On the Sensitivity of LES to Numerics and Grid Resolution in the Process of Landing-Gear Noise Prediction

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Outline

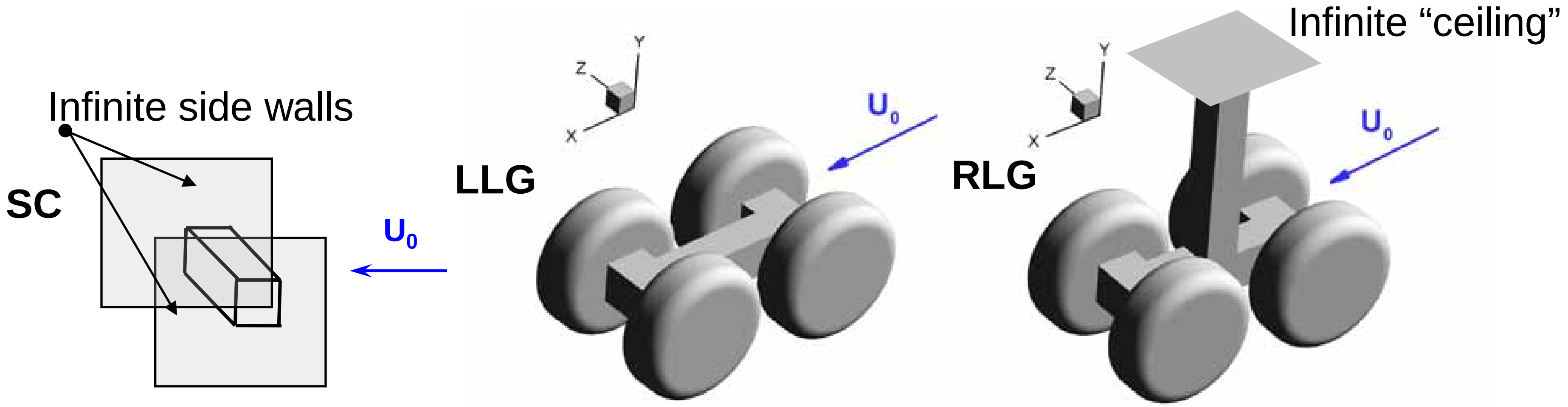
- Motivation and objectives
- Considered configurations
- Modeling and numerical details
  - Turbulence representation and numerics
  - Far-field noise prediction
- Study design
- Results and discussion
- Concluding remarks

Motivation and Objective

- Noise prediction by unsteady turbulence-resolving simulations is most promising
  - Wave of new work on Airframe Noise (cavities, landing gears, flap edges, slats, train components, etc.)
  - Very few comparisons of far-field noise, and tangible uncertainty, of the order of 5dB (higher than for jet noise)
- Many subtle aspects of effects of numerical dissipation and grid-resolution on LES-based AFN prediction remain unclear
  - Systematic investigation of these effects is needed
  - The study is complicated by the two-step nature of noise prediction: turbulence, followed by noise radiation
- Objective
  - To perform such a study aimed at the Landing Gear noise

Considered Configurations

- 3 configurations of successively increasing complexity are considered
  - Square Cylinder placed between two walls (SC)
  - Levitating Landing Gear (LLG)
  - Rudimentary Landing Gear (RLG)



- SC and LLG are fragments of the RLG, intentionally designed at Boeing as a public-domain test case for NASA-AIAA Workshops on Benchmark problems for Airframe Noise Computations (BANC)
  - Near-field measurements at NAL (India) for 2010 workshop
  - Noise measurements at U. Florida for 2012 workshop (both funded by Boeing)

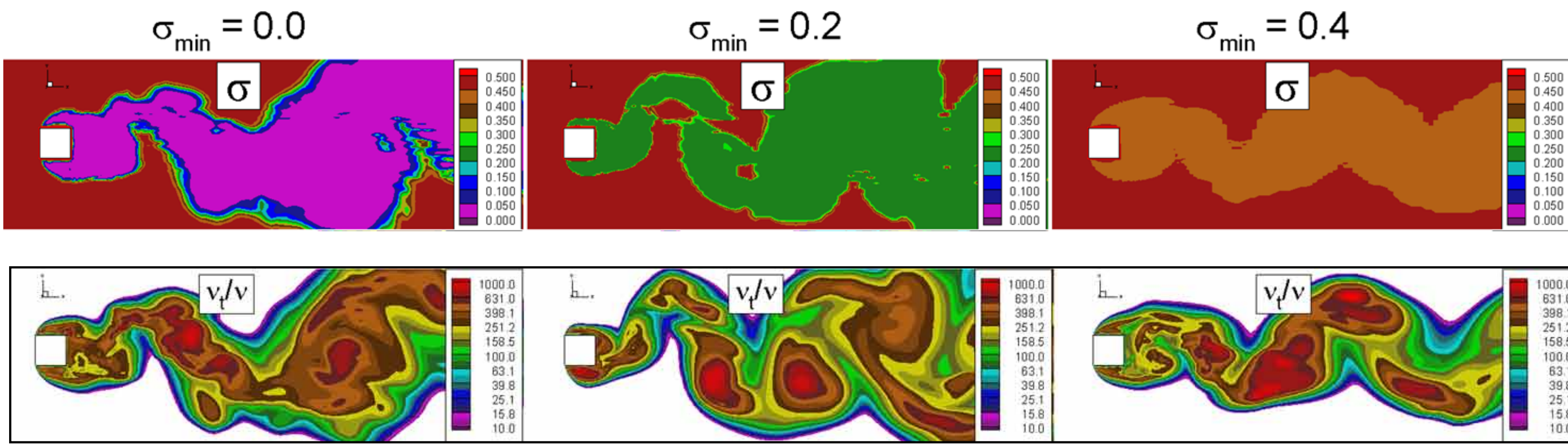
Modeling and Numerical Details

- For all the three configurations SA-Based Delayed Detached Eddy Simulations (DDES) of turbulence have been carried out and far-field noise has been computed with the use of Ffowcs Williams and Hawkings (FWH) approach
  - DDES is performed with the use of the multi-block (Chimera type) structured, high-order finite-volume NTS code
    - Employs hybrid (upwind/centered) approximation of the inviscid fluxes with an automatic blending of 3rd-order upwind and 4th-order centered approximations

$$F_{inv} = (1 - \sigma_{upw}) F_{ctr} + \sigma_{upw} F_{upw}$$

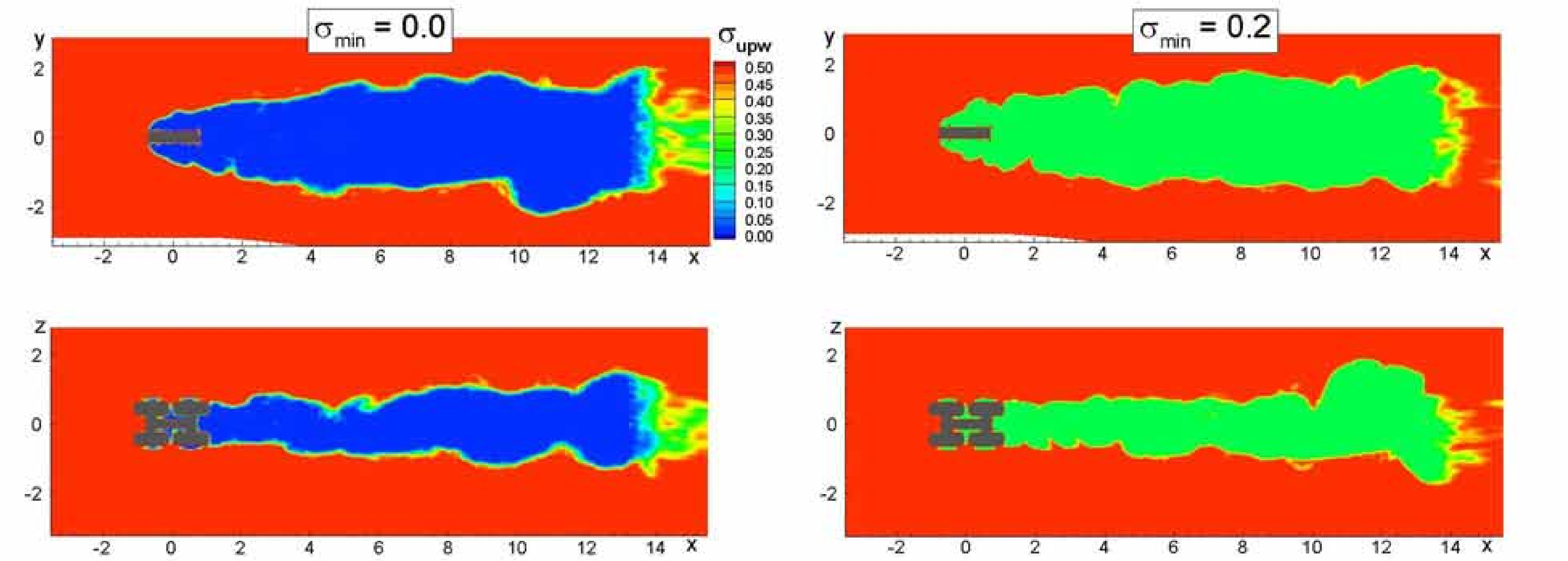
    - Solution-dependent function $\sigma_{upw}(x, y, z, t)$ varies within the range $[\sigma_{\min}, \sigma_{\max}]$ and is close to $\sigma_{\min}$ in LES region of DDES and to $\sigma_{\max}$ in its RANS and irrotational regions
    - Ensures numerical stability and low dissipation in LES region

Behavior of Blending Function of Hybrid 3rd Order upwind - 4th Order Centered Numerics: SC Flow



- The function behaves according to its design
  - Distribution is quite bipolar, close to s_{min} in LES and to s_{max}=0.5 in RANS and irrotational regions of DDES
  - s_{min} = 0 ensures minimal overall dissipation
  - Level of eddy viscosity is not affected much by s_{min}

Behavior of Blending Function of Hybrid 3rd Order upwind - 4th Order Centered Numerics: LLG Flow

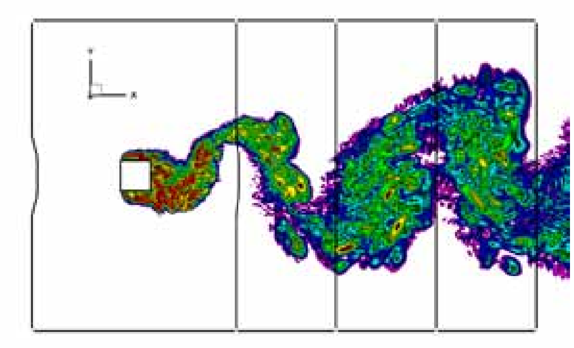


- Similar behavior of s_{upw} is observed in the RLG flow

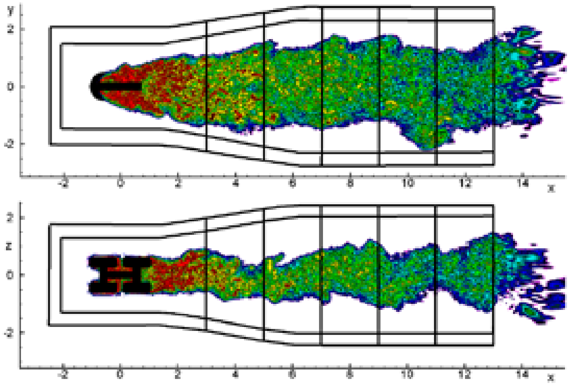
Far-Field Noise Prediction

- Far-field extrapolation is performed by Ffowcs Williams – Hawkings (FWH)
- Two types of FWH surfaces:
  - Solid (“Curle approximation”)
  - Porous (a set of closed nested surfaces to check sensitivity)
    - q Inflow and lateral parts of the P surfaces are in the irrotational region
    - q Virtually no effect of the choice of P surface has been observed, except for the very high end of the spectra

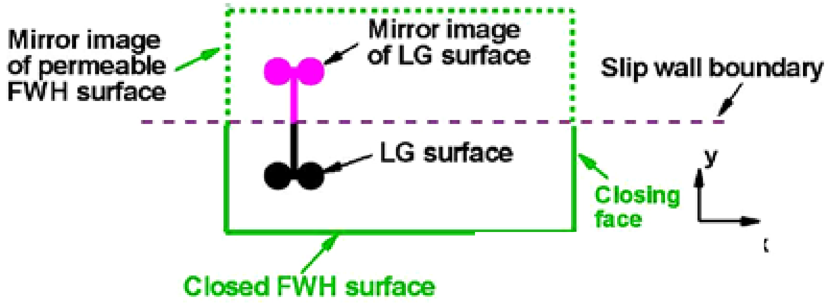
SC



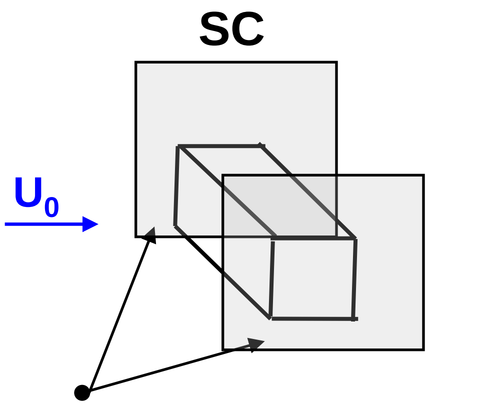
LLG

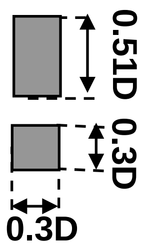


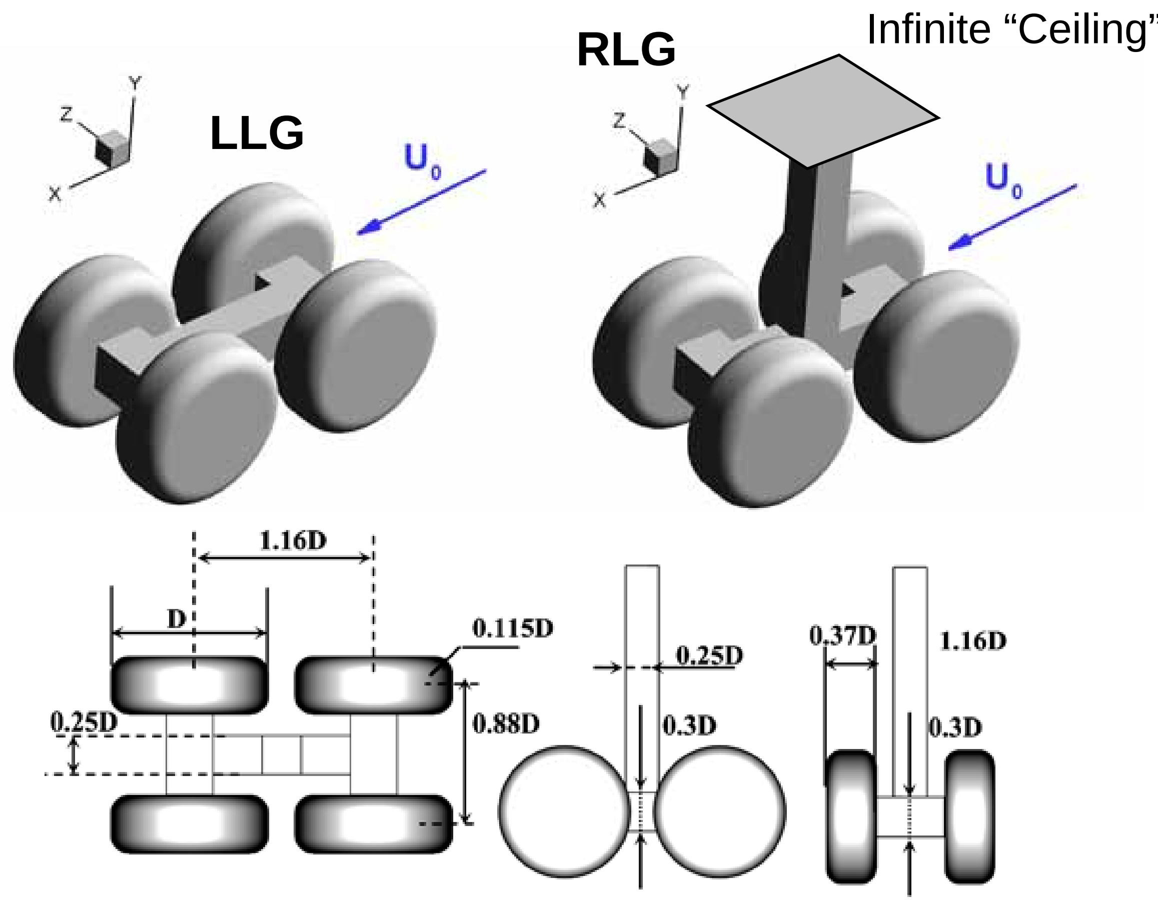
RLG: FWH surfaces are similar to those for LLG but include mirror images accounting for sound reflections by the “ceiling” (symmetry plane)



