Principles of Fluid Mechanics

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PRINCIPLES OF FLUID MECHANICS

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Preface

This book is designed to be used in an engineer's first course in fluid dynamics. In its preparation the author has been guided by four goals:

1. Present all principal concepts of fluid mechanics clearly without unnecessary mathematical complexity.
2. Incorporate many computer applications for the first time in any beginning text as an integral part of the written text, the worked examples, and the homework problems.
3. Illustrate all text material by many interesting, worked examples and drawings.
4. Present practical emphasis in the discussion of any theory.

As a result, this book has more worked examples, more computer examples, and more computer problems relative to its length than any other beginning fluids books. It also has more interesting homework problems relative to its length than most texts. The book also uses specially designed graphics to enhance readability and understanding. Examples have been designed using a special step-by-step format that the student can use in all future engineering problem solving. U.S. Customary System (USCS) and SI units are both used in worked examples, physical property tables, and homework problems.

Computers are as familiar to students today as the calculator and slide rule were to students of yesterday. In this text, for the first time, the use of computers is considered an integral part of problem solving, not an optional topic added to the end of a chapter or two. The emphasis is on numerical solutions to transcendental and differential equations, which formerly were solved using tedious manual methods. Computer calculations require equations, not look-up tables or empirical charts;

therefore, in this book these methods of presenting data have reduced emphasis. The empirical equations are useful in design optimizations as well. Examples and homework problems are designed to be solved by relatively simple programs of fewer than 50 lines of code. The most efficient numerical routines are not always used since it is the programming concept, not numerical expertise, which is the goal.

FORTRAN is used extensively since it is a powerful, fast language and many existing engineering programs are written in it. BASIC is too slow for more complex problems and Pascal, C, Forth, ALGOL, etc., are not universally known by engineering undergraduates. However, BASIC is universally available in personal computers; hence, some examples are solved in both BASIC and FORTRAN. The computer-oriented material is designed not to intrude on the fluid mechanics topics but to complement them. Of course, if computers are not to be used in the course, computer-based examples and homework problems can be omitted.

The organization of this book is designed to develop governing principles and equations in a logical order. Therefore, the first analytical chapter — Chapter 2 — develops the general, governing equations. Chapter 3 then discusses fluid statics, a special case of the general equations from the preceding chapter. Chapter 5, laminar flow, treats a class of flows contained in the general results of Chapter 2. Similarly Chapter 6, ideal flow, precedes Chapter 7, external flow, since ideal flow solutions are used as the outer boundary conditions for external, boundary layer flows.

Laminar and turbulent flows are treated separately since the analytical approaches are so different. Laminar internal or external flows are solvable analytically or numerically without resort to experiments, whereas almost all turbulent problems require some empiricism. Further, turbulent flows over planes, within conduits, and through open channels all have nearly identical solutions. Therefore, they are presented together in a logical sequence in one chapter — Chapter 8. The most current and computationally convenient forms of empirical equations are presented. The Navier-Stokes equations are not required, per se, and are not formally developed. If available, only simplified forms would be needed in this book anyway. Hence, valuable time is not wasted by first developing general equations only to simplify them prior to application.

Chapter 9 treats steady, compressible flow and Chapter 10 analysis turbomachinery. Chapter 11 considers final experimental equipment and experimental accuracy and precision.

This book is designed to be used in mechanical, civil, chemical, and aeronautical engineering curricula in one semester or two quarters. The first four chapters should be covered by all curricula. Mechanical engineers should then use Chapters 5 through 8, omitting sections on channel flow; Chapters 10 and 11 can be used in part as time permits. Civil engineering courses should include Chapters 5, 7, 8, and parts of 10 and 11, while chemical engineering students should be exposed to Chapters 7, 8, 10, and 11 with selections from Chapter 5 but omitting open channel flow sections in Chapter 8. Aerospace courses will use Chapters 6 through 9 with selections from 5 and 11, omitting the channel flow sections of Chapters 7 and 8. The text could be used in its entirety in a two-semester course. Each chapter concludes with a summary table of equations designed for easy reference later in the student's professional career.

