Wall-Resolved FSI Simulation of Modern Turbine Blades

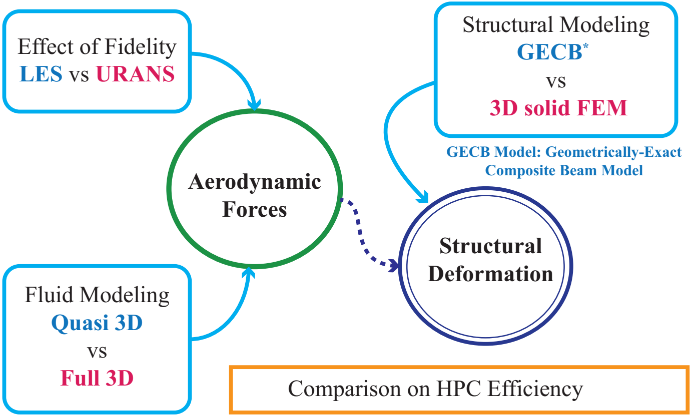
Assessment of fidelity on the aerodynamic forces and deformation of the blade

Mohsen Lahooti* **Rodolfo Puraca†** **Bruno Carmo†** **Rafael Palacios*** **Spencer J. Sherwin***

*Department of Aeronautics, Imperial College London
† Department of Mechanical Engineering, Escola Politécnica, University of São Paulo

Imperial College London

Objectives



Challenges

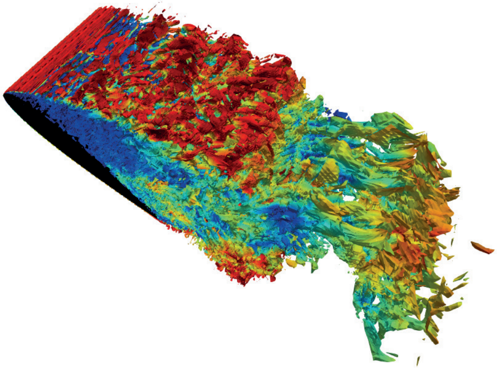
- **Separated flows**
  Thick boundary layer
  Leading/Trailing edges separation
  Vortex shedding/interactions
- **Anisotropic turbulence**

  High-fidelity methods (LES/DNS)

- **High *Re* flow**
  Grid Resolution $h/L \propto Re^{-3/4}$
  FLOPS scales as Re^3

  Efficient numerical method

  Highly scalable



LES simulation of NACA 0012 at
$Re = 1.56 \times 10^5 \quad \alpha = 16^\circ$
Q-criterion iso-contour colored by velocity

Overview of the two solvers

Nektar++/SHARPy

- High-fidelity (LES/DNS) method
- Quasi-3D approach: *Thick-strips*
- High-order spectral/hp method
- Beam model for structure
- Open-Source

OpenFoam/CalculiX

- Medium-fidelity (URANS) method
- Full 3D approach
- Second-order Finite-volume
- FEM modelling for structure
- Open-Source

Numerical Method

Thick Strip LES method

3*D* domain models as separate smaller domains: *Thick Strips*

- Spanwise thickness L_z
- Capturing local 3*D* turbulence
- Reduces computational expense
- Implicitly connected by structural dynamics
- High order hp elements in *xy*
- Fourier expansion in spanwise (*z*) direction

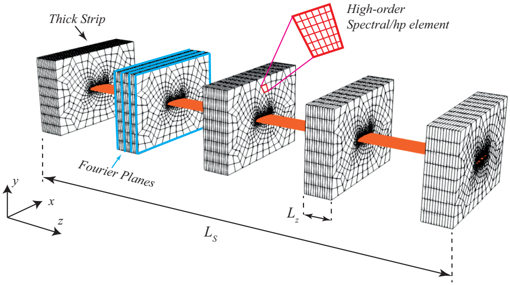


Figure: Ref- AIAA SciTech21

Imperial College London

Nektar++/SHARPy FSI Solver

Flow Solver

- Transformed Navier-Stokes equations
- Coordinate transformation to avoid remeshing

Inertial Coord. Body-fitted Coord.

