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Parametric study of flow-induced vibrations in cylinder arrays under single-phase fluid cross flows using POD-ROM

Elisabeth Longatte [a,*], Erwan Liberge [b], Marie Pomarede [a,b,c], Jean-François Sigrist [c], Aziz Hamdouni [b]

[a] IMSIA, UMR EDF-ENSTA-CNRS-CEA 9219, 7 boulevard Gaspard Monge, 91120 Palaiseau, France
[b] LaSIE, UMR 7356, CNRS-Université de La Rochelle, Avenue Michel Crépeau, 17042 La Rochelle cedex 1, France
[c] DCNS Research, 5 rue de l'Halbrane, 44340 Bouguenais, France

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ABSTRACT

Modeling numerically Flow-Induced Vibrations in heat exchangers at a microscopic scale requires high computational resources and time which are still unreachable. Therefore model reduction is investigated in the present work in order to address the issue of simulation computational time reduction. In the framework of POD-Galerkin projection methods, the purpose is to propose optimal a posteriori reduction strategies enabling error control on approximation as well as Reduced-Order Model (ROM) interpolation to deal with sensitivity analysis of solutions to parameter perturbations. A multi-phase fluid–solid POD-Galerkin-based method is proposed for modeling flows and vibrations in cylinder arrangements under single-phase fluid cross-flows. Moreover a single-POD basis method is evaluated in the context of ROM interpolation. This work is a first step in the development of robust ROM describing fluid and solid dynamics in the presence of turbulence, heat transfer effects and large magnitude structure displacements and deformations.

0. Introduction

Optimization of safety barrier reliability and Uncertainty Quantification (UQ) of physical models give rise to long-term research programs involving designers and engineers working on maintaining systems under operating conditions. The present article focuses on vibration risk assessment in heat exchangers in the context of lifecycle control and increase of mechanical components in spite of the very constrained conditions they are submitted to. In Pressurized Water Reactors (PWR) steam generators ensure the transition between the primary and secondary loops and are used to convert water into steam from heat produced by the core made of fuel assemblies. Each heat exchanger can measure up to 20 m and is made of regular confined arrangements of several thousands of thin elongated cylinders whose section diameter may be less than 2 cm. These cylinders are conveying the primary fluid and steam is produced, coming from the water on the shell side, so-called the secondary fluid. The heat exchanges take place at this stage in this area. Then the secondary steam is delivered to turbines for electric power generation. A brief dimensionless analysis of this geometrically complex system shows that as a first approximation under current conditions the dynamical behavior of these vibrating cylinders is independent on heat transfers. Therefore it is not necessary to account for thermal effects in the context of dynamical analysis. Due to geometry and to thermohydraulics conditions, most effects responsible for vibrations of cylinder arrays are due to Fluid Structure Interaction (FSI) and Flow-Induced Vibration (FIV) occurring at the external shell of the cylinders. They are due

* Corresponding author.
E-mail address: elisabeth.lacazedieu@edf.fr (E. Longatte).

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to the hydrodynamic unsteady load exerted by the external fluid on these structures. Moreover the component is such that cylinders are submitted to two-phase flows at the top and to single-phase flows at the bottom. Therefore as a first step, in the present article, one focuses on single-phase FIV at the bottom of the heat exchanger where flows are crossing mostly transversally the array. The purpose is to address the multi-physics multi-scale issue of stability analysis of dynamical response of cylinder arrangements submitted to external single-phase fluid flows in order to be able to establish accurate stability maps applicable for design. Therefore parameter perturbations must be investigated in order to account for possible large variations of parameter values during the lifecycle of these mechanical components.

