HANNAH & HILLIER

APPLIED MECHANICS

应用力学 第3版

THIRD EDITION

世界图书出版公司

J. Hannah
BSc(Eng), CEng, FIMechE, FIEE

M. J. Hillier
MSc(Eng), DIC, BSc

Applied Mechanics

Third Edition

世界图书出版公司

书　　名：Applied Mechanics　3rd ed.

作　　者：J.Hannah, M.J.Hillier

中 译 名：应用力学　第 3 版

出 版 者：世界图书出版公司北京公司

印 刷 者：北京中西印刷厂

发　　行：世界图书出版公司北京公司（北京朝内大街 137 号　100010）

开　　本：1/24　　711×1245　　　印　张：19.5

出版年代：2000 年 6 月

书　　号：ISBN 7-5062-4723-2/ O・303

版权登记：图字 01-1999-2129

定　　价：72.00 元

Preface to third metric edition

The first edition of *Applied Mechanics* was published over thirty years ago; the first metric edition was introduced in 1971 when the system of SI units (Système International d'Unités) was adopted as the primary system of weights and measures. Since my co-author, Mr M. J. Hillier, was no longer collaborating on the writing I carried out the revision for the third metric edition myself.

The aim, as in the past, has been to retain the original character of the book, with its emphasis on the practical applications of the subject, the implications for design and the importance of the many assumptions that have to be made in engineering analysis.

Key points in the treatment remain: the number of formulae to be memorized is kept to a minimum; each topic is followed by worked examples and a list of problems for practice; purely mathematical derivations such as the moments of inertia are omitted and only results stated; work likely to have been covered in preceding courses is omitted or revised briefly, including centres of gravity, uniform velocity and acceleration; topics such as friction, properties of materials and real fluids, the nature of experimental and graphical work, and dynamics of aircraft are covered in more detail than is usual at this level.

In this edition, the text, worked examples and problems have been thoroughly revised and the diagrams redrawn. In particular, the work on aircraft, rockets and helicopters has been expanded. Although this material is intended only as an introduction to these topics there is an advantage in bringing together in the exercises the principles of statics and dynamics of forces as well as those of thermodynamics, gas dynamics and fluid flows. Some descriptive work on propulsion systems and aerodynamics has been included to support the elementary mechanics. The coverage of gravitation and satellites in the appendix to Chapter 9 has been increased; to contain the size of the book Chapter 20 (Fluid in motion) and Chapter 21 (Experimental errors and the adjustment of data) have been slightly curtailed.

The text covers all the requirements of the units of study for the BTEC certificate and diploma courses in Engineering, and some of the aspects of the new work-related advanced GNVQ courses. It is hoped also that the book will continue to be useful as a supporting text to students on the early stages of higher diploma and degree courses and on comparable courses overseas.

I am indebted to the users of the book in many parts of the world and to those in industry, engineering and other institutions who have helped with information and advice. My particular thanks are due to my colleague of many years' standing Mr R. C. Stephens, for his most valuable and ever-ready assistance with this edition.

1994 John Hannah

Note on SI units

SI is the abbreviation, in all languages, for the full title 'Système International d'Unités', which is the rationalized form of the metric system of units agreed internationally. Of the seven fundamental or **base** units, four will be met with in this book, i.e. the *metre* (length), *second* (time), *kilogram* (mass), *kelvin* (temperature).

The sole **derived** unit for measuring work or energy is the *joule* and that for force is the *newton*. The SI is a coherent system of units since the product of any two unit quantities in the system is the unit of the resultant quantity. For example, unit velocity (metre per second) results when unit length (metre) is divided by unit time (second). Normally calculations in the text are carried out by converting all given quantities to these base units, but on occasion it has been found convenient to work in multiple or sub-multiple units. The kilojoule and kilonewton are particularly convenient. A few non-SI units whose use is accepted have been used where appropriate, for example, the *bar* (and its multiples) as a unit of pressure and the *knot*, a unit of speed, in aerial and marine navigation work.

For full information on SI units reference should be made to *SI International System of Units*, R. J. Bell and D. T. Goldman (National Physical Laboratory), published by H.M. Stationery Office (1986), and to British Standards No. 5555 and No. 350 Part I.

Contents

Preface to third metric edition		xiii
Note on SI units		xiv
Chapter 1 Statics		
1.1	Mass, force and weight	1
1.2	Forces in equilibrium: triangle of forces	3
1.3	Resultant and equilibrant: parallelogram of forces	4
1.4	Resolution of forces	4
1.5	Polygon of forces	5
1.6	Moment of a force	6
1.7	Couple	6
1.8	Principle of moments	6
1.9	Resolution of a force into a force and a couple	7
1.10	The general conditions of equilibrium	8
1.11	Free-body diagram	9
1.12	Contact forces; supports and connections	10
Chapter 2 Frameworks		
2.1	Forces in frameworks	22
2.2	Wind loads on trusses	24
2.3	Analytical methods: method of sections: method of resolution	31
Chapter 3 Friction		
3.1	Friction on a rough inclined plane	38
3.2	The angle of friction and total reaction	42
3.3	Application of angle of friction to motion on the inclined plane	43
3.4	Wedges	45
3.5	Toppling or sliding	49
3.6	The ladder problem	51
3.7	Further notes on friction and lubrication	53
3.8	The square-threaded screw	55
3.9	Overhauling of a screw	58
3.10	Tribology	63

