Analysis of Vortex Induced Vibration of a thermowell by high fidelity FSI numerical analysis based on RBF structural modes embedding

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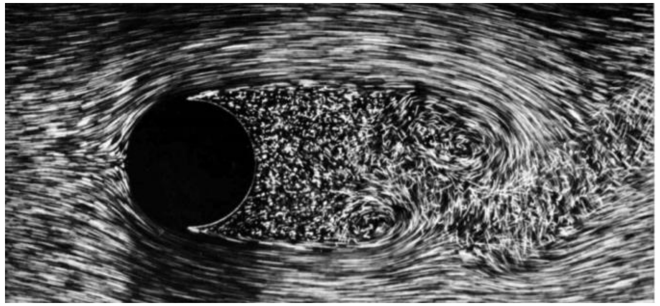
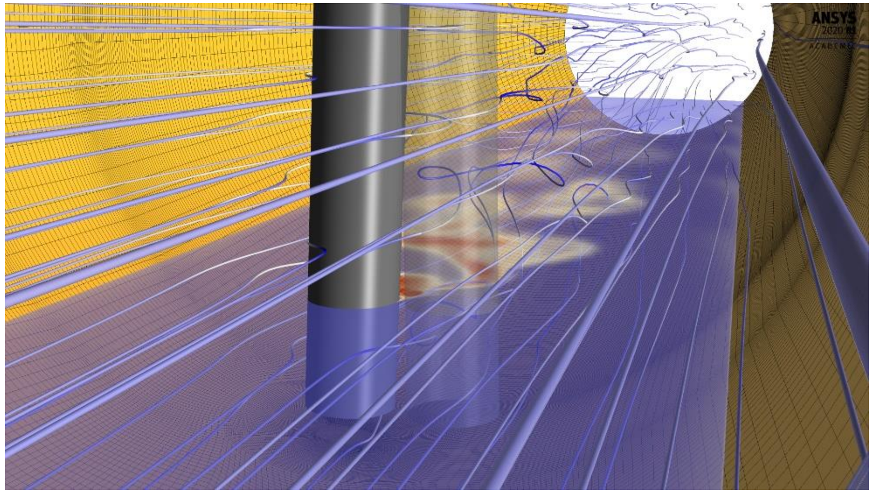
Outline



- Introduction
- Vortex shedding phenomenon
- Theoretical background
- Vortex induced vibration analysis
- Conclusions



Introduction and motivation

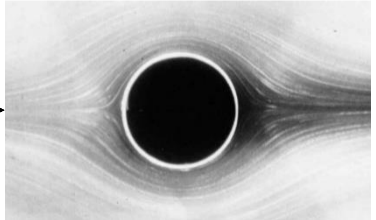
- Today the need for developing multi-physics approaches in order to address modern and complex design challenges is rising. A typical multi-physics phenomenon is the interaction between a **fluid and a structure**.
- The Fluid Structure Interaction is the interaction of a movable or deformable structure with an internal or a surrounding fluid flow.
- The proposed FSI modal approach allows the adaptation of the shape of the deformable structure according to **modes superposition.**
- The modal superposition FSI method is demonstrated on an industrial problem: the **vortex induced vibration of a thermowell**.

Vortex shedding phenomenon

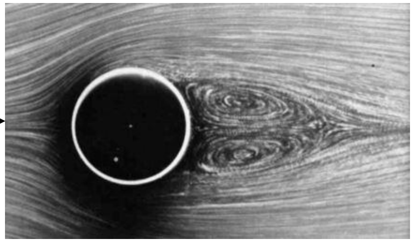
Vortex shedding is an oscillating flow that occurs when a fluid flows past a bluff body at specific Reynolds number. In this flow vortices detach periodically and alternately from the body generating a Von Kármán vortex street.

$$Re = \frac{\rho U D}{\mu}$$

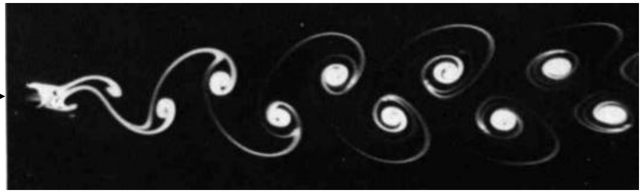
- *Re*<4 → Creeping laminar flow



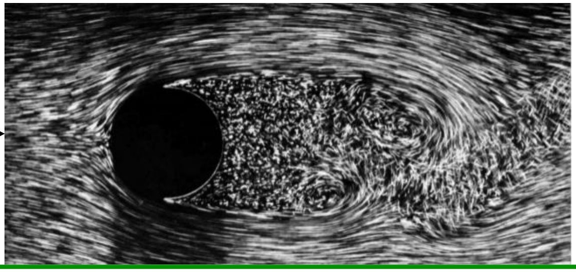
- 5<*Re*<49 → Symmetric and steady wake



- 49<*Re*<140-194 → Laminar vortex shedding

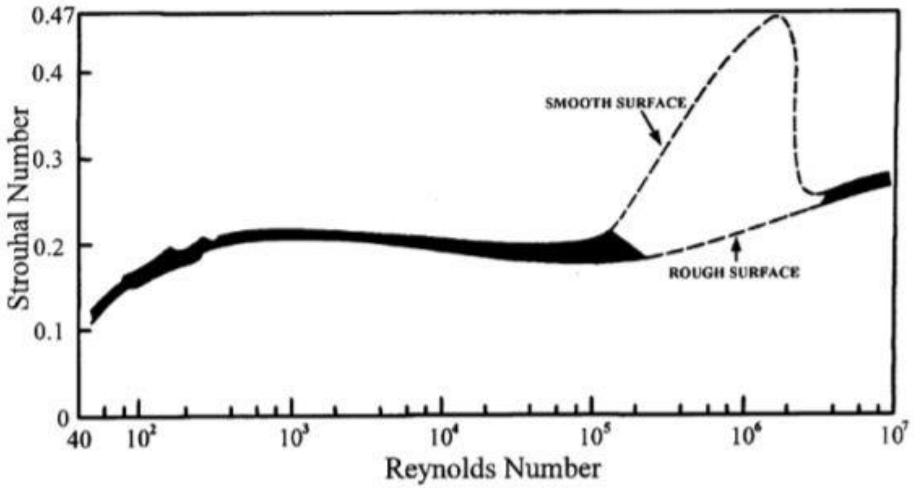


- 1000<*Re*<200000 → Sub-critical regime



Vortex shedding phenomenon

To describe the vortex shedding frequency, the **Strouhal** number is introduced: $St = \frac{fL}{U}$



The alternating detachment of vortices an unsteady cross-flow force with the same **frequency** as the vortex shedding and a streamwise unsteady force with a frequency about doubled.

If the **Strouhal frequency approaches a natural frequency** of the flexible body around which the vortex shedding appears, an oscillatory response may occur ⇒ **lock-in**.

Theoretical background

The proposed FSI method works by importing the **modal shapes in the CFD solver** with a **mesh morphing** tool, the numerical grid can be made implicitly elastic.

Modal analysis:

Second order differential system of equation of motion for a generic n-degrees-of-freedom system:

$$[\boldsymbol{M}]\ddot{\boldsymbol{y}} + [\boldsymbol{C}]\dot{\boldsymbol{y}} + [\boldsymbol{K}]\boldsymbol{y} = \boldsymbol{Q}$$

Hypothesis: conservative system, synchronous motion ⇒ eigenvalue problem:

$$[\boldsymbol{K}]\boldsymbol{v} = \omega_n^2[\boldsymbol{M}]\boldsymbol{v}$$

Mass normalization:

$$\boldsymbol{v}_i^T[\boldsymbol{M}]\boldsymbol{v}_i = 1$$

$$\boldsymbol{v}_i^T[\boldsymbol{K}]\boldsymbol{v}_i = \omega_{n,i}^2$$

Modal coordinates formulation:

Eigenvectors are orthogonal with respect to both stiffness and mass matrices:

$$\boldsymbol{v}_j^T[\boldsymbol{M}]\boldsymbol{v}_i = 0 \qquad i \neq j$$

$$\boldsymbol{v}_j^T[\boldsymbol{K}]\boldsymbol{v}_i = 0 \qquad i \neq j$$

⇒ eigenvectors are linearly independent ⇒ new reference system ⇒ modal matrix:

$$[\boldsymbol{v}] = [\boldsymbol{v}_1 \boldsymbol{v}_2 \dots \boldsymbol{v}_n]$$

Modal vector coordinates:

$$\boldsymbol{q} = [\boldsymbol{v}]^{-1}\boldsymbol{y} \qquad \Rightarrow \qquad \ddot{q}_i + 2\varsigma_i\omega_{n,i}\dot{q}_i + \omega_{n,i}^2 q_i = \frac{F_i(t)}{m_{ii}}$$

Each mode acts as a **single-degree-of-freedom dynamic system** and the overall system response can be calculated as a linear superimposition of each mode response.

