Fluid structure interaction analysis: vortex shedding induced vibrations

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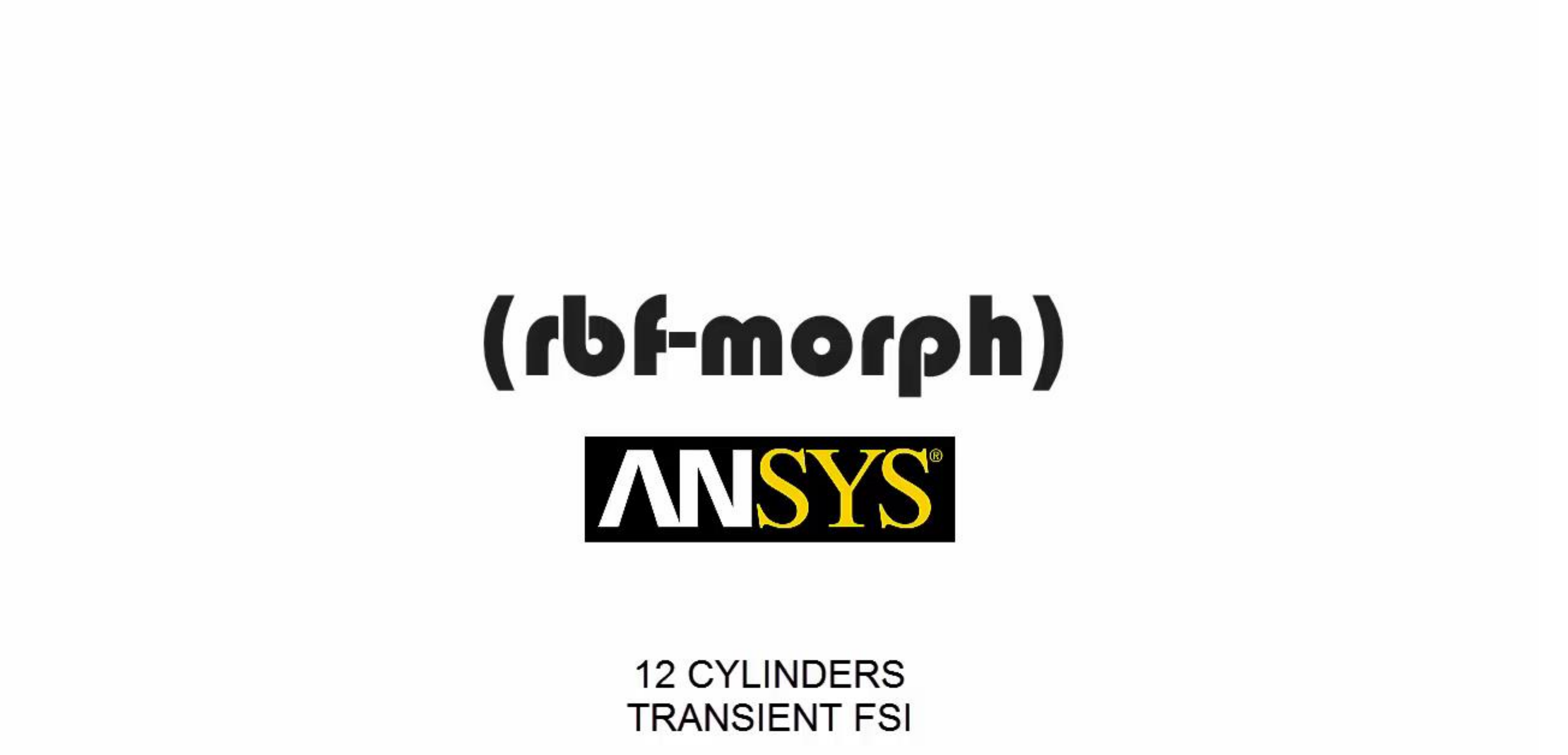
Outline

- Introduction
- Research path
- RBF Background
- Structural modes embedding
- Challenges
- Application Description
- Results
- Conclusions

Introduction

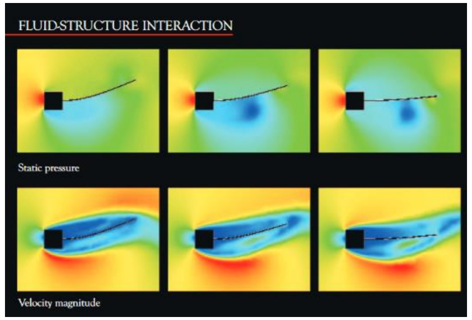
- **Fluid Structure Interaction** (FSI) analysis can be faced by high fidelity simulation coupling CFD and FEM solvers.
  - Steady state problems usually requires iterations between the fluid solver (that computes **loads** on the structure) and the structural one (that computes **displacements**).
  - Transient simulations needs continuum update (usually on time step basis using weak coupling)
- Two-way FSI foresees pressure **mapping** and mesh **deformation** at each iteration (data exchange is a bottleneck).
- Modal superposition approach requires data exchange **just at initialization**
- In the present work the mesh morphing tool **RBF Morph™** which is based on Radial Basis Functions (**RBFs**) is adopted for the deformation of the CFD mesh and for structural modes embedding.

