# Quantifying the impact of SGS models in actuator-line based LES of wind turbine wakes

**Hamid Sarlak**[1] & R. Mikkelsen[1]
J. N. Sørensen[1] & C. Meneveau[2]

[1] The Technical University of Denmark, *hsar@dtu.dk*
[2] The Johns Hopkins University, USA

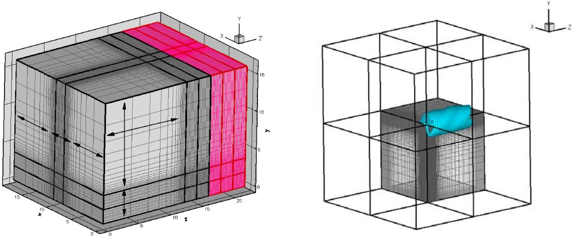
*Flow center meeting*
June 4th. 2013, DTU Wind Energy, Roskilde

# Outline

1. Ellipsys3D solver, governing equations and ACL modeling
2. Case 1: Blind test 2 Expr.
3. Case 2: One rotor in laminar and turbulent inflow
   - Laminar inflow simulation results
   - Turbulent inflow simulation results
   - Laminar-turbulent inflow inter-comparisons
4. Conclusions

# CFD Platform, Ellipsys3D

- FV discretization on non-staggered grid, written in general curvilinear coordinates
- Block structured grids, MPI-parallelized, Multigrid accelerated



- Coupled with *Flex5*: control, structural and aeroelastic analyses included for ACL.

# Governing Equations and SGS models used

Filtered $Navier - Stokes$ equations must be solved:

$$\nabla \cdot \mathbf{v} = 0. \quad (1)$$

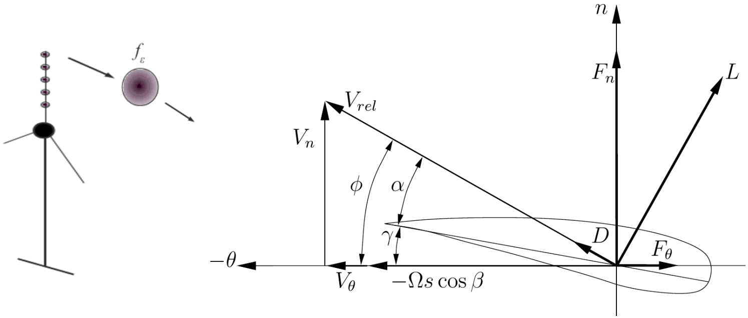
$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla p}{\rho} + \nabla \cdot [(\nu + \nu_{sgs}) \nabla \mathbf{v}] + \mathbf{f}, \quad (2)$$

Table: SGS models used for comparisons

| **Case name** | **SGS Eddy viscosity** |
|---|---|
| No SGS (NO) | $\nu_{sgs} = 0$ |
| Smagorinsky (SM) | $\nu_{sgs} = c_s \Delta^2 \lvert\bar{S}\rvert$ |
| Mix-$S$ (MS) | $\nu_{sgs} = c_{ms} \Delta^{1.5} q_c^{0.25} \lvert\bar{S}\rvert^{0.5}$ |
| Mix-$\Omega$ (MO) | $\nu_{sgs} = c_{mo} \Delta^{1.5} q_c^{0.25} \lvert\bar{\Omega}\rvert^{0.5}$ |
| Dyn. Smagorinsky (GM) | $\nu_{sgs} = c_{dyn} \Delta^2 \lvert\bar{S}\rvert$ |

DTU

# Wind Turbine Modeling: Actuator Line Concept (Sørensen and Shen 2002)




$$f = (L, D) = \frac{1}{2}\rho V_{\mathrm{rel}}^2 c\,(C_{\mathrm{L}} e_{\mathrm{L}}, C_{\mathrm{D}} e_{\mathrm{D}})$$

$$f_\varepsilon = f \otimes \eta_\varepsilon,\ \eta_\varepsilon(d) = \frac{1}{\varepsilon^2 \pi^{3/2}} \exp\left[-\left(\frac{d}{\varepsilon}\right)^2\right]$$

# Results, Case 1:

***Blind test 2: Ellipsys3D versus measurements***

# Blind test 2


(d)

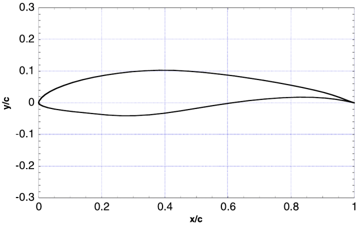
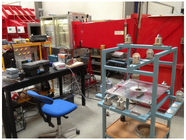