Geometries and Flow Regime







- All the simulations are carried out at
  - $Re_D=10^6$ (based on free-stream velocity and wheel diameter)
  - M=0.115

Design of the Study

1. Simulations of SC on three single-block grids refined by a factor of 2, and 2 again in Focus Region (same for time step) at $s_{\max} = 0.5$ and $s_{\min}$ varying from 0 up to 0.4
   – Allow assessment of both effect of numerical dissipation and effect of aggressive grid-refinement and, in addition, avoid possible inaccuracy caused by interpolation at inter-block boundaries of multi-block grids
2. Simulations of LLG at different values of $s_{\min}$ on a multi-block grid of about 22 million cells with a resolution similar to that of the SC coarse grid
   – Allow checking findings of SC simulations on the effect of $s_{\min}$ on a multi-block grid for the flow with turbulence impingement and eliminate effect of the RLG post and ceiling on the noise, thus facilitating analysis of obtained results
3. Simulations of full RLG configuration at different $s_{\min}$ on a grid similar to that of LLG and comparison with experiment
   – Allow comparison with experiment

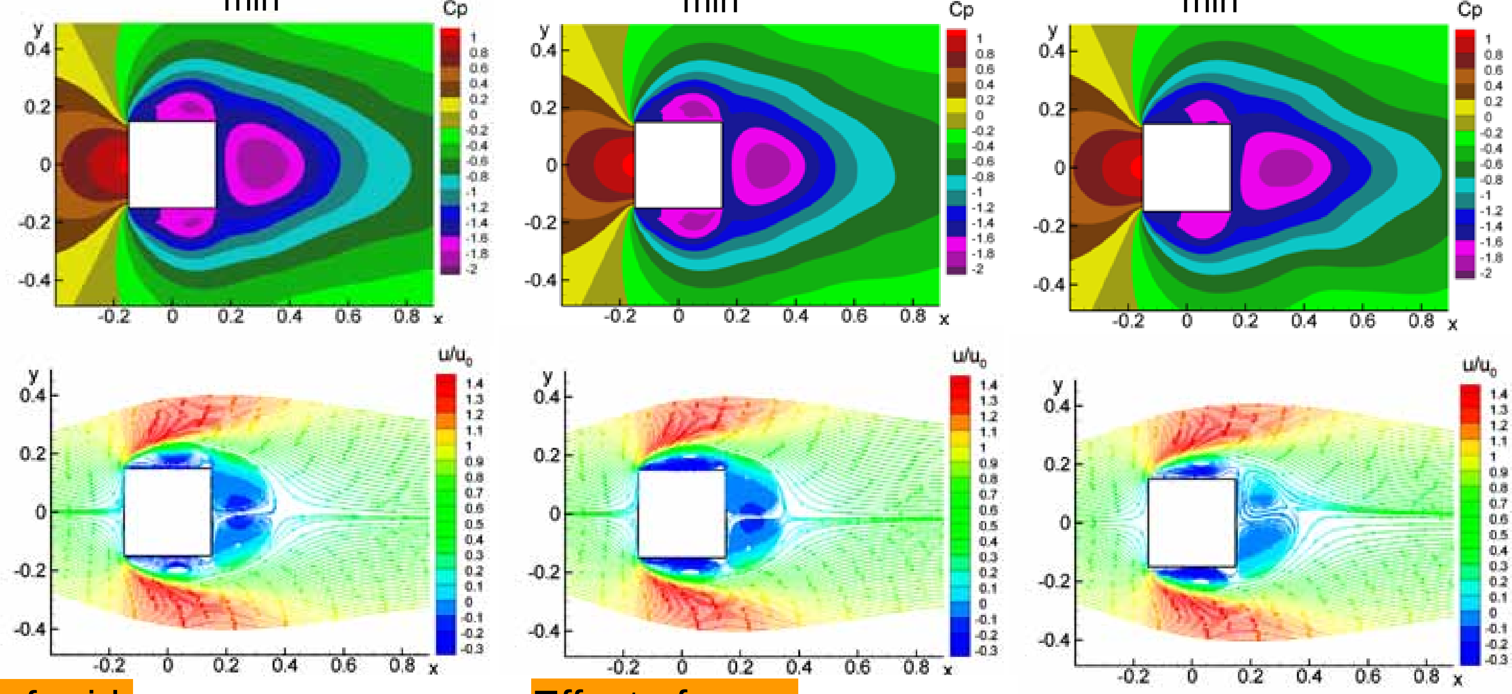
Mean Flow Predictions

Effect of Grid and s_{min} on SC Mean Flow

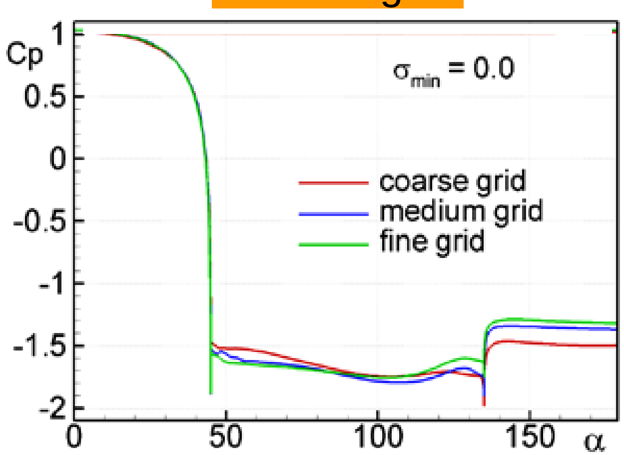
s_{min}=0 | s_{min}=0.2 | s_{min}=0.4

Pressure contours

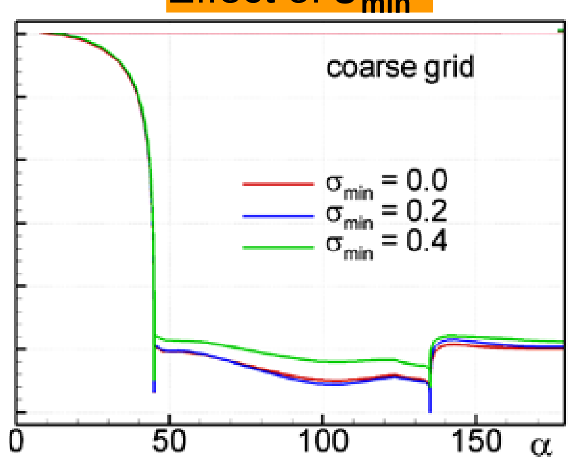
Streamlines colored by streamwise velocity



Effect of grid



Effect of s_{min}

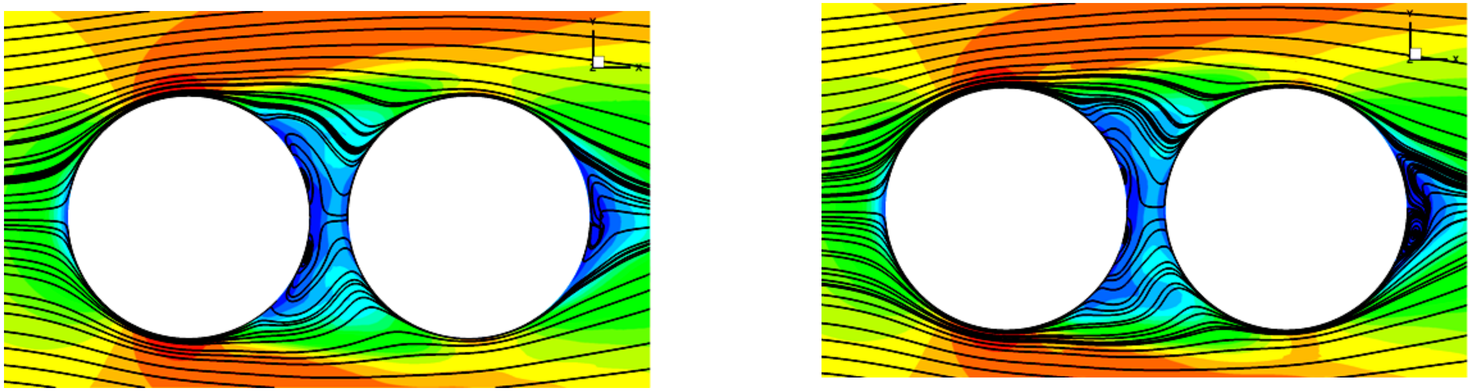


- Clear trend to grid convergence at s_{min}=0
- Virtually no effect of s_{min} within the range [0, 0.2]

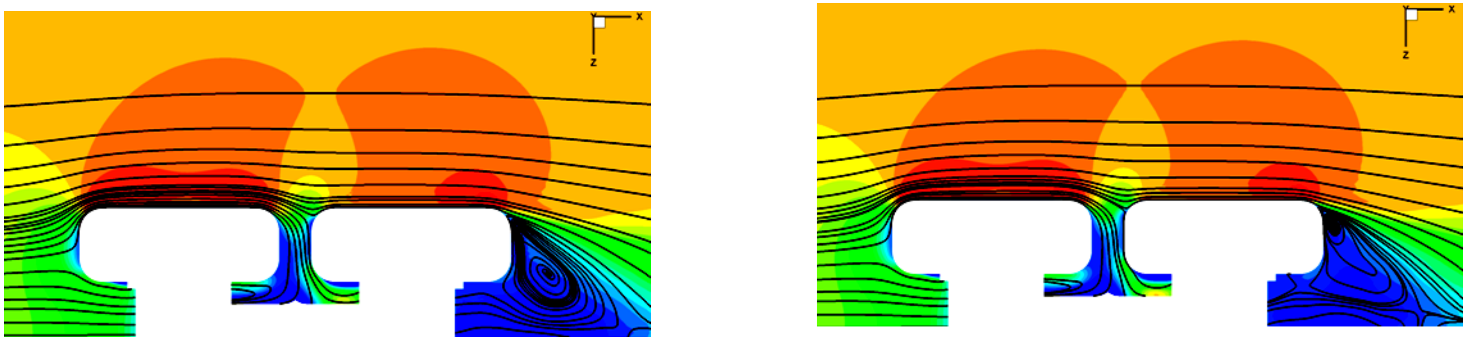
Effect of s_{min} on LLG Mean Flow

$s_{min} = 0.0$ $\quad$ $s_{min} = 0.2$

Wheels mid XY plane



Wheels mid XZ plane



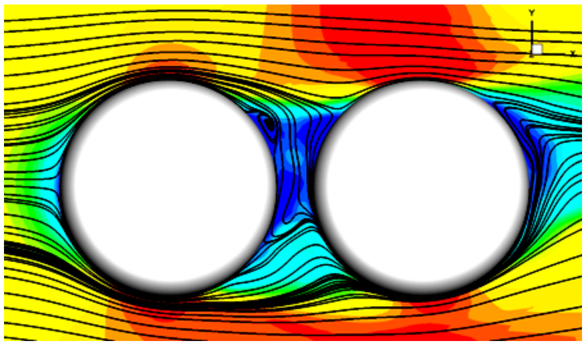
Streamlines and streamwise velocity contours

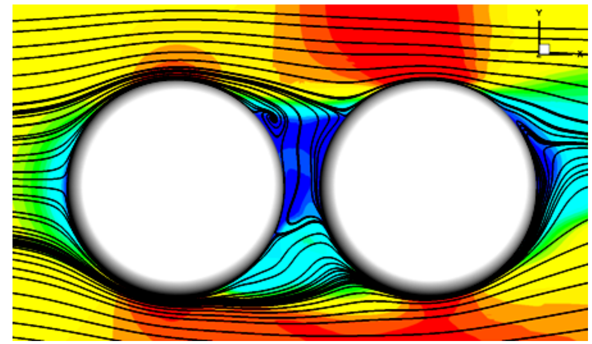
- Same is true for LLG configuration

Effect of s_{min} on RLG Mean Flow

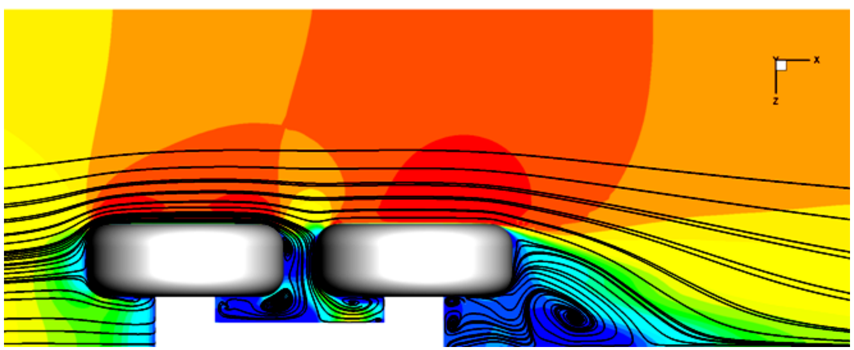
$s_{min} = 0.0$ $s_{min} = 0.2$

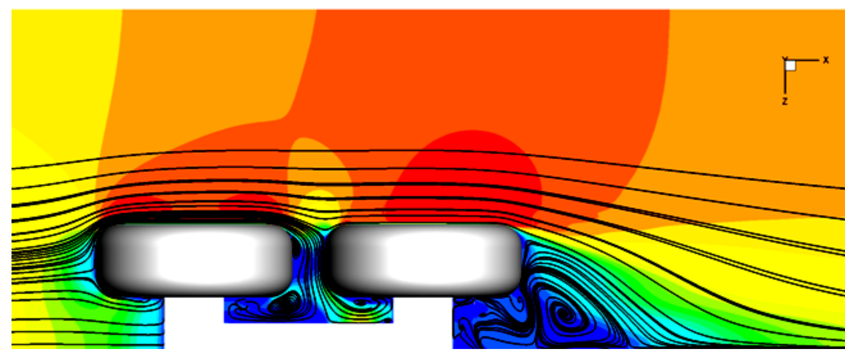
Wheels mid XY plane





Wheels mid XZ plane

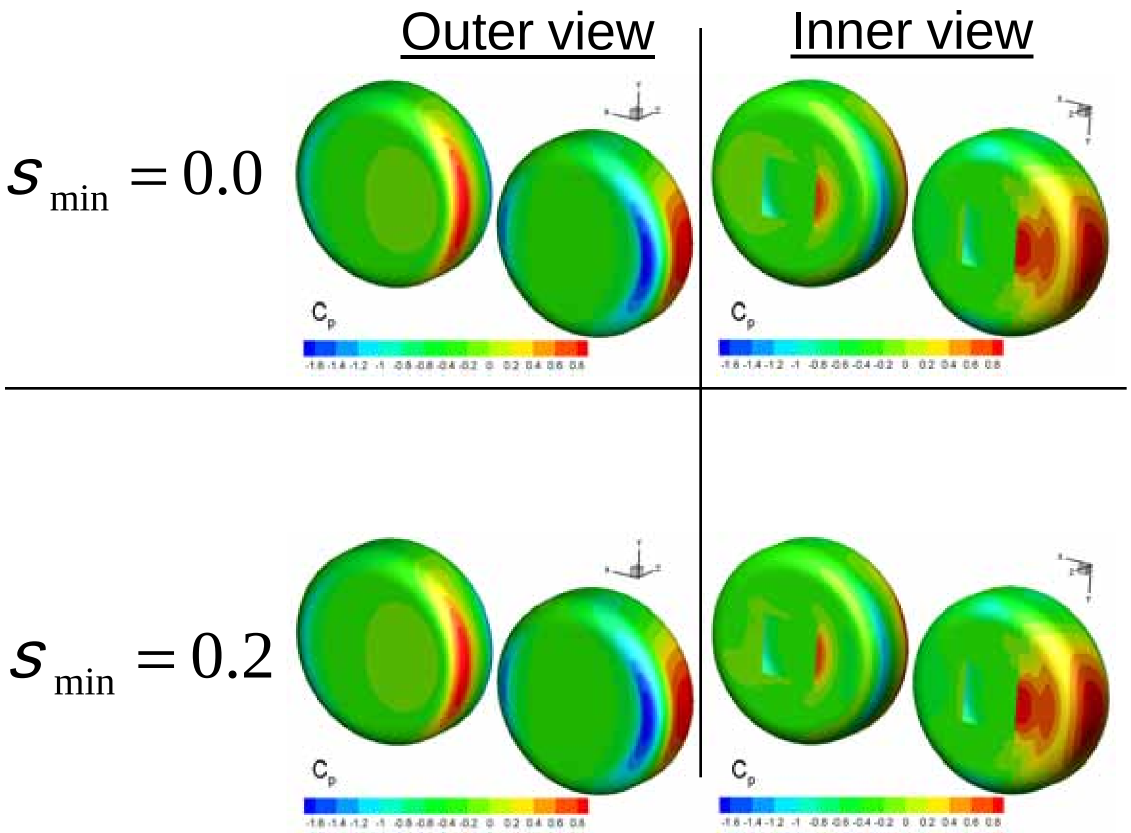


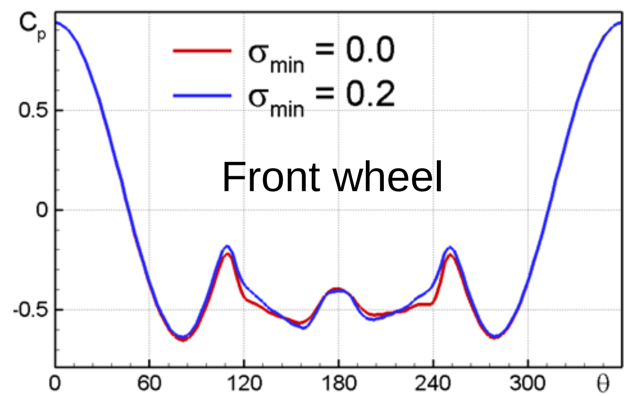


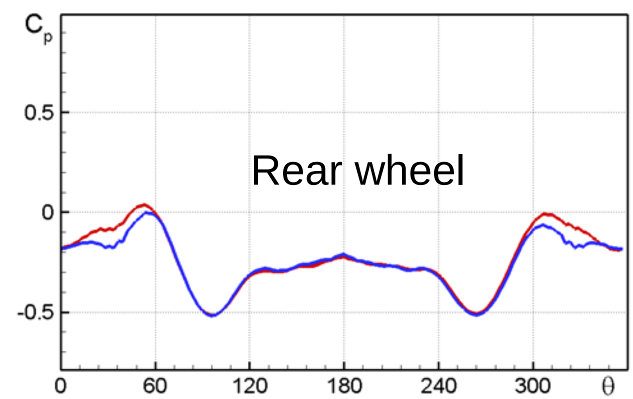
Streamlines and streamwise velocity contours

