STUDIES IN MECHANICAL ENGINEERING, 7

Fundamentals of Hydraulic Power Transmission

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IMRE KRÖELL DULAY

Technical University for Heavy Industry, Miskolc, Hungary

with, as coauthors,

FERENC FÜRÉSZ and GÁBOR HARKAY

Bánki Donát Mechanical Engineering College, Budapest, Hungary

and

JÁNOS LUKÁCS

Technical University for Heavy Industry, Miskolc, Hungary

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PREFACE

Rapid mechanization and automation of production processes, coupled with the comlexity of the kinematic systems of machines and the rising power transmitted, impose ever more demanding requirements on the power transmission and control systems. The liquid hydraulic system has advantages such as simple control of the characteristic parameters (speed, force and torque) of the transmission, simple protection against overload and easy distribution of the flow, which enable it to meet the increasing requirements.

A wide range of hydraulic energy converters are now manufactured, to standard dimensions, at the large development and production centres. Thus machine designers are relieved of problems related to the design and construction of the elements, and can concentrate on system planning.

In this book, we aim to provide a methodical summary of the fundamental transmission types and a description of their main characteristics. Hydraulic control devices are discussed according to the requirements of the transmission, but as the various products operate on the same principle, no detailed description of them is given. The systematic development and operational characteristics of the various hydraulic control devices are demonstrated.

The actuators of the energy converters of variable specific volume, such as the pressure-controlled and proportional control devices now generally used, are discussed in a similar way.

The theoretical fundamentals of alternating current transmissions, as a special province of the hydraulic transmission technique are described in a separate chapter.

Understanding of the theory is facilitated by examples given in each chapter. The last chapter of the book, in line with the preceding theoretical part, deals with the design of the hydraulic circuits of practical machines. Some basic knowledge of control techniques is required for the understanding of parts of the text.

The most frequently used symbols, and the relations between the SI (System International) and other measuring units, are listed in tabular form.

Ferenc Fürész
Gábor Harkay
Imre Kröell Dulay
János Lukács

Table 0–1.
Symbols and measuring units of the main technical and physical quantities

Name	Symbol	Measuring units SI	Measuring units other
Pressure	p, P	Pa, N/m^2	MN/m^2, daN/cm^2, bar
Flow rate	Q	m^3/s	dm^3/min, cm^3/s
Length	l, L, h	m	cm, mm
Diameter	d, D	m	cm, mm
Surface, area	A	m^2	cm^2
Volume	V	m^3	dm^3, cm^3
Specific capacity (geometric)	V_g	m^3/rad	cm^3/rad
Mass	m, M	kg	–
Density	ρ	kg/m^3	–
Velocity	v, c	m/s	cm/s
Gravitational acceleration	g	m/s^2	–
Angular frequency	ω	l/s	–
Kinetic frequency, frequency	f	l/s, Hz	–
Angular speed (r.p.m.)	n	l/s	l/min
Force	F	N	daN
Weight	G	N	daN
Moment (torque)	M	Nm	daNm
Energy	E	J	kJ
Work	W	J	kJ
Power	P	W	kW
Moment of inertia	Θ	kg m^2	–
Moment of inertia	I	m^4	cm^4
Momentum	I	kg m/s	–
Damping factor	B	N s/m	–
Spring stiffness	c_r	N/m	–
Modulus of elasticity	E	Pa	–
Bulk modulus of elasticity	K	Pa	daN/cm^2
Compressibility	β	1/Pa	cm^2/daN
Dynamic viscosity	η	Pas	Ns/m^2
Kinematic viscosity	ν	m^2/s	mm^2/s
Laminar friction resistance	R_L	N s/m^5	–
Turbulent friction resistance	R_T	N s^2/m^8	–
Hydraulic inductivity	L	N s^2/m^5	–
Hydraulic capacity	C	N/m^5	–
Inductance	X_L	N s/m^5	–
Capacitance	X_C	N s/m^5	–
Hydraulic impedance	Z	N s/m^5	–
Force constant	K_F	m^2	cm^2
Torque constant	K_M	m^3/rad	cm^3/rad
Velocity constant	K_v	l/m^2	l/cm^2
Angular velocity constant	K_ω	rad/m^3	rad/cm^3
Valve constant	K_T, K_N	N s/m^5	–
Hydraulic control sensitivity	ψ_Q	m^2/s	cm^2/s
Hydraulic conductivity	G_Q	m^5/Ns	–
Static compliance	z_h	m/N	–
	z_ϕ	rad/Nm	–
Dynamic compliance	z_v	1/Ns	–
	z_ω	1/Nms	–
Time	t, τ	s	min

(Table 0–1 cont.)

