Near-wake resolving FSI of wind turbine using high-fidelity simulation

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Overview

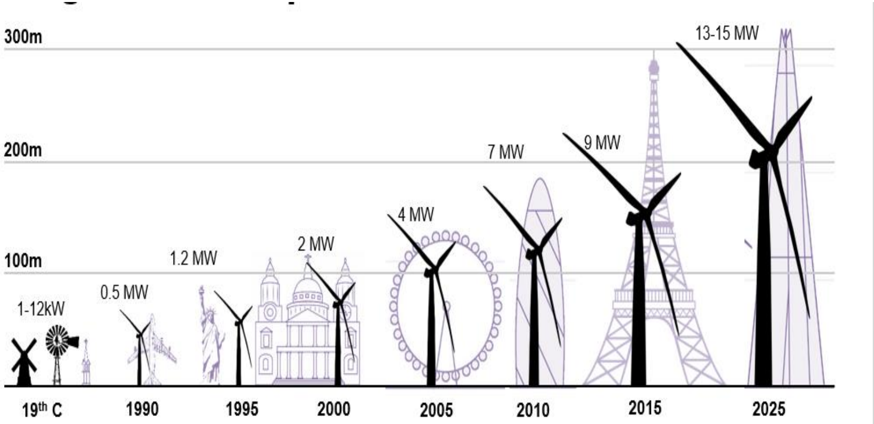
- Motivation
- Thick Strip method
- Numerical formulation
- Hybrid parallelization
- Numerical Tests
- Conclusion

Motivation

- Modern wind turbines aims at increasing output power
- Increase in size
- Large flexible blades
- Strong fluid-structure interaction

Source: powermag.com
https://www.powermag.com/ge-is-acquiring-worlds-largest-wind-turbine-blade-manufacturer/

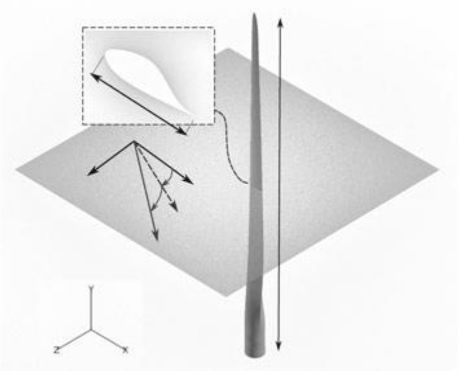
Evolution of wind turbine size and output

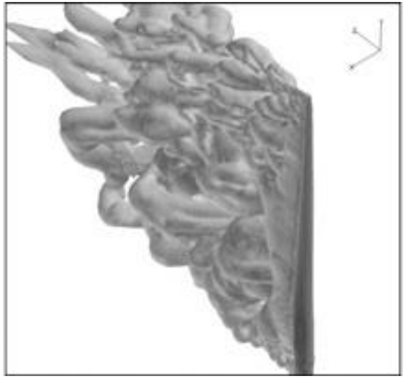


Source: Bloomberg New Energy Finance

Computational challenges in parked rotor modelling

- New design criteria: VIV of blade in parked condition
- High Re number
- Massively separated flows
- Anisotropic turbulence
- Requires high-fidelity simulation
- Number of DOF increases as $N^3 \geq Re^{9/4}$
- FLOPS scales $\propto Re^3$



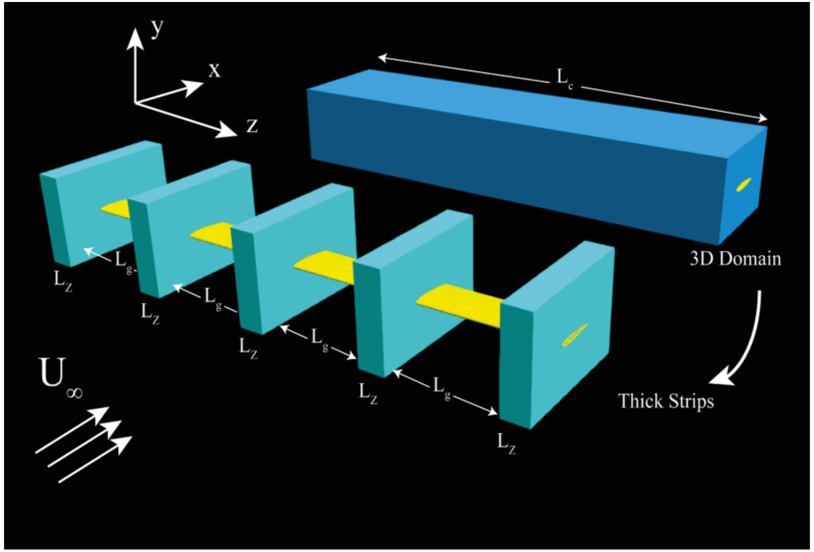


Figures Source: González et.al (2019)

