LES and Computational Aero-Acoustics

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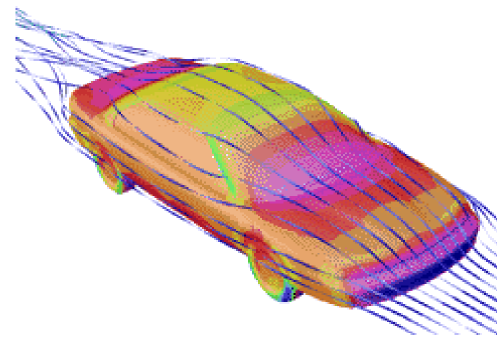
Outline

- 1. Introduction to LES and Computational Aero-Acoustics (CAA)
- 2. Basic equations
- 3. Current researches in LES and CAA
  - LES for airfoil flows
  - LES+CAA for airfoil flows
  - LES/AL for wind turbine flows
  - LES/AD for wind farm flows
- 4. Future perspectives

Introduction to LES and CAA

- Examples in *aero-acoustic research*



Introduction to LES and CAA

- Basic requirements for CFD and CAA
  - Access to powerful computer resources (parallel computers or pc clusters).
  - Access to efficient and accurate computer codes

- Computer resources required for different techniques (Spalart, 2000)

Table 1
Summary of strategies

Name	Aim	Unsteady	*Re*-dependence	3/2D	Empiricism	Grid	Steps	Ready
2DURANS	Numerical	Yes	Weak	No	Strong	10^{5}	$10^{3.5}$	1980
3DRANS	Numerical	No	Weak	No	Strong	10^{7}	10^{3}	1990
3DURANS	Numerical	Yes	Weak	No	Strong	10^{7}	$10^{3.5}$	1995
DES	Hybrid	Yes	Weak	Yes	Strong	10^{8}	10^{4}	2000
LES	Hybrid	Yes	Weak	Yes	Weak	$10^{11.5}$	$10^{6.7}$	2045
QDNS	Physical	Yes	Strong	Yes	Weak	10^{15}	$10^{7.3}$	2070
DNS	Numerical	Yes	Strong	Yes	None	10^{16}	$10^{7.7}$	2080

Introduction to LES and CAA

- Characteristics of wind turbine flows
  - Low speed or incompressible flow ($M<0.3$)
  - Rotational effects due to Coriolis and centrifugal forces
  - Tip loss effects
  - Turbulent inflow and wind shear
  - Wake effects
  - Yaw, coning and tilting effects.
  - Noise

Introduction to LES and CAA

- Noise gives annoyance for the nearby living people.

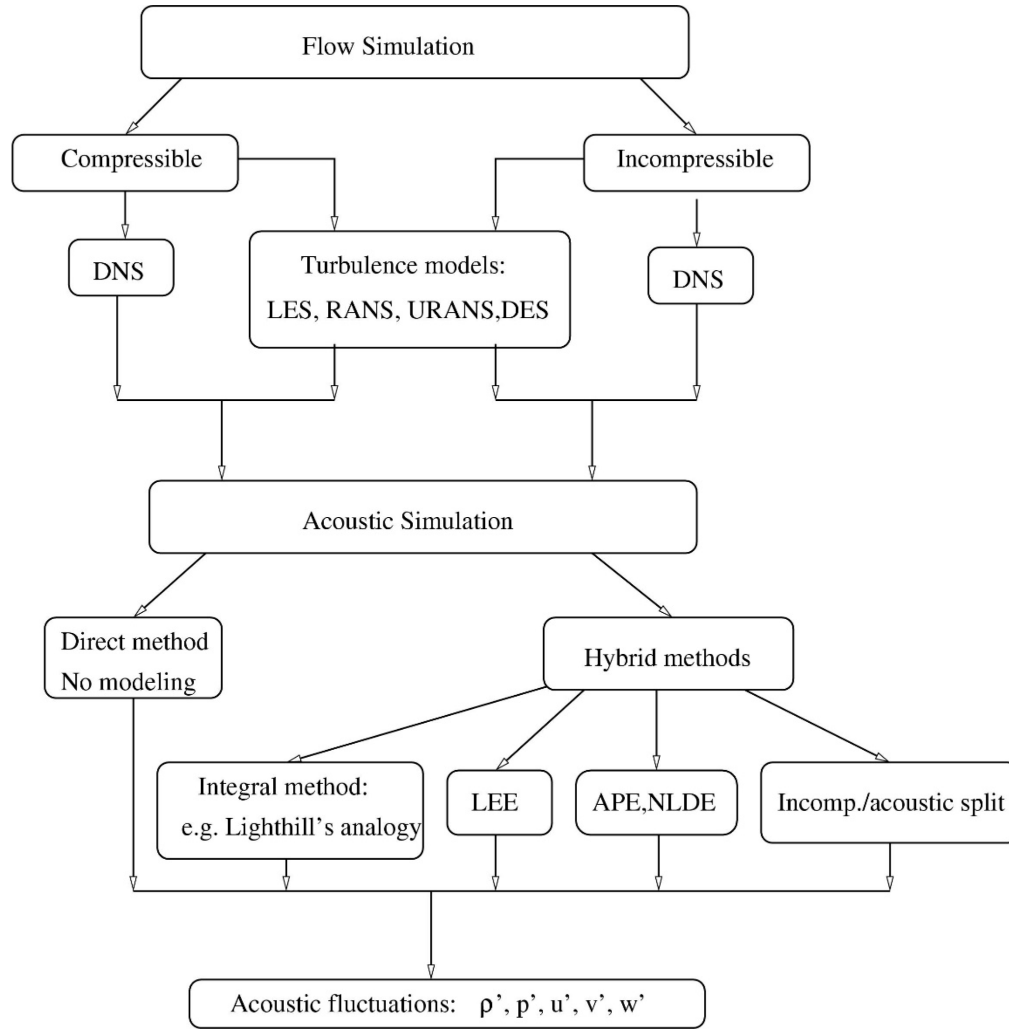
- Challenges
  - Small amplitude of sound waves, e.g., p'=0.1 Pa → 75dB (loud sound)
  - Wide range of frequencies, 20Hz-20kHz (audible frequency range)
  - Long computing time

- Facts about wind turbine flows (M<0.3):
  - Scale: Flow scale is about **M** (Mach number) times smaller than acoustic scale.
  - Speed: Acoustic waves propagate **1/M** times faster than flow velocity.
  - Location: Flow (vorticity) is located near walls and in wakes; acoustic waves are everywhere.

