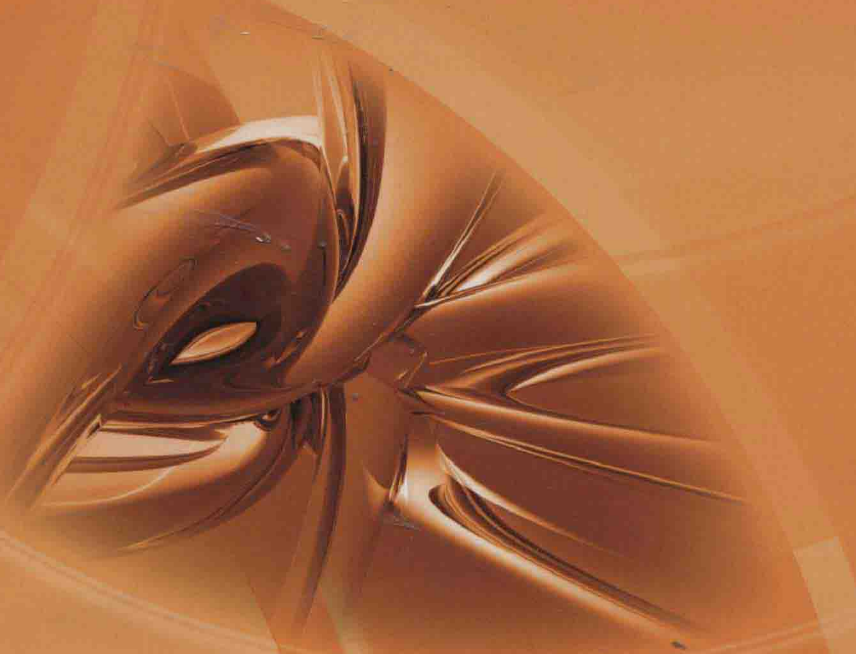
工业和信息化部“十二五”规划教材

HYDRODYNAMICS AND HYDRAULIC TRANSMISSION

流体力学及液压传动

Wang Xiufeng Zhou Hong

王秀凤 周 洪 编著



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内 容 简 介

Based on the author's rich teaching experience, this textbook is an accumulated effort to systematically and comprehensively introduce the fundamentals of hydrodynamics and hydraulic transmission. This textbook is roughly divided into hydrodynamics (20%) and hydraulic transmission (80%).

This is an English—language textbook for international students and undergraduates in Mechanical Engineering, with the 38 recommended teaching hours. The accompanying CD-ROM is a multimedia CAI courseware carefully made to assist teaching.

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Preface

In China, international student education has become an important new growth point of higher education development, and is also an important part of China's international affairs. With the internationalization of higher education, many international students would like to study in China's universities or colleges. Therefore, the internationalization process is greatly promoted in China. At the same time, the specialty teachers face challenges for teaching specialty courses in English, in which the textbooks as the course materials are obviously very important requirements.

Hydrodynamics and hydraulic transmission course is a specialty basic compulsory course for Mechanical Engineering, and has the engineering application background strongly. Textbook is the basic carrier to implement the curriculum teaching. Based on the author's rich teaching experience, this textbook is an accumulated effort to systematically and comprehensively introduce the fundamentals of hydrodynamics and hydraulic transmission. This textbook is roughly divided into hydrodynamics (20%) and hydraulic transmission (80%). Hydrodynamics discusses the physical properties, statics and dynamics of the fluid, which is the necessary foundation to understand hydraulic transmission. Hydraulic transmission discusses various components of the hydraulic system, their structural characteristics, operating principles and performance, as well as the performance of various control circuits containing those components, and the design and calculation of typical hydraulic system. This textbook focuses on the explanation of basic knowledge and basic concept, and has the characteristics of specification language, easy to understand, clarity, expressing the profound things in a simple way and the combination theory with actual. Furthermore, the design and arrangement of this textbook are suitable for the teaching regularity and students' cognitive regularity, and promote the coordinative development of students' knowledge, ability and quality. There is a CD - ROM multimedia CAI courseware accompanying this textbook. It improves the teaching effect and quality by manufacturing all kinds of vivid animation to learn and understand easily using AutoCAD、Flash、Photoshop、Animationpro and virtual reality technology. Therefore, the curriculum teaching is implemented lively and interestingly, and the international students can obtain more knowledge and information in the limited teaching hours. It can be met that the requirements of both the international students teaching in English and the bilingual education to cultivate the international compound talents for Chinese students.