Theoretical background

Unsteady FSI using modal superposition:

Hypothesis: modal force *F* can be considered constant within every time-step of integration

$$\Downarrow$$

$$q(t) = e^{-\varsigma\omega_n t}\left[q_0\cos(\omega_d t) + \frac{\dot{q}_0 + \varsigma\omega_n q_0}{\omega_d}\sin(\omega_d t)\right] +$$

$$+e^{-\varsigma\omega_n t}\left\{\frac{F}{\omega_d}\left[\frac{4\omega_d}{\varsigma^2\omega_n^2 + 4\omega_d^2} - e^{-\varsigma\omega_n t}\,\frac{2\varsigma\omega_n\sin(\omega_d t) + 4\omega_d\cos(\omega_d t)}{\varsigma^2\omega_n^2 + 4\omega_d^2}\right]\right\}$$

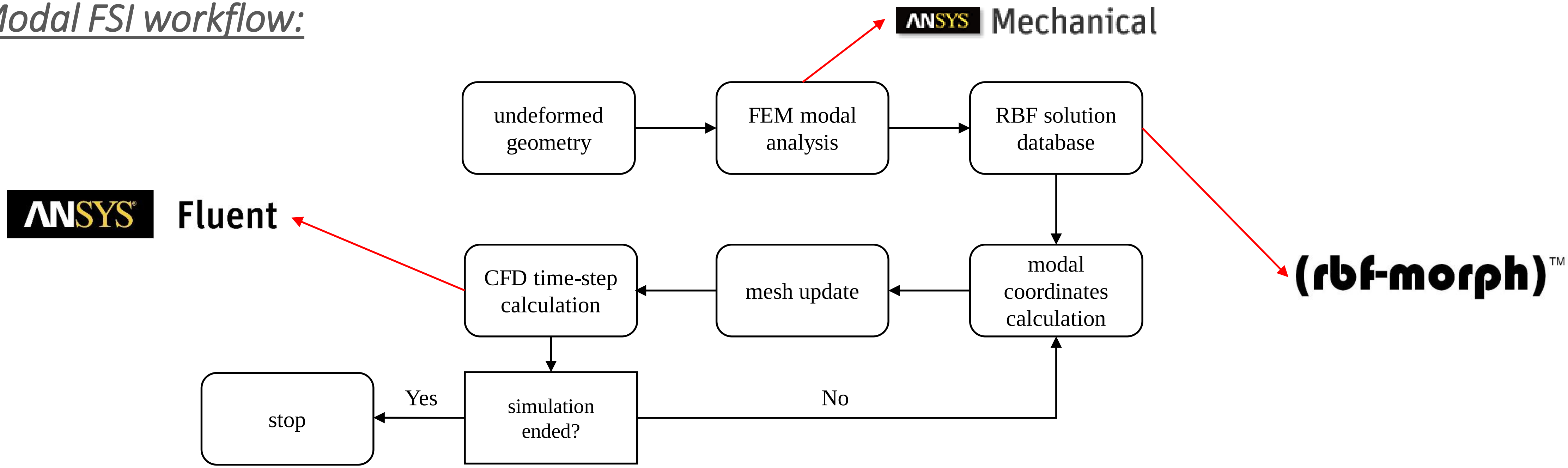
$$\Downarrow$$

$$\boldsymbol{y} = \sum_{i=1}^{\boldsymbol{n}} \boldsymbol{v}_i q_i$$

Not all the frequencies are excited ⇒ modes truncation.

Theoretical background

<u>*Modal FSI workflow:*</u>



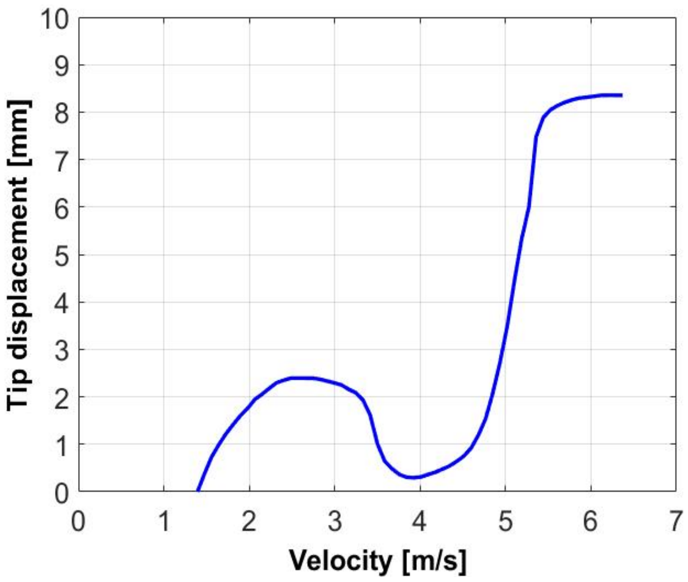
To speed up the mesh morphing step, the deformations associated with each modal shape are stored in memory. This is possible because the mesh deformations are obtained by linearly superimposing the action of each modal shape amplified by its modal coordinate:

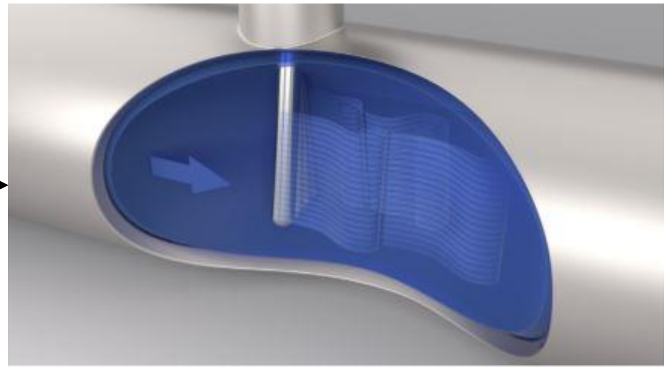
$$x_{CFD}(t) = x_{CFD_0} + \sum_{i=0}^{k} q_i(t)\Delta\mathbf{x}_i$$

Vortex induced vibration analysis

The tested thermowell, 470.219 mm in length, was equipped with accelerometers in the tip and immersed in a water flow loop evolving inside a 152.4 mm diameter pipe. To evaluate the flow induced vibrations, the water velocity ranged from 0 m/s to 8.5 m/s.

Results:



