GO-VIKING: A HORIZON EUROPE PROJECT ON FLOW-INDUCED VIBRATIONS

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ABSTRACT

Flow-induced vibrations (FIV) resulting from the Fluid-Structure Interaction (FSI) remain an area of concern in nuclear power plants. If not properly addressed, FIV can have large consequences to the operation and safety of these plants. With the increase in computational power, the use of numerical simulation tools to predict vibrations induced by the surrounding flow is rapidly increasing.

*In order to further advance the knowledge of solving FIV problems with the help of numerical tools, the Horizon Europe GO-VIKING (**G**athering Expertise **O**n **V**ibration **I**mpa**K**t **I**n **N**uclear Power **G**eneration) project was launched in mid-2022 in which 18 partners agreed to collaborate in this field for four years. The GO-VIKING project addresses issues with vibrations induced by the primary and secondary coolant in the nuclear power plants. Focus is put on two types of FIV issues, i.e. fuel rod fretting in fuel assemblies and fluid elastic instability occurring in steam generators, for both, single- and two-phase flows. The main objective of the GO-VIKING project is to develop, improve, and validate FSI methods, and to provide guidelines for the prediction and assessment of FIV phenomena in nuclear reactors.*

The current paper gives an overview of the roadmap to address the FIV numerical simulation challenges in the framework of the GO-VIKING project.

1. INTRODUCTION

The integrity of the nuclear steam supply system (NSSS) of a nuclear power plant (NPP) is essential for its safety and operability. Key NSSS components such as fuel assemblies (FA) or steam generator (SG) tubes are subject to several ageing challenges like high multiple corrosion mechanisms, neutron flux (embrittlement), and also long-term vibratory loads. Vibrations induced by coolant flow are particularly important challenges, as they lead to increased wear and tear and/or material fatigue, so that they have been and remain important contributors to key components' failures. Such failures can degrade NPP safety features and fail confinement barriers.

One pertinent example is that over 70% of all fuel rod leakages in U.S. pressurized water reactors (PWRs) are due to flow-induced vibrations (FIV), according to EPRI (EPRI, 2008). According to IAEA, grid-to-rod-fretting wear (GTRFW), resulting from such vibrations, is the cause of 58% of fuel failures in PWRs worldwide and one of the major causes of fuel failure in boiling water reactors (BWRs) (IAEA, 2010 and IAEA, 2019). The highly turbulent coolant flow in FA during operation results in asymmetric and fluctuating pressure on the fuel rods' surfaces. The pressure fluctuations are random, oscillate over a broad band of frequencies and amplitudes over the entire rod surface. This leads to dynamic grid-to-rod contacts and frictions, resulting in material wear in the contact region between the rod and its support.

FIV cause damage also in SG. In 2012, a SG tube rupture (SGTR) accident occurred in the US NPP San Onofre. Thereafter, an extensive wear of more than 3000 SG tubes was found in its units 2 and 3, leading to primary-to-secondary circuit coolant leaks. The SGs in these units were put in operation one year earlier. The principal reason for the extensive wear and the tube damage was found to be related to FIV (NRC, 2015). Since then, these units are in a shut-down condition. Steam generator tube rupture as a result of FIV has also been observed in many other reactors in the past (Kotthoff, 1984; MacDonald, 1996; Au-Yang. 2001; Païdoussis, 2006).

The recent trend, set by vendors, to further increase the thermal efficiency of heat exchangers, SGs, and other thermal equipment led to component designs with higher temperatures, increased mass flow rates, and thinner tube walls (Fischer, 2001). The enhancement of the heat transfer in the heat exchangers through increased flow velocities and thinner tube walls increases the susceptibility of the tubes to FIV. This is further increased by the ageing mechanisms that have a negative impact on the material wear and the mechanical contacts. Therefore, it is important to properly consider FIV loads in the component design and the operational surveillance and maintenance program. This also holds for power uprates and plant long-term operation (LTO) programs. As tests and measurements under operational conditions are often costly or not feasible, prediction of FIV loads by simulation could be a practical solution. The GO-VIKING Horizon Europe project gathers expertise from academia and research organizations, industry and technical safety organizations (TSOs) to synthesize and improve good practices, as well as to develop accurate simulation methods. These will support the prediction and evaluation of FIV by EU stakeholders, as well as their decision making on FIV countermeasures in the plants.