This textbook can be regarded as the English teaching materials in mechanical design

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manufacturing and automation, mechanical and electronic engineering, vehicle engineering, material forming and control engineering, mould design and manufacturing, light industry machinery and other mechanical engineering specialty of universities and colleges. Before learning this textbook, the knowledge of advanced mathematics, mechanical design and engineering mechanics should be mastered.

This textbook was written by Xiufeng Wang, Hong Zhou, participated by Tianyu Zhou, audited by Pang-chieh Sui, Yang Zheng and Yu Yan. The multimedia CAI courseware was made by Xiufeng Wang and Bao Meng. This textbook was written with the reference to some excellent textbooks and the related materials, and they played an important reference function, here we would like to appreciate. In addition, it is unavoidable that there are some mistakes in this textbook, so all criticism and corrections from experts and readers are welcome.

Authors

May, 2015 in Beijing

Contents

Chapter 1 Hydraulic Oil and Fundamental Hydraulic Fluid Mechanics

Hydraulic transmission transmits energy and signals by the hydraulic oil. Thus, the quality of hydraulic oil-the pros and cons of both physical and chemical properties, especially its mechanical properties has a great influence on the efficiency of hydraulic transmission system. Before the study of hydraulic transmission system, we should understand the hydraulic oil and its mechanical properties deeply in order to further understand the operating principle of hydraulic transmission and lay the foundation for the analysis and design of hydraulic transmission system.

1.1 Hydraulic Oil

1.1.1 Basic physical characteristics

1. Density

Density ρ (kg/m^3) is the fluid mass per unit volume. For a volume V, and mass m, the density of the fluid is described as

$$\rho = \frac{m}{V} \tag{1-1}$$

Density is an important parameter of a fluid. It changes with temperature and hydraulic pressure, but the changes can often be neglected because they are relatively subtle. Usually the density of hydraulic oil is 900 kg/m^3.

2. Compressibility

The compressibility of a hydraulic fluid is a property that volume reduced under the operating pressure. We use the bulk modulus of elasticity K to describe it, and define it as the ratio of the change of hydraulic pressure (Δp) to the change of relative volume ($\Delta V/V$).

$$K = -\frac{\Delta p}{\frac{\Delta V}{V}} \tag{1-2}$$

Usually K of typical hydraulic oils is $(1.4 \sim 2) \times 10^9$ N/m^3. It is negligible when the change of hydraulic pressure is small. If the hydraulic oil is mixed with air, however, its compressibility increases significantly. Such increase in compressibility may impact the performance of a hydraulic transmission system. Therefore, we should prevent air from mixing with the hydraulic oil.

The compressibility is usually not considered in the static analysis and calculation of the hydraulic transmission system.

3. Viscosity

Viscosity can be thought as the internal stickiness of hydraulic oil. Under the action of an external force, the cohesion between the fluid molecules will impede the hydraulic oil to flow, which is called friction force. This is referred to as the viscosity of hydraulic oil. The hydraulic oil has the viscosity property when it flows. The viscosity is an important property in studying of hydraulic oil flow and it is the basis of selecting hydraulic oil.

The sketch of viscosity is illustrated by Fig. 1 - 1.

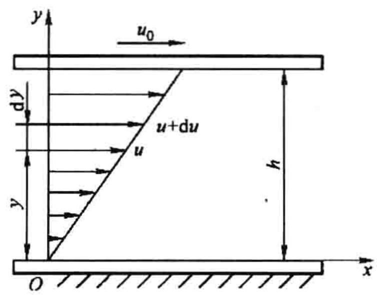


Fig. 1 - 1 Sketch of viscosity

The hydraulic oil is sandwiched between two paralleled plates and the lower plate is kept unmoved. The upper plate with a velocity u_0 moves to the right. Because of the cohesive force between the fluid molecules and the walls of plates, the hydraulic oil velocity close to the upper plate is u_0, and the hydraulic oil velocity close to the lower plate is zero. Therefore, the viscosity distribution between layers decreases linearly from top to bottom.

