Chapter 1

Introduction to the Book

The purpose of this book is to address separately, and then jointly, the subjects of hydrodynamics and vibration of structures. The book connects these two independent topics and shows the effect each has on the other. It concentrates on the vibration aspects of structures caused by fluid loading. The basics of both subjects are covered and the interrelationship of these two fundamental aspects of structures immersed in fluids is illustrated. The book includes both the theory and the application of the two concepts as they apply to incompressible fluids.

Hydrodynamics and vibration may be considered to be a cause and an effect. Generally the hydrodynamic interaction between a fluid system and a structure initiates a motion or vibration in the system encompassing the structure. Conversely, the vibration of a structure in the fluid, in turn, generates a change in the fluid motion in the vicinity of the structure.

1.1 What is Hydrodynamics?

Hydrodynamics is the science of expressing the dynamic movement of fluids in mathematical formulas. The discipline provides an analytical description of fluid dynamics following certain basic laws of fluid and some engineering principles. Since it is often difficult to represent a physical phenomenon with an equivalent mathematical analogy, it is critical that the hydrodynamic description adequately defines the physical concept. In developing the mathematical description, certain physical laws are satisfied giving rise to the basic equation of the fluid particle motion. This requires certain simplification and assumptions that are justified by the physical constraints. Similarly, certain boundary conditions must be met for a given hydrodynamic problem. This gives rise to what is commonly known as a boundary value problem consisting of a fundamental differential equation and a set of boundary conditions.

Take, for example, a structure that is placed in a fluid field, which is in motion. Mathematically, one needs first to describe the uninterrupted motion of the fluid. Even then, certain boundary conditions are imposed arising from the boundaries defining the containment of the fluid. For example, in an open channel flow, the bottom boundary is usually a solid surface, such as the river floor where the fluid must satisfy the bottom boundary condition. Similarly, the interface between the fluid free surface and the air will impose a second boundary condition known as the free surface boundary condition. When a structure is placed in the fluid, then the fluid flow in the vicinity of the structure will be distorted, which should be taken into account by another boundary condition that is determined by the shape of the submerged structure. This is commonly referred to as the body surface boundary condition. The fluid in this case should satisfy a far-field condition as well, at which point it should restore to its original form.

Once identified, the boundary conditions are then satisfied by posing the boundary value problem, and the solution is determined either analytically or numerically, depending on the problem's complexity. Essentially, this solution describes the fluid flow around the structure in terms of mathematical functions. This expression reveals the effect of the fluid upon the structure, including the distribution of fluid pressures or forces. If the structure is allowed to move or is flexible enough to distort due to fluid flow around it, then the displacement of the structure may be determined by considering the hydrostatic and dynamic properties of the structure.

The theory of hydrodynamics has been thoroughly described by Lamb (1945) and Milne-Thompson (1960), which should be excellent reference books for the readers. The books cover many aspects of theoretical hydrodynamics and develop the theory and formulation for fluid flows past submerged structures.

1.2 What is Vibration?

The subject of vibration deals with the dynamic behavior of structures when excitation forces are imposed upon them. The excitation can occur in the form of steady or oscillatory forces. The oscillatory forces themselves may be of single or multiple frequencies. These forces are caused by some external means such as the environment surrounding the structure or even internal means arising from the motion of the structure itself. In mechanical systems such as rotating machinery, the main cause of vibration arises from an imbalance in the rotation of the machine components. This may cause excessive wear and tear and even result in failure of the machine parts. Another cause of vibration is the interaction of a structure subjected to fluid flow. In this case, the vibration may cause excessive motions and stresses in the members of the structure and thus become the critical cause for the capsizing or failure of the structure.

Free vibration takes place when a system is displaced from its equilibrium position and released. In the absence of any external force, the system attempts to return to its equilibrium position and thus undergoes oscillation about this position. In all cases the structure or system has a natural frequency inherent to the system. The natural frequency is based on the mass of the structure and the restoring force in the system. While most systems are concerned with a single degree of oscillation with one natural frequency, it is possible to have multiple degrees of oscillation each having its own natural frequency from the free motion. Generally, the oscillatory motions from external excitation are periodic, having a single frequency. However, vibrations may be random, having a band of frequencies. In the former case, the excitation is a harmonic function while in the latter case, the forces are generally random. When the forcing frequency coincides with the natural frequency of the system, the system experiences a condition called resonance. In hydrodynamics, resonance is one of the most important phenomena and calls for careful examination.

