Jet Noise Computation Based on Enhanced DES Formulation Accelerating RANS-to-LES Transition in Free Shear Layers

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Outline

- Motivation and objective
- Brief presentation of new subgrid length-scale
- Example of its performance for DES-based noise prediction of subsonic round jet
  - Test-case details and numerics
  - Results and discussion
- Conclusions

Motivation and Objective

- It is well known that DES and similar RANS-LES approaches suffer from a significant delay of transition to turbulence in free and separated shear layers
  - ➢ This is a result of too high eddy viscosity convected from attached flow region treated in DES by RANS into its LES region and, also, by excessive production of subgrid viscosity on typical (relatively coarse) grids which have loose spacing in the lateral direction compared with the shear layer thickness
    - The effect is very strong and makes DES and other non-zonal RANS-LES hybrids non-applicable to jet-noise prediction
  - ➢ The issue has been resolved by exploring RANS-ILES (Implicit LES) approach, but:
    - It is zonal
    - Is non-applicable to flows, in which the “free” turbulence of shear layer interacts with bodies (e.g., as in the case of interaction of exhaust engine jet with a pylon or wing)
- These motivate a search for modifications to DES, which would allow resolving this issue in shear layers without deterioration of its performance in other flows or flow regopns

Background: New SGS Length-Scale

- The modifications should
  - ➢ Ensure a significant drop of SGS viscosity exactly in the early shear layers
  - ➢ Be “passive” in other flow regions
    - - This would result in unlocking natural Kelvin-Helmholtz (KH) instability of the shear layer and accelerating development of realistic 3D turbulence thus resulting in an enhanced accuracy of simulations
- Two such modifications are proposed accounting for important peculiar feature of *initial region* of high Reynolds number free shear layers, namely, *their nearly 2D character*
  - ➢ Both modifications concern a definition of subgrid length-scale entering SGS model

Modification 1

- For identification of quasi-2D flow regions, *the first modification* employs purely kinematic (i.e., not involving grid step) quaintly we have called “Vortex Tilting Measure” (VTM):

$$\mathrm{VTM} \equiv \frac{\sqrt{6}\,|(\hat{\mathbf{S}}\cdot\boldsymbol{\omega})\times\boldsymbol{\omega}|}{|\boldsymbol{\omega}|^2\sqrt{3\,\mathrm{trace}(\hat{\mathbf{S}}^2)-[\mathrm{trace}(\hat{\mathbf{S}})]^2}}$$

where $\hat{\mathbf{S}}$ is the strain tensor and $\boldsymbol{\omega}$ is the vorticity vector.

- It is designed so that:
  - ➢ In quasi-2D flow regions it is close to zero
  - ➢ In regions of developed 3D turbulence, it is close to 1.0, although with sharp excursions to small values
    - – Replacing a local VTM by its average over a current and closest neighbouring grid cells, <VTM>, excludes these excursions

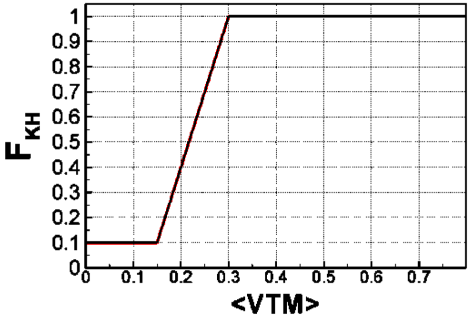
Modification 1

- Based on this behaviour of the <VTM>, empirical function F(<VTM>) is built, which varies from a small value in the initial quasi-2D part of mixing layer up to 1.0 in developed 3D turbulence:

$$F_{KH}(<\mathrm{VTM}>) = \max\{F_{KH}^{\min}, \min\{F_{KH}^{\max}, F_{KH}^{\min} + \frac{F_{KH}^{\max} - F_{KH}^{\min}}{a_2 - a_1}(<\mathrm{VTM}> - a_1)\}\}$$

Adjustable parameters of this function are set as follows:

$$F_{KH}^{\min} = 0.1, F_{KH}^{\max} = 1.0, \ a_1 = 0.15, a_2 = 0.3$$

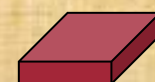
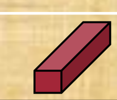


- Then, subgrid length-scale, Δ, entering LES mode of DES is multiplied by F_{KH} , thus reducing Δ and, therefore, the SGS viscosity in the early shear layer, where F is small, but not changing it in regions of developed turbulence

  - This is exactly the behavior of SGS viscosity in the LES mode of DES we would like to have

Modification 2

- *The second proposed modification* to the subgrid length-scale of DES is grid-dependent and takes into account peculiarities of typical grids used in early shear layers
  - ➢ These grids are strongly anisotropic and have “book”, “ribbon” or “pencil” cells

Type	Description	Sketch
Book	$\Delta y << \Delta x \sim \Delta z$	
Ribbon	$\Delta y << \Delta x << \Delta z$	
Pencil	$\Delta y \sim \Delta x << \Delta z$	

  - ➢ “Book” and “Ribbon” cells are inherited from upstream BL grids
  - ➢ “Pencil” cells are typical of high-aspect-ratio situations with $\delta_{shear\text{-}layer} << L_z$

Modification 2

- For such grids, none of existing definitions of subgrid length-scale in either DES or LES is optimal
  - The standard DES definition $\Delta = \Delta_{\max} \equiv \max(\Delta x, \Delta y, \Delta z)$

    is generally plausible, but in this situation it returns $\Delta = \Delta z$ which is *irrelevant in nearly 2D flow*

    - SGS model becomes too "dissipative", and DES effectively performs as URANS and defeats Kelvin-Helmholtz instability and transition to turbulence

  - The classical LES definition $\Delta = \Delta_{\mathrm{vol}} \equiv \sqrt[3]{\Delta x \, \Delta y \, \Delta z}$

    involves minimum cell sizes Δy or Δx, which do not affect real grid resolution on the book-, ribbon- and pencil grid types and, therefore, should not enter a subgrid length-scale

- The objective is to exclude control of both maximum (spanwise) and minimum grid-spacings in "2D" regions, i.e., to extract $\max\{\Delta x, \Delta y\}$

Modification 2

- This is achieved by making cross product of the unit vector of the direction of voritcity $\mathbf{n}_\omega$ with all the cell vertexes $\mathbf{r_n}$: $\mathbf{l}_n = \mathbf{n}_\omega \times \mathbf{r}_n$ and calculating the diameter of this set of points

$$\tilde{\Delta}_\omega = \frac{1}{\sqrt{3}} \max_{n,m=1,8} \left| \mathbf{l}_n - \mathbf{l}_m \right|$$

Here the 1/√3 factor is introduced to recover $\Delta \approx \Delta_{\max}$ for developed turbulence on isotropic (cubical) grids

➢ This is like taking a photo of the cell from the vorticity direction, and applying the Δ_{max} definition on this photo

– In *the initial region of shear layer* the vorticity vector is nearly aligned with *z* and $\tilde{\Delta}_\omega \Rightarrow \frac{1}{\sqrt{3}}(\Delta x^2 + \Delta y^2)^{1/2} = O(\max\{\Delta x, \Delta y\})$, whereas in fully developed 3D turbulence the scale reduces to the original DES definition

$$\tilde{\Delta}_\omega \Rightarrow O(\max\{\Delta x, \Delta y, \Delta z\})$$

Resulting definition of subgrid length-scale

- Combination of two outlined modification results in the following final definition of the length scale

