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Flow-Induced Vibrations in Engineering Practice

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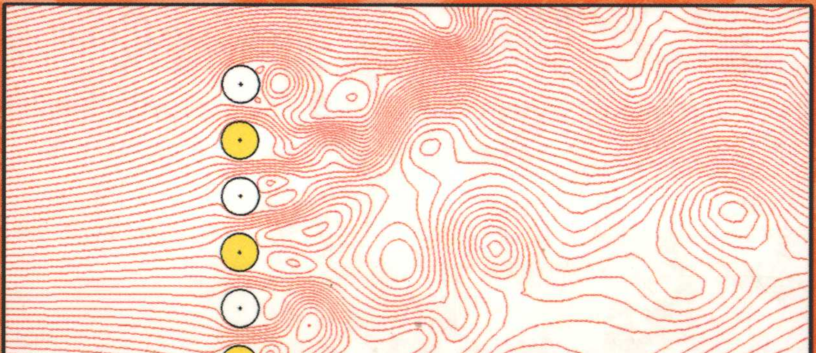

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Thanks are due to P. Anagnostopoulos & S. Seitanis for the use of the figure that appears on the front cover of this book. The cylinders marked in yellow are elastically mounted, and oscillate in the downstream direction upstream of the other four cylinders that remain fixed. In the instant shown the moving cylinders are at the maximum streamwise displacement. Details can be found in reference [85] of Chapter 3 of this book.

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Preface

Flow-induced vibrations are complicated flow-structure interaction phenomena that may have disastrous effects. The poor understanding of these phenomena may lead to severe damage, which, apart from the economic loss, may even claim human lives. Striking examples are the collapse of the Tacoma Narrows Bridge, USA, in 1940, and the collapse of three cooling towers of Ferrybridge power station, UK, in 1965. On the other hand, flow-induced vibrations of tube banks in heat exchangers or nuclear reactors, although not so spectacular as to attract global interest, may result in substantial costs, from the aspect of both the damage of installations and the loss of power-generating time.

The instability mechanisms that may give rise to flow induced vibrations may be of various kinds: vortex shedding, galloping, turbulence buffeting, fluidelastic instability, oscillatory flow, wave motion, etc. In some situations several mechanisms may be involved in the excitation of a structure, rendering the analysis more complicated. The great interest of academics and practitioners in these phenomena is evident from the large number of relevant papers being published in journals and presented at conferences. A vast number of data contained in various sources has been accumulated over the years, which often exceeds requirements for background reading or design purposes.

A compilation of the salient points of various flow-induced vibration mechanisms is attempted in the present text, as revealed by a look at the contents. The first chapter provides an overview of vibrations induced by vortex shedding, with reference to several experimental and computational efforts conducted for the investigation of the problem. Another approach to predict vortex-induced vibrations is by the use of mathematical models calibrated from existing data, which is the subject of the second chapter. A detailed description of the instabilities that lead to galloping vibrations is provided in the third chapter. The subject of the fourth chapter is related to the very important issue of fluidelastic instabilities of cylinder arrays in cross-flow. An investigation of the use of the well-known Connors' equation, applied extensively in such problems, is conducted therein. The fifth chapter deals extensively with the interaction between rotating shafts and the surrounding fluid media.

This book is suitable for both the newcomer in attempting his first study of the challenging field of flow-induced vibrations as well as the experienced researcher or practitioner.

The editor of this book would like to thank all authors for contributing their unique expertise, rendering this a useful text both to newcomers and active researchers in this broad and interesting field.

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Chapter 1

Vibrations induced by vortex shedding

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1 Introduction

Vibrations induced by the periodic shedding of vortices are those that most frequently occur in engineering practice. It is well-known that at Reynolds numbers in excess of approximately 40 the wake of a bluff body in steady flow consists of two staggered rows of vortices, which are being shed alternately from either side of the body.

This phenomenon is controlled by two dimensionless numbers; the Reynolds number, *Re*, and the Strouhal number, *S*. Where the bluff body is a circular cylinder, the Reynolds number is defined as

$$Re = \frac{UD}{\nu} \tag{1}$$

while the Strouhal number is given by

$$S = \frac{f_s D}{U} \tag{2}$$

where U denotes the free stream velocity, D the cylinder diameter, ν the kinematic viscosity of the fluid and f_s the vortex-shedding frequency. The various vortex-shedding patterns for different regimes of Reynolds numbers are quoted by Blevins [1].

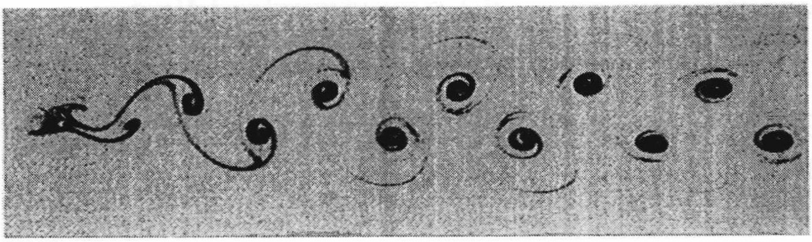

Figure 1: The wake of a circular cylinder at Re=105, as photographed by S. Taneda.

One of the pioneering contributions was von Kármán's inviscid analysis, therefore these double rows of vortices are referred to as "von Kármán's vortex street". These von Kármán's vortices have been observed both in the laboratory and in nature. Figure 1 is a typical example of the vortex-street wake of a circular cylinder at Re=105, whereas illustrations at high Reynolds numbers provide the satellite pictures of the vortices formed behind islands, made visible by the presence of clouds. With the enormous increase of power of digital computers in the last decades and the ensuing advances in computational techniques, the numerical simulation of vortex shedding behind bluff bodies became a very popular field of study. An example is the streakline pattern of Figure 2 at Re=106, obtained by

Anagnostopoulos [2] from a finite element solution. The agreement between the experimental and numerical visualization is reasonable.