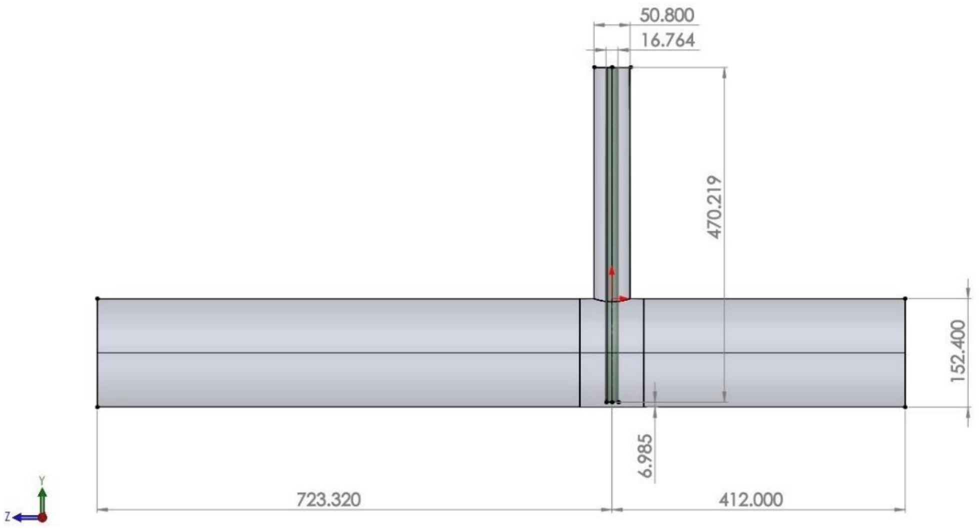


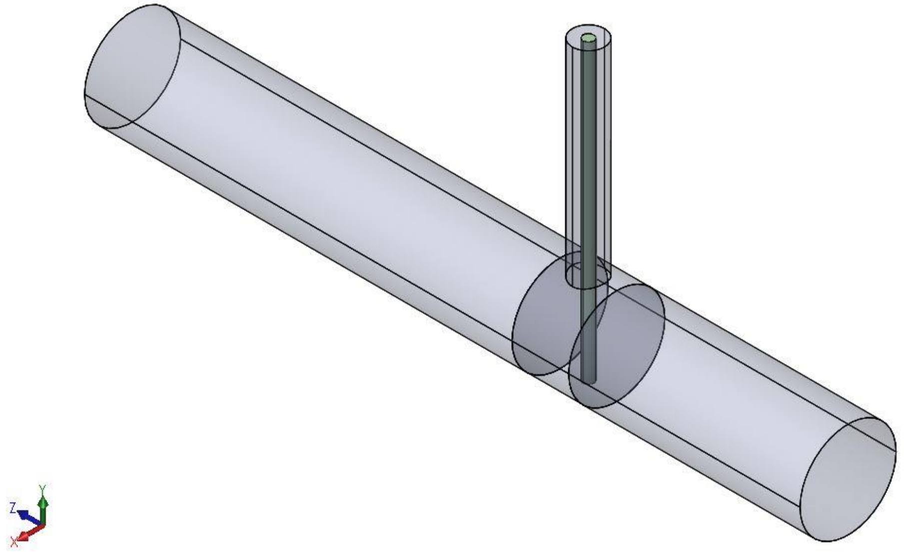
Two lock-in regions:

- In-line vibration: 2.33 mm maximum rms tip displacement at 2.44 m/s fluid velocity;
- Transverse vibration: 8.3mm maximum rms tip displacement at 6.4 m/s fluid velocity.

Vortex induced vibration analysis

Geometry:



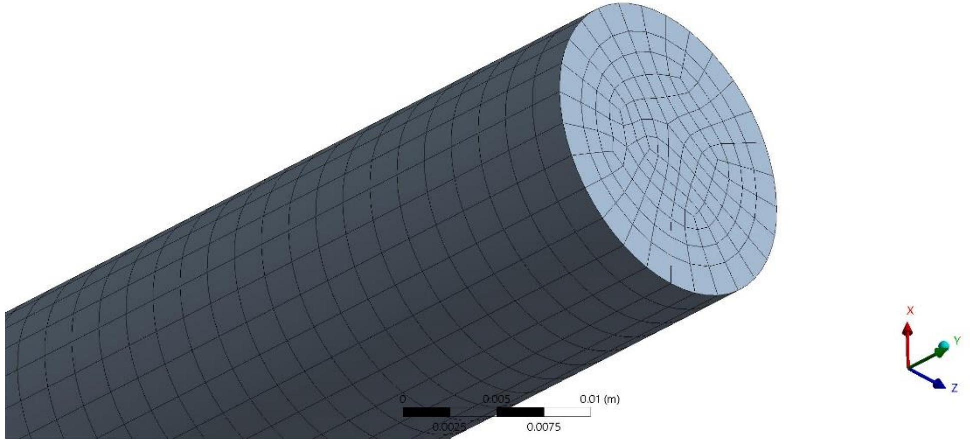


Modal analysis:

The first step needed to setup a FSI analysis based on the modal superposition method is to carry out a modal analysis of the deformable structure.

Material: 304/304L dual rated steel with a density of 7750 kg/m3, a Young's modulus of 200 GPa and a Poisson's ratio of 0.3.

FEM setup:



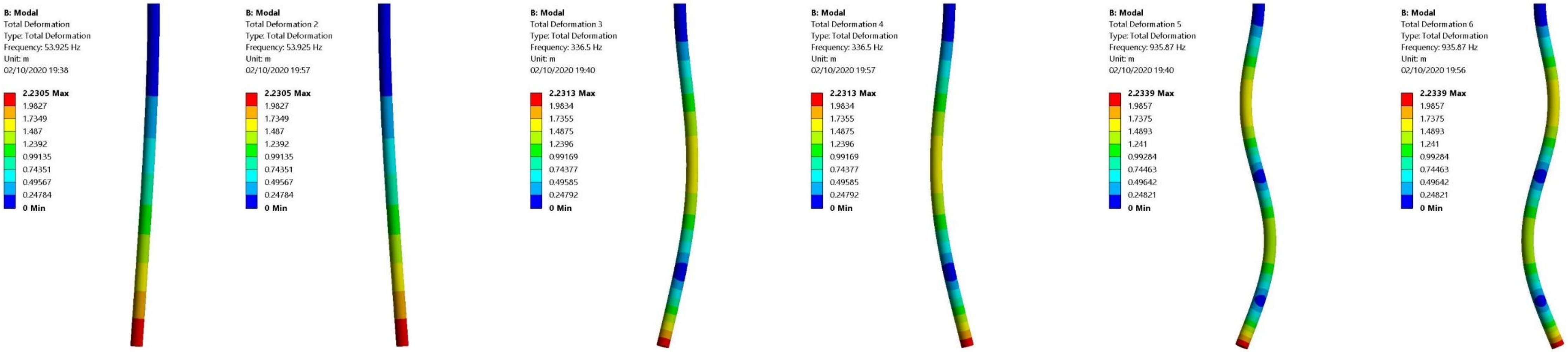
Key features:

- Uniform mesh to correctly represent the distribution of mass and stiffness;
- 2 mm element size;
- 34456 20-noded hexahedrons for a total of 148675 nodes;
- Cantilever beam;
- Neither damping nor pre-stress
- 12 modes extracted, but only the first 6 are employed in the FSI study.

Vortex induced vibration analysis

Modal shapes:

Algebraic multiplicity of two of the bending modes ⇒ six computed natural modes, correspond to only three distinct bending modes.



Analytical results: $\omega_{n,i} = \alpha_i^2 \sqrt{\frac{EI_B}{\rho A_B L_B^4}} \quad i = 1,2,3$

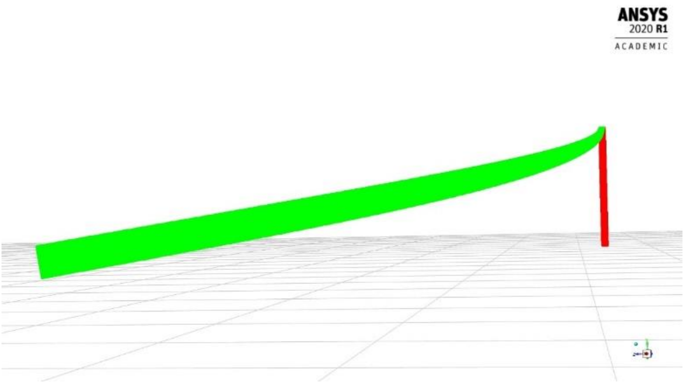
Mode	Analytical natural frequency [Hz]	FEM natural frequency [Hz]	Relative error [%]
1	53.883	53.925	-0.0779
2	337.681	336.499	0.34999
3	945.523	935.872	1.0207

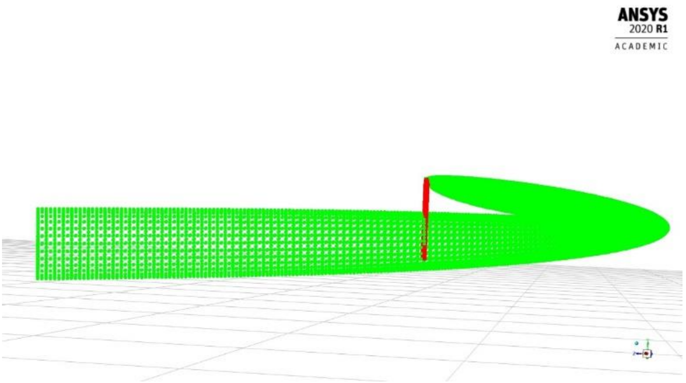
Vortex induced vibration analysis

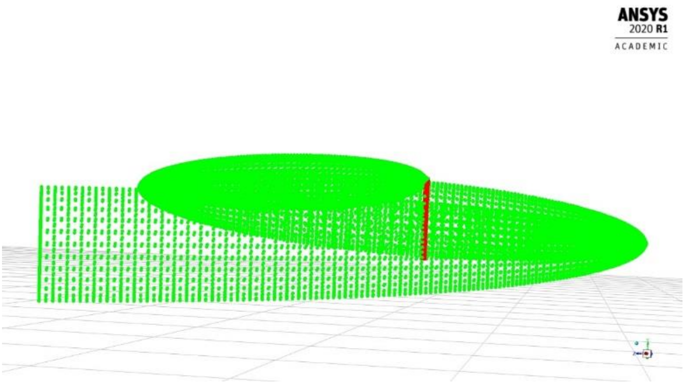
RBF solutions setup:

Two-step technique for each natural mode.