The current paper gives an overview of the roadmap to address the FIV numerical simulation challenges in the framework of the GO-VIKING project. Chapter two focusses on the structure of the collaboration and its objectives. Chapters three till six provide descriptions of main topics (axial FIV, FIV in SG, multiphase FIV, fast-running numerical methods) within GO-VIKING. Finally, in the last chapter a summary is given.

2. THE GO-VIKING HORIZON EUROPE PROJECT

The present chapter gives an overview of the GO-VIKING project. First, a short general description is given, followed by the roadmap to improve FIV simulation methods in nuclear industry.

2.1. The GO-VIKING project

The GO-VIKING project builds upon the VIKING (**V**ibration **I**mpa**K**t **I**n **N**uclear Power **G**eneration) initiative that started in 2020 as an in-kind collaborative effort under the SNETP umbrella (label from 09.2021) to improve the understanding and the prediction of FIV phenomena relevant to NPPs (Zwijsen et al, 2022).

The GO-VIKING project aims at improving the current state-of-the-art of FIV knowledge and analysis concerning the following global targets: improve overall NPP safety, enhance plant reliability in LTO and power uprate programs, reduce staff exposure, design components that are less susceptible to FIV, and increase the regulatory acceptance of FSI tools. Such improvements are impossible with the currently available FSI methods and tools that require very high computational effort. Further, without clear guidance for their application for the variety of FIV cases in nuclear reactors, and the lack of fast-running FSI methods, as well as the missing perspective for acceptance by the regulators, reaching these global targets is hindered. Therefore, the main objective of the GO-VIKING project is to develop, improve and validate FSI methods, and to provide guidelines for the prediction and assessment of FIV phenomena in nuclear reactors. Building on that, it aims to bring them into application at European nuclear stakeholders for improving the design, operation, and maintenance of key NPP components, and thereby, enhance both, safety and availability of existing nuclear reactors in Europe. Figure 1 gives an overview of the GO-VIKING concept.

The project started in June 2022 and will run for four years

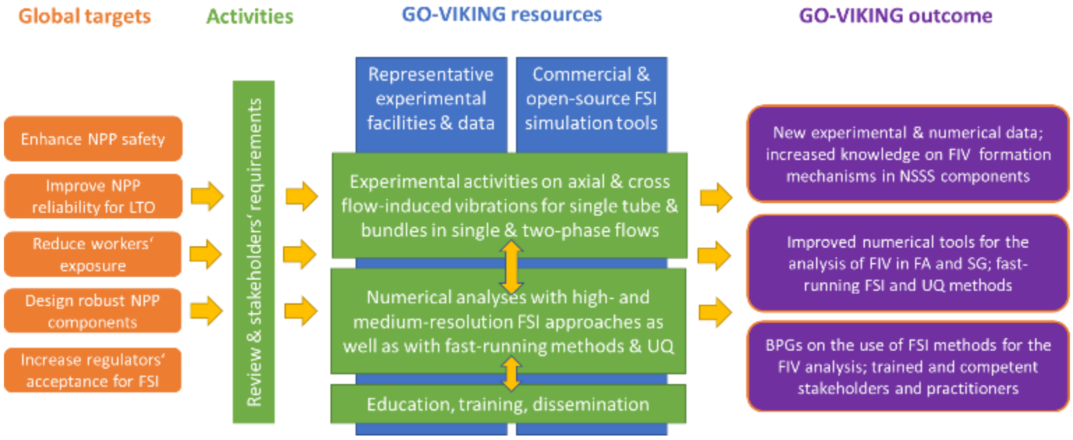

Figure 1. GO-VIKING concept

2.2. Roadmap to improve FIV simulation methods in nuclear industry

The main objective of the present project is to improve numerical tools to predict FIV in FA and SG, both in single and two-phase flow environment. The project partners review the current state-of-the-art and gather information on the needs for numerical FIV analysis and classify FIV challenges in three fields:

- **Flow-induced vibrations in fuel assemblies:** vibration phenomena in axial single-phase flow in a rod bundle are considered.
- **Flow-induced vibrations in steam generators:** vibration phenomena in single-phase cross-flow in a tube bundle are considered.
- **Multi-phase flow-induced vibrations:** vibration phenomena in two-phase axial and cross-flows are considered.

