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Numerical prediction of flow induced vibrations in nuclear reactor applications

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HIGHLIGHTS

- Numerical simulations of flow induced vibration of nuclear fuel rods in axial turbulent flows.
- Fluid-structure interaction simulations of strongly coupled problems.
- Assessment of partitioned coupling algorithms and discretization schemes suitable for strongly coupled FSI problems.
- Checking the effect of the use of different URANS models to simulate Turbulence Induced Vibrations.
- Validating the results obtained from the URANS models to experimental test cases.

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ABSTRACT

Flow induced vibration (FIV) plays an important role in nuclear industry. In nuclear reactors, the FIV are caused by a strong interaction between the fuel rods and the turbulent coolant flow around these rods. Numerical prediction of these strongly coupled fluid structure interaction (FSI) has been a challenge and is the main focus of this work. In this article, three aspects of FSI problems are numerically studied. In this first part, two different coupling schemes namely IQN-ILS and Guess-Seidel are thoroughly assessed for a laminar flow single rod experiment performed by Vattenfall (Lillberg et al. 2015). As a next step, a turbulent flow single rod experiment is selected to assess the capabilities of two different RANS models, i.e. a linear $k-\omega$ *SST* and a non-linear Reynolds Stress Model. Lastly, an application based experiment of Chen and Wambsganns (1972) is selected to validate the combined effect of the selected RANS model along with the coupling method.

1. Introduction

In nuclear power plants, flow induced vibration (FIV) may cause fatigue problems, stress corrosion cracking, possible failure modes and fretting wear (Luk, 1993). This may eventually leads to nuclear safety issues and substantial standstill costs due to unplanned outage. Reports of flow-excited failures of heat exchanger tubes began appearing in the 1950s (Weaver et al., 2000). As was the case for the San Onofre Nuclear Generation Station, where FIV led to premature wear in over 3000 tubes, causing a leak of radioactive coolant in recently renewed steam generators in Units 2 and 3. The increase in power density of nuclear plants often results in an increase of coolant flow, or a change of cooling liquid, or a change in the component material or dimensions. These changes may alter the flow and structural behavior, and cause flow-induced vibrations to become more prominent (Weaver et al., 2000). It is therefore important to asses this phenomenon early in the design process. Because of this, the field of FIV is becoming an increasingly important area of research in the nuclear field.

To correctly predict the FIV, a number of analytical models have been developed. However, these models are developed for slender bodies in axial flow by decomposing the fluid forces into an inviscid and viscous part. The contributions of these inviscid forces were first derived by Lighthill (1960), while the viscous forces were based on empirical relations, obtained from experiments on specific cases. The downside being the lack in accuracy when applied to other or less simplified cases. In a nuclear power plant, the use of high-density moderators leads to a low density ratio between the densities of the solid (ρ_s) and the fluid (ρ_f). Due to the high density fluid, the inertial forces that interact with solid bodies are of a higher order of magnitude. The high inertial forces have a direct effect on the dynamic behaviour of the solids, resulting in a strong coupling between fluid and the in-core structural elements. This phenomenon is also known as the Added-Mass Effect. When the

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added-mass effects are high, the coupling gets stronger, and hence, it is more viable to solve the problems numerically. Numerically simulating strongly coupled problems require a coupling between such fluid and structure solvers.

Fluid-Structure Interaction (FSI) problems can be numerically solved either by monolithic or the partitioned approach. The Monolithic approach solves the fluid and solid equations simultaneously as one set of equations, which can solve fully coupled problems. These solvers are problem specific and implementation of a new code could be required depending on the simulation. On the other hand, partitioned approach makes use of existing fluid and solid solvers which are coupled through an external coupling algorithm. Thus, this provides more flexibility and reliability in terms of the used solvers. The coupling algorithm for a partitioned solver acts as a post-processing step for each solver (solid and fluid), it iterates between the data inputs and outputs from the solvers till the required conditions are satisfied. Since the fluid and solid equations are solved separately, the coupling algorithm introduces a coupling error within the solution. For loosely coupled problems partitioned approach is very efficient, since the coupling errors involved are very low. However, most FSI problems faced in nuclear applications are strongly coupled. When dealing with strongly coupled problems, it is shown that partitioned solvers suffer from poor convergence or even instability, therefore a strongly coupled method is often necessary (Causin et al., 2005; Yang et al., 2008; Banks et al., 2014; Degroote, 2013).