The experiments have proved that friction force between the fluid layers can be described as

$$F_f = \mu A \frac{\mathrm{d}u}{\mathrm{d}y} \tag{1-3}$$

where μ= viscosity coefficient, also dynamic viscosity;

A= contact area between the fluid layers;

$\frac{\mathrm{d}u}{\mathrm{d}y}$= velocity gradient, which is the ratio of the hydraulic oil velocity along the plate clearance direction (y direction).

Eq. (1 - 3) is Newton's law for inner friction. It means that the viscosity of hydraulic oil is the fiction on per unit of area under per unit of velocity gradient.

Define τ as the friction force per unit area A

$$\tau = \frac{F_f}{A} \tag{1-4}$$

Substitute Eq. (1 - 3) into Eq. (1 - 4), we have

$$\tau = \mu \frac{\mathrm{d}u}{\mathrm{d}y} \tag{1-5}$$

The viscosity of hydraulic oil can be expressed in three ways, namely, dynamic viscosity (absolute viscosity), kinematic viscosity and relative viscosity.

(1) Dynamic viscosity (absolute viscosity) (Pa · s)

Rearrange Eq. (1 - 5)

$$\mu = \frac{\tau}{\frac{\mathrm{d}u}{\mathrm{d}y}} = \tau \frac{\mathrm{d}y}{\mathrm{d}u} \tag{1-6}$$

It means that if $\frac{du}{dy}=1$, then $\mu=\tau$, the inner friction force on per unit area of hydraulic oil between the fluid layers is called dynamic viscosity or absolute viscosity.

(2) Kinematic viscosity (m^2/s)

The kinematic viscosity ν is the ratio of absolute viscosity to fluid density, which is used in the analysis and calculation on hydraulic transmission system.

$$\nu = \frac{\mu}{\rho} \tag{1-7}$$

For example, No 10 machine hydraulic oil means that the average of fluid kinematic viscosity is 10 mm^2/s at 40 ℃, which is described as $\nu_{40}=10\ mm^2/s$.

(3) Relative viscosity

The relative viscosity is the viscosity tested by the special viscometer under a given condition, so it is also called conditional viscosity. The unit of relative viscosity is different according to different testing conditions, such as °E in China, SSU in the US, and R in England.

4. Viscosity-temperature relationship

The hydraulic oil viscosity is heavily affected by temperature of fluid. It is noted that the viscosity decreases with the increase of temperature, and rises the hydraulic oil leakage temperature so as to affect the performance of hydraulic transmission system. It is recommended that control the change of viscosity-temperature in a smaller scale to achieve a better performance.

5. Viscosity-pressure relationship

The viscosity of hydraulic oil increases with the rise of hydraulic pressure, because the distances between fluid molecules are reduced. Under lower hydraulic pressure (<5 MPa), we may neglect its effect. However, when hydraulic pressure is up to 10 MPa, we should consider pressure effect so that we can meet most requirements in engineering applications. We can calculate the viscosity as

$$\nu_p = \nu_0 e^{bp} \approx \nu_0 (1+0.03p) \tag{1-8}$$

where: ν_p = kinematic viscosity at pressure p;

ν_0 = kinematic viscosity under an atmospheric pressure;

b = viscosity-pressure coefficient, usually $b=0.002\sim0.003$ for common hydraulic oils;

p = hydraulic pressure.

6. Other characteristics

In addition to the aforementioned characteristics, there are also other considerations for the hydraulic oil, which cover physical and chemical fields, such as anti-inflammability, anti-oxygenation, anti-concreting, anti-foam and anti-corrosion, etc. The performance of hydraulic oil depends on these characteristics and properties. One can refer to the manual of hydraulic oil for further information.