As the aim is to provide the partners with high-resolution, reliable validation data for the developed models and methods, validation benchmarks will be organized. To do that, experimental test cases are selected for each of the three previously mentioned topics. The experimental results are used as inputs for numerical work in terms of CFD and CSM programs that are coupled to develop sophisticated 3D FSI tools for FIV evaluation for a variety of industrial configurations, ranging from single rods/tubes in water up to fuel rod/tube bundles in two-phase flows. The purpose is to address with different methods the following challenges in the simulation of FIV with FSI methods:

- **Turbulence modeling**: (Unsteady) Reynolds-Averaged Navier-Stokes (U)RANS turbulence models, hybrid models, Large Eddy Simulation (LES), Direct Numerical Simulation (DNS),
- **Fluid-structure interface tracking method**: chimera grids, Arbitrary Lagrangian Eulerian, Immersed Boundary Method;
- **Mechanical solver:** beam model, mass-spring system, external mechanical solver;
- **Coupling methods:** explicit or implicit, iterative or direct, one-way or two-way;
- **Two-phase flow modeling:** VOF, Eulerian-Eulerian, transition-regime models.

It is important to notice that one reference high-resolution (LES or DNS) simulation will be performed for all of the single-phase flow experiments to complement the experimentally generated data.

Knowledge and know-how gained from this work will be used as an input for fast-running model development to reduce the prohibitive CPU time of FSI simulations, as this is one of the main bottlenecks today. With the help of the fast-running models, efficient UQ methods will be developed to supplement best-estimate FSI analyses.

Further, the currently available FSI methods will be classified and their advantages/drawbacks, as well as applicability for the objectives of the project, will be evaluated.

The result of this work will be documented in specific requirements for advanced numerical methods and tools for FIV evaluation.

3. FLOW-INDUCED VIBRATIONS IN FUEL ASSEMBLIES

The main focus of this section is on the FIV under single phase axial flow conditions, which is particularly relevant for nuclear fuel assemblies. The main objective is to develop advanced simulation methods and tools to facilitate the understanding of FIV and to support free-of-failure operation of FA or other components in NPPs subjected primarily to axial flow. Specific focus is put on development of efficient simulation tools capable to provide reliable prediction of FIV in FA in an acceptable time and with reasonable computational costs, according to the needs of the nuclear industry. The development of medium-resolution models for fluid flow analysis in combination with low-resolution structural models and efficient FSI coupling algorithms is of particular interest.

For the purpose of validation of the numerical simulation tools existing experimental data from two test benchmarks will be utilized. The validation database is further supplemented by the results of high-resolution numerical simulations performed for each benchmark.

The results achieved will also provide input for reduced-order models (ROM) for fast-running methods to be developed (see section 6).

In the following sections a brief description of the experiments and the accompanying numerical simulations for each benchmark of this topic is provided.

3.1. Cantilever rod case

The University of Manchester (UoM) recently designed and realized a simplified test rig for fundamental studies of axial-flow-induced vibration of relevance for water-cooled nuclear reactor systems (Cioncolini et. al 2018). The main aim in designing this cantilever beam experimental setup, shown in Figure 2, is to generate benchmark experimental data in controlled conditions with non-invasive simultaneous resolution of structural vibration (via non-contact optical tracking) and fluid flow (via Particle Image Velocimetry (PIV)). Although simplified, the experimental configuration is representative for nuclear FA. Large vibration amplitude response of the test rod, induced by axial flow, requires a strong fluid-structure two-way coupling, making it particularly interesting for numerical simulation. Different experimental runs will be analysed with the numerical tools. The Reynolds number will be around 16.000 and the flow velocity around 1 m/s.

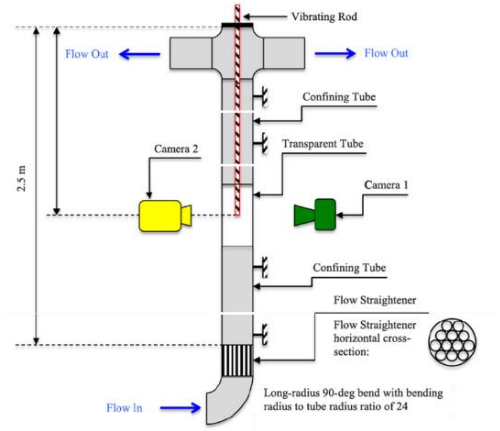

Figure 2. Axial flow-induced rod vibration test.