First step: loads the previously generated .pts file corresponding to the considered modal shape (first six).

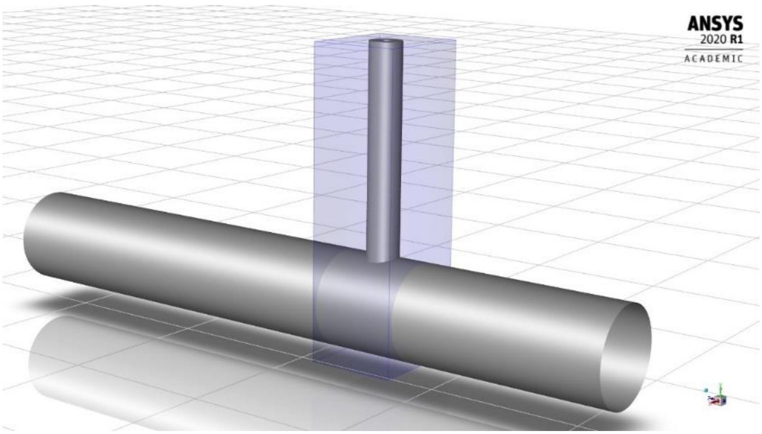


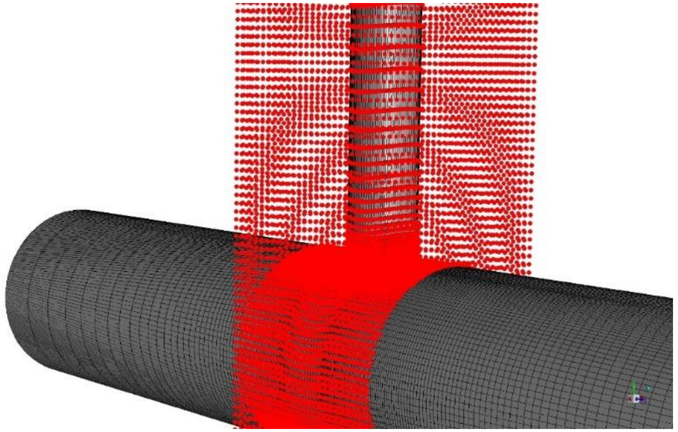


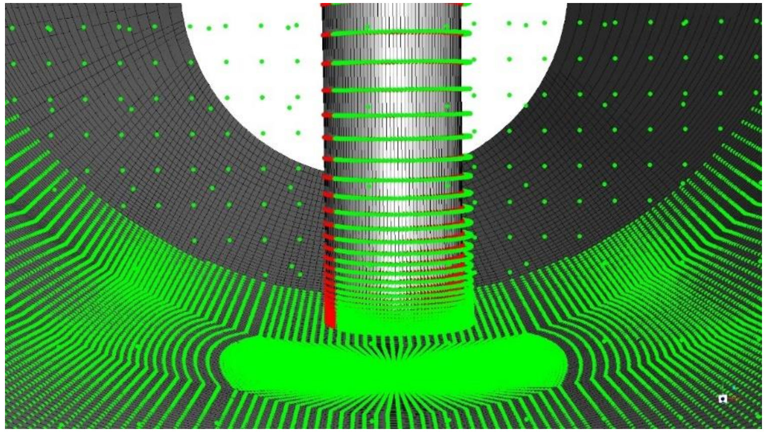


Vortex induced vibration analysis

Second step: the first RBF solution, amplified with a factor of 0.001 , is imposed as a motion law to the thermowell surface and a domain encapsulation is introduced to delimit the action of the morphing.



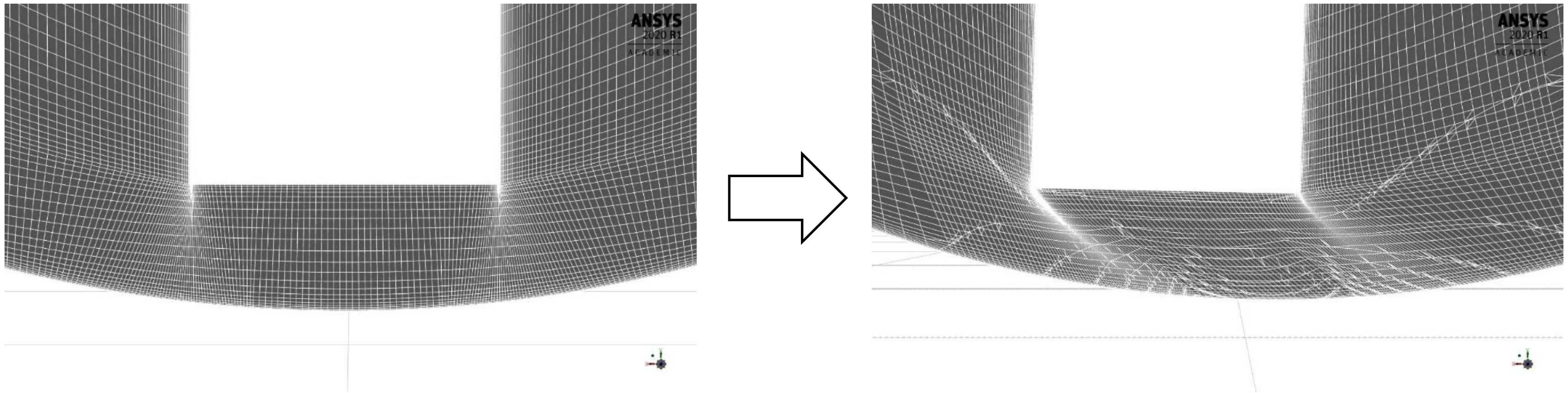




Vortex induced vibration analysis

<u>*Corrective RBF solutions:*</u>

Proximity of the tip of the thermowell to the boundary of the simulation volume (fixed) ⇒ high volume mesh distortion.



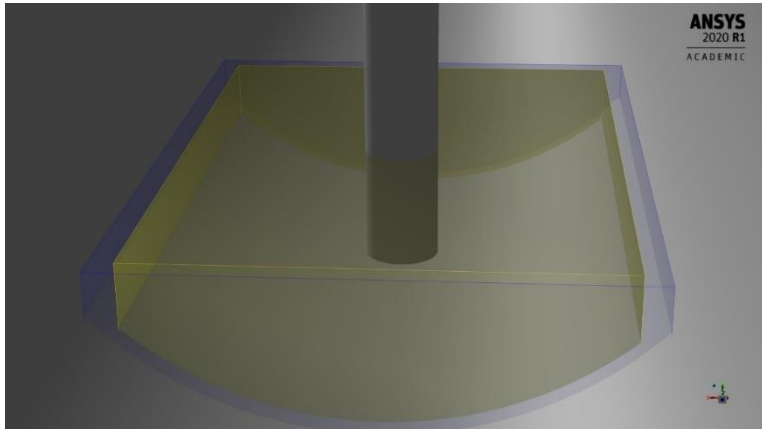
Quality evaluation:

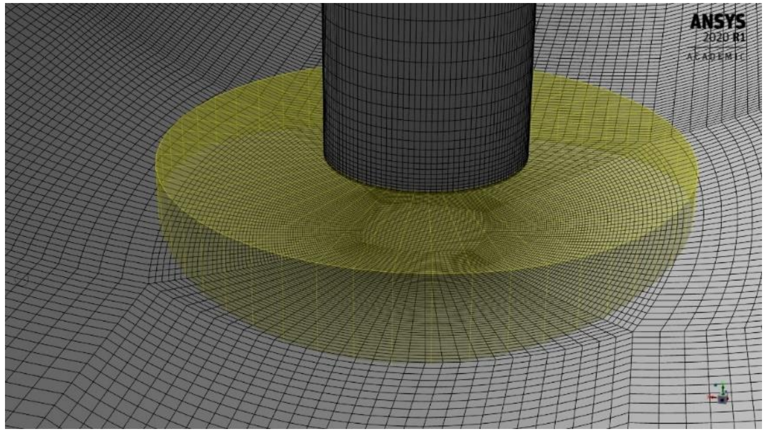
- minimum orthogonal quality: 0.016
- maximum cell squish index: 0.984

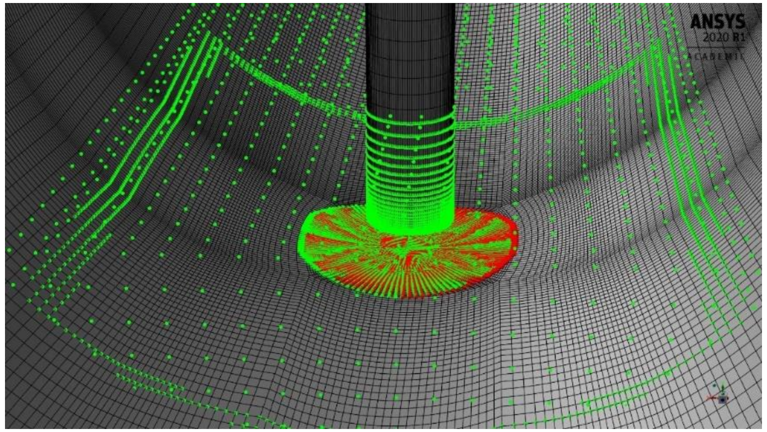
Three corrective solutions: shadow area rotation, shadow area translation, STL-target-derived.