Absolute vorticity contour
AVATAR 10 MW blade
95 deg AoA, Re~10M
DDES (8M cells) + beams

Thick strip method

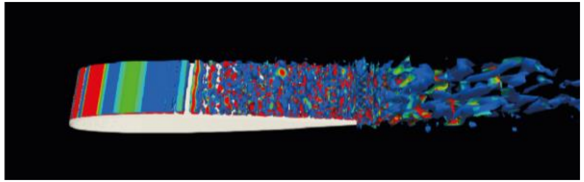
- 3D domain is modelled as several discrete fluid domains with finite length in spanwise direction, *thick strips*
- Each *strip* has a thickness of Lz
- Enables Capturing the local spanwise velocity correlations and locally 3D effects
- Strips are connected via structural dynamics



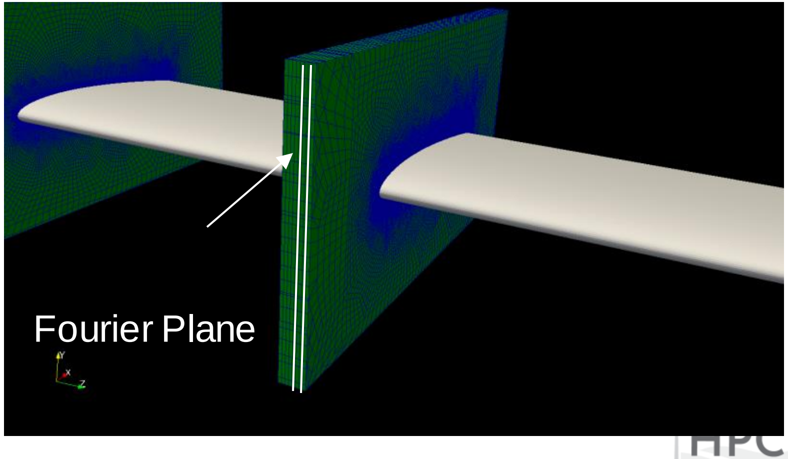
How does the *thick strip* method help?

- Requires minimum 8 Fourier planes per 10% of chord to estimate the forces
- Each plane have 2500 spectral elements
- blade with L=100c
  - Full 3D: Minimum 8000 planes!
  - Thick strip with 20 strips and Lz=0.2c : 320 planes
  - 96% reduction
  - Do need to understand what scale flow physics are tightly coupled

Even with use of thick strip method, still at least 10k+ cores is required for practical simulation of real flow conditions with $Re \sim O(10^6 - 10^7)$



Q-Criterion
Naca0012
Lz = 0.2
Re=150,000



Numerical Formulation

Nektar++/SHARPy coupling

The Nektar++/SHARPy FSI solver has been developed for VIV of slender cables in marine applincations

We are further developing it for wind turbine applications

- **Fluid Flow (Nektar++)**
  - Navier-Stokes Eq.
  - Spectral/hp element discretization
- **Structural dynamics (SHARPy)**
  - Geometrically-Nonlinear composite beams
- **FSI coupling (Nektar++/SHARPy)**
  - Explicit temporal coupling of two solvers

