Fluid structure interaction analysis: vortex shedding induced vibrations

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Outline

• Introduction
• Research path
• RBF Background
• Structural modes embedding
• Challenges
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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.
Introduction

12 CYLINDERS
TRANSIENT FSI

(rbf-morph)

https://youtu.be/A0WPDyhlr8Q
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)

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**:

  \[
  s(x) = \sum_{i=1}^{N} \gamma_i \varphi \left( \| x - x_{k_i} \| \right) + h(x)
  \]

  - radial basis
  - polynomial
  - distance from the i-th source point
RBF Background

• If evaluated on the source points, the interpolating function gives exactly the input values:
  
  \[ s(x_{k_i}) = g_i \]
  \[ h(x_{k_i}) = 0 \quad 1 \leq i \leq N \]

• The RBF problem (evaluation of coefficients \( \gamma \) and \( \beta \)) is associated to the solution of the linear system, in which \( \mathbf{M} \) is the interpolation matrix, \( \mathbf{P} \) is a constraint matrix, \( \mathbf{g} \) is the vector of known values on the source points:

\[
\begin{bmatrix}
\mathbf{M} & \mathbf{P} \\
\mathbf{P}^T & 0
\end{bmatrix}
\begin{bmatrix}
\gamma \\
\beta
\end{bmatrix}
= 
\begin{bmatrix}
g \\
0
\end{bmatrix}

M_{ij} = \varphi(x_{k_i} - x_{k_j}) \quad 1 \leq i, j \leq N

\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:

\[
\begin{align*}
    s_x(x) &= \sum_{i=1}^{N} y_i \varphi(x - x_i) + \beta_i^x x + \beta_i^y y + \beta_i^z z \\
    s_y(x) &= \sum_{i=1}^{N} y_i \varphi(x - x_i) + \beta_i^x x + \beta_i^y y + \beta_i^z z \\
    s_z(x) &= \sum_{i=1}^{N} y_i \varphi(x - x_i) + \beta_i^x x + \beta_i^y y + \beta_i^z z 
\end{align*}
\]

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

<table>
<thead>
<tr>
<th>RBF</th>
<th>( \varphi(r) )</th>
<th>RBF</th>
<th>( \varphi(r) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spline type (Rn)</td>
<td>( r^n, n \text{ odd} )</td>
<td>Inverse multiquadratic (IMQ)</td>
<td>( \frac{1}{\sqrt{1 + r^2}} )</td>
</tr>
<tr>
<td>Thin plate spline</td>
<td>( r^n \log(r), n \text{ even} )</td>
<td>Inverse quadratic (IQ)</td>
<td>( \frac{1}{1 + r^2} )</td>
</tr>
<tr>
<td>Multiquadratic (MQ)</td>
<td>( \sqrt{1 + r^2} )</td>
<td>Gaussian (GS)</td>
<td>( e^{-r^2} )</td>
</tr>
</tbody>
</table>
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

\[ X_{CFD} = X_{CFD_0} + \sum_{i=1}^{k} q_i \Delta X_i \]
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):

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

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

• 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: $\alpha=0^\circ$
• Material: steel ($\rho=7850\ kg/m^3$)
• Constraints: embedded pivot, clamp
• Fluid: water

References

• 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
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
Predicted vs. measured

Lock In

$C_{ref} \approx 16 \text{ m/s}$

$f_s \approx 900 \text{ Hz}$

Lock Off

$C_{ref} \approx 22 \text{ m/s}$

$f_s \approx 1200 \text{ Hz}$
Modes in air vs. modes in water

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

<table>
<thead>
<tr>
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<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
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<td>891.9 Hz</td>
<td>1118.8 Hz</td>
<td>1619.6 Hz</td>
<td>2902.7 Hz</td>
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</table>
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](http://www.rbf-morph.com)), RBF4AERO ([www.rbf4aero.eu](http://www.rbf4aero.eu)) and RIBES ([www.ribes-project.eu](http://www.ribes-project.eu))

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THANK YOU!
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