$$\bar{\mathbf{X}}(\bar{x}, \bar{y}, \bar{z}) \to \mathbf{X}(x(t), y(t), z(t))$$

- High-order Spectral/hp element method
- P-order polynomial expansion in xy
- Fourier expansion in z
- High-order stiffy-stable velocity splitting velocity correction scheme
- **Nektar++** www.nektar.info

Structural Solver

- Flexible multi-body solver
- Geometrically-Exact Composite Beam model
- Non-linear high deformation
- Static and Dynamic formulation
- Quadratic Finite Element method
- Newmark-β time integration
- ***SHARPy*** www.imperial.ac.uk/aeroelastics/sharpy/

OpenFoam/CalculiX FSI Solver

Flow Solver – OpenFoam

- Finite volume method
- OpenFoam solver: pimpleFoam (operating in PISO mode)
- URANS (k-w SST)
- Backward time scheme (Second Order)
- Simulation dt: 5×10^{-5} s
- **OpenFoam** www.openfoam.com

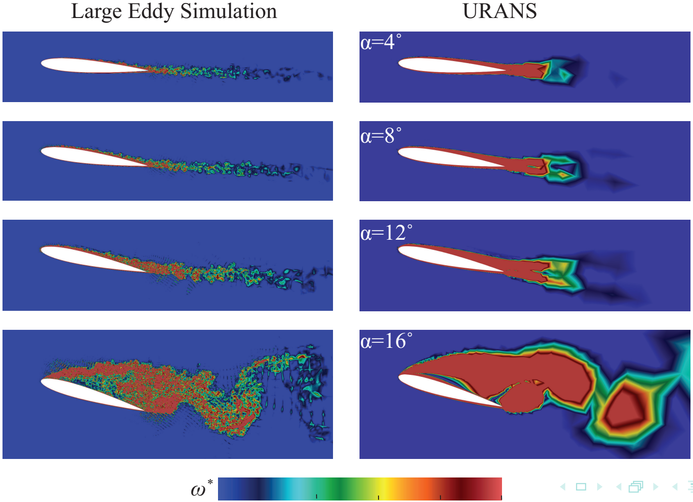
Structural Solver - CalculiX

- FEM with solid elements
- CalculiX solver: Nonlinear Dynamic Direct solver using Spooles
- Solid Section structure
- Orthotropic Elastic Material
- Simulation dt: 5×10^{-5} s
- **CalculiX** calculix.de

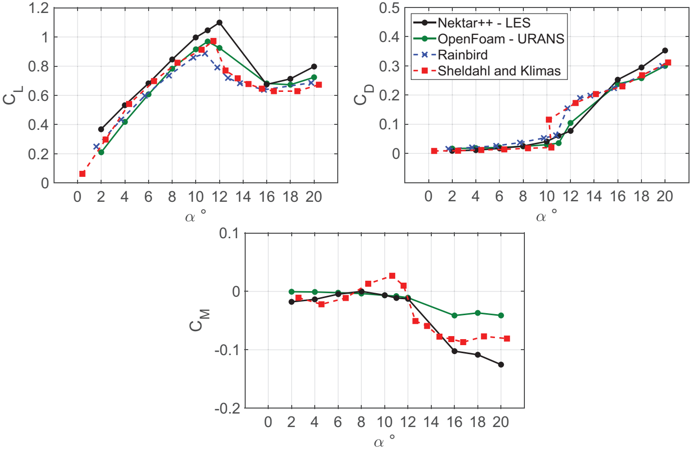
Coupling through preCICE (precice.org)