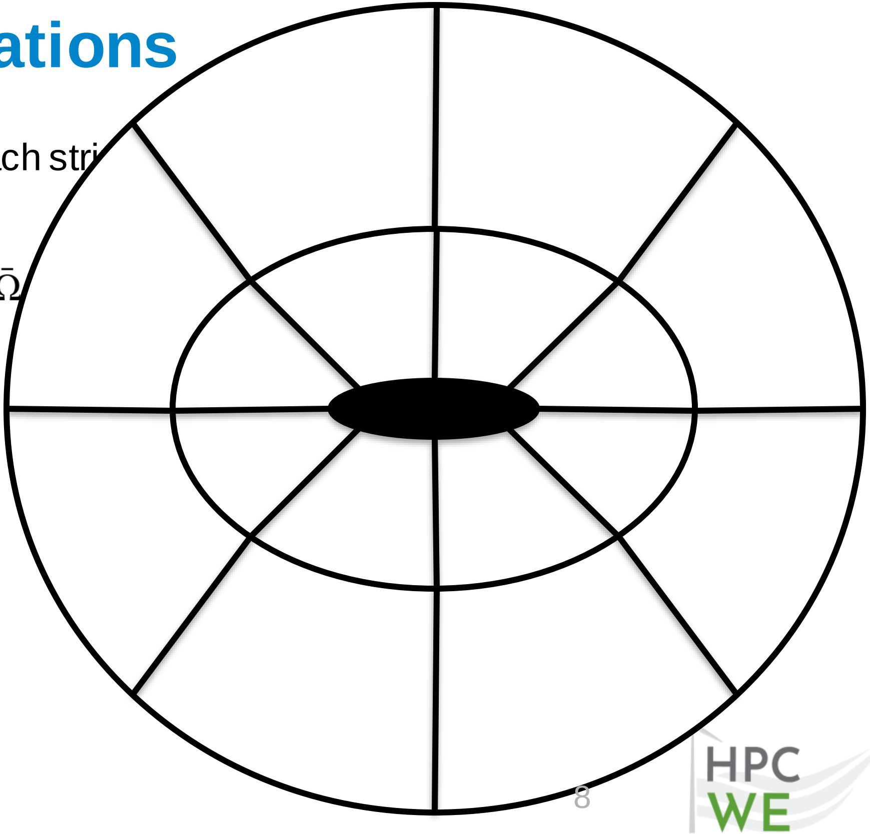
Fluid Flow: Navier-Stokes Equations

- Navier-Stokes in inertial coordinate $\overline{\mathbf{X}} = (\bar{x}, \bar{y}, \bar{z})$ in each stri

$$\frac{\partial \bar{\mathbf{u}}_n}{\partial t} + \bar{\mathbf{u}}_n \cdot \bar{\nabla}\bar{\mathbf{u}}_n = \frac{-1}{\rho}\bar{\nabla} p_n + \nu \bar{\nabla}^2 \bar{\mathbf{u}}_n$$

$$\bar{\nabla} \cdot \bar{\mathbf{u}}_n = 0$$

$\bar{\Omega}$



- Large deformation of structure would cause mesh deformation and distortion

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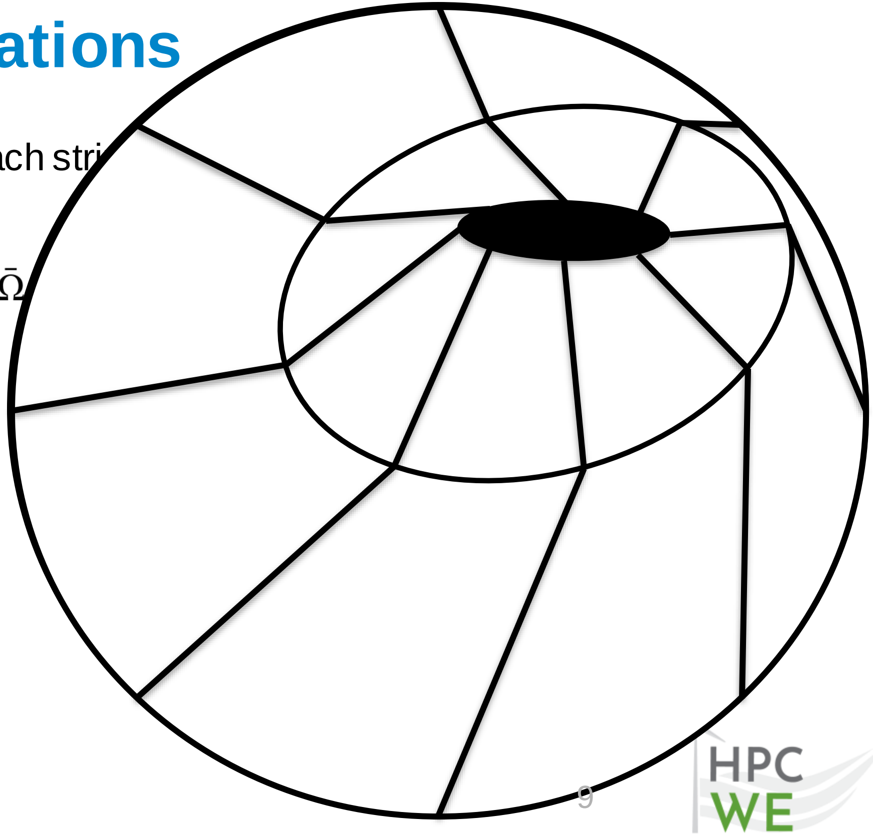
Fluid Flow: Navier-Stokes Equations



- Navier-Stokes in inertial coordinate $\overline{\mathbf{X}} = (\bar{x}, \bar{y}, \bar{z})$ in each stri

$$\frac{\partial \bar{\mathbf{u}}_n}{\partial t} + \bar{\mathbf{u}}_n \cdot \bar{\nabla} \bar{\mathbf{u}}_n = \frac{-1}{\rho} \bar{\nabla} p_n + \nu \bar{\nabla}^2 \bar{\mathbf{u}}_n$$

$$\bar{\nabla} \cdot \bar{\mathbf{u}}_n = 0$$

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- Large deformation of structure would cause mesh deformation and distortion

