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Numerical investigations on flow-induced vibration of fuel rods with spacer grids subjected to turbulent flow

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ABSTRACT

Fuel rods, one of the most important parts in the nuclear reactor core, are usually supported by spacer grid along the axial flow direction. Since those fuel rods are surrounded by high-velocity coolant, vibration will be induced, termed flow-induced vibration (FIV). The resulting oscillations may cause abrasion of the cladding, known as fretting wear. In order to predict this fretting wear more accurately, it is essential to study the vibration characteristics. In this paper, numerical simulation is carried out to investigate the interaction of fuel rods embedded in a spacer grid with mixing vane subjected to strong turbulent flow. The flow-induced vibration of fuel rods and the surrounding components are analyzed and reported in detail. It is found that the vibration is dependent on several parameters, such as wall shear forces and pressure. However, the fluid force acting on the fuel rod is mostly due to the pressure. The flow velocity has a significant influence on the flow-induced vibration in axial turbulent flow. The vibration of fuel rod is very weak when the flow velocity is low. The numerical method applied in this paper can be used to predict the vibrations of the fuel rods accurately and this will be useful for the further fretting wear evaluating, which should be helpful in the design of fuel assemblies.

1. Introduction

Nowadays nuclear reactor becomes more and more popular due to the increase of the pollution problem and the decrease of limited energy source of fossil fuel. However, fluid-structure interaction (FSI) phenomenon can occur in many components of nuclear power plants, such as steam generators, rod bundles and so on. The fuel rods in the pressurized water reactor (PWR) would vibrate induced by the coolant flowing through the fuel assemblies (Kim et al., 2008). This vibration of the fuel rods generate small amplitude (Paidoussis, 1981), which is mainly resulted by turbulence-induced excitation. Fluid-induced vibration (FIV) has an important effect on the safety and economical of nuclear power plants. FIV can cause fatigue damages in the fuel rods or induce grid-to-rod fretting wear (Blau, 2014). Radioactive material can be released due to prolonged fretting wear (Paidoussis, 2004). Therefore, understanding the non-linear vibration response of the fuel rods subjected to axial flow is fundamental to predicting the fretting wear.

The study of vibration induced by axial flow is a relatively new phenomenon and has not been seriously treated until 1950s (Paidoussis, 2004). However, this phenomenon has got more and more attentions because of its important application in nuclear industry (Liu et al., 2012a). Burgreen et al. (1958) made an initial study on vibration problems of fuel rods, which were induced by coolant axial flow. According to the recent published publications, it is obviously observed that the rod can experience random vibration. Paidoussis (1966a) investigated a linear model, which was applied to study the dynamic of a single cylinder in axial flow. They found that the cylinder would suffer from instabilities with the increase of velocity. Also, their linear model agreed well with experiment (Paidoussis, 1966b). Then, this model was used for multi-cylinders in a cluster. However, the result remarkably showed that it was different from the single cylinder (Paidoussis and Gagnon, 1984). In the experimental aspect, Au-Yang and Jordan (1980) measured the wall-pressure fluctuation around a fuel rod in a laboratory reactor. From 1975 to 1980, Kim and Stoudt (1975), Spore (1978), and Marek and Rehme (1979) had made a lot of assumptions and studies on the establishment of flow-induced vibration model. With the further study of the vibration mechanism, the forced vibration results from various sources, such as unsteady transverse flow or turbulence kinetic energy and so on. Curling and Paidoussis (1992) developed an analytical model for vibrations of cylinders in turbulent parallel flow. However, the results of model analysis are not agreement well with the experimental data. Based on Hamilton's principle, Lopes et al. (2002), Paidoussis et al. (2002) and Semler et al. (2002) firstly study the non-linear dynamics of cylinders in axial flow systematically. A described

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Nomenclature

υ	velocity
p	pressure
t	time
τ	stress tensor
w	velocity relative to the reference frame
ρ_s	density of solid
σ_s	stress tensor of solid
d_l	lateral displacement
f_s	forces loading on the surface of the solid
$\ddot{d}_s$	local acceleration vector of the solid
d_l	lateral displacement
d_a	axial displacement
d_x	displacement of the fuel rod in x direction
d_y	displacement of the fuel rod in y direction
d_z	displacement of the fuel rod in z direction
d	total displacement of the fuel rod
x_i	displacement of the fuel rod at the *i* time during vibration
d_f	displacements of the fluid
d_s	displacements of the solid
n_f	unit vector of fluid
n_s	unit vector of solid
D_h	hydraulic diameter
u_i	displacement of structure
L	length of the fuel rod
N	total number of data
V	inlet velocity

