Dynamic response of the VEGA C launch vehicle subjected to wind effect on ground

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Outline

- The specific FSI challenge
- Current and innovative solutions
  - Semiempirical approach valid for structures with circular sections
  - **Numerical modal Fluid-Structure Interaction (FSI)**
- Theoretical background of modal FSI based on RBF mesh morphing
- Details about the numerical framework
- Results: comparison of the two methods
- Conclusions

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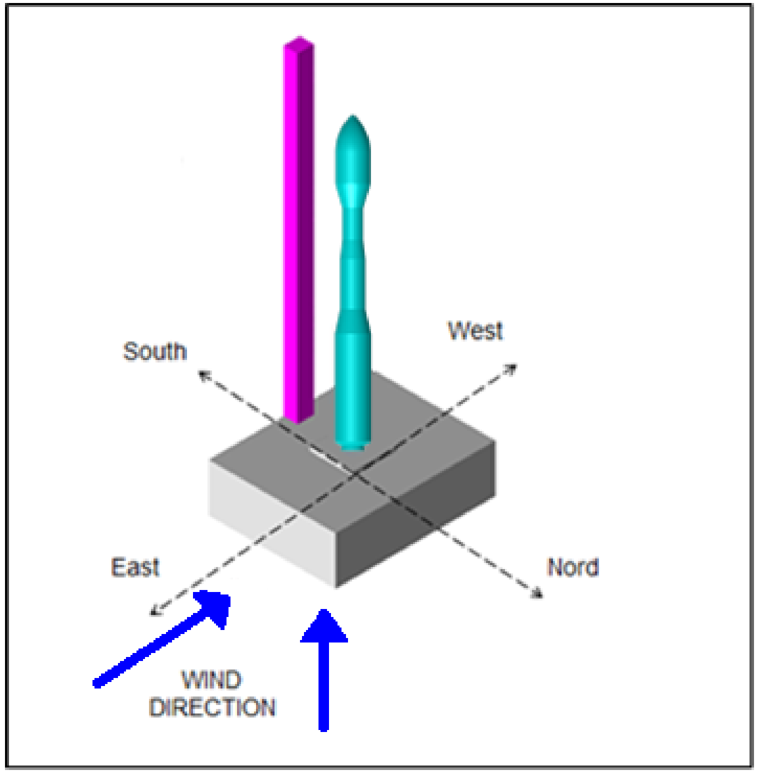
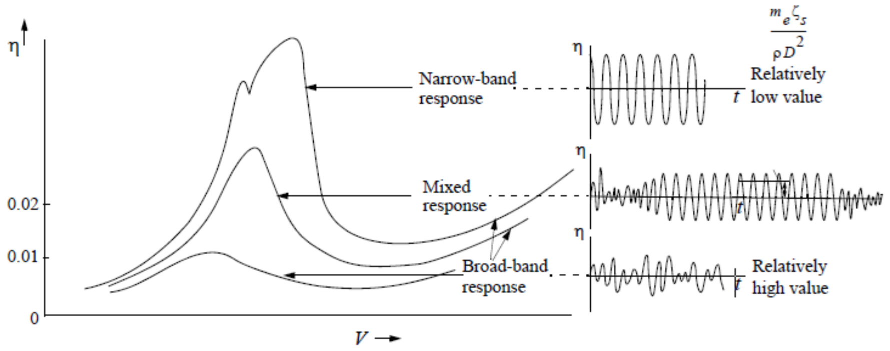
The wind effect on ground

- This study addresses the dynamic response of the launcher VEGA C subjected to wind loads on ground.
- The objective is to evaluate the risks related to the generation of Vortex Induced Vibration (VIV) mechanisms that interact with the modal properties of the structures.
- The KPIs are the dynamic contribution of moments acting on the base and the deflection of the nose tip.



Current and innovative solutions

- An internal AVIO code has been used to compute the dynamic response over a structure with a circular cross section subject to wind loads considering
  - The broad band dynamic response is calculated by linear random dynamics in the frequency domain.
  - The narrow band dynamic response is calculated by linear deterministic dynamics in the time domain.



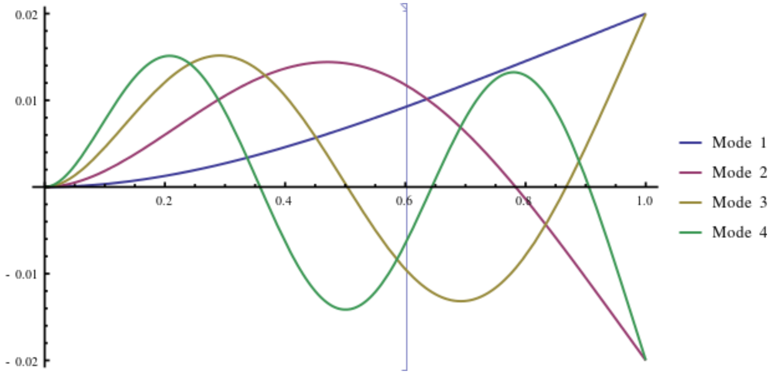
- Detailed high fidelity analysis, in which the fluid-structure interaction is taken into account by means of FEM and CFD simulations.
- The numerical FSI approach adopted is based on structural modes embedding.
- High fidelity results are intended to assess the safety of the current semi-analytical and explore possible design improvement margins

Theoretical background of modal FSI based on RBF mesh morphing

- Fluid-Structure Interaction (FSI), in most engineering applications, cannot be neglected.
- CFD analysts → boundaries rigid, verification of the aeroelastic performance to a post design phase
- Structural analysts → fluid as constant pressure on the walls
- Several techniques in literature, each one with pros and cons
- Mesh morphing technologies are a powerful link between CFD and CSM

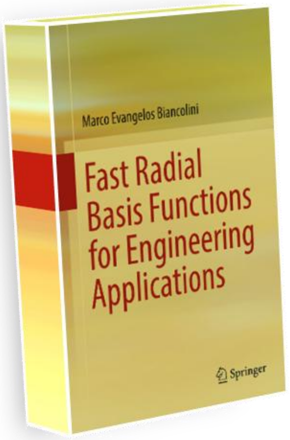
Modal superposition: overview

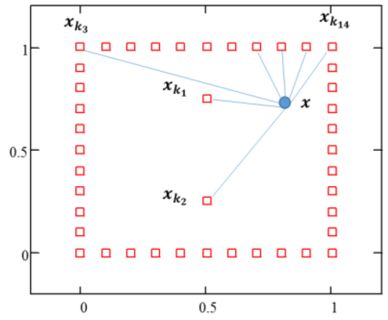
- Structural modes, and related frequency signature, represent the basic nature of the **dynamic behaviour** of a structure
- FSI with modal approach: **simplified environment** for static and dynamic aeroelastic mechanisms
- Limited to **linear** structural problems
- CFD is made flexible importing modes and frequencies, NO data exchange
- CFD mesh deformation required: RBF Mesh morphing