Vortex induced vibration analysis

Shadow area management: the shadow area is the portion of the duct surface linked to the tip of the thermowell through the structured mesh ⇒ to avoid the high mesh distortion, the surface nodes contained in this area had to follow the tip of the thermowell during the morphing action ⇒ rotation around the pipe axis and translation in the direction of the axis.

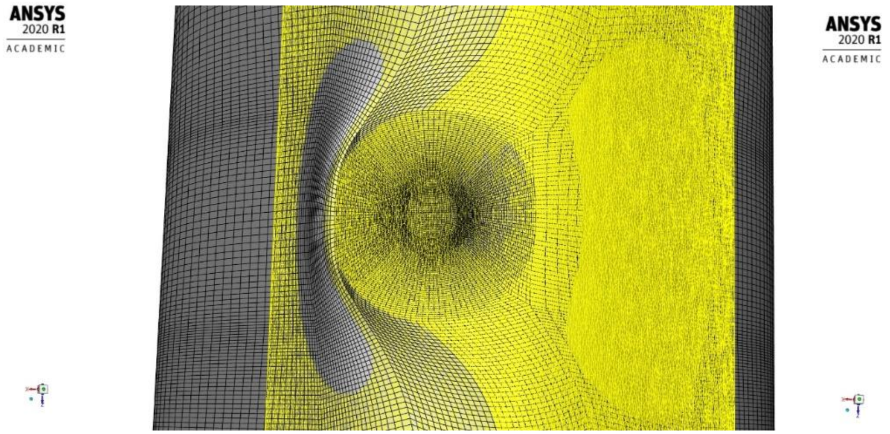


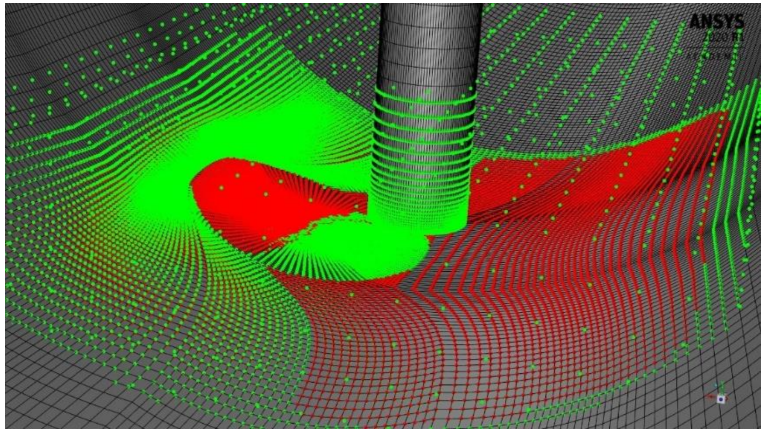




Vortex induced vibration analysis

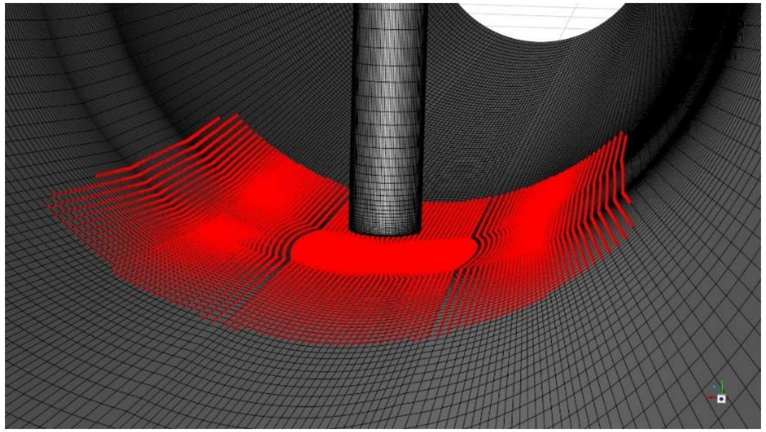
STL-target-derived corrections: the absence of source points on the rest of the duct surface caused the loss of direct control on its morphing ⇒ distortion of the cylindrical surface ⇒ STL-target motion:

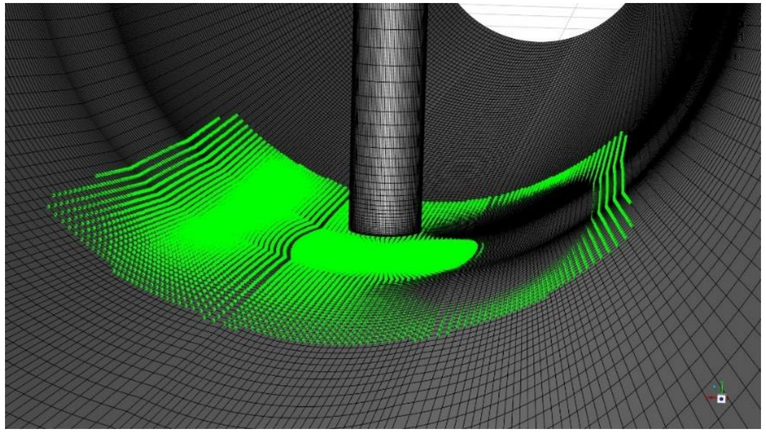




Vortex induced vibration analysis

The **recovery solution** has to be defined starting from the undeformed surface ⇒ tracking each node in the three available meshes (the starting one, the distorted one and the recovered one), the solution was defined starting from the undeformed mesh:





If the rotation of the shadow area is applied with an amplification factor lower than 15, the cylindricity of the duct can be recovered applying this STL-target-derived solution with a proportional amplification factor.