**Fig. 2.** Shape of the NREL S826 airfoil.

(e)

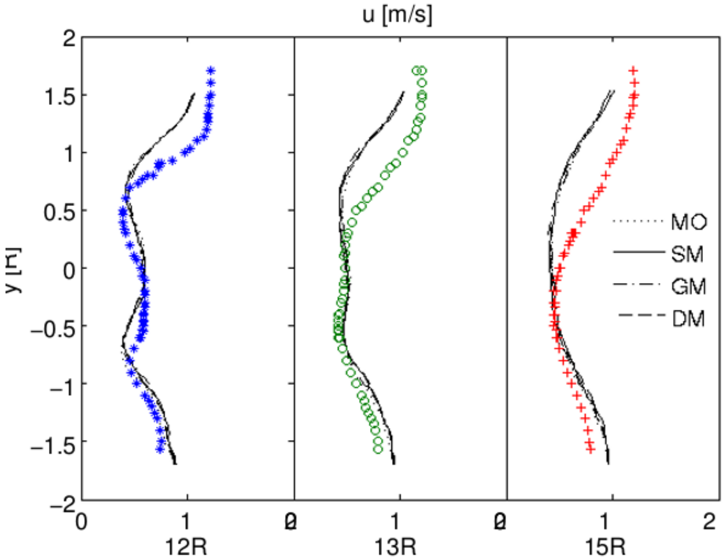


(f)

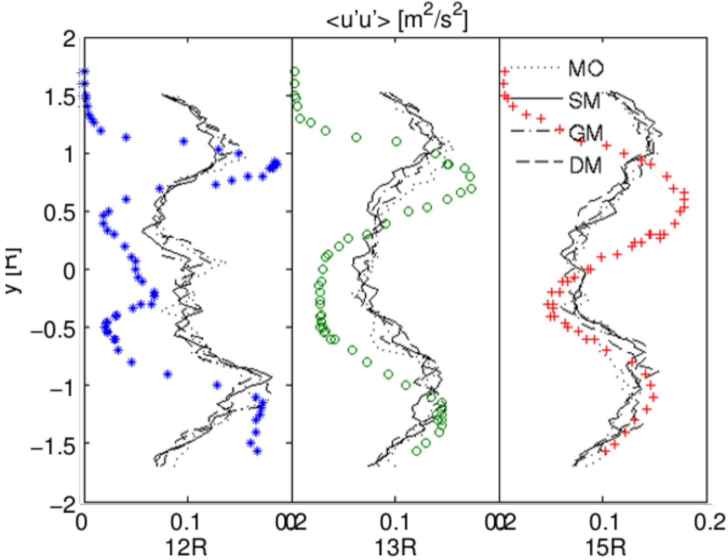
# Simulation set up for the "BT2"

- Tunnel (L,W,H)= $(12.7, 2.7, 2)$m. $D_r = 894mm$, $U_i = 10m/s$.
- NREL's s826 airfoil is used. The aerodynamic coefficients for Ellipsys simulations found based on 2D airfoil measurements in DTU wind tunnel.
- Spatial discretization: Blend of CDS and QUICK
- Dimensionless time step: $dt^* = dt.u_\infty/R = 0.004$
- Fixed rotational speed of $Omega = 127rad/s$ according to the experiments. $Re_r = 50,000$ $(U_\infty = 1, R = 1)$ in Ellipsys3D.
- $TI = 0.3\%$ on top of laminar inflow
- The numerical tunnel is resolved using ca. 8.4 million cells and the rotors are represented by 35 points along each blade