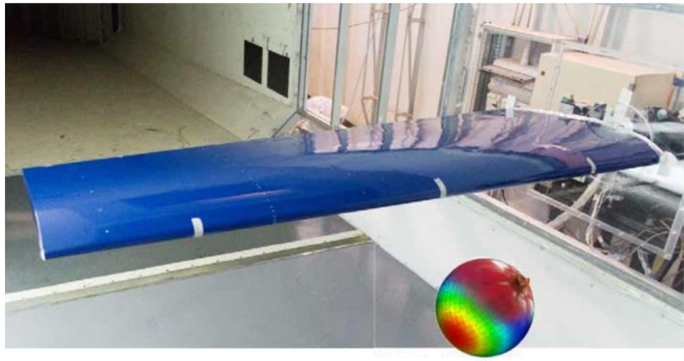


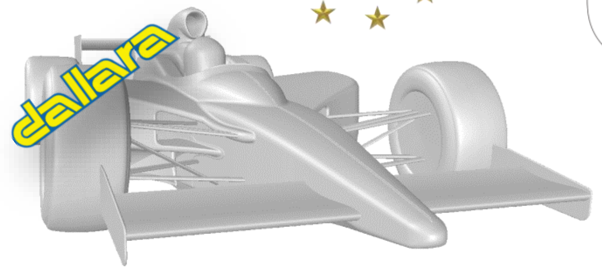
https://youtu.be/A0WPDyhlr8Q

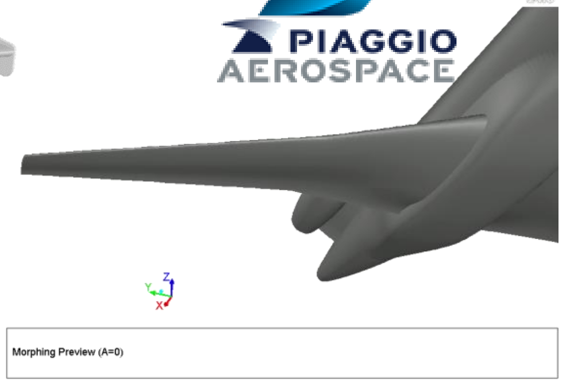
Research path

- The first UDF in 2005 (2D and 3D) for **time marching solutions**.
- RBF for **mesh morphing** and pressure mapping was introduced in 2009 with RBF Morph Fluent Add On.
- RBF Morph Stand alone for FSI with **OpenFoam** released in 2012.
- RBF4AERO (www.rbf4aero.eu) implementation (**cross solvers**, steady, 2-way and modal) 2013-2016
- RIBES (www.ribes-project.eu) implementation
- RBF Morph Fluent Add On **advanced FSI module** (steady and transient, HPC)
- 3 Awards! (2005, 2011, 2013)





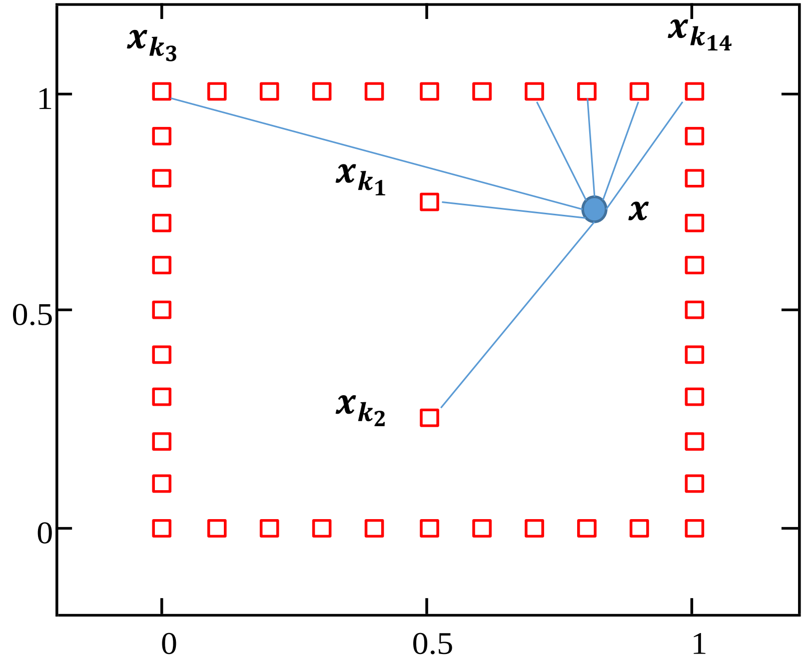




RBF Background

- RBFs are a mathematical tool capable to **interpolate** in a generic point in the space a function **known** in a discrete set of points (**source points**).
- The interpolating function is composed by a **radial basis** and by a **polynomial**:

$$s(\boldsymbol{x})=\sum_{i=1}^{N}\overbrace{\gamma_i\varphi\left(\underbrace{\left\|\boldsymbol{x}-\boldsymbol{x}_{k_i}\right\|}_{\text{distance from the i-th source point}}\right)}^{\text{radial basis}}+\overbrace{h(\boldsymbol{x})}^{\text{polynomial}}$$



RBF Background

- If evaluated on the source points, the interpolating function gives exactly the input values:

$$\begin{matrix} s(\boldsymbol{x}_{k_i}) = g_i \\ h(\boldsymbol{x}_{k_i}) = 0 \end{matrix} \quad 1 \le i \le N$$

- The RBF problem (evaluation of coefficients γ and β) is associated to the solution of the linear system, in which **M** is the interpolation matrix, **P** is a constraint matrix, **g** is the vector of known values on the source points:

$$\begin{bmatrix} \mathbf{M} & \mathbf{P} \\ \mathbf{P}^{\mathrm{T}} & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \boldsymbol{g} \\ 0 \end{pmatrix} \quad M_{ij} = \varphi\left(\boldsymbol{x}_{k_i} - \boldsymbol{x}_{k_j}\right) \quad 1 \le i, j \le N \quad \mathbf{P} = \begin{bmatrix} 1 & x_{k_1} & y_{k_1} & z_{k_1} \\ 1 & x_{k_2} & y_{k_2} & z_{k_2} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k_N} & y_{k_N} & z_{k_N} \end{bmatrix}$$

RBF Background

- Once solved the RBF problem each displacement component is interpolated:

$$\begin{cases} s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$

- Several different radial function (kernel) can be employed:

