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Analyses of fluid-solid coupling dynamics of elastic tubes vibrating in cross flows

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ABSTRACT

Treatments on dynamic interfaces and fluid-solid coupling are critical in systems of tubes vibrating in fluids that are common in tube-strings of deep-water oil drilling systems, marine cluster wells and heat exchangers. This paper proposes a "weakly" coupled algorithm for modeling vortex induced vibrations of elastic tubes submerged in cross flows. In the present algorithm, the elastic tube is discretized with beam elements and the fluid is discretized with volume elements, and the grids for both the tube and fluid is perfectly marched on the interface. Using the shape functions of beam elements, the formula for displacement, velocity, and force approximations are carried out, and convergence criterion analyses are also performed for the fluid-solid coupling interfaces. The present weakly coupling algorithm is developed with a sub-iteration loop to ensure accuracy in handling the dynamic coupling between the elastic tube and fluid. The vortex-induced vibrating characteristics are then analyzed for various elastic tubes at different natural frequencies. Intensive numerical studies are also conducted to examine the effects of the ratio of the elastic tube's natural frequency to the static flow's frequency. It is found that the change of frequency ratio has less effect on the fluid pressure and velocity distributions on the surface of the elastic tube, but more effects on the vibration of the tube. When the frequency ratio is less than 1.009, the vibrating amplitude, period and trajectory of elastic tube decrease with the increase of frequency ratio. While if the frequency ratio is more than 1.009, the vibrating amplitude, period and trajectory are almost unchanged and the elastic tube behaves similarly to a rigid tube. It is also found that there is a critical frequency ratio for a vortex-induced vibration to occur for tubes in cross flows. This finding is important for the prevention of violent vibrations of tubular structures in flows, such as deep-water oil drilling tube-strings, marine cluster wells and heat exchangers.

1. Introduction

Tubular structures are common slender and elastic structures used in engineering systems, such as oil and gas drilling systems, marine cluster wells and heat exchangers, as shown in Fig. 1. Because such slender tubes are often long and submerged in cross flows of the surrounding fluid, it may induce violent vibrations, which can even cause failure.

At present, numerical simulation and experiment are the two main research methods in studying vibrations of tubes in flows. Lai et al., 2005, 2006 applied computational fluid dynamics software Ansys/Flotran CFD to simulate the flow around a circular tube with fixed and elastic supports, and tubes with internal and external fluids. The vortex shedding induced vibration characteristics of circumfluence were studied for circular tubes. Wu et al. (Wu et al., 2013) established a three-dimensional fluid-structure coupling vibrating model using rigid motion equations and the Newmark integration method. The rule of fluid elastic instability was studied for tube bundle with square arrangement. Based on the moving grid, Ichioka (Ichioka et al., 1997) studied fluid elastic vibration for a heat exchanger in 1997 and analyzed the vibrating regularity of two tubes. Hassan and Hayder (2008) simulated fluid elastic vibration of tube bundle in a heat exchanger using the finite element method. Khulier, Al-Kaab et al. (Khulief et al., 2009) applied a node element method and the MATLAB finite element program to simulate fluid elastic vibration of a heat exchange tube. The vortex-induced vibration of elastic beams with fixed bottom was studied by Oviedo-Tolentino (Oviedo-Tolentino et al., 2014). Feng et al. (Feng et al., 2013a,b,2014) combined with dynamic grid control

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(a) (b)

Fig. 1. Tubes in engineering applications: (a) marine risers, (b) a typical heat exchanger.

technology to analyze the interaction between structure and fluid for elastic tubes using the finite volume method (FVM) and finite element method (FEM). The above-mentioned researches (Ni et al., 2015; Paidoussis and Semler, 1993; Wadham-Gagnon et al., 2007) have made great progress in the vortex induced vibration for circular tubes and heat exchangers. However, in all finite element method models, the elastic tube and fluids were discretized with solid elements, which required large CPU memory space and computer time. It is thus difficult to complete full scale studies on vibrating mechanism for more complex structures in fluids.