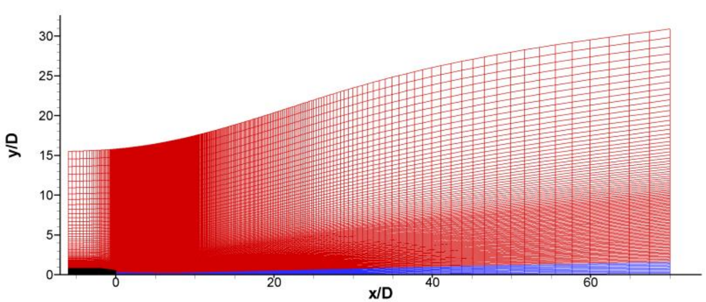
$$\Delta = \tilde{\Delta}_{\omega} F_{KH}(< \mathrm{VTM} >)$$

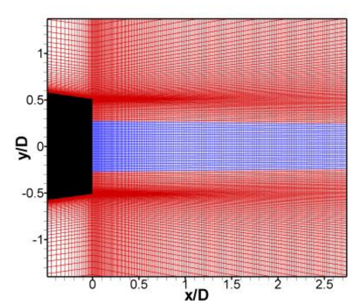
which satisfies the demands formulated above

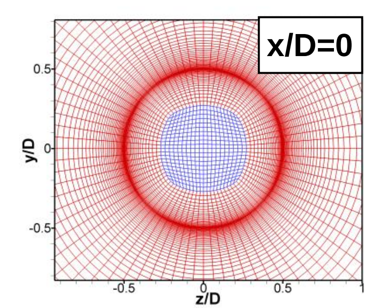
- Ensures a significant drop of SGS viscosity in the early shear layer
- Reduces to the standard Δ_{max} definition in the other flow regions
  - These properties of the new subgrid length-scale are demonstrated by simulations of turbulent jet discussed below

Test-case description and some details of numerics

- We consider M=0.9 round jet which was studied in numerous experimental and computational works and compare results of Delayed DES performed with the use of different subgrid length-scales with our previous ILES predictions
- All simulations are carried out with in-house NTS code
  - ➢ Finite-volume code; accepts multi-block overset grids of Chimera type
  - ➢ Inviscid fluxes are computed with high-order Roe-type schemes:
    - 3-rd order upwind-biased scheme in RANS region (nozzle)
    - Weighted 4^{th} -order centered / 5^{th} -order upwind-biased scheme in LES region
  - ➢ 2-nd order implicit time-integration (three-layer scheme)
- Baseline computational grid has 4.5 million cells
  - ➢ In the initial region of the shear layer the grid is strongly anisotropic (“ribbon” grid)
    - $r\Delta\phi / \Delta x = 5, \ \ \Delta x / \Delta r = 6$



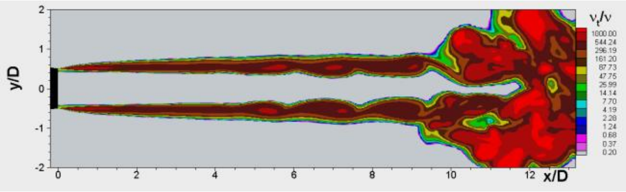




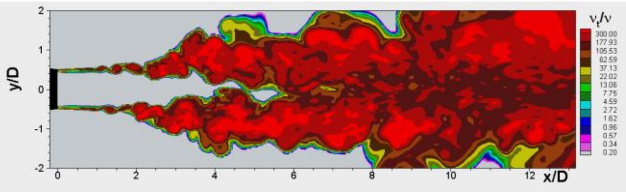
Effect of Proposed Length-Scale on Turbulence Representation

SGS Viscosity

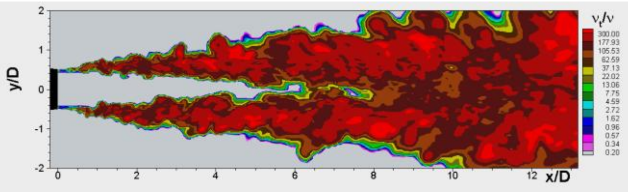
$\Delta = \Delta_{max}$



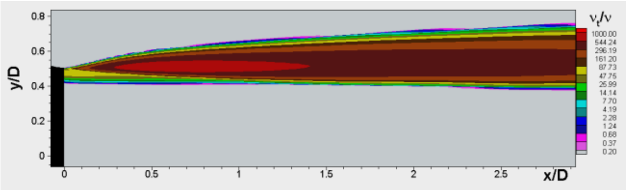
$\Delta = \tilde{\Delta}_{\omega}$

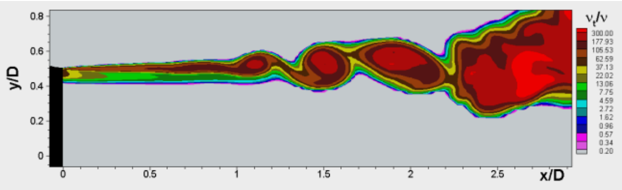


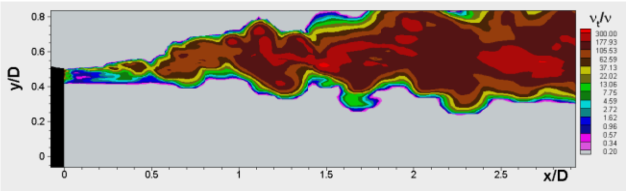
$\Delta = \tilde{\Delta}_{\omega} F_{KH}$



Close up views in the initial shear layer region







Drastic delay of transition

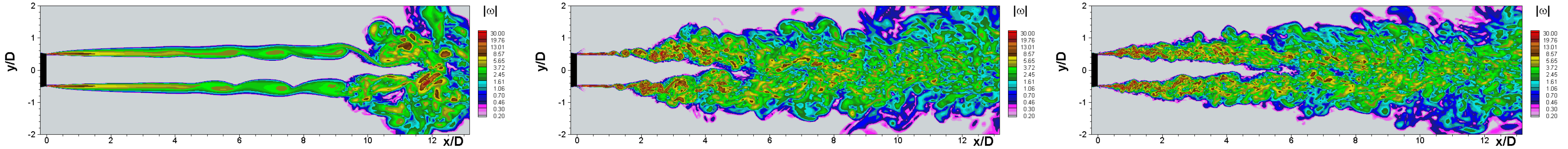
Faster but still not rapid enough transition

Rapid transition

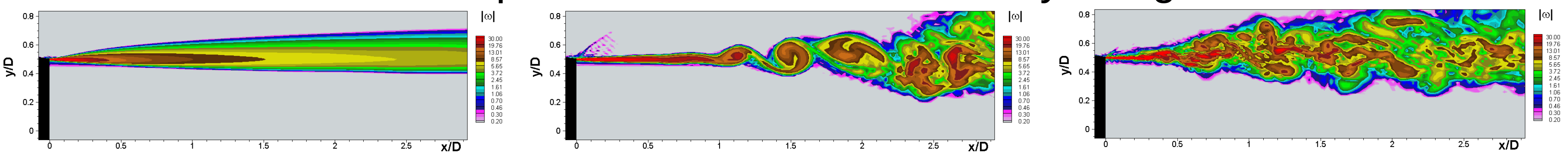
- Desirable significant drop of SGS viscosity in the initial part of the shear layer ensured by the use of $\Delta = \tilde{\Delta}_{\omega}$ and, especially by $\Delta = \tilde{\Delta}_{\omega} F_{KH}$ is clearly seen
- This, in turn, leads to unlocking KH instability and accelerating of transition to developed turbulence in the jet shear layer ("secondary transition" to turbulence in the shear layer)