RBF	φ(r)	RBF	φ(r)
Spline type (Rn)	r^n, *n odd*	Inverse multiquadratic (IMQ)	$\frac{1}{\sqrt{1+r^2}}$
Thin plate spline	$r^n\log(r)$ *n even*	Inverse quadratic (IQ)	$\frac{1}{1+r^2}$
Multiquadratic (MQ)	$\sqrt{1+r^2}$	Gaussian (GS)	e^{-r^2}

Structural modes embedding

- A certain number of **modes** is computed using FEA.
- An **RBF solution** is computed for each mode (constraining far field conditions and rigid surfaces, mapping FEA field on deformable surfaces). Modes on CFD mesh are stored.
- At initialization the CFD solver loads the modes and then:
  - the mesh deformation can be **amplified** prescribing the value of **modal coordinates**
  - **modal forces** are computed on prescribed surfaces by projecting the nodal forces (fluid pressure and shear) onto the modal shape

$$X_{CFD} = X_{CFD_0} + \sum_{i=1}^{k} q_i \Delta X_i$$

number of natural modes

nodal modes displacement

modal coordinate

Structural modes embedding

- Transient analysis is performed considering the loads frozen in the time step. Each modal coordinate is updated considering the analytic equation (as usual for transient modal analyses):

$$\ddot{q} + 2\zeta_i \omega_i \dot{q}_i + \omega_i^2 q_i = \frac{F_i(t)}{M_{ii}}$$

$$\xi(t) = e^{-\zeta\omega_n t}\left(\xi_0 \cos(\omega_d t) + \frac{\dot{\xi}_0 + \zeta\omega_n \xi_0}{\omega_d} \sin(\omega_d t)\right) + \frac{1}{m\omega_d}\int_0^t e^{\frac{-b(t-\tau)}{2m}} f(\tau) \sin\big(\omega_d (t-\tau)\big) dx$$

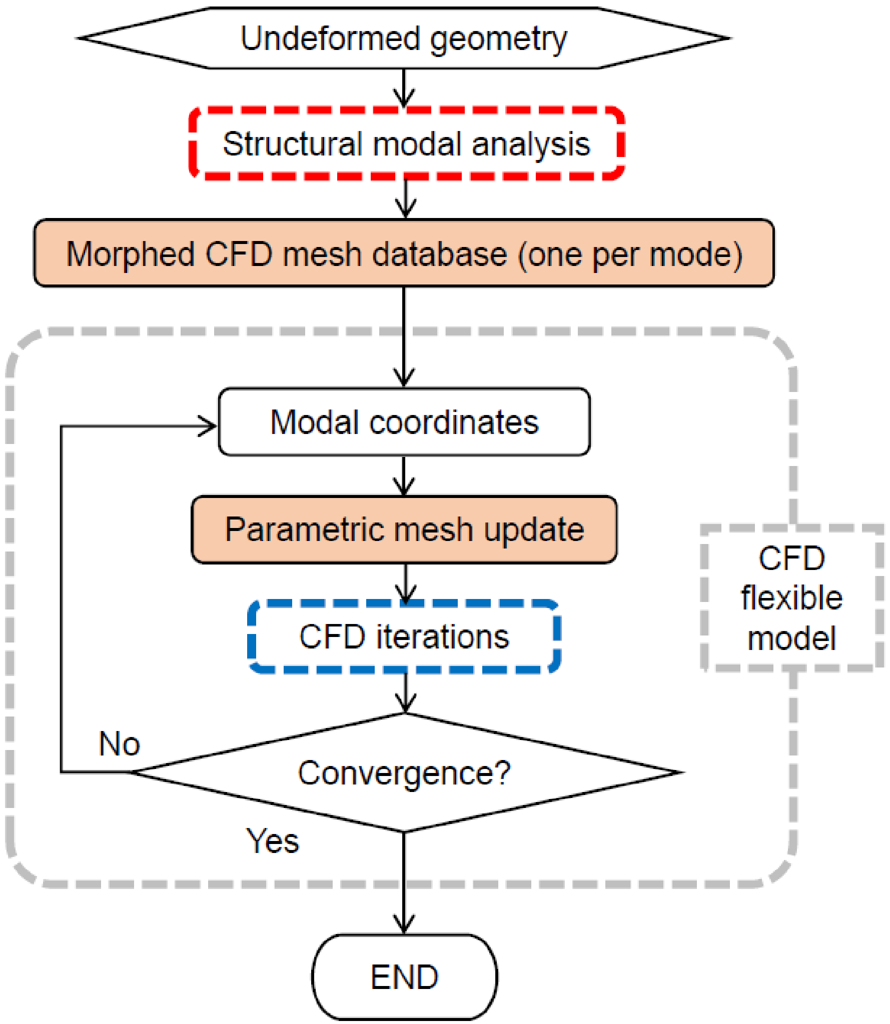
- Steady analysis is performed by updating the modal coordinates at a certain number of CFD iterations (usually 20-100):

$$\omega_i^2 q_i = \frac{F_i}{M_{ii}}$$

- Modes are normalized with respect to the mass (so that only the frequencies are needed).

Possible Simulation Scenario

- Steady FSI to account for structure elasticity (aircraft wings, propeller blades, racing)
- Transient simulations with prescribed motions
  - flapping devices
  - structural modes acceleration for Reduced Order Models in flutter analysis
- Transient simulation with vibrations excited by the flow (as in the presented example)
  - forced response
  - computation of damped frequencies

