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Fluid-structure interaction simulations using preCICE

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SUMMARY:
Problems involving Fluid-Structure Interaction, FSI, are extremely common in Wind Engineering. In the majority of the cases, it is possible to study such phenomena relying on simplified formulations, which can be calibrated based on tests performed in forced/free vibrations on sectional models. However, it is sometimes necessary to fully take into account the structure deformability. The paper presents the use of the open-source coupling platform preCICE to investigate vortex-induced vibrations of a full-scale 1:15 building model, with particular emphasis on the influence of gaps at service floors on both the static and dynamic structural response. The results are compared with those obtained for an equivalent non-gapped tower. The findings demonstrate that the presence of gaps alters the coherence of the vortex shedding process, leading to a reduction in the maximum vibration amplitude during lock-in.

Keywords: FSI aeroelasticity, Computational Wind Engineering, preCICE.

1. INTRODUCTION

Aeroelasticity, the two-way interaction between fluid flow and structural motion, is a fundamental phenomenon that must be considered when evaluating wind-induced loads and stability in many lightweight and flexible structures.

Traditionally, Fluid–Structure Interaction (FSI) problems in wind engineering have been investigated through Wind Tunnel Tests (WTT). When feasible, these assessments are commonly conducted using Reduced-Order Models (ROMs), which approximate the coupled fluid–structure behavior and can be calibrated using the response of sectional models subjected to forced and/or free vibrations. Representative examples include models for motion-induced loads proposed in (Barni et al., 2021, 2022; Chen and Kareem, 2003), as well as formulations for vortex-induced vibrations (VIV) described in (Tamura, 2020). This approach is highly efficient and often provides valuable physical insight into the dominant mechanisms governing the interaction. Nevertheless, it may become inadequate in several situations, such as when reliable ROM calibration is challenging, when the strip assumption is invalid due to rapidly varying cross-sections, or in the presence of non-uniform flow fields caused by aerodynamic interference or tip effects. In such cases, a fully aeroelastic modeling approach may be required.

These considerations, while originally framed in the context of WTT, are equally applicable to numerical investigations based on Computational Fluid Dynamics (CFD). In CFD, sectional models similarly offer significant reductions in computational cost compared to fully coupled aeroelastic simulations. However, given the well-known challenges associated with achieving accurate CFD predictions, it is unsurprising that most numerical studies on aeroelastic phenomena in wind engineering have focused on sectional models (see, for example, Álvarez et al., 2019; Li et al., 2021; Wang and Chen, 2022).

In this contribution, we present the experience gained by the authors in the setup of numerical simulations using full-aeroelastic models adopting the open-source software coupling platform preCICE. In particular, OpenFOAM is coupled with Python, in order to solve the fluid and the structural motion, respectively. Simulations are performed to investigate how structural gaps influence vortex shedding and the resulting vortex-induced vibrations in high-rise buildings, by analyzing how the presence of openings modifies the flow pattern and the aerodynamic forces acting on the structure.

2. SOFTWARE COUPLERS: PRECICE

In CFD-based Fluid–Structure Interaction (FSI), two main approaches are commonly used: monolithic and partitioned.

The monolithic approach solves the fluid and solid equations simultaneously within a single system of equations. This requires specialized software capable of handling both the fluid and structural problems together, and it does not allow the use of separate, dedicated solvers for each domain.

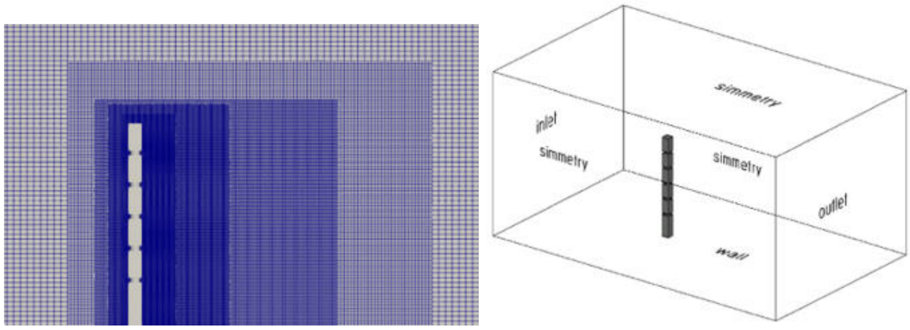
The partitioned approach, instead, employs two separate solvers: one for the fluid and one for the solid. The solvers exchange data at the interface between the two domains. In particular, fluid pressures and shear stresses act as loads on the structure, while the structural velocities at the wetted surface are imposed as boundary conditions for the fluid problem. This strategy allows the reuse of well-established and validated software for each physical domain and is therefore commonly preferred in practical applications.

The coupling platform `preCICE` (https://precice.org/) is an open-source library for multi-physics simulations based on a partitioned approach. It enables the coupling of different solvers, such as OpenFOAM for the fluid problem and Python for the solid part.