- Again, no visible effect of s_{min} on the mean velocity field

Effect of s_{min} on LLG Mean Flow



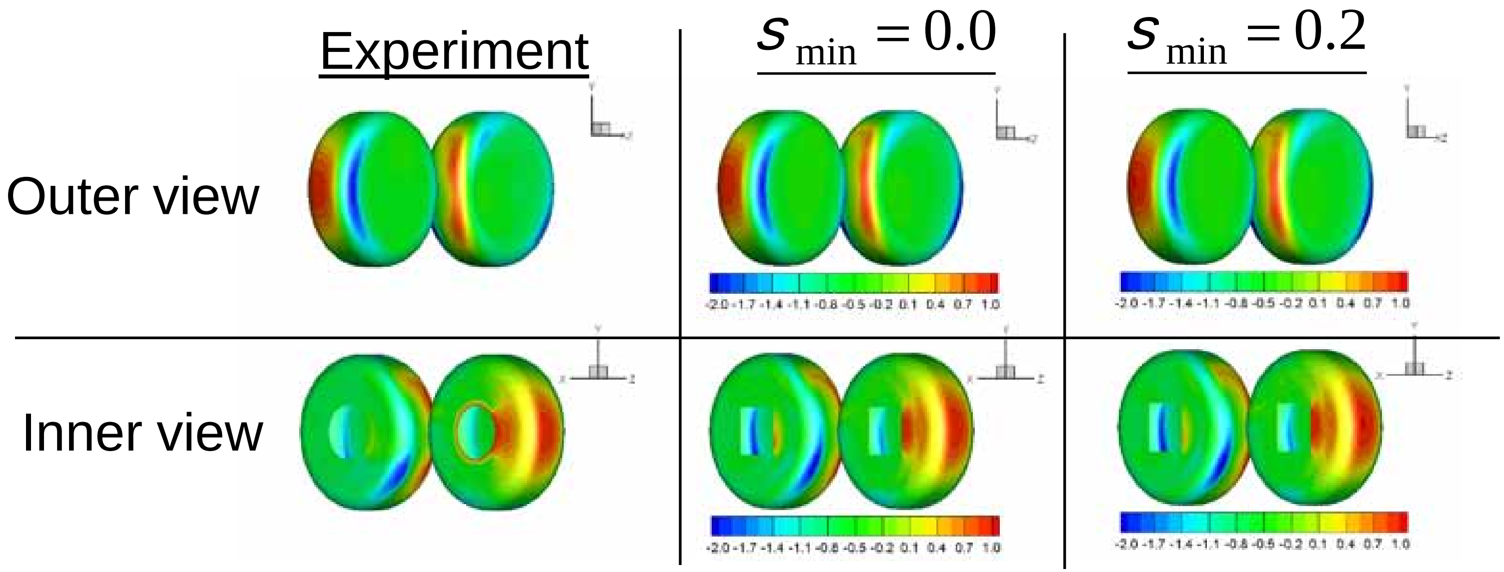


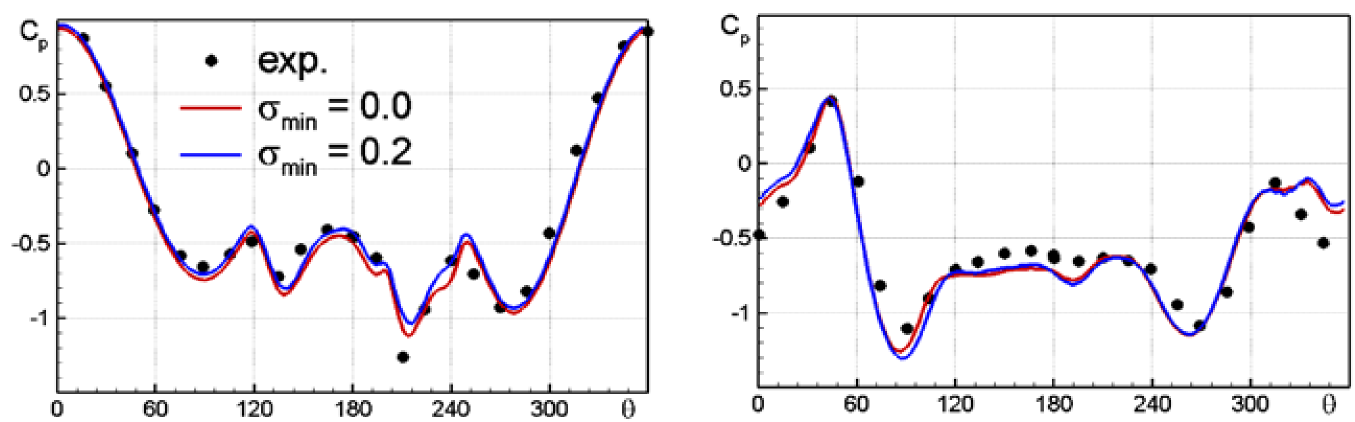


Cp distribution along central circumferential wheels line

- Virtually no effect of s_{min} on mean pressure

Effect of s_{min} on RLG Mean Flow and Comparison with NAL Experiment





Central circumferential line

- Again negligible effect of s_{min}, and both solutions agree well with experiment

Summary of Findings on Mean Flow Predictions

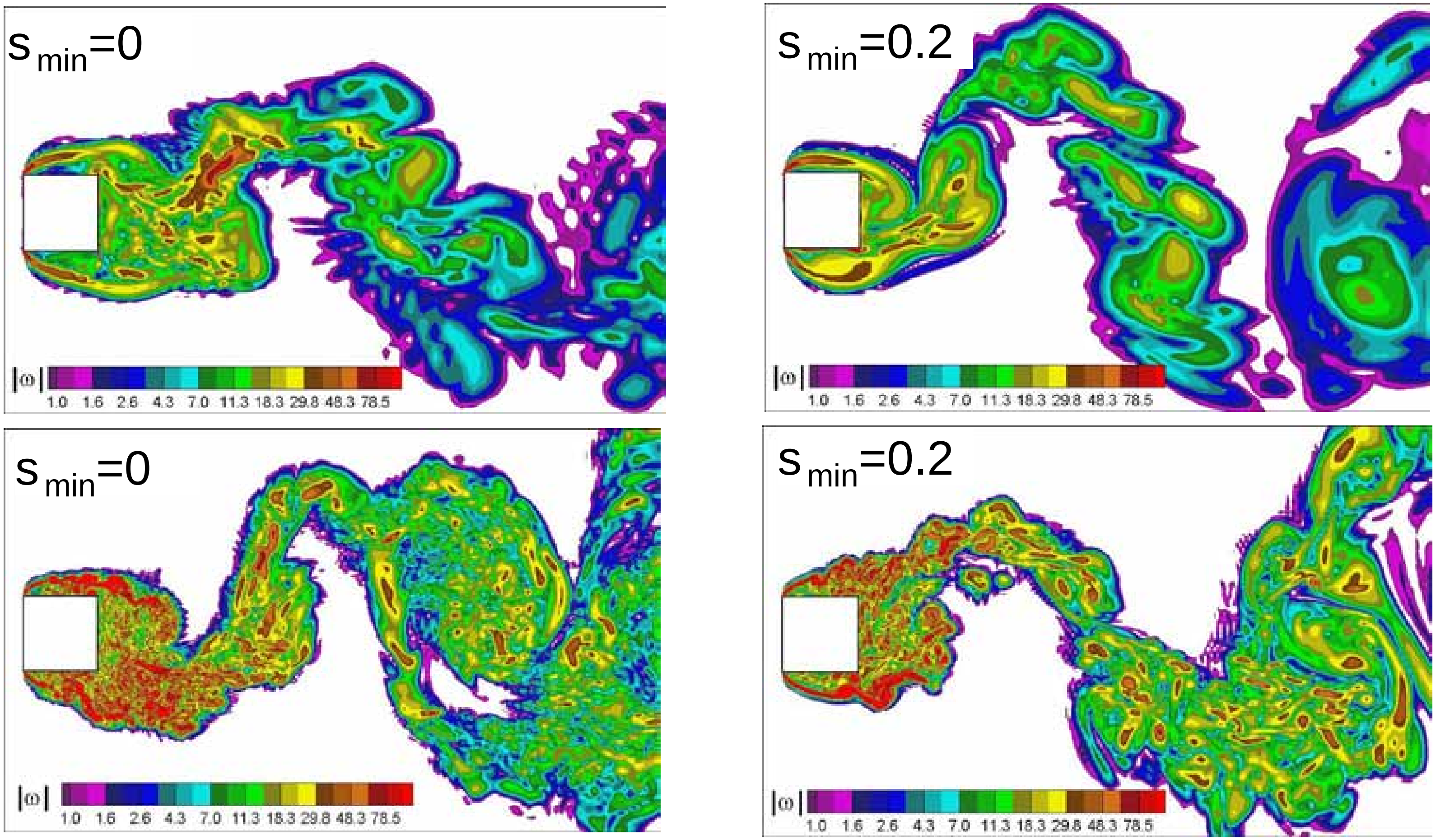
- Mean flow parameters experience insignificant variation with grid refinement and moderate (within the range [0, 0.2]) increase of the weight of the upwind scheme s_{min}

Turbulence Representation

Effect of s_{min} and Grid on Appearance of Turbulence: SC Flow

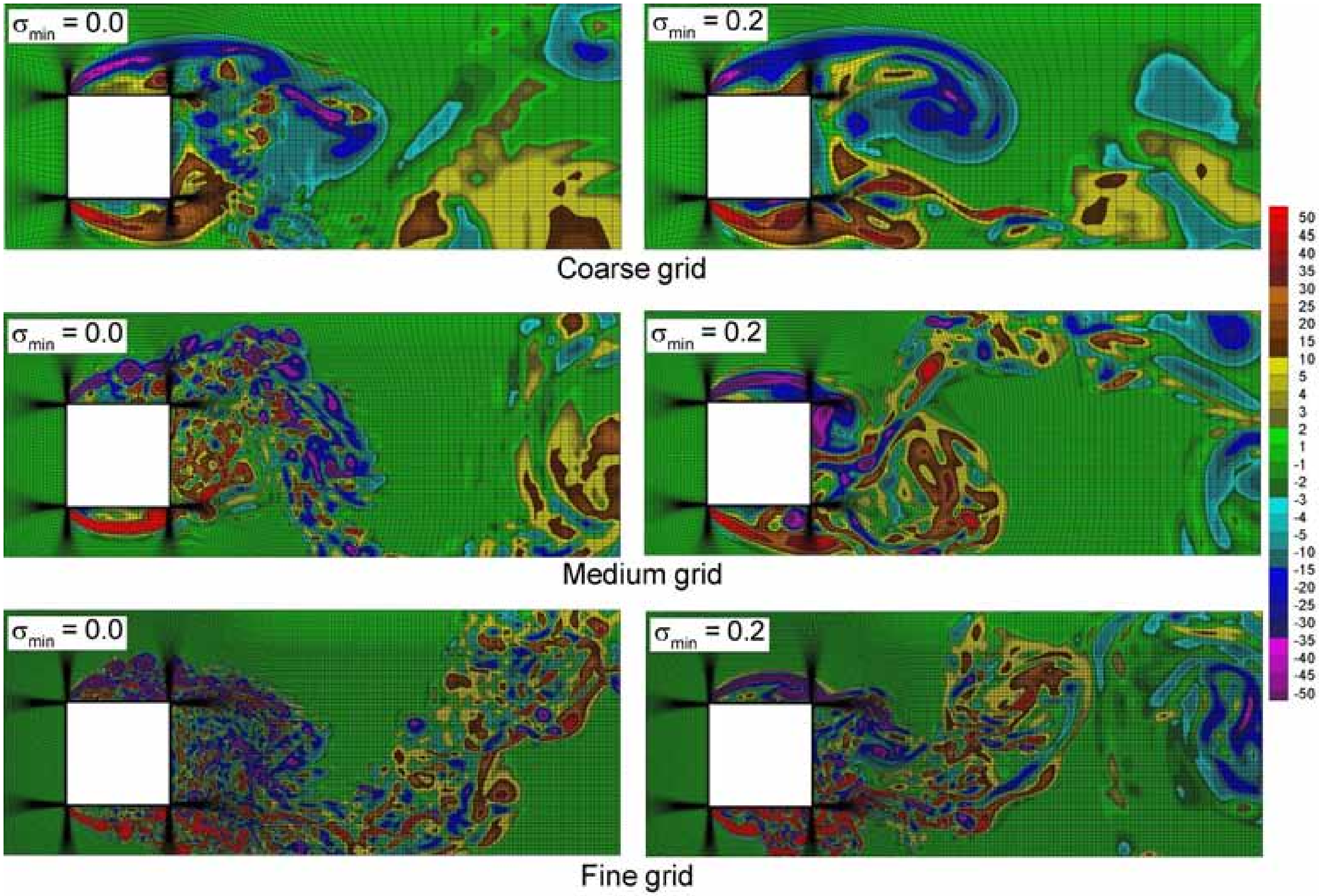
Coarse grid

Fine grid
(4 times)



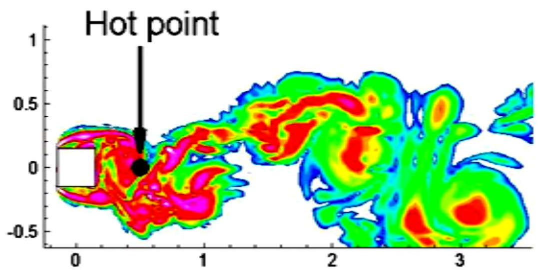
- Significant increase of “turbulent content” (resolved fine-grain turbulence) with grid-refinement and with decrease of numerical dissipation

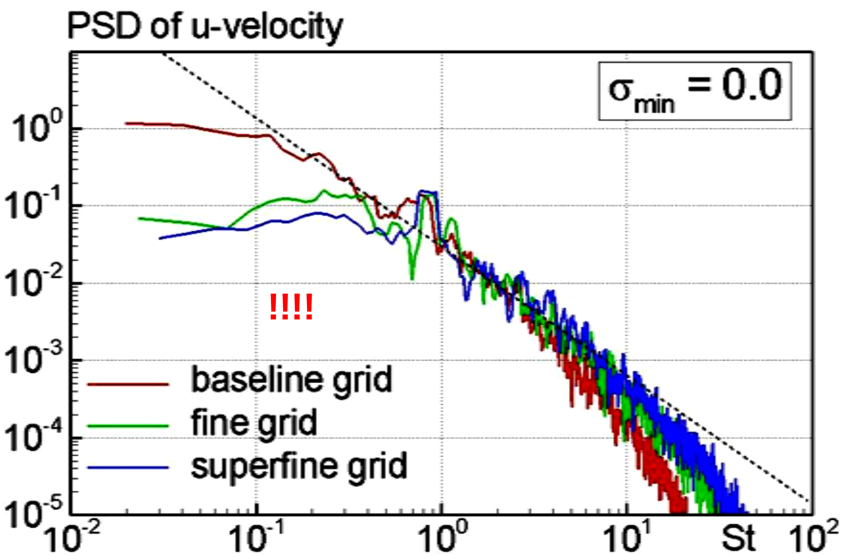
Relationship Between Small Eddies and Grid Spacing: SC Flow, Vorticity Contours