Vorticity Magnitude

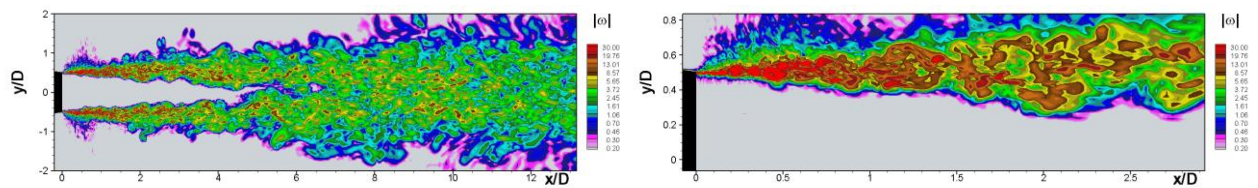
$\Delta = \Delta_{max}$ | $\Delta = \tilde{\Delta}_{\omega}$ | $\Delta = \tilde{\Delta}_{\omega} F_{KH}$



Close up views in the initial shear layer region



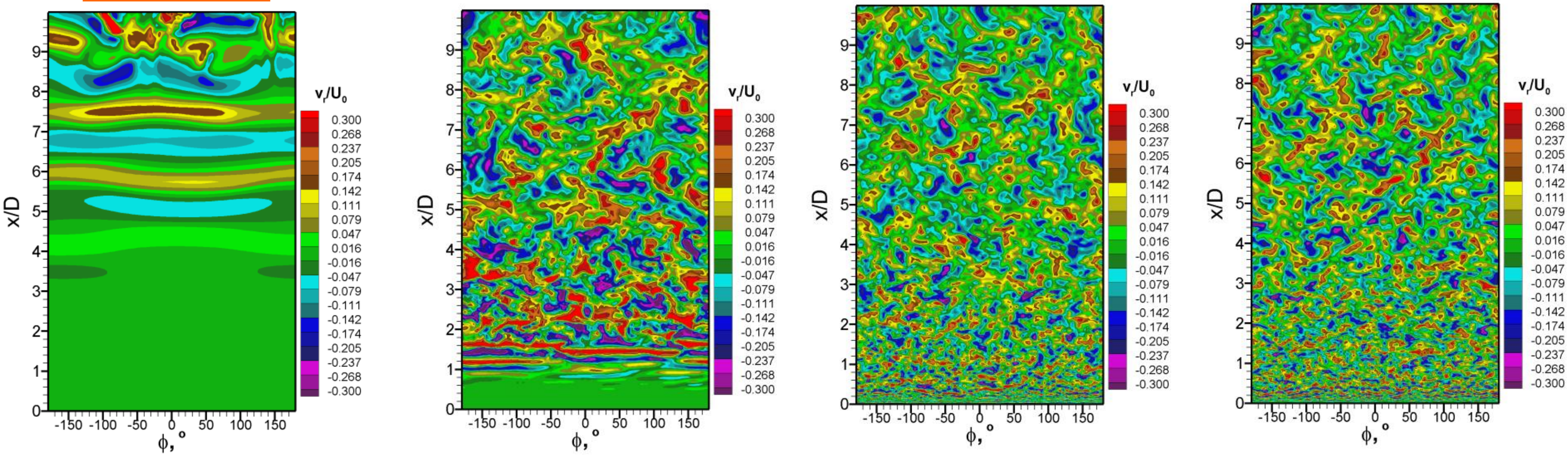
Implicit LES (zero SGS viscosity)



- These trends are more visible in the instantaneous vorticity fields from the simulations with different length-scales
  - The use of $\Delta = \tilde{\Delta}_{\omega} F_{KH}$ ensures virtually as rapid transition as ILES
  - With this length-scale transition looks more physical (does not have “explosive character”)

Radial Velocity

$\Delta = \Delta_{max}$ | $\Delta = \widetilde{\Delta}_{\omega}$ | $\Delta = \widetilde{\Delta}_{\omega} F_{KH}$ | ILES



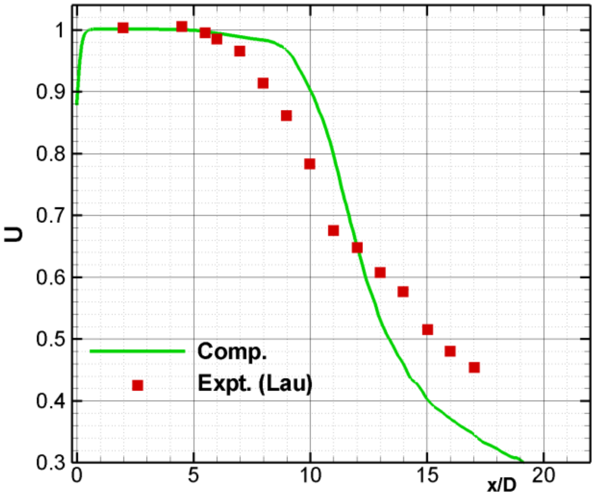
Contours of radial velocity on grid surface passing through nozzle edge

- Rapid but still smooth chaotization (development of natural 3D turbulent structures) ensured by $\Delta = \widetilde{\Delta}_{\omega} F_{KH}$ is seen also in the fields of radial velocity in the close vicinity of the nozzle exit

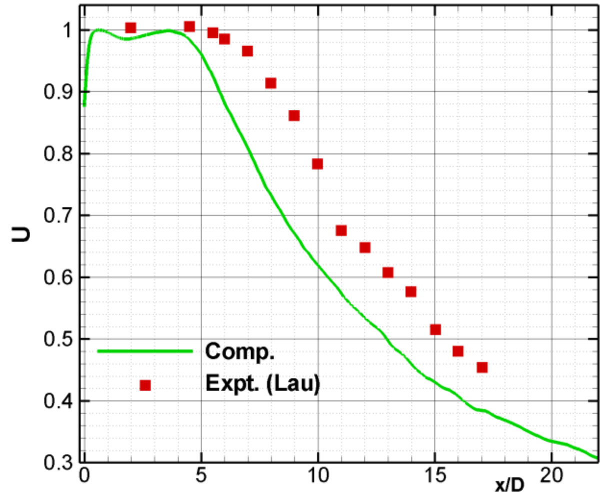
Effect of Proposed Length-Scale on Mean Flow Characteristics and Turbulence Statistics

