BBAA VI International Colloquium on:
Bluff Bodies Aerodynamics & Applications
Milano, Italy, July, 20-24 2008

FLOW INDUCED VIBRATION CHARACTERISTICS OF A CYLINDER IN CROSS FLOW AT LOW-REYNOLDS NUMBERS

M.H. Bahmani, M.H. Akbari
Department of Mechanical Engineering, School of Engineering, Shiraz University,
Molla-Sadra Ave., Shiraz 71348-51154, Iran
Email address: akbari@eng.shirazu.ac.ir

Abstract

In this paper we present numerical results of the dynamic response to fluid forcing on an elastically mounted rigid cylinder in low-Reynolds flow, allowed to oscillate transverse to a free stream. A vortex method is implemented to solve the two-dimensional Navier-Stokes equation in terms of vorticity. The Reynolds numbers ranges from 90 to 170, a regime that is fully laminar. The vortex pattern for different Reynolds number (Re) is also investigated. We found that in synchronous regime in this range of Re unlike turbulent regime where vortex shedding mode is of 2P and S+P type, vortex shedding mode is of 2S and C(2S) type. The numerical results exhibit acceptable agreement with available experimental data.

Keywords: Flow-induced vibration; Circular cylinder; Vortex method; Vortex shedding.

1 INTRODUCTION

The uniform flow past a circular cylinder is an important and fundamental topic in fluid mechanics. It is well known that when Reynolds number is above the critical value, vortex shedding appears behind the circular cylinder, resulting in periodic forces on the body, and can, if the body is elastically supported, cause it to vibrate. Such a vibration is termed Vortex-Induced Vibration (VIV). Vortex excited bodies can experience a non-linear phenomenon known as lock-in, whereby the vortex shedding and oscillation frequencies become synchronized. This synchronization can lead to an amplification of cylinder's vibrational response. Vortex induced vibration arises in many fields of engineering, such as heat exchanger tubes, marine cables, bridges and towers. The practical significance of VIV has led to a large number of studies. Much of the recent research is discussed in the review by Williamson and Govardhan [1].

To date the majority of studies of VIV of the cylinder have been experimental and at a Reynolds number where the flow is inherently turbulent and three dimensional, for example the work by Khalak and Williamsson [2]. The only laminar flow, free-vibration experiment that we have encountered in the literature is by Anagnostopolus and Bearman [3]. Hence, in this study two dimensional simulations have been performed for 90<Re<170 where the flow is fully laminar and two-dimensional, and the basic characteristics of the dynamic response and vortex shedding are investigated.

2 NUMERICAL APPROACH

The numerical algorithm developed and applied in this investigation is based on a vortex method described in detail by Akbari [4]. The motion of an incompressible, viscous fluid in two dimensions is described by the continuity and Navier–Stokes equations. These equations can be cast in terms of vorticity and a stream function as follows:

$$\frac{\partial \omega}{\partial t} + (\vec{u} \cdot \nabla)\omega = \nu \nabla^2 \omega \tag{1}$$

$$\nabla^2 \psi = -\omega \tag{2}$$

where ω, ψ, and $\vec{u}$ are the vorticity, stream function, and velocity vector, respectively, and ν is the kinematic viscosity of the fluid. Given the vorticity field, Eq. (2) can be solved for the stream function, the spatial derivatives of which give the velocity components. Applying an ‘‘operator splitting’’ method", Eq. (1) is splitted into convection and diffusion parts. It can be shown that the total derivative of vorticity is zero, or that the vorticity of a fluid particle is conserved. Therefore, the vorticity domain is discretized into vortex particles, the trajectory of which is dictated by the velocity field. This process provides us with a unique solution to the convection equation. An alternating-direction-implicit (ADI) finite difference scheme is used to solve the diffusion equation. The ‘‘no-flow’’ boundary condition is satisfied during the solution of the convection problem, and the ‘‘no-slip’’ boundary condition is satisfied through the generation of new vorticity on the solid boundary during each time-step. To find the detailed description of the scheme see Akbari [14].

Considering the motion in the transverse direction only and assuming rigid body motion, the equation of motion used to represent vortex-induced vibration is

$$m\ddot{y} + c\dot{y} + ky = F_y \tag{3}$$

where m is the cylinder mass, c the damping coefficient, k the structural stiffness, y the transverse cylinder displacement, and F_y is the transverse fluid force on the cylinder. once the force coefficient is known from the flow field calculations, Eq. (3) is integrated in time using a fourth-order Runge-Kutta algorithm.