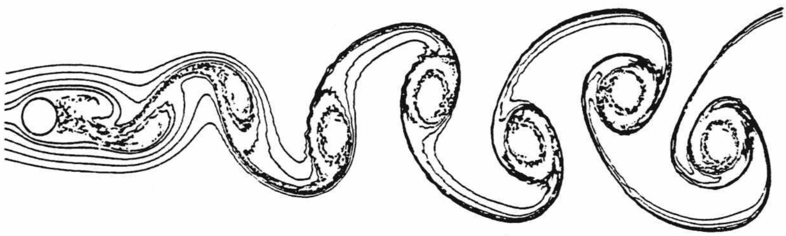

Figure 2: Streaklines past a cylinder at Re=106 (Anagnostopoulos [2]).

As the vortices are shed, a periodic force is exerted on the body, whose component in the transverse direction (lift force) has the same frequency as the vortex-shedding cycle, while the component in the stream-wise direction (drag force) has a frequency equal to twice the shedding frequency. The normalization of the hydrodynamic forces per unit cylinder length by $0.5\rho U^2 D$, where ρ denotes the fluid density, yields the non-dimensional drag and lift coefficients, C_D and C_L. An example of the time history of the hydrodynamic coefficients is given in Figure 3, for Re=200.

The force records of Figure 3 were derived assuming two-dimensional flow. However, the vortex shedding behind a body of constant cross-section along the span is not necessarily two-dimensional. For a circular cylinder, the vortices are shed at a slanted angle along the span when the Reynolds number exceeds 60, whereas the flow behind the body becomes three-dimensional for Reynolds numbers greater than 200 (Williamson [3]).

If the body is mounted elastically, and if its mass and the damping of the system are relatively small, these forces may induce vibrations on the body, if resonant conditions occur. Thus, if the vortex-shedding frequency approaches one of the natural frequencies of the body, vibrations may be induced in the transverse direction, whereas the vibrations will occur in the

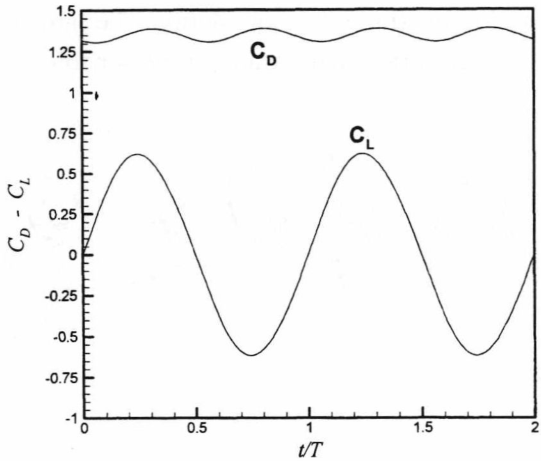

Figure 3: Hydrodynamic coefficients on a fixed cylinder at *Re*=200.

streamwise direction if one of the natural frequencies is close to twice the shedding frequency. In a case where one of the body's natural frequencies approaches the vortex-shedding frequency and another its duplicate a more complicated situation is observed, in which the vibrations occur in both directions. Since the amplitude of the transverse force is greater than that of the drag fluctuation as shown in Figure 3, the amplitudes of cross-flow vibrations are generally greater than those of oscillations in the streamwise direction. Hence, although the vortex-induced oscillations in the streamwise direction have received a considerable amount of attention, the ones in the cross-flow direction appear much more frequently in the literature.

When a bluff body is oscillating in a flow stream, vortex shedding can be dramatically altered. In some situations the vibrations of the body induced by vortex shedding are so large that they interfere with, and can control, the flow pattern. Consequently, the flow around a vibrating body can have significant differences from that when the body remains fixed. The fluid dynamic forces exerted on the body are usually magnified due to the oscillations, and, through a non-linear interactive process, the vibration of the body can be increased still further. An interesting phenomenon is that known as "lock-in" or "wake capture". If the oscillation amplitude exceeds a critical threshold, the vortex-shedding frequency diverges from that corresponding to a fixed cylinder, and becomes equal to the oscillation frequency, which approaches in many cases the natural frequency of the body. This synchronization effect acts to increase the range of flow velocities over which vibrations of high amplitude occur.

2 Forced oscillations

The lock-in effect is also observed when a cylinder is forced to oscillate sinusoidally in a uniform stream. In this case lock-in occurs when the driving frequency in the transverse direction approaches the natural shedding frequency, or the driving frequency in the streamwise direction approaches twice the natural shedding frequency. Forced oscillations were often used in laboratory experiments, in order to examine the effect of the cylinder motion on the flow field and on the hydrodynamic forces exerted on the cylinder. By using a suitable shaking mechanism, it is possible to generate a controlled vibratory motion at a wide range of amplitudes, A, and frequencies, f_c, which is not the case for a flexibly mounted body.

Griffin [4] conducted experiments for a vortex-excited cylinder and a cylinder forced to oscillate sinusoidally at similar conditions. The difference was that in the oscillations of the flexible cylinder small fluctuations of the amplitude were recorded at consecutive cycles, whereas the externally driven cylinder was forced to oscillate sinusoidally at the average amplitude of the vortex-excited oscillations. Although the average flow velocities in the wake displayed remarkable similarities in both cases, small differences were detected in the instantaneous values of the velocities.