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Time domain simulation of vortex-induced vibrations in stationary and oscillating flows

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ABSTRACT

This paper focuses on the further development of a previously published semi-empirical method for time domain simulation of vortex-induced vibrations (VIV). A new hydrodynamic damping formulation is given, and the necessary coefficients are found from experimental data. It is shown that the new model predicts the observed hydrodynamic damping in still water and for cross-flow oscillations in stationary incoming flow with high accuracy. Next, the excitation force model, which is one component of the total hydrodynamic force model, is optimized by simulating the VIV response of an elastic cylinder in a series of experiments with stationary flow. The optimization is performed by repeating the simulations until the best possible agreement with the experiments is found. The optimized model is then applied to simulate the cross-flow VIV of an elastic cylinder in oscillating flow, without introducing any changes to the hydrodynamic force modeling. By comparison with experiment, it is shown that the model predicts the frequency content, mode and amplitude of vibration with a high level of realism, and the amplitude modulations occurring at high Keulegan–Carpenter numbers are well captured. The model is also utilized to investigate the effect of increasing the maximum reduced velocity and the mass ratio of the elastic cylinder in oscillating flow. Simulations show that complex response patterns with multiple modes and frequencies appear when the maximum reduced velocity is increased. If, however, the mass ratio is increased by a factor of 5, a single mode dominates. This illustrates that, in oscillating flows, the mass ratio is important in determining the mode participation at high maximum reduced velocities.

1. Introduction

Slender structures such as pipelines and risers experience vortex-induced vibrations (VIV) when exposed to external fluid flow (Blevins, 1990). The vibrations are a result of the fluctuating lift and drag forces associated with flow separation and vortex shedding. Depending on the incoming flow and structural properties, significant dynamic stress may occur, causing fatigue damage accumulation which over time may lead to structural failure. Understanding and being able to predict VIV in realistic environmental conditions is therefore important to ensure the safety of slender structures.

A considerable amount of work has been done to increase the understanding of VIV, as reflected in the reviews by Sarpkaya (2004), Williamson and Govardhan (2004), Bearman (2011) and Wu et al. (2012). As the equations of motion governing viscous flow are difficult to solve, experiments have been the most important source of new insight. Examples of

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typical experiments are free vibration of elastically mounted rigid cylinders (Feng, 1968; Vikestad, 1998; Govardhan and Williamson, 2000; Jauvtis and Williamson, 2004) and cylinders undergoing forced motions (Sarpkaya, 1978; Moe and Wu, 1990; Morse and Williamson, 2009; Aglen and Larsen, 2011; Yin and Larsen, 2012). Experiments with long flexible structures have also been performed, both under controlled laboratory conditions (Chaplin et al., 2005; Trim et al., 2005; Huera-Huarte et al., 2014) and in field environments (Huse et al., 1998; Vandiver et al., 2006). These experiments focused on various flow situations such as uniform, sheared and stepped current, and in all cases the incoming flow was essentially stationary, i.e. constant in time.

In some situations, the relative current velocity may be non-stationary, either due to movement of the structure or oscillations in the incoming flow itself. For example, a riser connected to a floating platform will oscillate as a result of the wave-induced motions of the floater. The relative flow velocity caused by the riser moving back and forth in the water may cause vortex shedding and VIV if the motion amplitude is sufficiently large. VIV of an elastic cylinder in oscillating flow was studied experimentally by Fu et al. (2014). They found that the structure vibrated significantly due to vortex shedding, and noted some important differences compared to stationary flow VIV. For instance, they observed a characteristic developing process with vibrations continuously building up and dying out. VIV of spring mounted rigid cylinders in oscillating flow has previously been studied by several researchers such as Sarpkaya (1979) and Sumer and Fredsøe (1988).

In light of these experimental studies, and the fact that oscillating flows are relevant in several practical applications, the need for a mathematical model able to predict VIV in oscillating flows becomes evident. One possibility is to solve the Navier-Stokes equations numerically, but the required computational effort is generally large. The semi-empirical frequency domain methods VIVA (Triantafyllou et al., 1999), SHEAR7 (Vandiver and Li, 2005) and VIVANA (Larsen et al., 2009) are more efficient, but can only predict VIV in stationary flows. As illustrated by Chang and Isherwood (2003), the wake-oscillator can be used to simulate VIV in time domain for unsteady flow situations, but no comparison with experiment was included in this study. Liao (2001) was able to predict VIV in unsteady flow based on a relationship between an equivalent reduced damping and the resulting vibration amplitude. Recently, Resvanis (2014) proposed a dimensionless parameter which can be used to determine if the response in unsteady flow will be similar to the response in steady flow.

An alternative method for simulating VIV in time domain was proposed by Thorsen et al. (2014). In this semi-empirical method, the fluid forces are calculated based on the incoming flow velocity and the motion of the cross-section. The special feature is how synchronization between the vortex shedding and cylinder motion is taken into account. It has been shown that the model provides realistic results for several different cases, including flexible cylinders in uniform, sheared and stepped current (Thorsen et al., 2014b; Thorsen et al. 2015). The formulation includes no restriction on the time variability of the incoming flow velocity, which means it is theoretically suited for simulating VIV in oscillating flows. With this in mind, the outline of the present paper is as follows: Firstly, the original model (Thorsen et al., 2014) is slightly modified to improve the prediction accuracy in stationary flows. Secondly, the improved model is used to simulate a flexible cylinder in oscillating flow. The experiment by Fu et al. (2014) is used for comparison, allowing for direct assessment of the prediction accuracy. Finally, the model is used to explore the effect of changing certain key parameters. For instance, the reduced velocity is increased beyond what was considered in the actual experiment, resulting in the appearance of complex vibration patterns.

2. Time domain VIV model

2.1. Hydrodynamic force model

A stationary cylinder in an incoming undisturbed flow is subjected to time varying forces. The force component parallel to the flow is called drag, while the perpendicular component is named lift. Due to the vortex shedding process, the lift force oscillates with a frequency $f_s = \mathrm{St}U/D$ called the Strouhal frequency, where D is the cylinder diameter and U is the velocity of the flow. The Strouhal number St is generally a function of the Reynolds number and the surface roughness of the cylinder, but in the subcritical Reynolds number range, St is nearly constant and close to 0.2 (Norberg, 2003). If the cylinder is flexible, it will vibrate as a result of the oscillating fluid forces, and the movement of the cylinder alters the surrounding flow and the corresponding fluid forces. One of the most important effects is that the vortex shedding may synchronize with the cylinder motion, such that the frequency of the lift force deviates from the expected Strouhal frequency. In addition, there will be fluid resistance (damping) and added mass effects due to the velocity and acceleration of the cylinder.

The hydrodynamic force model used here was first presented by Thorsen et al. (2014). Some minor modifications were introduced (Thorsen et al. 2015), providing the starting point for the present paper. In these previous studies, hydrodynamic damping was modeled using a linear and quadratic term, and the empirical coefficients were found by minimizing the difference between this model and the model given by Venugopal (1996). Although this was quite successful, a tendency to over-predict the cross-flow vibration amplitude in uniform flow and under-predict it in linearly sheared flow was seen (Thorsen et al. 2015), which indicates that the model can still be improved. With this in mind, a new damping model is developed here, using actual measurements to adjust the empirical coefficients. As the total energy transfer between fluid and structure is determined from the energy delivered by the vortex shedding process and the energy subtracted by the hydrodynamic damping, altering the damping model will require a change in the excitation model to ensure that the net power transfer is physically correct. This is addressed further in Section 3.