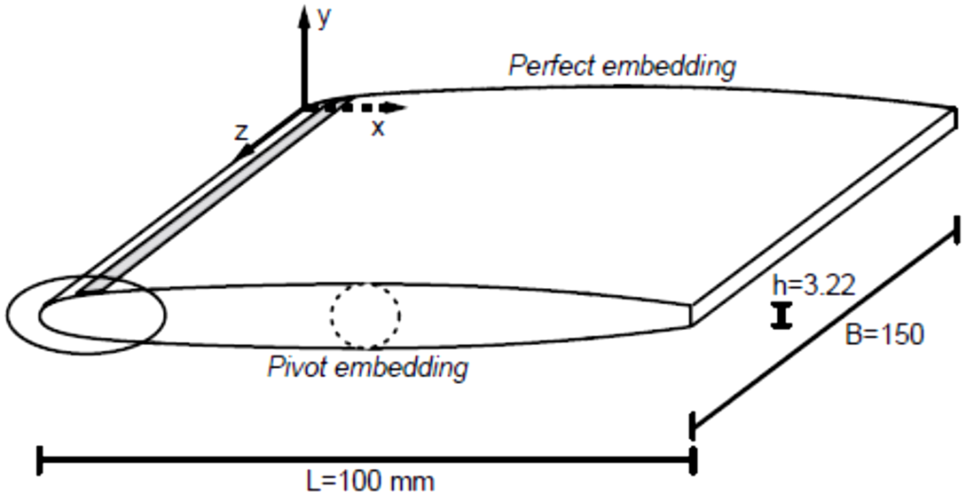


Challenges

- For **very Large models** (millions cells) pressure mapping and mesh update could be time consuming (Dallara GP2 example is a 250 millions mesh)
- Structural modes embedding **truncation error** has to be considered (especially for steady cases)
- Transient simulations can take hours (days). A **robust** and **reliable** process is a paramount!
- Modal superposition allows to go **10-12 times faster** than two-way in transient analysis
- Modal theory is limited to **linear structures**.

Application

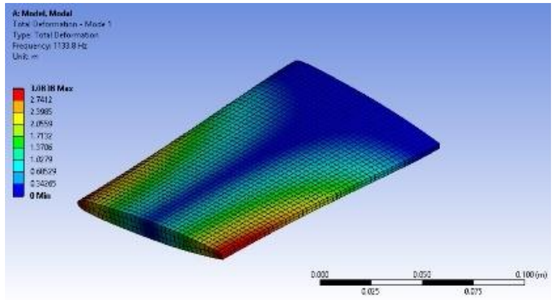
- NACA 0009 hydrofoil
- Angle of attack: α=0°
- Material: steel (ρ=7850 kg/m^3)
- Constraints: embedded pivot, clamp
- Fluid: water
- References



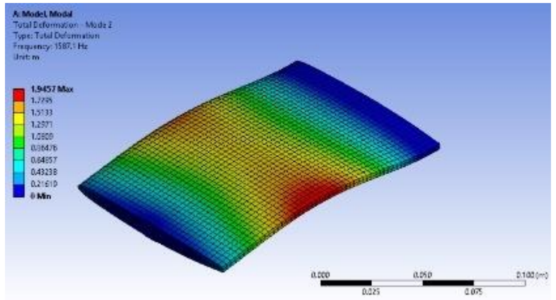
  - Ausoni, P., Farhat, M., & Avellan, F. (2012). The effects of a tripped turbulent boundary layer on vortex shedding from a blunt trailing edge hydrofoil. Journal of Fluids Engineering.
  - Ausoni, P., Zobeiri, A., Avellan, F., & Farhat, M. (2009). Vortex Shedding From Blunt and Oblique Trailing Edge Hydrofoils. IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems. Brno.

Application

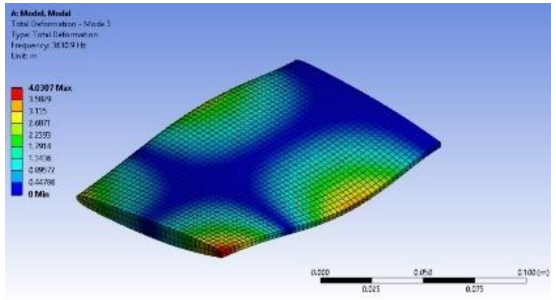
- modes in air (ANSYS Mechanical)



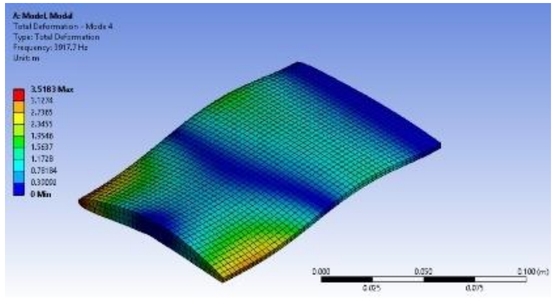
Mode 1 - First bending mode
1133.8 Hz



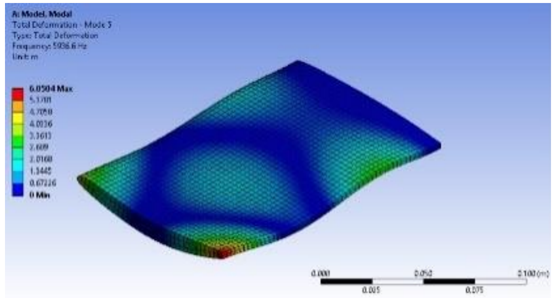
Mode 2 - First torsional mode
1587.1 Hz



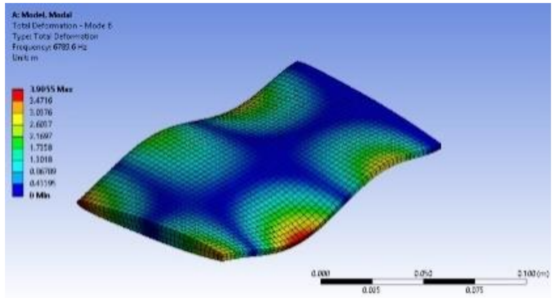
Mode 3 - Second torsional mode
3630.9 Hz