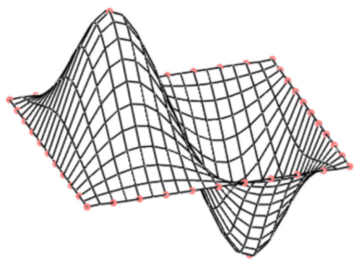


Radial Basis Functions

- RBF are at the core of the RBF Morph software family, integrated in ANSYS Workbench, Fluent and available standalone with the **rbfCAE platform**
- RBFs are a mathematical tool capable to **interpolate** at a generic point in the space a function **known** in a discrete set of points (**source points**)







radial basis — polynomial

$$s(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{k_i}\right\|\right) + h(\boldsymbol{x})$$

distance from the i-th source point

Radial Basis Functions

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

$$s(\boldsymbol{x}_{k_i}) = g_i \qquad 1 \le i \le N$$
$$h(\boldsymbol{x}_{k_i}) = 0$$

- The RBF problem is associated to the solution of the linear system:

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

Radial Basis Functions

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

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

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

Parametric mesh formulation

- Each node position of the volume mesh can be computed using its original position as input:

$$\boldsymbol{x}_{\boldsymbol{node}_{\boldsymbol{new}}} = \boldsymbol{x}_{\boldsymbol{node}} + \begin{bmatrix} s_x(\boldsymbol{x}_{\boldsymbol{node}}) \\ s_y(\boldsymbol{x}_{\boldsymbol{node}}) \\ s_z(\boldsymbol{x}_{\boldsymbol{node}}) \end{bmatrix}$$

- Modal theory is linear, no need to use the costly RBF formula each mesh update. The following linear combination is used:

$$\boldsymbol{X}_{\boldsymbol{CFD}} = \boldsymbol{X}_{\boldsymbol{CFD}_0} + \sum_{m=1}^{n} \eta_m \, \boldsymbol{\Delta u}_m$$

Modal superposition – steady FSI

- Modes and frequencies of a structure can be obtained solving the eigenvalue problem:

$$\boldsymbol{K}\boldsymbol{u} = \omega^2 \boldsymbol{M}\boldsymbol{u}$$

- Orthogonality of modes and low pass behaviour simplify the problem. Mass normalization further simplifies the framework:

$$\boldsymbol{\Delta u}_m^T \boldsymbol{M} \boldsymbol{\Delta u}_m = 1 \qquad \boldsymbol{\Delta u}_m^T \boldsymbol{K} \boldsymbol{\Delta u}_m = \omega_m^2 \qquad \boldsymbol{u} = \sum_{m=1}^{n} \boldsymbol{\Delta u}_m \, \eta_m = \boldsymbol{\Delta u} \, \boldsymbol{\eta}$$

$$\ddot{\eta}_m + {\omega_m}^2 \eta_m = F_m \qquad m = 1,2, \dots, n \qquad {\omega_m}^2 \eta_m = F_m$$

Modal superposition – unsteady FSI

- Equation of motion can be employed with finite differences
- Duhamel integral can be used to calculate modal coordinates

$$\eta(t) = e^{-\varsigma\omega_n t}\left[\eta_0\cos(\omega_d t) + \frac{\dot{\eta}_0 + \varsigma\omega_n\eta_0}{\omega_d}\sin(\omega_d t)\right] + e^{-\varsigma\omega_n t}\left\{\frac{1}{m\omega_d}\int_0^t e^{-\frac{b(t-\tau)}{2m}} f(\tau)\sin[\omega_d(t-\tau)]dx\right\}$$

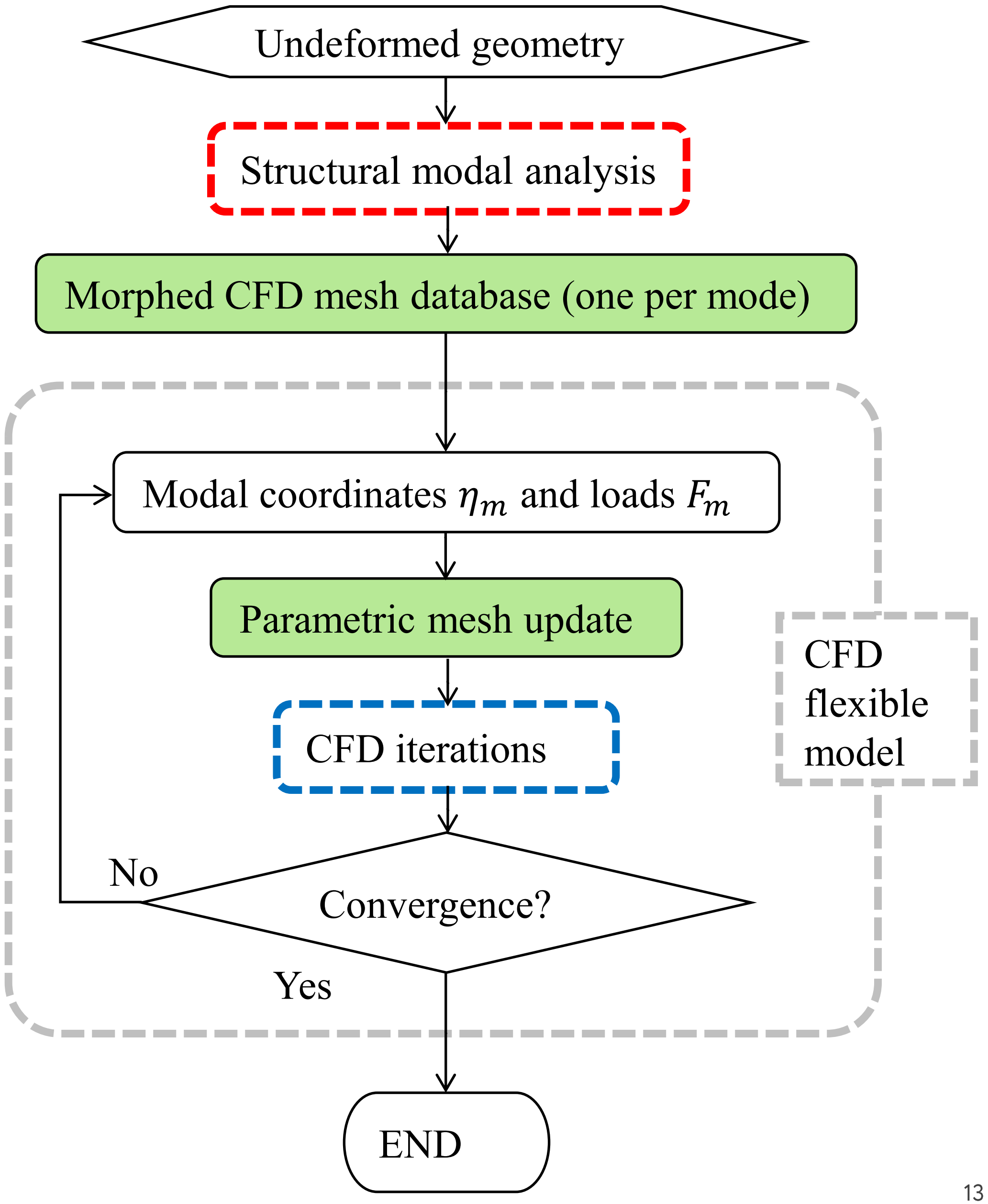
- For a generic numerical analysis, if the load is constant for each timestep, the Duhamel integral can be written as:

$$\omega_d = \omega_n\sqrt{1-\varsigma^2}$$

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

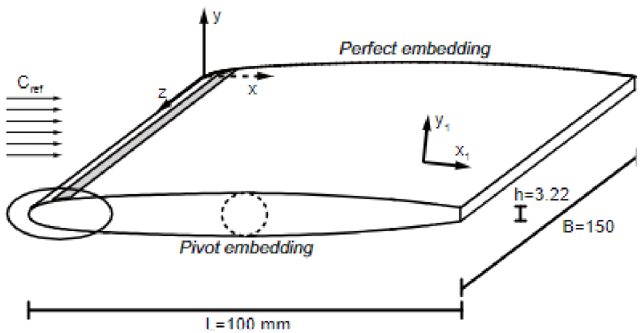
Modal superposition workflow

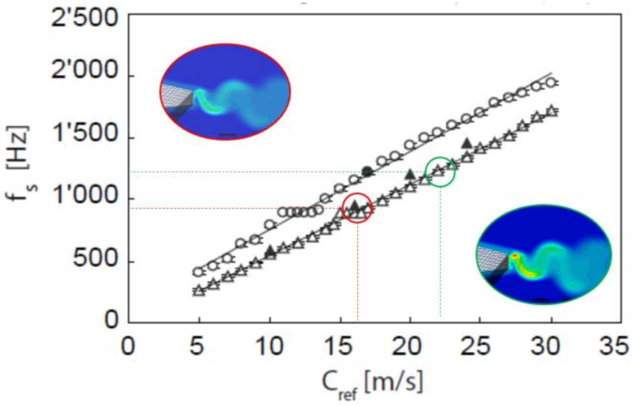
- No interpolation required, no data exchange required, modes are embedded as pre-processing
- Steady / unsteady FSI, FSI with prescribed motion
- How many modes to employ? Modal truncation error: modal basis qualification

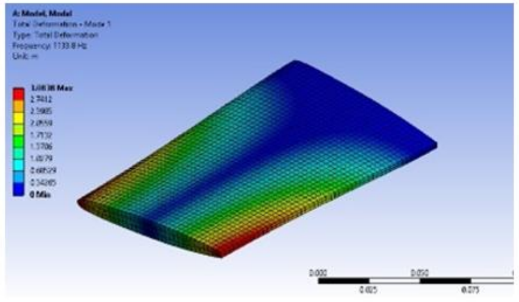


NACA0009 Hydrofoil test case

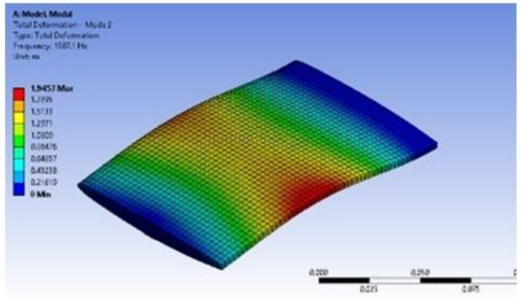
- Objective is to find lock-in and lock-off frequencies in water



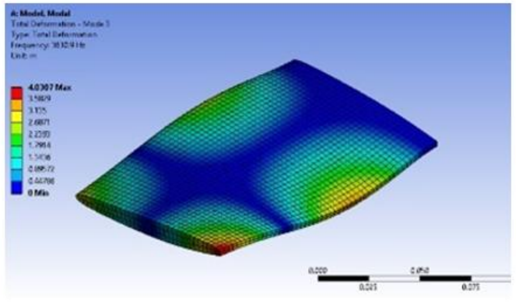




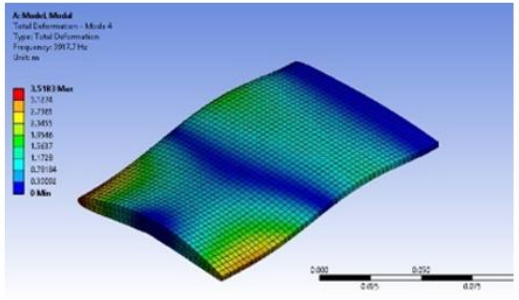
Mode 1 (1133.8 Hz)



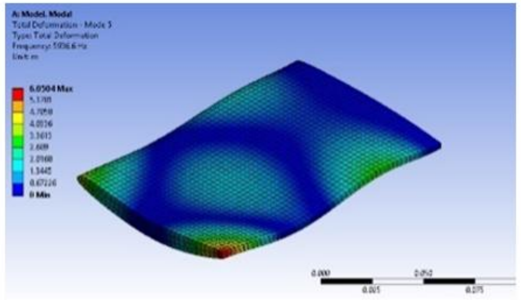
Mode 2 (1587.1 Hz)



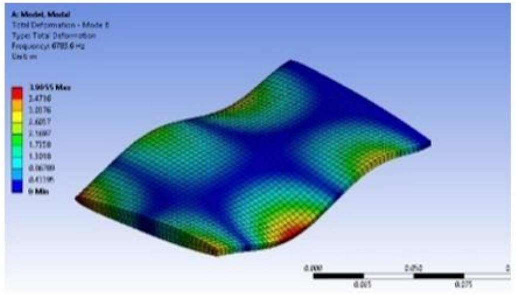
Mode 3 (3630.9 Hz)



Mode 4 (3917.7 Hz)