High-resolution simulations of the cantilever rod experiment will be performed using wall-resolved LES (Code_Saturne) and DNS (Nek5000). The results from these fine-resolution simulations will be validated against experimental data and used for further development and validation of medium-resolution simulation models, based on URANS approach.

3.2. ALAIN 5x5 PWR rod bundle

The ALAIN experiment had been performed by Framatome GmbH in Erlangen, Germany, with the aim to study complex FIV behaviour of different fuel assembly designs. The experimental setup is illustrated in Figure 3. It represents a reduced 5x5 PWR FA test bundle, placed in a channel of a low-pressure test loop with a square cross-section with a narrow nominal lateral gap between the bundle and test channel of 1.5 mm (at spacer grid positions). The vibration response of the fuel bundle was measured using laser for a wide range of the flow rates corresponding to Reynolds number between 50.000 and 120.000, based on average axial velocity, hydraulic diameter within the bundle and fluid properties of water at 4 bar pressure and 40°C temperature.

The simulations for this benchmark will be performed for the axial flow velocity corresponding to Reynolds number of 90.000. First, stand-alone CFD simulations using an appropriate medium-resolution for the full and high-resolution modelling approach (based on LES) for the reduced, single-span, configurations will be performed. The purpose of these simulations is to evaluate the global flow field and the detailed unsteady flow characteristics in the bundle, as well as to assess the requirements for medium-resolution approach. The results from CFD simulations can also be used to evaluate vibration response in the framework of decoupled FSI simulation.

In the second step, coupled FSI simulations, based on medium-resolution modelling, will be performed. For the FSI coupling either integrated or user implemented solutions in combination with commercial and open-source CFD codes (STAR-CCM+, ANSYS CFX, OpenFOAM) will be used.

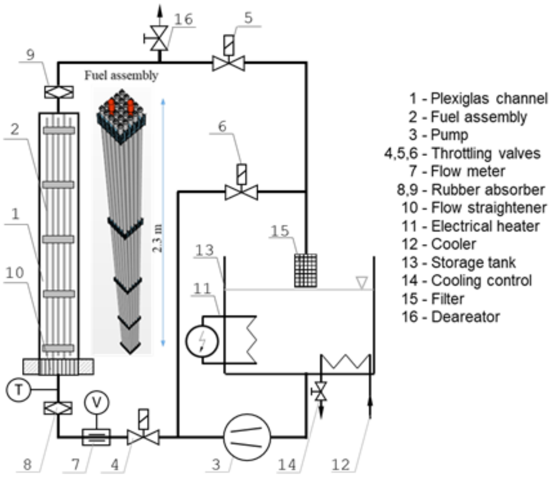

Figure 3. ALAIN 5x5 rod bundle FIV test setup.

4. FLOW-INDUCED VIBRATIONS IN STEAM GENERATOR TUBE BUNDLE

In the present section, the focus is put on the development, implementation and validation of beyond the state-of-the-art medium-resolution numerical tools to provide reliable assessment of structural vibrations, occurring in steam generators under single-phase cross-flow conditions. Hereto, new experimental and high-resolution data will be generated to allow the further development and validation of such tools. This experimental and high-resolution numerical data is obtained from two different experimental facilities: CEA's AMOVI and VKI's GOKSTAD. Descriptions of each facility are given in the next sections along with the accompanying numerical exercises.

4.1. AMOVI experiment

AMOVI (Cardolaccia, 2015) is a small modular and easy-to-maneuver loop aimed at studying cross-flows in tube bundles. It addresses low-turbulent regimes in a normal-square tube bundle of 3x5 tubes plus two columns of 5 semi-tubes. In the AMOVI facility, which is shown in Figure 4, the flow is at low pressure ($p < 5$ bar) and low-temperature ($T < 40$ °C) conditions. The diameter of the tubes is 12 mm with a pitch-over-diameter (P/D) ratio of 1.44, values similar to those used in steam generators of NPPs. The maximum volumetric flow rate in AMOVI is 4.2 l/s, which results in Re~2.3E+4 in the gap between the tubes. PIV, LDV and high-speed camera measurements are performed to provide data on the flow pattern inside the test section and the vibration characteristics of the central tube. Experiments will be performed with all tubes fixed, as well as with a central flexible tube.