Finally, I wish to thank several key individuals who greatly assisted me. Darleen McGovern translated my hieroglyphics, assembled the book, and made innumerable changes professionally and in the best possible spirit. Milton Van Dyke shared generously from his marvelous collection of fluid flow photographs. At least six anonymous reviewers improved the organization, completeness, and correctness of the book through their trenchant reviews. Frank Kreith suggested the project and smoothed the publishing path. On a personal level, Dottie Lang accepted my single-minded focus on this project for many months with good humor and understanding.

J. F. K.

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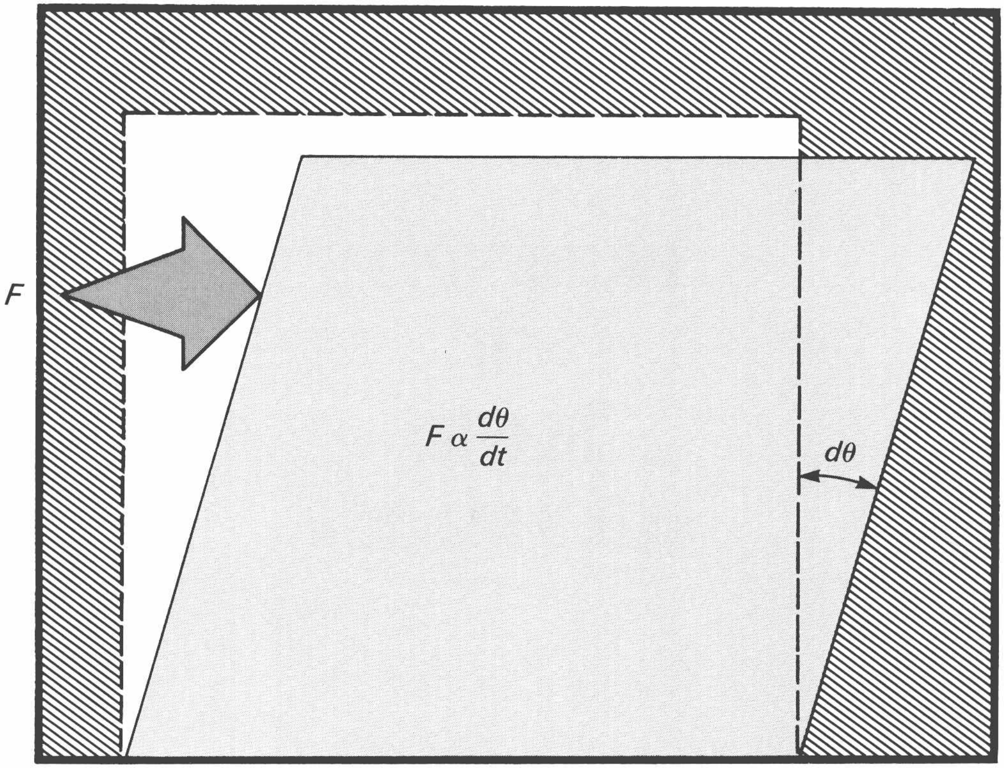
PRINCIPLES OF FLUID MECHANICS


F
$F \alpha \frac{d\theta}{dt}$
$d\theta$

1
Introduction

The objective of this chapter is to introduce the concept of a fluid and the characteristics thereof which govern its behavior in most situations of interest to engineers. The study of fluids is important to many generic engineering disciplines; the dynamic behavior of fluids is an integral part of heat transfer, hydraulics, and aerospace courses. In this chapter fluids are compared to solids to illustrate the unique properties of fluids. A brief historical overview of fluid mechanics is also presented.

WHAT IS A FLUID?

There are a number of ways of distinguishing a fluid from a nonfluid. A layperson might understand the difference when told that a fluid takes the shape of its container while a solid does not. Although this is true, it does not give the engineer much insight relative to the behavior of a fluid. Another way to distinguish between a solid and a fluid is to describe their respective responses to an applied force. If a force is applied *normal* to the surface of a confined fluid, the fluid compresses slightly, much like a solid. The change in fluid volume is linearly related to the applied force for small forces.

