A Treatise in Fluid Dynamics

流体动力学专论

Wen L. Chow and Yan Yong
周文隆 熊 焰 著

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Abstract

A Treatise in Fluid Dynamics is a textbook for beginning engineering students who have background of basic calculus and physics. This textbook follows a typical sequence of topics of dynamics of fluids by starting with an introduction to the subject, concentrating on terminologies, simple concepts, and clarifying adoption of the system and control volume approach to describe the motion of the fluid. It then follows by unsteady impressible incompressible flows, impressible potential flows, numerical computation of fluid dynamic problems, viscous flows, and open channel flows. A large numbers of examples, such as sluice gate, a sharp crested weir, jet-plate interaction, etc., are presented throughout the textbook to emphasize the applications of fluid dynamics to various practical problems. Some simple Fortran computer programs are provided for calculating incompressible potential flow past simple geometrical bodies based upon surface source distributions and other problems. As this textbook is the extended version of the lecture notes prepared by the first author throughout his career of teaching and research in the areas of gas dynamics, fluid dynamics and thermodynamics at the University of Illinois at Urbana-Champaign and Florida Atlantic University, it can serve as a useful reference book for graduate students and researchers in the related technical fields.

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Preface

This book is an extended version of the set of notes which the first author started to prepare and collect, when he began his career of teaching and research in the area of Gas Dynamics, Fluid Dynamics, and Thermodynamics, at the University of Illinois, and continued later at Florida Atlantic University. There are many reasons that we are publishing these materials as a textbook for the beginning engineering students in any universities or four-year colleges in this area. Fluid Dynamics is certainly a fascinating area with many special features in engineering. Thus, their utmost motivation in publishing this book is to share with the beginning students, their experience of learning of materials in the phenomena of flow of fluids.

Since the advent of high speed computers, we have learned much more, even at the basic and elementary levels, on many simple problems. This is of course obtained and established from their own research findings. They feel strongly that more complete stories concerning many simple and interesting problems must be told to the beginning students. Few of these examples are the flow through a sluice gate, a sharp crested weir, a jet-plate interaction, and vena – contracting flows. Thus, they are motivated to publish a textbook which will be useful for both ordinary undergraduate students, and more advanced engineering students.