With the progress in numerical methods, there have been several methods that have been introduced in the past, which can solve strongly coupled problems. In this study, two of these coupling algorithms, i.e. IQN-ILS and Gauss Seidel, are assessed for strongly coupled cases. The Gauss Seidel method is one of the earliest and a popular coupling scheme used in FSI solvers. Although, this method is simple and efficient in most of the cases, it has its own drawbacks, which would be discussed further in this article. The IQN-ILS is a Quasi-Newton method, which estimates the inverse Jacobian to attain the faster convergence. This is a state of the art coupling algorithm, which has shown better performance in some earlier studies (Degroote, 2010; Degroote, 2013; Banks et al., 2014). One of the aims of the present study is therefore to validate the capabilities of both the coupling methods to solve the strongly coupled problems. As a next step, one of these tested methods in combination with a turbulence model is used to predict flow induced vibrations. The description of these used coupling methods is given in Section 2. This is followed by the results and discussions related to the selected validation and the application cases in Section 3. The conclusions drawn from these test cases are summarized in Section 4.

2. Numerical methods

In a partitioned approach, the fluid and solid equations are solved with different numerical methods. The fluid domain is solved using a computational fluid dynamic (CFD) method and the solid using a computational solid mechanics (CSM) method. To be able to model the interaction of these two models, the two methods are coupled at the fluid-solid interface. A stable and efficient numerical technique is essential for the study of FSI. In the case of strongly coupled interaction, the solvers are called multiple times during a time step until both the kinematic and the dynamic equilibrium conditions are satisfied.

2.1. Governing equations of fluid

The Navier-Stokes (N-S) equations, govern the flow of fluid. The two main equations for an incompressible fluid in the N-S equations are the conservation of mass and momentum. The mass and momentum conservation equations are given by Liu et al. (2013):

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho_f\left(\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j}\right) = \nabla \cdot \sigma_f + \mathrm{f}_f \tag{2}$$

with, u being the fluid velocity, ρ_f the fluid density, t the time, σ_f the fluid stress tensor and **f** is the body force. For Newtonian fluids, the stress tensor can be written as:

$$\sigma = -p\mathrm{I} + \mu\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] \tag{3}$$

with, p the pressure and μ the fluid dynamic viscosity.

2.2. Governing equations of solid

The deformation of an elastic incompressible solid is governed by the conservation of momentum:

$$\rho_s \frac{\partial^2 \mathrm{d}_s}{\partial t^2} = \nabla \cdot \sigma + \mathrm{f} \tag{4}$$

with, d_s being the displacement of the structure, ρ_s the solid density, σ the solid stress tensor and f the body forces.

2.3. Coupling between the fluid and solid equations

At the interface between the solid and the fluid, the kinematic condition requires the velocity of the fluid to be equal to the time derivative of the displacement of the solid interface:

$$\frac{\partial \mathrm{d}_s}{\partial t} = u_f \tag{5}$$

The dynamic condition requires the stress on the interface due to the fluid and solid surface normal to be equal, also called as equality of traction:

$$\sigma_s \cdot \mathrm{n}_s = -\sigma_f \cdot \mathrm{n}_f \tag{6}$$

The subscript s and f depicts the structural solver and fluid respectively. When using a Dirichlet-Neumann decomposition, the flow equations can be solved for a given velocity (or displacement) at the fluid-structure interface (Dirichlet boundary condition), and the solid equations are solved for a given traction distribution on the interface (Neumann boundary condition). Assuming, the displacement vector as, $\mathbf{x} = \mathrm{d}_s$ and traction as $\mathbf{y} = \sigma_f \cdot \mathrm{n}_f$, the response of the structure solver can be therefore written as:

$$\mathbf{x} = S(\mathbf{y}) \tag{7}$$

where $S(\mathbf{y})$ is the function resolving the structure equations (Eq. (4)). Similarly, for fluid solver:

$$\mathbf{y} = F(\mathbf{x}) \tag{8}$$

where $F(\mathbf{x})$ is the function resolving the fluid equations (Eqs. (1) and (2)). At each time step, the fixed point equation must be satisfied

$$\mathbf{x} = S \circ F(\mathbf{x}) \tag{9}$$

where $S \circ F(\mathbf{x}) = S(F(\mathbf{x}))$. Therefore, the residual function, $R(\mathbf{x})$ is calculated as

$$R(\mathbf{x}) = S \circ F(\mathbf{x}) - \mathbf{x} \tag{10}$$

To reach convergence, this residual should be minimized, which can be done using an optimization algorithm. Well known approaches in FSI are the Gauss-Seidel method, fixed under-relaxation, Aitken under-relaxation, and the IQN-ILS method (Degroote, 2013).