3 RESULTS AND DISCUSSION

To have a basis for comparison, we first investigated the flow past a stationary cylinder. We obtained the time history of lift and drag coefficients for different Reynolds numbers, and checked the frequency of vortex shedding. These results compared favorably with the previously published corresponding results.

Our main purpose here is to investigate the vortex induced vibration of a circular cylinder with low damping in a laminar regime. Simulations were conducted for several mass ratio and damping ratios. The case with m^*=149.1 and ζ=0.0012 for which experimental results are available, was first investigated, and good agreement between the present numerical results and the corresponding experimental results in [3] were obtained. Once the accuracy of the method was established by the above results, other cases with different mass ratios and damping ratios were studied in order to ascertain the dependency of the system response to these parameters.

For each case we investigated the time history of transverse displacement and lift force at different reduced velocities, and checked the vortex shedding and oscillation frequency to find the lock-in regime. As an example, the displacement response of the cylinder is shown in Fig. (1) for a sample case for which Re=100, m^*=149.1 and ζ=0.0012. As seen, there is a beating effect in the response and the vibration amplitude of the cylinder is small in this case.

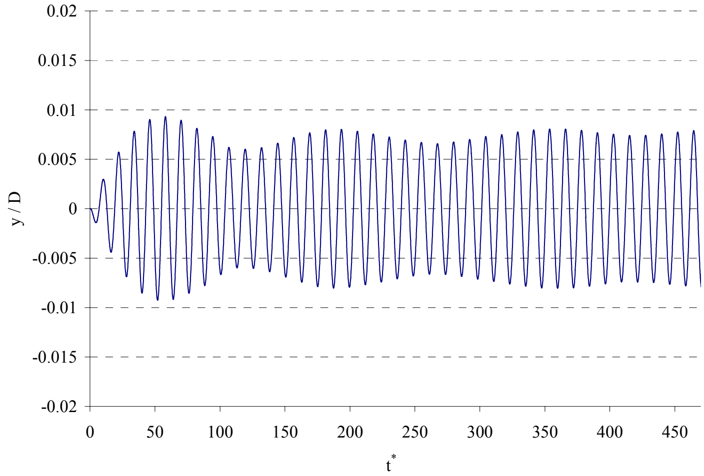

Figure 1: Cylinder displacement histogram for U^*=5.6 (Re=100), m^*=149.1, ζ=0.0012.

We investigated the variation in the maximum amplitude and frequency of the cylinder oscillation and the vortex shedding frequency as a function of the Reynolds number. The results for a case with m^*=149.1, ζ=0.0012, for example, are shown in Fig. (2). For each case (with given mass ratio and damping ratio) we obtained the Reynolds number band over which lock-in phenomenon occurs.

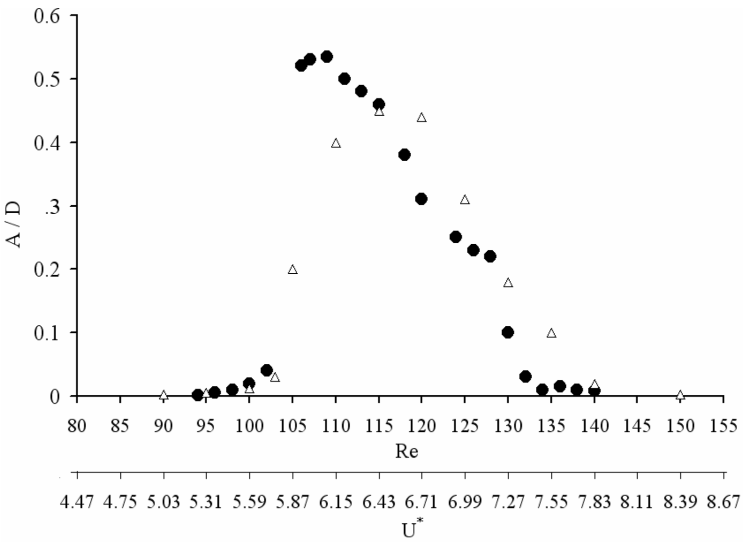

Figure 2: Variation of the maximum non-dimensional cylinder displacement with Re number and reduced velocity for a case with m^*=149.1, ζ=0.0012; Δ, present numerical results; ●, experimental results [4].

