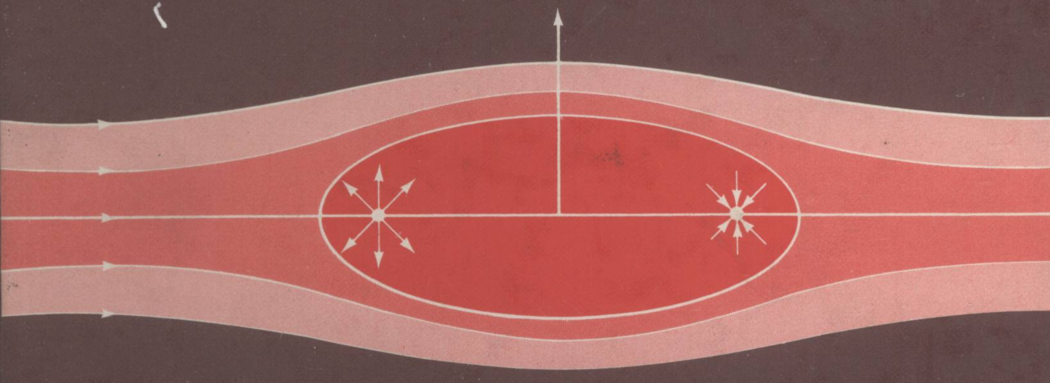
Introduction to FLUID MECHANICS

second edition



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second edition

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Introduction to Fluid Mechanics

To Connie

and

Elizabeth, Jimmy, Thomas, and Constance

To the memory of my wife,

Florence H. Haberman

Preface to Second Edition

This textbook is intended to provide the undergraduate engineering student with an understanding of the basic principles of fluid mechanics. Many texts in fluid mechanics have appeared in recent years, some of them finding extensive use in undergraduate curricula. However, it was felt that there was a need for an introductory text that provides the necessary motivation for an engineering student, one that stresses the applications of current interest to the engineer. In this text, our approach is to keep the derivation of the fundamental equations and principles at an uncomplicated mathematical level; the results of these derivations will always be tied to a real physical situation. Numerous worked-out examples are provided throughout to illustrate the utility of the fundamental equations in describing various physical situations.

The first five chapters serve as a core, to be required of all engineering students of fluid mechanics. The remaining chapters are devoted to applications of the core material, with the particular chapters to be studied depending on the department. For example, the civil engineer would be primarily interested in Chapters 6, 10, 14 and 15; the mechanical engineer, Chapters 7, 9, 11, 12, 13, 15 and 16; the aerospace engineer, Chapters 7, 8, 9, 11, 13, 15 and 16. The text is arranged so that each of the foregoing groups of chapters can be taken independently; intervening chapters can be omitted with no loss of continuity.

After a great deal of consideration, we made the decision to use SI units exclusively in this edition of the text. Outside the United States, use of SI units is widespread. In the United States, we are in the midst of the changeover from English units; it will probably be ten to twenty years before complete conversion is a fact. However, for those companies involved with international markets, conversion to SI has already been accomplished or will have to be accomplished in the very near future. Certainly, every engineering graduate coming out of college today should be familiar with, have a feel for, and be able to work with SI units. Sometime in the professional career of today's engineering graduate, perhaps very soon after graduation, complete change to the SI will take place—the timing will depend on the nature of the company or business in which he is employed. For this reason, we believe it incumbent on the engineering educator and the textbook writer to teach engineering subject matter using SI units. As more SI textbooks appear, there will be more engineering graduates familiar with and using SI units. This factor will be a major one in the conversion of American engineering practice to the SI.

In the Second Edition, the material on fluid statics has been placed early in the text to correspond to the location of this material in most courses in fluid mechanics. Further, the number of problems at the ends of the chapters has been virtually doubled, with a more orderly progression of such problems from easy to difficult. Finally, a chapter on dynamic response and control has been added to supplement the material that was already available in the First Edition. This new chapter is again intended to provide application of the course material presented in the initial chapters of the book; potential use of this chapter depends on the nature and type of the course being taught and the student body for which it is intended.

We would like to thank Dr. William Janna of the University of New Orleans and Dr. Colin Marks of the University of Maryland for reviewing the manuscript and offering many helpful suggestions for the Second Edition. We would also like to thank our many colleagues and students for their help with the revision. Finally, we thank Elizabeth John for her assistance in typing portions of the revised manuscript.

