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DAMPING AND FLUID-STRUCTURE INTERACTION EFFECTS FOR A CYLINDER IN A CROSS FLOW

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ABSTRACT

Traditionally, fast Fourier transform (FFT) is used to analyse stationary time series in fluid mechanics research. This approach is inadequate when FFT is used to examine time series obtained from fluid/structure interaction studies. The reason is the difficulty of extracting damping information from a FFT analysis. This information is important to vibration studies. The present investigation proposed to used an approach based on the auto-regressive moving analysing (ARMA) identification technique to analyse the time series obtained from a numerical simulation of a uniform cross-flow past an elastic cylinder. Damping characteristics of the fluid/structure system as well as its natural frequencies for a number of elastic cylinders are examined. The results are very encouraging, even though experimental measurements are not available for verification.

INTRODUCTION

A common fluid-structure interaction problem is the flow-induced vibrations on bluff structures caused by vortex shedding from the structures. The induced vibrations are driven by the force fluctuations due to the vortex shedding, and the vortex shedding is influenced by the vibrations. The interactions between fluid and structure play an important role in determining the dynamical behaviour of the structures and the fluid motion. To correctly treat the coupling between the fluid and structure, whether in experimental research or in numerical simulations, it is crucial to be able to identify the important characteristics of the fluid/structure system, such as the damping and the natural frequencies. There has been a number of experimental studies on fully-coupled fluid-structure interaction problems, e.g. the experiments of Feng (1968), Griffin & Ramberg (1982) and Khalak & Williamson (1996). Various numerical approaches have also been proposed to tackle the same problem, such as a time marching technique proposed by Jadic *et al.* (1998), a vortex-in-cell (VIC) discrete method used by Zhou et al

(1998a) and a direct numerical simulation carried out by Newman & Karniadakis (1997). However, none of their studies has attempted to deduce damping characteristics from their results.

The aim of the present work is to use the ARMA technique (Mignolet & Red Horse, 1994) to analyse the time series of the forces and cylinder displacements which are obtained from the simulation for an elastic circular cylinder in a two dimensional cross-flow using the VIC discrete vortex method. The cylinder is allowed to vibrate in both x- and y-directions. The damping ratio and the natural frequencies of the fluid/structure system, and also the shedding frequency are examined in detail. The flow Reynolds number, *Re*, is kept at 200 for all calculations.

NUMERICAL METHOD

The VIC discrete vortex method is used to simulate a 2-D flow past an elastic cylinder. The VIC method represents the flow field by a large number of point vortices. The motion of the fluid is then solved through tracking the evolutions of the point vortices, which includes two procedures: the convection and diffusion. The velocity field for the convection is obtained by solving the Poisson equation for the stream function on a mesh, where the fluid at infinity is assumed to be uniform with a velocity U_∞ in the x-direction. Far downstream, the vorticity is set to zero. The diffusion is solved using a finite difference scheme on the same mesh. More details can be found in Zhou *et al.* (1998b). The cylinder motion is described by the equation,

$$\frac{d^2\bar{\chi}}{dt^2} + 2\alpha\omega_n\frac{d\bar{\chi}}{dt} + \omega_n^2\bar{\chi} = \frac{\bar{F}}{m}$$

where $\bar{\chi}$ is the displacement vector, α the structural damping factor, $\omega_n = 2\pi f_n$ and f_n is the natural frequency of the cylinder, $\bar{F}$ is the force and m is the mass per unit length of the cylinder. The equation is solved using the Runge-Kutta method.

DATA ANALYSIS

An approach using the ARMA identification technique (Mignolet & Red Horse 1994) is used to analyse all time series obtained from the simulations. There are several steps in this approach. First, it represents the time series data using an AR (Auto-regressive) model, which predicts the present values as a linear combination of the past values and a white noise deviate. The model is obtained by solving a linear system of equations. These results are then used to initialise an MA matrix polynomial. Afterwards, an iterative procedure is employed to determine the ARMA model that provides, at the same time, a "best" fit of both the time series data and the AR model. Finally, the estimates of the natural frequencies, damping ratios and mode shapes are obtained from the auto-regressive part of the ARMA model. A more detailed discussion of this technique can be found in Mignolet & Red Horse (1994).

In general, the higher the order of the model, the better the fit between the model and the original time series. In order to determine the optimal order for the problem studied in the present work, a group of investigations using different order has been carried out before the results are actually considered. It is found that for most of the cases investigated, the approach with orders higher than 60 gives very consistent results. Therefore order 70 is chosen for all cases.