→→→ Flow-acoustics splitting technique with two different meshes

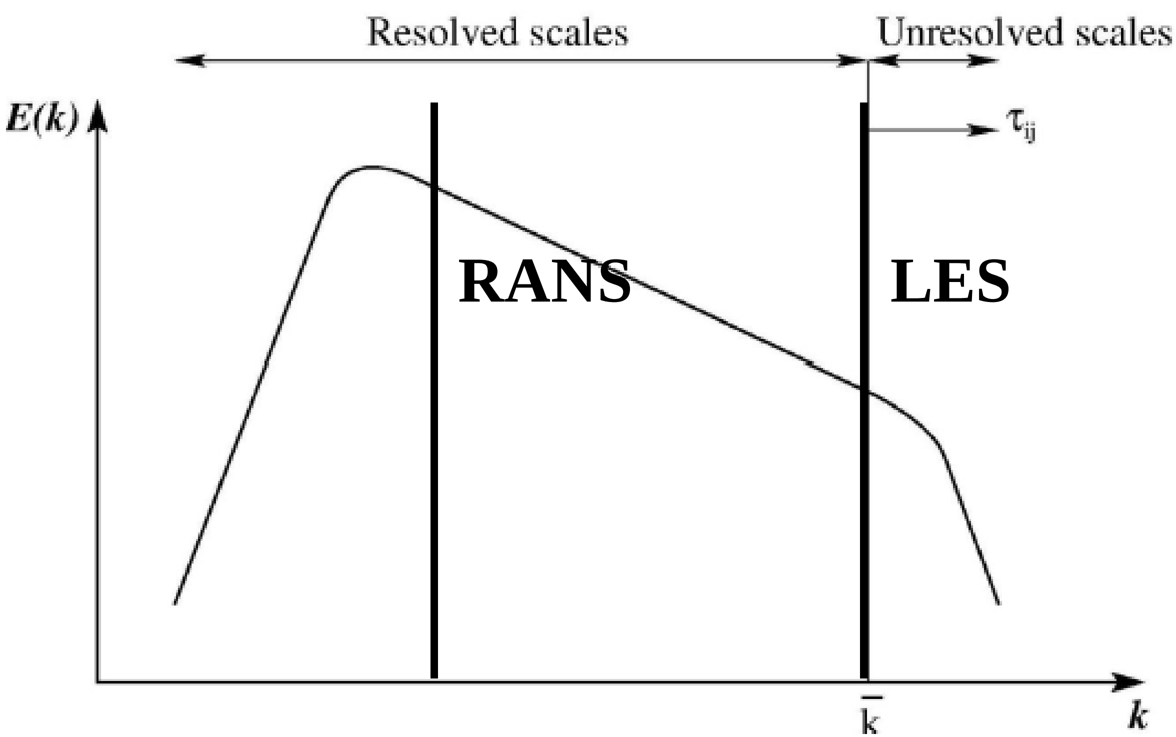
Introduction to LES and CAA

- Various models
  - – direct method, expensive
  - – hybrid method, cheaper



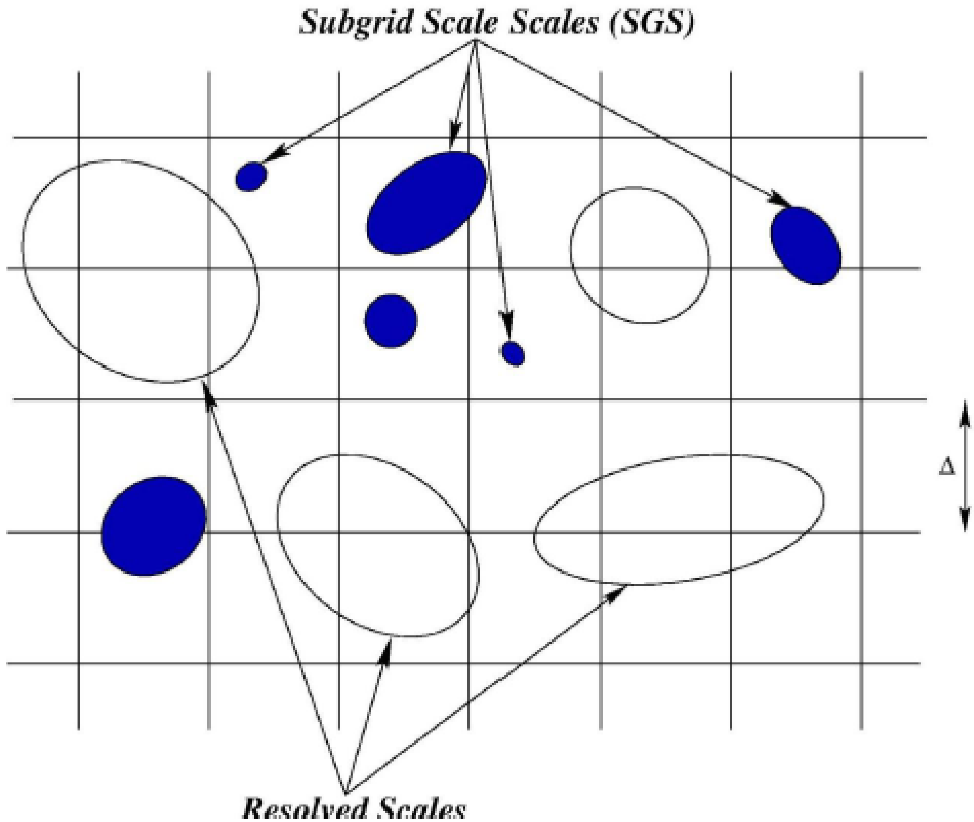
Introduction to LES and CAA

- Energy spectrum



Introduction to LES and CAA

- Flow solution



Basic Equations

- Flow-acoustics splitting technique

The acoustic equations are obtained from a decomposition of the compressible variables, such as:

$$f = F + f^* = \overline{F} + F' + \overline{f^*} + \{f^{*\prime}\}$$
$$= \overline{F + f^*} + F'$$

$$\longrightarrow$$

$$u_i = \overline{U}_i + U_i' + u_i^*$$
$$p = \overline{P} + P' + p^*$$
$$\rho = \rho_0 + \rho^*$$