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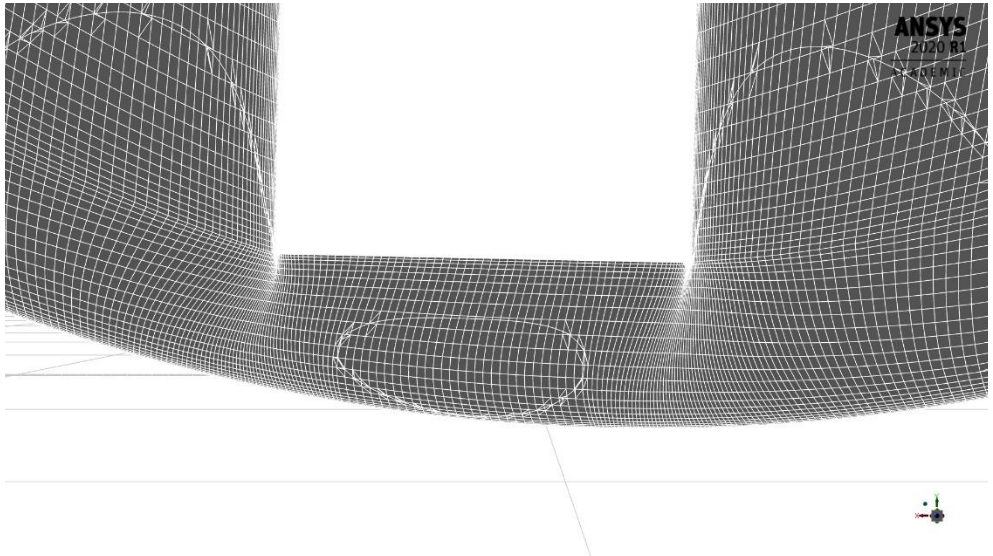
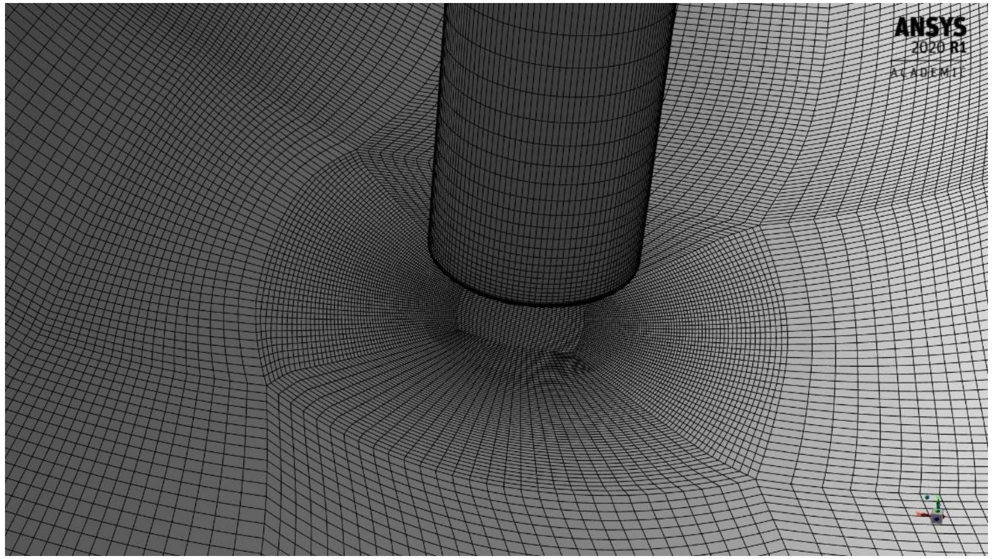
Effects of the corrective solutions:





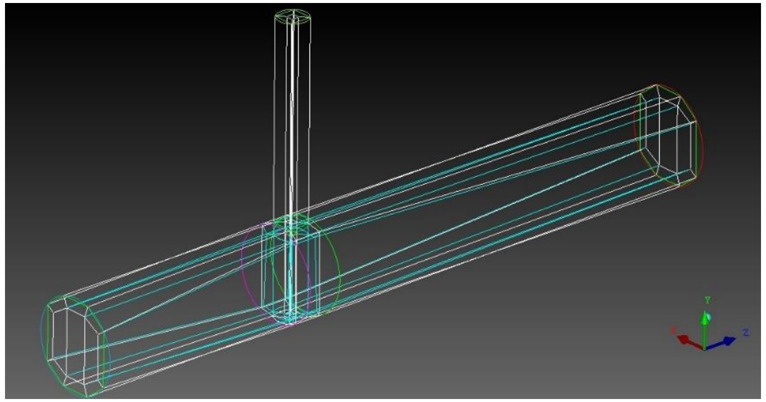
- Improvement in morphing quality (lower mesh distortion);
- Preservation of the cylindricity of the duct;
- Correct positioning of the shadow area.

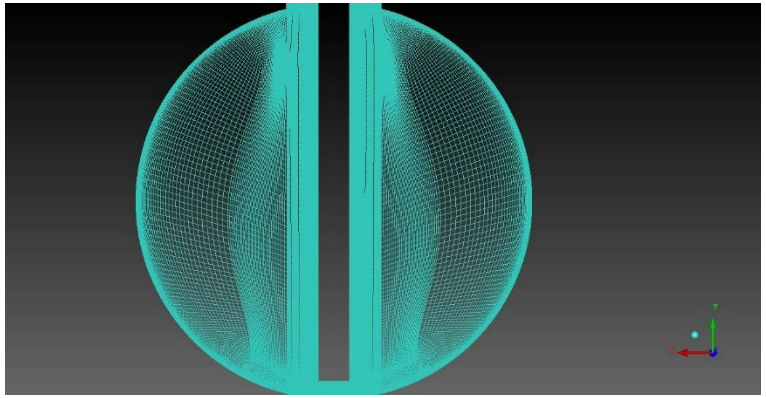
Vortex induced vibration analysis

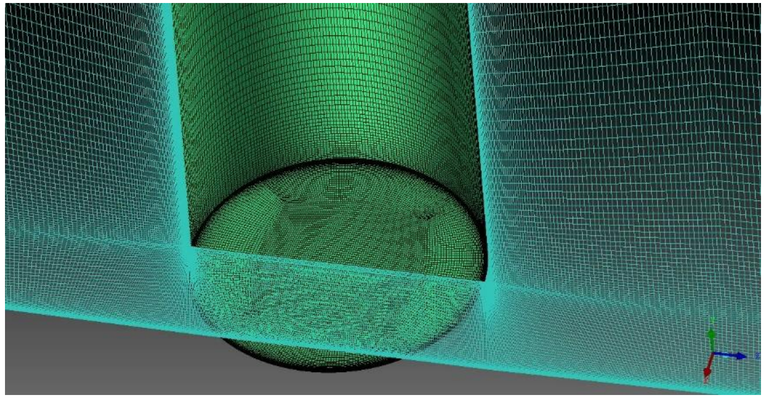
3-D computational grid:

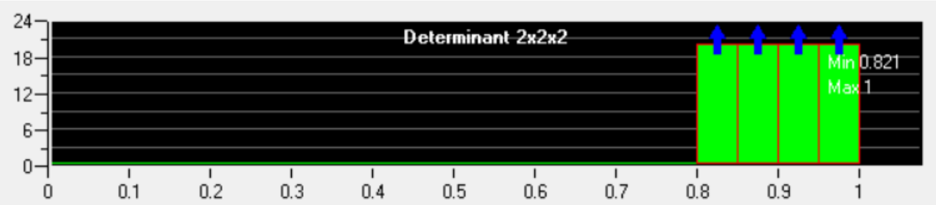
The geometry has been discretized into a computational domain through ANSYS® ICEM CFD™ using the setup validated in the 2-D analysis. The obtained mesh is structured, multiblock and composed of hexahedrons.

Key features: $y^+<1$ for the first row of cells near the walls, 1.2 growth factor after the first row, refinement in the wake, 3158640 hexahedral cells.