Mode 4 - Second bending mode
3917.7 Hz



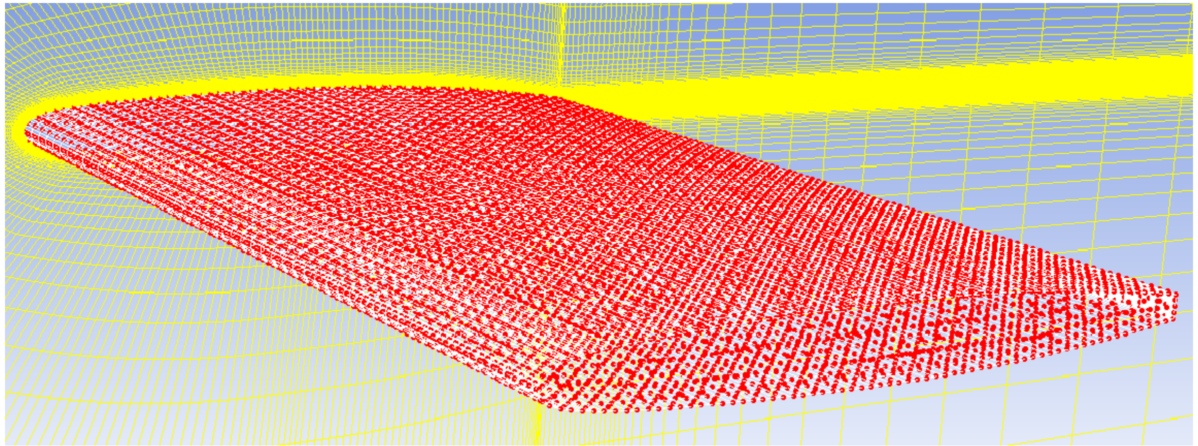
Mode 5 - Third bending mode
5936.6 Hz

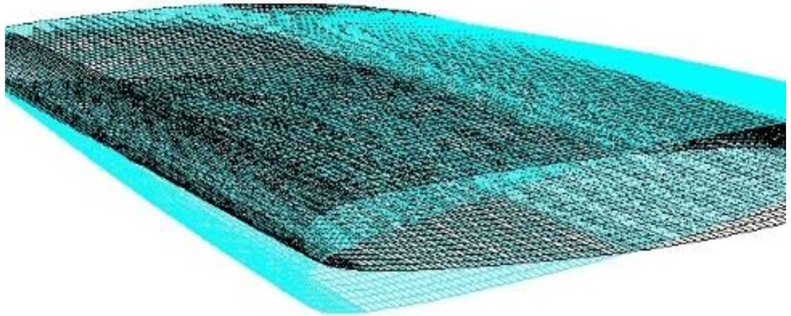


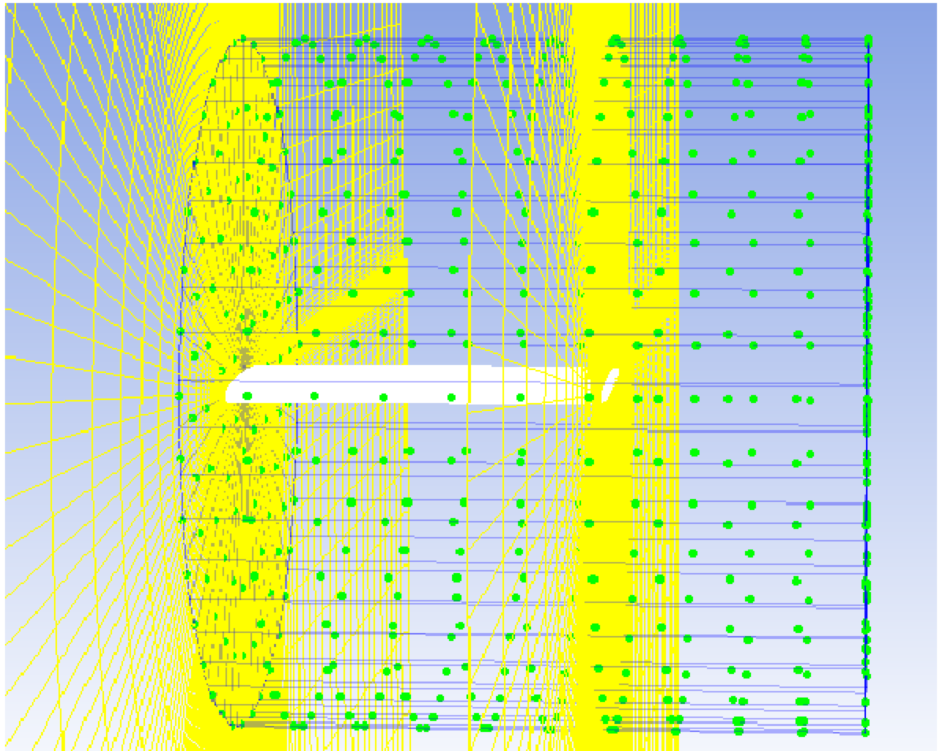
Mode 6 - Third torsional mode
6789.6 Hz

Application

- RBF set-up (applied to the CFD model with RBF Morph)

