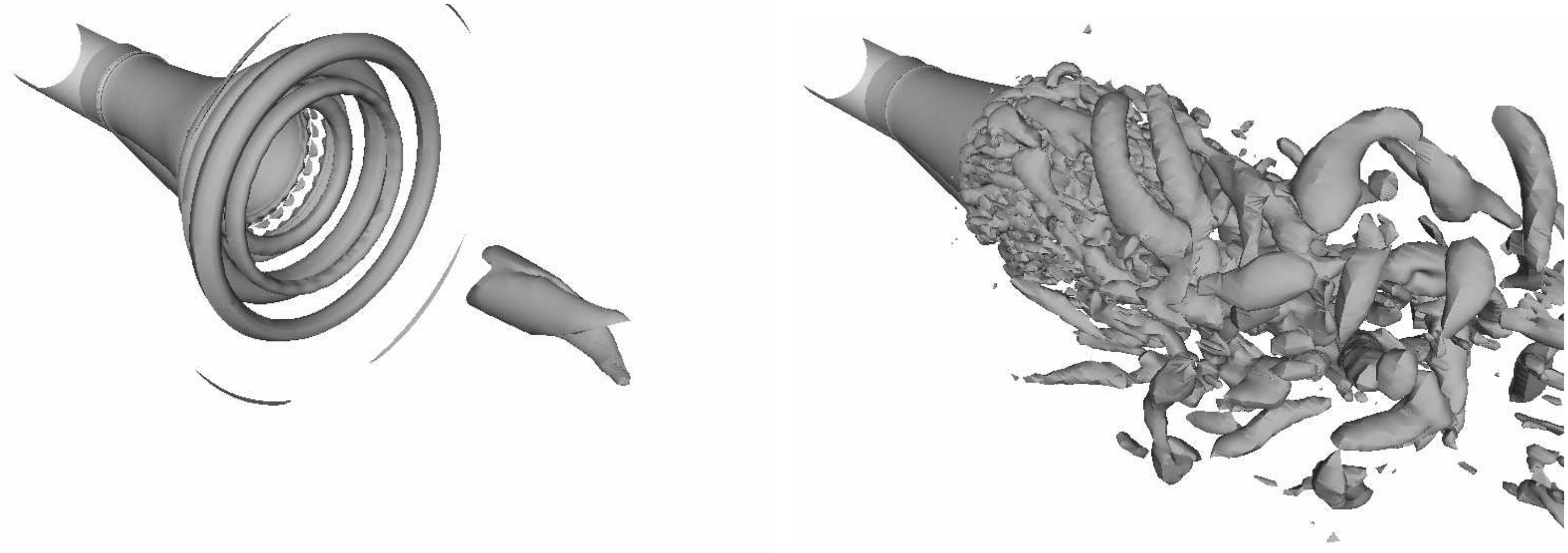
Spectral power density of the wall pressure at the diffuser exit. Left: Variation of the filter width on grid A. [$\cdot -$]: $\alpha = 3$. [$-$]: $\alpha = 4$. Right: Influence of grid resolution when using the same filter coefficient $\alpha = 3$. [$\cdot -$]: Grid A. [$-$]: Grid B. The figures are based on 4,000 computational time steps which equals 1 s of real time.

Resolved vortices



Positive iso-surfaces of the normalised second invariant of the strain rate tensor, $II^*_{\mathcal{V}} = 0.5$. Left: Filtered $k - \omega$ model ($\alpha = 3$), grid A. Torus-shaped vortices are formed and convected downstream from the exit of the diffuser. Right: Filtered $k - \omega$ model ($\alpha = 3$), grid B. Unsteady vortices are formed at the exit of the diffuser. They are stretched orthogonally to the flow before being convected downstream.

Resolved vortices



Positive iso-surfaces of the normalised second invariant of the strain rate tensor, $II_{\mathcal{S}} = 0.05$. The results are from a simulation in which the filtered $k - \omega$ model ($\alpha = 3$) was used on grid A (left) and grid B (right). On the coarser grid, torus-shaped vortices that originate from the boundary layer of the diffuser are formed at the diffuser exit and interact with smaller, counter-rotating torus-shaped vortices. A vortex shape reminiscent of a double helix is formed in the dump. A fully turbulent flow is obtained from the simulation on the finer grid.

Conclusions

- Filtering is in some cases necessary in order to obtain unsteady solutions.
- The filtering procedure improves the time-averaged results as long as it is applied with some caution, i.e. it should not be active in the near wall region. Additional testcases using wall functions on a coarser grid showed that, for these cases, the solutions were not as sensitive to the value of alpha.
- The main frequency of the flow is not sensitive to of the choice of the filter width.
- A grid refinement introduces overtones, but also a high density of a lower frequency.

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