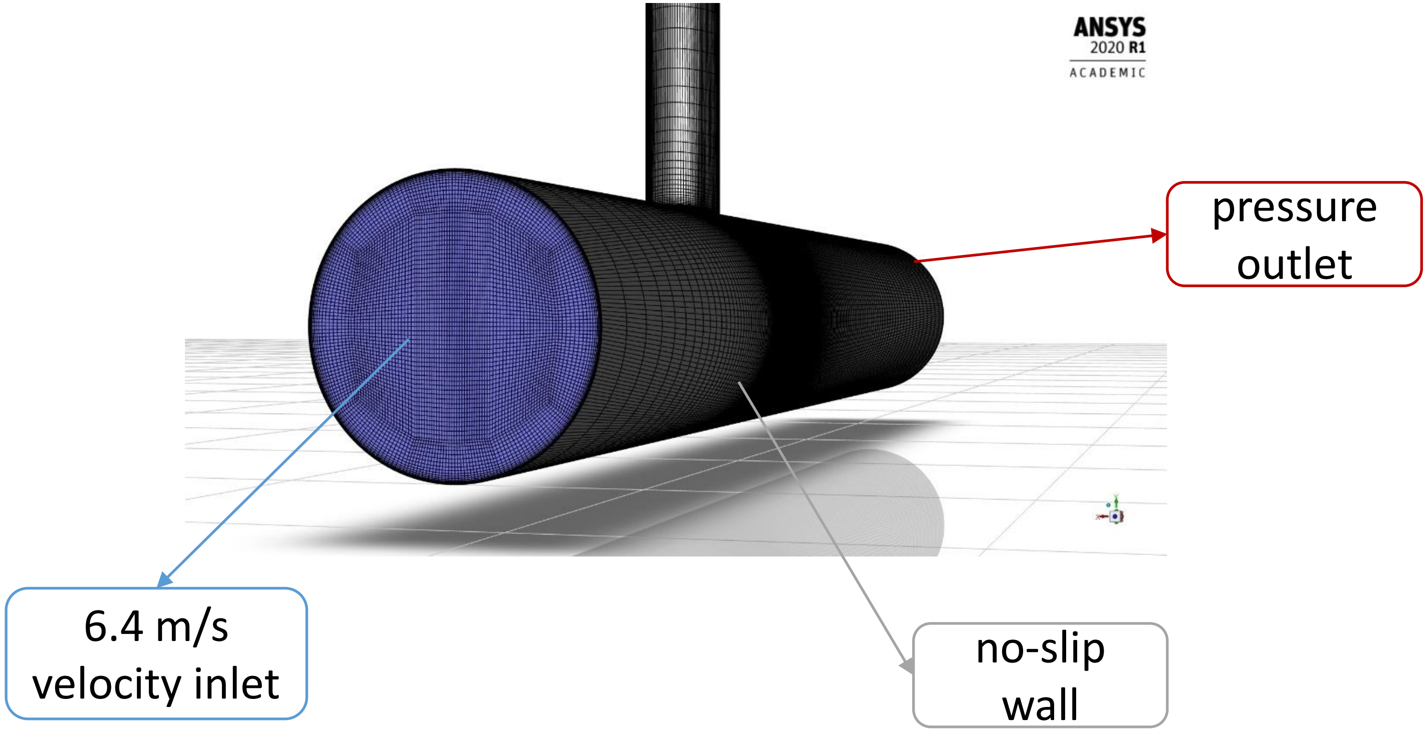






Vortex induced vibration analysis

<ins>*CFD setup:*</ins>



Key features:

- Water density: 998 kg/m^3;
- Water viscosity: 0.001002 kg/(m·s);
- *Re*: 100000;
- Pressure-based solver;
- Constant density;
- URANS with SST k-ω;
- SIMPLE pressure-velocity coupling;
- Second order scheme for pressure;
- Second order upwind scheme for momentum and turbulence parameters;
- Lest squares cell based scheme for gradient;
- First order implicit transient formulation;
- Time-step size: 10^{-4} s;
- Computer-controlled convergence criterion: 10^{-5} residual of the continuity equation.

Vortex induced vibration analysis

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FSI setup:

1. Parameters definition ⇒ morphed surfaces, RBF solutions, frequencies, time-step size, damping ratio;
2. Files loading ⇒ an executable that handles the unsteady FSI analysis and a scheme function that handles the corrective solutions;
3. FSI environment initialization ⇒ the RBF solutions are loaded and stored in memory;
4. Commands setting ⇒ *(shadow_control)* and *(modal-q-update)* executed at the end of each timestep.

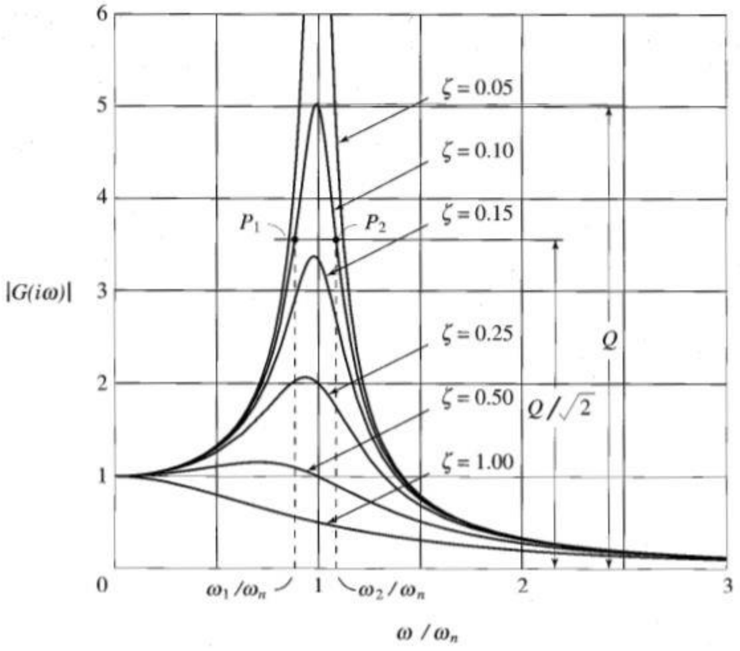
(modal-q-update)**:** calculates the values of the modal forces projecting the nodal forces onto the modal shapes, updates the modal coordinates and applies the mesh morphing over-imposing linearly each solution.

(shadow_control)**:** computes and enforces the amplification factors of the corrective.

Vortex induced vibration analysis

Damping ratio:

The accuracy of any dynamic solution is dependent on the damping assigned to the model, usually defined as a percentage of the critical damping, also called “damping ratio”.



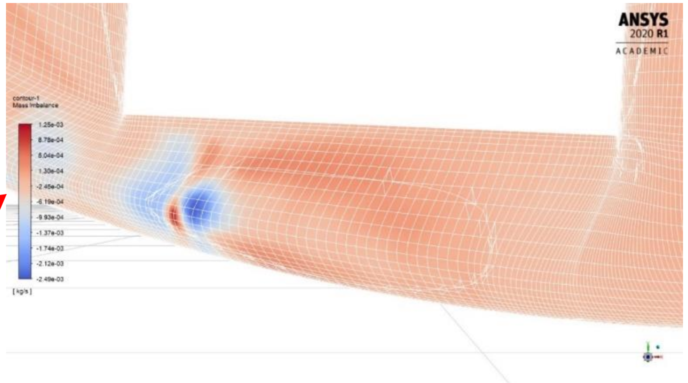
It is a property that should be experimentally measured, not available in the experimental data ⇒ literature guidance:

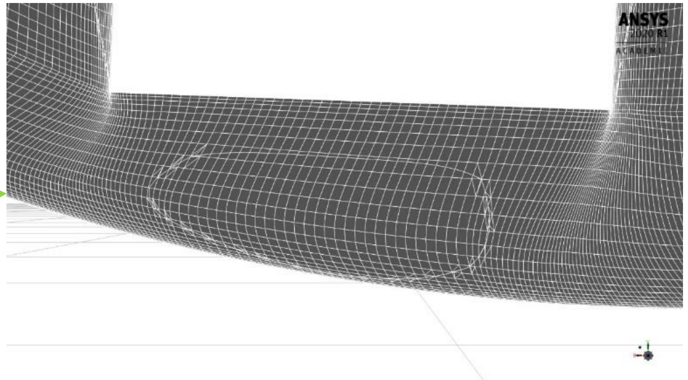
System	Damping ratio
Metals (in elastic range)	<0.01
Continuous metal structures	0.02 to 0.04
Metal structure with joints	0.03 to 0.07

Parametric study:

The simulations ran on a HPC node equipped with 256 GB of RAM and four Intel® Xeon® Gold 6152 CPU, each featuring 22 cores @ 2.1 GHz. Out of the overall 88 cores, 30 were used to run the simulations.

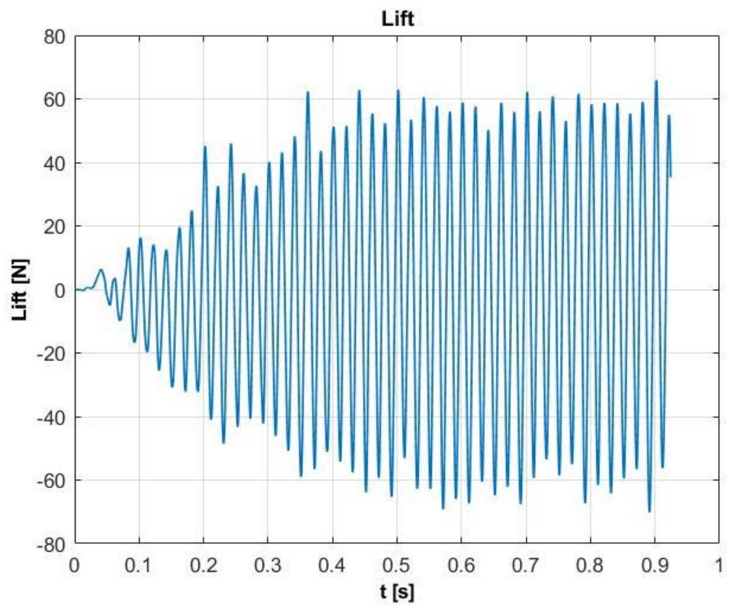
Damping ratio	Maximum RMS transverse tip displacement at dynamic steady state [mm]	Relative error [%]
0.01	Not reached	-
0.02	Not reached	-
0.05	6.45	22.3
0.04	8.48	-2.17
0.041	8.304	-0.048