RESULTS AND DISCUSSIONS

Calculation was first carried out for a rigid circular cylinder in a cross flow with $Re = 200$ in order to obtain a baseline for comparison. The Strouhal number St ($= f_S{}^* D/U_\infty$) is found to be 0.1922, where $f_S{}^*$ is the shedding frequency for the rigid cylinder and D is the cylinder diameter. The calculations are then carried out for an elastic cylinder, where the mass ratio M^* ($= m/\rho D^2$) is taken to be 1 and a reduced damping parameter Sg ($=8\pi St^2 \alpha M^*$) is chosen as 0.01. The frequency ratio $f_n/f_S{}^*$ varies from 0.65 to 5.2.

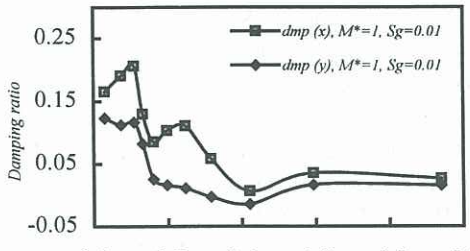

Figure 1. Damping

Figure 1 shows the results of the damping ratio of the fluid/structure system obtained by analyzing a group of cylinder displacement time histories in both the x and y directions using the ARMA approach. The damping ratio represents the ratio of energy dissipated to the total energy of the structure per cycle. The results indicate that when the natural frequency is far from the vortex shedding frequency where the vibration of the cylinder is very weak, the damping ratio is small. The damping ratio generally increases as $f_n/f_S{}^*$ decreases. However, a minimum occurs at $f_n/f_S{}^* = 1.30$ where the cylinder vibration is known to have the maximum amplitude at this frequency ratio (Zhou *et al.* 1998b).

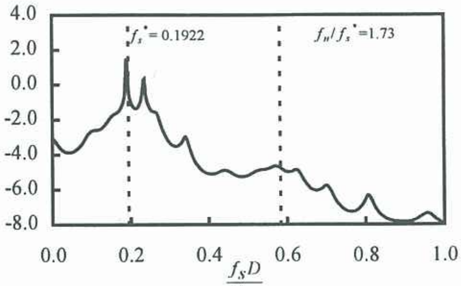

Figure 2. Spectral analysis.

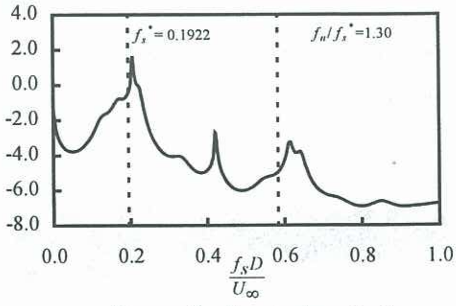

Figure 3. Spectral analysis.

Figures 2, 3, and 4 show the results from the spectral analysis for the y displacement for $f_n/f_S{}^* = 1.73$, 1.30 and 0.87, respectively. Figure 2 clearly shows two peaks around the value of 0.1922, where one is associated with the vortex shedding frequency and the other with the natural frequency of the fluid/structure system. As f_n/f_s^* decreases to 1.30, only one peak occurs at a frequency value larger than 0.1922, as shown in Figure 3. It seems that the vortex shedding frequency is locked by the natural frequency of the system. As f_n/f_s^* decreases further and switches over 0.1922, the shedding frequency shifts to a lower value than 0.1922. This is seen in Fig. 4. Three figures all show that the third harmonics plays a notable role in the y-direction motion.

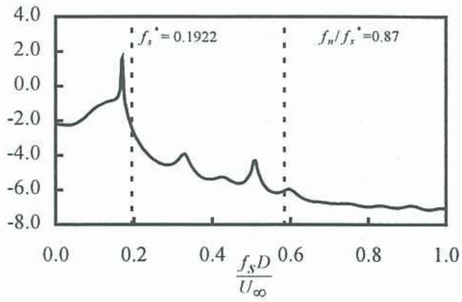

Figure 4. Spectral analysis.

Figure 5 shows the vortex patterns in the wake for the case of $f_n/f_s^* = 1.30$. It is seen that the vibrations of the cylinder have changed the vortex patterns in the wake significantly.

Figure 5. Vortex patterns in the wake, $f_n/f_s^* = 1.30$, $M^* = 1$, $Sg = 0.01$, $Re = 200$.

CONCLUSIONS

The approach using ARMA has shown a good ability in detecting the frequency and the damping ratios, even when two frequencies are very close. The results show that the vortex shedding frequency shifts to be closer to the natural frequency of the fluid/structure system due to the vibration of the cylinder, and is locked by the natural frequency when the two frequencies are close enough. The results also indicate that in the transverse direction the third harmonics plays a notable role in the motion of the system.

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