In this study, a hybrid FEM/FVM model is created to study the vortex-induced vibrations of tubes in flows in a cylindrical container. We take the full advantage of the slenderness of the tubular structure, the elastic tube is discretized with beam elements and FEM is used. Only for the bulky fluid in the cylindrical container, volume elements and FVM are used. Therefore, the number of elements is greatly reduced, enabling intensive studies on vortex-induced vibrations. In our beam-volume element model, a "weakly" coupled algorithm is developed for the elastic tube with cross flows of the surrounding fluid. Using the established beam-volume element model and the present weakly coupled algorithm, the vortex-induced vibrating characteristics are analyzed for tubes at different natural frequencies. Studies have also conducted to validate the present weakly coupled algorithm for vortex-induced vibrating problems. Our beam-volume element model and the present weakly coupled algorithm will provide an effective computational method for simulating vibrations of multiple bundles in complex flows.

In section 2, the vibration experiment device is designed and described for the tube in a cylinder and the acceleration curve of elastic tube is acquired by GWT-2B-axis accelerometer. A model with an elastic tube submerged in a cylindrical container is established in Section 3 and it proposes a "weakly" coupled algorithm for modeling vortex induced vibrations of elastic tubes submerged in cross flows. In section 4, studies have also conducted to validate the present weakly coupled algorithm for vortex-induced vibrating problems. The vortex-induced vibrating characteristics are then analyzed for various elastic tubes at different natural frequencies.

2. Experiment

2.1. Experimental apparatus

As shown in Fig. 2, according to geometric similarity and kinematic similarity, the vibration experiment device is designed for the tube in a cylinder. The size of the cylinder is: the length is 1.8 m; the outer diameter is 1.5 m. The size of the elastic tube is: the length is 2.0 m, the outer diameter is 20 mm and its wall thickness is 2 mm. Its circulatory system is shown in Fig. 3. The fluids are delivered into the tube from tank 5 by pump 4. Through valve 3, the fluid is flowing into inlet *a* and *b*. The valve 3 is used to adjust the fluid velocity.

As shown in Fig. 4, the test instrument is a GWT-2B biaxial acceleration sensor, which is placed at the midpoint of the tube axis. The size is $\Phi 12 \times 21$ and the frequency is in the range of 0–400 Hz. The installation step is as following: firstly, the sensor is placed on the sensor holder. Secondly, the slender wire is penetrated into the sensor socket. Finally, the sensor is imported into the plexiglass tube by the slender wire and rotated to the correct position.

2.2. Experimental procedures

Before experiment, the inlet velocity can be changed by adjusting the opening and closing of the reducing flange. The reducing flange can be fully closed, half open and fully open. The calculated method of inlet velocity is as follows: close the cylinder outlet, then open the reducing flange and record the time of the fluid filling the entire cylinder, the inlet velocity can be calculated according the cylinder volume at last. The inlet velocity is 1.381 m/s, 1.841 m/s, and 2.236 m/s when the reducing flange is in the state of fully closed, half open and fully open, respectively.

During the experiment, the elastic tube is placed in the cylinder. When the fluid level is stable in the container, the vibration acceleration of the elastic tube is collected by GWT-2B biaxial acceleration sensor (Fig. 4).

Seen in Fig. 5, the inlet flow velocity is 2.236 m/s and the experiment is carried out when the frequency ratio of the tube is 1.407 (E = 3.5 GPa). Using GWT-2B-axis accelerometer to monitor the vibration, the acceleration curve of elastic tube is finally acquired.

3. Coupled modeling and algorithm

3.1. Modeling of fluid-solid coupling

Consider a simplified problem of an elastic tube submerged in a fluid in a cylindrical container, as shown in Fig. 6. To induce a cross flow, two openings are created on, respectively, the top and bottom surfaces of the cylindrical container. The model is divided into two domains, structural domain Ω_s and fluid domain Ω_f. The inlet boundary of the fluid (on the top opening) denoted by $\Gamma_D^{f(1)}$ is prescribed with flow velocity *u*. The boundary of the fluid on the container inner wall surface denoted by $\Gamma_D^{f(2)}$ is set as free-slip condition. The outlet boundary (on the bottom opening) denoted by Γ_N^f is set with given pressure *p*. The interface between the fluid and the solid is denoted by Γ_N^f, where a fluid-solid coupling condition is set.

Assume that the cross section of the elastic tube is circular with uniform thickness. We use a hybrid FEM/FVM method to solve the dynamic problem considering the coupling effects of the tube and the cross flow. If the elastic tube and the fluid in the cylindrical container are both discretized with a number of solid elements, the model would