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Analysis of flow-induced vibration of steam generator tubes subjected to cross flow

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HIGHLIGHTS

- The dynamics of tubes subjected to cross flow is investigated.
- A three-dimensional CFD model, coupled with a structural model is obtained.
- The relationship between pitch and displacement for two tubes is analyzed.
- The mutual influence of two contiguous tubes in cross flow is discussed.

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ABSTRACT

Flow-induced vibration of PWR steam generator tubes is one of the key problems to be considered in nuclear engineering. In this paper, the dynamics of tubes subjected to cross flow is investigated. A fully coupled model for fluid dynamics and structure is used to analyze this fluid–structure problem. The study begins with an analysis of a single tube subjected to cross flow, and the dynamics and flow patterns of the system are investigated. Time trace, power spectral density (PSD), phase-plane plot and Poincaré map are used to characterize the motion of the tube. Then, the dynamical behaviours of two tubes with in-line and parallel configuration are studied, and the mutual influence of the two tubes is analyzed. The relationship between pitch-to-diameter ratio and non-dimensional displacement for two contiguous tubes is investigated. Finally, the interactions within a 3 × 3 tube bundle in cross flow, and the vibration responses of the 9 tubes are investigated.

1. Introduction

Fluid–structure interaction (FSI) is one of the important problems of steam generators in nuclear power plants. The tubes of steam generators, which undergo a cross flow, are highly susceptible to flow-induced vibration (FIV). The vibration may lead to fretting wear on the contact surface of tubes with supporting plates. The evaluation of this flow-induced vibration is involving on the fluid dynamics calculation for the flow characteristics and the structural analysis.

The conditions leading to vibration of tubes subjected to cross flow have been investigated extensively in the past years. A bulk of experimental and theoretical studies have been carried out to investigate the vibration characteristics of tubes with various configurations subjected to cross flow. Connors (1970) proposed the earliest model to evaluate the flow-induced vibration of the steam generator tubes. Cheng and Finnie (1996) derived an equation of motion of tubes subjected to an uniform cross flow, and then predicted the vibration response of tubes and fluid dynamic forces. Fournier et al. (2007) simulated fluid flow in a pressurized water reactor (PWR) core. Cui et al. (2008) adopted direct method to investigate fundamental characteristics of flow-induced vibration and stabilities of parallel-plate fuel assemblies in cross flow. Hassan and Hayder (2008) conducted a time-domain model to calculate the critical flow velocity and tube-support interaction force. Sigrist and Broc (2008) and Kuehlert et al. (2008) used Homogenization

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Nomenclature

C	damping matrix
D	tube diameter
D_i	tube inner diameter
D_o	tube outer diameter
E	Young's modulus
F	fluid load
K	stiffness matrix
L	tube length
M	mass matrix
P	pressure
P_x	X-directional pitch
P_y	Y-directional pitch
Re	Reynolds number
t	time
u, v, w	velocity components
U	inlet fluid velocity
y	Y-directional displacement of tube

Greek symbols

μ	fluid viscosity
ρ_f	fluid density
ρ_s	solid density

method to investigate FSI effects on steam generator tube bundles. Prakash et al. (2009) analyzed modal frequencies of tube bundle induced by cross flow in heat exchangers. Park et al. (2009) suggested an indirect input force estimation theory to calculate turbulence flow induced force exerted on fuel rods in a PWR.

Owing to the improvement in computational theory, various numerical approaches have been adopted to evaluate FSI effects of tubes in cross flow. Eisinger et al. (1995) created a numerical model of tube bundle, coupled with a finite element solver to simulate the flow-induced vibration. Longatte et al. (2003) suggested a fully coupled method with periodic boundary conditions to simulate the dynamical behaviour of a tubes in cross flow. Kim and No (2004) used Large-Eddy Simulation (LES) to investigate the characteristics of a realistic 4×4 and 5×5 cylinders in cross flow. Kim and Mohan (2005) validated LES model, and calculated the forces on a tube in high Reynolds number cross flow. Oakley et al. (2005) used Detached-Eddy Simulation (DES) to simulate a full FSI of single tube in high Reynolds number cross flow. Ahn and Kallinderis (2006) adopted arbitrary Lagrangian–Eulerian (ALE) to investigate characteristics of a tube in cross flow. Kim and Choi (2006) conducted a new immersed boundary method (IBM) to simulate the flow pattern and dynamical behaviour of a tube subjected to cross flow. Borazjani et al. (2008) adopted a strong coupled model to analyze vibration of tubes undergoing arbitrarily large deformation in cross flow. Lee et al. (2010) developed a modified immersed finite element method (IFEM) to assess vibration characteristics of tubes in cross flow. Simoneau et al. (2010) used LES, coupled with subgrid approach to investigate FSI model. Simoneau et al. (2011) used a fully coupled approach to further improve the assessment of fluid structure interaction problems, and analyzed the vibration response of tubes subjected to cross flow.