Flow over *NACA0012* section

Vorticity contours $Re = 1.56 \times 10^5$



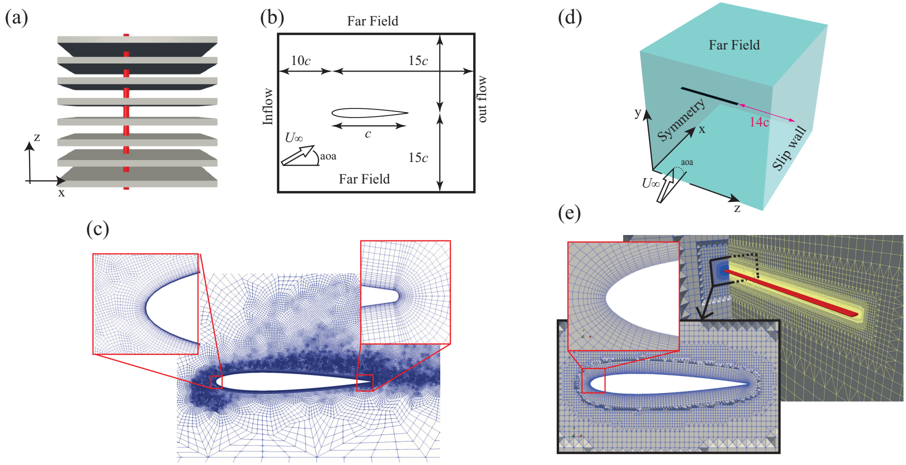
NACA0012 Aerodynamics coefficients



FSI of Cantilever blade

Imperial College London

Computational Domain



Imperial College London

Flow conditions

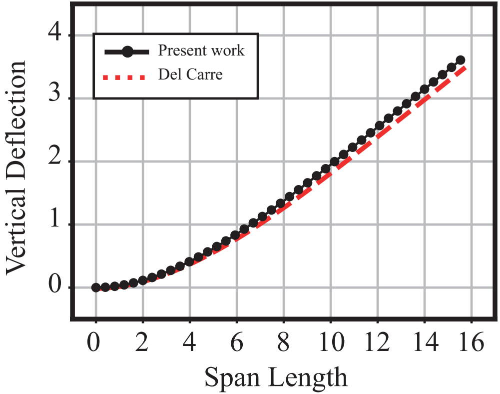
Parameter	Value
Re	1.56×10^5
$U_\infty [ms^{-1}]$	25
$g \quad [ms^{-2}]$	9.754
$c \quad [m]$	1
$L_s^* = L/c$	16

	Nektar++	OpenFoam
$DoF[\times 10^6]$	15.2	9.1
y^+	< 1	100
L_z^*	1	$--$
N_{strips}	8	$--$

Imperial College London

Cantilever Blade: Equilibrium before stall

- $Re = 1.56 \times 10^5$
- Angle of attack $\alpha_0 = 4^\circ$
- $g = 9.754\ m/s^2$
- Del Care: beam + UVLM
- Number of Strips $N_s = 4, 8, 12$ tested, $Ns = 8$ selected

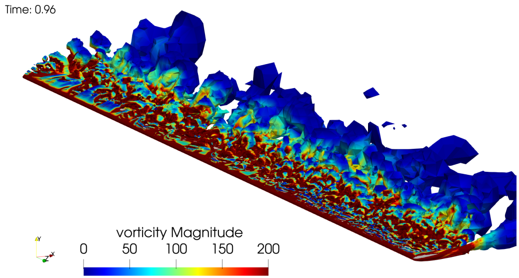


3D effect and tip loss correction

Tip loss Correction

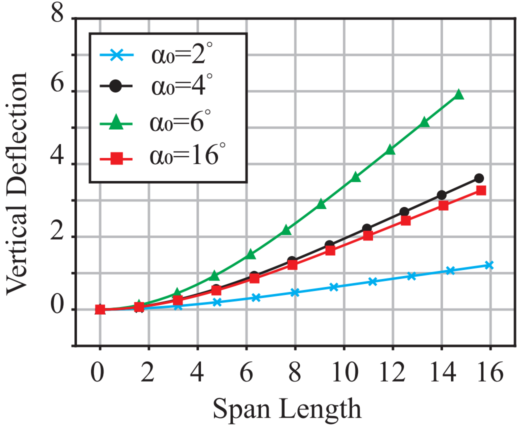
$$F_{\text{tip}} = \frac{2}{\pi}\arccos\left(e^{-b\frac{1-s^*}{s^*}}\right)$$

