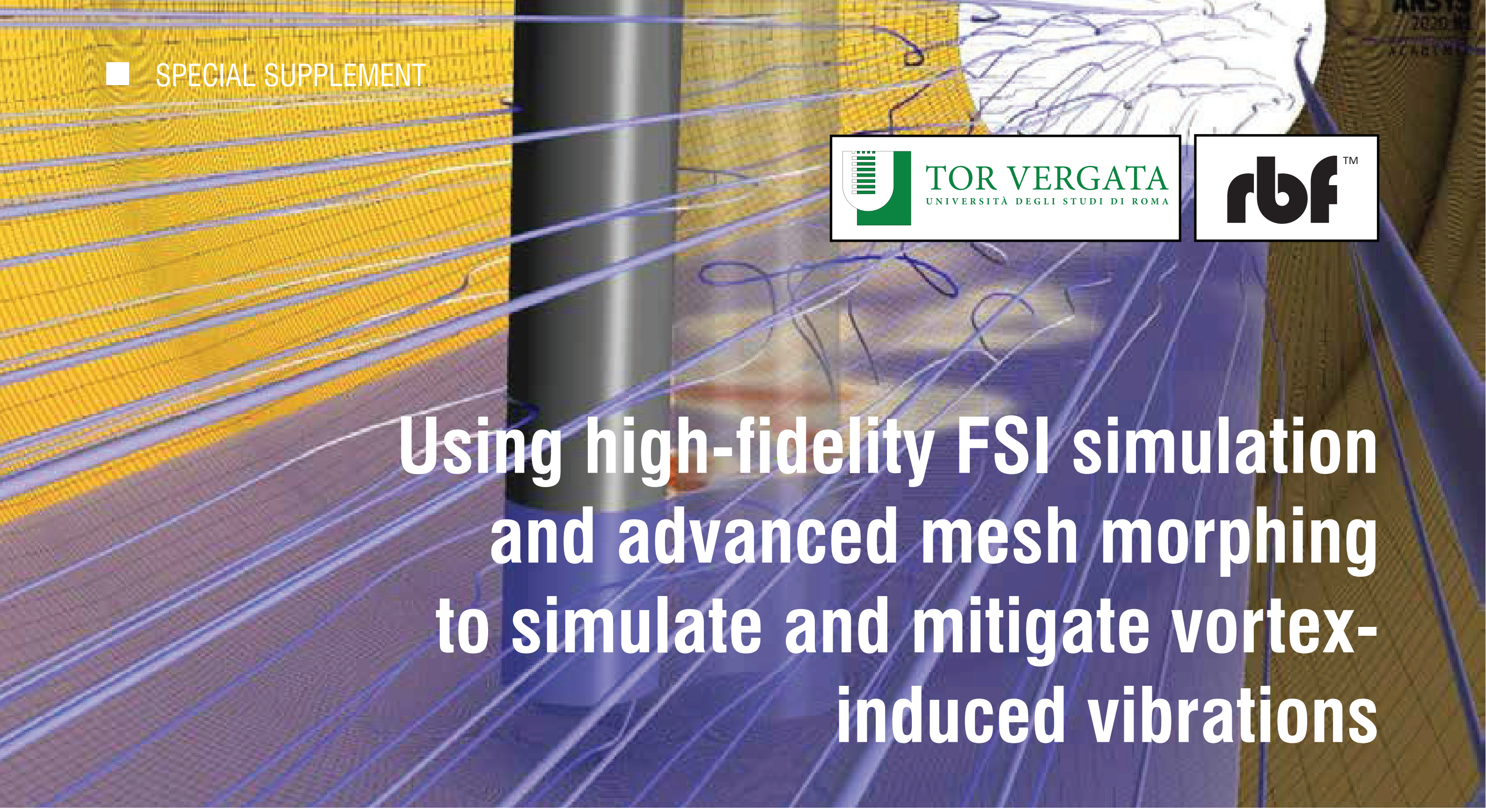

Using high-fidelity FSI simulation and advanced mesh morphing to simulate and mitigate vortex-induced vibrations

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This study discusses the complex and challenging problem of controlling vortex-induced vibrations (VIV). The fluid-structure interactions (FSI) involved pose two types of problems: firstly, structural and fluid analysis skills are required and the various experts need to interact correctly for a successful outcome; secondly, accurate modelling requires state-of-the-art tools to combine the computational fluid dynamics (CFD) and the computational structural mechanics (CSM).