Introduce the relations to the compressible equations

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) &= 0 \\
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j + p_{ij}) &= 0 \\
p &= p(\rho, S) \\
T\frac{DS}{Dt} = c_p \frac{DT}{Dt} - \frac{\beta T}{\rho}\frac{Dp}{Dt} &= \phi + \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)
\end{aligned}$$

Basic Equations

- Filtered incompressible Navier-Stokes equations (LES)

$$\frac{\partial \overline{U}_i}{\partial t} + \frac{\partial \left(\overline{U}_i \overline{U}_j \right)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \overline{P}}{\partial x_i} + \nu \frac{\partial^2 \overline{U}_i}{\partial x_j^2} - \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\frac{\partial \overline{U}_i}{\partial x_i} = 0$$

$$\tau_{ij} = \overline{U_i U_j} - \overline{U}_i \overline{U}_j = \left(\overline{\overline{U}_i \overline{U}_j} - \overline{U}_i \overline{U}_j \right) + \left(\overline{\overline{U}_i U'_j + U'_i \overline{U}_j} \right) + \overline{U'_i U'_j}$$

$$\tau_{ij} = \nu_t \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij}$$

SGS model: The mixed scale model (for example)

$$\nu_t = C \left| \vec{\overline{\omega}} \right|^{\alpha} k^{(1-\alpha)/2} \Delta^{(1+\alpha)}, \; 0 \le \alpha \le 1$$

$$k \approx \frac{1}{2} \sum_{j=1}^{3} \left(\overline{U}_j - \tilde{\overline{U}}_j \right)^2$$

Basic Equations

- Acoustic equations (CAA)

$$\frac{\partial \rho^*}{\partial t} + \frac{\partial f_i}{\partial x_i} = 0$$

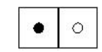
$$\frac{\partial f_i}{\partial t} + \frac{\partial}{\partial x_j}\left[f_i\left(\bar{U}_j + u_j^*\right) + \left(p^* + \frac{2}{3}\rho^* k \right)\delta_{ij} \right] = \frac{\partial}{\partial x_j}\left[-\rho_0 \bar{U}_i u_j^* + \rho^* \left(\nu + \nu_t\right)\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \right]$$

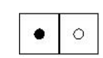
$$\frac{\partial p^*}{\partial t} - c^2 \frac{\partial \rho^*}{\partial t} = -\frac{\partial \bar{P}}{\partial t}$$

$$f_i = \rho u_i^* + \rho^* \bar{U}_i$$

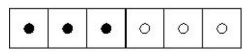
$$c^2 = \frac{\gamma\left(\bar{P} + p^*\right)}{\rho_0 + \rho^*}$$

Basic Equations

- Flow solver (EllipSys code)
  - Finite volume method with cell-centred / Multi-block 
  - Multi-grid for the pressure equation
  - SIMPLE / SIMPLEC with the improved Rhie-Chow interpolation
  - Second-order backward differentiation in time
  - Second-order central difference in space (QUICK for the convective terms)

- Acoustic solver 1
  - Finite volume method with Cell-centred / Multi-block 
  - SIMPLE / SIMPLEC with the improved Rhie-Chow interpolation
  - Crank-Nicolson in time
  - Second-order central difference in space (QUICK for the convective terms)

Basic Equations

- Acoustic solver 2
  - Wavenumber optimized finite difference schemes
  - Multi-block 
  - 4^{th}, 6^{th}, 8^{th}, 10^{th}, 12^{th} - order explicit and implicit schemes in space
  - 6^{th}, 8^{th}, 10^{th} – order filter schemes
  - 4th - order RK for time advancing

Current researches in LES and CAA

- LES for airfoil flows: Flow past a S806 airfoil at Re=40 000 and AOA=12°

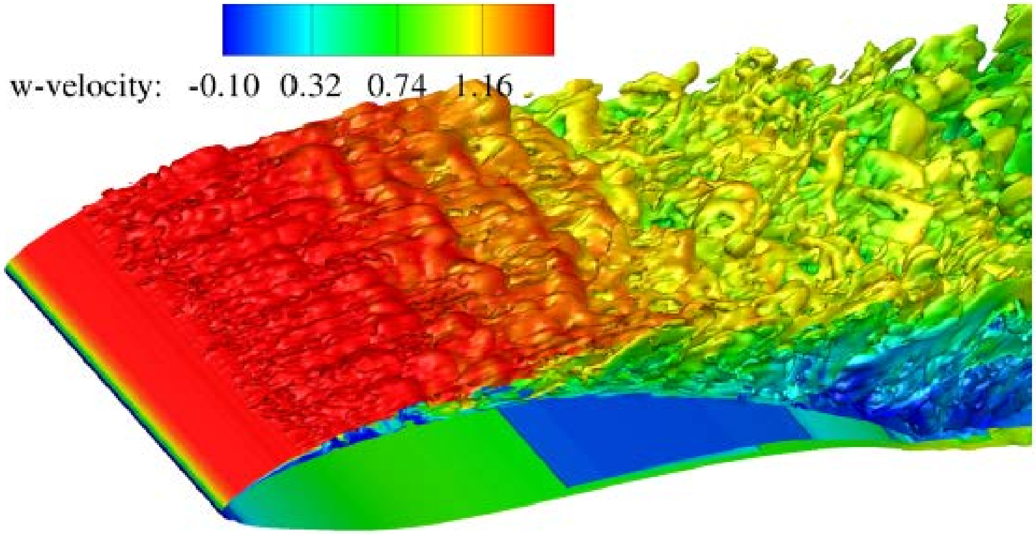


Figure: Iso-vorticities colored by the streamwise velocity magnitude.