In the present paper, a three dimensional fully coupled model is adopted to analyze the fluid flow through tubes, and the vibration characteristics of tubes. The dynamics of a single tube subjected cross flow, and the velocity contours are first investigated. Time trace, power spectral density (PSD), phase-plane plot, and Poincaré map are used to analyze the dynamical behaviour of the tube. Then, the dynamical behaviours of two in-line tubes and two parallel tubes, the velocity contour and the mutual influence of two tubes are studied; the relationship between the pitch-to-diameter ratio and the non-dimensional displacement for two contiguous tubes is investigated. Finally, the interactions within a 3×3 tube bundle, the dynamical behaviours of 9 tubes, and the velocity contour are investigated.

2. Mathematical models

In this study, a three-dimensional CFD model with a moving grid is proposed, and the fluid force acting on tubes is numerically simulated using the CFD code CFX-14.0, which utilizes a cell-vertex pressure based finite volume formulation.

The CFD code employs an Arbitrary Lagrangian–Eulerian (ALE) formulation and a moving/deforming mesh model to simulate the boundary motion. In the CFX model, diffusion transport equations are used to smoothly propagate motion at boundaries into the solution domain, and preserve the existing boundary layer meshes.

2.1. The CFD model

The basic transport equations for fluid flow are the continuity and the momentum equations. For incompressible viscous flows, the continuity equation is defined as

$$\nabla \cdot U = 0, \tag{1}$$

and the momentum equation is defined as

$$\rho_f \left(\frac{\partial U}{\partial t} + U \cdot \nabla U \right) - \mu \nabla^2 U + \nabla P = F, \tag{2}$$

where $\triangledown$ is the divergence operator, ρ_f is the fluid density, U is the velocity vector (u, v, w), t is the time, μ is the fluid viscosity, P is the

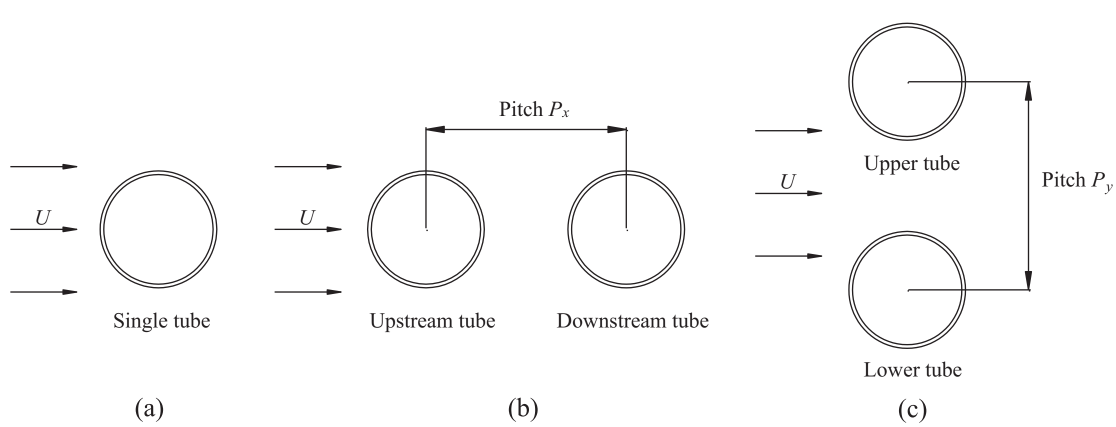

Fig. 1. Schematics of tubes subjected to cross flow: (a) single tube, (b) two in-line tubes, (c) two parallel tubes.