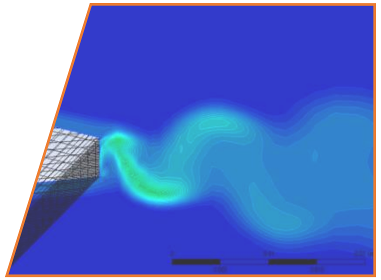




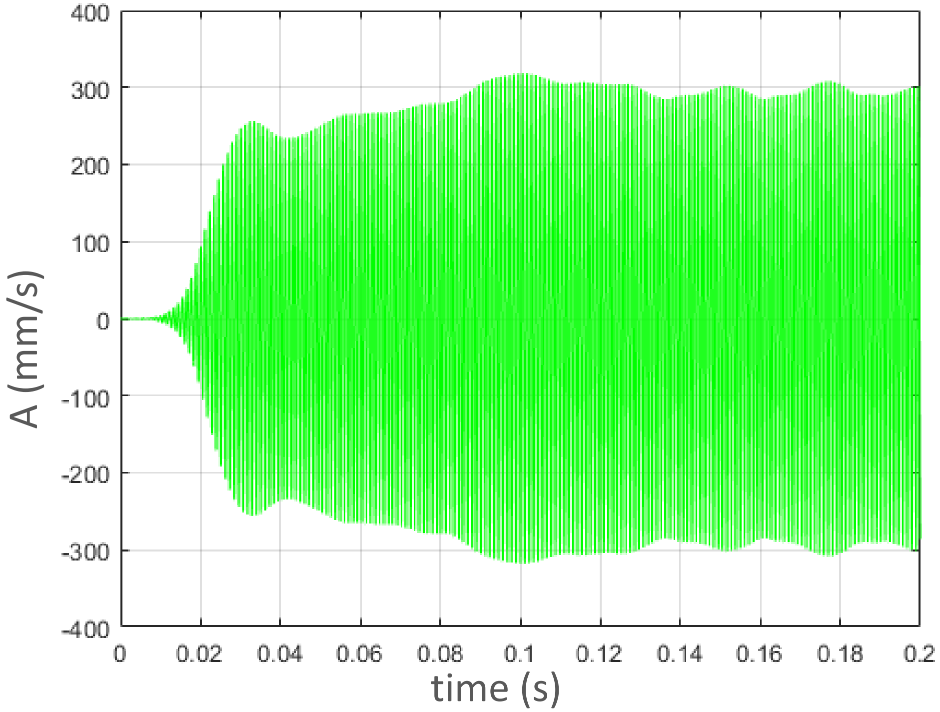


Lock in (predicted with ANSYS Fluent after 37h on 32 cores)

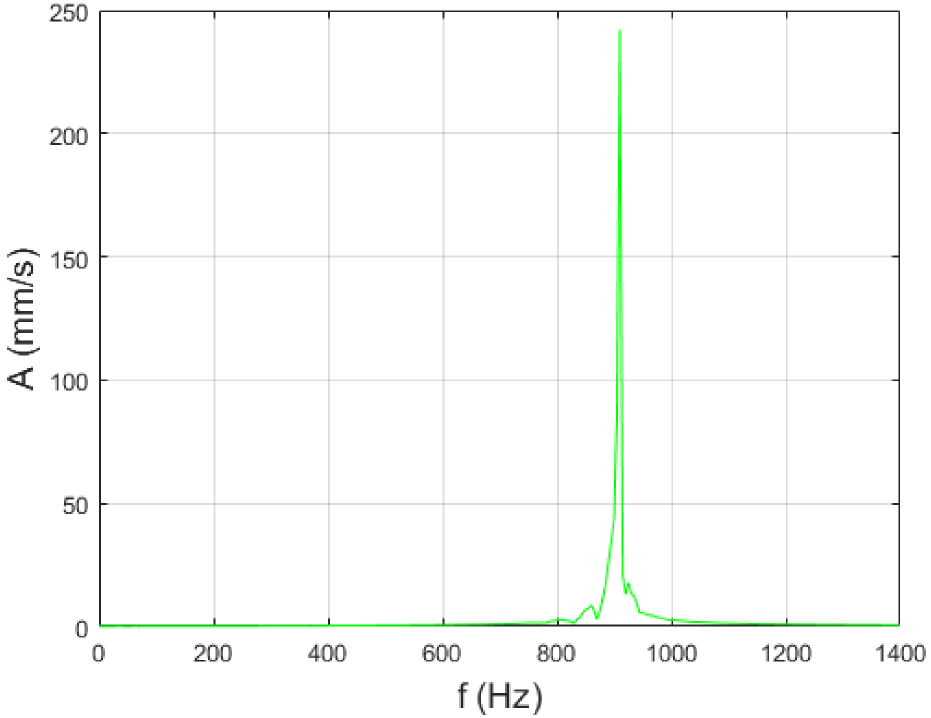
- Probe at (0.08000 m, 0.03788 m, 0.1125 m)
- Observed frequency 909.91 Hz
- Imposed speed 16 m/s



Probe vertical speed

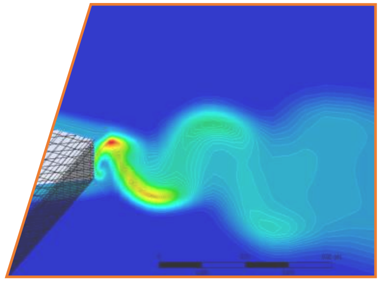


Probe vertical speed FFT

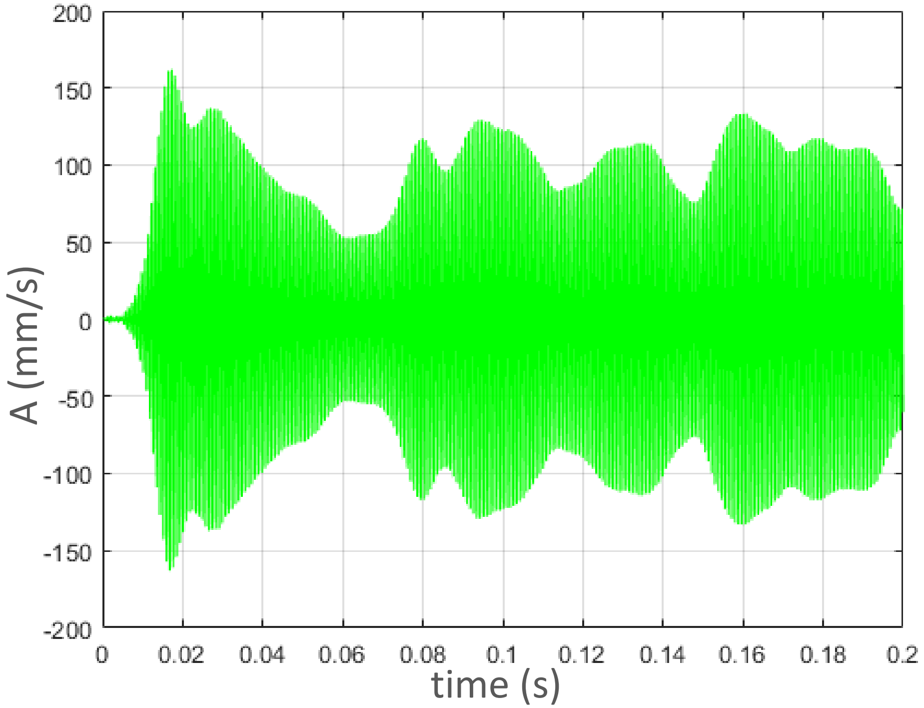


Lock off (predicted with ANSYS Fluent after 37h on 32 cores)