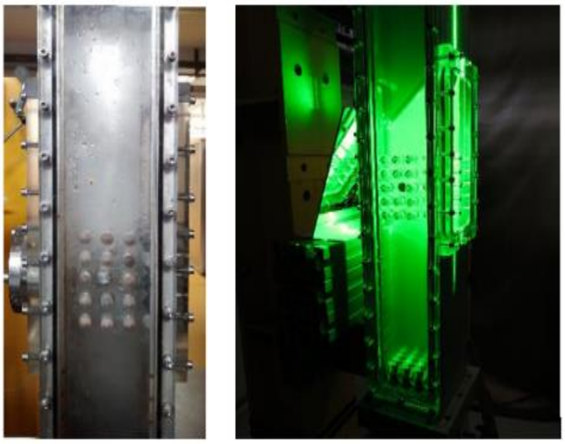

Figure 4. AMOVI test facility at CEA.

The experimental data from AMOVI will be supplemented with high-resolution simulations in Code_Saturne using a wall-resolved LES model and the Arbitrary Lagrangian Eulerian (ALE) approach. The generated results will be compared with experimental data and utilized for the development and validation of medium-resolution models based on hybrid (Zonal LES, Stress Blended Eddy Simulation) and URANS turbulence methods.

4.2. GOKSTAD experiment

At VKI, a new experiment named GOKSTAD (**GO**-VI**K**ING experimental **S**e**T**up to **A**ssess flow-induced vibrations by cross flow in tube bun**D**les) will be designed and built to generate new high-resolution data of single-phase, cross-flow induced vibrations of flexible tubes within a tube bundle. It will be a square tube bundle of 7x7 tubes using water as medium, with the aim to perform experiments at a Reynolds number higher than what is currently available in the literature. A sketch of the water loop of the proposed new GOKSTAD experiments is provided in Figure 5.

The design will be flexible, allowing to vary the number and position of the flexible tubes. Furthermore, the facility will be sustainable such that it will be easy to use in future experimental campaigns. Time-Resolved Particle Image Velocimetry (TR-PIV) is used to measure the flow field (mean, fluctuating components, Reynolds stresses), essential for the proper validation of the flow solver used in FIV models. Data will be generated for a range of flow velocities, as well as for cases involving all fixed tubes, one central moving tube, as well as two moving tubes, placed either behind or above each other. The exact parameters of the experimental runs (inlet and gap velocities, Reynolds number, etc.) will be determined in the first few months after the project begin together with the GO-VIKING partners performing numerical simulations.

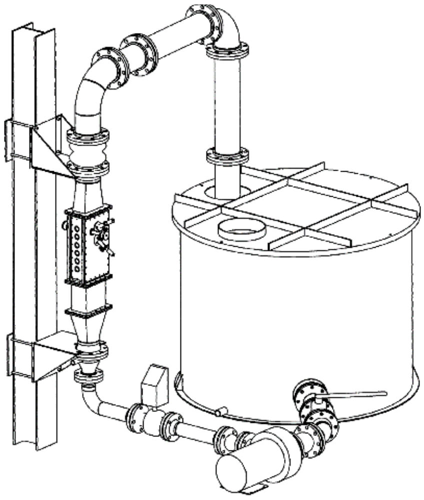

Figure 5. Sketch of the GOKSTAD water loop.

High-resolution simulations of GOKSTAD using Nek5000 coupled to Diablo and based on an ALE approach will be performed. Results hereof are to be compared with experimental data and also to be used for the further development and validation of medium-resolution models. For GOKSTAD, the latter work is done using STAR-CCM+ with a low Reynolds URANS and/or hybrid method in combination with the ALE approach, as well as with a low and/or high Reynolds URANS method in Code_Saturne with the ALE approach and/or in NEPTUNE_CFD using an Immersed Boundary method.