3. CASE SETUP

The building model is a prism with square section of 28 meters and a total height of 420 meters, resulting in an aspect ratio of 1:15. The structure includes five vertical gaps, each 10 meters high, accommodating a central circular core with a diameter of 20 meters.

In the numerical model, we consider for both case studies the mesh reported in Fig. 1, which has a total of about 12 M cells and a characteristic size in the proximity of the stack of $B/32$. Both smooth and turbulent inflow conditions are simulated. Wall conditions are applied on all sides, and an outlet pressure is applied at the outflow. Regarding numerical schemes, linear schemes are adopted for all terms apart from nonlinear convective terms, for which LUST is employed. Time integration is obtained relying on the Crank–Nicolson scheme with a non-dimensional time step equal to $dt \cdot U/B = 0.008$, leading to a maximum Courant number equal to 0.8 in the proximity of the structure. Simulations are performed adopting the well-known k-equation LES model.



(a) (b)

Figure 1. Overview of the mesh adopted for the fluid part: (a) top view and (b) section.

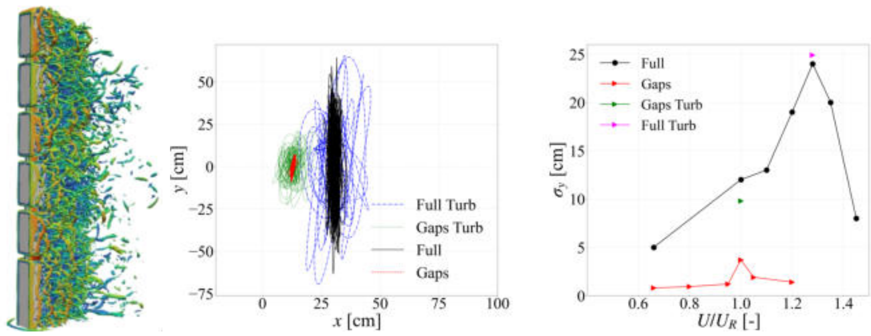
The solid part of the model consists of discrete points that represent the body's mesh structure. The model's displacement is determined through a dynamic transient modal analysis, which requires solving the decoupled modal equations of motion. The modal shapes for the modes were derived in accordance with the guidelines established by CNR 2018. A summary of the modal properties reported in Tab. 1. Damping has been assumed to be equal to 6%.

Table 1. Modal parameters of the solid model.

Mode	Frequency [Hz]	Modal mass [kg]
1^{st} (along x axis)	0.0738	3.85×10^{6}
2^{st} (along y axis)	0.0763	3.85×10^{6}
3^{st} (around z axis)	0.292	8.64×10^{8}

4. RESULTS

Firstly, the model has been tested in static condition without activating the two-way coupling. Figure 2 (a) provides an overview of the main vortical structures in the proximity of the stack. It can already be seen that gaps in the building can effectively reduce the formation of large, coherent wake vortices. Subsequently, the body has been allowed to move and subjected to a steady inflow velocity. Different inflow velocities have been tested spanning the range in the proximity of the lock-in condition. Fig. 2 (b) shows the orbit of the cross-wind displacement at the top of the model at the respective resonant velocities of the two cases, both in smooth and turbulent flow. The configuration with spanwise gaps shows a significantly reduced response compared to the full model, evidencing mitigation of the aeroelastic behavior. Figure 2 (c) shows the standard deviation of the transverse wind displacement, σ_y, as a function of the reduced velocity. For the full model, a clear peak appears, identifying the lock-in region. The gapped configuration displays markedly lower σ_y values over the entire range, with a strongly attenuated peak. For turbulent inflow conditions, notably higher displacement amplitudes are observed, both in the displacement orbits and in the σ_y response, which can be attributed to the presence of more coherent vortical structures developing in the dynamic case. Simulations resulted to be approximately twice as costly, in terms of computational time, with respect to static conditions.



(a) (b) (c)

Figure 2. Simulation results: (a) overview of the vortical structures in the vicinity of the body, visualized using the Q-criterion ($Q = 3$); (b) orbit of the cross-wind displacement at the top of the model at the respective resonant velocities of the two cases; and (c) standard deviation of the cross-wind displacement, where U_R denotes the resonant velocity assuming $St = 0.12$.

5. CONCLUSIONS

This contribution assessed the use of the open-source coupling platform `preCICE` for Wind Engineering applications, demonstrating an efficient partitioned workflow that combines well-established tools such as `OpenFOAM` for advanced FSI simulations. The methodology was applied to investigate vortex-induced vibrations of a 1:15 full-scale building model, with particular focus on the effect of service-floor gaps on both static and dynamic structural response. Comparison with an equivalent configuration without spanwise openings shows that the introduction of gaps disrupts the coherence of vortex shedding, resulting in a significant reduction of peak vibration amplitudes within the lock-in region. The performed simulations, as expected, highlighted a notable increase of the computational costs with respect to the fixed obstacle, corresponding to approximately a factor 2 for the present model. Despite such shortcomings, preCICE appears to be a potentially interesting tool in the context of Wind Engineering due to its flexibility and modularity.

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