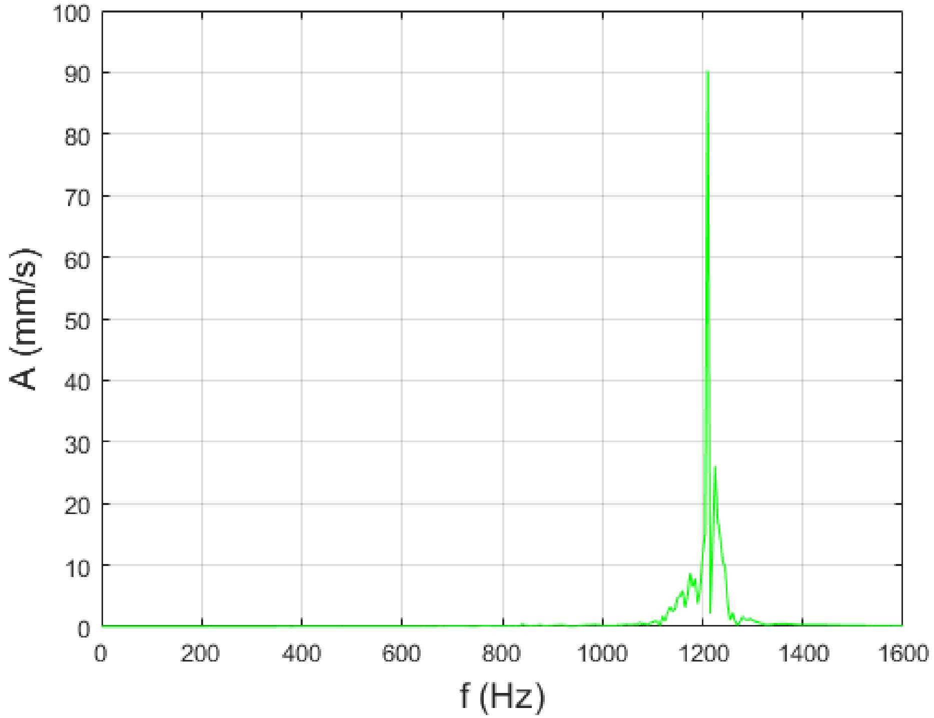
- Probe at (0.08000 m, 0.03788 m, 0.1125 m)
- Observed frequency 1209.9Hz
- Imposed speed 22 m/s