5. FLOW-INDUCED VIBRATIONS IN MULTI-PHASE FLOWS

In the present section, the focus will be on the use of three two-phase flow FSI experiments (both for axial- and cross-flow conditions), dedicated to the development and validation of two-phase FIV tools. Hereto, two-phase flow and structural measurements will be performed to have a rich validation database. With this database, numerical tools will be developed and improved in order to be as accurate as possible for different flow regimes. The developed tools are expected to provide the possibility for deeper understanding of FIV for two-phase flows in general, and SG in particular.

The diversity of the input coming from the different partners and the stakeholders provide an excellent basis for the development of an optimal solution. One of the main outcomes of this topic will be the guidance for practical use of the simulation tools based on the assessment of different numerical approaches to be used within the foreseen benchmarks.

In this section three benchmarks will be considered:

- Cantilever rod subjected to axial two-phase flow (previously discussed in section 3 for the single flow configuration),
- TREFLE: 5x5 square tube bundle subjected to an air-water cross flow,
- TITAN: 5x5 triangular tube bundle subjected to an air-water cross flow

For each case, different partners using different numerical simulation approaches and tools will perform the calculations.

5.1. Cantilever rod under two-phase flow

The Cantilever rod facility described in chapter 3 on single-phase axial flow-induced vibrations will be modified in order to perform similar experiments, though now for two-phase air-water mixture flows. The facility will be equipped with an extra device to measure the void fraction distribution.

Numerical simulation of this experiments will be computed by three partners based on various methods in terms of turbulent modeling, fluid-structure interface tracking method, and mechanical resolution, such as a URANS approach with the Immersed Boundary (IB) method of NEPTUNE_CFD, the internal FSI solver of ANSYS FLUENT using URANS or a hybrid method and an URANS based ALE method implemented in the coupled code NEPTUNE_CFD-FEniCS.

5.2. TREFLE

TREFLE is a 5x5 square tube bundle to study two-phase FIV with air-water mixture. The tube diameter will be 30 mm, while their length – 300 mm. One or more moving tubes will be installed in the bundle. The void fraction will be varied between 0% and 100%. For the measurements optical probe, wire-mesh sensors and high-speed camera will be used. The objective of this experiment is to validate FIV codes by generating data with measurements of the central tube displacement and of the void fraction upstream and downstream the tube for various inlet void fractions. The purpose of this experiment is to have two-phase flow and vibration measurements simultaneously for an in-line bundle. This is important for the specification of realistic inlet boundary conditions in the simulations, as these can have a large influence on the obtained results.

Five partners will simulate this experiment with different tools: NEPTUNE_CFD with the Generalized Large Interface Model, STAR-CCM+ with an ALE method, OpenFOAM coupled with Deal.II with the preCICE coupling interface, based on the ALE method, the NEPTUNE_CFD code with an IB method, and the intrinsic FSI solver of ANSYS FLUENT. For the latter, if deemed necessary, full coupling with ANSYS FLUENT Mechanical will be used.

5.3. TITAN

CEA proposes experimental data for tubes vibrations under two phase flow (water-air mixture) with increasing difficulty for codes and numerical methods testing. These data have been obtained with the TITAN triangular mock-up. The bundle consists of 5x6 stainless tubes, with two columns of half-tubes at both lateral plates to minimize wall effects. A flow straightener is placed upstream the test section to regulate the inlet flow direction. Each test has been done with a void fraction kept constant. Flow is increased until fluid-elastic instability (critical velocity) is reached. RMS displacement amplitude over flow pitch velocity is available. For the present case, the triangular tube lattice and the higher Reynolds number (~250.000) are the main numerical challenges.

Four partners will simulate this experiment with very different approaches: the two-phase CFD Code ANSYS FLUENT, STAR-CCM+ with its ALE approach, OpenFOAM coupled to Deal.II via the preCICE coupling interface and NEPTUNE_CFD with an IB method and the Generalized Large Interface model

6. FAST-RUNNING METHODS, UNCERTAINTY QUANTIFICATION AND BEST PRACTICE GUIDELINES

Methods that can provide valuable information with similar accuracy to the one of the original, full-order model, but at significantly lower computational cost, are termed fast-running methods. Such methods often include reduced order models (either of the CFD, or of the CSM domain. Since the CFD simulation is typically orders of magnitude more costly than the CSM solution, remarkable efforts in this European project are dedicated to the generation of fast-running FSI methods with increased fluid flow calculation efficiency.