1.1.2 Requirements and selection of hydraulic oil

In a hydraulic transmission system, the hydraulic oil has two functions, i. e., for energy transmission and for lubrication. So it affects the reliability, stability, efficiency and longevity of the hydraulic transmission system. The selection standards for hydraulic oils are an appropriate viscosity, good property in favorable viscosity-temperature, a good lubricity, chemical and environmental stabilities, compatibility with other system materials, heat transfer capability, high bulk modulus, low volatility, low foaming tendencies, fire resistance, good dielectric properties, nontoxic or allergenic, non-malodorous characteristics, low cost, and being easily available.

The viscosity is a key factor in the selection of hydraulic oil. Too high or too low viscosity will harm the hydraulic transmission system. Higher viscosity results in the higher viscous resistance force, and lower viscosity results in larger hydraulic oil leakage. Generally, it is recommended that the hydraulic oil viscosity is 10～60 mm^2/s.

In a typical hydraulic transmission system, if the hydraulic pressure is high, it is better to choose the hydraulic oil with high viscosity so as to reduce leakage; if the velocity is high, it is better to choose the hydraulic oil with low viscosity in order to reduce the pressure loss; if the temperature changes widely, it is better to choose the hydraulic oil with high viscosity and good viscosity-temperature.

To sum up, we should choose the hydraulic oil according to the request of hydraulic pump. Different hydraulic pumps fit for different hydraulic oil viscosity, as listed in Tab. 1-1.

Tab. 1-1 Range of hydraulic oil viscosity adapted to pumps

Types		Viscosity/($mm^2 \cdot s^{-1}$)		Types	Viscosity/($mm^2 \cdot s^{-1}$)	
		5～40 ℃	40～80 ℃		5～40 ℃	40～80℃
Vane Pumps	$p<7$ MPa	30～50	40～75	Gear pumps	30～70	95～165
	$p\geqslant 7$ MPa	50～70	50～90	Radial piston pumps	30～50	65～240
Screw pumps		30～50	40～80	Axial piston pumps	30～70	70～150

1.2 Hydrostatics

For hydrostatic we study the laws when the fluid is stagnant.

1.2.1 Characteristics of static pressure

1. Static pressure of the fluid

Hydraulic pressure is the amount of force per unit area. For the fluid at rest, only normal forces exist. Static pressure is the action of normal force per unit area, N/m^2 or Pa.

Namely

$$p = \frac{F}{A} \tag{1-9}$$

where F is the normal force acting on surface area A.

2. Characteristics

(1) The direction of static pressure always points inwardly to the acting surface.

(2) The values of inside pressures created by a fluid at rest are equal at any point in every direction.

1.2.2 Generation and transmission of static pressure

1. Generation of static pressure

A containeris filled with fluid. The pressure acting on the surface of the fluid is p_0. We calculate pressure p at a depth h point in the fluid shown in Fig. 1 - 2(a). We take a tiny cylindrical element (the length is h, and cross-sectional area is ΔA) as the object. The forces acting on it along y axis are shown in Fig. 1 - 2(b). F_G is the weight, namely

$$F_G = \rho g h \tag{1-10}$$

where g is acceleration of gravity in SI, $g=9.81\ \text{m/s}^2$.

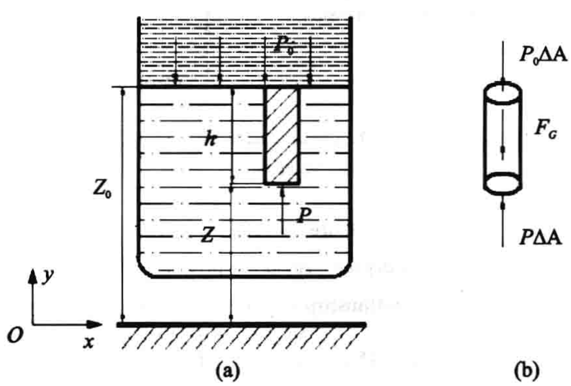


Fig. 1 - 2 Fluid at rest in a container

The static equation of equilibrium of tiny cylindrical element is $\sum F_y = 0$.

$$p\Delta A = p_0\Delta A + F_G\Delta A = p_0\Delta A + \rho g h\Delta A \tag{1-11}$$

Dividing both sides of Eq. (1 - 11) by ΔA, then

$$p = p_0 + \rho g h \tag{1-12}$$

Eq. (1 - 12) is the basic equation for hydrostatics and it shows

(1) Pressure p in the rest fluid involves two parts: surface pressure p_0 and pressure caused by weight $\rho g h$.