Centerline Velocity

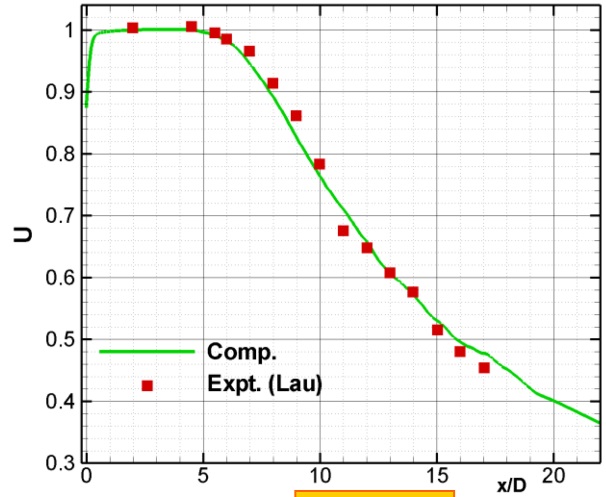
$\Delta = \Delta_{max}$



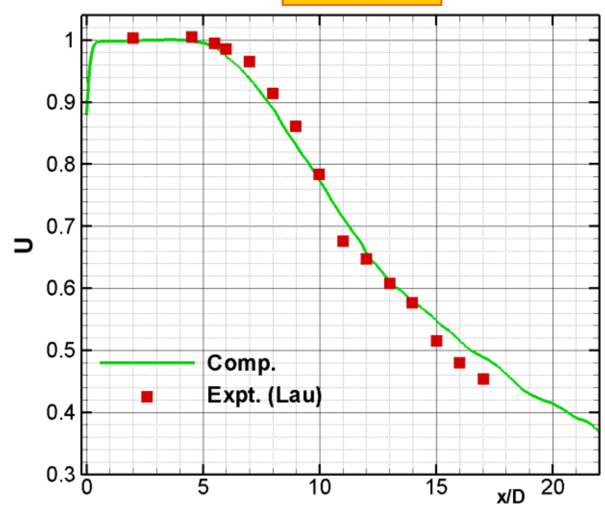
$\Delta = \widetilde{\Delta}_{\omega}$



$\Delta = \widetilde{\Delta}_{\omega} F_{KH}$



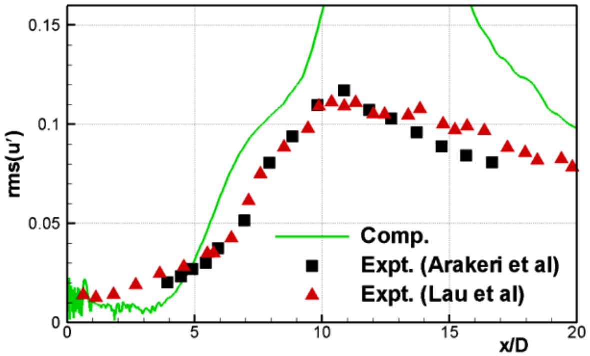
ILES



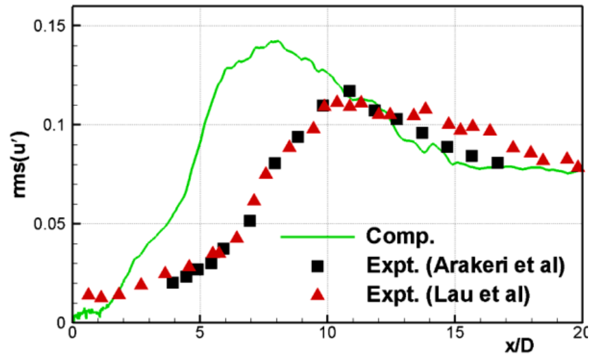
- Consistently with the flow visualizations, effect of proposed length-scale modifications on the mean centerline velocity turns out to be very positive
  - Simulation with $\Delta = \widetilde{\Delta}_{\omega} F_{KH}$ predicts it incomparably better than the standard DDES and even somewhat better than ILES

RMS of Centerline Velocity Fluctuations

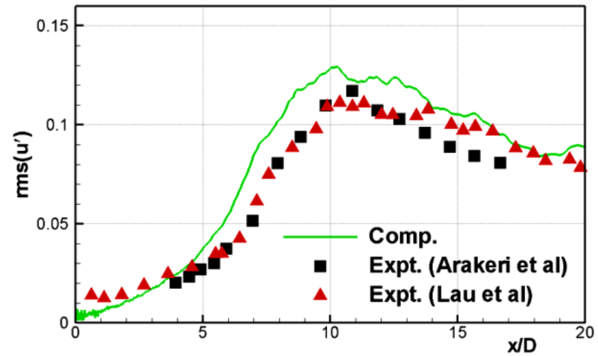
$\Delta = \Delta_{max}$



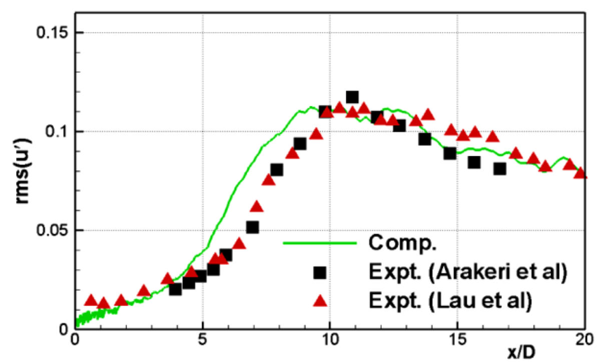
$\Delta = \tilde{\Delta}_{\omega}$



$\Delta = \tilde{\Delta}_{\omega} F_{KH}$



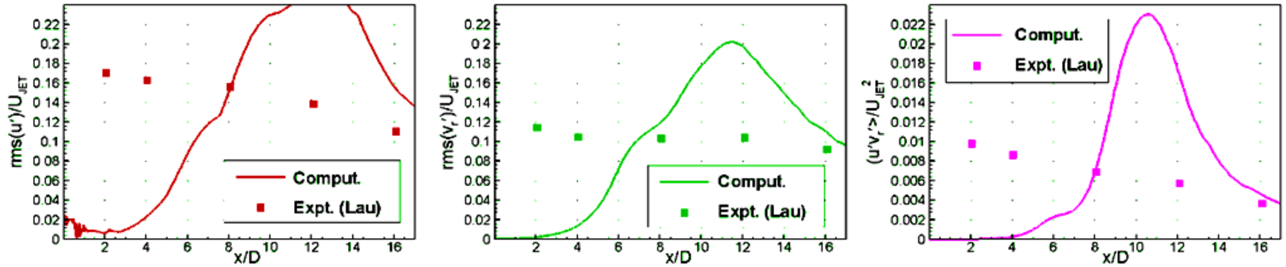
ILES



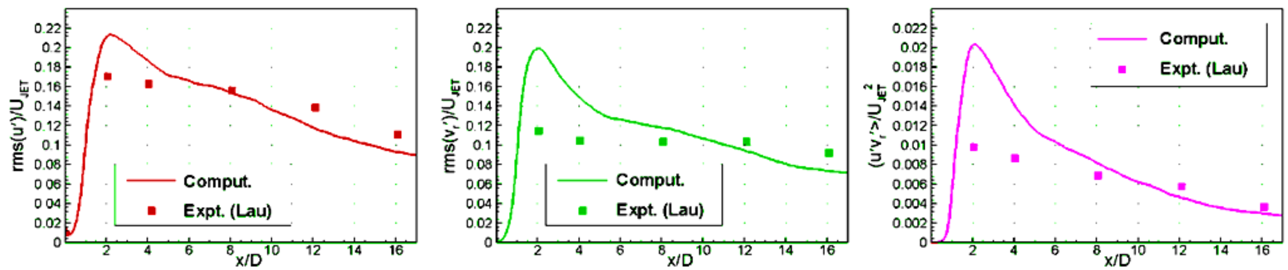
- Nearly same conclusions can be drawn with regard to the RMS of centerline velocity fluctuations…

