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Development of an Anisotropic Pressure Fluctuation Model for the Prediction of Turbulence-Induced Vibrations of Fuel Rods

K. Zwijsen (NRG), N. van den Bos (NRG), E.M.A. Frederix (NRG),
A.H. van Zuijlen (TU Delft) & F. Roelofs (NRG)

ANS Webinar - Year in Review: Nuclear Thermal Hydraulic Achievements of 2023
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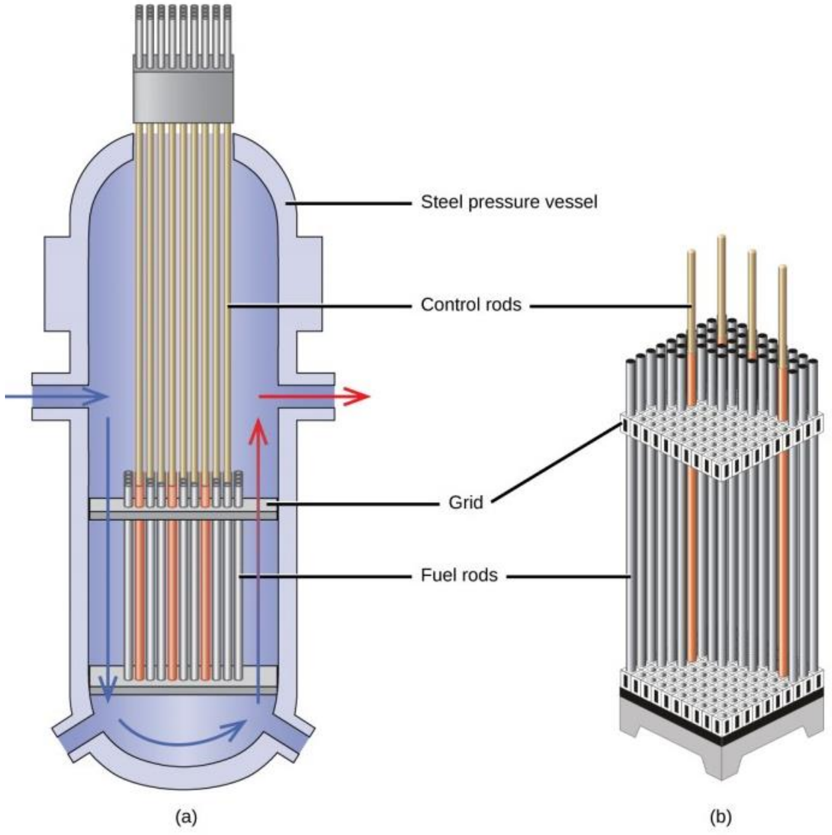
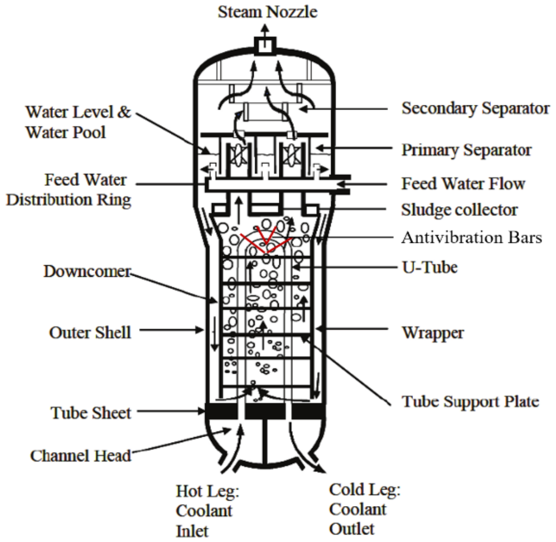
Flow-Induced Vibrations in NPPs

- FIVs are driven by energetic flow that contacts a flexible structure
- In NPPs: coolant impinging on slender structures
- FIV might appear in steam generators (SG), reactor cores and other plant components
- FIV may increase in time as a result of:
  - altering the nominal conditions
  - accidents/transients
  - ageing and degradation of structures
- FIV lead to material wear and eventually structure damage
  - substantial costs due to unplanned/longer outages
- Therefore, reactor components have to be designed against FIV



FIV in Steam Generators (SGs)

- Cross-flow at inlet and U-bend
- Flow-induced forces can lead to Steam-Generator Tube Rupture (SGTR)



PWR SG schematic (Bonavigo, 2011)

Mihama (Japan), 1991
SGTR upper U-bend
Activation of the ECCS
Caused by incorrect insertion of anti-vibration bars 20 years before
Replace SG

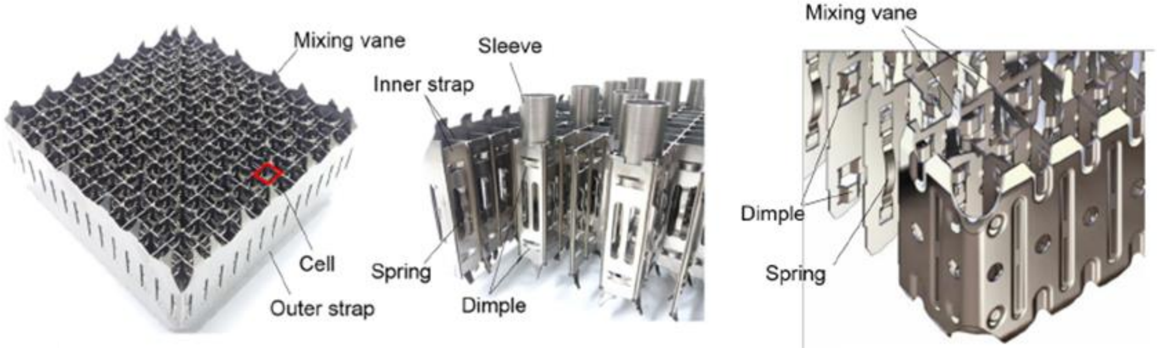
San Onofre (US), 2012
(NRC website)

- SG tube leak in unit 3 > shutdown
- SGs replaced in 2011
- Unexpected wear in ~10% of tubes (units 2 & 3)

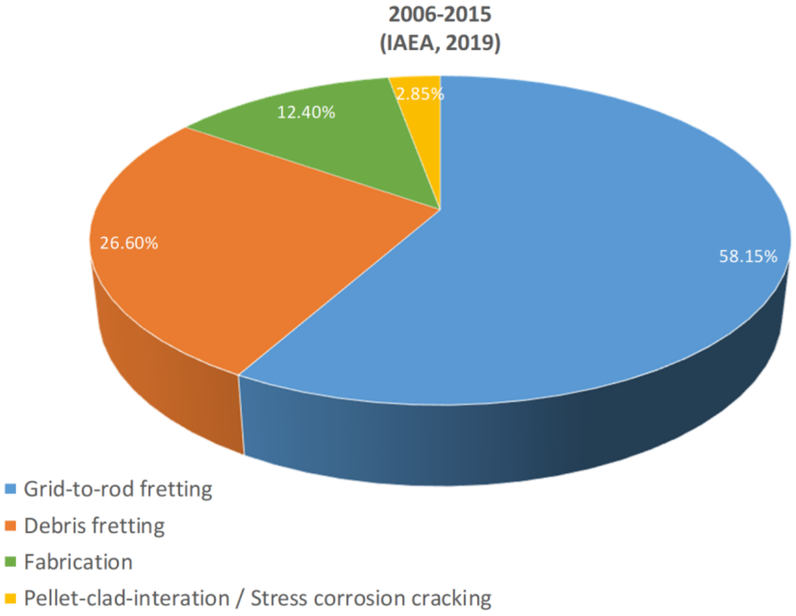
Permanent shut-down of both units

FIV in Fuel Assemblies (FAs)

- Grid-to-rod fretting is the largest source of fuel damage in PWRs (IAEA, 2019)
- In period 2006-2015: 58% of fuel damages in PWRs due to grid-to-rod fretting



Spacer grid scheme (Yoo et al., NED, 2019)



Grid-to-rod fretting in an EDF PWR 1300 (IAEA, 2010)

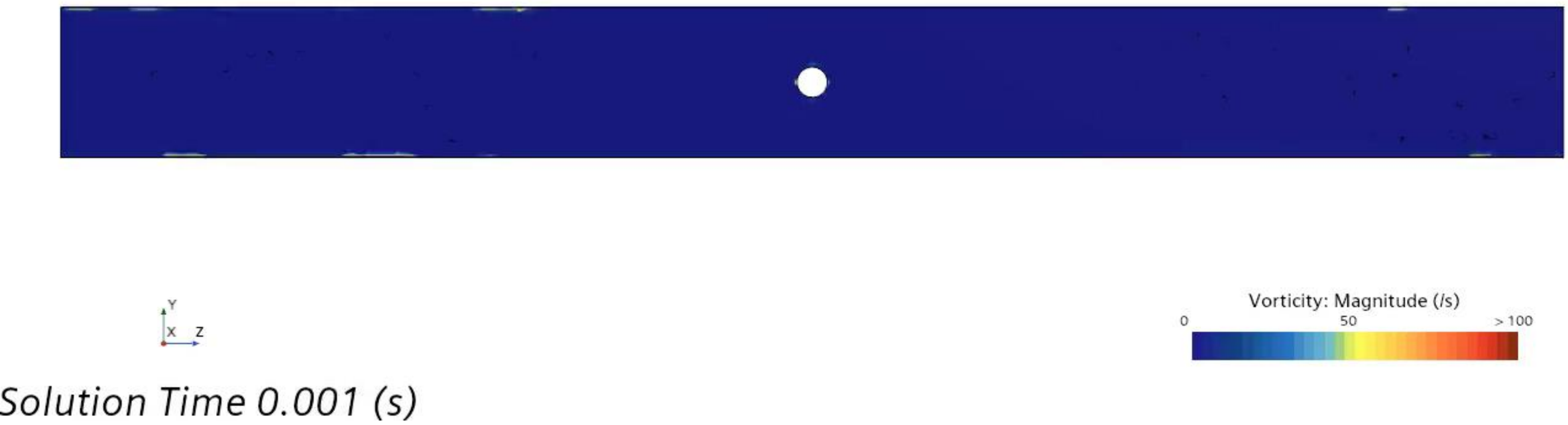
Flow-Induced Vibration excitation mechanisms

Flow excitation mechanisms, classified according to Pettigrew et al. (NED, 1998):

- Periodic Wake Shedding: occurs immediately downstream of structures subjected to cross flow. When periodic wake shedding occurs periodic fluid forces are generated. If the periodicity of the fluid forces coincide with the natural frequency of the structure resonance may occur. Known as Vortex-Induced Vibration (VIV).
- Turbulence Excitation: Locally or upstream generated turbulence resulting in random pressure fluctuations around the surface of components causing them to vibrate. Known as Turbulence-Induced Vibration (TIV).
- Acoustic Resonance: occurs when the periodic wake shedding frequency coincides with the natural frequency of the acoustic cavity formed by the structures surrounding the tube bundle.
- Fluid Elastic Instability: This is a result of coupling between fluid-induced dynamic forces and the elastic vibration of structures. When the energy absorbed by structure from the fluid dynamic forces is higher than the energy dissipated by damping, instability occurs. This occurs beyond a certain critical velocity.