Advanced mesh morphing enabled by the radial basis function (RBF) is key here: it enables you to create an efficient and fast workflow for strong coupled fluid structure interaction analysis while making that workflow parametric with respect to the design, so that you ultimately have the ability to steer the design toward the desired VIV behavior.

We used structural modes embedding technique to render the fluid solution "flexible". The dynamic characteristics of the system were calculated with Ansys Mechanical for the Finite Element Analysis (FEA); these were then incorporated into Ansys Fluent to solve the fluid aspect using RBF Morph mesh morphing software. The method is demonstrated for a specific application: the design of a thermowell immersed in a water flow. The numerical results obtained were compared with experimental data and showed a satisfactory agreement, thus demonstrating that the superposition of structural modes approach, with a suitable mesh morphing configuration, is able to address unsteady FSI problems with the necessary accuracy for industrial applications.

Today there is an increasing need to develop multi-physics approaches to address complex design challenges. The numerical methods adopted must include coupled field analyses that allow the combined effects of the multiple physical phenomena acting on a given system to be evaluated. One of the most interesting multi-physics phenomena with a wide range of applications is the interaction between a fluid and a structure. This interaction can occur for several reasons: it may be the working principle of the system; it may focus on creating a lightweight design for the structure; or it may be used to refine the design.

Fluid structure interaction (FSI) plays a key role in a wide range of engineering fields, such as automotive, aerospace, marine, civil and biomedical. To numerically solve the interaction, the deformation of the computational fluid dynamics (CFD) mesh is needed to accommodate the changes in the shape of the structure. In the present work, a radial basis functions (RBF) based mesh morphing algorithm is used to change the CFD mesh according to the deformed shape of the structure. The FSI approach we propose allows the mesh to be adapted to the shape of the deformable structure by superposition of its natural modes during the course of the CFD calculation.

The underlying notion for the proposed workflow is to compute the fluid forces on the surface of the structure, along with the inertial loads at each step, as modal forces to determine the amplitude of each modal shape. By superimposing the modal shapes, the overall deformation of the structure can be obtained at each instant and can be imposed in the CFD model by morphing the CFD mesh. The method is implemented to study an industrial problem: the vortex-induced vibration of a thermowell immersed in a stream of fluid.

Thermowells are cylindrical fittings used to protect temperature sensors (such as thermometers or thermocouples) installed in industrial processes. In such a configuration, the fluid transfers heat to the wall of the thermowell which, in turn, transfers heat to the sensor. The use of a thermowell, in addition to protecting the sensor from the effects of the pressure and chemicals of the process fluid, allows the sensor to be easily replaced without emptying the tank or pipes. However, thermowells are subject to potential flow-induced vibrations generated by vortex shedding that may cause failure due to bending fatigue. Consequently, particularly in modern applications involving high-strength piping and high fluid velocity, the dynamics of the system must be carefully evaluated to prepare ad-hoc countermeasures, such as twisted square thermowells, to limit this phenomenon. A numerical method capable of reliably reproducing the fluid-structural coupling is therefore needed to rapidly evaluate different designs and reduce the time to market of new products.

Modal FSI implementation

Beginning with the undeformed configuration, the flexible components of the system are modelled and studied using a structural modal analysis in order to extract a suitable set of eigenvalues and eigenvectors.

The obtained modes are used to generate an RBF solution for each shape. At this stage, the far-field conditions and rigid surfaces must be constrained, while the FEM results must be mapped to the deformable surfaces of the CFD domain. The RBF solutions obtained constitute the modal basis that, suitably amplified, permits the structural deformation under load to be represented, generating an intrinsically aeroelastic domain. This process is known as "RBF structural modes embedding". To accelerate the mesh morphing phase, the deformations associated with each modal shape are stored thereby containing the numerical cost of the morphing process to a small fraction (around 10%) of the cost of a single CFD iteration.