Mesh: 1024x256x64=16.8x10^6

Current researches in LES and CAA

- LES for airfoil flows: Flow past a S806 airfoil

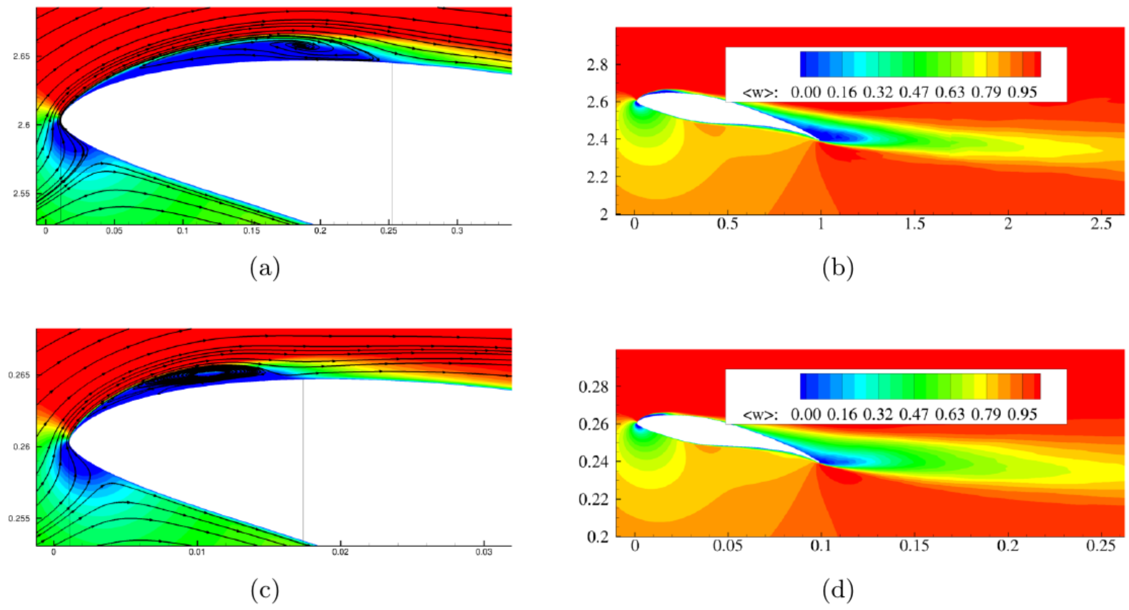


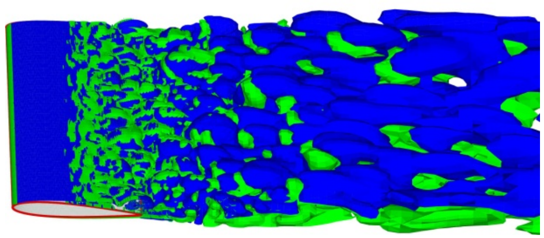
Figure: (a, b) Re = 40 000 at α= 12º; (c, d) Re = 100 000 at α= 12º.

Current researches in LES and CAA

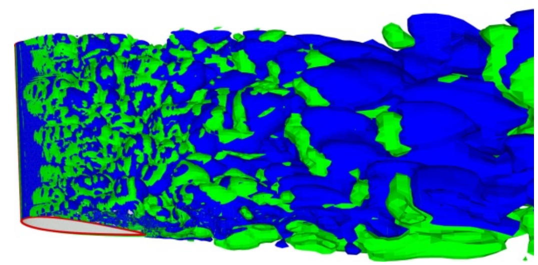
- LES for airfoil flows: Flow over a NACA 0015 airfoil at Re = 160,000.