The arrangement of materials in this book follows a typical sequence of topics of dynamics of fluids for a beginner with the background of basic calculus and physics. Chapter one serves as an introduction to the subject of fluid dynamics, concentrating on the terminologies, simple concepts, and clarifying the adoption of the system (or Largrangian) and control volume (or Eulerian) approach to describe the motion of the fluid. Basic equations are given in both system and control volume approach and their transformation relationship between them. Since inviscid flow treatment is emphasized, Bernoulli's principle is derived first, and shows the Bernoulli's constant is constant throughout the flow, if flow is irrotational. The stream function is also defined and introduced. Chapter two deals with the unsteady incompressible flow. Examples introduce the flow approaching to their steady flow solutions. Some examples of spherical symmetry are also introduced. Chapter three discusses the incompressible potential flow. It shows the irrotationality is the necessary and sufficient condition for the potential flow. The governing Laplace equation is linear; emphasizing the principle of superposition. After the elementary axially symmetric flows are introduced, the powerful method of surface-source distribution is subsequently discussed, including its application to calculating airfoils with angle of attack. Chapter four deals with numerical computation of fluid dynamic problems. It points out the differences between the elliptic, parabolic and hyperbolic types of differential equations governing all fluid dynamic problems. The method of hodograph transformation is introduced, showing its expedient character to deal with those flows with the effect of gravity controlling the flow. The flows associated with free overfall, a sluice gate, a sharp-crested weir, Vena-contracting effects and jet-plate interaction are presented in details. Chapter five presents viscous flow of fluids. It points out the ubiquitous character of turbulent flows. Fully developed laminar flows are introduced first. The method of solving the homogenous Poisson equation in the rectangular domain is introduced to illustrate the usefulness to the similar problem in the heat conduction with a uniform heat generation in the same rectangular domain. The boundary layer concept was thoroughly discussed, and illustrated through the numerical solution of the Falkner-Skan equation. A section is devoted to study the separated flows leading to the conclusion that the base-drag always contributed a significant portion of the total drag experienced by any body in flight. A brief review of the turbulence modeling up to the present is also given. It is pointed out that the work done by Professors Gao and Yong (the second author), which does not contain any empirical constant, nor the service of the wall function for the flow near the wall. This is a tremendous achievement in the area of turbulent flows. It is now concluded that the turbulent flows, seemly governed by stochastic nature, is now believed to be deterministic after all. Chapter six deals exclusively with open channel flows. The definitions of static head, dynamic head, total head. Energy grade line, hydraulic grade line and uniform flows are clarified and the assumption of hydrostatic pressure distribution is always valid, which offers considerable limitations to the flow. Since Manning's formula has been established through extensive testing, it is assumed that it is applicable to all open-channel flows. It is also pointed out that there is considerable similarity between the open-channel flow and compressible gas flow. The governing dimensionless parameter in open channel flow is the Froude number, while that for the compressible gas flow is the Mach number. The similarity between the hydraulic jump and shock wave, the super-critical flow ($Fr>1$), and streaming water flow($Fr<1$) and the supersonic flow ($Ma>1$), and the subsonic flow ($Ma<1$) are the obvious different inviscid flow regimes even though the fluids are really viscous. The accessibility of flow regimes in open channel flows are presented and discussed. The specific energy for flows with arbitrary Cross-sectional area are defined and discussed. Some flow cases, such as the flow of a free overfall, and the flow through a sluice gate, and the sharp-crested weir, are again introduced and examined through a series of examples indicating that the influence of the downstream sharp crested weir to the upstream sluice gate flows are introduced to show the down stream influences affecting the upstream flows.

Some simple Fortran computer programs, for calculating incompressible potential flow past simple geometrical bodies based upon surface-source distributions, and other problems are also available in the disk along with the textbook.

The first author is deeply grateful to his teacher at the University of Illinois at Champaign-Urbana, Illinois, Professor Helmut H. Korst, for not only learning the basics from him as a teacher, but also working as a colleague, doing research in Separated Flows. Certainly his direct or indirect influence to the authors in writing this book can never be underestimated. The first author is also greatly indebted to his colleague, Dr. Tad Alva L. Addy, whose indelible effort in the early stage of this project can be found everywhere in this book. The first author is also very grateful to Prof. B. T. Chao, who is a teacher, a friend of the first author, and a research colleague working together in the area of slip flows. Finally, the first author is deeply indebted to his wife, Rhoda, whose incessant support in many ways to this effort made the completion of this project possible.

Boca Raton
Florida
USA
2008. 9

Date: June 16, 2008

This is to certify that this is a photo-copy of the USA Passport of Mr. Wen Lung Chow (or Wen L. Chow), who is an American citizen of USA (Passport Number P209578168). This is also to certify that the person who holds this document, is Dr. Yan Yong. In the absence of Mr. Chow, Mr. Yong shall assume the authority of representing Mr. Chow in dealing any legal matters related to Mr. Chow.

Wen L. Chow

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CHAPTER 1 BASIC EQUATIONS GOVERNING THE FLOW OF FLUIDS

The phenomenon of flow of fluid appears everywhere in nature. Flows of water in the river and the lake, movements of ocean currents and air streams within the atmosphere, are few of the numerous examples surrounding us. Flights of airplanes or rockets, movements of land vehicles on the ground, and ships in the river, all involve the mechanics of fluid. Such a diversified and pervasive area of flow of fluid is so important that we must have a comprehensive understanding of the physical events related to the flow of fluid.