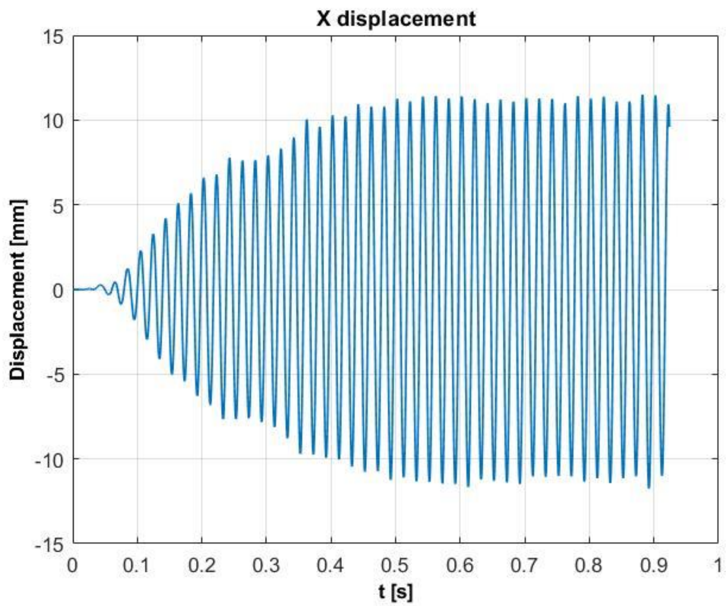




Vortex induced vibration analysis

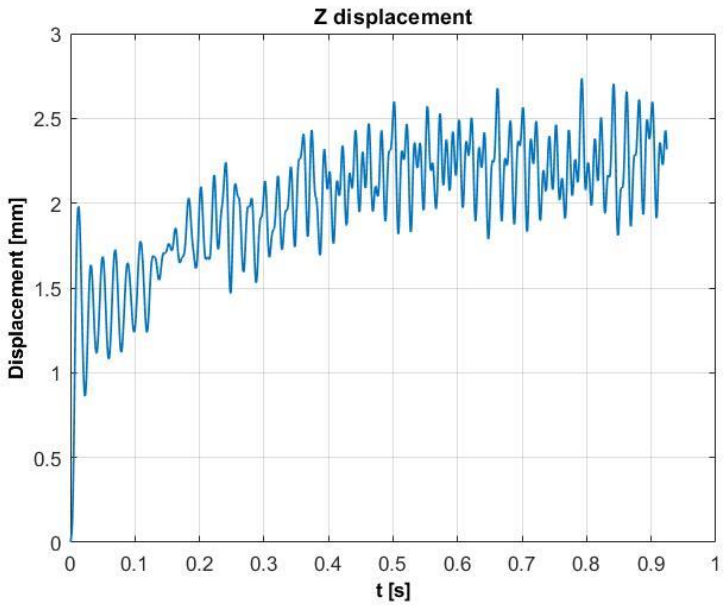
FSI analysis results:

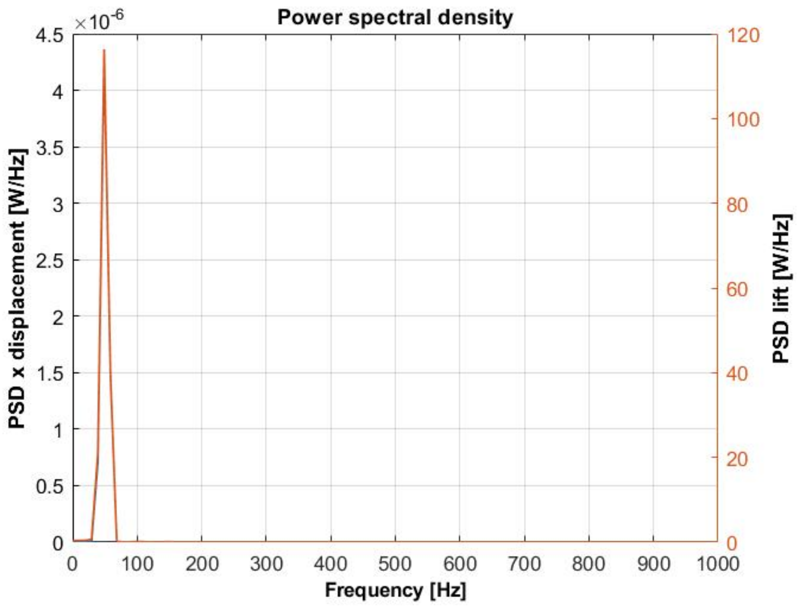




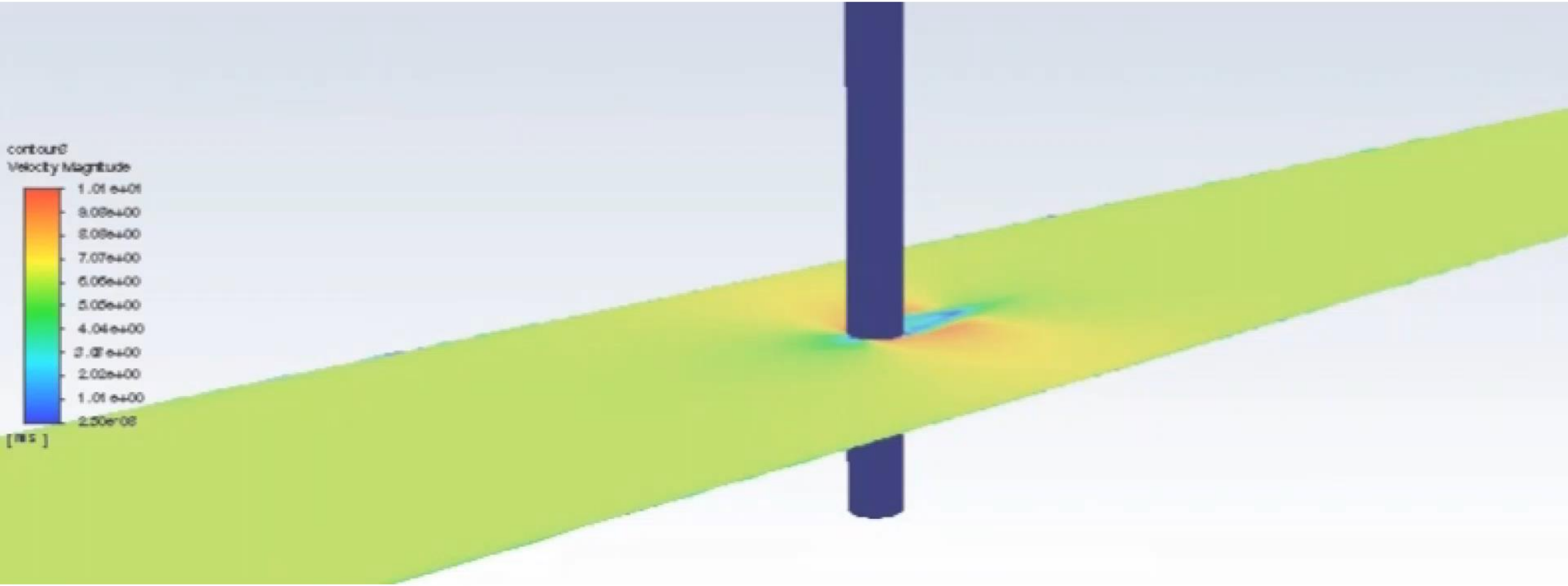
Synchronization between the vortex shedding and the thermowell oscillation ⇒ lock-in ⇒ vortex induced vibration.

Vortex induced vibration analysis





Both signals are characterized by a dominant frequency of 48.8 Hz, close to the first natural frequency of the thermowell as expected from the obtained resonance but with some deviation caused by the structural and the water damping.


Velocity Magnitude
1.01e+01
7.07e+00
4.04e+00
1.01e+00

Conclusions

- The objective of the presented work **was successfully achieved**: by properly setting up the modal superposition method for the FSI analysis, it was possible to accurately simulate the vortex induced vibration observed in the thermowell;
- Thanks to RBF mesh morphing a **reliable and robust** FSI transient solver has been implemented;
- The approach is fast and can be adopted to tackle **complex industrial problems**;
- Further developments:
  - ➢ Gathering more comprehensive experimental data;
  - ➢ Analysis of other fluid velocity to capture the lock-in region of the in-line vibration and the lock-off regions;
  - ➢ Analysis with different mesh setups and turbulence models (sensitivity study);
  - ➢ Submerged natural modes calculation;
  - ➢ Assessment of the non-linearities influence on the system dynamics.

Thank You For Your Kind Attention!

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