12 blocks (3 radial and 4 tangential) of 64x64x64 cells=3.15x10^6

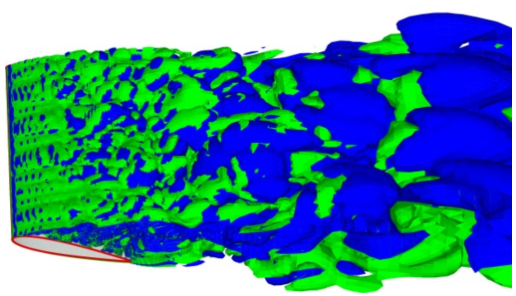
α=6^o



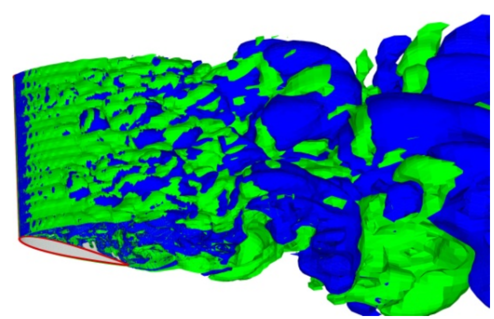
α=10^o



α=16^o

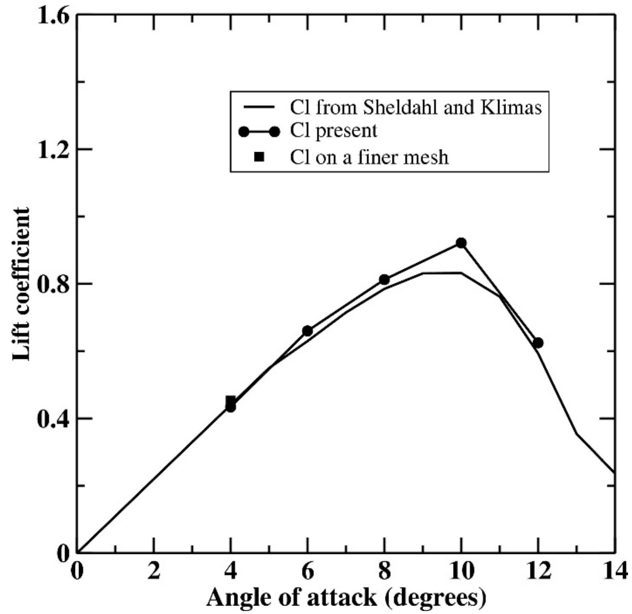


α=20^o



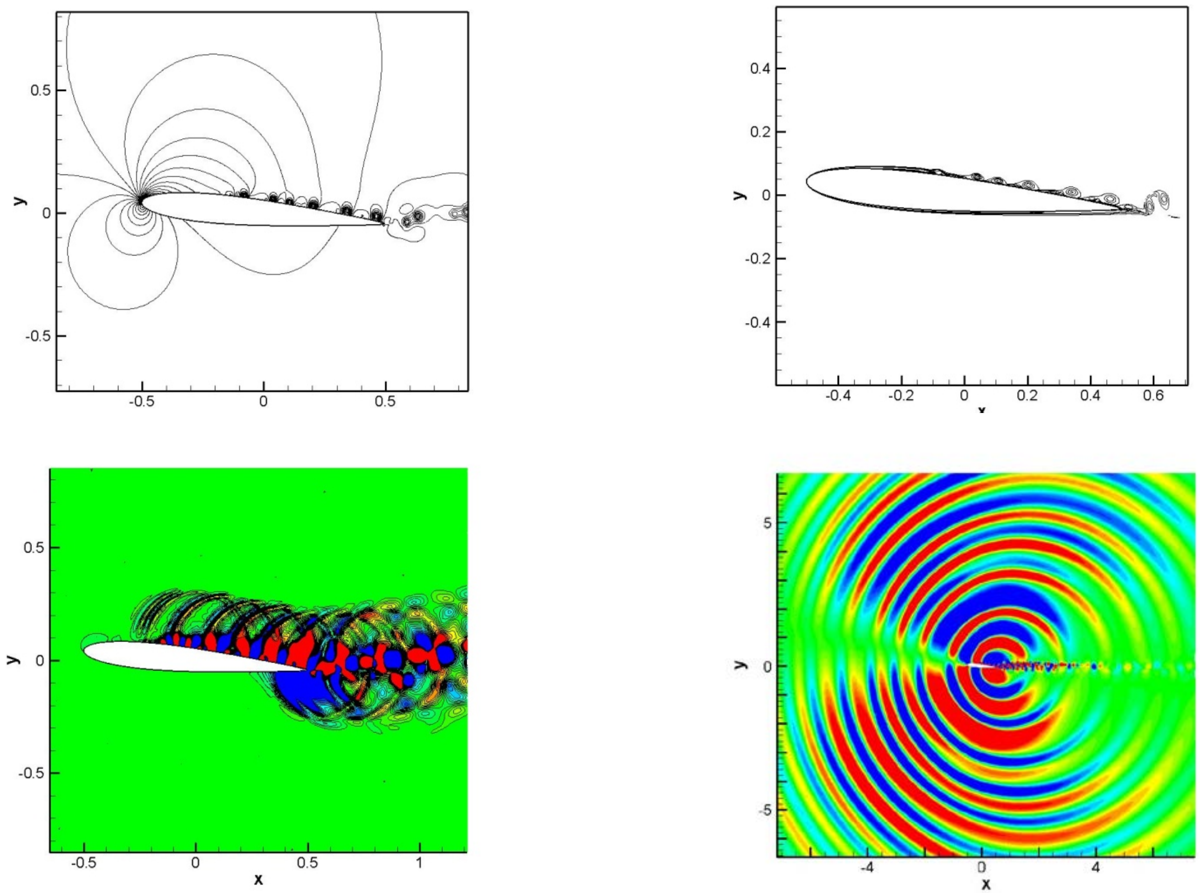
Current researches in LES and CAA

- LES for airfoil flows: Flow over a NACA 0015 airfoil at Re = 160,000.



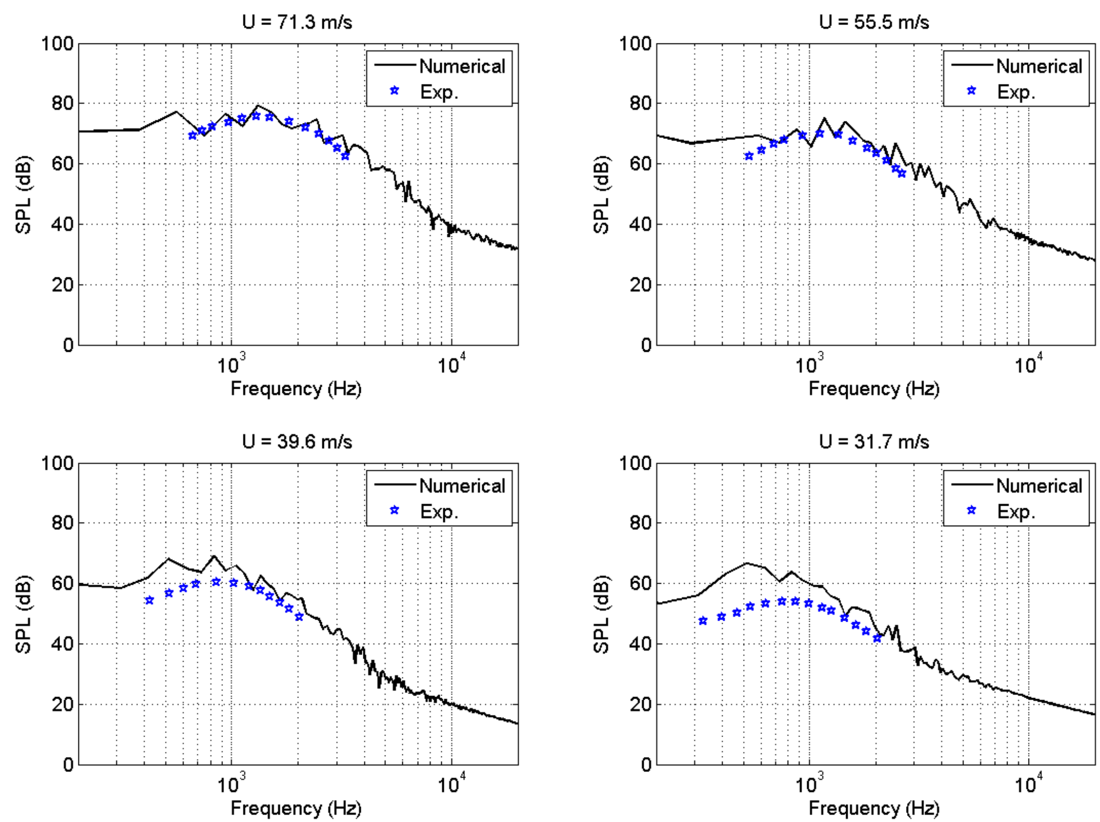
Current researches in LES and CAA

- CAA for airfoil flows: Flow over a NACA 0012 airfoil at Re = 100,000, α= 5º and M = 0.2.