Longitudinal Distributions of Maximum Resolved Stresses

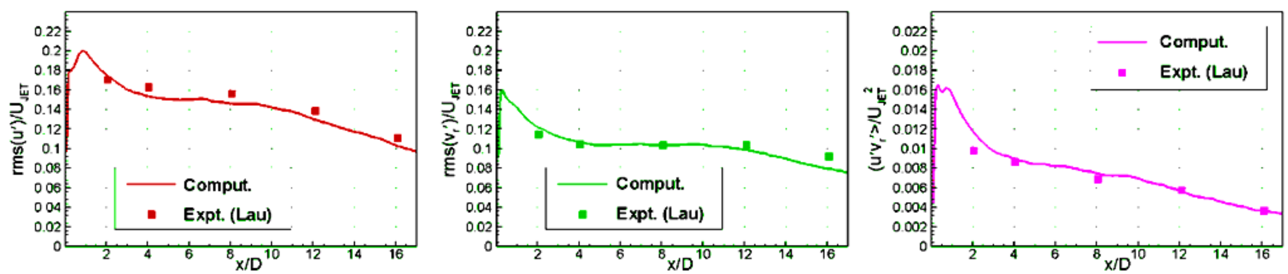
$\Delta = \Delta_{max}$



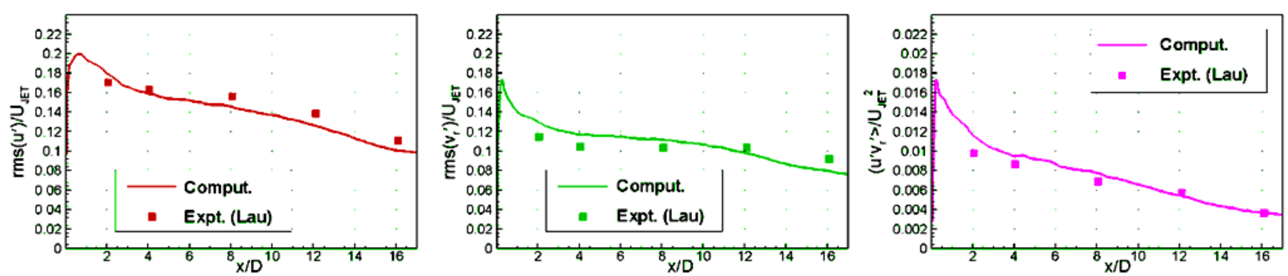
$\Delta = \tilde{\Delta}_{\omega}$



$\Delta = \tilde{\Delta}_{\omega} F_{KH}$



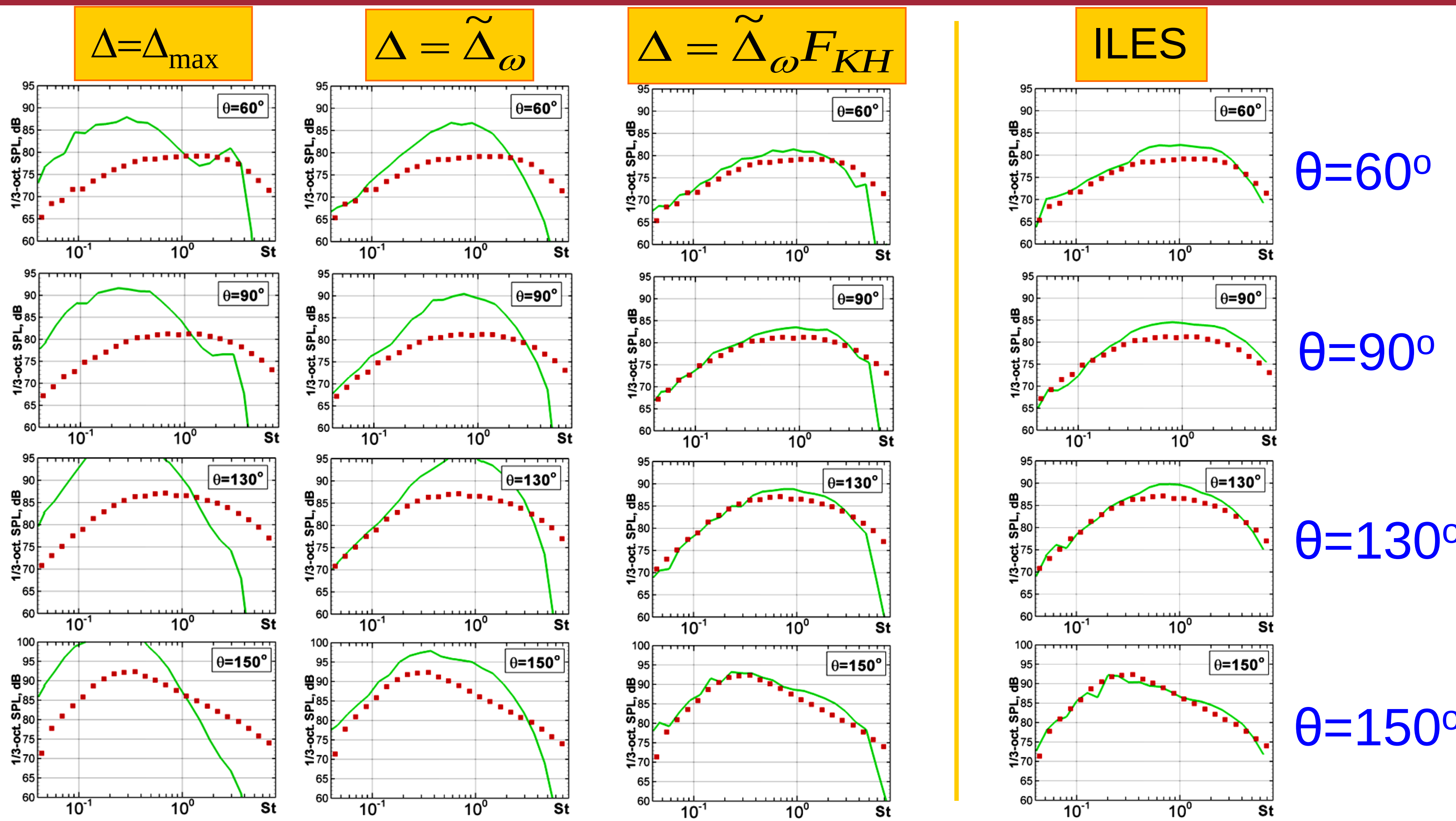
ILES



- … and regarding maximum Reynolds stresses along jet shear layer

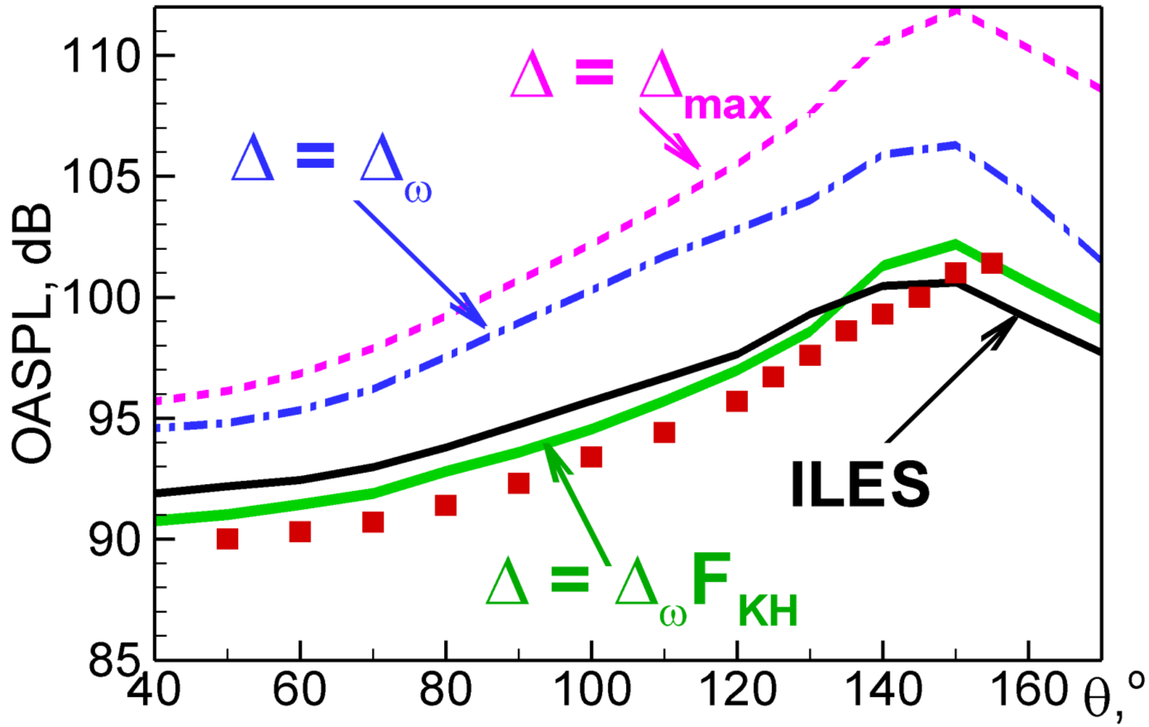
Effect of Proposed Length-Scale on Far-Field Noise