(2) Pressure p increases with the increase of depth h.

(3) The pressure of any point at a given depth h is the same, so isobaric surface is horizontal.

(4) Conservation of energy:

Divide both sides of Eq. (1 - 12) by ρg, then

$$\frac{p}{\rho g}=\frac{p_0}{\rho g}+h \tag{1-13}$$

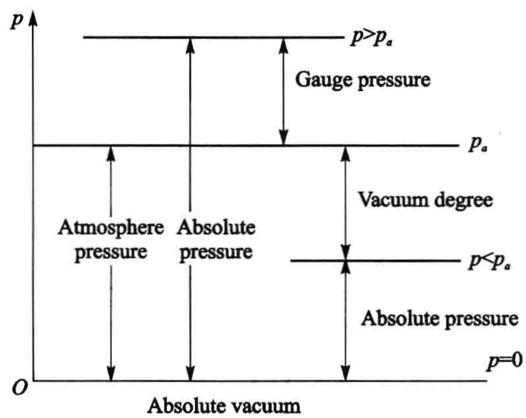
Substitute $h=Z_0-Z$ into Eq. (1 - 13)

$$\frac{p}{\rho g}+Z=\frac{p_0}{\rho g}+Z_0 \tag{1-14}$$

Here, $p/\rho g$ is the hydraulic pressure energy per unit mass fluid, Z is potential energy at per unit mass fluid. Eq. (1 - 14) states that the total energy is conserved at any given point.

2. Definition and units of hydraulic pressure

We describe the hydraulic pressure as absolute pressure, gage pressure and vacuum degree. If p_a is atmospheric pressure, their relationships are shown in Fig. (1 - 3).



Absolute pressure = Gauge pressure $+p_a$

Vacuum degree = Absolute pressure $-p_a$

Fig. 1 - 3 Relationship between hydraulic pressures

The unit of hydraulic pressure in SI is the Pascal (Pa), which is one Newton per square meter (N/m^2). Other engineering units of hydraulic pressure are

$1\ \text{bar}=1\times10^5\ \text{Pa}$, $1\ \text{mH}_2\text{O}=9.8\times10^3\ \text{N/m}^2$, $1\ \text{mmHg}=1.33\times10^2\ \text{N/m}^2$

Example 1 - 1 A container contains the hydraulic oil shown in Fig. 1 - 4. Its density $\rho=900\ \text{kg/m}^3$, force acting on the piston surface $F=1\ 000$ N, piston area $A=1\times10^{-3}\ \text{m}^2$. Neglecting the piston mass, try to calculate the static pressure p at $h=0.5$ m.

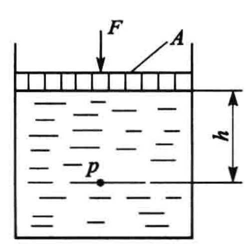


Fig. 1 - 4 Calculation of fluid static pressure

Solution

According to Eq. (1 - 12), the pressure at depth h,

$$p=p_0+\rho gh$$

Here $$p_0=\frac{F}{A}=\frac{1\ 000}{1\times10^3}=10^6\ (\text{Pa})$$

Therefore $p = p_0 + \rho g h = 10^6 + 900 \times 9.81 \times 0.5 = 1.0044 \times 10^6$ (Pa)

From this example, the hydraulic pressure caused by fluid weight ($\rho g h$) is relatively small and $p \approx p_0 = 10^6$ Pa, so it is often neglected in the later chapters of this book.

3. Transmission of static pressure

Pascal's law states that the hydraulic pressure exerted on a confined fluid is simultaneously transmitted in all directions and acts with equal force on all areas. It is also called as the static transmission principle. Its application is shown in Fig. 1 - 5.