Mode 5 (5936.6 Hz)



Mode 6 (6789.6 Hz)

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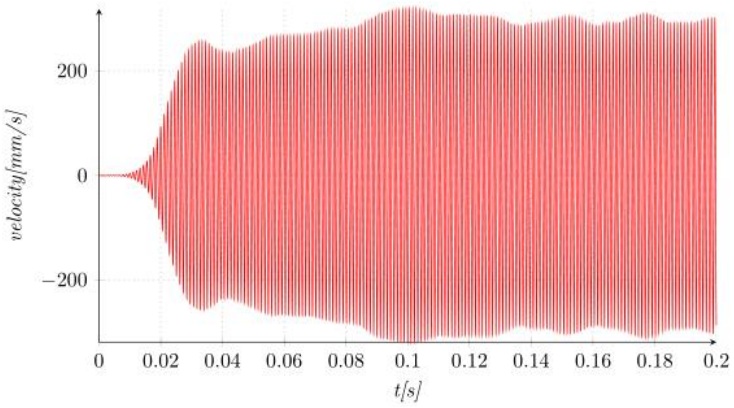
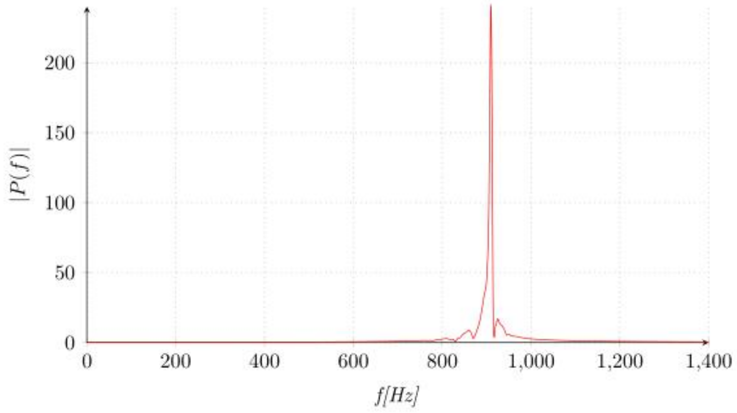
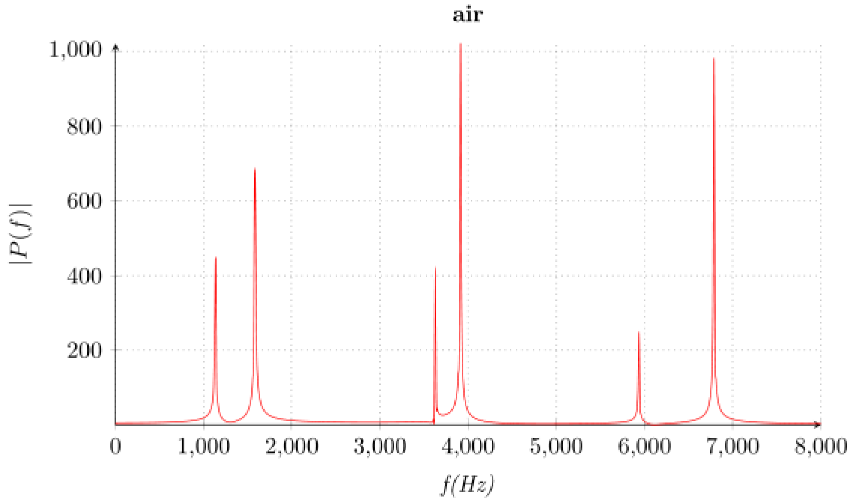
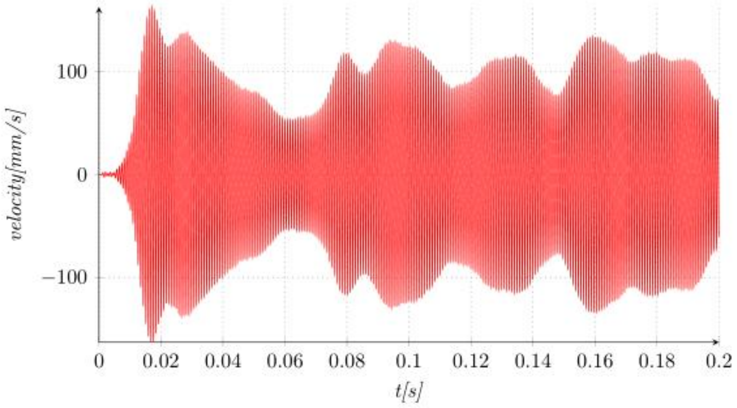
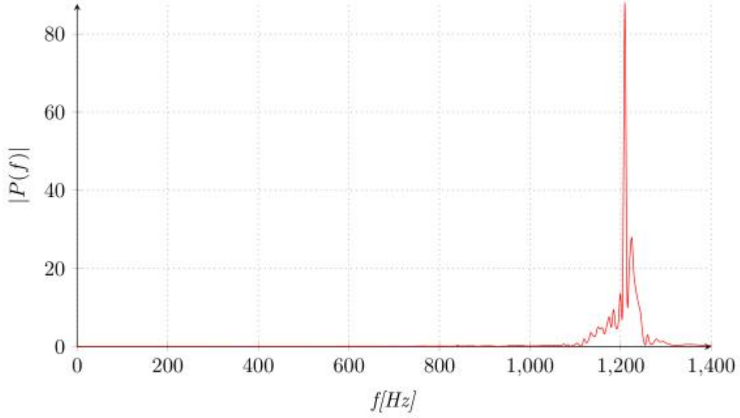
NACA0009 Hydrofoil test case