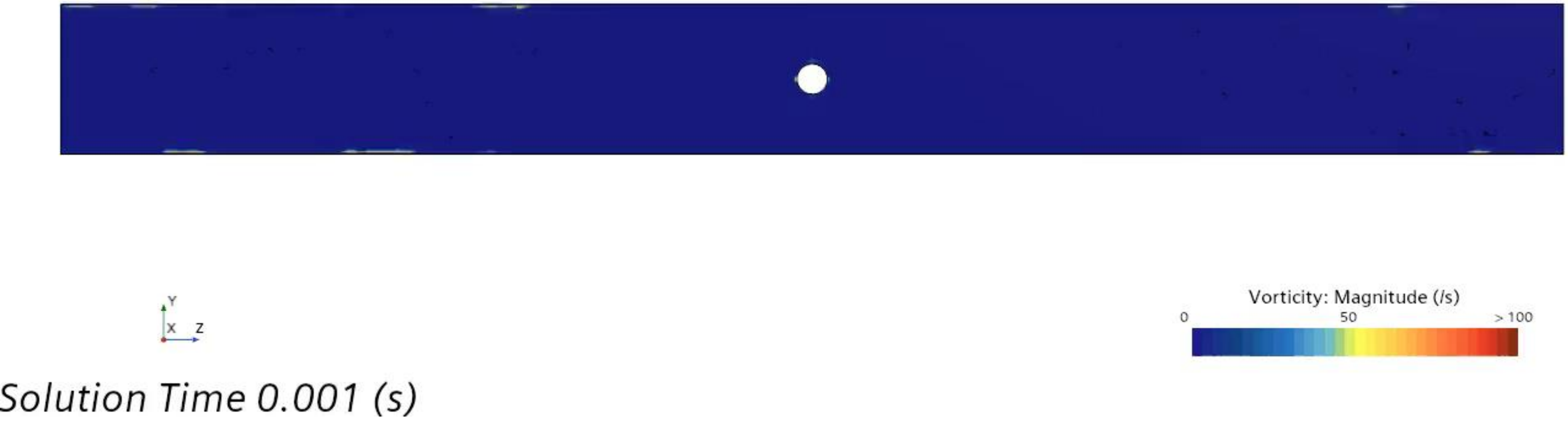
Vortex-Induced Vibration: no resonance

Vortex-Induced Vibrations: no resonance → small displacements



Vortex-Induced Vibration: resonance

Vortex-Induced Vibrations: resonance → large displacements

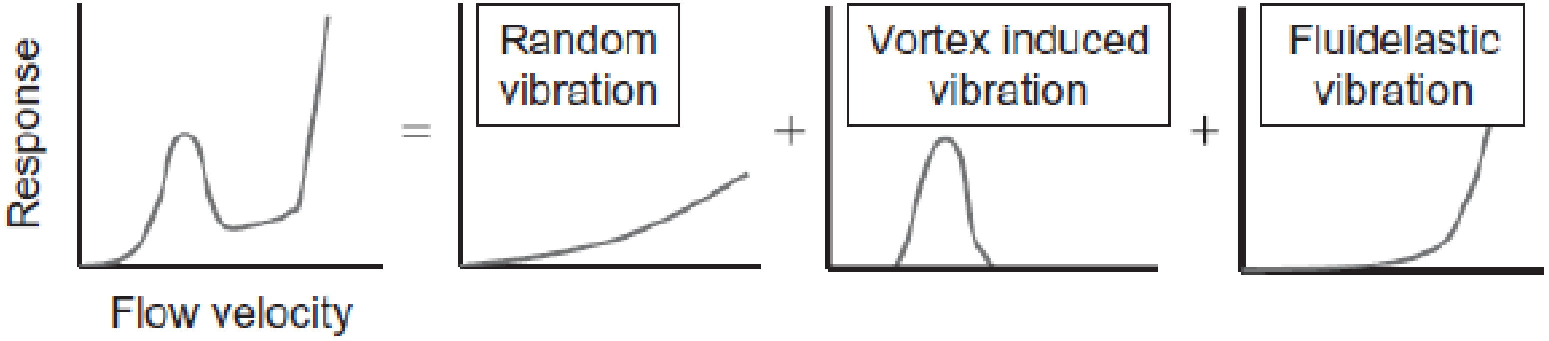


FIV impact for NPPs

Flow excitation mechanisms impact for Nuclear Power Plants (NPPs):

- Periodic Wake Shedding (VIV): significant around certain frequency band, possibly damaging.
- Turbulence Excitation (TIV): significance generally increases with increasing turbulence level. Long-term damaging (GTRF).
- Acoustic Resonance: significant around certain frequency band, possibly damaging.
- Fluid Elastic Instability: very significant beyond critical velocity. Can cause serious damage.

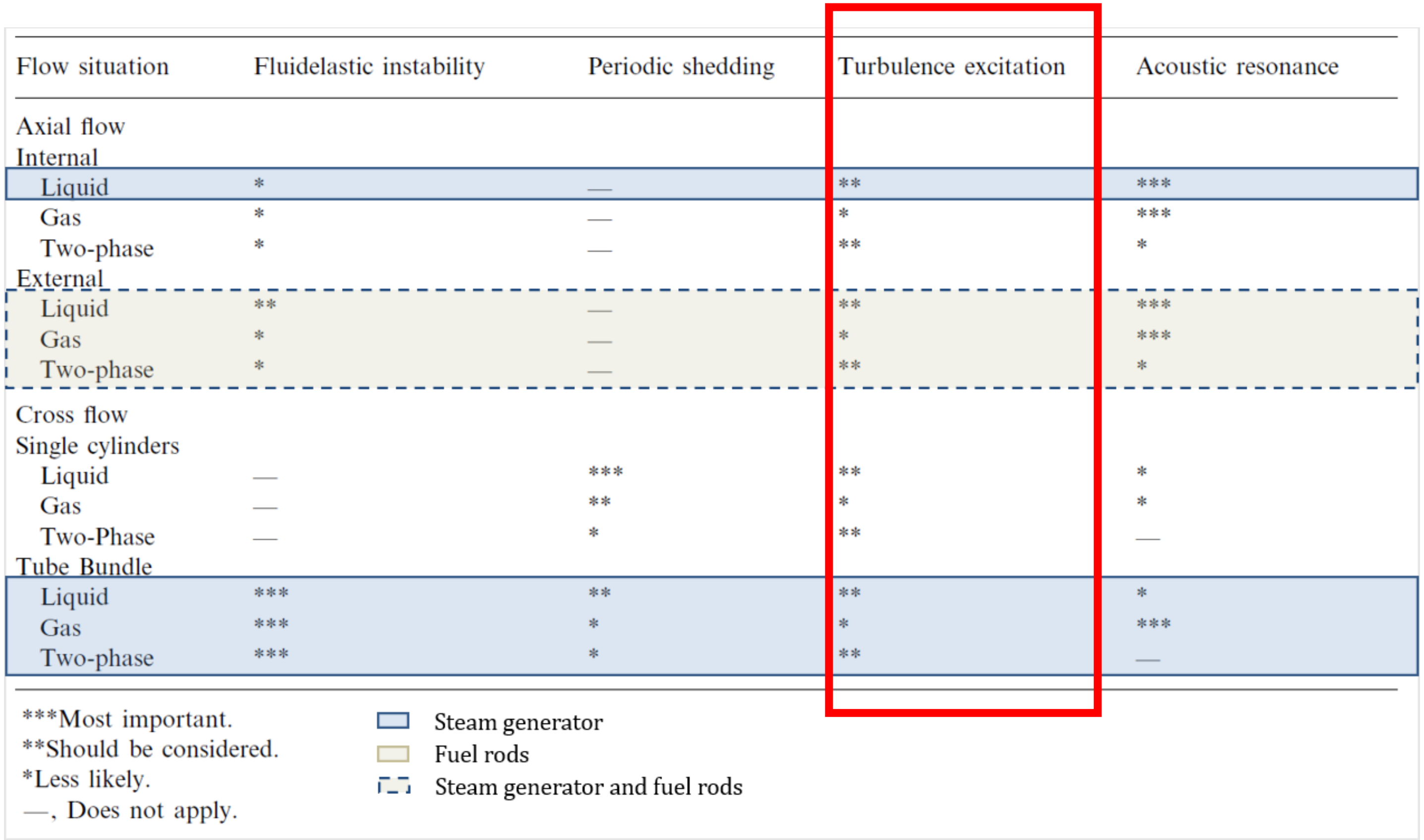
→ For NPPs: design should prevent FEI, minimize impact from TIV and VIV.