The proposed FSI modelling technique belongs to the class of weak approaches because, for the purposes of an unsteady analysis, the loads are considered to be fixed during each time-step. The modal forces are calculated on the prescribed surfaces (i.e. the deformable ones) by projecting the nodal forces (pressures and shear stresses) onto the modal shapes. The mesh is updated at each time step during the course of the CFD transient calculation according to the calculated modal coordinates. The mesh morphing tool used was RBF Morph, with Ansys Fluent for the CFD, and Ansys Mechanical 2021 R1 for the FEM solver.

Experimental study

The industrial problem studied concerns a vortex-induced vibration on a thermowell immersed in a fluid flow. The case study experiment was measured and recorded by Emerson Electric Co., the multinational corporation that owns Rosemount which manufactures the thermowell studied (www.emerson.com/en-us/asset-detail/rosemount-twisted-square-a-new-twist-on-thermowell-design-1800740).

The purpose of the experiment was to evaluate the flow-induced vibrations on a traditional cylindrical thermowell design, shown in Fig. 1. The 470.219 mm-long sensor was equipped with an accelerometer in the tip and immersed in a flow of water inside a 152.4 mm-diameter pipe.

The water velocity ranged from 0 m/s to 8.5 m/s. The accelerometer enabled the evolution of the tip displacement to be reconstructed. The results gathered are summarized in Fig. 2 in terms of the mean square root of the tip displacement as a function of the fluid velocity.

Two lock-in regions are observed: an in-line vibration lock-in region, and a transverse vibration lock-in region. In the in-line vibration lock-in region, the maximum Root Mean Squar (RMS) tip displacement in the direction of the flow is 2.33 mm, recorded at a fluid velocity of 2.44 m/s. In the transverse vibration lock-in region, the maximum RMS tip displacement in the cross-flow direction is 8.3 mm, recorded at a fluid velocity of 6.4 m/s. The vibrations are induced by organized vortices that shed in sheets along the axial length of the stem and that generate alternating forces. If the shedding frequency approaches a natural frequency of the thermowell or its half, transverse or in-

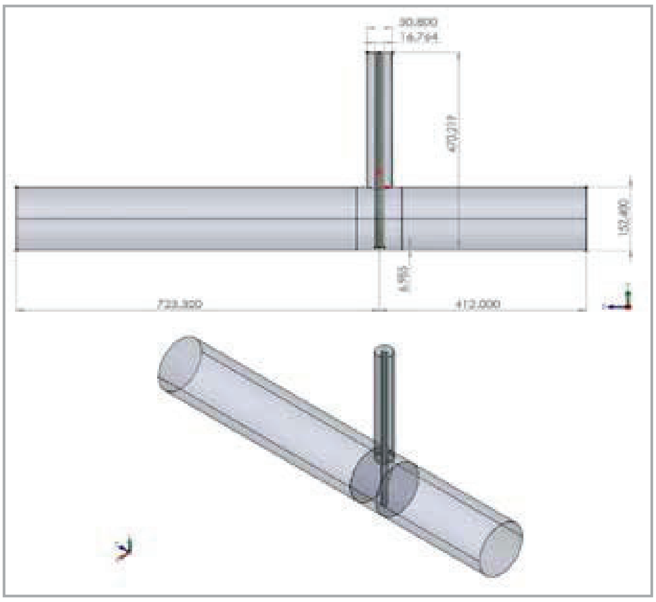

Fig. 1 - CAD model of the analyzed system

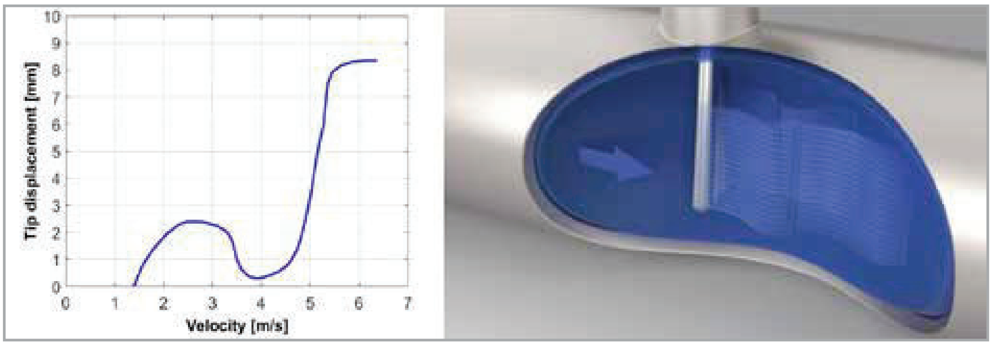

Fig. 2 - Experimental results, RMS tip displacement vs fluid velocity

line vibrations are excited and a failure of the sensor may occur. Failure conditions have been reached for the cylindrical thermowell at velocities greater than 6.4 m/s. The purpose of this work was to numerically capture the transverse vibration lock-in region of the cylindrical thermowell.