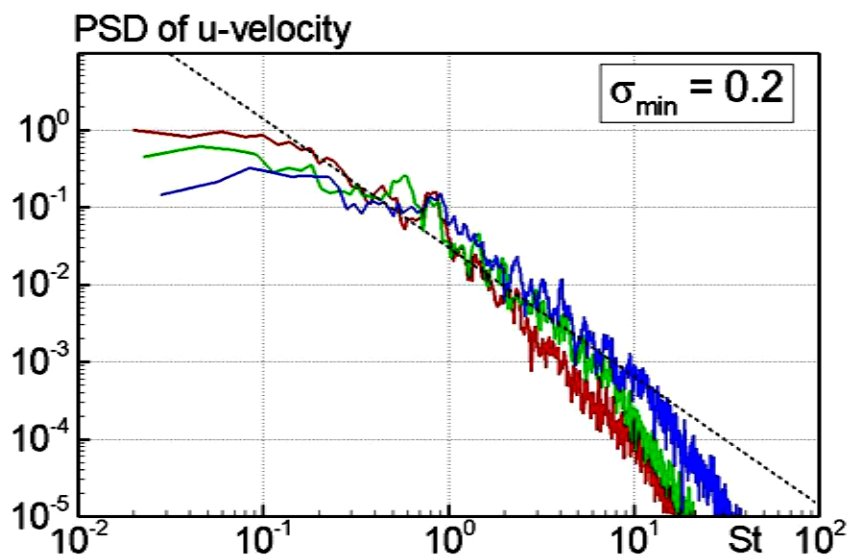


- At s_{min}=0, there are some eddies with sizes of nearly 2-3 cells:
  - Are they spurious (amounting to numerical “wiggles”)?
  - Recall momentum equation contains 2^{nd} derivatives

Quantitative Effect of s_{min} and Grid on Resolved Turbulence: SC Flow



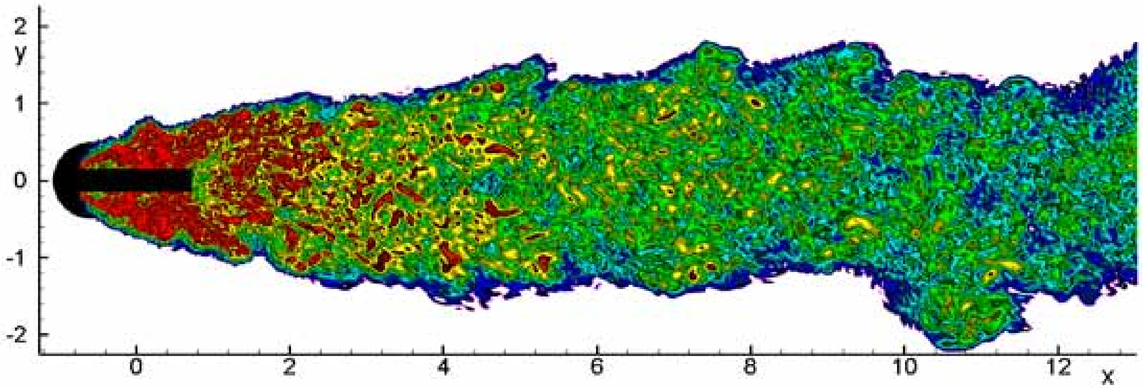




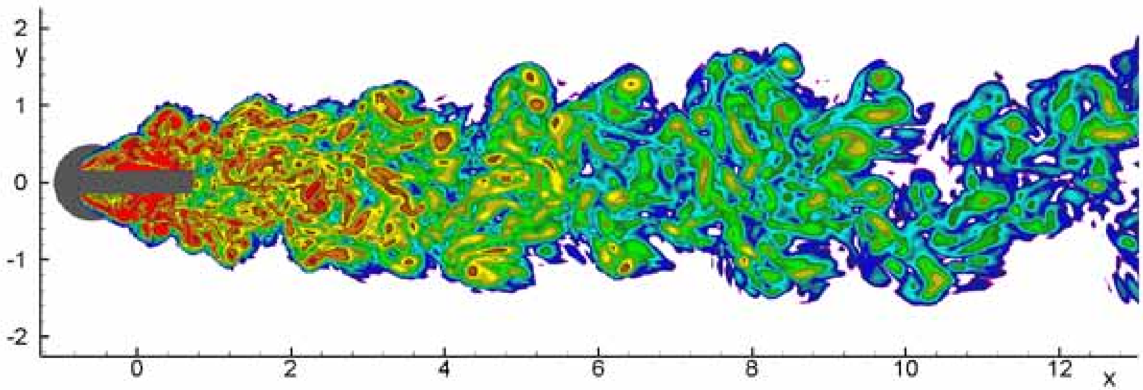
- “Normal” response to increase of dissipation and grid-refinement
  - At s_{min} = 0.2 high frequencies are damped somewhat stronger
  - Grid-refinement leads to a longer inertial (“-5/3”) range

Effect of s_{min} on Appearance of Turbulence: LLG Flow

s_{min}=0

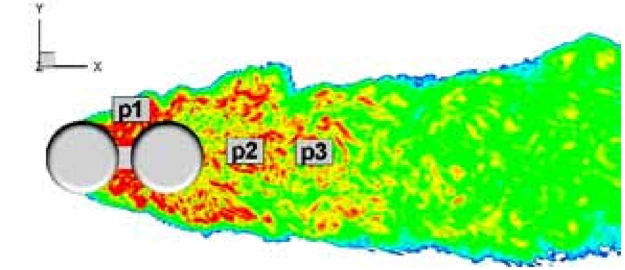


s_{min}=0.2



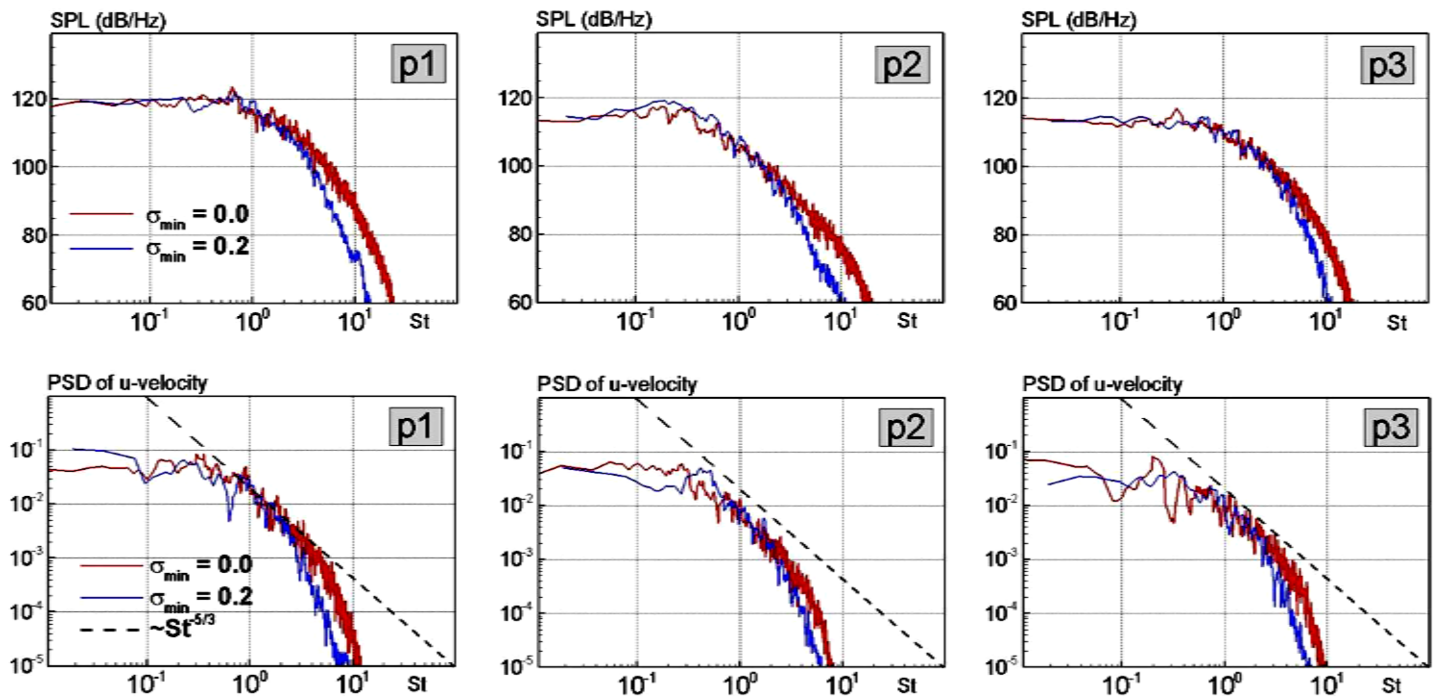
- Similar observations as for the SC flow
  - No visible numerical wiggles at s_{min}=0
  - Strong damping of fine-grained turbulence at s_{min} =0.2

Quantitative Effect of s_{min} on Resolved Turbulence: LLG Flow



Pressure

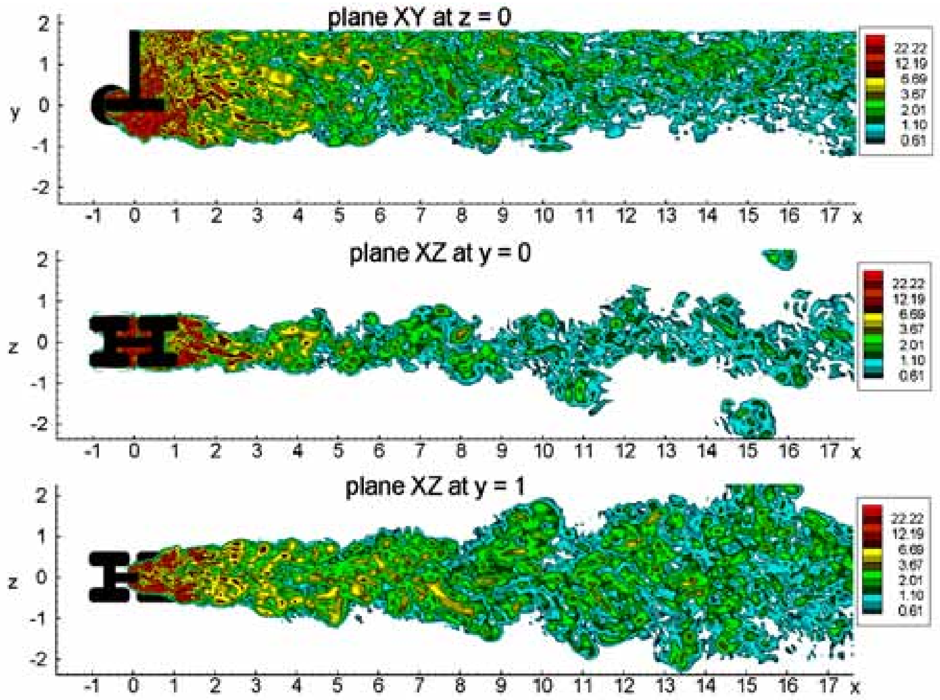
Velocity



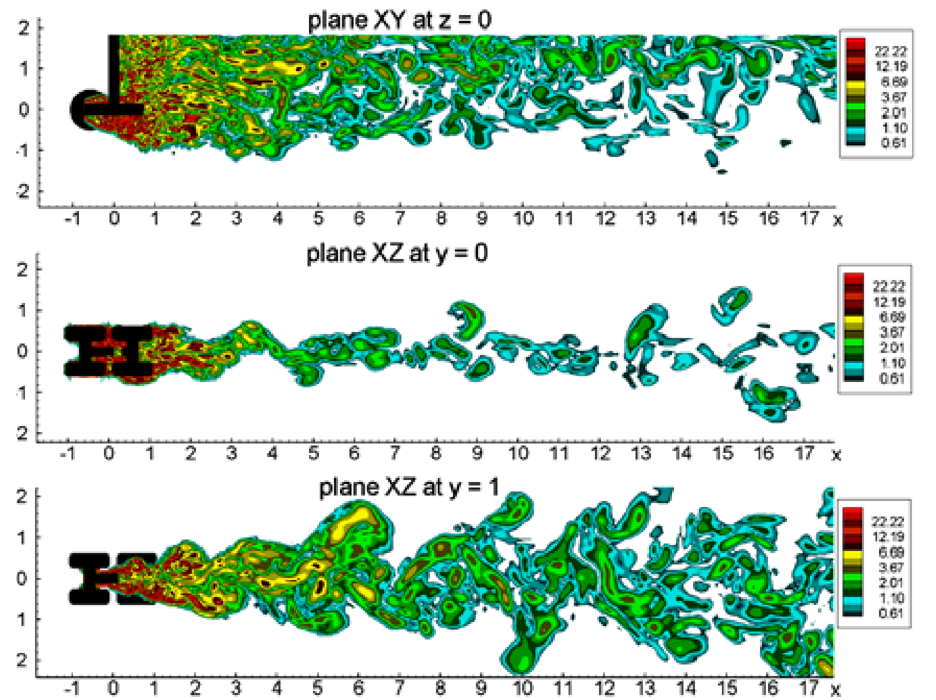
- Again, normal reaction of spectra to increase of numerical dissipation
  - Only high frequencies are affected

Effect of s_{min} on Appearance of Turbulence: RLG Flow

$s_{min} = 0$

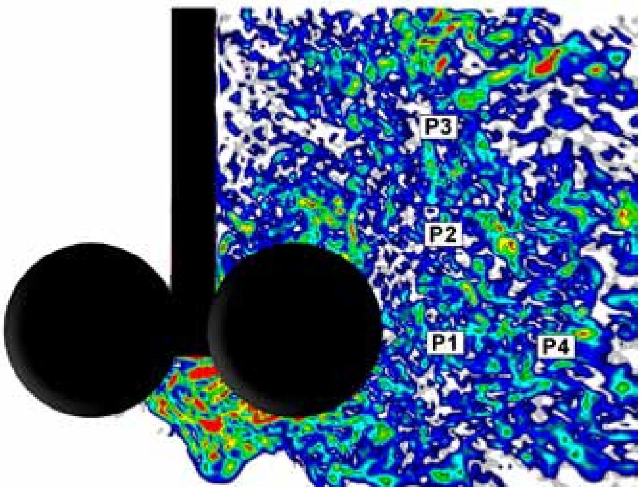


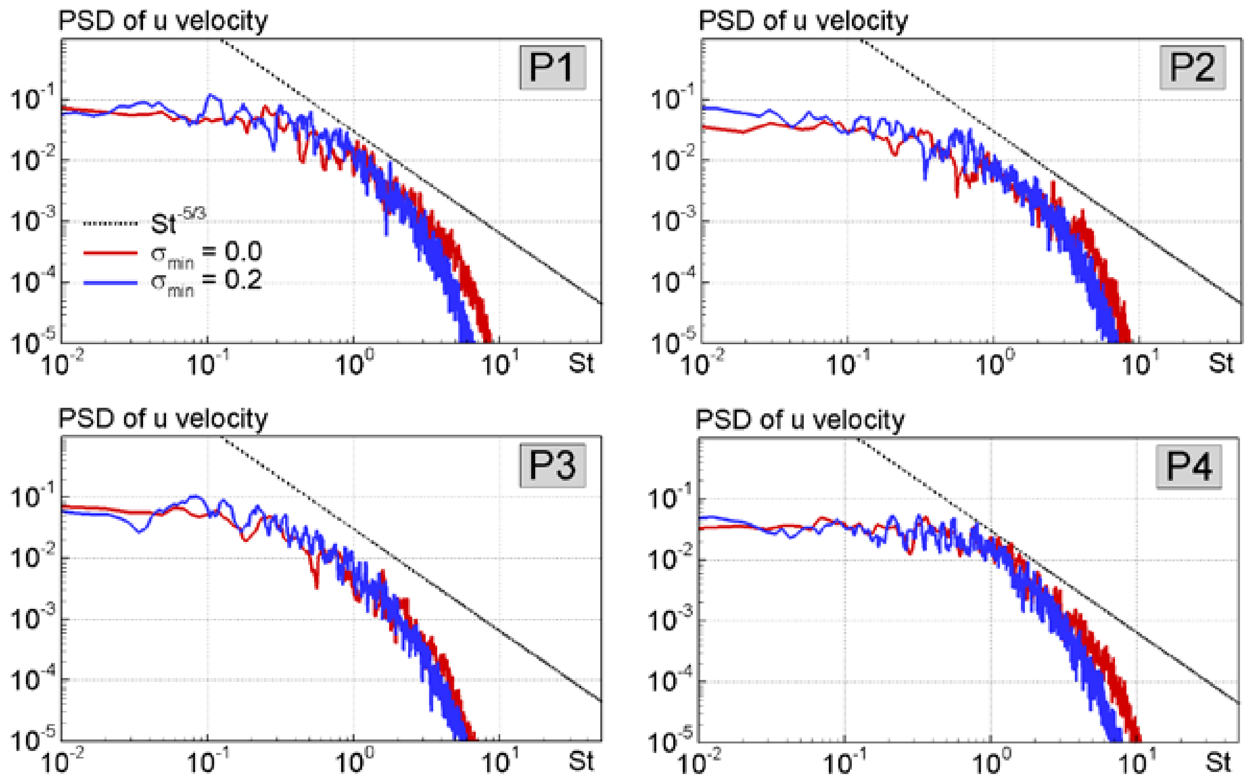
$s_{min} = 0.2$



- Similar observations as for SC and LLG
  - No visible flaws of resolved turbulence at $s_{min} = 0$ and quite visible damping of fine-grained turbulence $s_{min} = 0.2$
- This trend is the natural reaction of an LES to increase of numerical dissipation