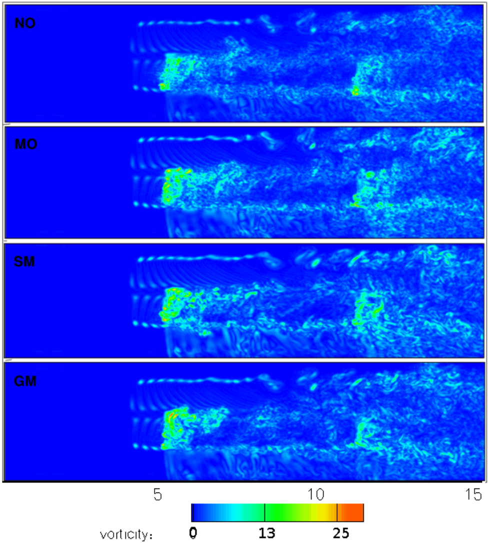
# Time averaged streamwise velocity



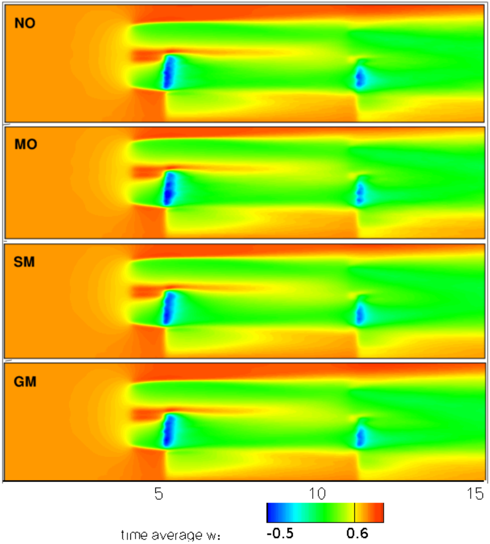
# Time averaged turbulent stress component $\overline{u'u'}$



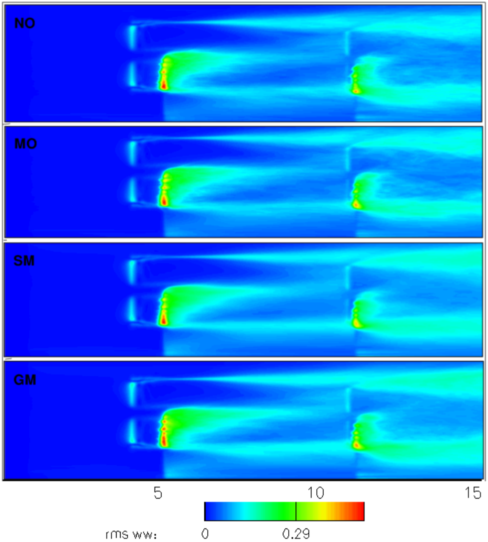
# Instantaneous vorticity contours



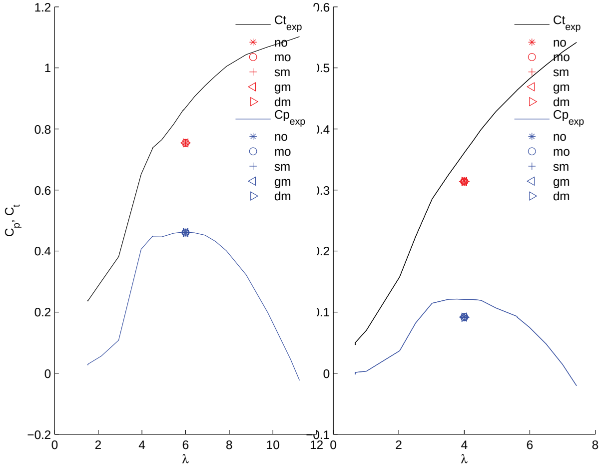
# Time averaged velocity contours



# Time averaged normal stress contours



# Power and thrust coefficient



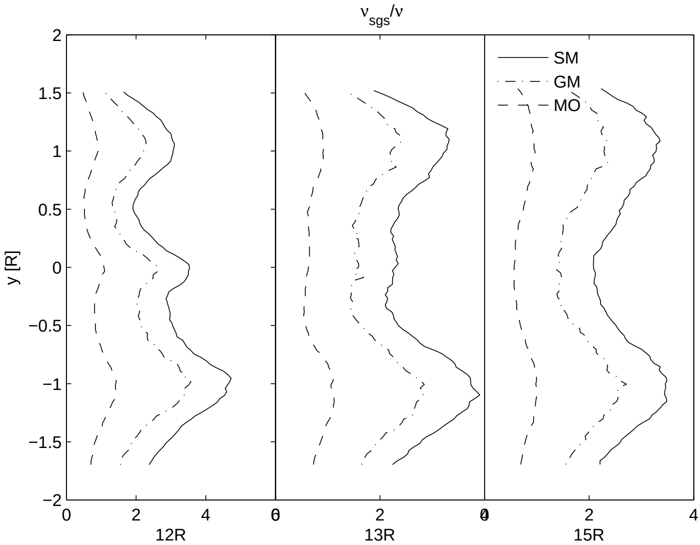
# Conclusions so far

- Simulations mimic the measurements **fairly well** using **all** SGS models
- Power and thrust coefficients are under-estimated except the $C_p$ for the upstream turbine
- Power and thrust predictions are identical for all models

**Questions:**

- Is the simulation set-up accurate enough?
- How accurate is the solver in terms of numerical dissipation?
- Are the SGS models effective at all?