Greek symbols

Δt	time step
ξ	dimensionless axial coordinate of the fuel rod
ρ	density

Subscript

f	fluid
s	solid
h	hydraulic

nonlinear theory is the prediction of divergence amplitudes, and that is to be, how these vary with flow and many other quantitative factors of dynamical behavior. Then, Karagiozis et al. (2008) thought that cylinder in axial flow is susceptible to fluid-elastic instability. It has been a difficult problem to study the mechanism of flow-induced vibration in axial flow. Therefore, it is very useful to use computational fluid dynamics (CFD) to solve the all-known difficulties in vibration experiments, especially in the fluid-solid coupling models. Computational Fluid Dynamics (CFD) rapidly becomes an important analysis tool for fluid-induced vibration. Karoutas et al. (1995) was the earliest user to use CFD to study flow-induced vibrations in the nuclear field. Imaizumi et al. (1995) used the CFD program to calculate the three-dimensional flow field of a PWR fuel rod bundles. Most of CFD works are beginning to concentrate on the vibration characteristics in the fuel rod with the spacer grids in axial flow.

Most of the research works focused on the vibration mechanism of rods in the axial flow. In fact, spacer grids not only affect the surrounding fluid field but also have a strong influence on the dynamic response of the fuel rods. The spacer grid design adopted a better thermal performance, however it makes the flow more complex, which may generate stronger vibration. There are few studies which involves the vibration responses of rods in complex flow field. For the vibration of fuel elements in reactors, most researches conducted to date focused on the vibration which were induced by fluid-elastic instability and turbulence in axial flow. However, there is no further analysis of the vibration mechanism which is associated with some specific parameters. The object of this paper is to compute fluid-induced vibration of fuel rods with spacer grids in turbulent axial flow through the numerical approach. Compared to experiments such as fluctuation pressure, wall shears, and RMS displacement etc., it shows that more vibration response parameters can be obtained through the simulation. The influence on vibration mechanism was analyzed by the simulation results. In turbulent axial flow, the dynamic response of rod is researched, which lays a foundation for further study on fretting wear. All in all, the key goal of this research is to provide some key guidelines of fuel assembly and design an optimization way to eliminate of wear and surface damage.

2. Numerical method for fluid-structure interaction (FSI) problem

2.1. Governing equations

For FSI problems, the governing equations of both fluid and structure are required to solve simultaneously. The fluid domain and the deformation of solid interact with each other. Therefore, an arbitrary Lagrangian-Eulerian (ALE) description of the flow governing equations was adopted for prediction of the response of fluid-structure interaction systems (Donea et al., 1982). In this study, the fluid is assumed as incompressible Newtonian fluid. Then the governing equations for the fluid flow could be described by the following equations (Hughes et al., 1981):

$$\begin{cases} \nabla\cdot\upsilon = 0 \\ \frac{\partial p}{\partial t} = (w-\upsilon)\cdot\nabla\rho-\rho\nabla\cdot\upsilon \\ \rho\left(\frac{\partial\upsilon}{\partial t}\right) = \rho(w-\upsilon)\cdot\nabla\upsilon + \nabla\cdot\tau-\nabla p \end{cases} \tag{1}$$

where υ is velocity, p is the pressure. ρ, t and τ are the density of fluid, time and stress tensor. w is the velocity relative to the reference frame.

In this study, the structure is assumed to be an elastic solid. So the governing equation of the structure satisfies Newton's second law, which is

$$\rho_s\ddot{d}_s = \nabla\cdot\sigma_s + f_s \tag{2}$$

where ρ_s is the density of the solid, σ_s is the solid stress tensor, f_s is the forces loading on the surface of the solid, and $\ddot{d}_s$ is the local acceleration vector of the solid domain.

FSI problems comply with the basic conservation principle, so there also should be conservative at the fluid-solid interface. At the fluid-solid interface, the kinematic condition requires that the displacement of the fluid is equal to the displacement of the solid; 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 (Ter Hofstede et al., 2017):

$$\tau\cdot n_f = -\sigma_s\cdot n_s d_f = d_s \tag{3}$$

where d_f and d_s are the displacements of the fluid and solid domain, respectively. n_f and n_s are the unit vector, respectively.

2.2. The fluid-structure interaction solver

The numerical scheme of fluid-structure interaction was studied by several investigators. FSI problems can be solved by different approaches (Ter Hofstede et al., 2017). Those approaches can be classified into two types: monolithic approach and partitioned approach (Hou et al., 2012). Hron and Turek (2006) proposed a method of solving the