1/3-Octave Far-Field Noise Spectra at Different Polar Angles



- Crucial improvement of prediction of the jet aerodynamic characteristics naturally results in a similar improvement of the jet noise prediction
  - In this respect, DDES with $\Delta = \tilde{\Delta}_{\omega} F_{KH}$ turns out to be quite competitive with ILES

Overall Noise Directivity



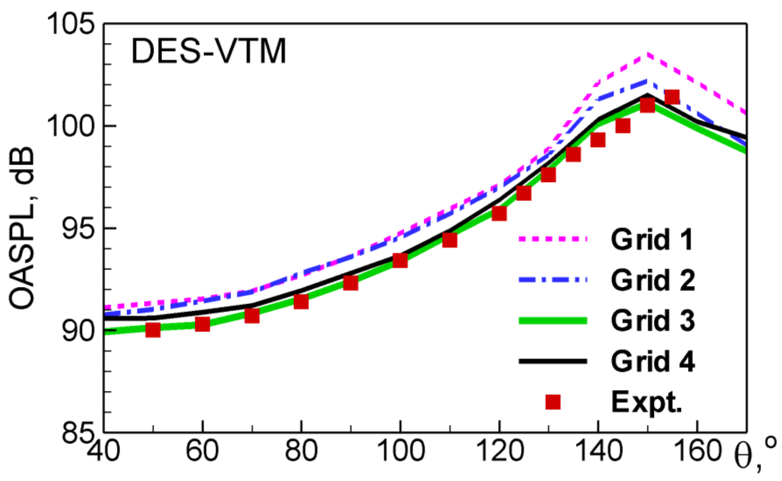
- Consistently with behavior of noise spectra in the vicinity of spectral maxima, the use of $\Delta = \widetilde{\Delta}_{\omega} F_{KH}$ ensures a better than ILES prediction of the directivity curve

  - ➢ Almost no overestimation at small angles
  - ➢ No noise “deficit” at large angles close to direction of max noise radiation

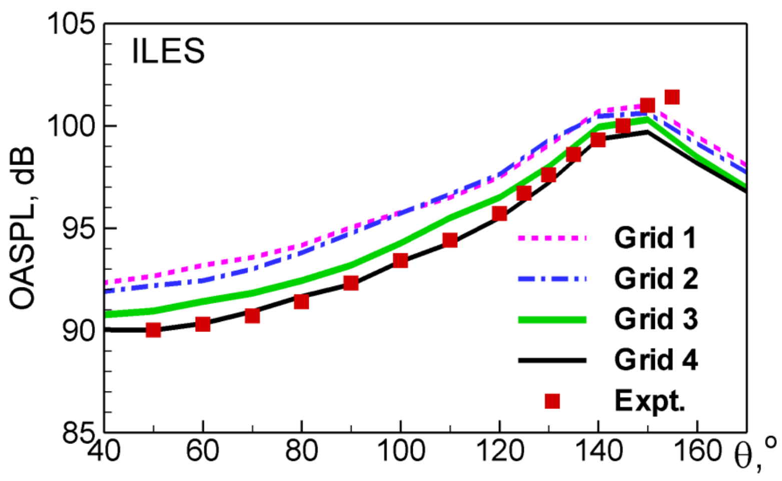
Some Results of Grid-Refinement Study

- Similar simulations have been carried out on a set of 4 successively refined grids (from 1M to 23M cells)
  - ➢ They demonstrate weaker grid-sensitivity and more “firm” grid-convergence than in ILES-based simulations in terms of mean flow parameters, turbulent statistics, and far-field noise

$$\Delta = \tilde{\Delta}_{\omega} F_{KH}$$



ILES



Conclusion

- Solution-dependent (based on flow kinematics) modification to the standard definition of subgrid length-scale of DES is suggested aimed at elimination of delay of transition from RANS-to-LES in the early regions of separated shear layer typical of the original DES
- The modification is successfully tested on a subsonic (M=0.9) round jet
- In general, the new definition seems to be a simple and robust remedy to the issue of delayed RANS-to-LES transition in separated and free shear layers the non-zonal hybrid RANS-LES approaches currently suffer from

Thanks for your attention!

SA-vs. WALE-bases DDES Combined with Proposed Subgrid Length-Scale

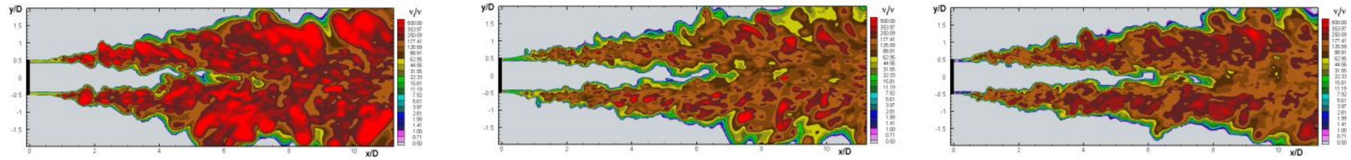
WALE-Bases DDES

- This recently proposed model (see Mockett et al., proceedings of 5th HRML symposium, 2014) is based on a re-formulation of original SA SGS model
  - At equilibrium (i.e., assuming "generation=dissipation") it reduces to the WALE SGS model rather than to the Smagorinsky model as the SA SGS does
- An advantage of the WALE SGS model in the context of the present study is that it automatically distinguishes between the quasi-2D situations such as initial part of plane shear, where it returns very low eddy viscosity, and 3D turbulence, in which the regular SGS model activity is recovered
- Hence, WALE-based DES is an alternative to the proposed VTM measure of flow two-dimensionality. However it is
  - More complex
  - Less universal
- Below we compare these two approaches

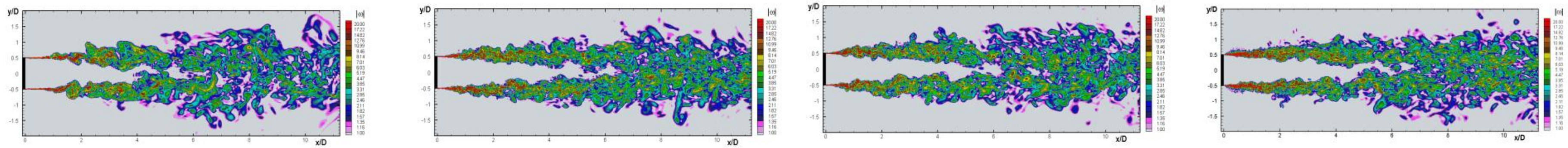
Turbulence Representation

$\Delta = \Delta_{\max}$ (WALE) | $\Delta = \tilde{\Delta}_{\omega}$ (WALE) | $\Delta = \tilde{\Delta}_{\omega} F_{KH}$ (SA) | ILES