Quantitative Effect of s_{min} on Resolved Turbulence: RLG Flow





- Just as for the SC and LLG configurations, increase of s_{min} up to 0.2 results only in somewhat earlier spectra cut off

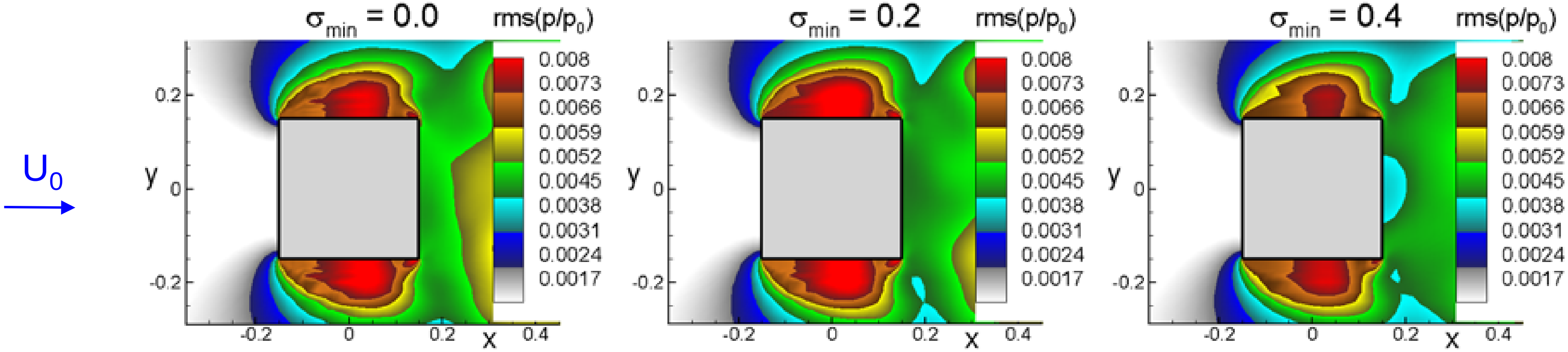
Summary of Findings on Turbulence Representation

- Dependence of turbulent flow characteristics on grid and s_{min} is well in line with what should be expected in LES
  - Grid-refinement at constant s_{min} results in a visible enhancement of turbulence resolution with corresponding widening of the inertial range in the power spectra of velocity fluctuations
  - Increase of s_{min} on a fixed grid leads to damping of fine-grained turbulence
  - No numerical “wiggles” in the flow visualizations are detected either on the coarse or on the four times refined grid

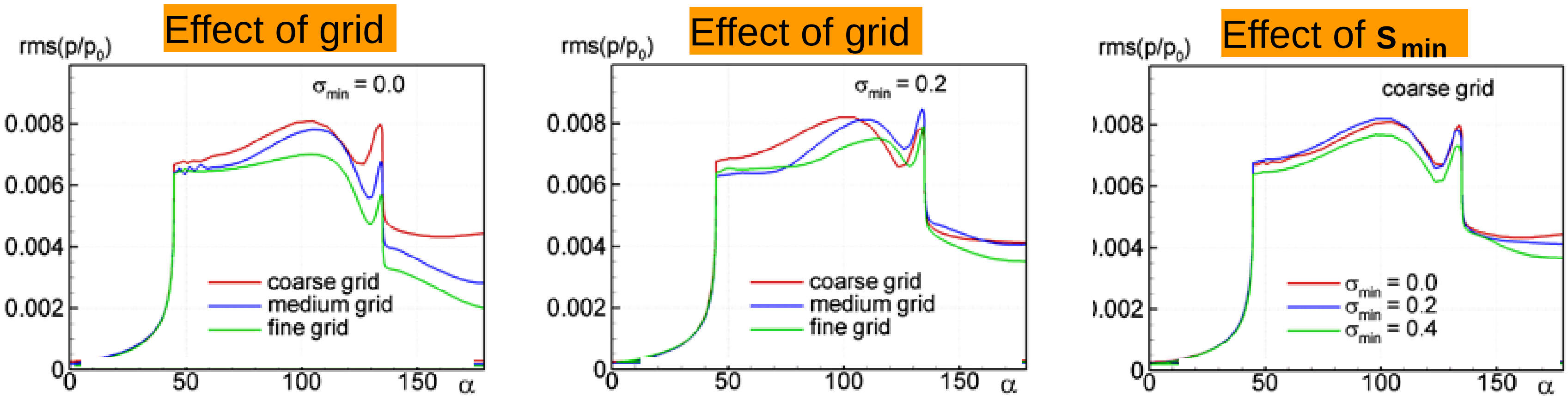
- Independently of the grid used, simulations at $s_{min}=0$ can be qualified as more accurate than those performed with more dissipative schemes ($s_{min}>0$)
  - All the spectra smoothly fall below a -5/3 trend well before the cut-off, which appears conservative. There is no “pile-up”

Unsteady Wall Pressure
and
Near Field Noise

Effect of Grid and s_{min} on Unsteady Wall Pressure: SC Flow



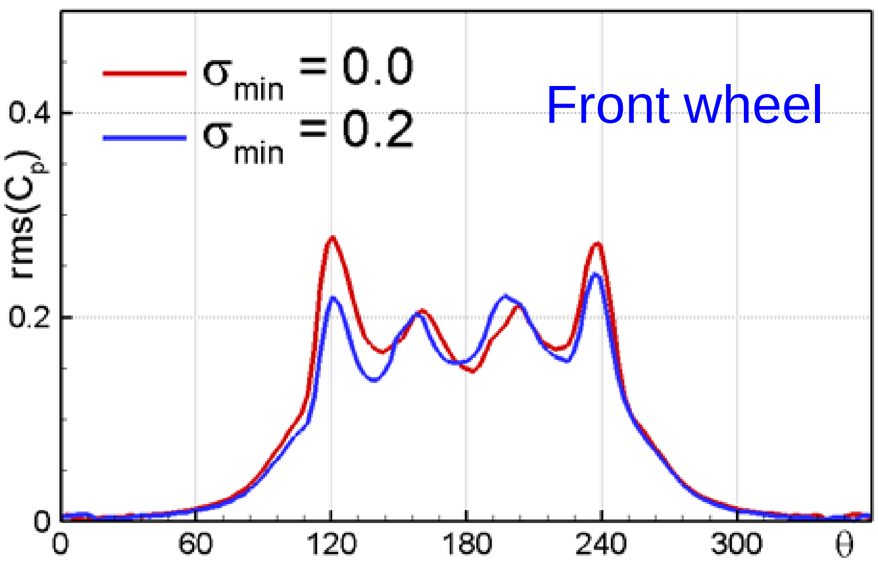
Contours of RMS Cp (coarse grid)

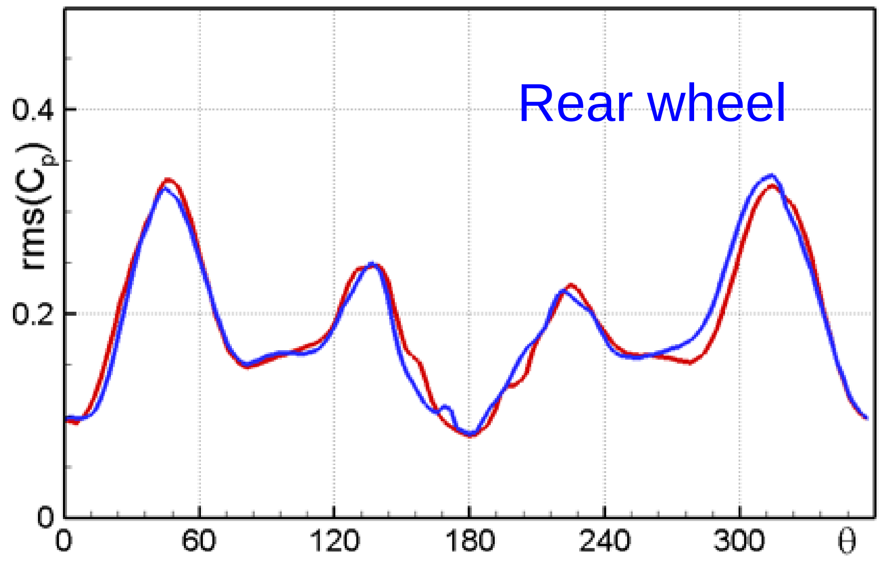


Distribution RMS Cp over SC surface

- Effect of grid is rather strong
  - Is somewhat stronger at s_{min} =0.0, but with a hint to grid convergence
- Effect of s_{min} is marginal

Effect of s_{min} on Unsteady Wall Pressure: LLG Flow

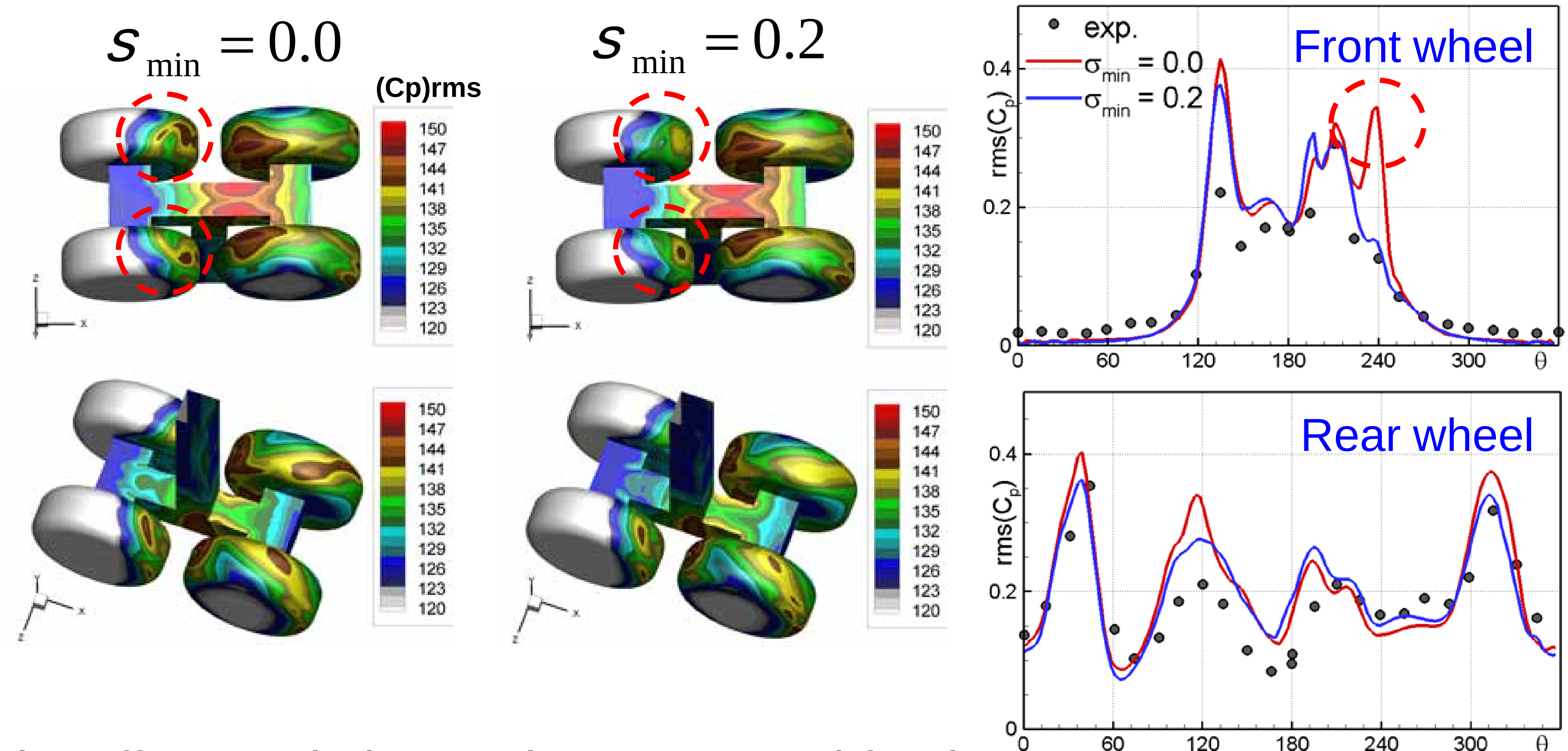




Distributions of RMS Cp along central circumferential wheels' line

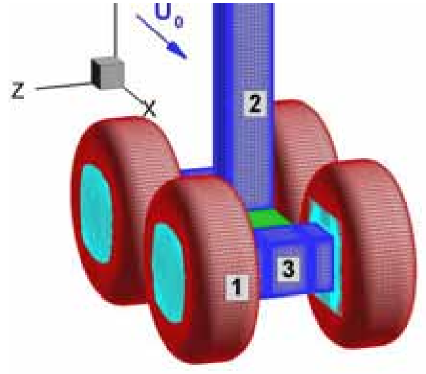
- For the front wheel the effect of s_{min} is mostly pronounced in the vicinity of the peaks at separation points (q=120º and 240º)
  - Increase of s_{min} leads to somewhat smoother distributions
- For the rear wheel the effect is weak

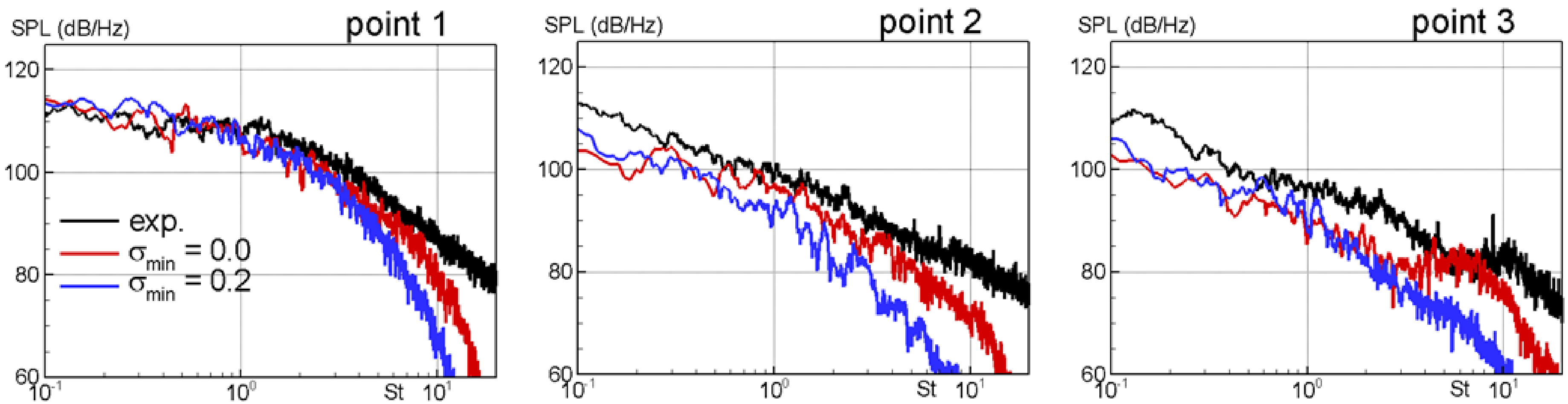
Effect of s_{min} on Unsteady Wall Pressure: RLG Flow



- The effect again is mostly pronounced for the front wheel but is very local (similar to the LLG)
  - For the RLG, it is observed in the small vicinity of the "lower" separation point (q =240º)
- Agreement with experiment is better at s_{min}=0.2

Effect of s_{min} on Unsteady Wall Pressure Spectra for RLG Flow and Comparison with NAL Experiment





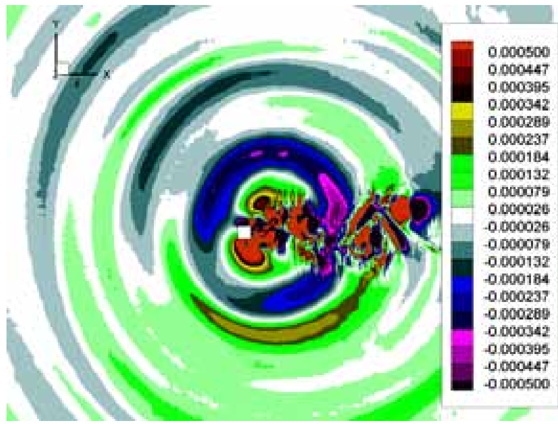
- Increase of s_{min} leads to an earlier fall off of the spectra and to worse agreement with experiment

Effect of s_{min} on Resolved Pressure Waves: SC (Coarse Grid)