Current researches in LES and CAA

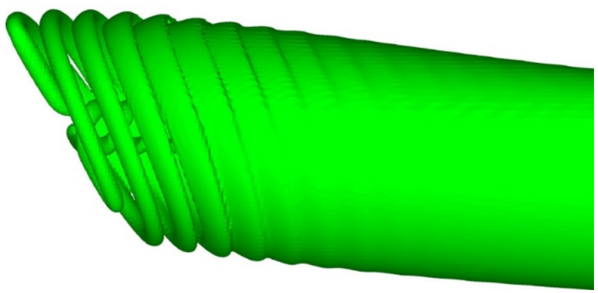
- CAA for airfoil flows: Flow over a NACA 0012 at α= 6.7° and Re= 2.15×10^5, 2.68×10^5, 3.76×10^5, 4.83×10^5

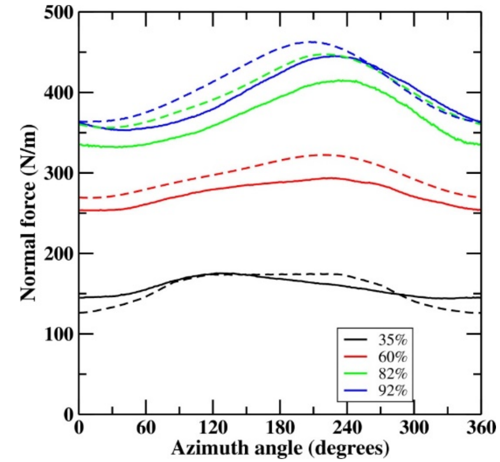


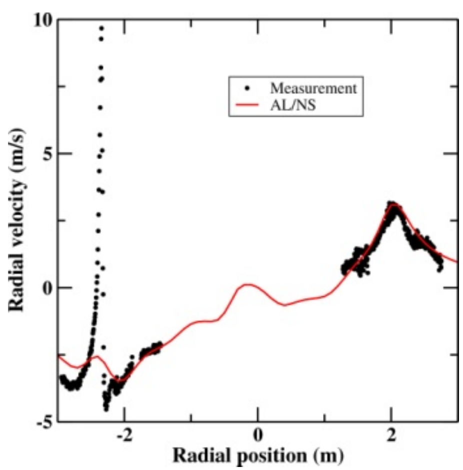
Current researches in LES and CAA

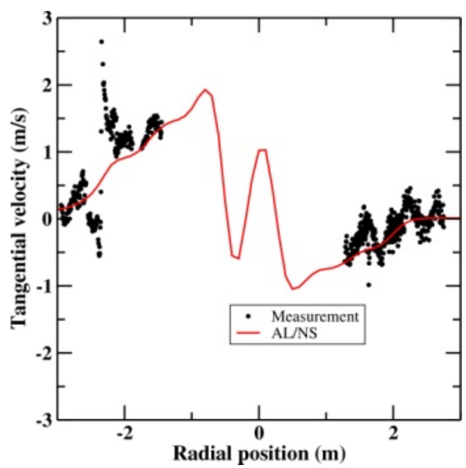
- LES/AL for wind turbine flows: the MEXICO rotor