Name	Symbol	Measuring units	
		SI	other
Time constant	T	s	h
Temperature	ϑ	K	°C
Heat	W	J	kJ
Heat transfer coefficient	κ	J/m² s K	kJ/m² h°C
Linear thermal expansion	α	l/K	l/°C
Efficiency	η	–	–
Power transmissibility	G	–	–
Degree of irregularity	δ	–	–
Ratio of piston areas	φ	–	–

Table 0–2.
Basic units of SI

Basic physical quantity	Symbol
Length	m
Mass	kg
Time	s
Current intensity	A
Thermodynamic temperature	K
Luminous intensity	cd
Mass volume	mol

Table 0–3.
Interpretation of indices used with the symbols

a	accumulator, counter force, apparent
av	average
ax	axial
b	switching on, internal, inlet, input, tilting
C	capacity, controllability
c	control
cl	clamping, compressive
cr	critical
d	depression, draining, piston
D	piston
dyn	dynamic
e	forward, lifting, resultant, even, empty weight
eff	effective
f	phase, fluid, main, filter
F	restriction, restrictor
g	gas, geometric, generator
h	backward, hydraulic, linear displacement, cylinder
id	ideal
i, j, k, . . . z	operative indices
k	mixture, switching off, outlet, ambient, external

(Table 0–3. cont.)

l	apparent, air, load
L	inductivity, laminar
m	motor, reactive, actuating force
mean	mean
M	torque, operating position
nec	necessary, required
nl	no-load
o	oil
odd	odd
op	operating, opening
p	power, pump, pipeline
r	radian, spring
red	reduced
R	friction resistance
s	auxiliary, friction, lowering
st	static
sup	supporting
t	time, charge
tank	tank
T	turbulent, overflow
tot	total
Q	flow rate
v	linear motion, loss, return, line
vol	volumetric
W	work
z	closing
x, y, z	in direction x, y, z
φ	angular displacement
max	maximum
mech	mechanical
perm	permissible
min	minimum
n	nominal, rated
N	pressure reducing
Δ	difference, change
ω	rotary motion
A, B	between points A and B
0	barometric, theoretical value, series development position
1, 2, 3	in position 1, 2, 3
1–2	between positions 1 and 2

Table 0–4.
Relationship between the technical and SI system

	Technical system	SI system
Force	1 kp = 9.80665 N	1 N = 0.101972 kp
Work, energy	1 kpm = 9.80665 J	1 J = 0.101972 kpm
Power	1 kpm/s = 9.80665 W	1 W = 0.101972 kpm/s

Note: 1 daN = 10 N

(Table 0–4 cont.)

Conversion of work and energy units

	J	kWh	kcal	kpm
1 J	1	2.77778×10^{-7}	2.38846×10^{-4}	0.101972
1 kWh	3.6×10^{5}	1	859.845	3.67098×10^{5}
1 kcal	4186.8	1.163×10^{-3}	1	426.935
1 kpm	9.80665	2.72407×10^{-6}	2.34225×10^{-3}	1

Note: The basic unit of energy in the SI system is the joule (J), power = watt (W)
$1\ J = 1\ kg\ m^2/s^2 = 1\ W\ s = 1\ N\ m = 10^7$ erg.

Conversion of power units

	kW	kpm/s	LE	kcal/h
1 kW	1	101.972	1.3596	859.845
1 kpm/s	9.80665×10^{-3}	1	0.013333	8.4324
1 LE	0.735499	75	1	632.44
1 kcal/h	1.163×10^{-3}	0.118594	1.58125×10^{-3}	1

Note: 1 LE = 75 kp m/s = 75 × 9.80665 = 735.4987 N m/s = 735.499 W.

Units of pressure and their relationships

	N/m²	at	torr	bar	atm
1 N/m²	1	1.01972×10^{-5}	7.50062×10^{-3}	10^{-5}	0.986923×10^{-5}
1 at	9.80665×10^{4}	1.0	735.559	0.980665	0.967841
1 torr	133.3224	1.35951×10^{-3}	1.0	1.333224×10^{-3}	1.3158×10^{-3}
1 bar	10^{5}	1.01972	750.062	1.0	0.986923
1 atm	1.01325×10^{5}	1.033227	760.0	1.01325	1.0

Note: 1 Pa = 1 N/m²; 1 at = 1 kp/cm² ≈ 1 daN/cm² = 10 N/cm²; 1 bar = 10^3 mbar = 10^6 μbar.