In this regard, the natural frequency and damping in a system are important computation. In most cases the natural frequency is easy to determine. The restoring force may be represented as a spring in the system. The spring may be an external device, e.g., attached springs, or mooring lines or it may be internal, e.g., buoyancy or righting moment of a floating structure. All systems include an inherent damping function. The damping arises from the dissipation of energy by resistance, e.g., friction or interaction of the structure with the fluid. While the magnitude of damping may vary depending on the system under consideration, no physical structural system exists without some damping. Theoretically, the response of a system "blows up" or is greatly magnified in the absence of damping; however, the response is finite (although perhaps unacceptably large in magnitude) for all physical systems due to the presence of this damping.

The vibration problem associated with many types of structures has been extensively covered in the Handbook of Vibration [Harris and Crede (1976)], which is an excellent reference book for the reader. This book may be consulted to learn more about vibration of machines and structures and their applications.

1.3 Interrelationship of Hydrodynamics and Vibration

As stated earlier, this book aims to address the aspects of hydrodynamics causing vibration and motions in a structure. The structure resides in a fluid flow, which exerts an external force (or moment) on the structure. The structure displaces from its equilibrium position under the action of this force and tends to return to its original equilibrium position due to the restoring forces (or moments) acting on it. This introduces an oscillation of the structure in the fluid. The oscillation frequency may correspond to the frequency of the fluid motion or else one of its harmonic or subharmonic frequencies. The initial disturbance of the structure introduces a motion at the natural frequency of the structure as well. The structure continues to oscillate as long as the external force from the fluid is present. In the absence of the fluid force, the structure comes to rest at its equilibrium position as long as it is stable. For certain conditions, instability may result, which may lead the structure to a new equilibrium position.

The interrelationship of these two subjects is complex and multifaceted. The fluid flow introduces forces on the structure, and the structure and its restraints react to the forces exerted by the fluid flow around or through it. If the structure is floating and restrained by external means, then the restraining members experience reactive forces from the motion of the structure. On the other hand, if the structure is flexible, then the pressure distribution on the component of the structure introduces deflections. If the flow is time dependent, then this motion or deflection becomes time dependent, having generally the same frequencies as the fluid flow. The structure itself has its own modes of frequencies. If the fluid flow frequencies happen to coincide with any of the modal frequencies of the structure, then the structure is excited by these frequencies, giving rise to the natural frequency of vibration. This book will address the aspects of fluid flow and how it imposes forces on structures under various conditions. In addition, it will show how these forces give rise to vibration in the structure.

1.4 Overview of Contents

The basic theories of hydrodynamic and vibration are given respectively in the first two chapters. Most of the remaining chapters make use of these theories in dealing with their inter-relations. The book specifically addresses how the theory in these two areas can be applied to practical structures residing in fluids.

The basic theory of hydrodynamics is the subject of Chapter 2. The description of common quantities, such as potential function and the basic governing equations of fluid flow, including the continuity equation and Bernoulli's equation are given. The forces on a structure due to steady fluid flow and time dependent flow are derived. The effect of the free surface flow on a submerged structure is developed.

The basic theory of the vibration problems is introduced in Chapter 3. The chapter covers the modes of vibration and different aspects of vibration of a rigid body. The free and forced vibrations of structures are derived. Here the single and multiple degrees of vibration of rigid bodies subjected to simple harmonic motion are analyzed. The multi-degree system includes multiple degrees of freedom of a single body as well as motions of interconnected multiple bodies. Handling of certain nonlinearities, such as nonlinear restoring forces and nonlinear damping in the system are addressed and specific examples of such types of nonlinearities are illustrated. Examples are given showing how the theory may be applied in a practical problem.

Chapter 4 describes the modeling laws and model testing for systems where hydrodynamic forces are coupled with vibration. This section describes the methods of testing vibratory systems in prototype and model scale. Facilities that are used in performing these tests are described. The instruments and testing methods generally used for such systems are addressed. Specific examples of testing moving structures in fluid and some associated problems encountered are illustrated.

Many of the vibration problems encountered in the fluid field are random in nature. Chapter 5 deals with the probabilistic nature of the random signals. It reviews the statistical quantities of importance that are necessary to describe a random signal. The probable maxima of a random signal are best described by the probability theory. The probability distribution and density functions are defined, and certain common probability distributions necessary in the vibration theory are introduced. A brief description of the power spectrum is given. The method of computing the response spectrum for a linear and nonlinear vibrating system is provided. An example shows how these quantities are estimated, and discusses the practical applications of these estimates.