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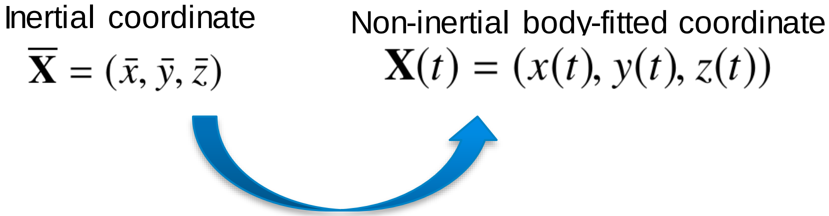
Mapping: Transformed NS equations

- Avoiding dynamic re-meshing
- Coordinate transformation
- Non-inertial body-fitted coordinates


Inertial coordinate

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

Non-inertial body-fitted coordinate

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

$$J = \left|\frac{\partial \bar{\mathbf{X}}}{\partial \mathbf{X}}\right| = \left|\frac{\partial \bar{x}_i}{\partial x_j}\right|$$

Navier-Stokes eq. in transformed coordinates

$$\frac{\partial \mathbf{u}_n}{\partial t} = \mathbf{N}(\mathbf{u})_n - \mathbf{G}(p)_n + \mathbf{L}(\mathbf{u})_n$$

$$\mathbf{D}(\mathbf{u})_n = 0$$

$$\mathbf{N}(\mathbf{u})_n = -u^j u^i_{,j} + V^j u^i_{,j} - u^j V^i_{,j}$$

$$\mathbf{G}(p) = g^{ij} p_j$$

$$\mathbf{L}(\mathbf{u}) = \nu g^{jk} u^i_{,jk}$$

$$\mathbf{D}(\mathbf{u}) = \frac{1}{J} \nabla \cdot (J u^j)$$

$$V^j = -\frac{\partial x^j}{\partial t}$$

Spectral/hp element method [Nektar++]

- Approximation of $u(x,y)$ using tensor product of basis functions in xy domain

$$u^{\delta}(x,y) = \sum_n \phi_n(x,y)\hat{u}_n = \sum_n \phi_p(x)\phi_q(y)\hat{u}_{pq}$$

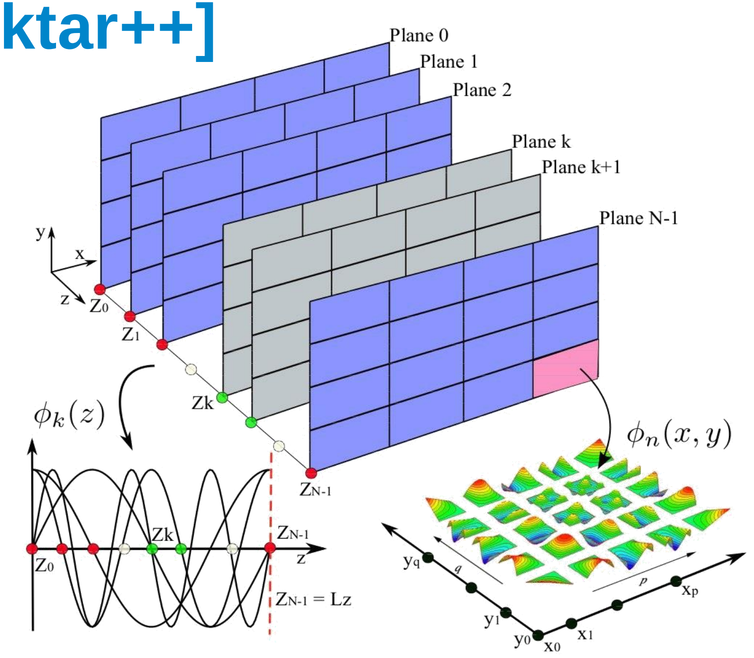
$$u^{\delta}(x,y) = \sum_n \phi_{pq}(x,y)\hat{u}_{pq}$$

- Approximation of $u(z)$ using Fourier expansion

$$u^{\delta}(z) = \sum_n \phi_n(z)\hat{u}(z_j) = \sum_{n=0}^{N-1} \hat{u}_k\, e^{ikz_j}$$

- Final approximation to discrete variable $u^{\delta}(x,y,z)$

$$u^{\delta}(x,y,z) = \sum_{pqk} \phi_{pq}(x,y)\phi_k(z)\hat{u}_{pqk}$$



Source of figure: Bolis 2013

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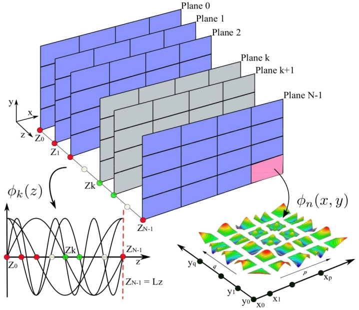
Spectral/hp discretization of N.S. equations

- Using Fourier expansions with total number of M modes

$$\mathbf{u}_n(\mathbf{x},t) = \sum_{m=0}^{M-1} \hat{\mathbf{u}}_{\mathbf{nm}}(x,y,t)\, e^{i\beta m z} \qquad p_n(\mathbf{x},t) = \sum_{m=0}^{M-1} \hat{p}_{nm}(x,y,t)\, e^{i\beta m z} \qquad \beta = 2\pi/L_z$$