Vibrational Response as a Superimposition of Different FIV mechanisms (Kaneko et al., 2014, Academic Press)

FIV relevance for NPPs

FIV mechanisms relevance for Nuclear Power Plants (NPPs) → TIV always present



Flow situation	Fluidelastic instability	Periodic shedding	Turbulence excitation	Acoustic resonance
Axial flow				
Internal				
Liquid	*	—	**	***
Gas	*	—	*	***
Two-phase	*	—	**	*
External				
Liquid	**	—	**	***
Gas	*	—	*	***
Two-phase	*	—	**	*
Cross flow				
Single cylinders				
Liquid	—	***	**	*
Gas	—	**	*	*
Two-Phase	—	*	**	—
Tube Bundle				
Liquid	***	**	**	*
Gas	***	*	*	***
Two-phase	***	*	**	—

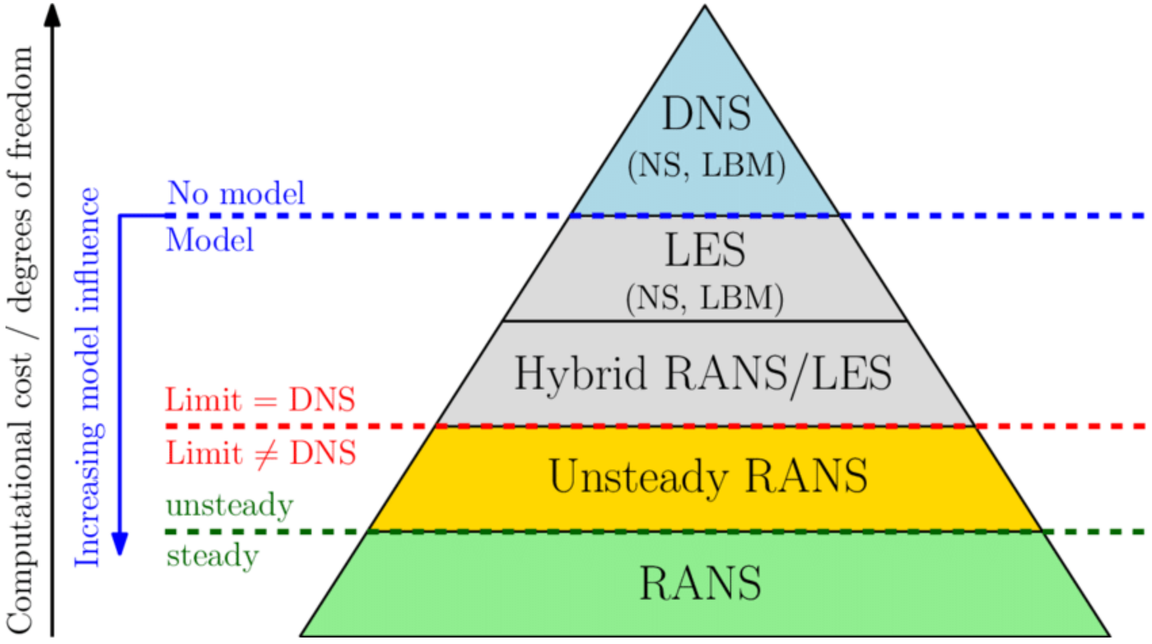
***Most important.
**Should be considered.
*Less likely.
—, Does not apply.

▭ Steam generator
▭ Fuel rods
⬚ Steam generator and fuel rods

Vibration excitation mechanisms (amended from Pettigrew et al., NED, 1998)

TIV: predicting numerically

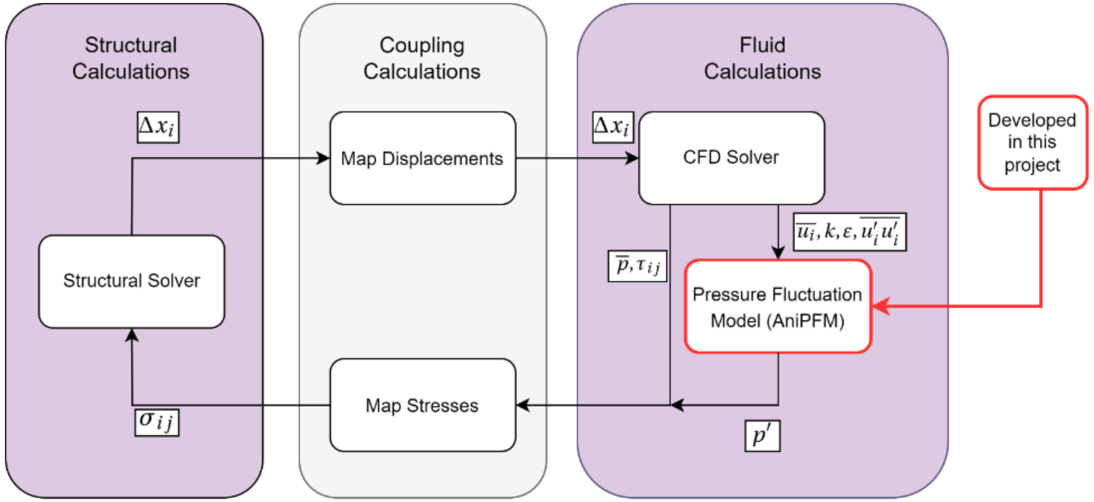
- Turbulence-Induced Vibrations main cause of Grid-to-Rod Fretting (GTRF)
  - As a result of local fluctuating turbulent velocity and pressure fields
- Modelling TIV can reduce risk and improve maintenance planning.
- Need scale-resolving methods (LES/DNS)
- Two-way coupling LES-CSM expensive
- Need to save computational costs
- Structure side: Reduced-Order Model (ROM)
  - Beam elements
  - Modal methods (e.g. ANSYS MOR)
- Fluid side: URANS + synthetic turbulence
  - Anisotropic Pressure Fluctuation Model (AniPFM)



Hierarchy of Computational Fluids Dynamics (CFD) methods (Sagaut et al., World Scientific, 2013)

Objective

- TIV can be modelled with Fluid-Structure Interaction (FSI) simulations.
- High-fidelity methods (DNS & LES) are too expensive.
- Solution: use a pressure fluctuation model (PFM).
- Scope: incompressible, single phase, axial flow.



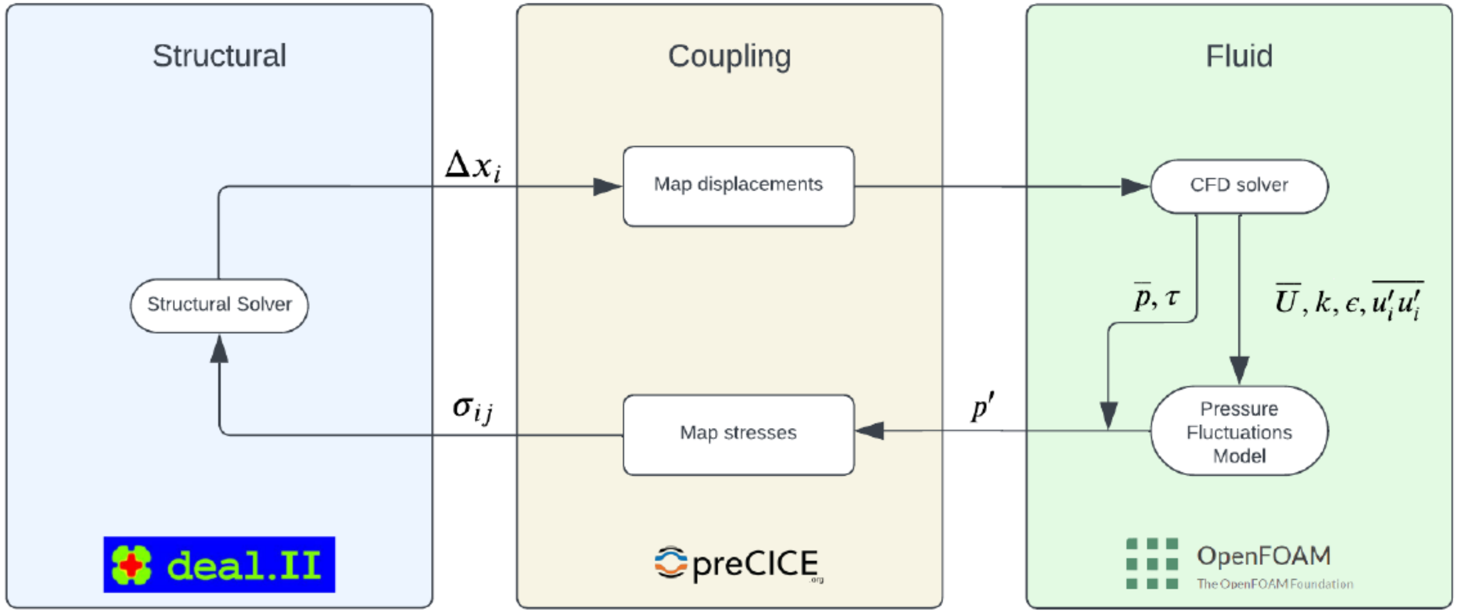
FSI framework

General FSI framework:

- Structural solver
- Fluid solver
- Coupling program

At NRG:

- Deal.II
- OpenFOAM, with AniPFM embedded
- preCICE



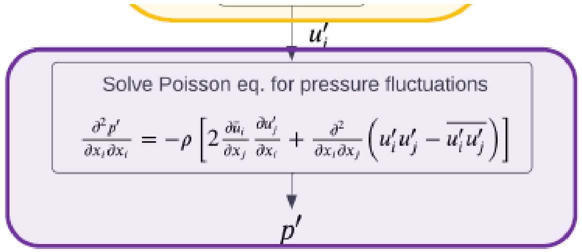
Pressure fluctuations

- Governing equation:

From URANS

- $$\frac{\partial^2 p'}{\partial x_i \partial x_i} = -\rho \left[2 \frac{\partial \bar{u}_i}{\partial x_j} \frac{\partial u'_j}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j} \left(u'_i u'_j - \overline{u'_i u'_j} \right) \right]$$