Chapter 6 develops the theory of random vibration based on the material presented in Chapter 5. Many structures placed in fluids experience random motion resulting from the fluid forces. Theory of random input and random output that can describe such a system is addressed in this chapter. The statistical and spectral theory applied in latter chapters is discussed here. The method of developing the solution in the frequency domain as well as the time domain is shown. Several examples are discussed in which the vibration of structures in fluid was experienced.

The flow of fluid past a structure not only affects the structure, but also changes the fluid field round it. The fluid structure interaction problems are described in Chapter 7. This chapter is divided into two parts. The first part considers the structure placed in steady flow while the second part describes the effect of time dependent flow on a submerged structure. In the latter case, the flow is considered oscillatory as well as random, thus both harmonic and random vibration of structures in fluid are considered. Damping present in the system is quantified, and the effect of damping in limiting the motion of structures is shown. Flexible structures undergo vibration, which includes deformation of the structure as well. In particular, the equations of motion of a tensioned riser placed vertically in the fluid field are considered. The practical aspects of the various terms in this equation are discussed, and the methods to solve for the vibration of the flexible body in fluid are provided. The coupling effect of a large body attached to smaller flexible members may be important. In particular, examples of floating structures moored in the ocean with mooring lines are given, and the dynamics of mooring lines themselves are discussed.

Vortex shedding is an important fluid effect that has very important practical consequences in the design of structures placed in flowing fluids. The effect of vortices and the Vortex-Induced Vibration (VIV) is the subject of Chapter 8. In this chapter, the mechanism of the formation of vortices past a fixed or moving structure in fluid is revealed. Convenient guidelines that can be used to determine vortex formation in terms of nondimensional variables are highlighted. The frequency of vortex induced vibration and the effect it will have on the vibration of a structure is addressed. The lock-in mechanism in which the frequencies of the fluid flow and structure vibrations coincide is explored. The VIV of cables, risers and pipelines in steady and oscillatory flows is described, and the corresponding eigenfrequency problem is evaluated. Finally, the mitigation of VIV problem and its various means are investigated.

The theories outlined in Chapters 1 through 8 have many applications in the real world. Chapter 9 compiles several practical prototype problems of fluid-structure interaction. These practical examples apply the theory outlined in the previous chapters. Many of these examples are actual field studies or laboratory experiments. The important lessons learned or the pitfalls and success of these studies are illustrated here.

The interrelationship among the various topics is schematically shown in Fig. 1.1. The chapters, in which these subjects are covered, are also indicated in parenthesis.

1.5 References

1. Harris, C.M., and Crede, C.E. (Editors), Shock and Vibration Handbook, McGraw-Hill, 1976.

2. Lamb, H., Hydrodynamics, 6th Edition, Cambridge University Press, New York, 1945.

3. Milne-Thompson, L.M., Theoretical Hydrodynamics, Macmillan Company, 1960.

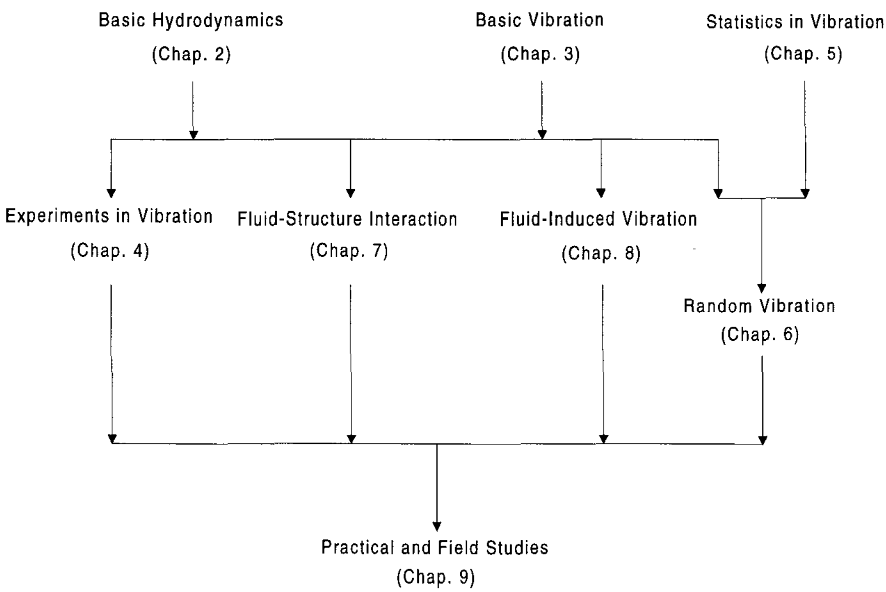

Fig. 1.1 Interrelationships among Various Topics in the Book