

Contents

I

Challenges of a Precision Engineer

1	Speak the right language	3
1.1	Translate requirements to specifications	3
1.2	Definitions	4
1.2.1	Degrees of freedom	4
1.2.2	Target and true value	5
1.2.3	Tolerance and allowance	6
1.2.4	Accuracy, repeatability, reproducibility and precision	6
1.2.5	Resolution	7
1.3	Schematic representation	8
1.3.1	Schematic representation of basic elements	8
2	Comprehend physical phenomena	11
2.1	Compliance or lack of stiffness	11
2.2	Inertia	12
2.3	Thermal effect	13
2.4	Shortening effect	14
2.5	Play	15
2.6	Friction, stick, spin, slip and sliding	16
2.7	Vibrations	20

2.8	Hysteresis, virtual play and micro-slip	23
2.8.1	Hysteresis	23
2.8.2	Virtual play	25
2.8.3	Micro-slip	26
2.9	Other physical phenomena	28
3	Select optimal strategies	29
4	Predict system behaviour	35

II

Toolbox of a Mechanical Engineer

5	System stiffness	39
5.1	Parallel and series	39
5.2	Transmission ratio	41
5.2.1	Translation to translation	41
5.2.2	Rotation to rotation	42
5.2.3	Translation to rotation	44
5.2.4	Rotation to translation	45
5.2.5	Effects of transmission ratio	45
5.3	Energy method	45
5.4	Examples	46
5.4.1	Truss	46
5.4.2	Shaft	47
5.4.3	Multiple springs in a circular lay-out	50
5.4.4	Stiffness in preloaded system	51
6	Element stiffness and loadability	53
6.1	Rotational stiffness for torsion	54
6.1.1	Twisting, warping and stiffening effect	54
6.1.2	Torsional and warping stiffness	56
6.2	Rotational stiffness for bending	61
6.2.1	Cantilever beam subjected to a bending moment	61
6.2.2	Simply supported beam subjected to a moment	62
6.2.3	Composed beam subjected to a moment	62
6.3	Translational stiffness for lateral deformation	66
6.3.1	Cantilever beam subjected to a transverse force	66
6.3.2	Simply supported beam subjected to a transverse force	68
6.3.3	Cantilever beam forced into a straight lateral displacement	69

6.4	Translational stiffness for longitudinal deformation	71
6.4.1	Beam subjected to a longitudinal force	71
6.4.2	Composed beam subjected to a longitudinal force	72
6.4.3	Cantilever beam subjected to eccentric longitudinal force	72
6.4.4	Deformed composed beam subjected to longitudinal force	74
6.4.5	Loadability for compression	76
7	Contact stiffness and loadability	81
7.1	Approximating stiffness and loadability	83
7.1.1	Transferring variables to a set of parameters	83
7.1.2	Stresses, deformation and stiffness for elliptical contact areas	85
7.1.3	Stresses, deformation and stiffness for rectangular contact areas	87
8	Parasitic displacement	89
8.1	Parasitic displacement due to shortening	89
9	Static behaviour	91
9.1	Static characteristics	91
9.1.1	Static characteristics of basic elements	91
9.1.2	Static characteristics of some basic systems	93
9.1.3	Total play in systems with multiple springs	100
9.1.4	Example of static characteristic	101
9.2	Systems with micro-slip	105
9.2.1	Micro-slip in a clamp	105
9.2.2	Micro-slip in a bolted joint	109
9.2.3	Micro-slip in a belt drive	109
10	Dynamic behaviour	113
10.1	Free vibration	113
10.1.1	Free vibration without damping	113
10.1.2	Free vibration with viscous damping	114
10.2	Forced vibration	116
10.2.1	Forced vibration without damping	117
10.2.2	Forced vibration with viscous damping	119
10.2.3	Analysis of the behaviour	120
11	Thermal behaviour	123
11.1	Temperature change	123
11.1.1	Effect of change in temperature on size of object	123

11.1.2	Effect of change in energy on temperature	125
11.2	Energy transfer by heat	125
11.2.1	Thermal radiation	125
11.2.2	Conduction	126
11.2.3	Radiation versus conduction	127

III Design strategies for precision engineering

12	Prevent too high stresses	131
12.1	Design exact-constraint	131
12.1.1	Definitions	131
12.1.2	Why design exact-constraint	135
12.1.3	Design and analysis	138
12.1.4	Systems in series	145
12.1.5	Adding redundant constraints	147
12.1.6	Methods for analysing degrees of freedom	148
12.2	Use elastic averaging	148
12.3	Avoid a step in the stiffness	149
13	Minimize deviation	151
13.1	Divert and neutralize forces	152
13.1.1	Use a force-frame	152
13.1.2	Prevent warping	153
13.1.3	Neutralize acceleration forces	153
13.2	Strive for a high stiffness	154
13.2.1	Aim for a low transmission ratio	154
13.2.2	Design in parallel	155
13.2.3	Optimise stiffnesses of springs when designing in series	156
13.2.4	Choose a short force path	156
13.2.5	Apply loads in stiff directions	156
13.2.6	Strive for a high element stiffness	160
13.2.7	Strive for a high contact stiffness	160
13.3	Strive for a low mass	163
13.3.1	Consider material efficiency of system	164
13.3.2	Consider energy density of elements	166
13.3.3	Consider cross section of element	167
13.3.4	Truss and sheet compared	167