Assume the area of the bigger cylinder is A_1, and the force acting on the big piston is F_1, so the hydraulic pressure is $p_1 = \frac{F_1}{A_1}$. If the area of the smaller cylinder is A_2, the force acting on the small piston is $F_2 = p_2 A_2$. Accounting to Pascal's law, $p_1 = p_2$, then

$$F_2 = p_2 A_2 = \frac{A_2}{A_1} F_1 \qquad (1-15)$$

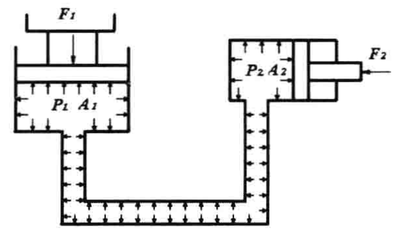


Fig. 1 - 5 Application of Pascal's law

The above equation states that only a small force can lift a heavy load since $\frac{A_2}{A_1} < 1$. Further to know, neglecting the weight of the piston and other resistance, if $F_2 = 0$, then $F_1 = 0$. We arrive at an important conclusion in hydraulic transmission that the hydraulic pressure exerted on a confined fluid depends on the external load.

1.3 Hydrodynamics

Hydrodynamics in this section studies principles of velocity and hydraulic pressure for a flowing fluid. The equations of continuity, Bernoulli and momentum are basic motion equations that describe the dynamics laws in a flowing fluid. They are the theoretical foundation of hydraulic transmission.

1.3.1 Basic concept

1. Ideal fluid and steady flow

(1) Ideal fluid is inviscid and incompressible.

(2) A steady flow means that the fluid pressure, velocity and density at a point do not change with time when fluid is flowing.

2. Flow stream and flow cross-sectional area

(1) Flow stream

We define the lines drawn in the flow field as the streamlines shown in Fig. 1 - 6 s_1, s_2, s_3. The velocity direction at any point on the streamline is tangent to the streamline at this point.

The features of the streamlines are that they cannot intersect; their shape does not change when the fluid flows steadily; and they are smooth curves.

The flow stream is a set of streamlines at cross-sectional area A shown in Fig. 1 - 7. It has the features of streamlines, and any points in the fluid field cannot pass through the surface of the flow stream. When A tends to infinitesimal dA, the flow stream is called as the tiny flow stream. Therefore, the hydraulic pressure and the velocity of each point on dA are the same, respectively.

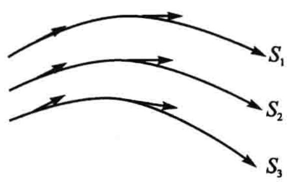


Fig. 1 - 6 Streamlines

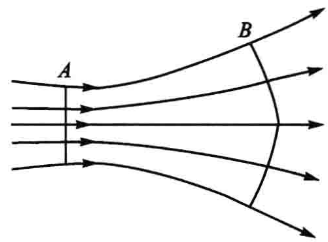


Fig. 1 - 7 Flow stream

(2) Flow cross-sectional area

Flow cross-sectional area is perpendicular to the streamlines in the flow stream, such as sections A and B in Fig. 1 - 7. The velocity at each point on the cross section is perpendicular to this section.

3. Flow rate and average velocity

When the fluid flows steadily, we define flow rate Q as the fluid volume passing through a given section per unit time.

A tiny flow stream in the pipe is shown in Fig. 1 - 8(a). Assume the flow cross-sectional area is dA, the velocity on dA is u, then the tiny flow rate dQ passing through a differential area of the section is described as

$$dQ = u dA \tag{1-16}$$

A total flow rate Q is obtained by integration over section A,

$$Q = \int_A u dA \tag{1-17}$$

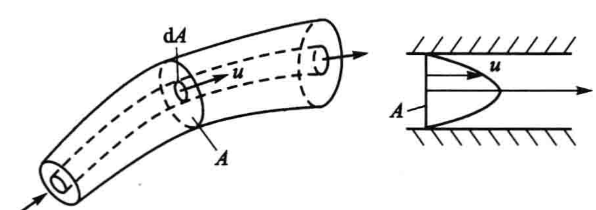


Fig. 1 - 8 Sketch of flow rate and average velocity

The velocity distribution across section A is a parabola shown in Fig. 1 - 8(b). Average