6.1. ROMs for the CFD domain

Within GO-VIKING project novel data-driven and projection-based ROMs for the fluid component will be developed with the aim at closely reproducing the physics of the full-order models. Such methods will be constructed by building a data-set of time-resolved fluid simulations with forced displacement of the domain walls, followed by system-identification techniques (Sarma, 2018).

Another fast-running approach will be based on building a ROM that predicts the turbulence pressure spectrum from significantly cheaper RANS or

URANS models. The further development of the NRG Pressure Fluctuation model (PFM) together with a URANS turbulence model will allow to predict the pressure fluctuations driving the structural vibrations at a much more reasonable computational cost (Kottapalli et al 2019).

Additionally, a third fast-running method for the CFD domain will be developed and implemented. The proposed approach is based on the generation of synthetic turbulent fluctuations in combination with standard URANS approach (Filonov et al, 2020).

6.2. ROMs for the CSM domain

ROMs can be used not only for the CFD, but also for the CSM domain. Recently, efforts to couple structural ROMs with detailed scale-resolving CFD simulations for the evaluation of FIV phenomena in nuclear power reactors were made (Papukchiev, 2022). Within the project, beam models will be developed in order to speed up the calculation on the CSM side. The beam models will substitute the detailed 3D modelling of the investigated rods/tubes, and will, hence, accelerate the FSI simulation. Further, the ANSYS MOR (Model Order Reduction) (Einzinger, 2014), based on the mode-superposition method, which uses the natural frequencies and mode shapes, generated from a modal analysis to characterize the dynamic response of a structure to transient or steady harmonic excitations, will be implemented for a tube bundle in a cross-flow and validated. A MOR technique will be developed and implemented for the analysis of the vibration response of the AMOVI tube bundle described above.

6.3. Uncertainty Quantification

Fast-running models including ROMs are an essential element to make uncertainty and sensitivity analyses (UaSA) for FSI simulations, based on input uncertainty propagation, attractive. The need for Uncertainty Quantification (UQ) methods for FIV analyses became visible in the Horizon 2020 MYRTE (MYRTE, 2015) and SESAME (SESAME, 2015) projects, where the validation of FIV analyses in tube bundles proved to be challenging due to variations in the experiments of the inlet conditions, tube alignment, spacing, end conditions and contacts, as well as approximations in the numerical models.

In GO-VIKING, FSI simulations will be combined with non-intrusive UQ techniques, such as polynomial chaos expansion (PCE) or Monte Carlo (MC) approaches. These UQ techniques permit the calculation of the distribution of modal characteristics (eigenfrequency and damping ratio) for the model by performing a relatively limited number of FSI simulations. Further, the RANS turbulence closure error on the output of interest will be quantified with Bayesian estimates of the model corrections, derived from high-fidelity data. In addition, global sensitivity analyses will be performed.

The developed UQ approaches will lead to a fast identification of high importance input parameters, needed for best-estimate calculations when used as evidence to support safety cases.

6.4. Best Practice Guidelines for FIV analysis

Based on the available deliverables, the main outcomes of the GO-VIKING project will be evaluated. The gained experience and knowledge throughout the whole project on the use of FSI methods for FIV will be used to synthesize Best Practice Guidelines on the use of FSI methods for FIV evaluation for vendors, operators and regulators. These will be discussed with stakeholders and international partners. Their feedback will be considered in the final version of the document.

7. CONCLUSION

To improve the understanding and the prediction of FIV phenomena, relevant to nuclear power reactors, eighteen partners, ranging from vendors, operators, and TSOs to universities and research organizations, started in June 2022 the Horizon Europe GO-VIKING project. Within this project, experimental and numerical activities are combined to: (i) increase the experimental database of FIV inside NPPs; and, (ii) improve the existing capabilities of the numerical tools to simulate and predict these phenomena.

An overview of the GO-VIKING consortium was provided along with information about the project structure, including the main FSI topics and the tasks to be carried out. Furthermore, details of all planned experimental and numerical work that will be performed, were also presented.

The project will run for a total of four years, with the final product of the project being the Best Practice Guidelines that summarize the gained experience and knowledge throughout these years on the use of FSI methods for FIV evaluation. These will be disseminated to vendors, operators and regulators in order to support them in the design, evaluation and decision making in the field of FIV in nuclear power reactors.

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10. TRADEMARKS

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