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1

Basic Concepts

1.1 INTRODUCTION

The subject of fluid mechanics is of great significance to man; the passage of blood through our veins, the falling of the rain through the atmosphere, the currents in the oceans and the seas are all examples of fluid flow. One is interested in studying fluid mechanics in order to utilize and control the effects of fluid flow for the benefit of society. It is the purpose of this textbook to acquaint the student with laws describing the behavior of fluids in motion and to indicate the application of these laws. The student has become familiar with the field of particle and solid body dynamics; in the next section we shall indicate in what ways fluid mechanics is different from solid mechanics.

1.2 SOLIDS VERSUS FLUIDS

In order to distinguish between a solid medium and a fluid medium, we shall examine the response of each substance to an applied shear force. Consider a solid bar with one end rigidly attached and the other free. Apply a torque to the free end, as shown in Figure 1.1. As long as the resultant stress does not exceed the yield stress of the material, the bar will twist until an equilibrium position is reached, with the final position dependent on the magnitude of the applied torque and the elastic properties of the bar.

Let us place a fluid between two concentric cylinders, with the inner

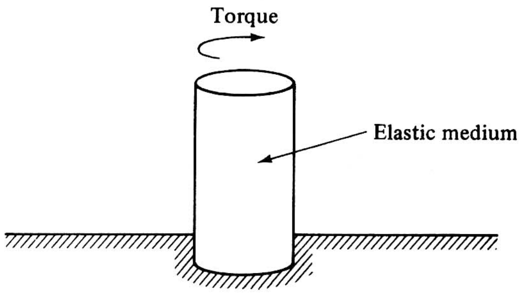


Figure 1.1

cylinder held fixed, and apply a torque to the outer cylinder (Figure 1.2). When the shear force is applied to the outer cylinder, a fluid is incapable of reaching an equilibrium position; instead the outer cylinder will continue to rotate as long as the shear force is maintained. The magnitude of the angular velocity will depend on the magnitude of the applied torque and fluid properties. This response to an applied shear force forms the basis of the definition of a fluid, namely, a substance that is unable to resist the application of a shear force without undergoing a continuing deformation.

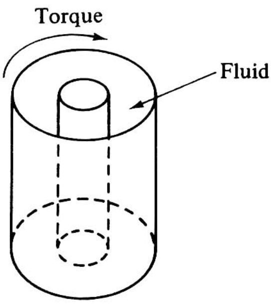


Figure 1.2

1.3 VELOCITY FIELD OF FLUID AND RIGID BODIES

When a rigid body is in motion, there is a definite relationship between the velocities of the various particles comprising the body. For example, if the body is translating, all particles must have the same velocity (Figure 1.3).

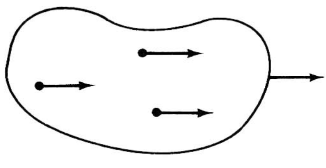


Figure 1.3

If the body is rotating about an axis, the velocities of the particles are linearly dependent on the distance from the axis of rotation (Figure 1.4).

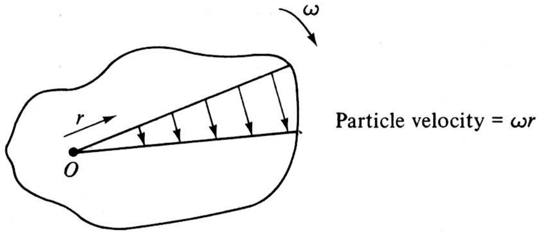
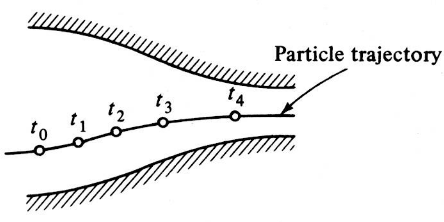


Figure 1.4

When we consider the motion of the particles in a fluid body, however, we find that no such simple relationship exists between the velocities of the various particles. Unlike those in a rigid body, the particles in a fluid body are not rigidly attached to each other. Therefore, the relative motion of adjacent fluid particles becomes more complex. In order to describe completely the motion of a fluid, information about the velocity of each particle of the fluid is necessary. Each fluid particle in the flow has a definite value of velocity at every instant. As the particle moves in the flow field, its velocity changes with location and time. In rigid body dynamics, it is customary to follow a particle as it moves about in space. This approach could also be taken in describing the motion of a fluid particle as it moves about in the flow field. However, in describing the motion of a fluid, it is more convenient to use an alternate approach, that is, to define the flow field by specifying the velocity-time history at each point in the field.