- Navier-Stokes equation: Set of 2D decoupled equation for each mode

$$\frac{\partial \hat{\mathbf{u}}_{nm}}{\partial t} + \widehat{\mathbf{N}(\mathbf{u}_n)}_m = \frac{-1}{\rho}\tilde{\nabla}\hat{p}_{nm} + \nu\tilde{\nabla}^2\hat{\mathbf{u}}_{nm} + \hat{\mathbf{f}}_{nm} \qquad \tilde{\nabla}\cdot\hat{\mathbf{u}}_{nm} = 0$$



Source of figure: Bolis 2013

- Spatial discretization using high order spectral/hp element
- Pressure-velocity system solved using stiffy stable high-order velocity correction scheme

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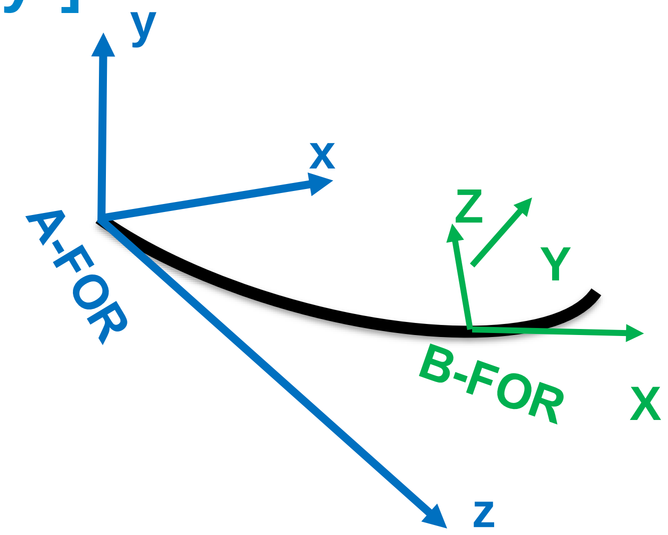
Structural dynamics [SHARPy]

- Long rotor blades approximated by beam
- Geometrically-exact composite beam equation
- Non-linear and high deformation
- Representing the structure using two frame of reference (FOR)
- Using Hamiltonian principle and FEM discretization, final form of discrete equation

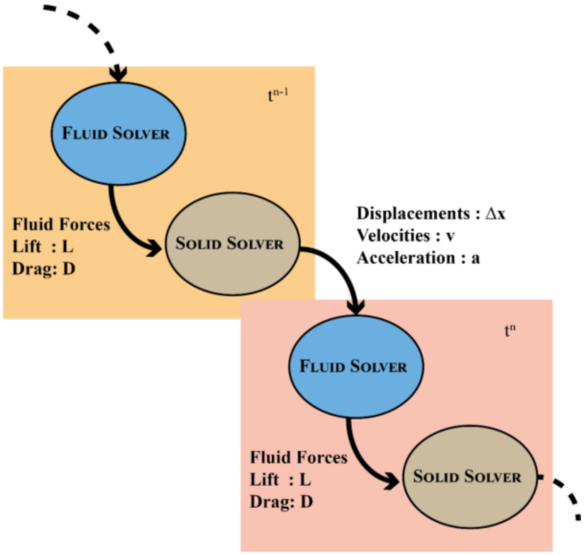
$$\mathcal{M}_{\eta}(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}} + \mathbf{Q}_{gyr}(\boldsymbol{\eta}) + \mathbf{Q}_{stif}(\boldsymbol{\eta}) = \mathbf{Q}_{ext}(\boldsymbol{\eta})$$

- $\boldsymbol{\eta}$ is state variable (displacements and rotations)
- Gyr, strif and ext: gyroscopic, stiffness and external forces