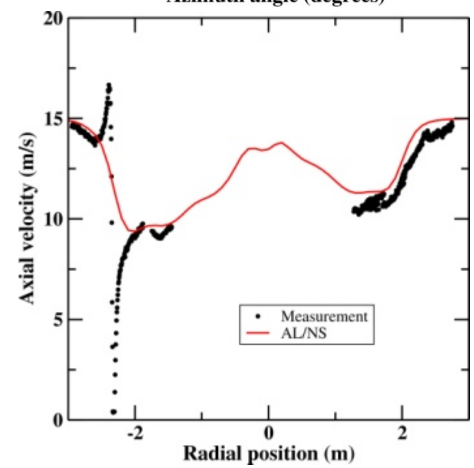
Mesh: 192x192x320=11.8x10^6







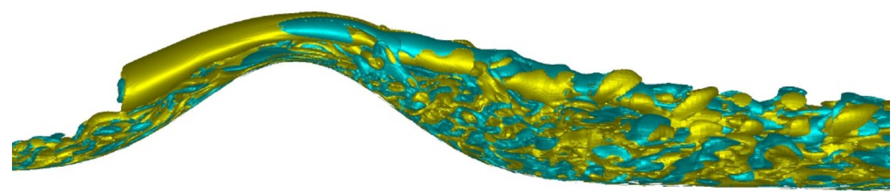


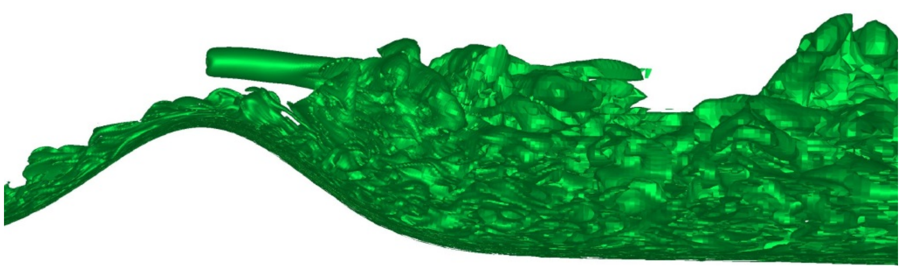


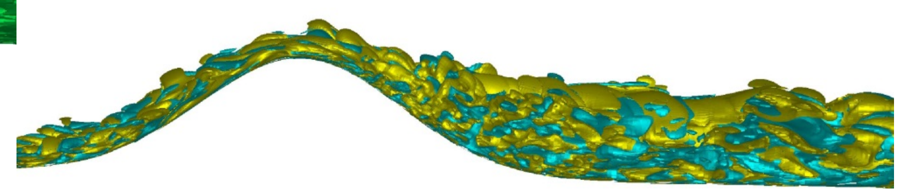
Current researches in LES and CAA

- LES/AL for wind turbine flows: a wind turbine on a hill

Mesh: $48 \times 64^3 = 12.6 \times 10^6$

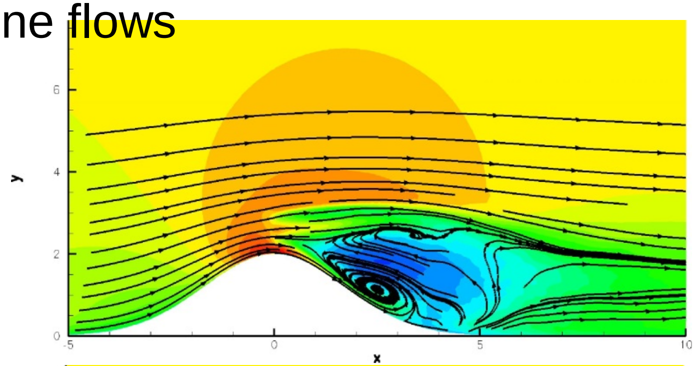




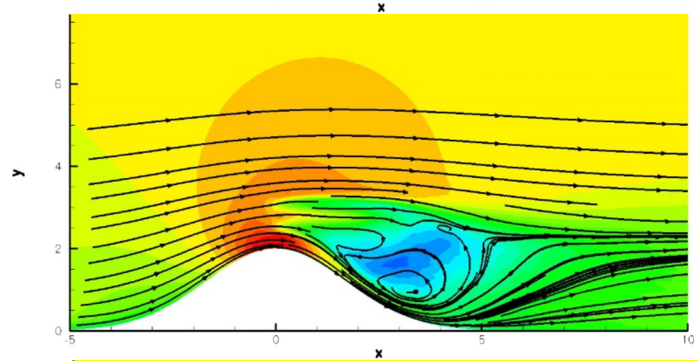


Current researches in LES and CAA

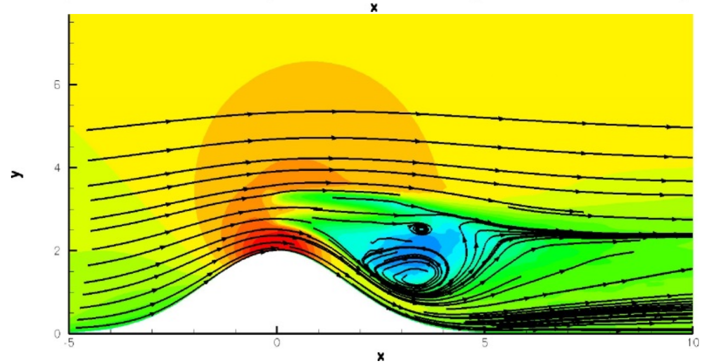
- LES/AL for wind turbine flows



H = 60 m



H = 80 m

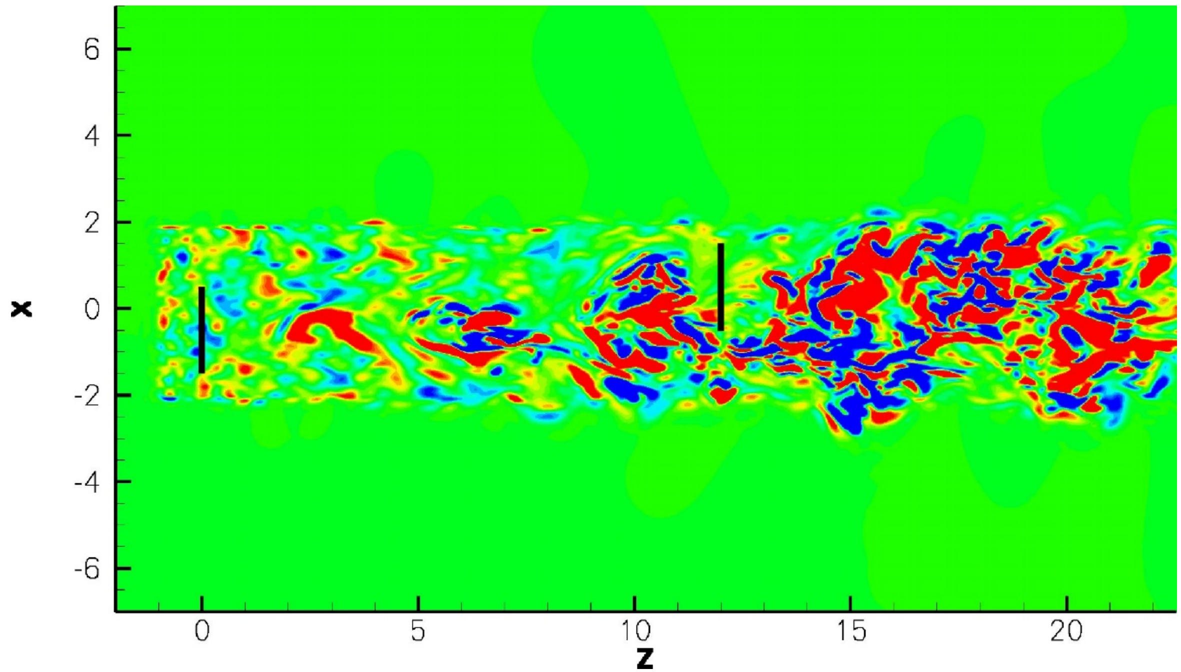


H = 100 m

Current researches in LES and CAA

- LES/AL for wind turbine flows: Two turbines in tandem

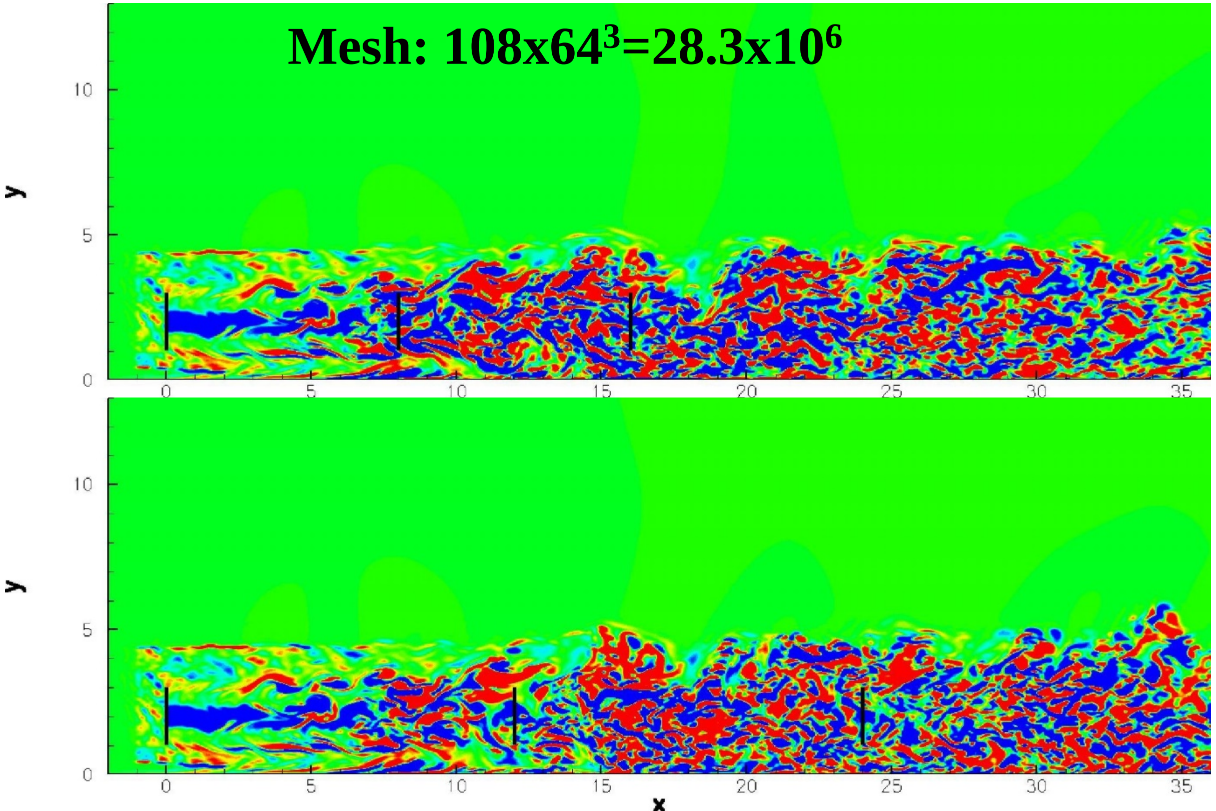
Mesh: $72x64^3=18.9x10^6$



Iso-vorticity plot of two 2MW Tjæreborg turbines in tandem at a hub wind speed of 10 m/s at a separation distance of 6D (the centers are staggered of 1R in the x direction).

Current researches in LES and CAA