As far as numerical modeling is concerned, a fully three-dimensional microscopic-scale model of the bottom area of the heat exchanger tube array under single-phase fluid cross flow under real operating conditions characterized by Reynolds numbers of order of 10^5 would lead to solving systems involving more than 10^{10} degrees of freedom which is still unreachable in practice even by using most advanced High Performance Computing (HPC) resources. Therefore superposition methods have been introduced in the context of first order asymptotic developments in order to perform linear stability analysis of these systems and exhibit major mechanisms involved in dynamical instability occurrence. Using space domain decompositions dimensionless parameter effects have been studied independently. Nevertheless HPC simulations performed on small-size domains are not yet convenient for design since they still require long computations of several hours to several days according to Reynolds numbers to be considered and to turbulence models to be involved. Therefore Reduced-Order Modeling (ROM) is investigated in order to deal with this problematic of reducing computational time. It is investigated in the present work by considering as a first step a two-parameter configuration where only Reynolds number and reduced velocity can vary while other parameters like mass ratio, Scruton number and pitch ratio of the cylinder arrangement are given. The basic idea is to use few High-Fidelity (HF) computations with a classical method (such as Finite Volumes and Finite Elements) to build low computational time models. Then ROMs have an initial cost, but this cost can be charged off if the models are used for large set of parametric values. The success of such approaches can be quantified by the large field of their applications. For example, ROMs have been used for studying different configurations of thermal management of data centers (Samadiani and Joshi, 2010), for controlling wave energy converters (Hesam and Shoori, 2014), fluid flow control at high Reynolds numbers (Semaan et al., 2016; Balajewicz et al., 2016) or in aeronautics (Kim, 2016). One way also explored is computation on smartphone, for which ROM approaches seem to be the appropriate solution. For example, Modesto et al. (2015) proposed an application for smartphone for computing disturbances in the Barcelona harbor in quasi real time using a ROM approach. On the same thing, ROM using a few/small resources could be used in a context of volunteer computing (Nouman Durrani and Shamsi, 2014) for a large parametric studies.

Few works exists on ROM development for FIV or FSI context. All works consist in adapting or extending the Proper Orthogonal Decomposition (POD) to this problematic. The POD is the most famous method for ROM in fluid mechanics and it has naturally been extended and adapted to the cases of flow in the presence of moving boundaries. For FSI cases similar to aeroelasticity, i.e where the fluid domain could be considered as fixed, the Navier–Stokes equations are linearized and projected on a POD basis (Barone et al., 2009b; Lieu et al., 2006). For small vibrations at the surface of the structure, Bourguet et al. (2011) proposed a Hadamar formulation associated with a ROM-POD. For large fluid domain motion of deformation, Rozza (2009) used POD on a parametric mesh and next built ROM for stationary problems on different meshes. In case of imposed displacement of the structure, Balajewicz and Farhat (2014) proposed an immersed boundary ROM with a modified formulation. The ROM is directly built in an immersed boundary solver and is available only for imposed displacement of the solid domain. Among the previous proposed methods, none allows to solve a FSI problems with a large displacement of the structure, i.e cases where the fluid modifies the behavior of the structure, which interactively also changes the flow. The issue of using POD for moving domains deals with the paradox of computing a POD basis which is a spatial basis on a changing (i.e. a time-evolving) domain. Liberge and Hamdouni (2010) and Liberge et al. (2010) proposed a POD-multiphase formulation available for FSI problems with large displacement of the domain. The method consists in computing a POD basis of an interpolated velocity field on a reference grid, and next in projecting a multiphase formulation on this POD basis. It is recalled in the next section. This method has been successfully used for small and large displacements of a cylinder in a cross fluid flow for known parameters.

This paper explores the behavior of POD-multiphase ROM when the parameter values are different from those used to build the POD basis. In the first part, the principles of the POD, the POD-multiphase and the ROM parameter sensitivity analysis methods are explained. Next, the parameter sensitivity of the cylinder vibrations in a cross fluid flow is studied and results are discussed.

1. Theory

One considers $\Omega \subset \mathbb{R}^3$ such that $\Omega = \Omega_f(t) \cup \Omega_s(t) \cup \Gamma_i(t)$ with Ω_s the solid domain, Ω_f the fluid domain and Γ_i the fluid–solid interface. One defines the external boundary of the domain : $\Gamma_f = \partial\overline{\Omega} \setminus \Gamma_i$. The normal vector $\mathbf{n}$ is oriented as pointing out towards outside the solid domain. One defines a velocity field $\mathbf{u}$ over the whole domain $\Omega \times [0, T]$ where T corresponds to the last time where the dynamics of the system is considered.