A-FOR is body fixed
B-FOR is local frame attached to elements

FSI Loose Coupling

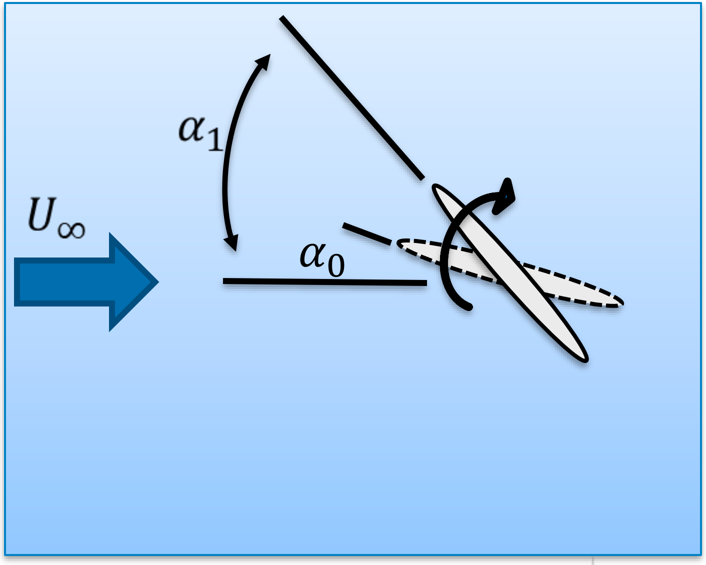


- Get **x**, **v** and **a** from SHARPy
- Update domain mapping, calculate source terms for Navier Stokes Equation
- Solve Flow Fields
- strip-wise integration of surface tractions
- consistent interpolation to structural nodes
- Solve structure dynamics
- send **x**, **v** and **a** to Nektar++

Loose coupling typically robust for high mass ratio

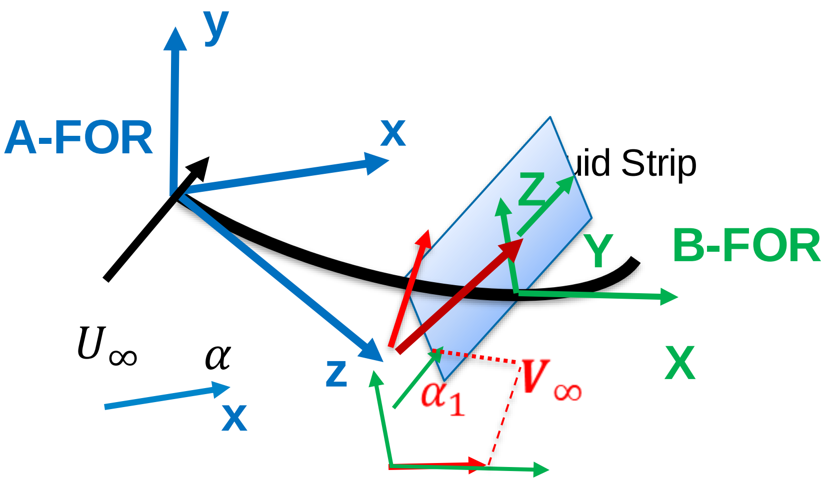
New feature of the FSI solver: Structural torsion

- Rotation of structure changes the effective angle of attach and hence fluid forces and moments
- Nektar++/SHARPy coupling have been used for marine Viv of slender cables
- Having only translational mapping (in old solver) flow can not see this effect.
  - Using rotational mapping
  - Correction of inlet velocities



Inlet velocity correction

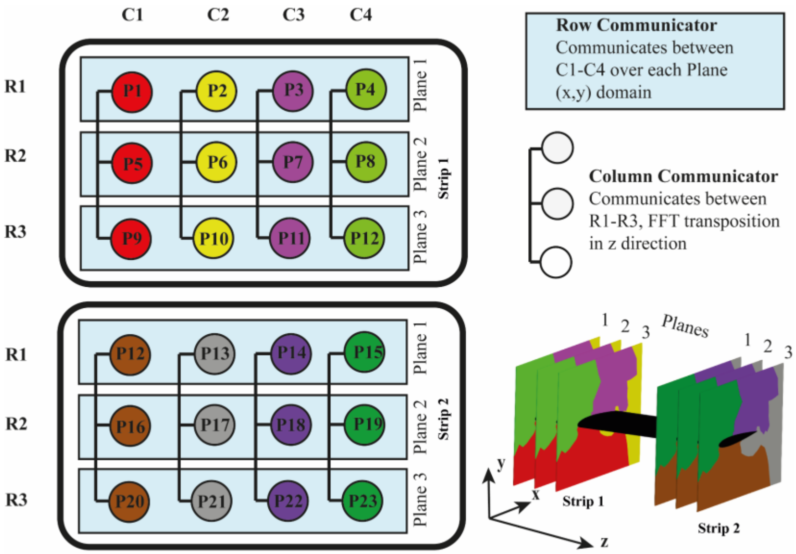
- From Solution of structure, Cartesian rotation vector Ψ is computed at each structural node
- Rotation matrix is computed at those nodes $\boldsymbol{C}^{AB}(\Psi)$
- New velocities computed at each structural nodes $\boldsymbol{V}_\infty = \boldsymbol{C}^{AB}(\Psi) \cdot \boldsymbol{U}_\infty$
- Computed velocities are interpolated to the location of strips



- Velocity vector is modified at inlet boundary of each strips
- Suitable for final static deformation.
- *For dynamic response simulation*, rotational mapping will be incorporated into solver.