The key difference between a solid and a fluid is very apparent when a *tangential* force is applied to an unconfined volume of each. The solid will react and a small relative displacement called *strain* will result (strain is technically the small displacement divided by an original reference length). However, when a shear force is applied to a fluid, the fluid deforms and continues to deform as long as the force is applied. Experimentally it has been found that the reaction produced in a fluid to a force F is proportional to the *rate* of strain or deformation rather than to the deformation itself as in the case of a solid. Strict proportionality applies only for Newtonian fluids. Figure 1.1 shows the preceding characteristic of a fluid schematically.

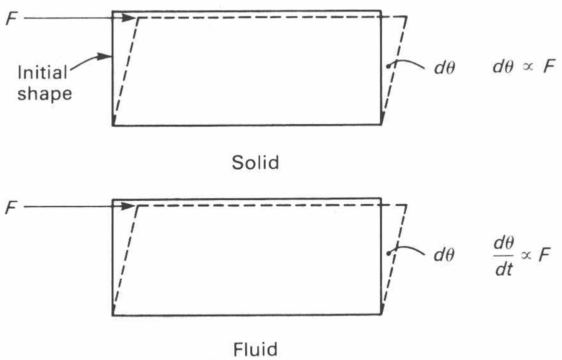
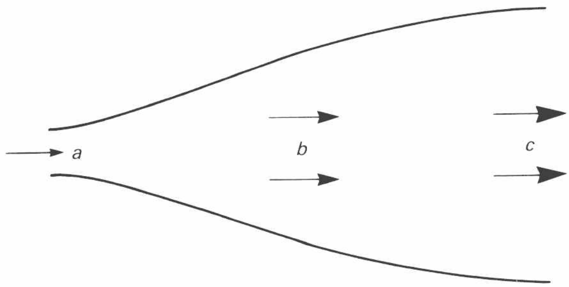


FIGURE 1.1 Relationship between displacements and forces for solids and fluids. Forces are proportional to rates of change of angles such as θ in fluid elements.



Velocity $a >$ velocity $b >$ velocity c

FIGURE 1.2 Fluid particles can move at different speeds at different points in a fluid system. Such motion in solids is impossible.

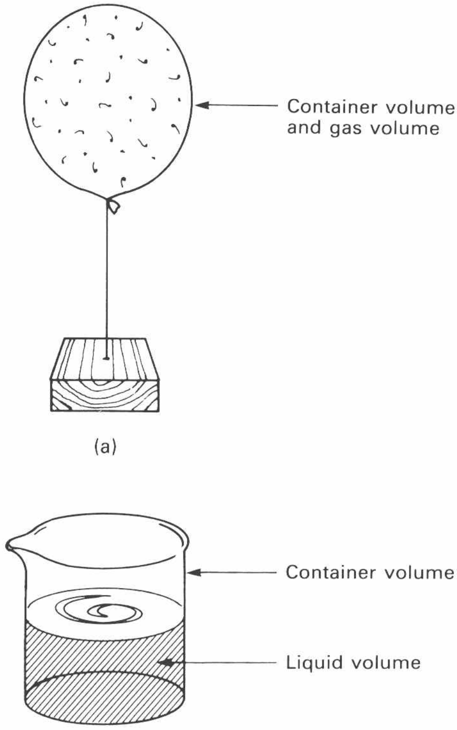
Another difference between a solid and a fluid is the nature of translational motion in each. When a solid body moves, all molecules of the solid remain in the same geometric relation to one another. However, when a fluid moves in translation, all molecules need not maintain their respective positions. Another way of stating this characteristic is that the relative velocity of particles in a solid in translation is zero, whereas in a fluid it need not be zero. Figure 1.2 shows a diverging section of pipe. Leonardo da Vinci discovered that the mass flow at each section of such a pipe must be the same. Since the flow area increases in the direction of flow, the velocity must decrease. Consequently in the system of Fig. 1.2 downstream fluid particles move more slowly than upstream ones, a phenomenon experienced only with fluids.