$$s^* = z/L_s$$



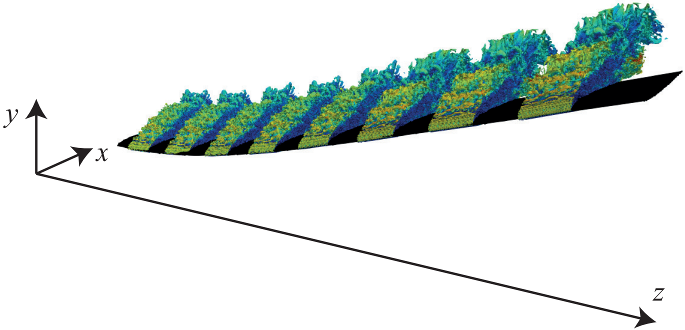
Imperial College London

Effect of α_0 on the blade Deformation



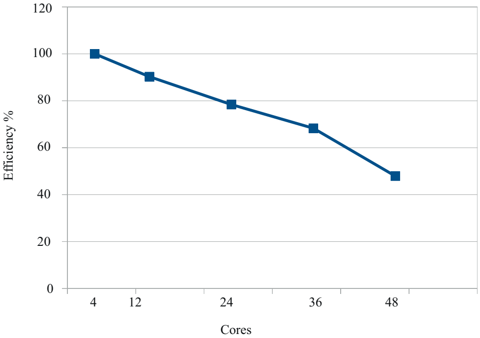
Cantilever Blade at stall

- $Re = 1.56 \times 10^5$
- $\alpha_0 = 16°$
- $g = 9.754\ m/s^2$
- 8 Strips
- Iso-contour $Q = 10$
- Color $|\mathbf{V}^*| = [0 - 2]$

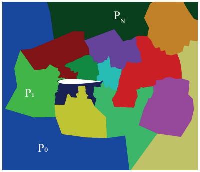


HPC Performance and Efficiency

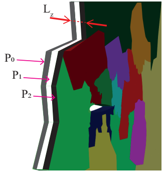
OpenFoam/CalculiX



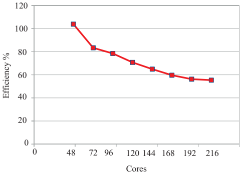
Nektar++/SHARPy: Strong scaling

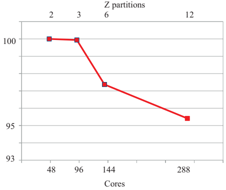


Domain decomposition in xy plane

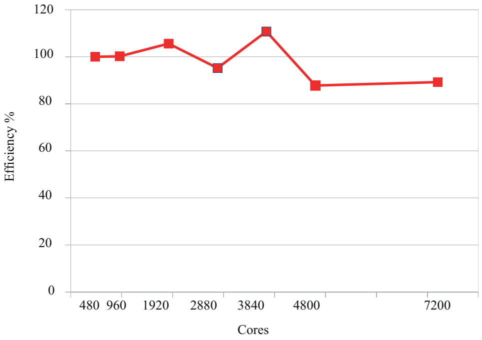


Partitioning in Z direction





Nektar++/SHARPy: Weak Scaling



Imperial College London

Comparison of the two solvers

Nektar++/SHARPy

- Resolved turbulent structures
- Captures the anisotropic turbulence
- restricted to beam model for solid
- Quasi-3D flow field
- Highly-scalable
- High computational cost
- Enabling FSI LES/DNS simulation for very slender structure
- Suited for moving structures with massively separated flows

OpenFoam/CalculiX

- RANS modeling
- Captures isotropic turbulence
- Flexibility on solid modeling
- Full 3D flow field
- Good scalability
- lower computational cost
- Suited for medium-stage design in industry
- Suited for structures with low flow separation

Conclusion

- Two FSI solvers are developed for for highly-deformable slender structure
- Each targeted specific range of application
- Both needs high performance computations
- Comparison on the aerodynamic coefficients are presented
- Work is in progress for comparison of the deformations

Wall-Resolved FSI Simulation of Modern Turbine Blades

Dr. Mohsen Lahooti*

MSc. Rodolfo Puraca†

Dr. Bruno Carmo†

Prof. Rafael Palacios*

Prof. Spencer J. Sherwin*

* Department of Aeronautics, Imperial College London

† Department of Mechanical Engineering, Escola Politécnica, University of São Paulo

This project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement No 828799.

High Performance Computing in Wind Energy (https://www.hpcwe-project.eu/)

Thanks from ICL to Dr. David Scott and EPCC for helping on the scaling test for Nektar++/SHARPy solver

Thanks to EPSRC for the computational time made available on the UK supercomputing facility ARCHER via the UK Turbulence Consortium (EP/R029326/1)

Thanks to Imperial College HPC for the computational time made available