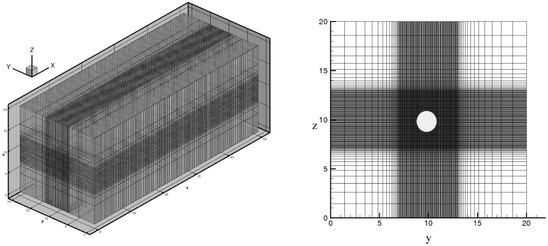
# Time averaged normalized eddy viscosity



# Results, Case 2:

***One rotor in laminar and turbulent inflow***

# Numerical set up




(h) (i)

Figure: (a) 3D view of the grid used for the simulations (b) white circle showing the location of the actuator line (7R downstream). The grid consists of $144 \times 144 \times 576$ (12 M) cells

DTU

# Numerical set up

- Spatial discretization: A hybrid scheme consisting of $4^{th}$ order central differencing and $3^{rd}$ QUICK for the convective terms and $2^{nd}$ order central differencing for the rest of the terms. $2^{nd}$ order backward Euler for the time integration
- Dimensionless time step: $dt^* = dt.u_\infty/R = 0.005$
- Fixed rotational speed of $1.8rad/s$ i.e, in 1 sec. 200 iterations and $100^o$ rotation. $Re_r = 50,000$ $(U_\infty = 1, R = 1)$.
- Actuator line with Gaussian smearing factor $\epsilon = 2.2\Delta$ used
- Two cases are run, one with laminar inflow and the other with 7% ambient turbulence applied on the upstream rotor

# Laminar inflow: Time averaged Streamwise velocity

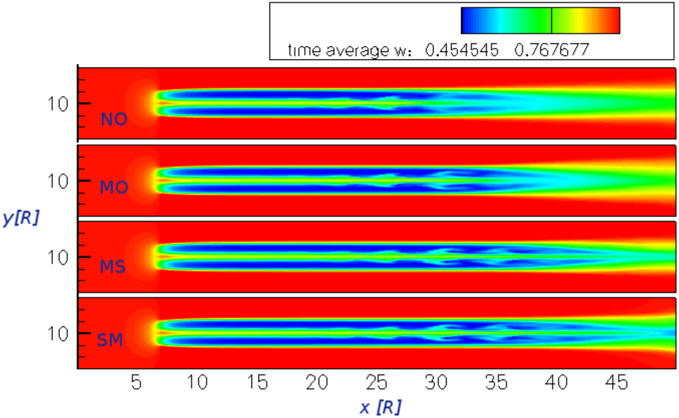
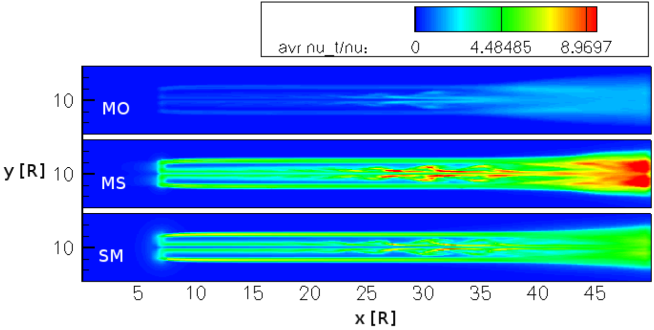



Figure: Streamwise mean velocity contours in laminar inflow

# Laminar inflow: Time averaged Eddy viscosity

The Mix-O predicts the lowest time averaged eddy viscosity (other than NO SGS case of course!).