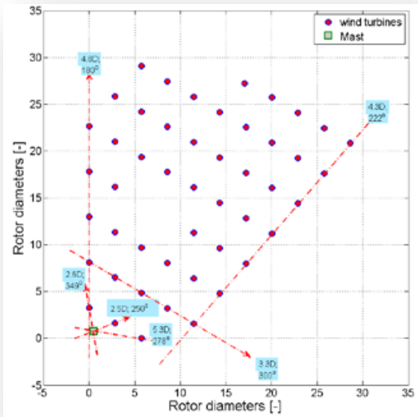
- LES/AL for wind turbine flows: Three turbines in tandem

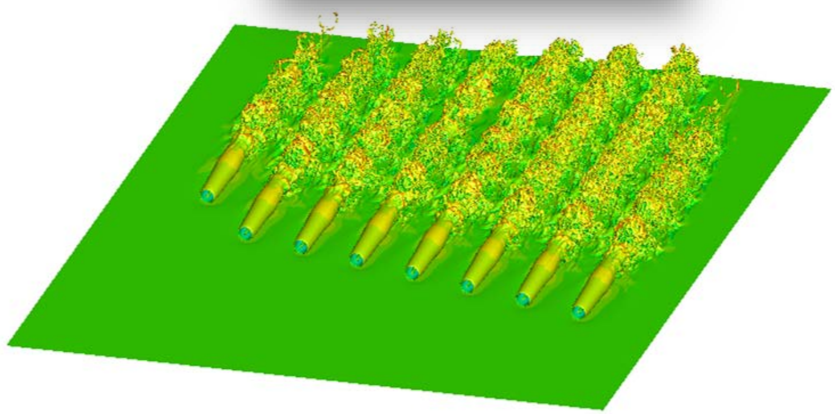


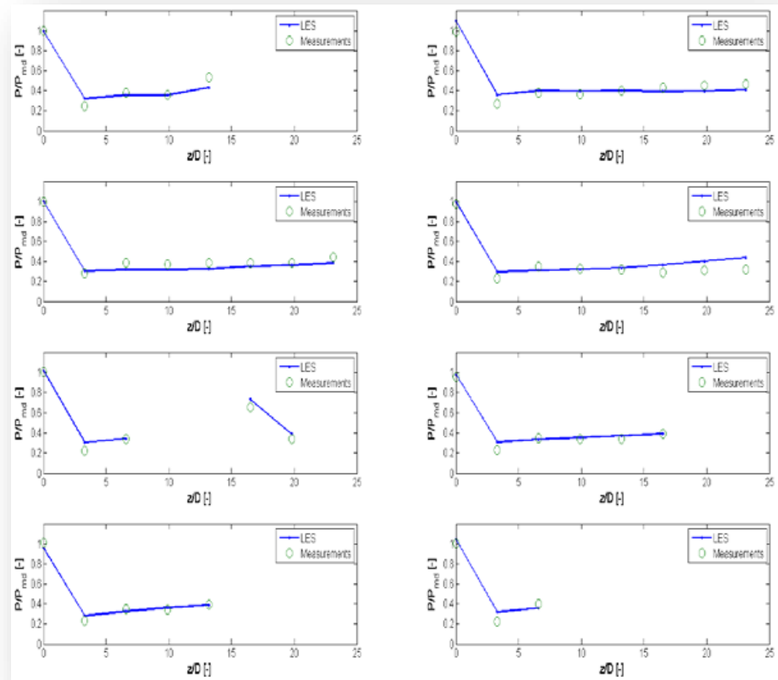
Vorticity plot of three 2MW Tjæreborg turbines in tandem at a hub wind speed of 10 m/s at separation distances of 4D (up) and 6D (down).

Current researches in LES and CAA

- LES/AD for wind farm flows: Lillegrund wind farm with 48 2.3MW turbines.







Mesh: $144 \times 64^3 = 36 \times 10^6$

Future perspectives

With the older clusters:

- LES and CAA with fully resolved geometry are possible for airfoil flows.
- LES is possible for wind turbine flows with simple turbine models (AD/AL/AS).
- LES is possible for wind farm flows with AD.

With the new cluster

- CAA is possible for wind turbine flows with simple turbine models.
- LES and CAA with full resolved geometry may be possible for a wind turbine.
- LES and CAA may be possible for wind farm flows with AL.