

DONALD F. YOUNG
BRUCE R. MUNSON
THEODORE H. OKIISHI

A BRIEF INTRODUCTION TO
FLUID MECHANICS

2ND
EDITION

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This book was set in Times Roman by York Graphic Services and printed and bound by R.R. Donnelley & Sons.
The cover was printed by Phoenix Color Corp.

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Library of Congress Cataloging in Publication Data:

Young, Donald F.

A brief introduction to fluid mechanics / Donald F. Young, Bruce R. Munson, Theodore

H. Okiishi—2nd ed.

p. cm.

Includes bibliographical references.

ISBN 0-471-36243-3 (alk. paper)

I. Fluid mechanics. I. Munson, Bruce Roy, 1940– II. Okiishi, T. H. (Theodore Hisao), 1939– III. Title.

TA357.Y68 2000

620.1'06—dc21

00-025726

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Newton's Second Law—The Linear Momentum and Moment-of-Momentum Equations

5.2.1 Derivation of the Linear Momentum Equation

Newton's second law of motion for a system is

$$\frac{D}{Dt} \int_{\text{sys}} \mathbf{V} \rho dV = \sum \mathbf{F}_{\text{sys}}$$

Since momentum is mass times velocity, the momentum of a small particle of mass ρdV is $\mathbf{V} \rho dV$. Thus, the momentum of the entire system is $\int_{\text{sys}} \mathbf{V} \rho dV$ and Newton's law becomes

$$\frac{D}{Dt} \int_{\text{sys}} \mathbf{V} \rho dV = \sum \mathbf{F}_{\text{sys}} \quad (5.14)$$

When a control volume is coincident with a system at an instant of time, the forces acting on the system and the forces acting on the contents of the coincident control volume (see Fig. 5.2) are instantaneously identical, that is,

$$\sum \mathbf{F}_{\text{sys}} = \sum \mathbf{F}_{\text{contents of the coincident control volume}} \quad (5.15)$$

Furthermore, for a system and the contents of a coincident control volume that is fixed and nondeforming, the Reynolds transport theorem (Eq. 4.17 with b set equal to the velocity, and B_{sys} being the system momentum) allows us to conclude that

$$\frac{D}{Dt} \int_{\text{sys}} \mathbf{V} \rho dV = \frac{\partial}{\partial t} \int_{\text{cv}} \mathbf{V} \rho dV + \int_{\text{cs}} \mathbf{V} \rho \mathbf{V} \cdot \hat{\mathbf{n}} dA \quad (5.16)$$

or

$$\begin{array}{lcl} \text{time rate of change} & & \text{time rate of change} \\ \text{of the linear} & & \text{of the linear} \\ \text{momentum of the} & = & \text{momentum of the} \\ \text{system} & & \text{contents of the} \\ & & \text{control volume} \end{array} \quad + \quad \begin{array}{l} \text{net rate of flow} \\ \text{of linear momentum} \\ \text{through the} \\ \text{control surface} \end{array}$$

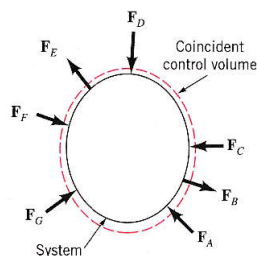


FIGURE 5.2 External forces acting on system and coincident control volume.

Equation 5.16 states that the time rate of change of system linear momentum is expressed as the sum of the two control volume quantities: the time rate of change of the *linear momentum of the contents of the control volume*, and the net rate of *linear momentum flow through the control surface*. As particles of mass move into or out of a control volume through the control surface, they carry linear momentum in or out. Thus, linear momentum flow should seem no more unusual than mass flow.

For a control volume that is fixed (inertial) and nondeforming, Eqs. 5.14, 5.15, and 5.16 suggest that an appropriate mathematical statement of Newton's second law of motion is

$$\frac{\partial}{\partial t} \int_{cv} \mathbf{V} \rho dV + \int_{cs} \mathbf{V} \rho \mathbf{V} \cdot \hat{\mathbf{n}} dA = \sum \mathbf{F}_{\text{contents of the control volume}} \quad (5.17)$$

We call Eq. 5.17 the *linear momentum equation*.

The forces involved in Eq. 5.17 are body and surface forces that act on what is contained in the control volume. The only body force we consider in this chapter is the one associated with the action of gravity. We experience this body force as weight. The surface forces are basically exerted on the contents of the control volume by material just outside the control volume in contact with material just inside the control volume. For example, a wall in contact with fluid can exert a reaction surface force on the fluid it bounds. Similarly, fluid just outside the control volume can push on fluid just inside the control volume at a common interface, usually an opening in the control surface through which fluid flow occurs.



V5.4 Force due to a water jet

5.2.2 Application of the Linear Momentum Equation

The linear momentum equation for the inertial control volume is a vector equation (Eq. 5.17). In engineering applications, components of this vector equation resolved along orthogonal coordinates, for example, x , y , and z (rectangular coordinate system) or r , θ , and x (cylindrical coordinate system), will normally be used. A simple example involving one-dimensional, steady, incompressible flow is considered first.

EXAMPLE 5.5

As shown in Fig. E5.5a, a horizontal jet of water exits a nozzle with a uniform speed of $V_1 = 10$ ft/s, strikes a vane, and is turned through an angle θ . Determine the anchoring force needed to hold the vane stationary. Neglect gravity and viscous effects.

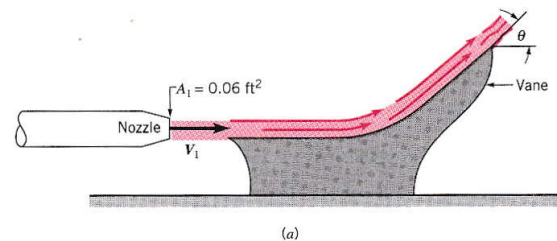


FIGURE E5.5a