- Deduced from Navier-Stokes and continuity equations.
  - Use hereto: $\boldsymbol{u} = \bar{\boldsymbol{u}} + \boldsymbol{u}'$ and $p = \bar{p} + p'$
- Velocity fluctuations $\boldsymbol{u}'$ are unknown.
  - Synthetic turbulence model



u'_i

Solve Poisson eq. for pressure fluctuations

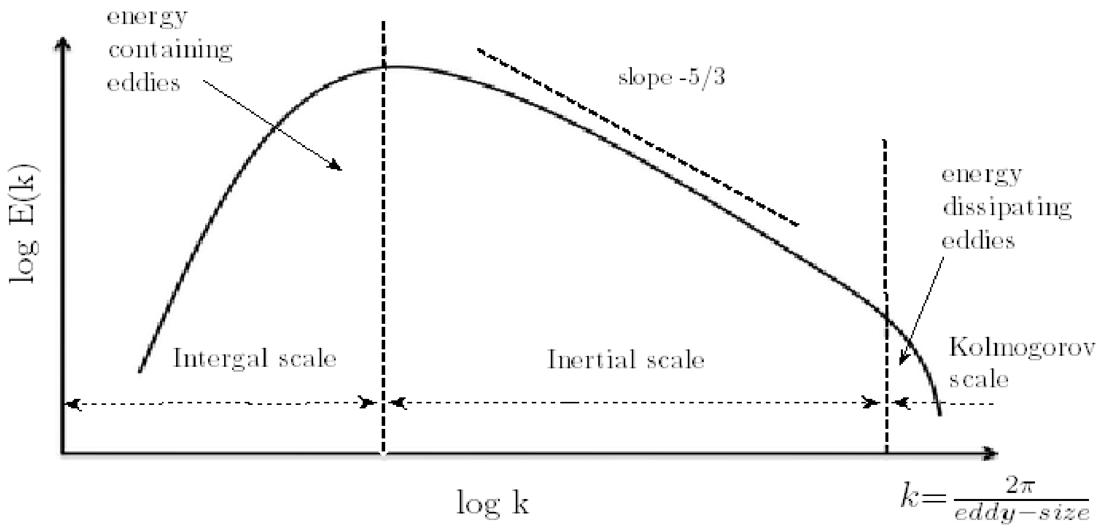
$$\frac{\partial^2 p'}{\partial x_i \partial x_i} = -\rho \left[2 \frac{\partial \bar{u}_i}{\partial x_j} \frac{\partial u'_j}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j} \left(u'_i u'_j - \overline{u'_i u'_j} \right) \right]$$

p'

Generation of pressure fluctuations

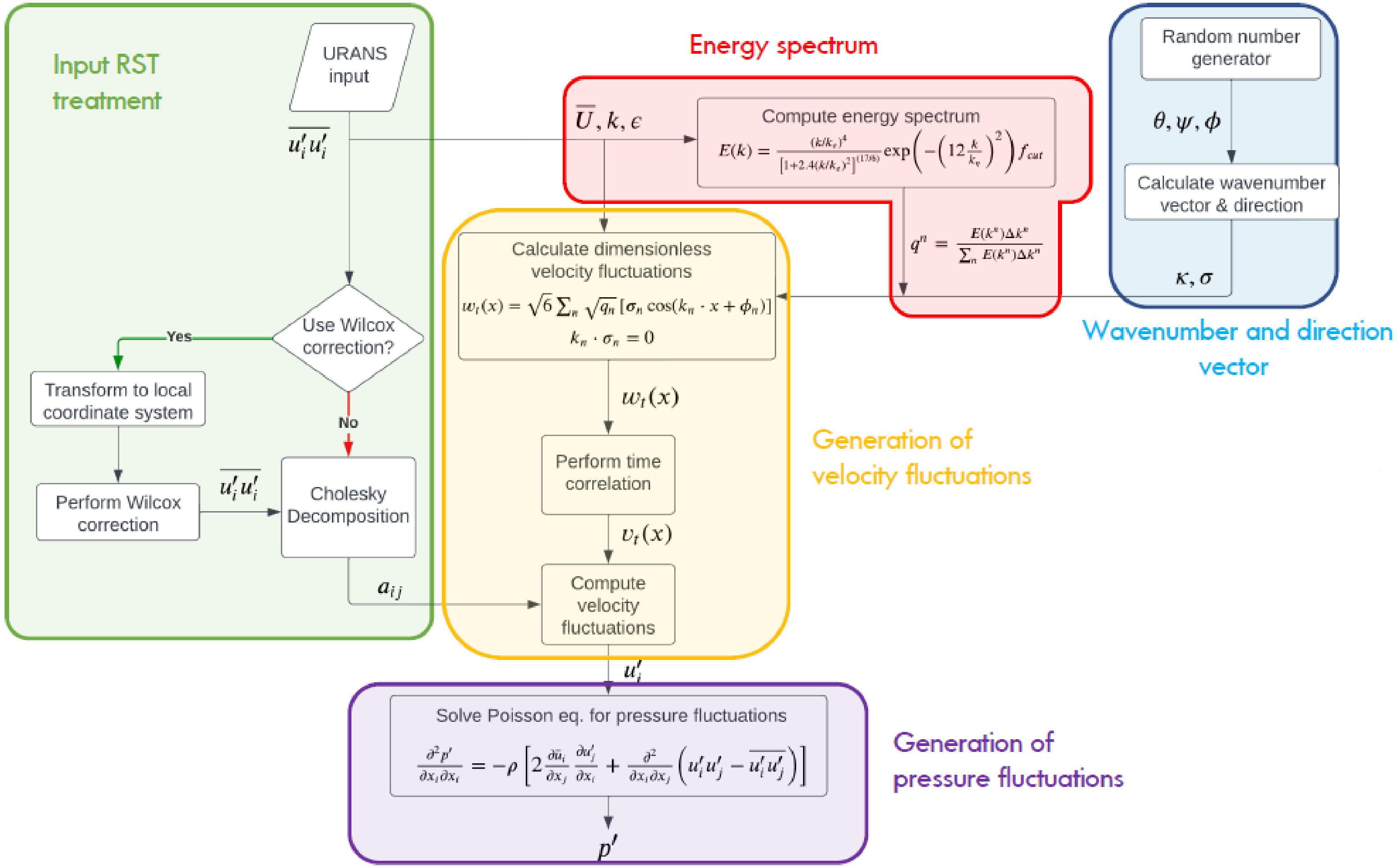
Synthetic Turbulence Requirements

- Must adhere to continuity equation.
- Must model the distribution of energy accurately.
- Reynolds stress tensor must be replicated.
- Must imitate the stochastic nature.
- Time correlation must be approximated.



Anisotropic Pressure Fluctuation Model

- Modular structure of interacting components.



Input RST treatment

URANS input

$\overline{u_i' u_i'}$

Use Wilcox correction?

Yes

Transform to local coordinate system

Perform Wilcox correction

$\overline{u_i' u_i'}$

No

Cholesky Decomposition

a_{ij}

Energy spectrum

$\overline{U}, k, \epsilon$

Compute energy spectrum

$$E(k) = \frac{(k/k_e)^4}{\left[1+2.4(k/k_e)^2\right]^{(17/6)}} \exp\left(-\left(12\frac{k}{k_\eta}\right)^2\right) f_{cut}$$

$$q^n = \frac{E(k^n)\Delta k^n}{\sum_n E(k^n)\Delta k^n}$$

Random number generator

θ, ψ, ϕ

Calculate wavenumber vector & direction

κ, σ

Wavenumber and direction vector

Calculate dimensionless velocity fluctuations

$$w_t(x) = \sqrt{6}\sum_n \sqrt{q_n}\left[\sigma_n \cos(k_n \cdot x + \phi_n)\right]$$

$$k_n \cdot \sigma_n = 0$$

$w_t(x)$

Perform time correlation

$v_t(x)$

Compute velocity fluctuations

Generation of velocity fluctuations

u_i'

Solve Poisson eq. for pressure fluctuations

$$\frac{\partial^2 p'}{\partial x_i \partial x_i} = -\rho\left[2\frac{\partial \bar{u}_i}{\partial x_j}\frac{\partial u_j'}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j}\left(u_i' u_j' - \overline{u_i' u_j'}\right)\right]$$

p'

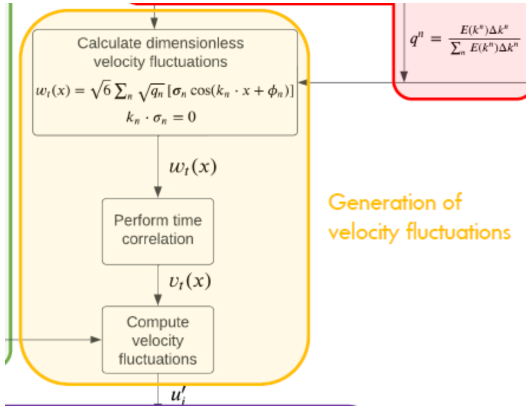
Generation of pressure fluctuations

Dimensionless Velocity fluctuations

- Dimensionless velocity fluctuations are modelled by a Fourier series.
- Stochastic distribution is introduced.