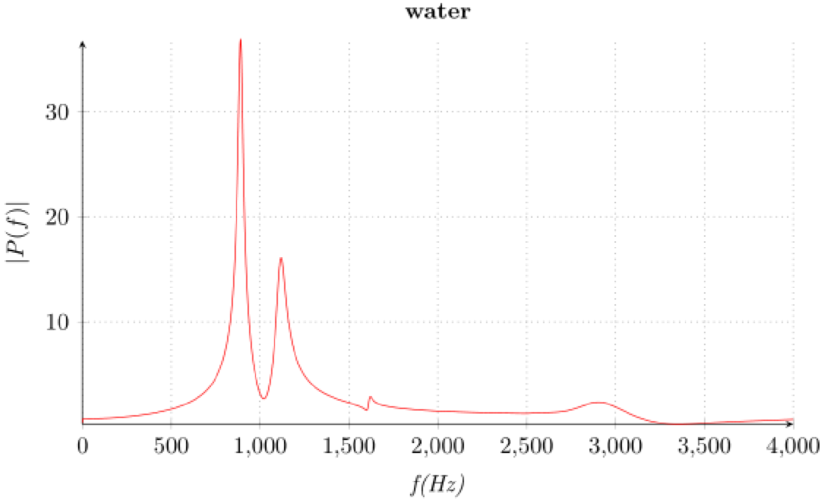




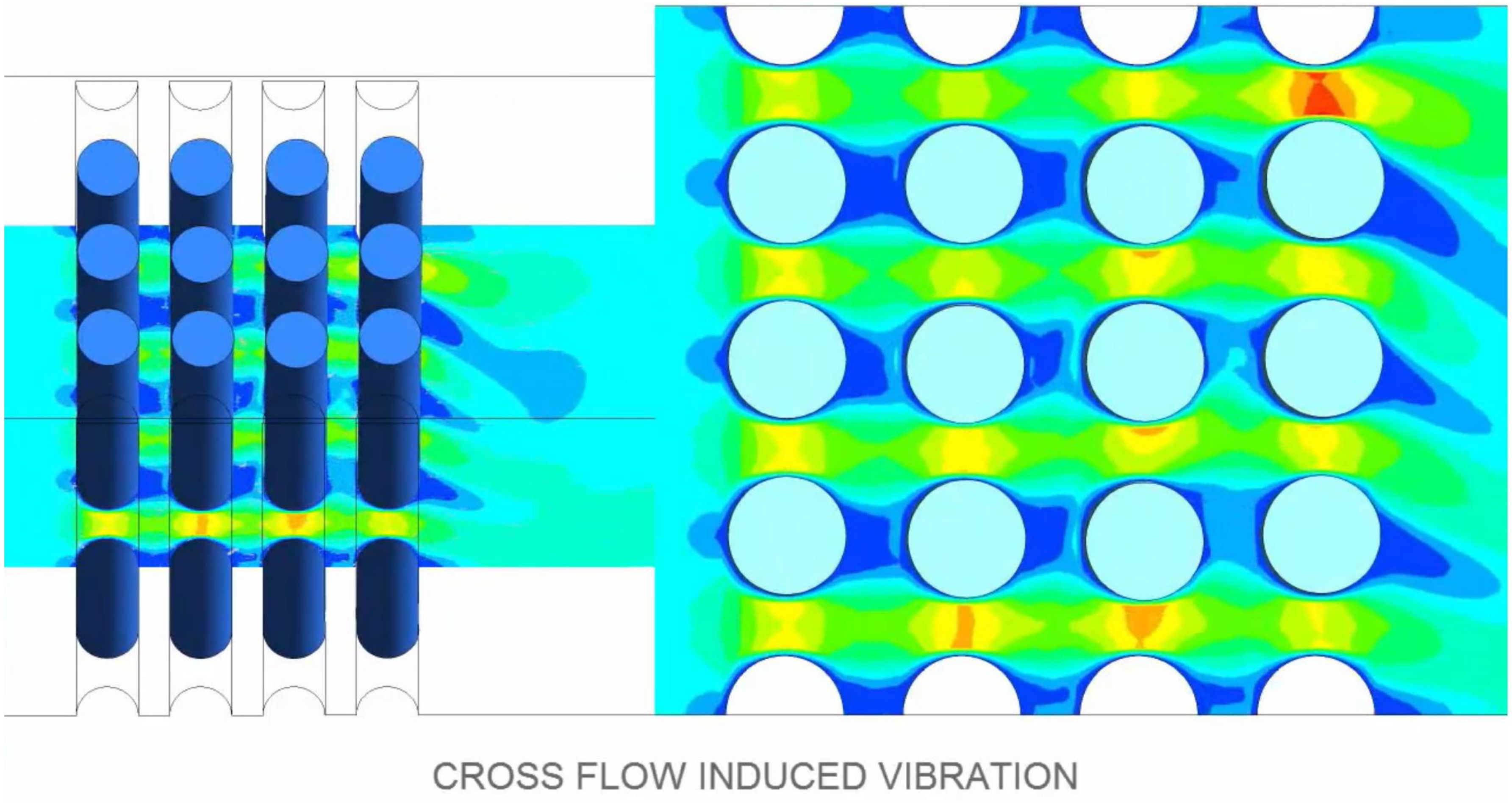






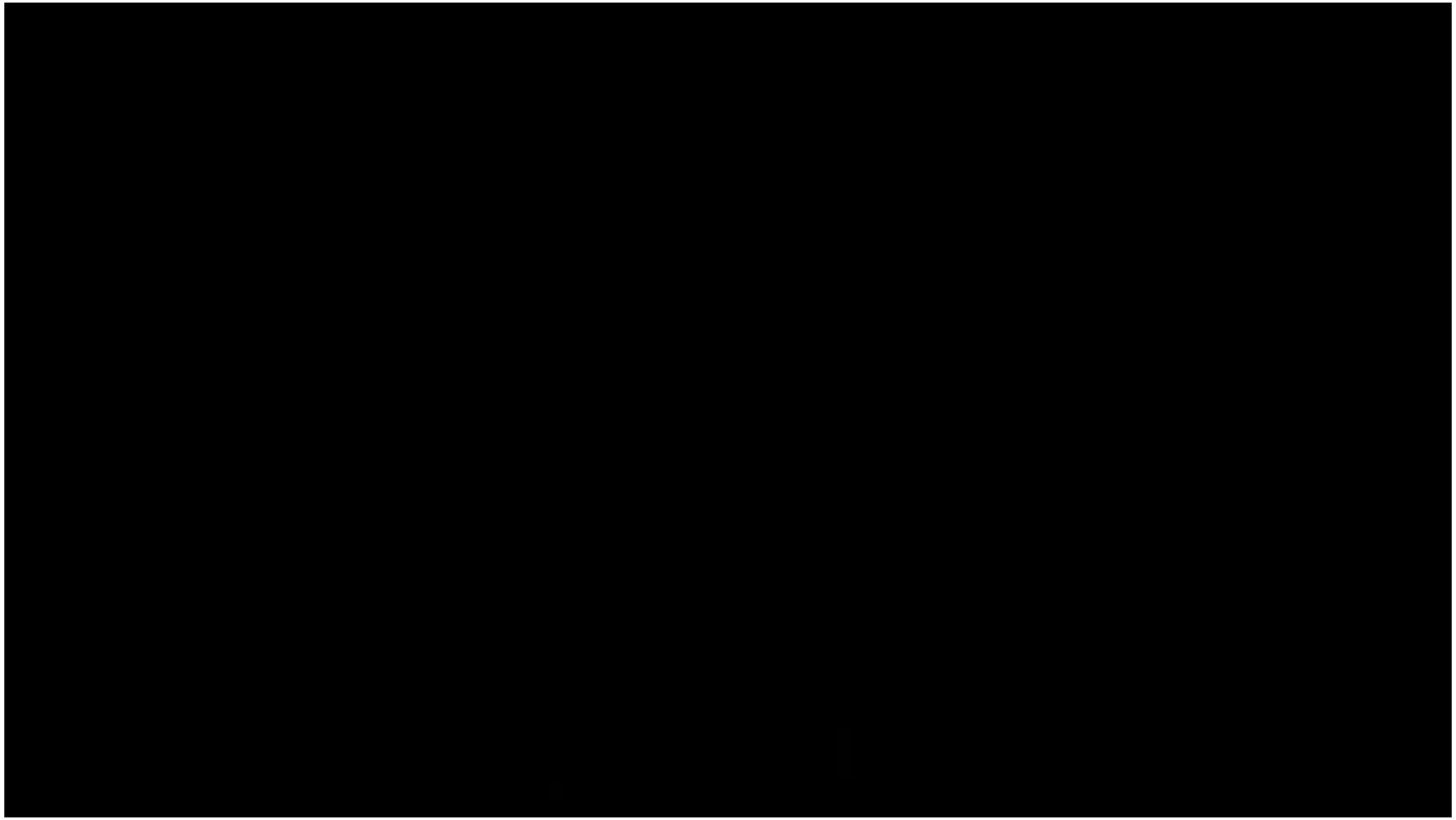


Vortex shedding



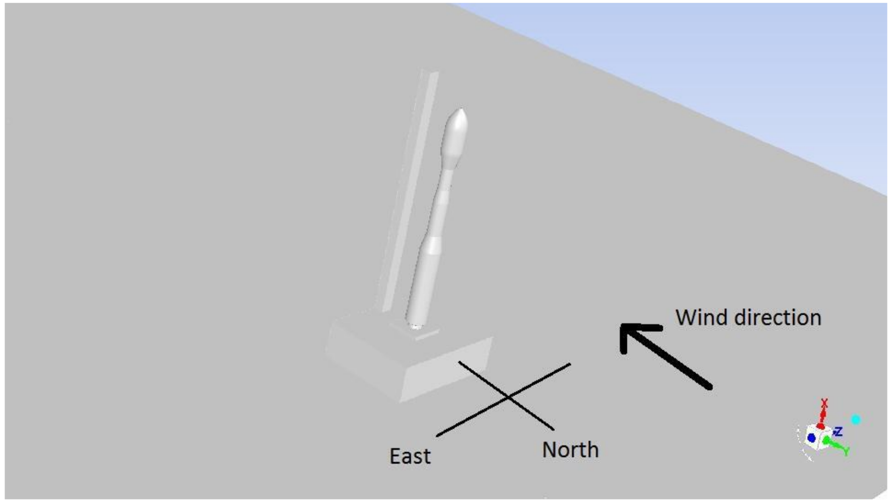
https://youtu.be/A0WPDyhlr8Q

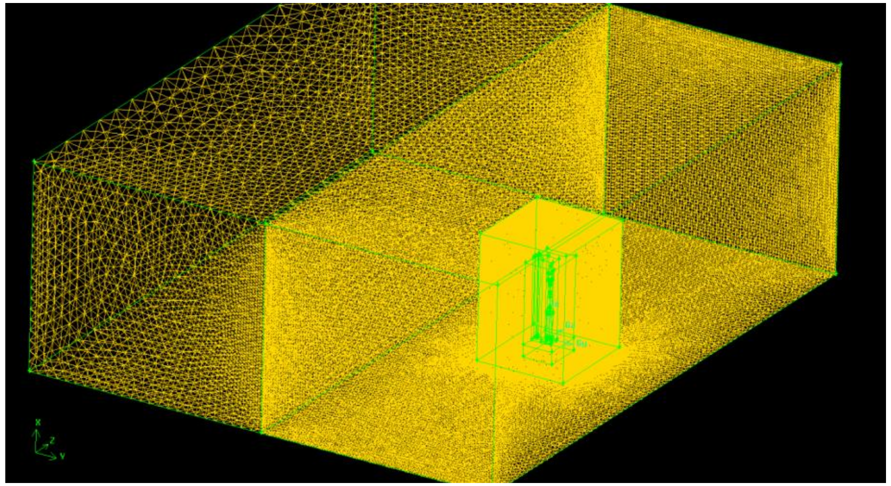
Vortex shedding



CFD model

- The CFD solver Ansys Fluent is adopted
- The grid has been refined to capture the unsteady flow conditions according to URANS
- Mesh motion is enabled during the CFD run according to the embedded structural modes