Solids and liquids also differ in their rotational motion characteristics. Molecules or particles in a solid matrix rotate with zero relative motion. Fluids may move in this fashion, although it is more common for shear to exist, causing relative motion of the fluid particles. A common example is the vortex in a cup of tea just after stirring has stopped. Fluid velocities differ at each point along any radius.

Two Classes of Fluids—Liquids and Gases

Fluids can be divided into two groups with fundamentally different characteristics. Liquids and gases differ in nearly all the physical characteristics of interest to the fluids engineer. However, both are fluids. A familiar difference between the two is the ability of gases to occupy uniformly any volume in which they are confined. But liquids occupy a volume that is not related to the volume of the confining container. The upper surface (in the presence of gravity) forms the free surface of the liquid volume as shown in Fig. 1.3.

Liquids and gases differ in their behavior when compressed. When a liquid is compressed, it changes volume only slightly relative to the volume change a gas would undergo when exposed to the same force. To illustrate this compare water to air. If water is compressed, its volume decreases only 0.005% per applied atmo-



(b)

FIGURE 1.3 (a) Gases expand to fill uniformly the container in which they are confined; (b) liquids maintain a fixed volume independent of the container volume.

sphere. However, under a pressure change from 1 to 2 atmospheres (atm), the volume of air will be reduced by 50% as required by the ideal gas law. At higher pressures, the relative change in air volume is smaller, but the difference between air and water compressibility is always several orders of magnitude.

The Continuum Model of a Fluid

When we analyze a physical situation such as the flow of a fluid, we use a model. A model is a conceptual analog of a physical situation which embodies all important characteristics of the physical situation. The selection of the model must be done with care since all analytical results are derived from the conceptual model. A well-known physical principle is Newton's second law, which stipulates that forces applied to a body determine its acceleration according to a linear mathematical relationship. The second-law equation, $F = ma$, is the *mathematical model* of this particular characteristic of the universe.

In our study of fluid mechanics, we use many models. The most fundamental model has to do with the nature of fluids. Although we know that a fluid consists of atoms or molecules, it is difficult and inconvenient to describe fluid behavior in this context. The molecular approach to fluid mechanics becomes analytically unwieldy when applied to all but the most simple monatomic gases. The mechanics of real fluids are almost always based upon the continuum model which asserts that a fluid does not consist of discrete particles but is rather a continuum within which the variation of properties from one point to another occurs continuously and not by discrete steps. This assumption immediately permits the use of the calculus to analyze fluid behavior.

The validity of the continuum model has been well established since the results of analyses based upon this model agree very well with careful experiments. The reason that the continuum model is useful is that the phenomena being analyzed occur on a physical size scale much larger than the atomic-molecular scale. Therefore, the representation of a real fluid by this model is justifiable if the important, molecule-caused characteristics of the fluid are included in the model.

IMPORTANT CHARACTERISTICS AND PROPERTIES OF FLUIDS

Throughout this text various properties of fluids will be used repeatedly. In this section we define each property, give its units, and provide conversions between various common sets of units. Illustrative values of important properties will be given.

Pressure

Pressure is defined as the normal stress (force per unit area) at a point on any plane in a fluid at rest. Since pressure is a stress, it is a member of the class of surface forces, distinct from body forces discussed below. Pressure is taken to be positive in compression in keeping with the solid mechanics sign convention. Only very pure fluids are capable of sustaining a tensile stress; hence, in this book we always deal with positive pressure.

Mathematically, pressure is defined by Eq. (1.1).

$$p \equiv \lim_{A \to 0} \frac{F}{A} \qquad \textbf{(1.1)}$$

where F is the normal force applied to vanishingly small area A. Using our continuum model, we permit A to approach zero even though a real fluid has a lower area limit determined by the pertinent molecular scale.

In the above definition of pressure the force can be expressed in pounds (lb_f) or Newtons (N) and the area in square feet, square inches, or square meters. The resulting most common units for pressure are then lb_f per square foot (psf), lb_f per