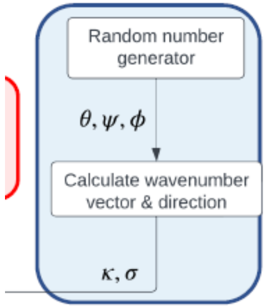
$$\mathbf{w}_t(\mathbf{x}) = \sqrt{6}\sum_n \sqrt{q_n}\left[\boldsymbol{\sigma}_n \cos(\mathbf{k}_n \cdot \mathbf{x} + \phi_n)\right]$$

$$\boldsymbol{k}_n \cdot \boldsymbol{\sigma}_n = 0$$



Generation of velocity fluctuations

- q_n: amplitude, based on modified Von-Karman energy spectrum
- K_n: inverse of eddy length scale
- σ_n : direction vector of n-th mode
- ϕ_n: phase of n-th mode



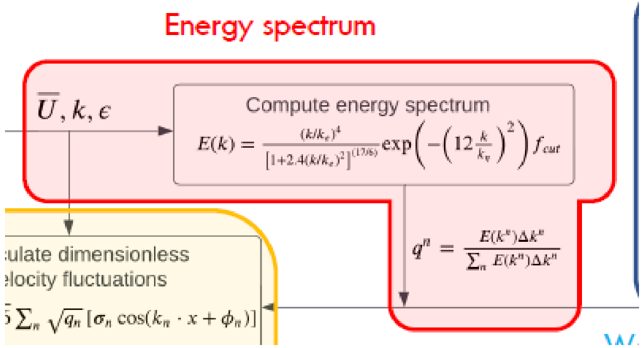
Wavenumber and direction vector

Energy spectrum

- Amplitude is defined by the input energy spectrum.

$$E(k) = \frac{(k/k_e)^4}{[1+2.4(k/k_e)^2]^{(17/6)}} exp(-(12\frac{k}{k_\eta})^2) f_{cut}$$

$$q_n = \frac{E_k(k_n)\Delta k_n}{\sum_n^N E_k(k_n)\Delta k_n}$$



Energy spectrum

$\overline{U}, k, \epsilon$

Compute energy spectrum

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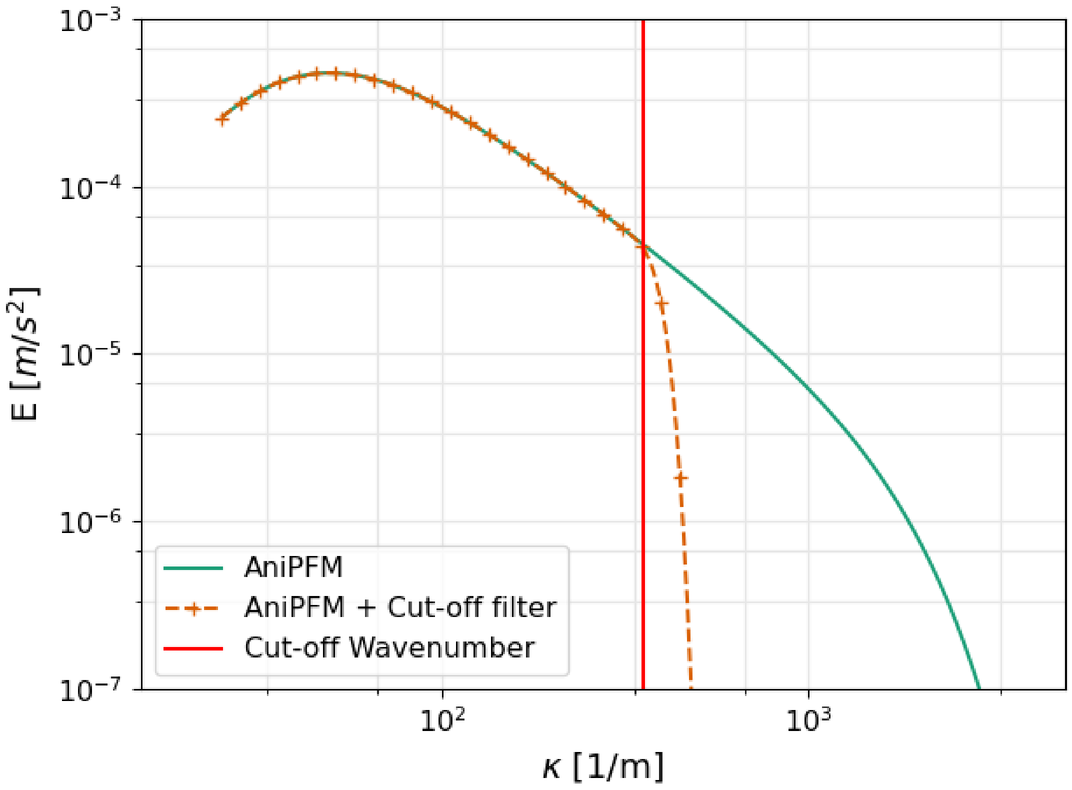
$q^n = \frac{E(k^n)\Delta k^n}{\sum_n E(k^n)\Delta k^n}$

ulate dimensionless
elocity fluctuations

$\sum_n \sqrt{q_n}\,[\sigma_n \cos(k_n \cdot x + \phi_n)]$



Time Correlation Methods

- Pure convection

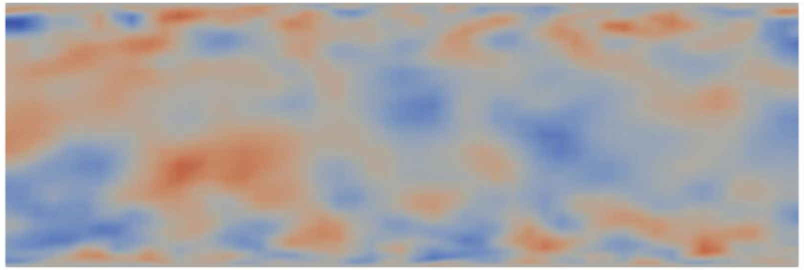
$$\mathbf{v}_t(\mathbf{x}) = \sqrt{6}\sum_n \sqrt{q_n}\left[\sigma_n \cos(\mathbf{k}_n \cdot (\mathbf{x} - \mathbf{U}t) + \phi_n)\right]$$

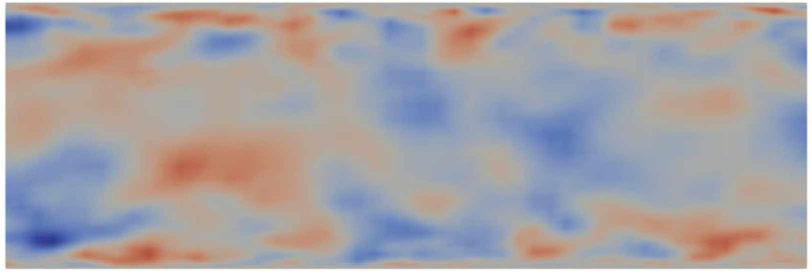
- Convection & exponential correlation

$$\frac{\partial \mathbf{v}_t^{m-1}}{\partial t} + \overline{u_j}\frac{\partial \mathbf{v}_t^{m-1}}{\partial x_j} = 0$$

$$\mathbf{v}_t^m(\mathbf{x}, t) = a\mathbf{v}_t^{m-1}(\mathbf{x}) + b\mathbf{w}_t^m(\mathbf{x})$$

Mean flow direction



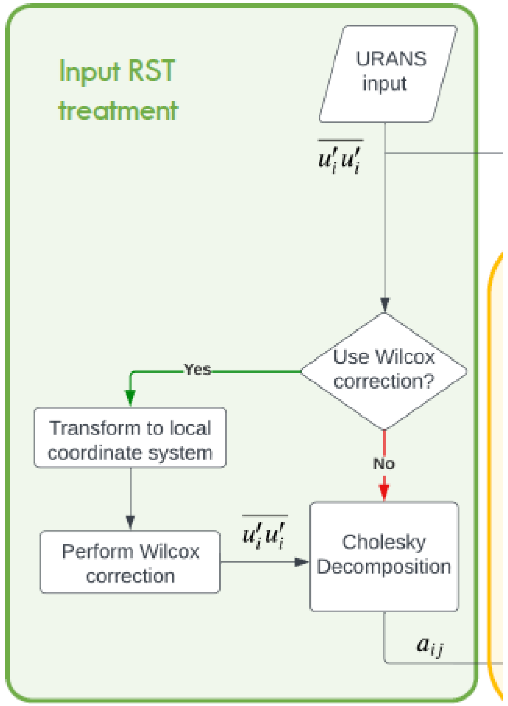


Reynolds Stress Replication

- Currently have isotropic velocity fluctuations
- Desired result: $< u'_i u'_j >= R_{ij}$
- Define the scaling tensor a_{ij} such that $R_{ij} = a_{ji} a_{ij}$

$$u'_i(\mathbf{x}, t) = a_{jk} \mathbf{v}_t(\mathbf{x}, t)$$

- Introduces anisotropy



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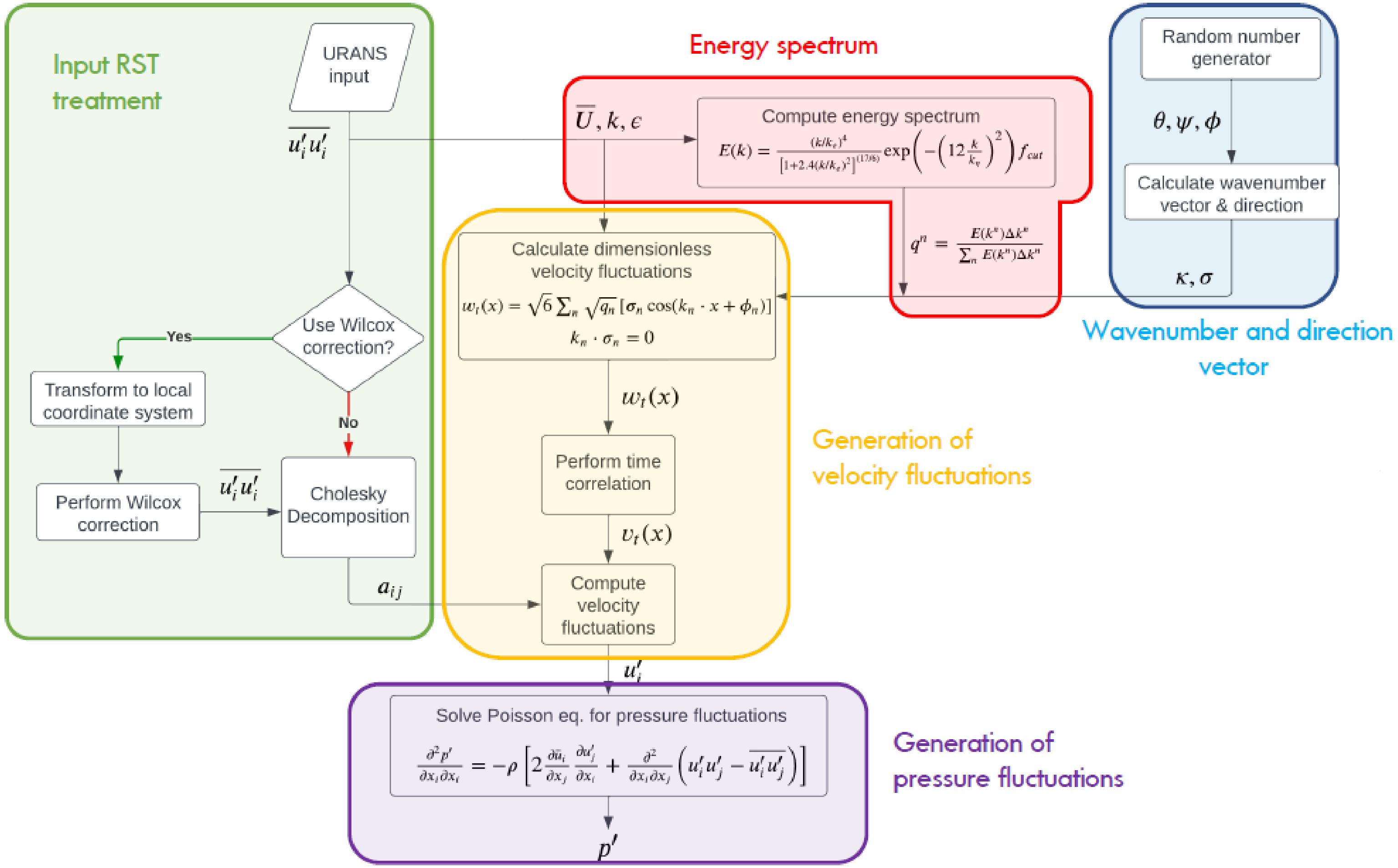