Efficient use of resources by leveraging Hybrid parallelization

- MPI communicator splits down into Cartesian like array
- Rows communicators for domain decomposition
- Column communicators for FFT transposition
- Each column further breaks down into rows (strips) and columns (Fourier planes in each strips)



Row Communicator
Communicates between C1-C4 over each Plane (x,y) domain

Column Communicator
Communicates between R1-R3, FFT transposition in z direction

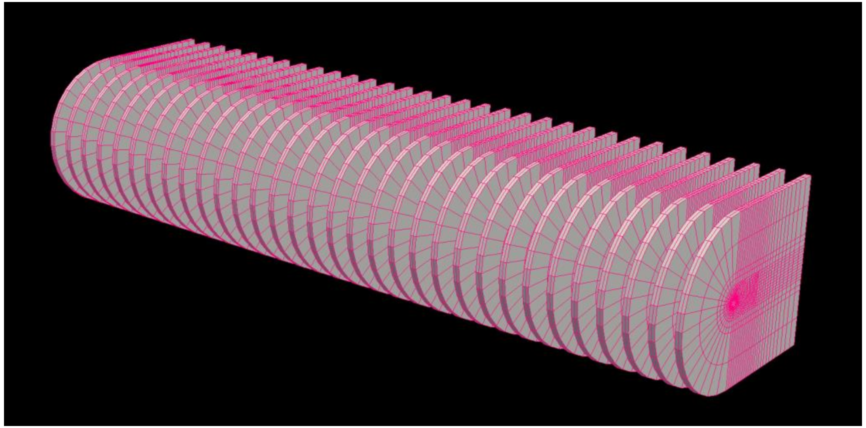
Allows us to leverage multi-core architecture with a direct solver

Numerical Tests

Flow over slender cable

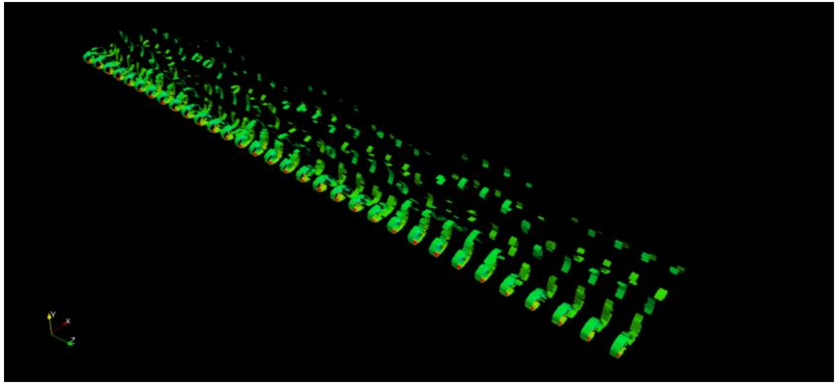
Reproducing the problem from Bao et al. 2016.

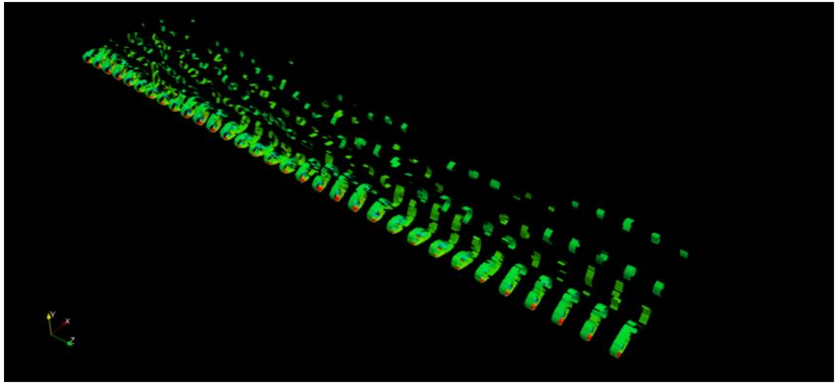
- Re = 500
- $L^* = \frac{L}{D} = 32\pi$
- 16 strips
- $L_Z^* = {}^{\pi}/_{8}$
- 283 spectral elements
- NumModes = 6
- $\frac{\rho_{cylinder}}{\rho_{fluid}} = 1.64$
- $\frac{EI}{\rho U^2 D^4} = 264$ $\frac{EA}{\rho U^2 D^2} = 2.52 \times 10^8$