Fluid dynamics is a special branch of science dealing with the motion of any fluid. It is an important and basic discipline that almost any practical engineer must have some understandings in this area. In some situations, the phenomenon associated with the flow of a fluid may be so complicated that it is difficult to identify any important mechanisms of the physical event. We should realize, however, that the motion of any material must be governed by the basic principles. Thus, our primary objective in the study of fluid dynamics is to attempt to explain the motion of a fluid through basic principles and to understand the motion of the fluid under any conditions.

1.1 BASIC PRINCIPLES

Basic principles, which will be applied to study the mechanics of a fluid, are:

- The conservation of mass;
- The conservation of momentum, or the Newton's Second Law of Motion;
- The conservation of energy, or the First Law of Thermodynamics.

Other principles are involved with the flow of fluid and will be presented and discussed at appropriate times. But the three listed above are fundamental to the study of fluid mechanics. We must accept these basic principles since nothing has been observed in nature, which is contradictory to these principles. Our task then is to apply these fundamental principles to the region of fluid in motion. The methods of application of these principles will be discussed in later sections. Before we begin such a detailed study, we must familiarize ourselves with the important concepts, ideas, and terminology involved with the study of fluid in motion. Also, we must know the properties of the fluid, which we shall be dealing with.

1.2 BASIC CONCEPTS IN THE FORMULATION OF THE FLOW OF A FLUID

To study the motion of a fluid, we must identify a fluid element and describe the flow events associated with it. One way of doing this is to identify a particular element of fluid and describe the detailed motion of this element. This is the familiar kind of description adopted to study the dynamics of a particle or a rigid body, and is called the particle or Lagrangian approach. However, this is not a convenient way to study the motion of a fluid. Another way to describe a fluid motion is to specify the flow properties of the fluid at a specific location within a physical region; this is the field or Eulerian approach; and is adopted here to study the motion of the fluid. The weather map is a good example of the Eulerian approach. Since all principles of conservation are always referring to a specific mass of fluid (the Lagrangian approach), and we shall adopt the Eulerian approach in our study, we must discuss these two schemes in detail and establish the relationship of transformation between them.

1.2.1 Lagrangian Formulation

Within the Lagrangian scheme, we focus our attention on a particular element of the fluid and describe its flow events as time proceeds. For example, we may express the spatial location of an element of fluid as a function of time, t: $X(t)$, $Y(t)$, and $Z(t)$. The velocity and acceleration of this element of fluid is found by differentiating these functions with respect to t. We may also use functions of the form $P(t)$, $T(t)$, and $\rho(t)$ to express, respectively, the pressure, temperature, and density of this element of fluid as functions of time. However, to make this representation meaningful, we must have some means to identify these quantities for each fluid element in the flow field. One way of identifying a fluid element is to define its spatial location at a given time. For example, when $t=t_0$, we assume that the selected element of fluid is located at $X(t_0)=a$, $Y(t_0)=b$, and $Z(t_0)=c$. Thus at any time $t>t_0$, the location of this fluid element is given by functions of the form: $X(a,b,c,t)$, $Y(a,b,c,t)$, and $Z(a,b,c,t)$; these functions depend on both time and the initial location parameters (a,b,c). If the values of these initial location parameters are changed, e.g., into (a',b',c'), we are then describing these relations for different elements of the fluid. Thus, the initial location parameters identify fluid elements throughout the flow-field. The Lagrangian formulation of fluid motion is depicted in Fig. 1. 1.

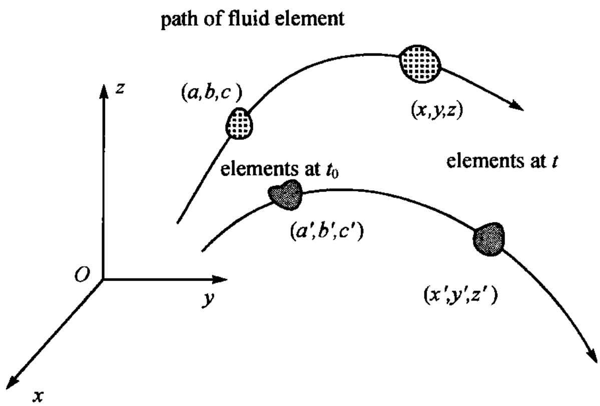

Fig. 1. 1 Path of Different Fluid Elements

Although we shall not employ the Lagrangian method of flow description, a conceptual understanding of this approach is nevertheless important, since all basic principles are given in this Lagrangian scheme. Again, we may simply say that X, Y, and Z are functions of time, t, in the Lagrangian scheme of description.