Numerical analysis

The study presented in this paper was conducted by using the FSI module included in the RBF Morph package. The FSI module allowed to tackle the VIV analysis using the structural modes embedding

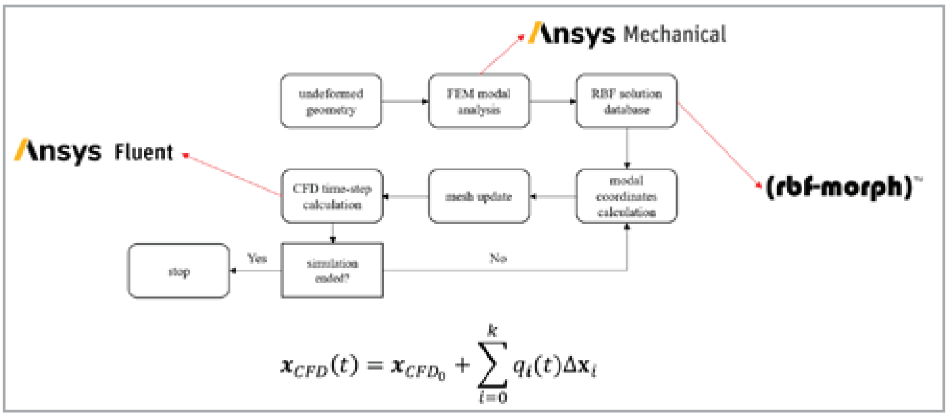

Fig. 3 - FSI workflow based on structural mode embedding by RBF Morph

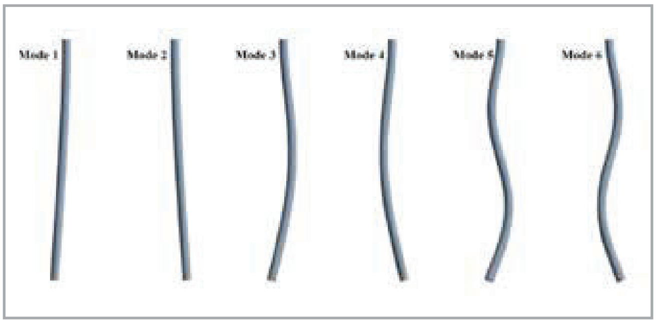

Fig. 4 - First six modal shapes calculated with the FEA model

method. The workflow is sketched in Fig.3. The structural and fluid domains each have to be modelled in appropriate locations and with consistent units. During initialization, the structural modes calculated by Ansys Mechanical are transferred into the Ansys Fluent CFD model by RBF Morph. Once the modes are incorporated, the "flexible" CFD model is able to: adapt the shape according to the modal coordinates, evaluate the modal forces acting on the wetted surfaces, and evolve the time solution of the structural modal coordinates.

The first six modes were extracted from the FEM modal analysis and adopted to populate the modal base adopted for the FSI analysis. The shapes of the six modes are shown in Fig. 4 where the first, second and third shapes can be seen bending in the two directions.

The shapes of the modes were extracted in terms of the displacements of the FEA mesh nodes belonging to the sensor surface and normalized with respect to mass; then they were used for the RBF Morph configuration depicted in Fig. 5. It is worth noting that once the configuration for one of the modes is completed it can be easily and automatically replicated for the entire modal base required.

The top left of Fig.5 shows the morphing domain, which is restricted to the region where shape deformations are expected to occur; RBF source points are created to control the morphing of fixed parts (top right of Fig.5) and the deforming parts (bottom left of Fig.5). For this particular case, the proximity of the tip of the thermowell to the boundary wall of the pipe created a challenging problem. In fact the large displacements that the thermowell is expected to undergo due to the vortex induced vibrations, combined with the need to maintain a cylindrical shape for the pipe wall, would result in a significant distortion of the mesh if the nodes in the pipe wall were imposed as fixed.