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Generation of velocity fluctuations

u_i'

Solve Poisson eq. for pressure fluctuations

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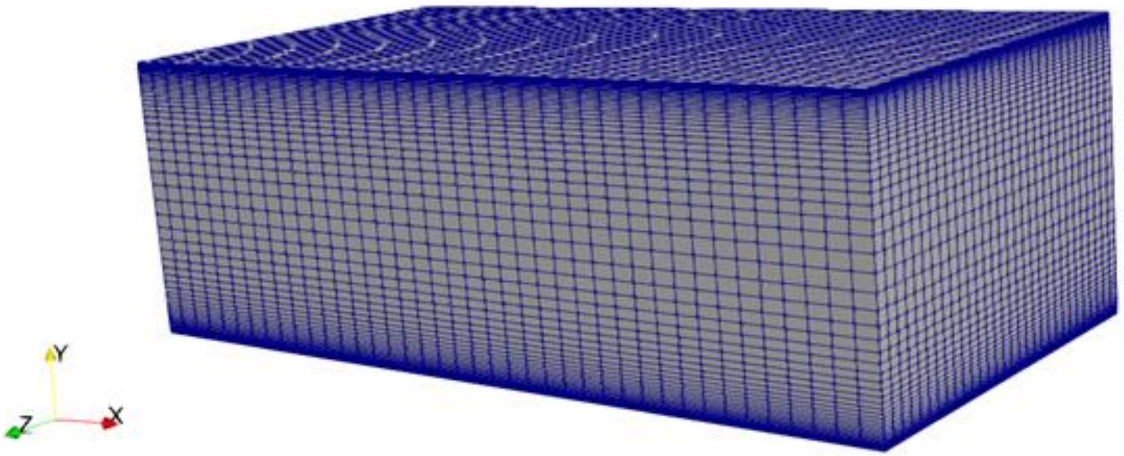
p'

Generation of pressure fluctuations

Channel flow test case

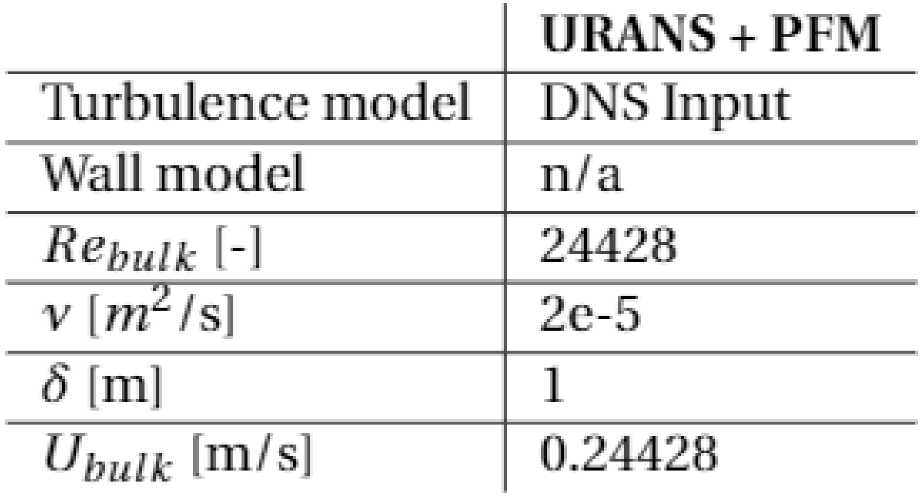
- Create box of Lx by Ly by Lz
  - Lx = 6 δ
  - Ly = 2 δ
  - Lz = 3 δ
- Create mesh
  - Uniform in x and z
  - Non-uniform in y
- Boundary conditions:
  - Periodic in x and z direction
  - Wall at y = 0 and y = 2 δ
- Momentum source equal to the bulk velocity

Example of mesh: 40x60x30



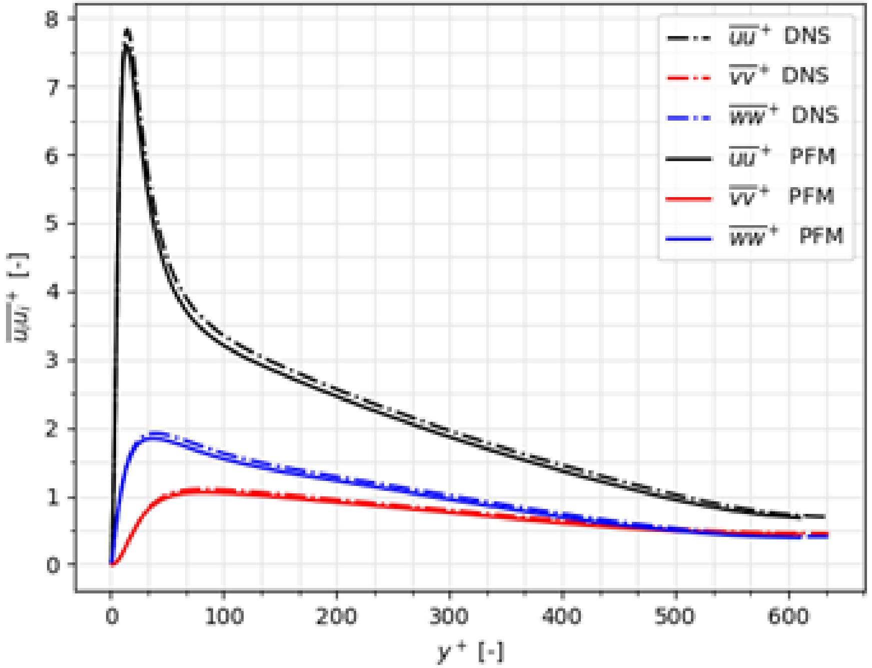
Channel flow test case

- Test case: turbulent channel flow at $Re_\tau = 640$
- DNS data from Abe et al. (JFE, 2001)
- DNS data is used as input “RANS” solution
- This results in $Re_{bulk} = \frac{U_{bulk} 2\delta}{\nu} = 24428$
- ν and δ are set, from this U_{bulk} is determined
- First cell has $y^+ \approx 1$, i.e. no wall models

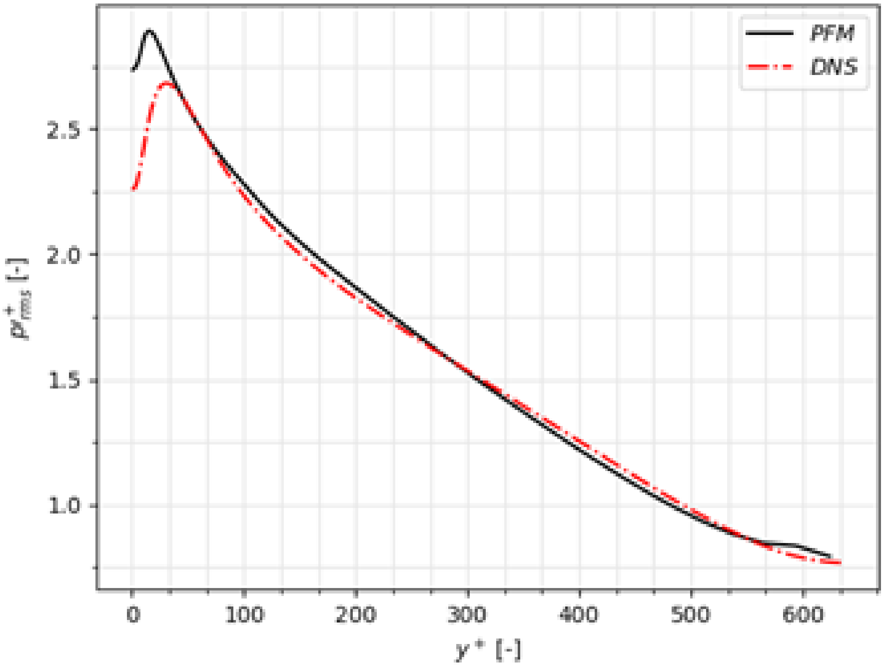


	URANS + PFM
Turbulence model	DNS Input
Wall model	n/a
Re_{bulk} [-]	24428
ν [m^2/s]	2e-5
δ [m]	1
U_{bulk} [m/s]	0.24428