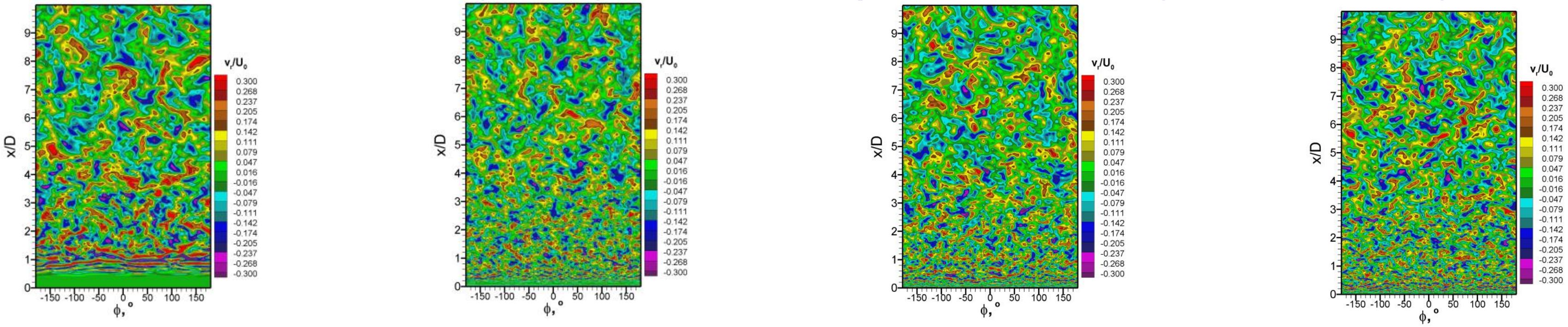
Contours of SGS eddy-viscosity



Contours of vorticity magnitude



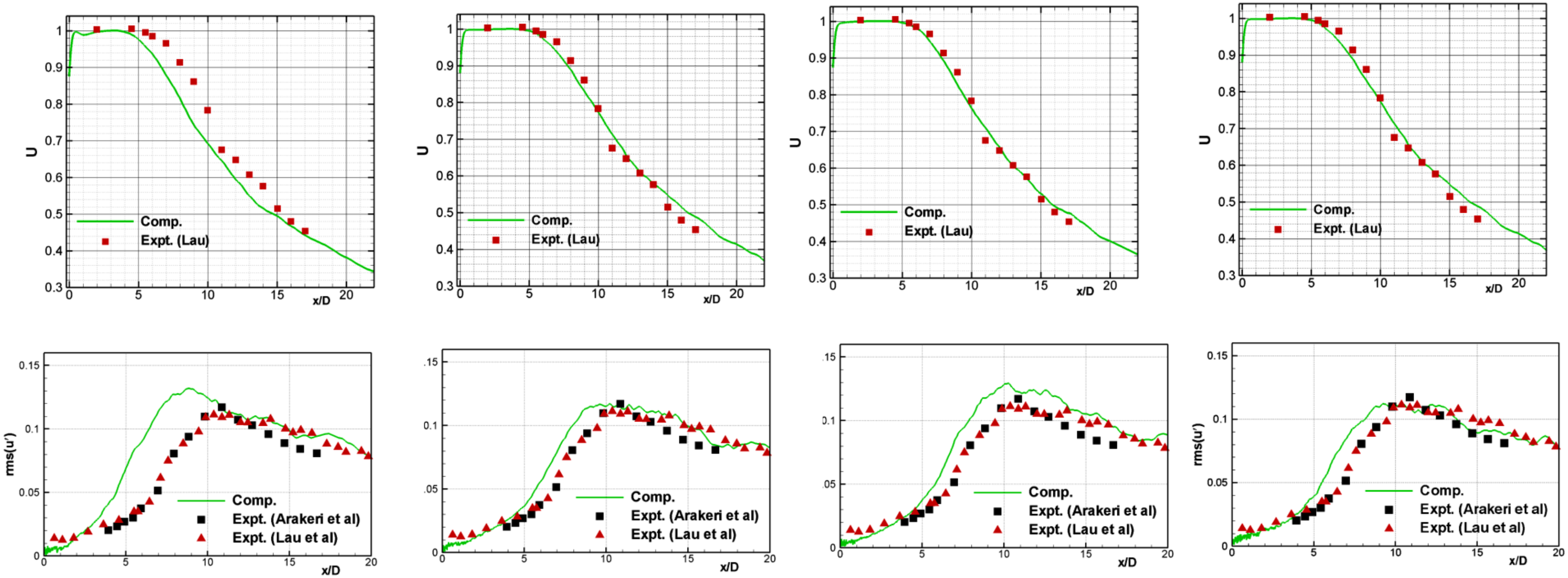
Contours of radial velocity on grid surface passing through nozzle edge



- As far as turbulence representation is concerned, both approaches (WALE with $\Delta = \tilde{\Delta}_{\omega}$ and SA with $\Delta = \tilde{\Delta}_{\omega} F_{KH}$) are close to each other, tangibly better than WALE DDES with $\Delta = \Delta_{\max}$ and are nearly equivalent to ILES

Centerline Velocity and RMS of its Fluctuations

$\Delta = \Delta_{max}$ (WALE) | $\Delta = \tilde{\Delta}_{\omega}$ (WALE) | $\Delta = \tilde{\Delta}_{\omega} F_{KH}$ | ILES



- Same is true for the mean centerline velocity and its fluctuations …

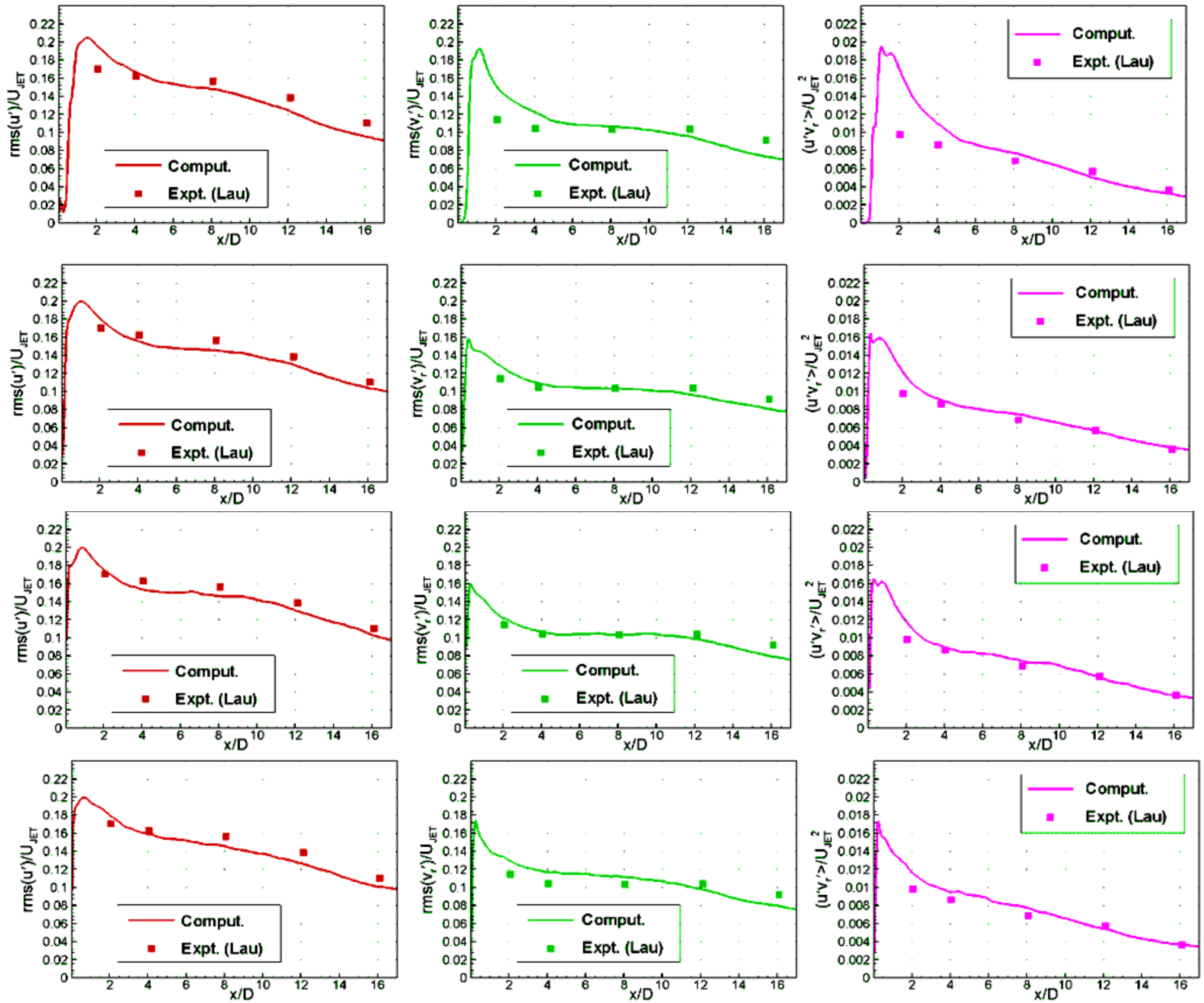
Longitudinal Distributions of Maximum Resolved Stresses