13.4 Strive for optimal damping	172
13.4.1 Viscous damping	173
13.4.2 Coulomb damping	173
13.4.3 Hysteretic damping	174
13.4.4 Eddy current damping	176
13.4.5 Tuned mass damping	176
13.4.6 Active damping	180
13.5 Strive for a low stiffness	180
13.5.1 Reduce impact forces	180
13.5.2 Isolate from environment	181
13.5.3 Increase predictability	181
13.6 Strive for thermal stability	182
13.6.1 Strive for a constant temperature	182
13.6.2 Use a temperature invariant system	183
13.7 Use symmetric designs	185
13.8 Average errors	186
13.9 Use systems in series	187
13.9.1 Compensate for parasitic movement	187
13.9.2 Use dual stage system	188
13.10 Optimize measurement and control	189
13.10.1 Use a metro-frame	189
13.10.2 Aim for a optimal measurement	189
13.10.3 Choose optimal position for actuator and sensor	190
13.10.4 Correct the control value	192
14 Prevent relative movement	193
14.1 Avoid (micro-)slip	193
14.1.1 Design monolithic systems	193
14.1.2 Use screwing	194
14.1.3 Use adhesives	194
14.1.4 Avoid difference in strain	195
14.2 Minimize difference in strain	196
14.2.1 Align neutral lines for bending	196
14.2.2 Increase stiffness of clamped object in the clamp	196
14.2.3 Decrease contact area when clamping	197
14.2.4 Increase friction force	198
14.3 Add preload	198
14.3.1 Avoid play	198
14.3.2 Provide preload force	199

14.4	Prevent movement in one direction	200
15	Facilitate relative movement	201
15.1	Avoid all mechanical contact	201
15.1.1	Use ferrofluid bearing	202
15.1.2	Use hydrostatic bearing	202
15.1.3	Use aerostatic bearings	203
15.1.4	Use magnetic bearing	203
15.2	Use flexure mechanisms	204
15.2.1	Use sheet flexure as hinge	205
15.2.2	Use cross flexures as hinge	206
15.2.3	Use parallel flexures as linear guide	208
15.2.4	Reinforced flexures with mid-section	209
15.2.5	Use notch hinges	210
15.2.6	Aim for low or zero stiffness	213
15.3	Optimise sliding	215
15.3.1	Reduce friction force	215
15.3.2	Minimize the effects of wear	216
15.4	Optimise rolling	218
15.4.1	Rolling bearings	218
15.4.2	Strive for pure rolling	218
15.4.3	Rolling in a hinge	219
16	Manage energy	223
16.1	Store energy	223
16.1.1	Store kinetic energy by using a balance mass	223
16.1.2	Store elastic potential energy by using springs	224
16.1.3	Store potential energy by using a mass and a spring	225
16.2	Dissipate energy	227
16.2.1	Use friction for braking	227
16.2.2	Use eddy current braking	227

IV

Design concepts for precision designs

17	Linear guiding	231
17.1	Carriage with V-groove on rail with spindel drive	231
17.2	Slide with ball screw, University of Twente	234
17.3	Carriage with V-groove with magnetic drive, AAE	235

17.4	Conveyor belt for linear motion	236
17.5	Conveyor belt for positioning, Sioux-CCM	239
17.6	Parallel sheet flexures as linear guide	243
18	Manipulating and adjusting	245
18.1	Manipulators with a high transmission ratio	245
18.2	Mechanisms with notch hinges	246
18.3	Manipulator for six degrees of freedom	247
18.4	Adjustment in two DOF in a printhead, NTS	248
19	High dynamic positioning	251
19.1	Positioning of crystals, MI Partners	251
19.2	High dynamic manipulating of optical stage, JPE	256
20	Torque transmission	259
20.1	Coupling of suspended shafts with one rod	259
20.2	Coupling of suspended shafts using four flexures	260
20.3	Coupling of suspended shafts using a hollow tie rod	261
20.4	Helical coupling in a printer, Canon	261
20.5	Self centring couplings	262

V

Appendices

A	Efficiency of beams	267
B	Answers to exercises	273
C	Tables	275
	Bibliography	281
	Index	287