Channel flow test case



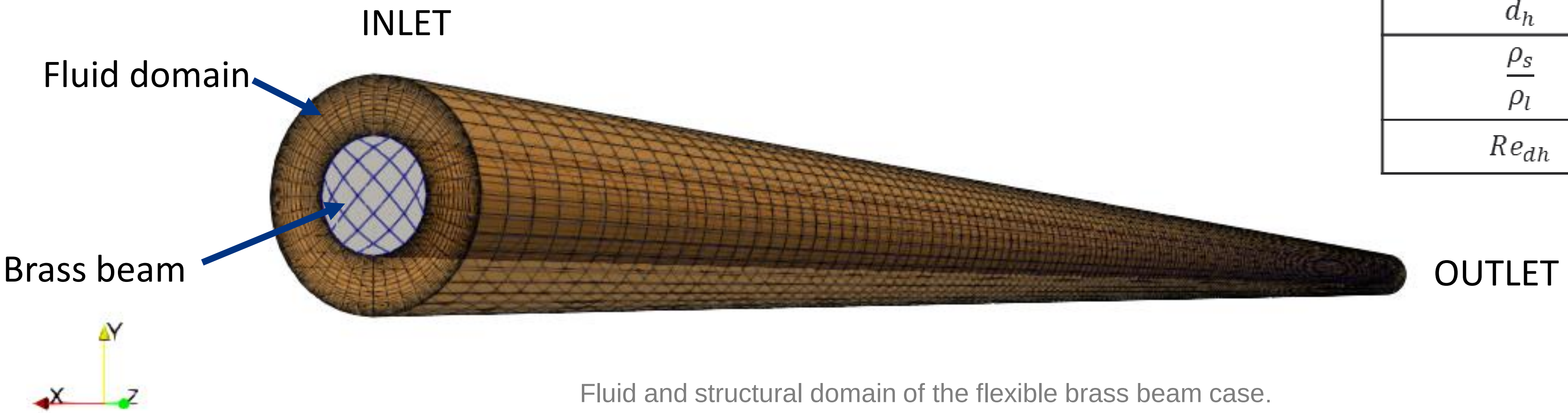
Reynolds stresses as function of y^+: demonstrates anisotropy of PFM



RSM of p' as function of y+: good match with DNS data. Tough to get great match at wall though due to mesh size.

FSI test case

- Modelled after experiment of Chen & Wambsganns (NED, 1972).
- Closely mimics turbulence induced vibrations found in nuclear reactors.

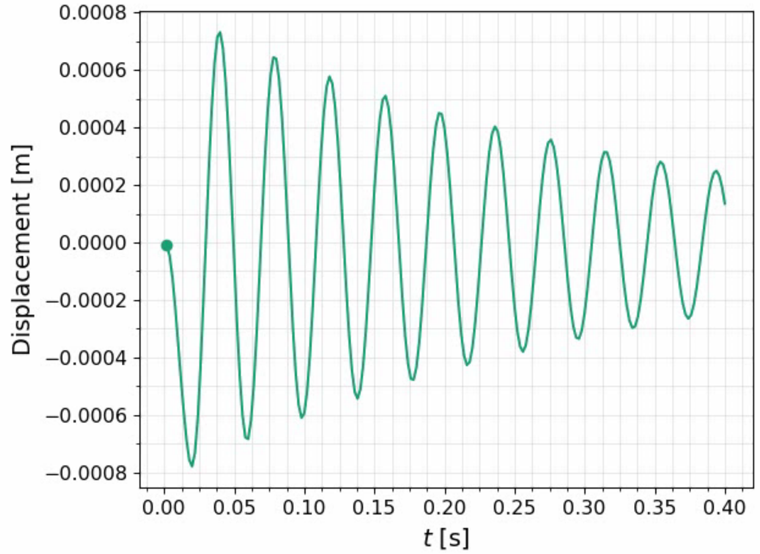


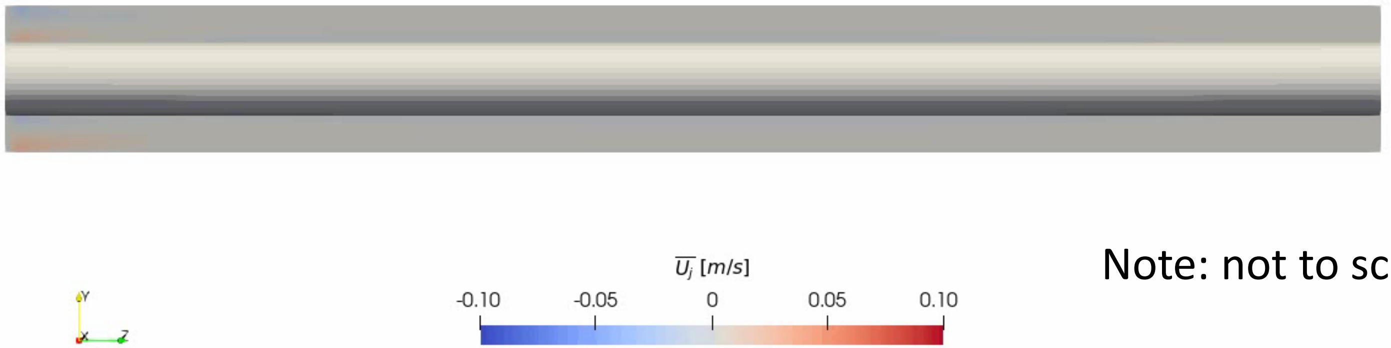
$\frac{L}{d_h}$	93.7
$\frac{\rho_s}{\rho_l}$	8.4
Re_{dh}	101,600-419,100

Fluid and structural domain of the flexible brass beam case.

FSI test case

- Pure URANS FSI, no aniPFM
- Initial force is necessary to excite the beam.
- Amplitude dampens out over time.

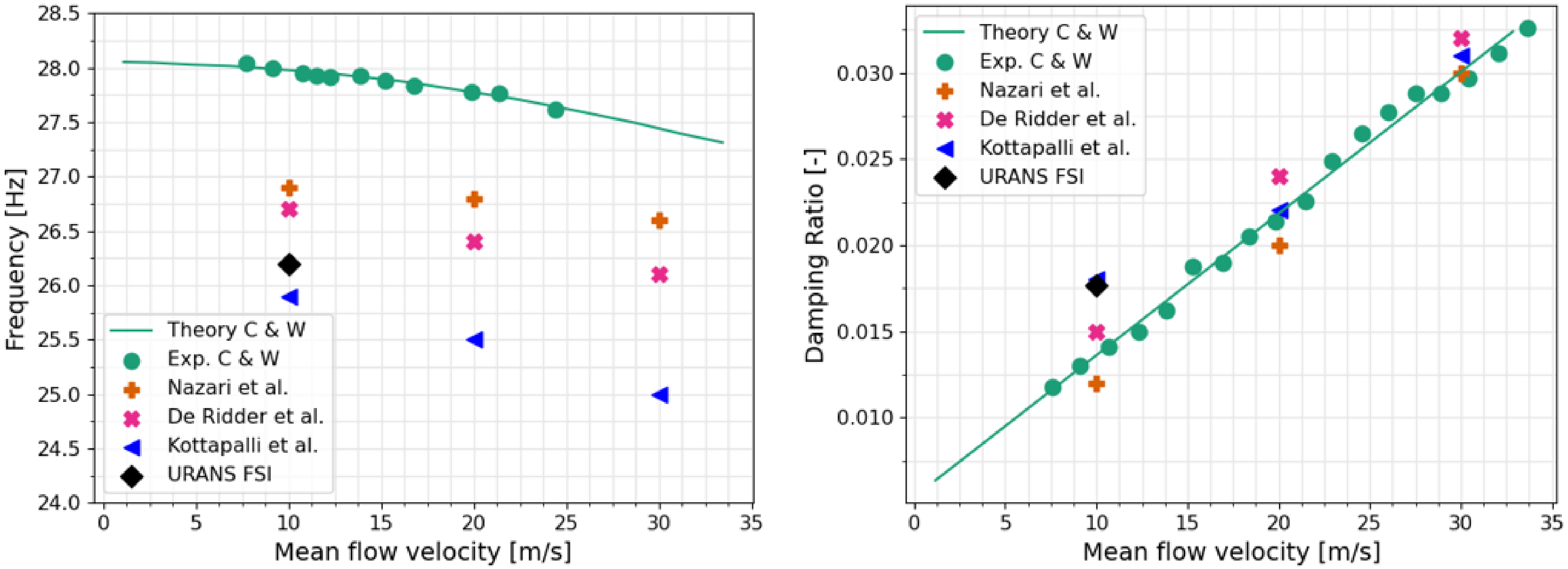




Note: not to scale!