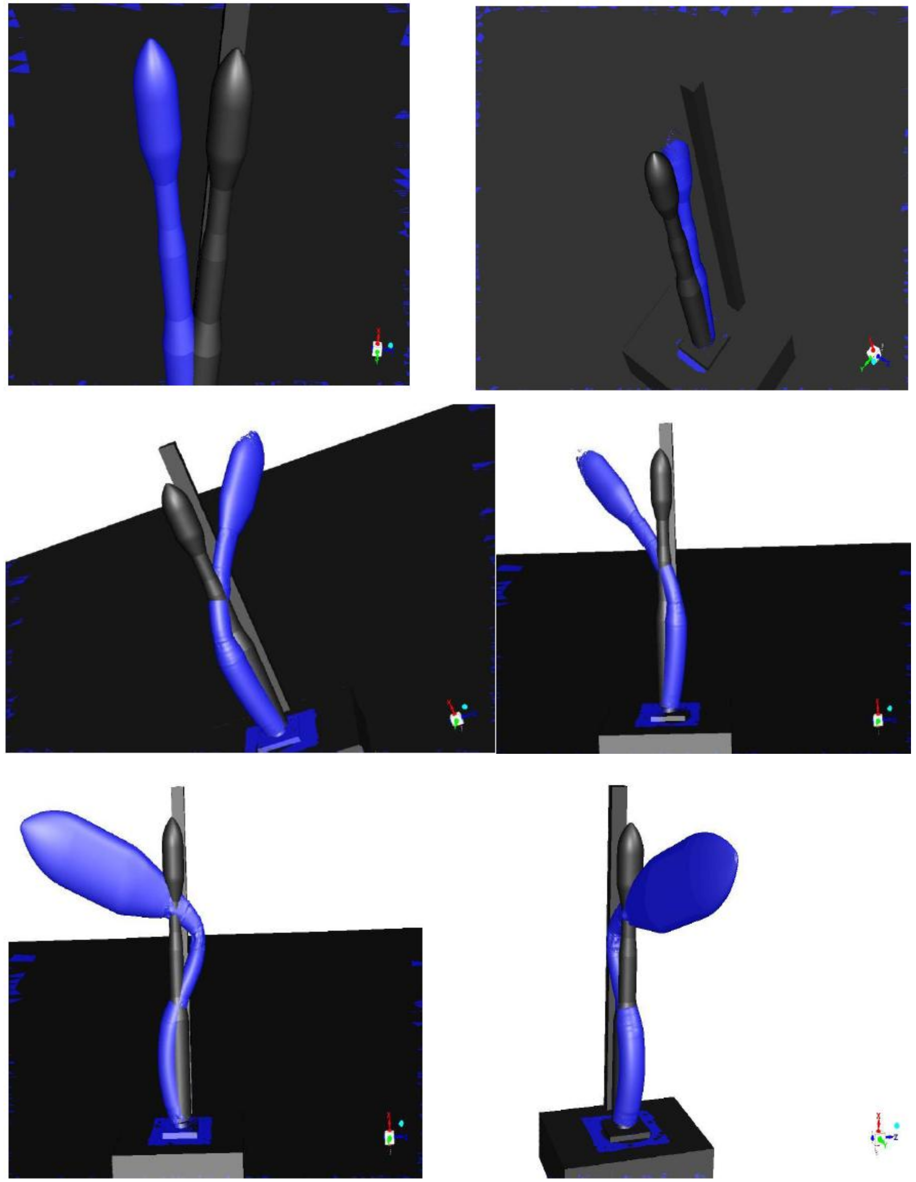




FEA model

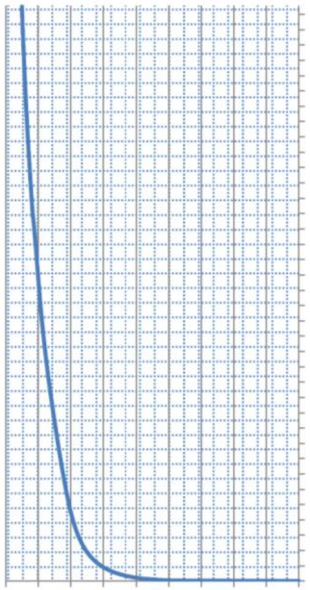
- The FEA solver MSC Nastran is adopted
- Eigenmodes are computed on the full model
- Modal results are extracted as grid displacements for the nodes at the wetted surface
- The first three modes are considered for this study (bending, bending, mixed torsion-bending)
- Constraints are represented by the ground connection

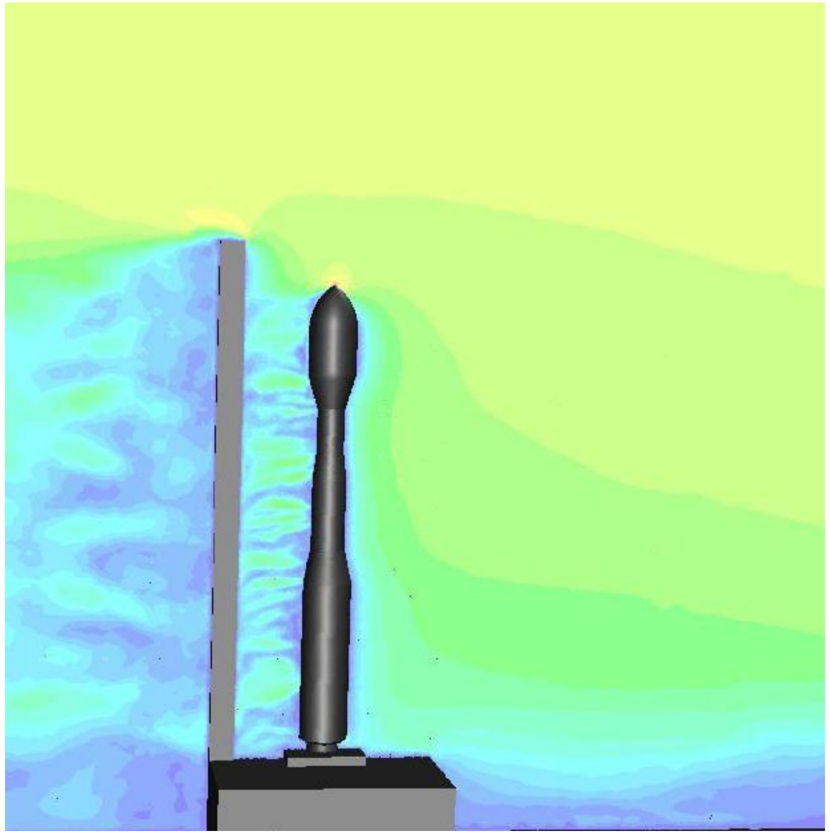
Mode	Frequency/fK_{min1}
1st bending	1.43
2nd bending	10.74
3rd bending	23.70



FSI simulation

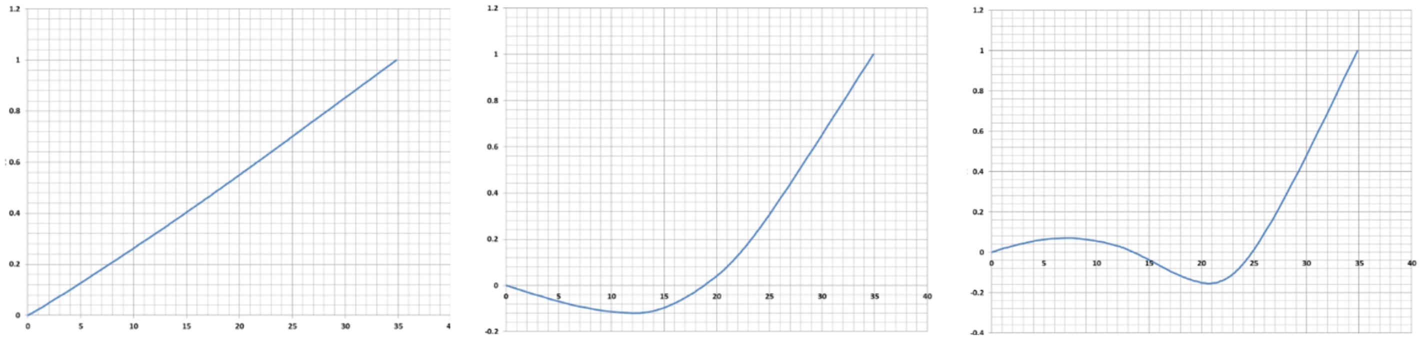
- For the CFD simulation, an inlet velocity profile, constant in time but changing with altitude, has been considered.
- The profile takes into account gust effects, which are also modelled as function of the altitude.
- The amplitude of the vibration at the tip and the constraint bending moment at the ground are collected