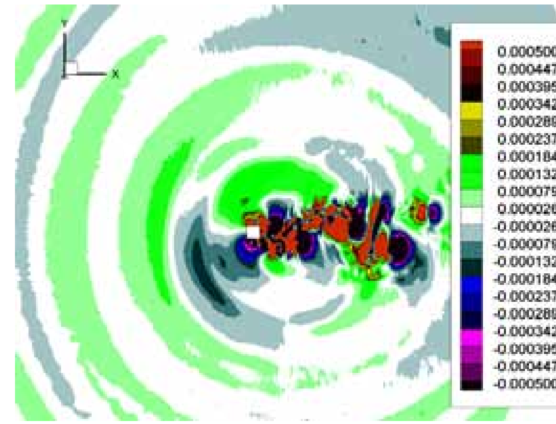
Contours of

$\P p / \P t$

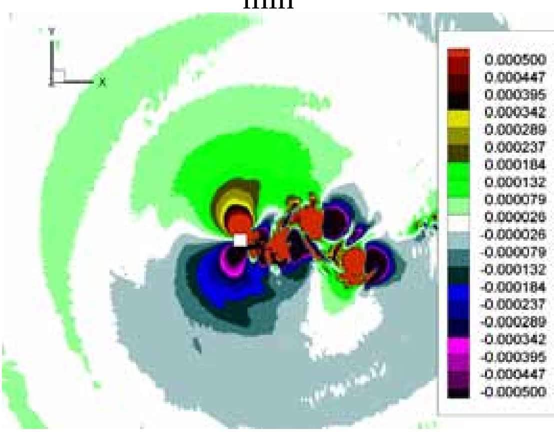
$s_{\min} = 0.0$



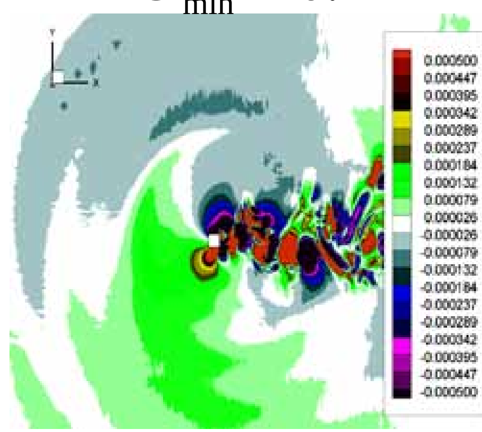
$s_{\min} = 0.05$



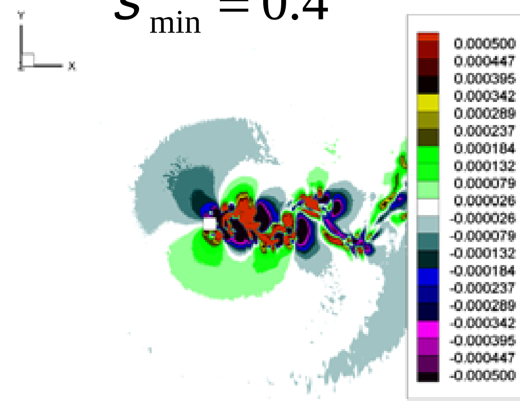
$s_{\min} = 0.1$



$s_{\min} = 0.2$

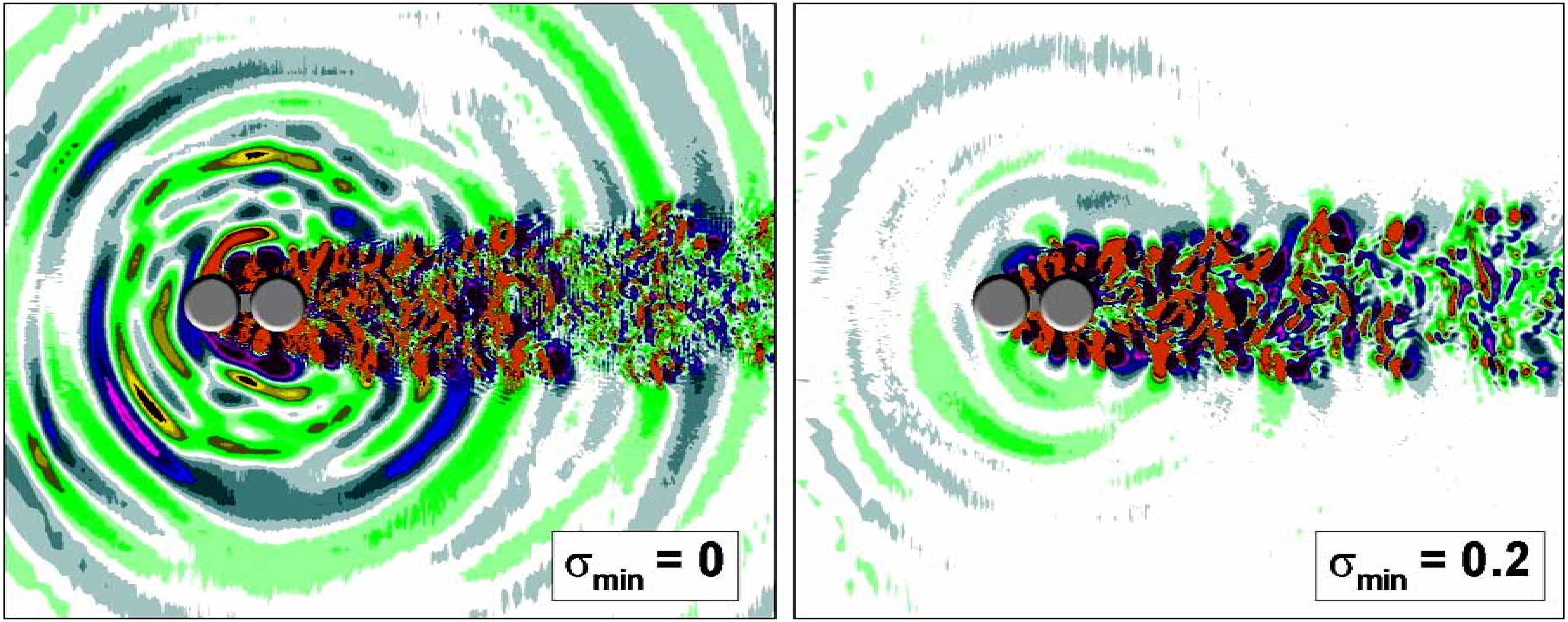


$s_{\min} = 0.4$



- Effect is independent of FWH processing and very strong
  - Even at s_{min}=0.05, short waves which look quite “realistic” are noticeably damped and at s_{min}=0.4 they are *completely filtered out*

Effect of s_{min} on Pressure Waves in Near-Field: LLG Flow

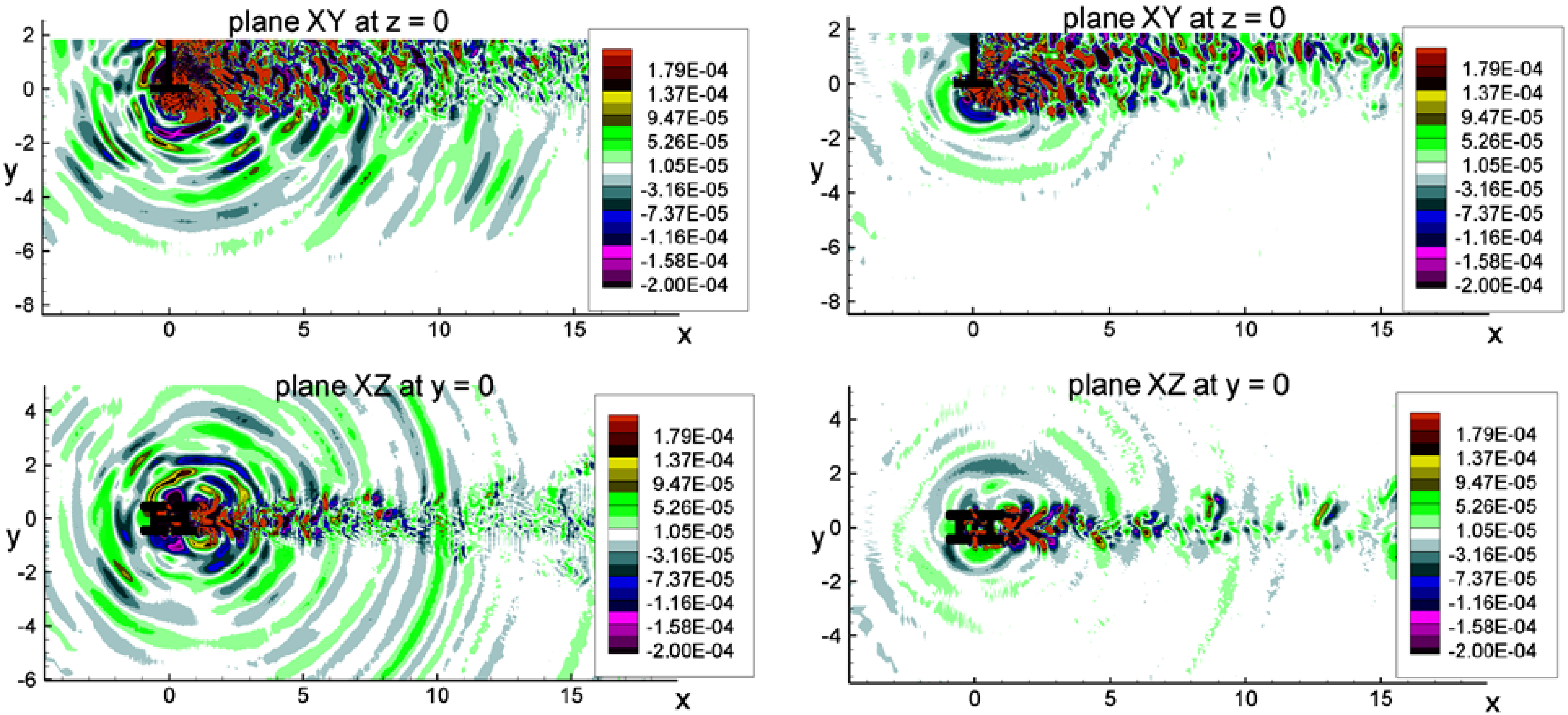


Contours of ¶p / ¶t

- Just as for SC, short waves are much weaker at $s_{min} = 0.2$

Effect of s_{min} on Pressure Waves in Near-Field: RLG Flow

$s_{\min} = 0.0$ $\qquad\qquad$ $s_{\min} = 0.2$

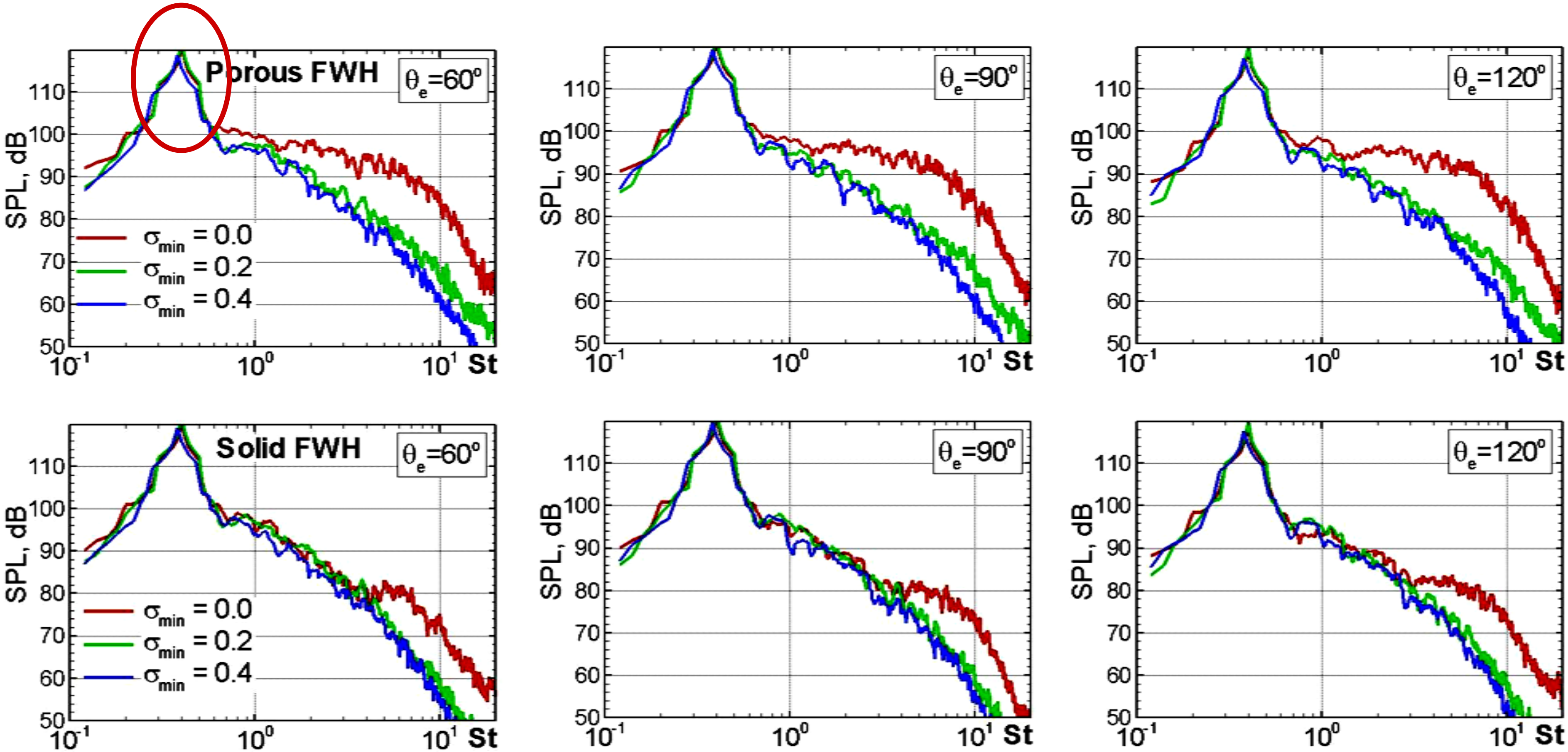


- Again, increase of s_{min} leads to strong damping of short waves

Summary of Findings on Unsteady Wall Pressure and Near-Field Noise

- In contrast to the mean flow, the effect of increase of numerical dissipation on unsteady pressure and, especially, on near-field sound waves is strong
  – Increase of s_{min} leads to damping of the medium and high frequency sound

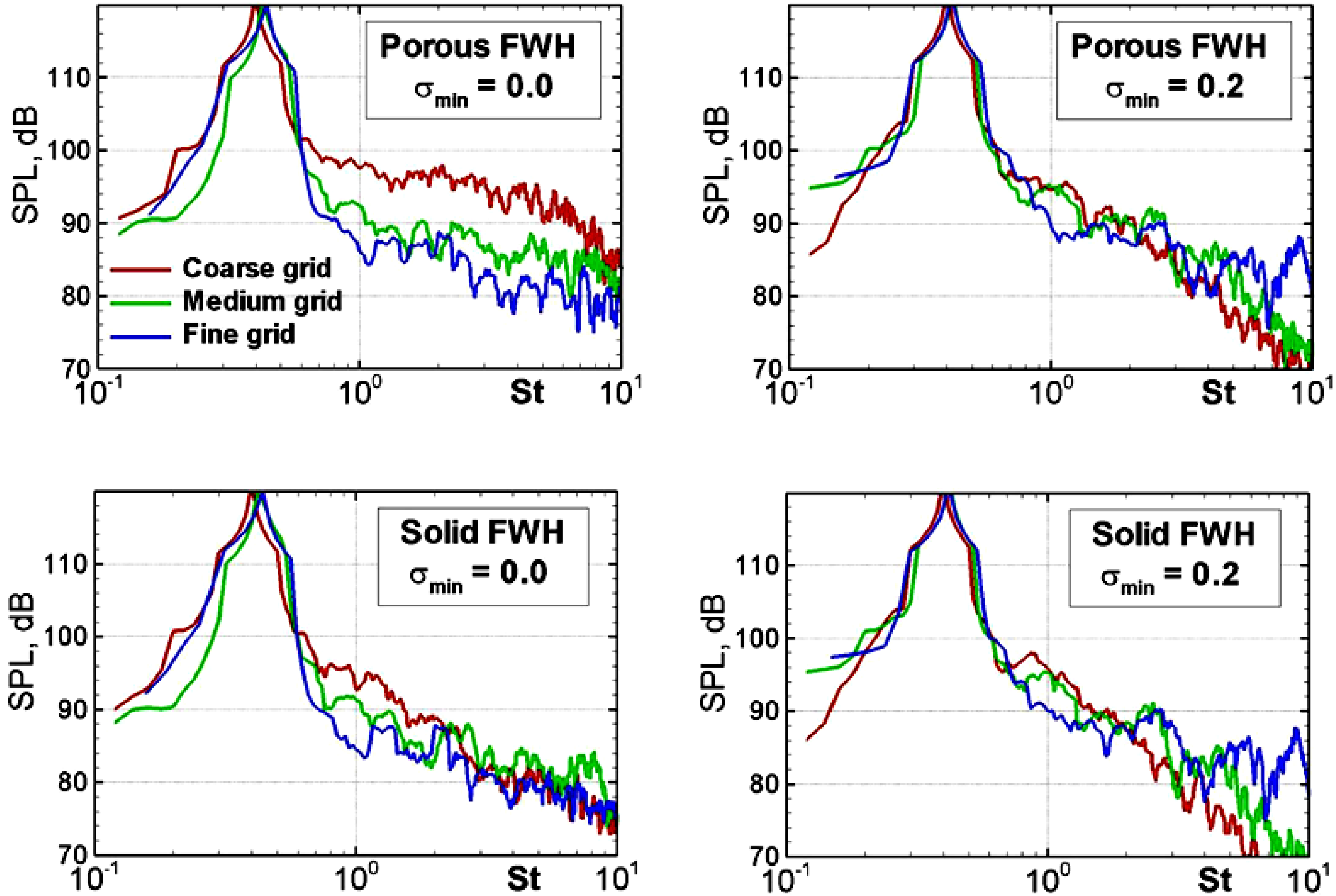
Effect of s_{min} on Far-Field Noise: SC Flow (Coarse Grid)