1.2.2 Eulerian Formulation

Rather than focusing our attention on a particular element of fluid in the flow field and following its motion, the Eulerian scheme of formulation describes the fluid motion at a specific spatial location in the flow field at a certain time. For example, if $\bar{V}(x,y,z;t)$ is the velocity field which describes the fluid velocity at a location (x,y,z) and time t, this function describes the variation of the velocity vector of the fluid throughout the space and with time. In the Eulerian approach, the spatial coordinates, (x,y,z), and time, t, are all independent. The velocity field, temperature field, density field, etc., are all typical properties of interest within the Eulerian method of description. This Eulerian scheme of describing the fluid motion is depicted in Fig. 1. 2. Thus, we may simply say that x, y, z and t are all independent variables in the Eulerian method of description.

Since all fundamental principles of mechanics and thermodynamics are specified for a particular element of matter (or a region of matter), we must develop the transformation relationship between the Lagrangian and the Eulerian schemes.

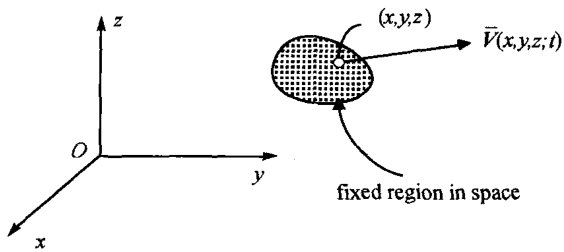

Fig. 1.2 Fluid Motion Described by Eulerian Scheme

1.2.3 Differentiation in the Eulerian Scheme

To initiate the discussion of transformation between the Lagrangian and the Eulerian schemes, the local fluid density, ρ, is selected for consideration. The function $\rho(x, y, z; t)$ represents the density of a fluid as a function of the space coordinates, (x, y, z), and time, t. The change in density, $\mathrm{d}\rho$, between two points separated spatially by $\mathrm{d}x, \mathrm{d}y, \mathrm{d}z$ and in time $\mathrm{d}t$, is given by

$$\mathrm{d}\rho = \frac{\partial\rho}{\mathrm{d}x}\mathrm{d}x + \frac{\partial\rho}{\partial y}\mathrm{d}y + \frac{\partial\rho}{\partial z}\mathrm{d}z + \frac{\partial\rho}{\partial t}\mathrm{d}t$$

The change in density, $\mathrm{d}\rho$, between a point P at (x, y, z, t) in Fig. 1.3 and any arbitrary neighboring point can be determined from the above expression. However, of all the neighborhood points of P, in Fig. 1.3, there is only one point P' at time $t+\mathrm{d}t$, where the fluid occupied the point P at time t. Thus, the two points P and P' are linked by the fact that they were occupied at the times t and $t+\mathrm{d}t$, respectively, by the same element of fluid due to the fluid motion. The change in density, $\mathrm{d}\rho$, between these two points, P and P', now represents the change in density of this particular element of fluid and $\mathrm{d}x$, $\mathrm{d}y$ and $\mathrm{d}z$ are precisely the distances traveled by this element of fluid within the time interval $\mathrm{d}t$. In order to attach special meaning to these differential quantities under this condition, a special notation is adopted. This differential change of density is written in this notation as

$$\mathrm{d}\rho = \frac{\partial\rho}{\partial x}\mathrm{d}x + \frac{\partial\rho}{\partial y}\mathrm{d}y + \frac{\partial\rho}{\partial z}\mathrm{d}z + \frac{\partial\rho}{\partial t}\mathrm{d}t \tag{1.1}$$

