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Numerical simulations of rod assembly vibration induced by turbulent axial flows

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ABSTRACT

In this paper, various aspects relevant for nuclear applications of bare rod bundles in axial turbulent flows are studied by means of numerical simulations. The work first investigates the fluid dynamics properties of the flow field in the narrow gaps between the rigid rods and then it focuses on the study of the dynamics of the vibrations of the flexible rods. A two-rod assembly is examined first; the system consists of two identical rods in turbulent axial water flows with a small pith-to-diameter ratio and a large wall-to-diameter ratio. In the case of rigid rods, it is found that the flow field is characterized by the presence of strong axial flow pulsations in the gap between the rods with a characteristic frequency close to that observed in previous experimental works at a similar Reynolds number. Subsequently, strongly coupled numerical fluid-structure interaction (FSI) simulations are performed in order to study the flow induced vibration (FIV) of the rods. It is found that a buckling of the rods occurs because the fluid in the gaps pushes the rods apart which then undergo sustained vibrations because of the velocity fluctuations. Furthermore, due to the hydrodynamic coupling, the vibrations of the rods are not independent from each other but the system vibrates as a whole, as confirmed by the spectral analysis which shows the existence of a pair of frequencies around each of the natural frequencies of the structure in vacuo. A seven-rod assembly with the same pitch-to-diameter ratio of the two-rod case is then studied. Numerical simulations reveal the presence of strong flow pulsations in the gaps, although the frequency of the pulsations is slightly lower that than observed in the two-rod case. In the numerical FSI simulations, a very complicated rod-to-rod interaction is observed with the appearance of large vibrations and buckling deformation.

1. Introduction

In a nuclear power plant, flow-induced vibration (FIV) of nuclear fuel rods is an important phenomenon arising from the coupling of flexible cylindrical rods with the surrounding fluid flow. This phenomenon has been extensively study both experimentally and analytically because of the importance of taking the vibrations of the flexible structures into account during the design of a nuclear power plant. A typical fuel assembly in pressurized nuclear reactors consists of hundreds of slender hot irradiated rod cooled by fast-flowing water; failures in these reactors can be caused by grid-to-rod fretting which is directly linked to the flow-induced vibration problem and can cause wear, rod failure and fuel leakage. In addition to nuclear fuel rods, several other components in a nuclear power plant, like heat exchanges or pipe lines, can experience flow-induced vibration and fluidelastic instabilities.

Fluid-elastic vibration can occur in cross-flow as well as in axial flow conditions (Païdoussis, 1983). Compared to the cross-flow case, the vibrations in axial flow are generally small, but they can wear and fret the rods or can be responsible for fatigue damages (Kim et al., 2009; Blau, 2014). The small-amplitude vibrations of cylinders in axial flow are usually caused by the near and far field pressure fluctuations in the flow filed; the former mechanism is due to fluctuations of the pressure in the turbulent boundary layer, the latter is induced by the propagating disturbances induced, for example, by upstream obstacles, pipe bends or pump pulsation (Païdoussis, 1998). In a typical fuel assembly, the fuel rods are closely packed together hence the vibration of one rod will affect the dynamics of the surrounding elements because of the fluid-dynamic coupling created by the presence of the fluid, hence the rods will respond like a system rather than as independent elements (Chen, 1975).

In the past few decades, the study of FIV of slender bodies in axial flow has been relying on the availability of simplified analytical models or experimental data. A review of theoretical models for the analysis of FIV of slender bodies in axial flow can be found in several papers (Païdoussis, 1981; Blevins, 1979; Wang and Ni, 2009). Most of these models are based on the use of linear theory of elastic beam in

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combination with the potential flow theory and semi-empirical methods for the description of inviscid and viscous fluid effects, respectively. Linear models are able to predict correctly the vibration around small deformation of the rods as well as the onset of buckling modes, but are no longer valid when the fluid-elastic instabilities occur. In this respect, non-linear models have been developed to study the dynamics of the instabilities of a single rod but, to the authors' best knowledge, no analytical non-linear model has been developed for cluster of rods. On the other hand, in experimental studies it can be extremely complicated to measure the small rod vibrations in complex fuel assemblies, furthermore, the results can be affected by a high level of incertitude coming from not completely know parameters of experimental set-up, such us rod constraints and operational conditions.

In this prospective, numerical Fluid-Structure Interaction (FSI) simulation based on the use of Computational Fluid Dynamic (CFD) and Computational Structural Mechanics (CSM) represents an alternative to the classical theoretical models and can complement the experimental measures. In the last decade, several numerical studies have been performed for a single and multiple fuel rods; these include FSI simulation of flow-induced vibration with URANS turbulent models, one-dimensional Euler-Bernoulli beam models (Liu et al., 2012; Liu et al., 2012; Liu et al., 2013) and three-dimensional solid elements (De Ridder et al., 2013; De Ridder et al., 2015; De Santis and Shams, 2017). High fidelity large-eddy simulations have been used in other works (Christon et al., 2016; Elmahdi et al., 2011) to simulate fuel rod vibration and grid-to-rod fretting in pressurized water reactors, however, the flow induced forces were computed first by considering the structure as rigid and then, in a subsequent step, the structural problem was solved by applying the forces extracted from the CFD simulations.