The difference between the two approaches can be seen by the following example. Water flows continuously through a converging nozzle as shown in Figure 1.5. First, let us follow a fluid particle as it moves through the nozzle. The position and velocity of the particle at successive equal time intervals are shown. It can be seen that the particle accelerates as it moves through the nozzle; in other words, the particle velocity increases with time.

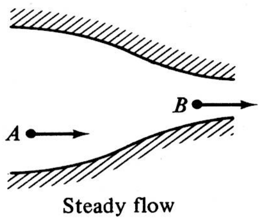
Another way of describing the same flow field is to specify the particle velocity at each point as a function of time. When the velocity at each point



Time	Particle Velocity (m/s)
t_0	2.0
t_1	3.0
t_2	5.0
t_3	6.0
t_4	7.2

Figure 1.5

in the flow field does not change with respect to time, the flow is called steady. Figure 1.6 gives the velocity-time history at point A and at point B in the flow field for the case of steady flow. Note that even in steady flow, a fluid particle can accelerate as it moves through the nozzle. Again, it is emphasized that steady flow implies that the fluid velocity at a point remains constant with time. Here, for steady flow, the velocity at point A is always 3 m/s (meters per second), and the velocity at point B is always 7.2 m/s.



Time	Velocity of Fluid Particle at A (m/s)	Velocity of Fluid Particle at B (m/s)
t_0	3	7.2
t_1	3	7.2
t_2	3	7.2
t_3	3	7.2
t_4	3	7.2

Figure 1.6

The second approach is preferred in fluid mechanics, for the description of flow at given locations is usually desired. For example, in a study of river flow about a bridge pier, the flow velocities at points in the vicinity of the pier and the resulting forces on the pier are of interest. To try to determine the flow at a given location from the particle location-time history of the first approach would be a far more complex task.

In order to obtain an indication of the flow pattern in a velocity field, we make use of *streamlines.* A streamline is a line drawn in the fluid at a given instant of time such that there is no flow across that line. Thus, at the given instant, the velocity of every fluid particle on the streamline is in the direction tangent to the line. By considering a sufficient number of such streamlines in the flow field, at a given instant, we obtain the flow pattern in the flow field, that is, a description of the direction of the velocities of the fluid particles. For steady flow, the streamline pattern does not change with time. The streamline pattern for flow through the nozzle of Figures 1.5 and 1.6, for steady flow, appears in Figure 1.7.

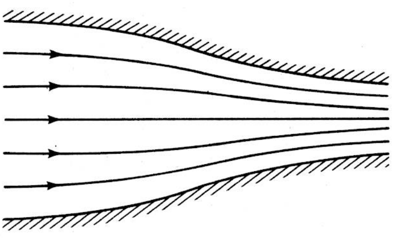


Figure 1.7

1.4 UNITS AND FLOW PROPERTIES

In any engineering subject, considerable care must be taken to use a consistent set of units. The system of units to be used throughout this text will be the International System (SI). The primary dimensions consist of mass, length, time, and temperature. In SI units, the unit of mass is the kilogram (kg), the unit of length is the meter (m), the unit of time is the second (s), and the unit of temperature is the degree kelvin (K).

In SI units, the unit of volume is the cubic meter (m^3), although another commonly used unit is the liter (l), where 1000 liters = 1 cubic meter.

The units of length, time, and temperature generally present little difficulty for the student. However, the differentiation between units of force and mass is not as easily grasped and should be reviewed. Force and mass are related by Newton's law of motion, $F = ma$. In SI units, the unit of force is the newton (N), which is defined as the force required to accelerate a mass of 1 kilogram at the rate of 1 meter per second per second. In other words,

$$1 \text{ N} = 1 \text{ kg}\cdot\text{m/s}^2$$

It must be recognized that weight is a force, namely, the force with which a mass is attracted to the earth or some other body. According to the law of conservation of mass, the mass of a body remains constant, independent of its distance from the earth's surface. However, the weight of a body will decrease as it is moved away from the earth's surface.

The following multiplying prefixes will be used throughout this text in conjunction with the various units:

Factor	Prefix	Symbol
10^6	mega	M
10^3	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ

For example, 1 kN = 1000 newtons, 1 mm = 0.001 meter, 1 μg = 0.000001 gram.

Units of energy, including heat and work, are joules (J), where 1 J = 1 N·m. Power, the rate of doing work, has the units of joules per second, or watts (W), where 1 W = 1 J/s.

We discussed velocity and the velocity field in Section 1.3; other flow properties are of interest as well. Two such properties are pressure and density. The *mean pressure* over a plane area in a fluid is defined as the ratio