To avoid this high mesh distortion, an advanced corrective strategy was implemented to allow nodes belonging to the pipe wall that are close to the tip in the clearance region to slide on the cylindrical surface. First, a "shadow" area was defined so that the portion of the pipe surface defined by the projection of the thermowell tip would follow the sensor tip during the morphing action.

Then, a projection of the deformed pipe surface mesh onto the original cylindrical surface, after mesh morphing, was made. This complex task was accomplished by combining three pre-calculated RBF solutions.

The first two solutions allowed the shadow area to be assigned an appropriate rotation around the axis of the pipe, and a translation in the direction of the axis itself, in order to keep it constantly under the tip; the third solution, based on RBF Morph's STL-target technology,

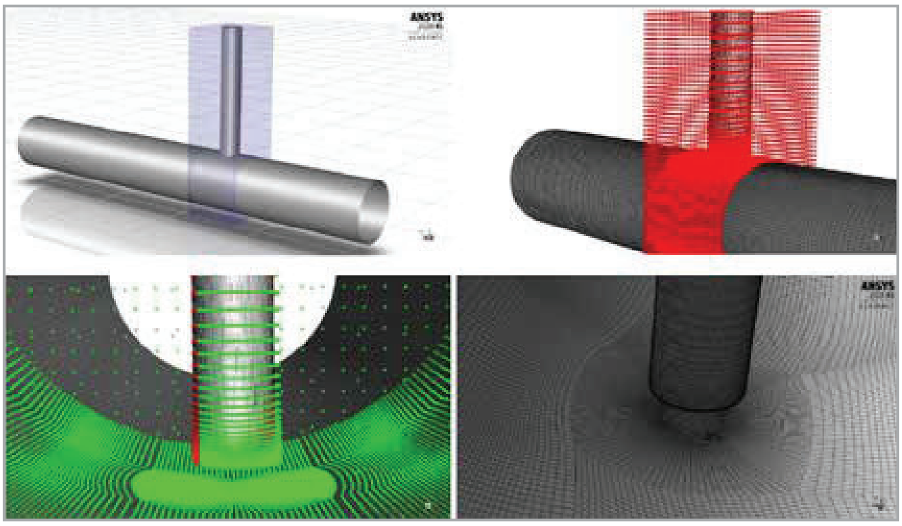

Fig. 5 - RBF Morph configuration to control the embedding of a structural modal shape

allowed the selected nodes to be projected onto a target surface (and thus to recover the cylindrical shape of the pipe).

The bottom right image of Fig. 5 represents the surface mesh around the thermowell tip obtained after morphing by applying the described correction procedure. Note the high quality of morphing, the correct placement of the shadow area, and the preservation of the cylindrical shape of the pipe.

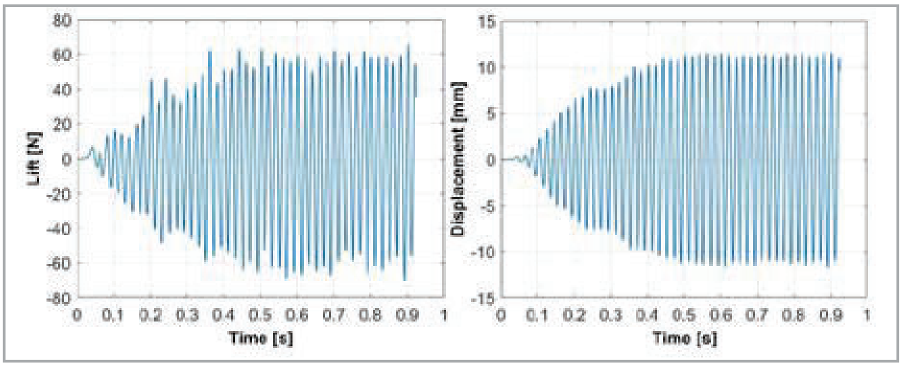

Fig. 7 - Temporal evolution of the lift on the thermowell (left) and the transverse displacement of the tip (right)

The fluid dynamics domain was discretized with a structured, multiblock mesh consisting of 3.16M hexahedra. To accurately solve the boundary layer up to the wall, the thickness of the first cell layer was set to obtain a dimensionless wall distance (y+) of less than one. The SST k-ω turbulence model was adopted. At the inlet, the velocity-inlet boundary condition was set by imposing a flow velocity of 6.4 m/s. At the outlet, a pressure condition was set. The unsteady incompressible RANS calculation was performed with a time-step of 10^{-4} s. The structural damping ratio was set to 0.041, following guidance found in the literature and a parametric study (www.springerprofessional.de/en/analysis-of-vortex-induced-vibration-of-a-thermowell-by-high-fid/19244678). The mesh was updated at each time step by calculating the modal coordinates and amplification factors of the corrective solutions.

