

Contents

<i>Preface</i>	v
<i>Nomenclature</i>	xi
1 Fluid flow calculations	1
1.1 Power	1
1.1.1 Pumping	2
1.1.2 Pressures	2
1.2 The steady flow equation	3
1.2.1 Useful forms of the equation	4
1.2.2 Orifices	4
1.2.3 Oil temperature rise	6
1.3 Flowrates	6
1.3.1 Flow through tubes	7
1.3.2 Capillary (small-bore) tubes	8
1.3.3 Connecting pipelines	8
1.3.4 Turbulent flow	9
1.3.5 Approximations used in calculation	9
1.3.6 Annular passages	10
1.3.7 Viscosity variations	11
1.4 Compressibility	11
1.4.1 Compressibility flowrates	11
1.4.2 Dilation of containers	12
1.4.3 Air content	13
1.4.4 Flexible hoses	14
1.4.5 Surges	14
1.4.6 Pressure waves	16
<i>Problems</i>	17
2 Dynamic analysis	21
2.1 First-order systems	21
2.1.1 A first-order fluid system	22
2.1.2 A first-order electrical system	23
2.1.3 A first-order hydraulic servomechanism	24
2.1.4 The first-order equation	25
2.2 The step input	26
2.2.1 Response of first-order systems to step input	27
2.2.2 Response as a function of time	27
2.3 Ramp input and response for first-order systems	28

2.4	Harmonic input	29
2.4.1	Harmonic response of first-order systems	29
2.4.2	Graphical representations	30
2.4.3	Harmonic response locus	32
2.4.4	Logarithmic plots	33
2.5	Second-order systems	34
2.5.1	A second-order electrical circuit	36
2.5.2	The second-order equation	37
2.6	Response of second-order systems to ramp input	39
2.7	Harmonic response of second-order systems	39
2.7.1	Harmonic response locus	40
2.7.2	Logarithmic plots	40
	<i>Problems</i>	41
3	Hydraulic frequency	45
3.1	A single-acting hydraulic jack	45
3.2	A double-acting cylinder	47
3.3	A double-acting cylinder with a long exhaust pipeline	48
3.4	An oil hydraulic motor with two pipelines	50
	<i>Problems</i>	52
4	Variable pump systems	54
4.1	The pump	55
4.2	The motor	55
4.3	Open loop systems	56
4.3.1	Steady state operation	56
4.3.2	Dynamic analysis	57
4.4	Closed loop (position control) systems	58
4.5	Practical systems	60
	<i>Problem</i>	60
5	Linear control theory	61
5.1	Algebraic stability criterion (Routh–Hurwitz)	61
5.2	Open loop relations	63
5.2.1	First-order example	63
5.2.2	Third-order example	63
5.2.3	General case	65
5.2.4	Harmonic input	65
5.2.5	Open loop harmonic response locus	65
5.2.6	Open loop testing	66
5.3	Nyquist stability criterion	67
5.4	Adequate stability	67
5.4.1	Gain and phase margins	67

5.4.2	Logarithmic locus	68
5.4.3	Maximum closed loop dynamic magnification	69
<i>Problem</i>		71
6	Pumps	72
6.1	Types of pump	72
6.2	Flow irregularities	75
6.3	Constant-pressure sources	79
7	Flow through valves	81
7.1	Four-way spool valves	81
7.1.1	Critical centre valves	82
7.1.2	Flowrate prediction	83
7.1.3	Open centre type (underlapped four-way valve)	86
7.2	Three-way spool valves	88
7.3	Nozzle-flapper valves	88
<i>Problems</i>		90
8	Valve-controlled systems	91
8.1	Four-way valve system	91
8.2	Pure inertia analysis	92
8.2.1	Analysis with friction and leakage	93
8.3	Valve position servos	95
8.3.1	The 'velocity constant'	96
8.3.2	Governing equation	96
8.4	Feedback lever system (with a four-way valve)	98
8.5	Valve servo characteristics	99
8.5.1	Stability	99
8.5.2	Harmonic response	100
8.5.3	Description of harmonic response	101
8.5.4	Open loop characteristics	106
8.5.5	Adequate stability	106
9	Electrohydraulic servo valves	107
9.1	Flow control valves	107
9.2	Valves with coil armatures	108
9.2.1	A single-stage valve	108
9.2.2	A two-stage valve	110
9.3	Valves with torque motors	112
9.4	Valve dynamics	114
9.4.1	Torque motors	114
9.4.2	Two-stage operation	115
9.4.3	Simplified representations of valve characteristics	116

9.5	Comments on electrical supplies	117
9.5.1	Pulse width modulation	118
10	Electrohydraulic servomechanisms	120
10.1	'Proportional' systems	121
10.1.1	Analysis	123
10.1.2	Precision	125
10.2	Velocity control	126
10.2.1	Pump control	126
10.3	Compensated control	127
10.3.1	Analysis	127
10.3.2	A possible electrical network	128
10.3.3	Systems with a compensating network	131
10.4	Valve characteristics	132
11	Conclusion	133
Appendix A	Spool valve stroking forces	134
A.1	Flow forces	134
A.1.1	Steady flow	134
A.1.2	Transient flow	136
A.2	Effective moving mass	137
A.3	Frictional forces	138
A.4	Summary	139
	<i>Problem</i>	140
Appendix B	Three-way valve systems	141
B.1	Valves	141
B.1.1	Critical centre type	142
B.1.2	Open centre type (underlapped three-way valve)	142
B.2	Three-way valve system	143
B.3	Three-way valve servo	145
B.3.1	Governing equation	145
Appendix C	Special purpose valves	148
C.1	Poppet valves	148
C.2	Single-stage relief valve	149
C.3	A flow control valve	151
C.3.1	Forces	152
C.3.2	Flowrates	152
Appendix D	Numerical examples	155
D.1	Question (i)	155

Contents

xi

D.1.1 Calculation of answers to question (i)	155
D.1.2 Answers to question (i)	159
D.2 Question (ii)	159
D.2.1 Calculation of answer to question (ii)	159
D.2.2 Answer to question (ii)	160
Appendix E Hydraulic lock	161
General Problems	165
<i>References</i>	169
<i>Index</i>	171