FSI simulations of a large fuel assembly remains very challenging and computationally expensive, but at the same time they could be extremely helpful to shed light on the mechanisms of the flow induced vibration and fluid-dynamic instability in fuel assembly. In this work, numerical simulations of FIV in axial flows are performed considering tightly coupled FSI problems, extending the work previously done for a single rod (De Santis and Shams, 2017) to the case of a two- and seven-rod fuel assembly. The objective of this work is to study the characteristics of the fluid flow passing through the rods of a fuel assembly and to understand the dynamics of the vibrations of its components. Furthermore, it is well know that axial flows in narrow inter-cylinder gaps can result in trains of vortices whose frequency depends on the Reynolds number and the width of the gaps (Hooper and Wood, 1984), in this perspective, the properties of the fluid dynamic field are also investigated.

The remaining of the paper is organized as follows. In Section 2, the numerical approach for FSI problems is briefly recalled. In Section 3, the structural model is constructed and the fluid domain is described. In Section 4 the fluid dynamic simulation of a turbulent flow in a two-rod bundle case is performed, then full FSI computations are considered to study the dynamics of the vibrating rods. In Section 5 the seven-rod bundle system is analyzed. Finally, Section 6 concludes this paper.

2. Numerical simulation of fluid-structure interaction problems

In numerical simulations of FSI problems, the fluid and structural governing equations must be solved simultaneously with proper transmission conditions between the two domains. At the fluid-solid interface, the flow induced forces represent the external loads for the structural problem; the displacement and the velocity of the surface of the structural material represent the boundary conditions for the fluid problem. For the CFD grid to remain conform to the FSI boundary mesh deformation algorithms must be adopted to smoothly propagate the deformation of the boundary surface into the interior of the fluid mesh. This framework for FSI problems is generally referred to as three-field formulation (Lesoinne et al., 1993).

In this work, the fluid flow is assumed to be governed by the incompressible Navier-Stokes equations solved on deforming grids by the means of the arbitrary Lagrangian-Eulerian (ALE) formulation (Donea et al., 1982). The structure is assumed to be governed by the Newton's second law for linear elastic solids. Furthermore, kinematic compatibility and dynamic equilibrium conditions are enforced at the fluid-solid interface.

Broadly speaking, FSI problems can be solved with two approaches: monolithic (Hron and Turek, 2006) and partitioned (Degroote, 2013). The latter approach is used here because it has several advantages which include reduced computational complexity, software modularity and exploitation of of-the-shelf software components. In particular, the adopted coupling method used in this work is based on the use of Gauss-Seidel iterations between the fluid and the structural solvers with Aitkens under-relaxation factor (Küttler and Wall, 2008): at each time step, the fluid and the structure are solved iteratively until convergence is reached. The approach has been validated in previous works for FSI simulation of bare and wire-wrapped rods (De Santis and Shams, 2017; ter Hofstede et al., 2017; De Santis and Shams, 2017).

The FSI simulations are performed by using the commercial software STAR-CCM+ (version 10.6) (STAR-CCM+, 2015) in which the governing equations of fluid are solved by the means of a finite volume approach, whereas the governing equation of the structure are solved with a finite element method.

3. Description of the numerical set-up

In this section the description of the numerical models of the structural and fluid-dynamic problems used in the current work is reported.

3.1. Design of the numerical fuel rod model

The structural model of the fuel rod used in this work is designed according to the specifications of the experimental set-up used by De Pauw and coworkers (De Pauw et al., 2015) to perform experimental measurements of flow induced vibrations of rods in axial water flow. The rod consists of a cylindrical stainless steel tube and its dimension are the same of the actual fuel rods to be used in the MYRRHA assembly (Baeten et al., 2014), which is a research reactor aiming to demonstrate the feasibility of the lead-cooled fast reactor concepts.

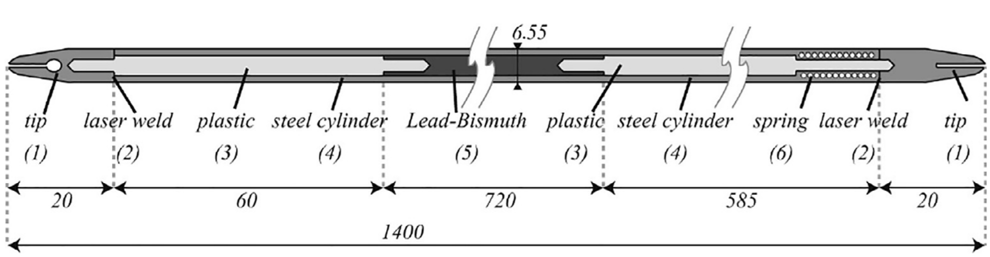

Fig. 1. Sketch of the experimental model of the fuel rod (De Pauw, 2015).