- The effect of s_{min} is strong, going from 0 to 0.2, then weak from 0.2 to 0.4, and is more pronounced for the porous FWH surfaces (ignore strong noise from vortex shedding)

Effect of s_{min} and Grid on Far-Field Noise: SC Flow

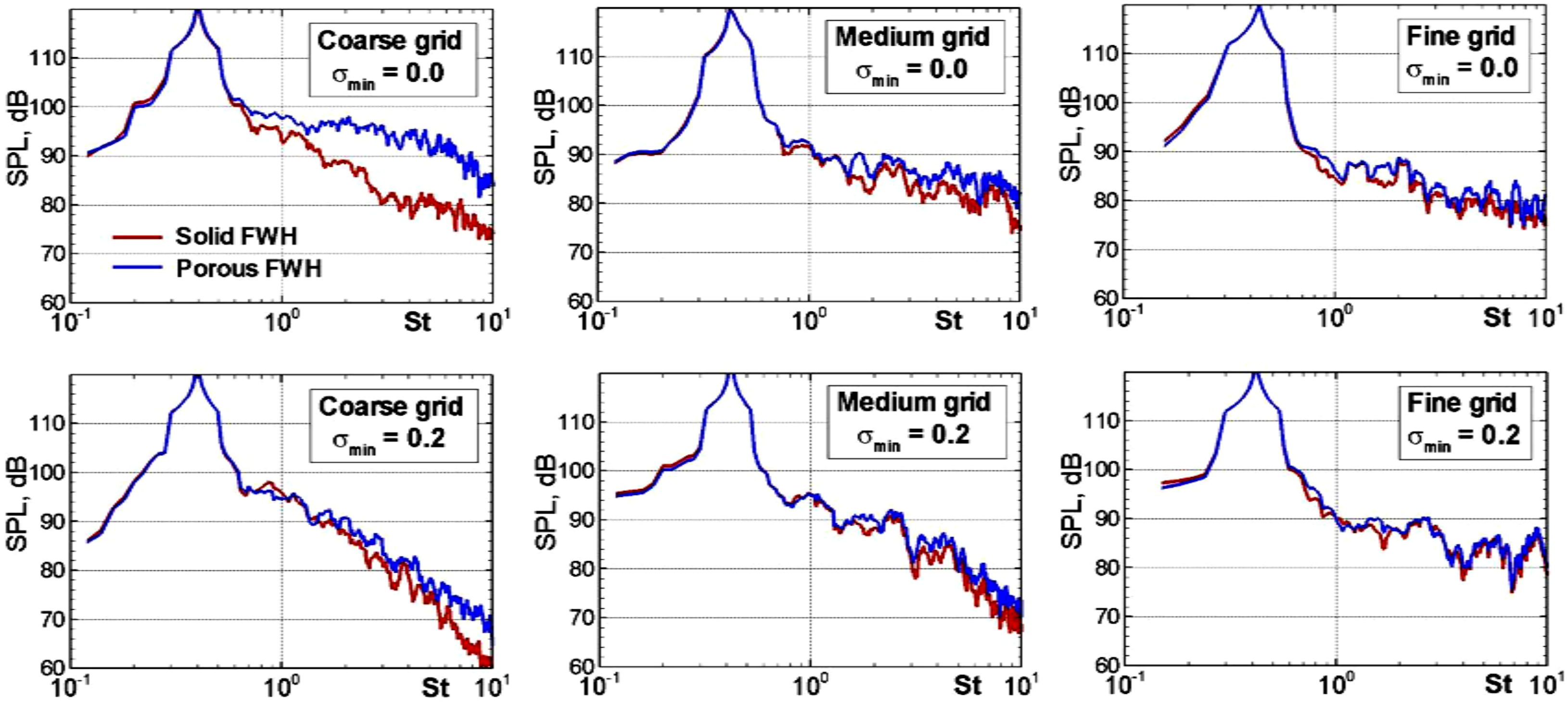
$q=90^o$



Signs of grid-convergence are seen for s_{min}=0, but not for s_{min}=0.2

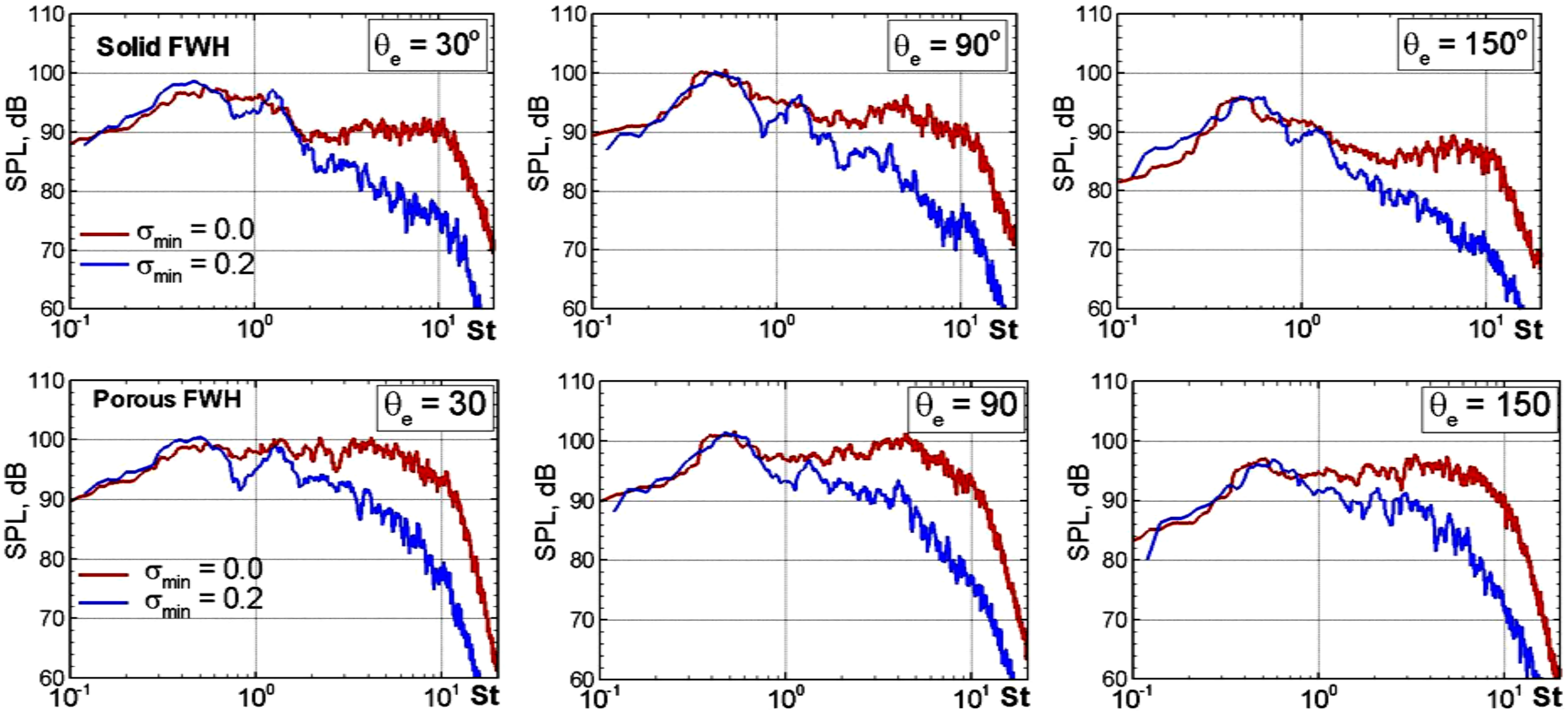
Effect of s_{min} and Grid on Quadrupole Input: SC Flow

q=90o



- “Quadupole input” (difference between SPL computed with P and S control surfaces) is strongest on the coarse grid with the low dissipation (s_{min}=0)
  - It decreases with grid-refinement (better resolution of small scales) and with increase of numerical dissipation (damping of small scales)

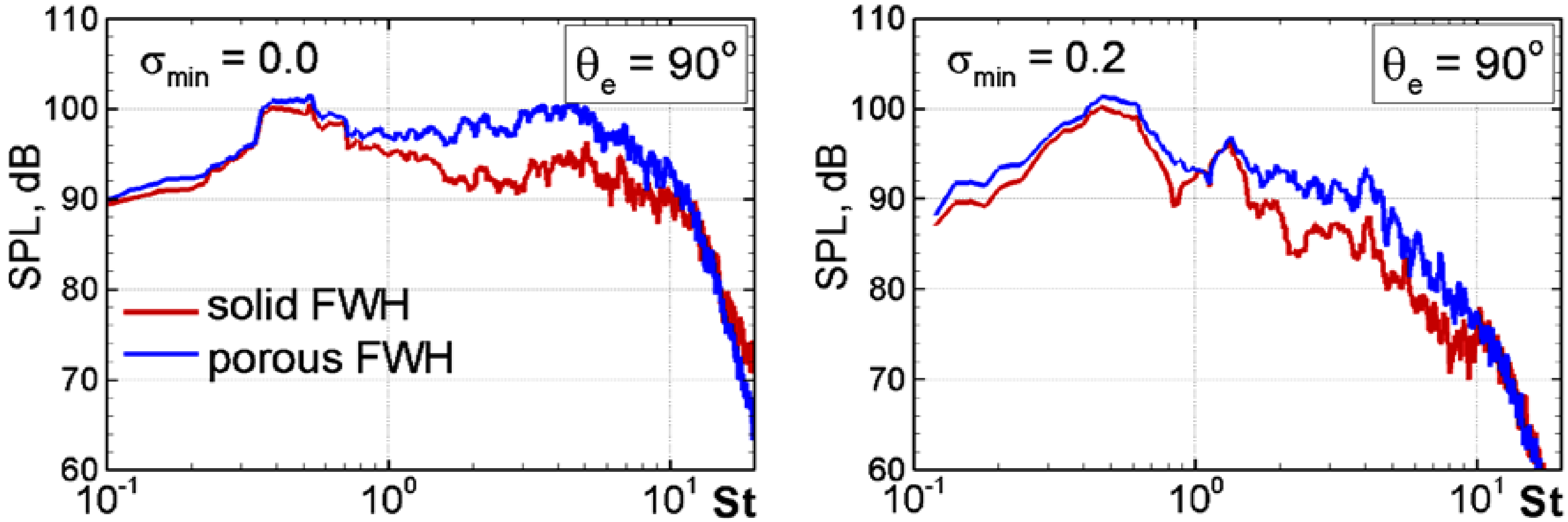
Effect of s_{min} on Far-Field Sound Spectra: LLG Flow



- Similar to SC on the coarse grid, large difference between noise computed with P and S surfaces and between s_{min} = 0 and 0.2, even over intermediate frequency range
  - P noise is stronger than S noise
  - s_{min} = 0 noise is stronger than s_{min} = 0.2 noise

Effect of grid and s_{min} on Quadrupole Input: LLG Flow

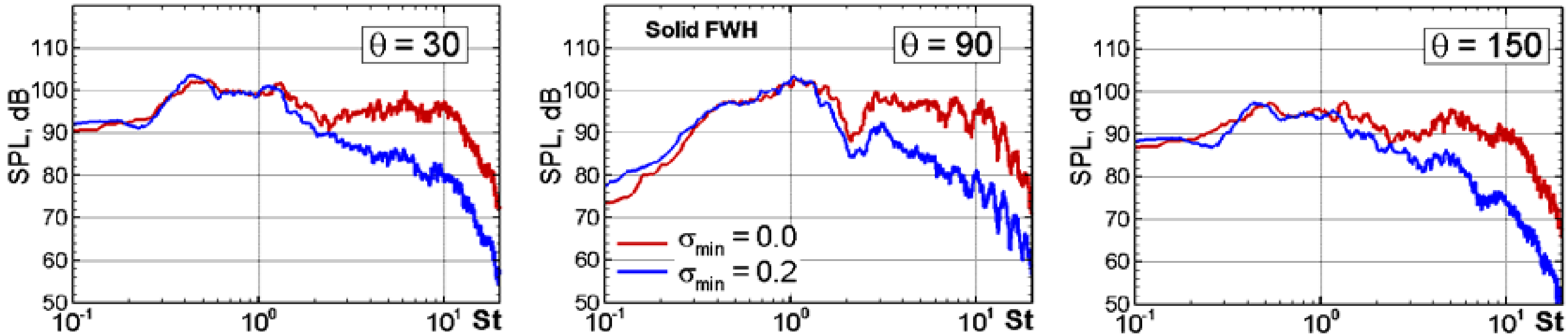
$q=90^{o}$



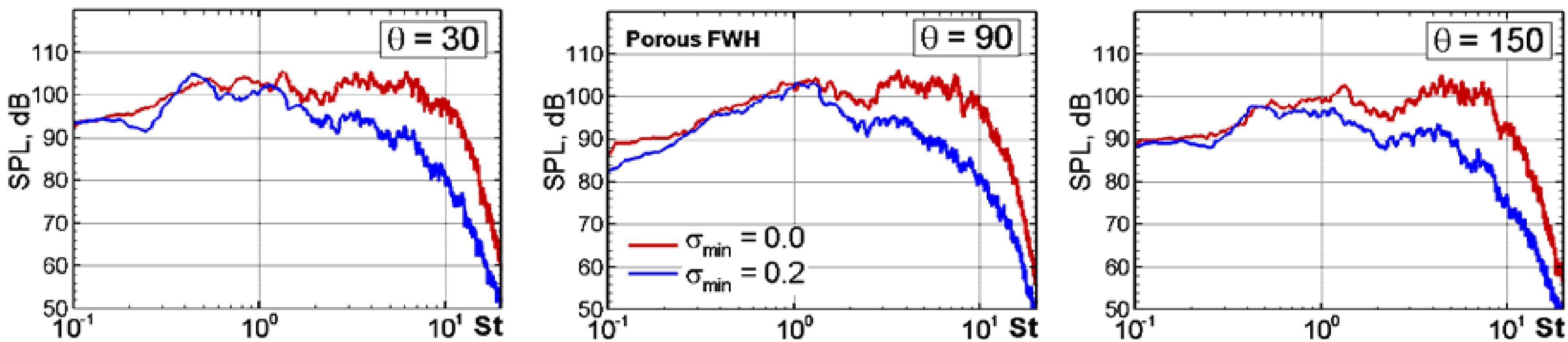
- The trend observed for SC holds valid for LLG:
  - The apparent quadrupole input is strong and decreases (but does not vanish) with increase of numerical dissipation
  - The quadrupole input is weak at low frequencies, as predicted by Curle (M = 0.115)