Thick strips distribution along the cable

Vorticity contours showing traveling waves as a result of cable motion





$t^* = 112$

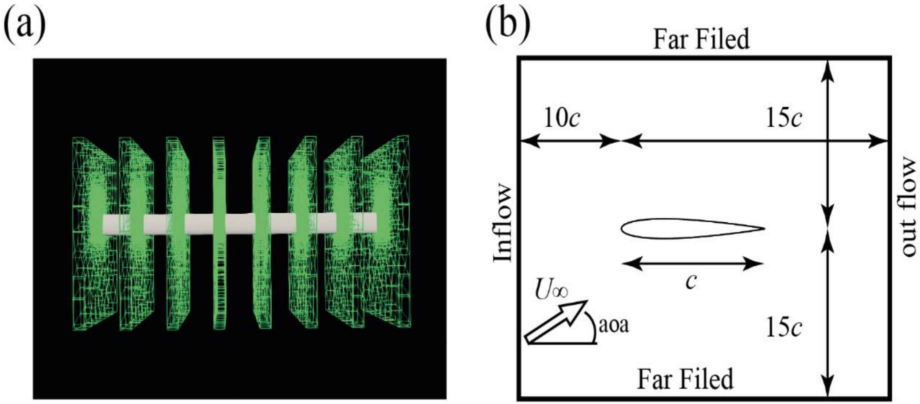
$t^* = tU_\infty/D$

$t^* = 450$

Static deformation of slender blade

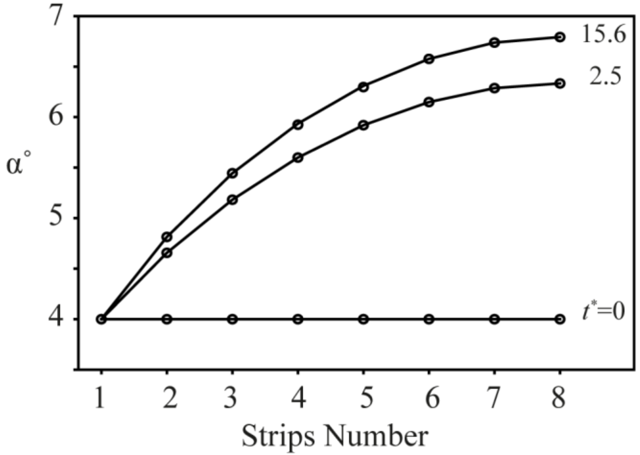
- Re = 1.56×10^5
- Blade section NACA0012
- $L = 16\,m$
- 8 Strips
- 8 Fourier planes per strips
- $L_z^* = 0.1$
- $U_\infty = 25\,m/s$
- $g = 9.754\,m/s^2$

The problem definition is taken from
Smith et al. 2001.
Simpson and Palacios 2013

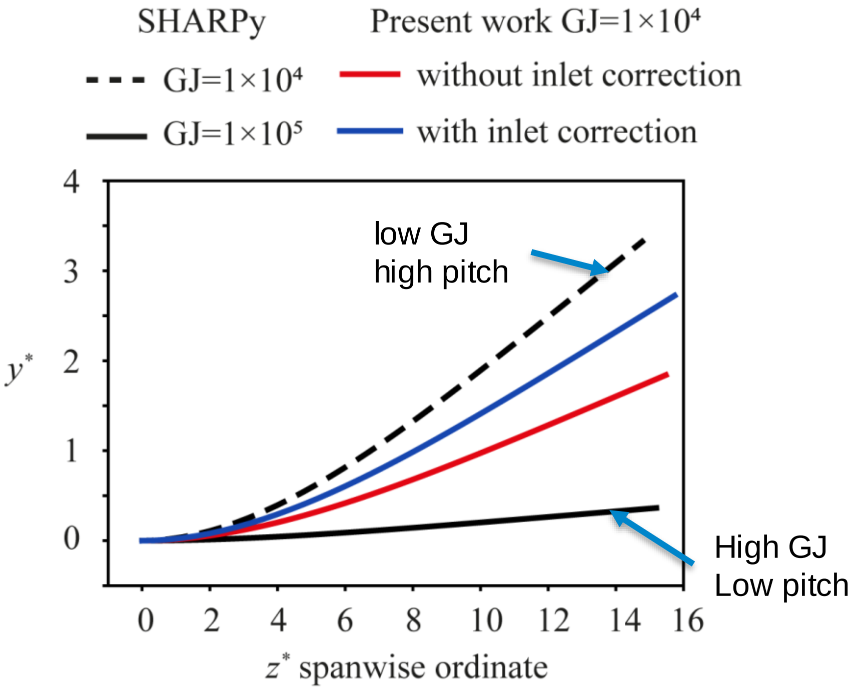


a) Solution domain consisting of the blade and thick strips
b) Schematic of the solution domain (side view) with domain dimensions and boundary conditions

Deformation in vertical plane and evolution of AoA



Change of angle of attack for each strip over the time



Effect of blade torsional motion on deformation

Conclusion

- High-Fidelity FSI simulation tool using Nektar++/SHARPy coupling
- Efficient LES approach using thick strips methods
- Targeting massively separated flows with high angle of attach for blades in parked conditions
- Efficient use of computational resources via hybrid parallelization
  - Looking to leverage effort in vectorization by Nektar++ team
  - Collaboration with EPCC, University of Edinburgh for profiling and scaling test of the FSI code
- Adding rotational mapping for coordinate transformations and torsional movement of structure
- Development of fluid solver to support non-constatnt cross sections along the structure

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