(a)

Figure: Normalized eddy viscosity contours in turbulent flow

# Turbulent inflow: Time averaged Streamwise velocity

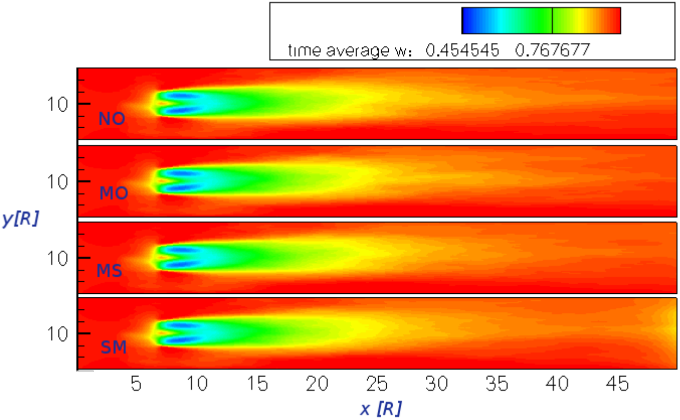
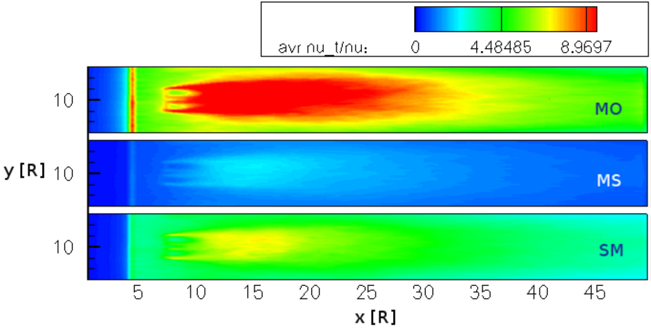



Figure: Streamwise mean velocity contours in turbulent flow

# Turbulent inflow: Time averaged Eddy viscosity

The Mix-S predicts the lowest time averaged eddy viscosity (other than NO SGS case of course!).

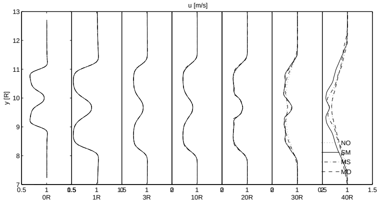



(a)

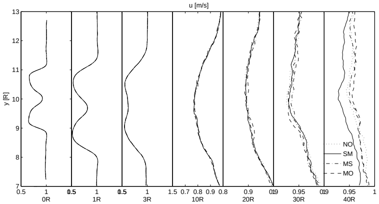
Figure: Normalized eddy viscosity contours in turbulent flow

DTU

# Laminar vs Turbulent inflow:Time averaged Wake deficit



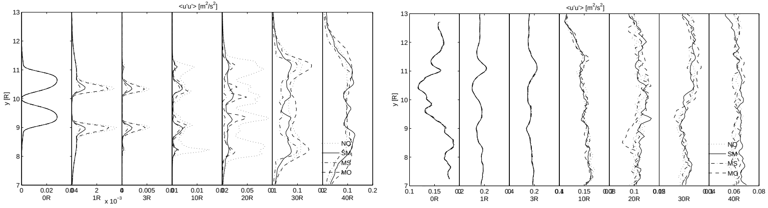

(a)




(b)

Figure: Wake development in (a) laminar and (b) turbulent inflow

# Laminar vs Turbulent inflow: $\overline{< u'u' >}$




(a) (b)

Figure: Comparison of stress tensor component $\overline{< u'u' >}$ for (a) laminar and (b) turbulent inflow

# Laminar vs Turbulent inflow: Time averaged Eddy viscosity

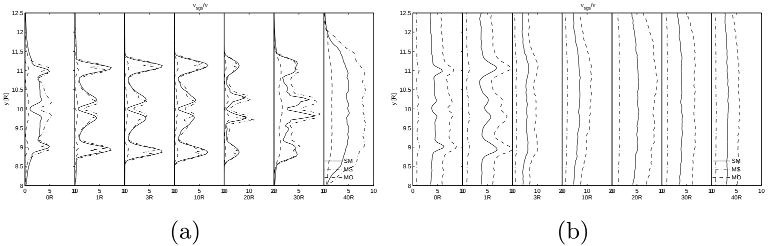



Figure: Comparison of the normalized eddy viscosity for (a) laminar asnd (b) turbulent inflow

# Conclusions

Wake structure behind actuator lines were simulated for two different cases up to 40 R downstream:

- The wake region in laminar inflow case grows less rapidly and extends further downstream in a more concentrate fashion, as compared to the turbulent inflow case, in which the wake grows (recovers) much faster
- Results show that the sub-grid scale models have a strong impact on the eddy viscosities
- Results show very little dependence of mean velocity profiles with respect to SGS models for both laminar and turbulent inflows, although in the very far wake, effects begin to be visible.
- Results show strong dependence of Reynolds stress profiles with respect to SGS models for the case of laminar inflow.