We also investigated the velocity field for each case. Fig. (3) shows the instantaneous vorticity field at four selected Reynolds numbers for the case with m^*=149.1 and ζ=0.0012. For all the range of Reynolds numbers considered here, vortex shedding is of 2S type (two oppositely vortices are shed per cycle). Parts (a) and (d) of the figure show the vorticity contours for Re=100 and Re=150 respectively, where lock-in did not occur. The vorticity contours in these cases are very similar to those for a fixed cylinder at the same Reynolds numbers. Parts (b) and (c) of the figure show vorticity contours for two case where lock-in has occurred. Comparing with the contours for a fixed cylinder at the same Re, we see that vortex spacing is smaller for the oscillating cylinder. It shows that that the vortex shedding frequency diverges from that predicted by the Strouhal relation. In these cases the vortices in the wake coalesce giving rise to the C(2S) mode of vortex shedding (as described by Williamson and Roshko [5]). The C(2S) is very similar to the 2S mode except that vortices coalesce in far wake.

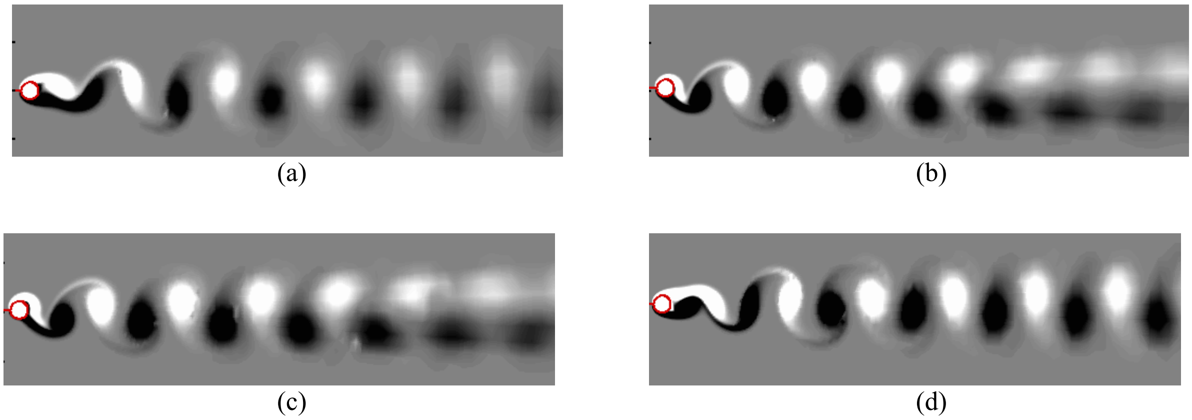

Figure 3: Instantaneous vorticity contours for a free-vibrating circular cylinder at different Reynolds numbers: (a) Re = 90; (b) Re = 105; (c) Re = 110; (d) Re = 150.

4 CONCLUSIONS

The numerical results for dynamic response of a flexible cylinder exhibit acceptable agreement with available experimental data presented in [5]. Our main purpose in this work was to investigate the system response in low-Reynolds flow regime and compare the results to previous similar works and to those for turbulent flow (for example the results in [2]). We found, for example, that in the synchronization regime unlike turbulent flow where the vortex shedding is of 2P or S+P type, in low-Reynolds flow the vortex shedding mode is of 2S or C(2S) type.

REFERENCES

[1] C.H.K. Williamson. R. Govardhan. Vortex-induced vibrations. *Annual Review of Fluid Mechanics,* **36**, 413-455, 2004.

[2] A. Khalak & C.K.H. Williamson. Motion, forces and mode transitions in vortex-induced at low mass-damping. *Journal of Fluids and Structures,* **13**, 813-851, 1999.

[3] P. Anagnostopoulos. P.W. Bearman. Response characteristics of a vortex-excited cylinder at low Reynolds numbers. *Journal of Fluids and Structures*, **6**, 39-50, 1992.

[4] M.H. Akbari, Bluff-body flow simulations using vortex methods, Ph.D. thesis, Department of Mechanical Engineering, McGill University, Montréal, Canada, 1999.

[5] C.H.K. Williamson & A. Rashko, Vortex formation in the wake of an oscillating cylinder. *Journal of Fluids and Structures*, **2**, 355-381, 1988.