The change in density, $\mathrm{d}\rho$, between these two points, P and P', now represents the change in density of this particular element of fluid. The term $\mathrm{d}\rho$ is the infinitesimal change in the dependent variable, ρ, of the same element of the fluid, and the distances $\mathrm{d}x$, $\mathrm{d}y$, $\mathrm{d}z$ are precisely the distances traveled by the same fluid element within the time interval $\mathrm{d}t$. After dividing by $\mathrm{d}t$, we obtain

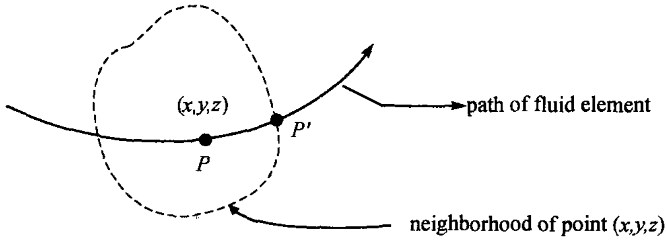

Fig. 1.3 Points P and P' are Occupied by the Same Fluid Element at Different Times of t and $t + \mathrm{d}t$ Respectively

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{\partial \rho}{\partial x}\frac{\mathrm{d}x}{\mathrm{d}t} + \frac{\partial \rho}{\partial y}\frac{\mathrm{d}y}{\mathrm{d}t} + \frac{\partial \rho}{\partial z}\frac{\mathrm{d}z}{\mathrm{d}t} + \frac{\partial \rho}{\partial t}$$

If the components of the velocity vector, $\bar{\mathbf{V}}$, in the Cartesian system of coordinates are denoted by

$$V_x = \frac{\mathrm{d}x}{\mathrm{d}t} = u, \qquad V_y = \frac{\mathrm{d}y}{\mathrm{d}t} = v, \qquad V_z = \frac{\mathrm{d}z}{\mathrm{d}t} = w$$

the above equation becomes

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{\partial \rho}{\partial t} + V_x\frac{\partial \rho}{\partial x} + V_y\frac{\partial \rho}{\partial y} + V_z\frac{\partial \rho}{\partial z} = \frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + v\frac{\partial \rho}{\partial y} + w\frac{\partial \rho}{\partial z} \qquad (1.2)$$

with u, v, w as the components of the velocity vector in the Cartesian system of coordinates. This equation can be rewritten in a compact form using the velocity vector, $\bar{\mathbf{V}}$, and the vector operator, ∇. With this notation, Eq. (1.2) can be expressed as

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{\partial \rho}{\partial t} + (\bar{\mathbf{V}} \cdot \nabla)\rho \qquad (1.3)$$

The symbol$(\bar{\mathbf{V}} \cdot \nabla)$represents the summation of terms given by

$$V_x\frac{\partial}{\partial x} + V_y\frac{\partial}{\partial y} + V_z\frac{\partial}{\partial z}$$

which is obtained directly from the rule of dot multiplication of the velocity vector

$$\bar{\mathbf{V}} = \bar{\mathbf{i}}V_x + \bar{\mathbf{j}}V_y + \bar{\mathbf{k}}V_z$$

and the vector operator

$$\nabla = \bar{\mathbf{i}}\frac{\partial}{\partial x} + \bar{\mathbf{j}}\frac{\partial}{\partial y} + \bar{\mathbf{k}}\frac{\partial}{\partial z}$$

when expressed in the Cartesian coordinate system: (x, y, z). In Eq. (1.3), $\partial\rho/\partial t$ represents the time rate of change of density at a fixed (x, y, z) location and $(\bar{\mathbf{V}} \cdot \nabla)\rho$ represents the time rate of change of density experienced by the fluid element due to its movement within the region of density variation. This is easily understood that in a unit time, the fluid travels a distance of V_x in the x direction, and it would experience the density change of $V_x\partial\rho/\partial x$