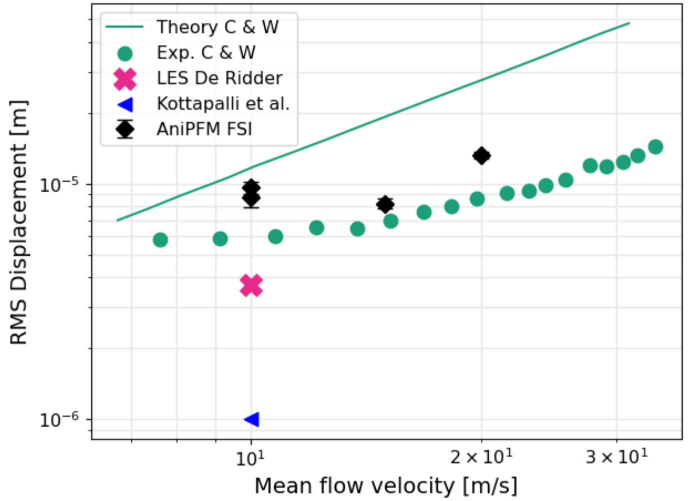
FSI test case

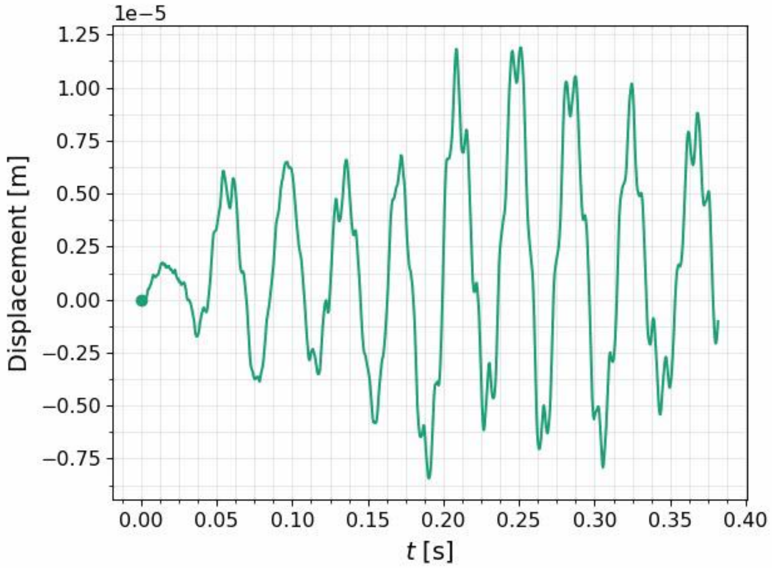
- Pure URANS FSI, no aniPFM
- Frequency close to experimental value (5.7% error)

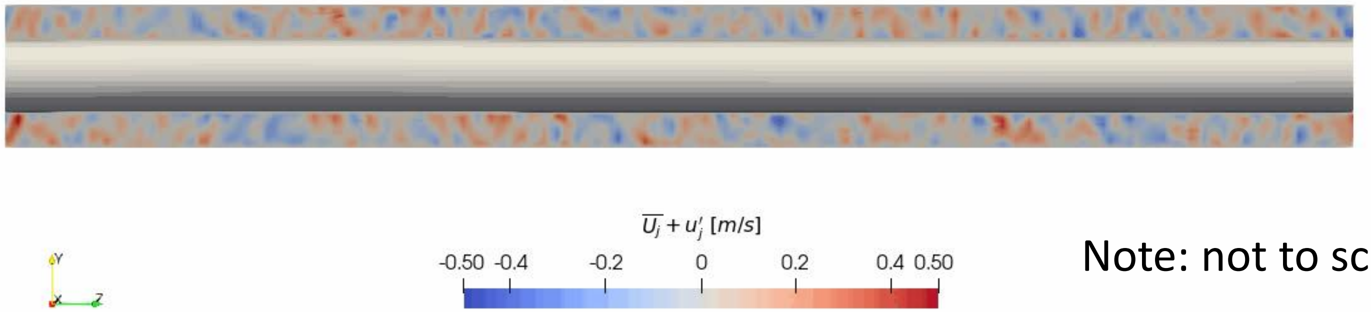


FSI test case

- URANS + aniPFM
- No initial forcing necessary.
- Multiple natural modes can be identified



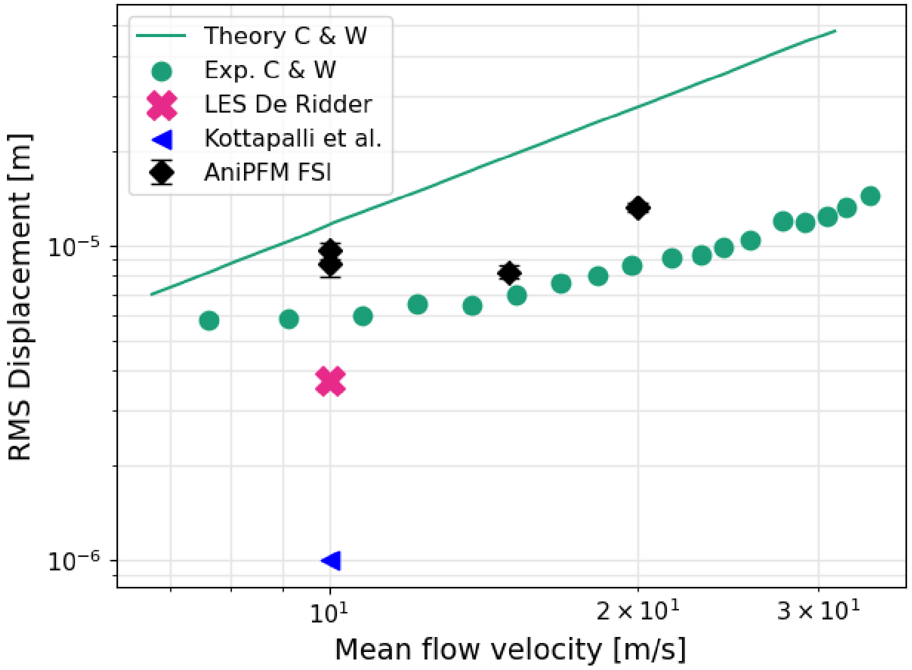




Note: not to scale!

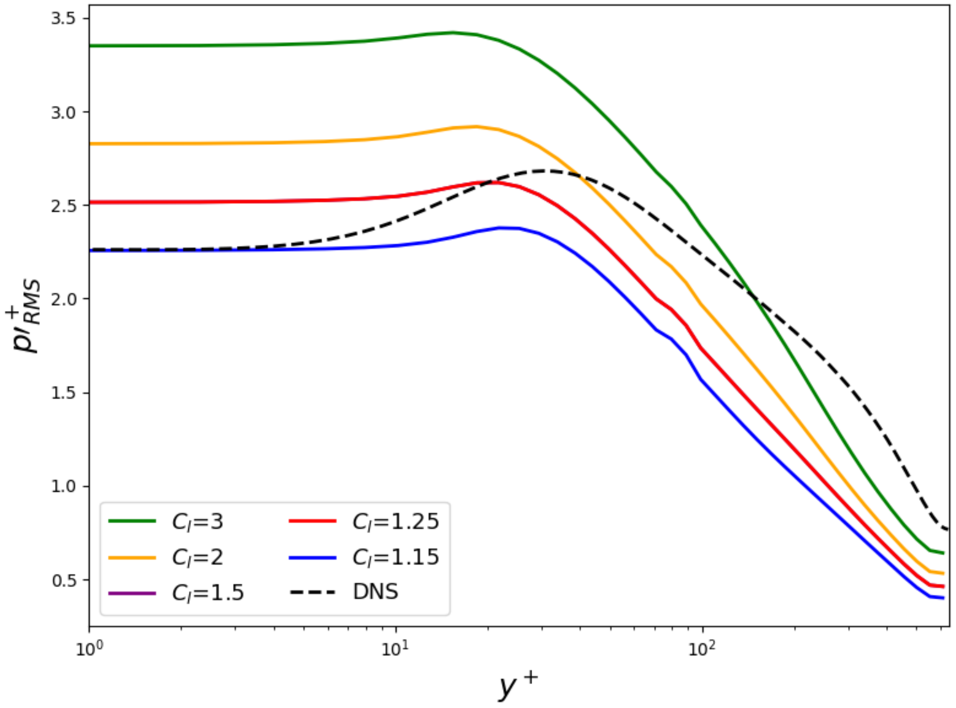
FSI test case

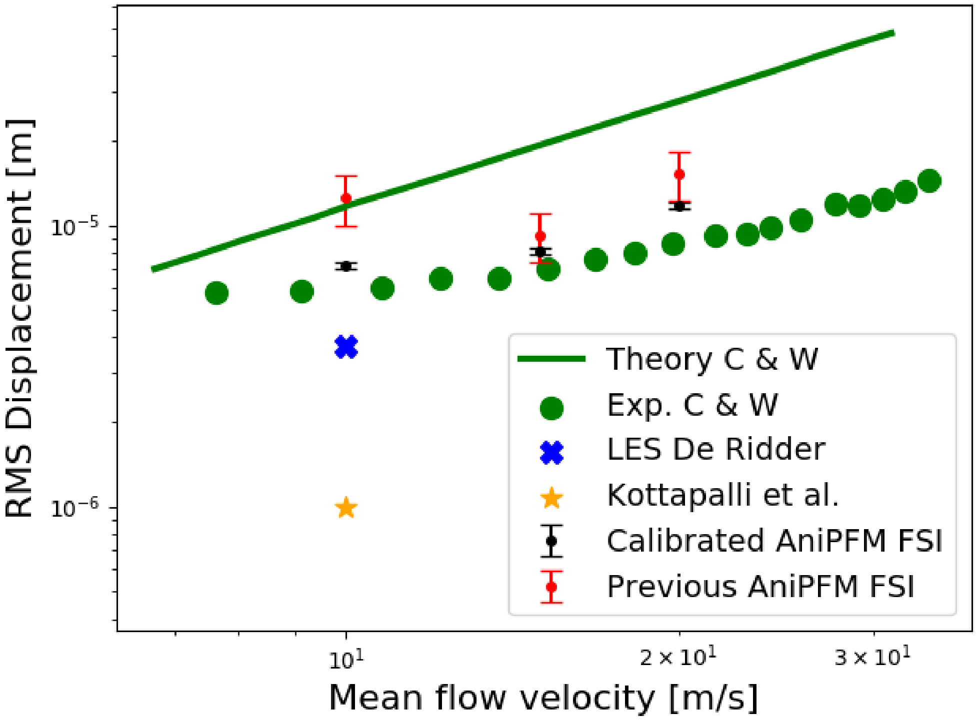
- URANS + aniPFM
- Better prediction than old, isotropic, model (Kottapalli et al.)



Very recent results

- Calibration of model against DNS of channel flow case (Abe et al., JFE, 2001)
- Applied calibrated model to FSI test case (Chen & Wambsganns, NED, 1972)





Conclusions + future work

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- Improved Pressure Fluctuation Model → aniPFM
- Includes anisotropy, convection and time correlation
- Test cases show model able to reproduce structural vibrations

- Future Work:
- Further validation of AniPFM against other flow and FSI cases.
- Work further on implementing anisotropy
- Couple to a Reduced-Order Model (beam elements) on structural side

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Thank you!

Kevin Zwijsen

NRG

zwijsen@nrg.eu

www.go-viking.eu

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