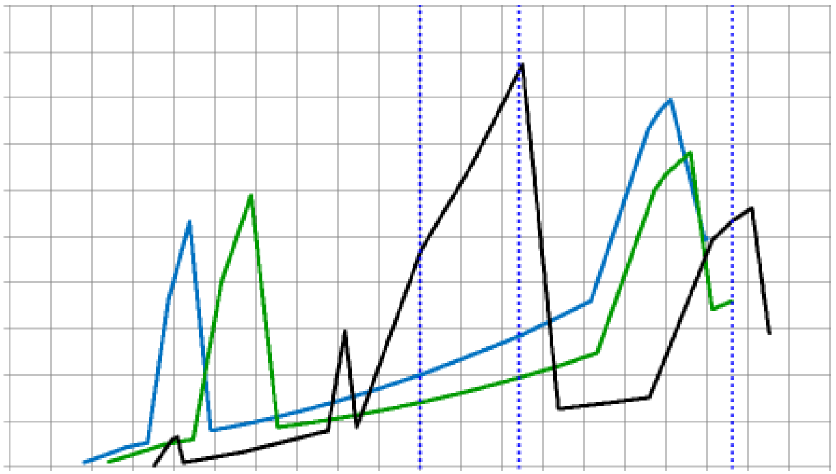


Results – in house code

	K_{min}	K_{max}
1st mode	1.0	1.3
2nd mode	10.8	10.9
3rd mode	25.7	25.8



Mode I + Mode II + Mode III



K_{min}

	$V_{m35} = V_{m35p1}$	$V_{m35} = V_{m35p2}$	$V_{m35} = V_{m35p3}$	$V_{m35} = V_{m35p4}$ Peak (mode I)	$V_{m35} = V_{m35p5}$ Peak (mode II)
Tip displacement (m)	1.00	1.00	1.86	2.65	0.99
Base moment (Nm)	1.42	1.00	2.15	3.20	1.33

K_{max}

	$V_{m35} = V_{m35p1}$	$V_{m35} = V_{m35p2}$	$V_{m35} = V_{m35p3}$	$V_{m35} = V_{m35p4}$ Peak (mode I)	$V_{m35} = V_{m35p5}$ Peak (mode II)
Tip displacement (m)	0.68	1.00	1.86	2.57	0.61
Base moment (Nm)	1.58	1.00	2.11	3.05	0.79

Results – FSI high fidelity

- The in house tool gives a base moment and a tip displacement that are 46.78% and 55.35% higher than the ones obtained with the FSI analysis.
- An approximation of the dynamic contribute of the base moment can be obtained considering the LV as a single beam with an extremity clamped to the ground:

$$M_b(d_{tip}) = K_\theta \theta \cong \frac{K_\theta}{L} d_{tip}$$

	Mean	Max	Min
DX	0.000	0.000	0.000
DY	-0.063	0.295	-0.445
DZ	0.008	0.139	-0.129
Magnitude	0.101	0.447	0.001

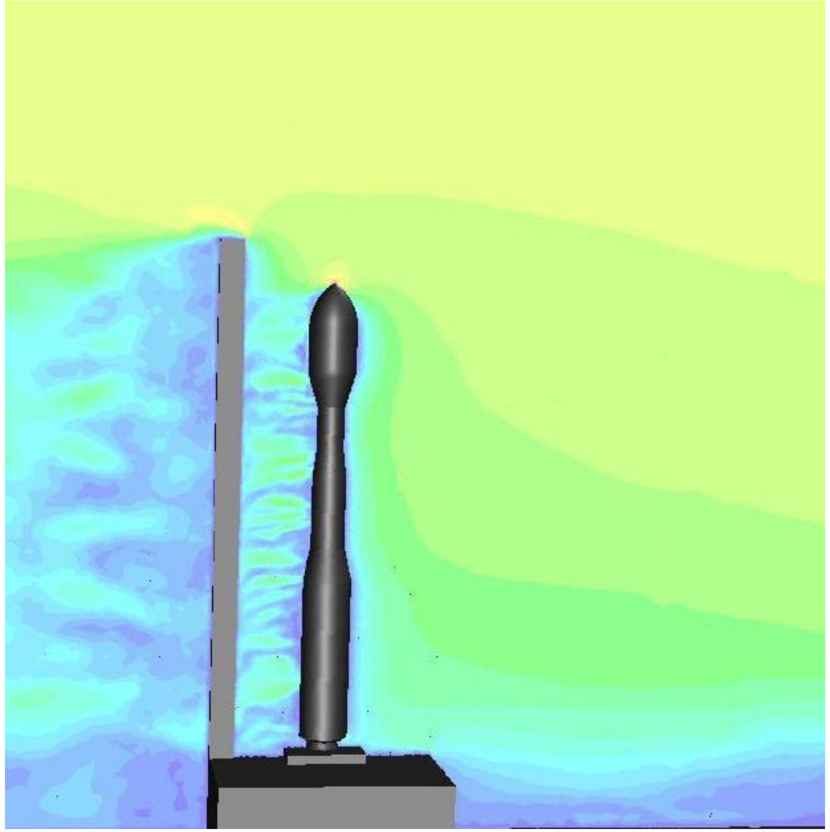
	ε (%) in house code (base moment)	**ε (%) in house code (displacement)**
VEGA C (in house code)	0	0
VEGA C (RBF Morph)	46.78	55.35

Conclusions

- The base moment increases significantly both for 1st and 2nd mode with respect to the stiffness increase; for 3rd mode the base moment shows very low values.
- The highest tip displacements are achieved for the 1st mode.
- The total bending moment at the base of the LV evaluated using K_{min} and K_{max} are lower than the maximum dimensioning base moments for Stand-by on Launch Pad Load Case; therefore it is possible to define the following range of ground global rotational stiffness: $1 \cdot 10^{8}$ Nm/rad $< K < 2 \cdot 10^{8}$ Nm/rad;

Conclusions

- In order to check the results obtained with the in house tool, a more detailed analysis, in which the fluid-structure interaction is taken into account, has been performed by means of FEM and CFD simulations, using RBF Morph.
- The analysis led to values of tip displacement and base momentum (evaluated with a simplified formula) that are half of the ones obtained with the in house tool.



Thank you!

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