$\Delta = \Delta_{max}$ (WALE)

$\Delta = \tilde{\Delta}_{\omega}$ (WALE)

$\Delta = \tilde{\Delta}_{\omega} F_{KH}$

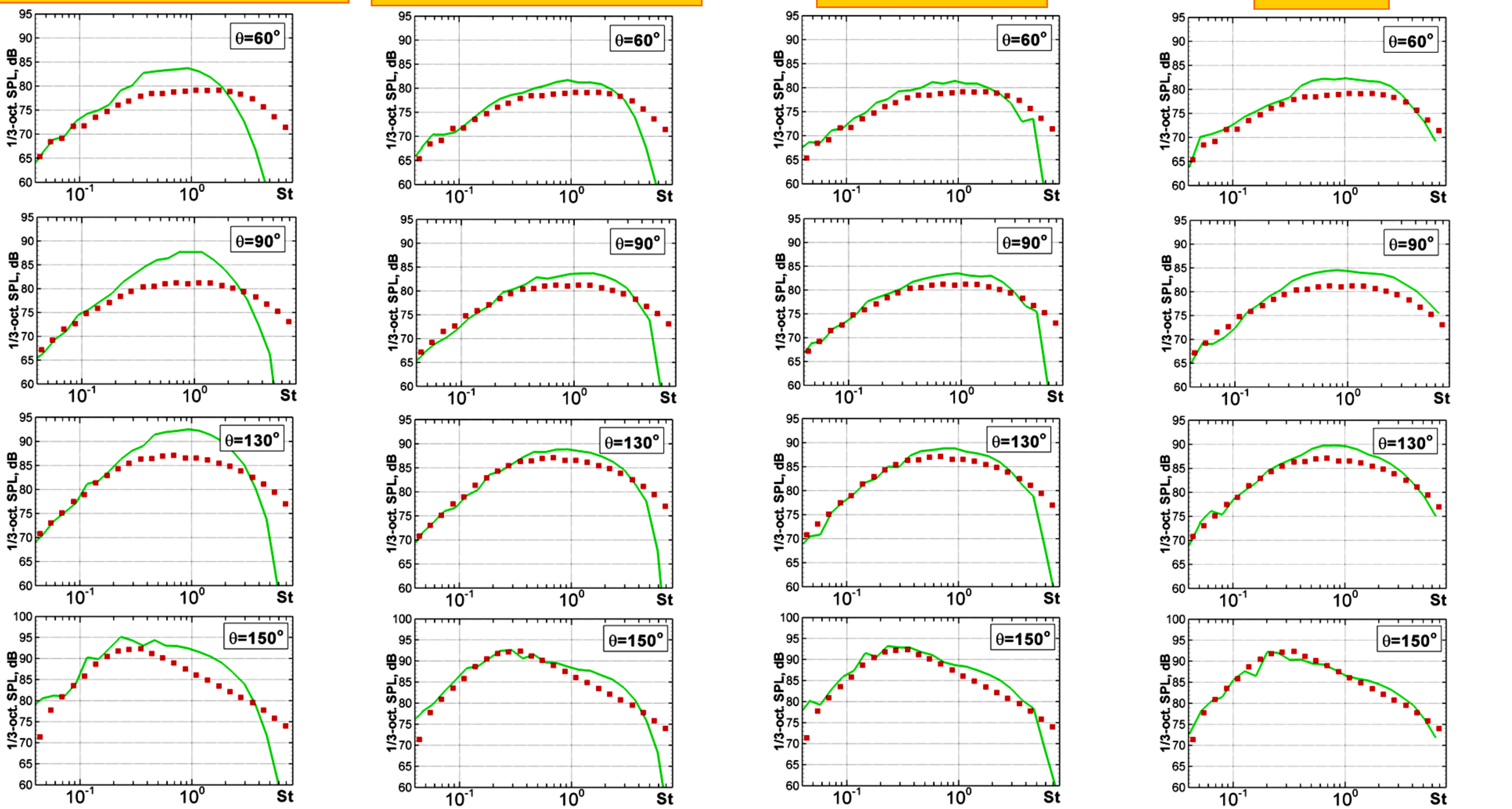
ILES



- … for maximum Reynolds stresses along jet shear layer and…

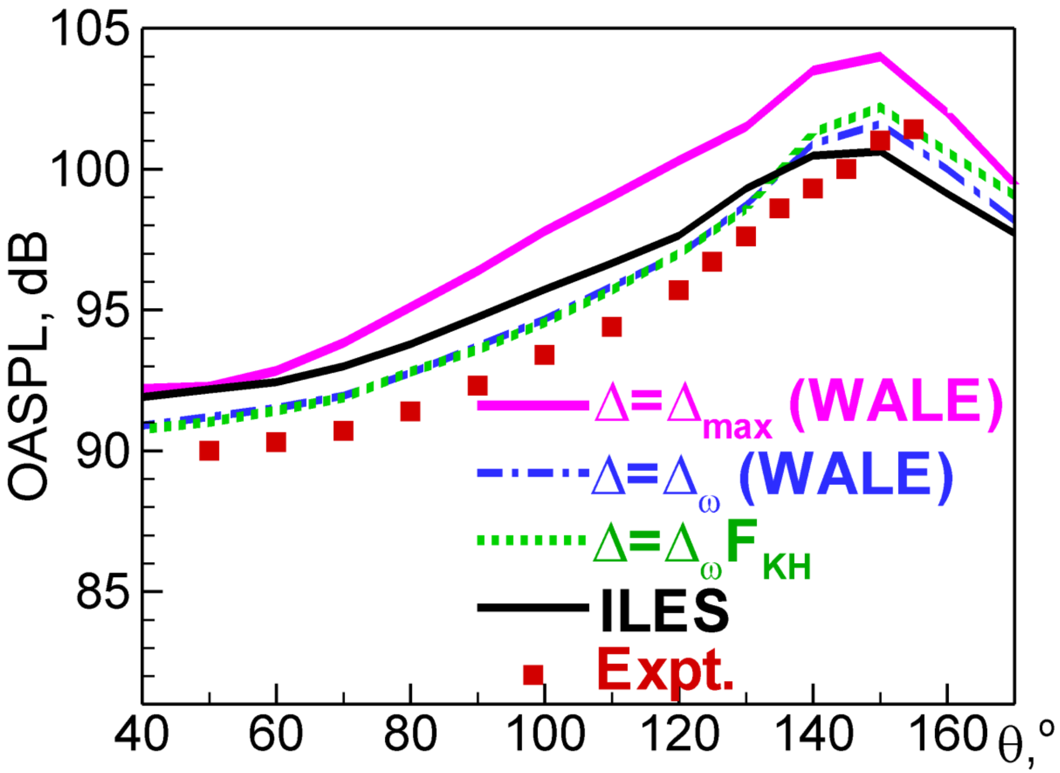
1/3-Octave Far-Field Noise Spectra

$\Delta = \Delta_{max}$ (WALE)	$\Delta = \tilde{\Delta}_{\omega}$ (WALE)	$\Delta = \tilde{\Delta}_{\omega} F_{KH}$	ILES



- … for the far-field noise, both the spectra and…

Overall Noise Directivity



- … overall noise directivity predictions