CHAPTER 1

HYDRAULIC CALCULATIONS (BASIC FORMULAE). MECHANICAL PROPERTIES OF THE HYDRAULIC FLUID

1.1 UNIT SYSTEMS. INTERPRETATION OF THE FLOW RATE

The power transmitting medium of hydraulic systems is a fluid. The measurement units for the systems operating with higher power are derived from the energy per unit volume of the fluid participating in the power transmission:

$$\frac{E}{V}\ \frac{ML^2T^{-2}}{L^3} = P\,ML^{-1}\,T^{-2}.$$

This quantity is called the total pressure. Its units which frequently occur are: Pa (Pascal), N m^{-2}, MN m^{-2}, bar, daN cm^{-2}.

Relationships between the units:

$$1\ \text{Pa} = 1\ \text{N m}^{-2} = 10^{-6}\ \text{MN m}^{-2},$$

$$1\ \text{bar} = 1\ \text{daN cm}^{-2} = 10^{5}\ \text{N m}^{-2} = 0.1\ \text{MN m}^{-2}.$$

Derivation of the total pressure reveals the fact that it contains all the components of the Bernoulli equation, thus in the case of ρ = constant, the formula for a given part of the flow is:

$$P_i = p_i + \gamma h_i + \frac{\rho}{2} v_{ik}^2 .$$

The potential energy term is usually negligible in mechanical engineering relative to the other two, and thus the formula for total pressure is the following:

$$P_i = p_i + \frac{\rho}{2} v_{ik}^2 .$$

The first component is the hydrostatic pressure, and the second is the hydrodynamic pressure.

Variation of the pressure components is shown in Fig. 1–1. for different flow sectional areas.

Apart from the pressure the most frequently occurring parameter in hydraulic calculations is the fluid volume passing during unit time, which is called the flow rate:

$$Q = \frac{\partial V}{\partial t} = \frac{\Delta V}{\Delta t} L^3T^{-1}. \tag{1.1}$$

Usual units: m^3h^{-1}, dm^3min^{-1}, m^3s^{-1}, cm^3s^{-1}.

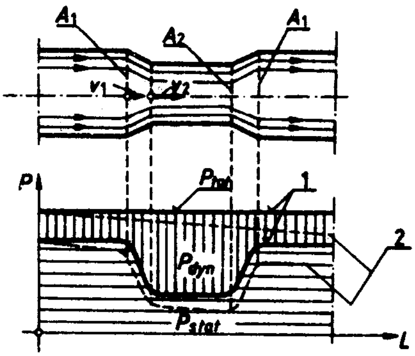

Fig. 1–1. Variation of the total pressure components in cases of different flow sectional areas
1 ideal fluid; *2* actual fluid

The fluid volume expresses the intensity of the flow, which in the case of stationary flow can also be calculated from the continuity equation

$$Q = A_i v_{ik} = \text{constant.} \tag{1.2}$$

According to the formula (1.2) the fluid volume passing through any sectional area of the flow during unit time is constant, provided that the density of the fluid is regarded as constant.

1.2 HYDRAULIC RESISTANCE, INDUCTIVITY, CAPACITY

The terms resistance, inductivity and capacity in hydraulic power transmission can be used analogously to electrical practice, since the static pressure can be regarded as corresponding to the voltage and the flow rate to the electric current.

1.2.1 PRESSURE LOSS ARISING FROM HYDRAULIC RESISTANCE. FRICTIONAL (VISCOUS) RESISTANCE

The total pressures measured in two sectional areas during steady flow of the fluid are generally different, i.e.:

$$P = P_1 - P_2 = (p_1 - p_2) + \frac{\rho}{2}(v_1^2 - v_2^2).$$

If the two sectional areas of the flow analysed are equal, then the difference of the total pressures equals the difference of the static pressures. The pressure difference is required for compensation of the force produced by the friction of the fluid particles. The frictional force depends on the characteristics of the fluid, the type of flow and on the flow sectional area.

Since power transmission losses decrease the hydrostatic pressure component in every case (as measurable with a manometer), each hydraulic resistance can be calculated