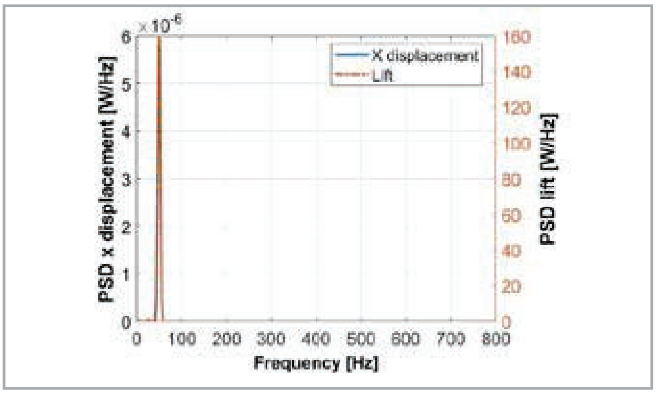

Fig. 8 - Power spectral density distributions of the lift and of the transverse displacement of the tip

Results

Fig. 6 shows the contours of the magnitude of velocity on a plane perpendicular to the thermowell axis for two different flow times corresponding to the maximum transverse displacements, in both the positive and negative directions.

Fig. 7 illustrates the temporal evolution of side force on the thermowell; it also shows the temporal evolution of the transverse tip displacement. The maximum RMS transverse tip displacement of 8.304 mm shown is in good agreement with the experimental data available. The power spectral density distributions of the two signals (the temporal evolution of side force and transverse tip displacement) as a function of frequency are shown in Fig. 8. A dominant frequency of 48.8 Hz was observed for both signals, confirming the correct acquisition of the lock-in condition.

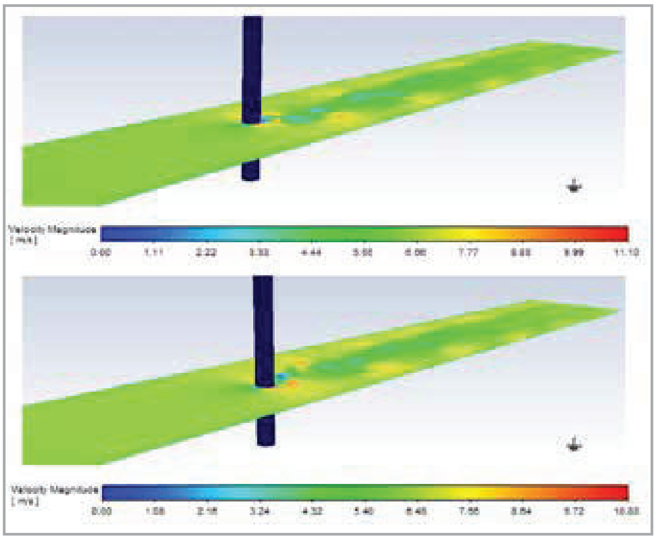
Fig. 6 - Velocity magnitude oscillation contours at t=0.8425 s (top) and t=0.8525 s (bottom)

Conclusions

The work presented focused on an FSI analysis methodology based on the modal superposition approach. It was applied to the study of vortex-induced vibration of a thermowell. The problem of mesh adaptation was addressed with an RBF-based mesh morphing technique that provided a particularly fast and robust configuration.

The configuration studied represents a particularly challenging problem for the mesh morphing tool. The proximity of fixed and moving boundaries, in fact, results in strong mesh distortions that significantly limit the tolerable displacement. The morphing software used allowed a particularly efficient set of corrective solutions to be configured that enabled the very large displacements relative to the dimensions to be managed. The results of the unsteady FSI analysis conducted were compared with the experimental data and provided a good agreement with the measurements.

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