Probe vertical speed



Probe vertical speed FFT

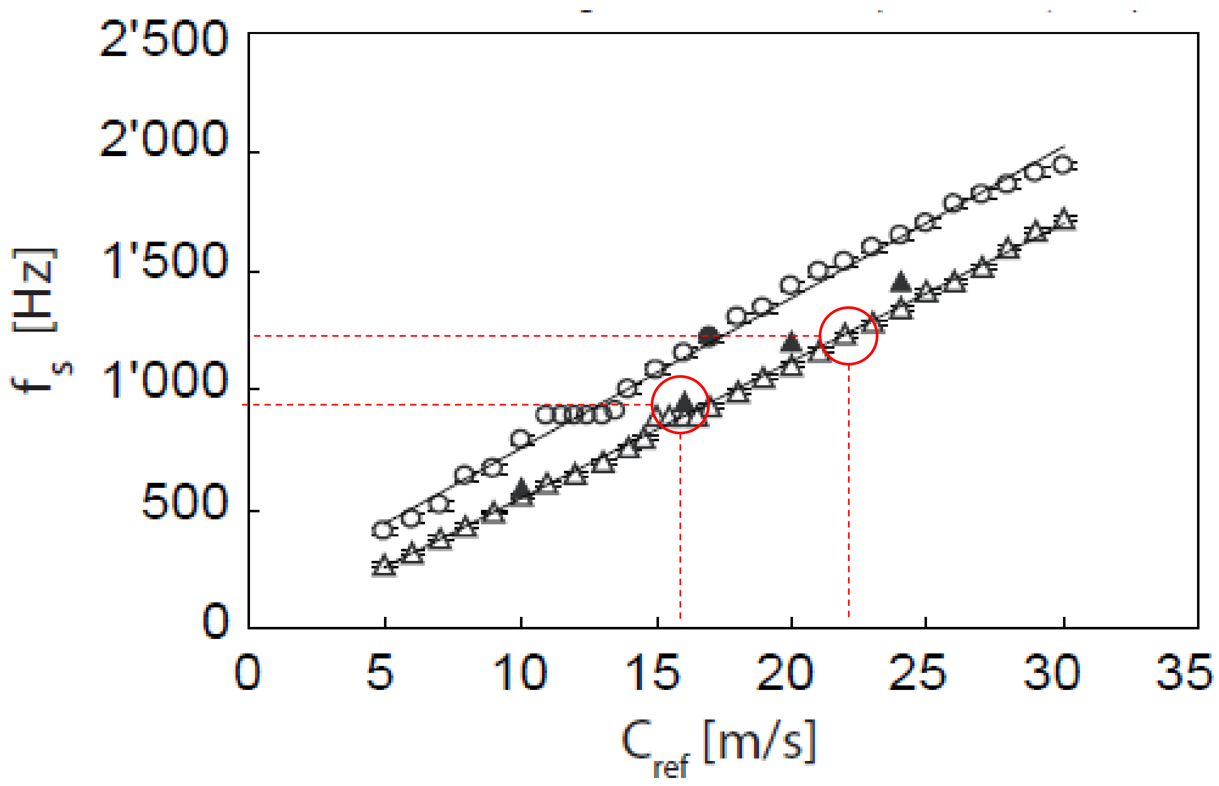


Predicted vs. measured

Lock In

Cref ≅ 16 m/s

fs ≅ 900 Hz



Lock Off

Cref ≅ 22 m/s

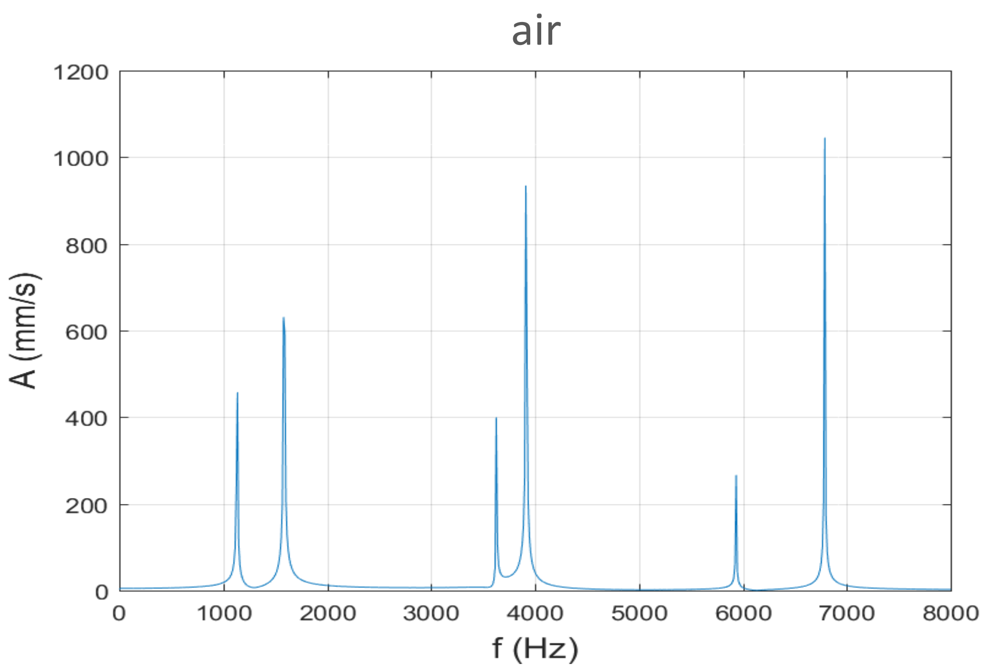
fs ≅ 1200 Hz

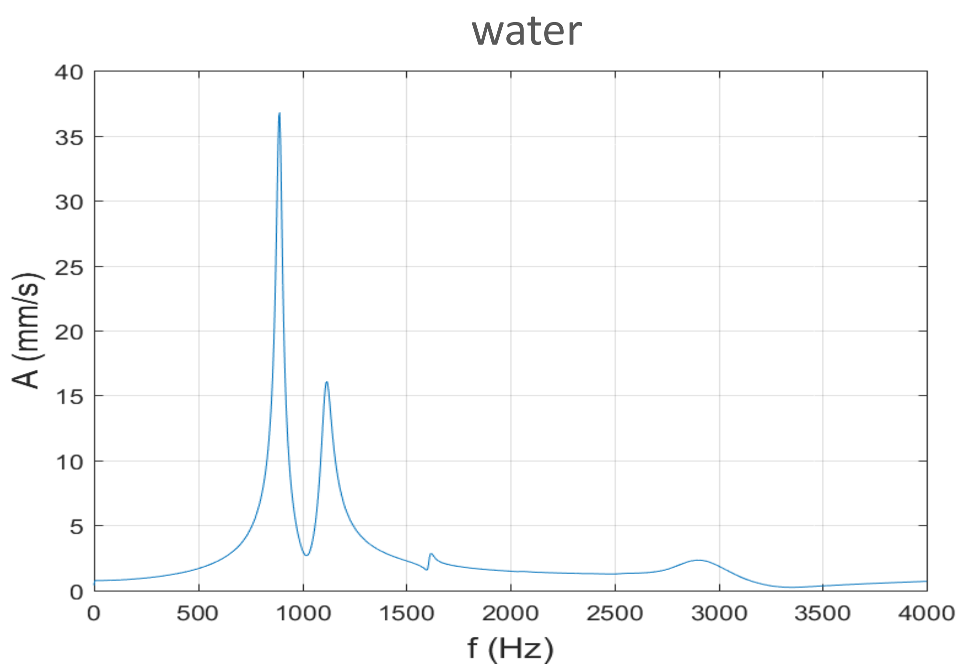
Modes in air vs. modes in water

- Transient response in water with initial conditions an all the modes
- Modes in water computed with FFT

Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
1133.8 Hz	1587.1 Hz	3660.9 Hz	3917.7 Hz	5936.6 Hz	6789.6 Hz

Mode 1	Mode 2	Mode 3	Mode 4
891.9 Hz	1118.8 Hz	1619.6 Hz	2902.7 Hz





Conclusions

- In this work an FSI approach based on modal superposition based on **mesh morphing** techniques is presented
- Transient analysis is conducted computing modes by ANSYS Mechanical and then embedding modes within ANSYS® Fluent with RBF Morph™
- Excellent **HPC performances** are observed 12x vs. full two-way FSI
- A very **good agreement** is noticed in the ability of capturing resonances in the lock-in lock-off speed range
- The transient solver can be used for the computation of natural **modes in water**
- More **FSI applications** on RBF Morph (www.rbf-morph.com), RBF4AERO (www.rbf4aero.eu) and RIBES (www.ribes-project.eu)

THANK YOU!

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