Effect of s_{min} on Far-field Noise Spectra: RLG Flow

Solid FWH

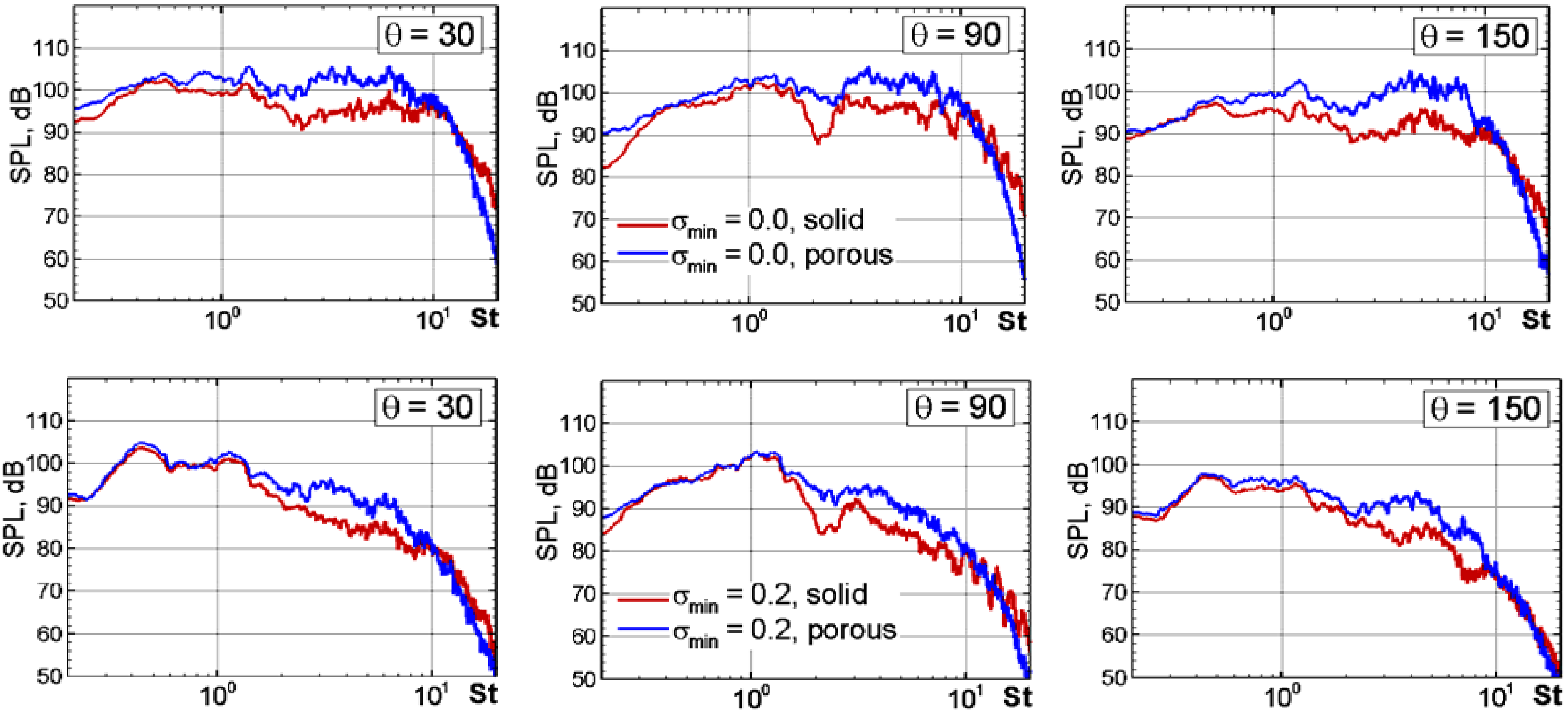


Porous FWH



- In line with the SC and LLG findings, increase of s_{min} results in a significant decrease of the high frequency noise predicted with both solid and porous FWH surfaces…

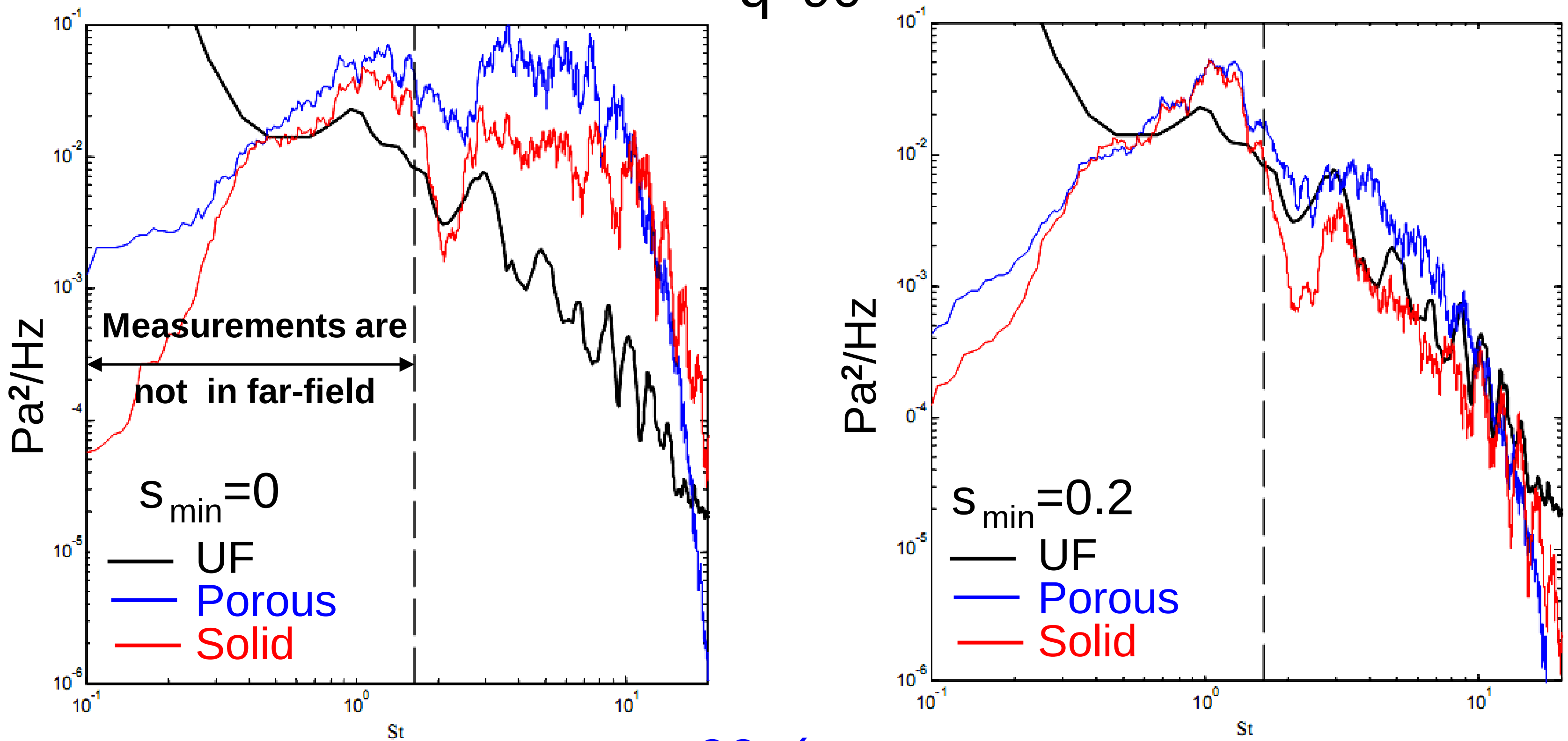
Effect of s_{min} on Quadrupole Input: RLG Flow



- … and decrease (*but not vanishing*) of the quadrupole input

Comparison of Far-Field Noise and with Experiment of University of Florida ("Blind Test")

$q=90^o$

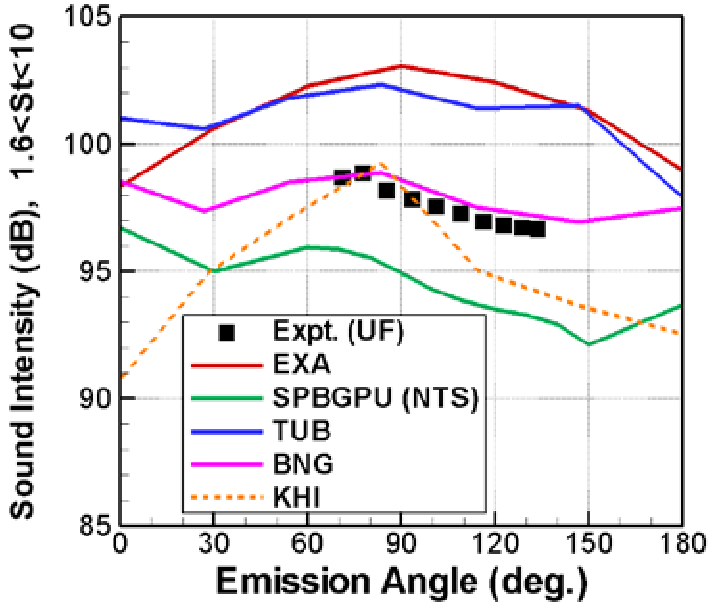


Sound spectra at $q=90^o$ (courtesy of D. Wetzel)

- Increase of $\mathbf{s_{min}}$ up to 0.2 results in much better agreement with the data and in a decrease of the quadrupole input in the far-field noise
  - These "good" trends come from less-accurate (more dissipative) numerics

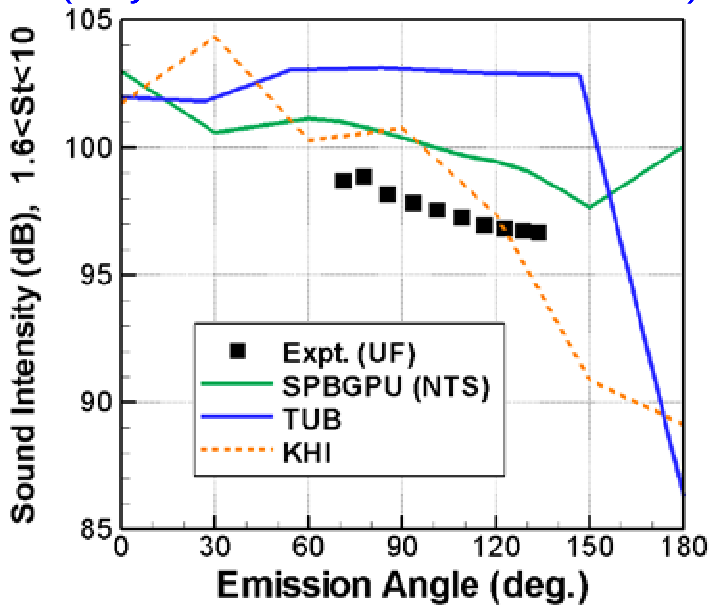
Some Results of X-Plotting at BANC-II Workshop (2012)

Solid FWH Surface



Porous FWH Surfaces

(only three datasets are available)

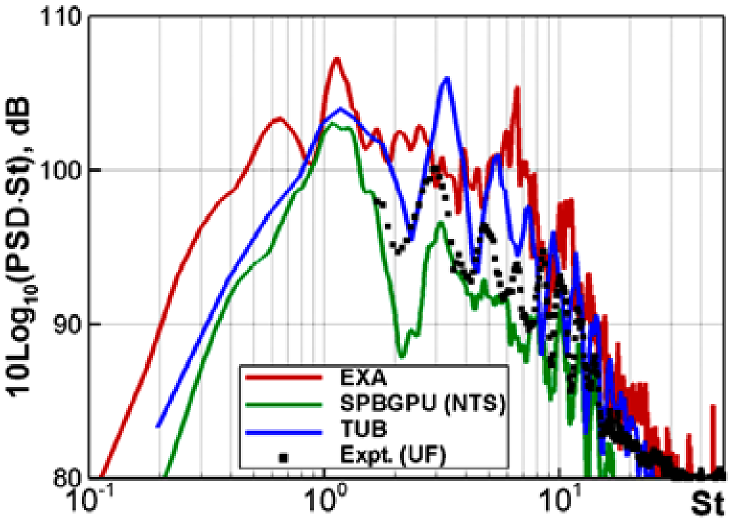


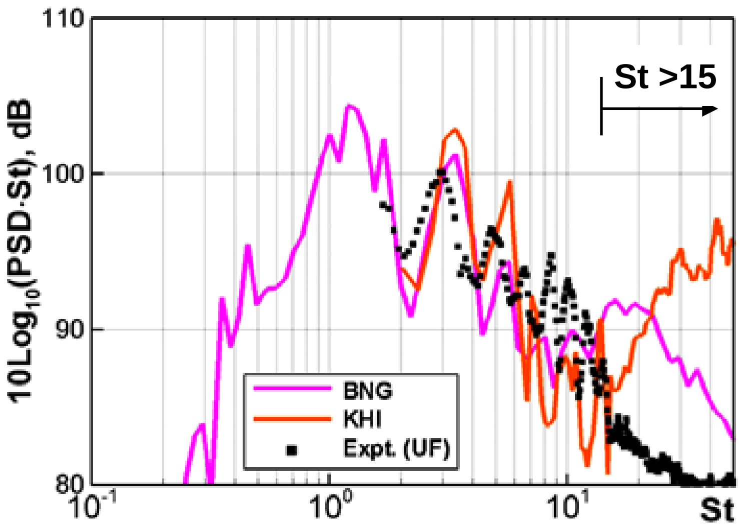
Sound intensity over $1.6 < St < 10$ (courtesy of D. Wetzel)

- Total scatter about 7dB, except near ends of the range
- CFD surrounds experiment with solid and exceeds it with porous FWH surfaces
  - Best agreement is reached by Boeing (BNG) with solid FWH surfaces; hybrid (centered – upwind biased) numerics with grid about 58 M cells

Some Results of X-Plotting at BANC-II Workshop (2012)

Spectra at 90^0 from Solid FWH Surface
(power spectral density pre-multiplied by frequency)



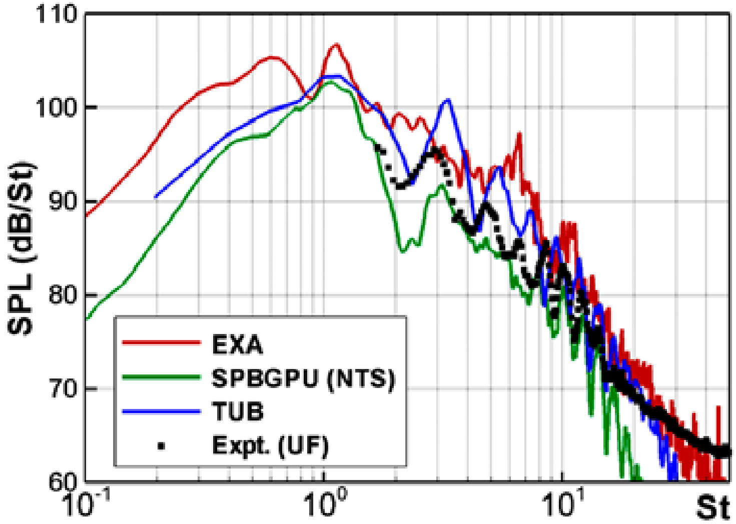


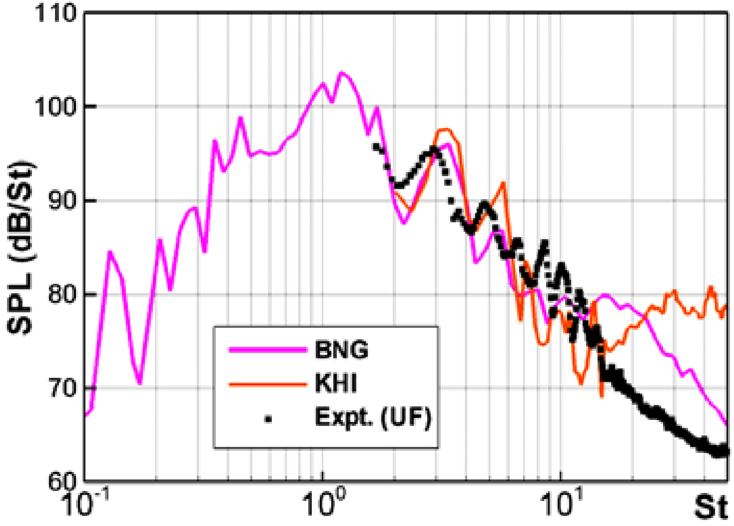
Courtesy of D. Wetzel

- Total scatter is:
  - About 10 dB over middle range (2 < St <10), including experiment
  - Much larger over upper range (St >15)
- Interference patterns ("hills and valleys") are in a pretty good agreement
- BANC-II results are generally in line with present study

Some Results of X-Plotting at BANC-II Workshop (2012)

Spectra at 90^0 from Solid FWH Surface





Courtesy of D. Wetzel

- Total scatter is:
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Summary of Findings on Far-Field Noise Prediction

- The findings are consistent with the near-field sound observations
  - In contrast to aerodynamics and turbulence, far-field noise predictions on coarse grids with moderate dissipation (s_{min}=0.2) seem to be "more accurate" than those with minimal dissipation (s_{min}=0)
  - The use of numerics with minimal dissipation (s_{min}=0) on "coarse" grids:
    - Results in drastic overestimation of the noise computed with the use of both solid and porous FWH surfaces
    - Leads to an unexpectedly large (considering the low Mach number) input of quadrupole noise at high frequencies (violation of Curle Approximation)
  - Both effects tangibly weaken with grid-refinement and increase of s_{min}

General Concluding Remarks

- The study reveals a strong and troublesome effect of numerical dissipation on Landing-Gear noise predictions
- Previously, the effect has not been studied any systematically, and as of today the control of the level of dissipation (upwinding) in codes with “automatic” blending of centered and upwind schemes does not rely on any rigorous criteria of “quality” of resolved turbulence
- This situation, which we believe is typical for most (if not all) LES-based airframe noise studies, cannot of course be considered as satisfactory
- Unless this issue is resolved, a convincing and reliable LES-based prediction of airframe noise is hardly possible
- Accumulated experience suggests that, with limited computer power ruling out fine grids and thus sufficient resolution of complex industrial flows, the addition of “moderate” upwinding may be recommended as a pragmatic way to reach acceptable accuracy for noise prediction
- The use of Solid FWH surfaces also gives “better” answers, although it is questionable based on theory