Chapter 4 Velocity and Acceleration

4.1	Average speed	64
4.2	Constant speed	64
4.3	Varying speed	64
4.4	Velocity	66
4.5	Motion in a straight line	66
4.6	Summary of formulae for uniform acceleration	67
4.7	Freely falling bodies	68
4.8	Relative velocity; velocity diagram	69
4.9	Angular velocity of a line	73
4.10	Motion of a body in a plane	73
4.11	Velocity triangle for a rigid link. Application to mechanisms	75

Chapter 5 Inertia and Change of Motion

5.1	Newton's laws of motion	81
5.2	Inertia and mass	81
5.3	Force	82
5.4	Weight	83
5.5	The equation of motion	84
5.6	Units of mass and force	85
5.7	Inertia force	86
5.8	Active and reactive forces	87
5.9	Variable forces	88
5.10	Tractive resistance	88
5.11	Tractive effort	91
5.12	Driving torque on a vehicle	94
5.13	Maximum possible tractive effort	95
5.14	Application of inertia force to connected bodies	98
5.15	The simple hoist	100

Chapter 6 Motion in a Circle

6.1	Centripetal acceleration	103
6.2	Centripetal force	104
6.3	The inertia force in rotation	105
6.4	Centrifugal force	105
6.5	Dynamic instability	107
6.6	Vehicle rounding a curve	109
6.7	Superelevation of tracks: elimination of side-thrust	109
6.8	Passenger comfort – the pendulum car	113
6.9	Overturning of vehicles	115

Chapter 7 Balancing

7.1	Static balance – two masses in a plane	119
7.2	Dynamic balance – two masses in a plane	119
7.3	Method of balancing rotors	120
7.4	Static balance – several masses in one plane	121
7.5	Dynamic balance of several masses in one plane	122

7.6	Dynamic forces at bearings	125
7.7	Car wheel balancing	127
Chapter 8 Periodic Motion		
8.1	Periodic motion	130
8.2	Simple harmonic motion	130
8.3	Simple harmonic motion derived from a circular motion	131
8.4	Periodic time	134
8.5	Frequency	134
8.6	Amplitude	135
8.7	Dynamics of simple harmonic motion	138
8.8	The mass and spring	139
8.9	Simple pendulum	145
8.10	Resonance	147
8.11	Periodic motion of a conical pendulum	150
Chapter 9 Dynamics of Rotation		
9.1	Angular acceleration	154
9.2	Angular velocity–time graph	155
9.3	Use of $\omega - t$ graph	156
9.4	Dynamics of a rotating particle	159
9.5	Dynamics of a rotating body	161
9.6	Inertia couple	162
9.7	Accelerated shaft with bearing friction	162
9.8	Shaft being brought to rest	162
9.9	Units	163
9.10	Values of I for simple rotors	163
9.11	The hoist	167
	Appendix to Chapter 9; Gravitation: Satellites	170
Chapter 10 Work, Energy and Power		
10.1	Work done by a force	180
10.2	Work done in particular cases	181
10.3	Work done by a torque	182
10.4	Springs	183
10.5	Energy	186
10.6	Kinetic energy: work-energy equation	187
10.7	Potential energy	188
10.8	Units of energy	189
10.9	Strain energy	191
10.10	Conservation of energy	194
10.11	Kinetic energy of rotation	195
10.12	Total kinetic energy of a rolling wheel	196
10.13	Power	200
10.14	Power developed by a torque	201
10.15	Efficiency	201
10.16	Power to drive a vehicle	204
10.17	Function of a flywheel	207

Chapter 11 Impulse and Momentum

11.1	Linear momentum: impulse	212
11.2	Units of impulse and momentum	213
11.3	Force varying with time	214
11.4	Conservation of linear momentum	216
11.5	Impulsive forces	217
11.6	Note on the use of momentum and energy equations	217
11.7	Explosions	217
11.8	Collision of two bodies	221
11.9	Collision of perfectly elastic bodies	222
11.10	Inelastic collisions	224
11.11	Collision of partially elastic bodies	229
11.12	Angular momentum and impulse	232

Chapter 12 Aircraft and Rockets

12.1	Reaction propulsion	235
12.2	Jet propulsion aircraft	235
12.3	Notes on aircraft speeds	236
12.4	Thrust of a jet	236
12.5	Compressible and incompressible flow	237
12.6	Mass flow rate of air	238
12.7	International standard atmosphere (ISA)	239
12.8	Power developed by a turbo-jet engine	239
12.9	Propeller-driven aircraft	243
12.10	Notes on lift and drag forces on an aircraft	247
12.11	Forces on an aircraft in flight	249
12.12	Take-off and landing	253
12.13	Banking of an aircraft	256
12.14	Helicopters	258
12.15	Rocket propulsion: thrust	262
12.16	Forces on a rocket in flight	265

Chapter 13 Direct Stress and Strain

13.1	Stress	273
13.2	Strain	274
13.3	Relation between stress and strain: Young's modulus of elasticity	274
13.4	Compound bars	277
13.5	Thermal strain	281
13.6	Sign convention	282
13.7	Effects of thermal strain	283
13.8	Poisson's ratio: lateral strain	287
13.9	Strain energy: resilience	289
13.10	Application of strain energy to impact and suddenly applied loads	292
13.11	Hoop stress in a cylinder	295
13.12	Axial stress in a cylinder	296
13.13	Tangential stress in a spherical shell	297

13.14	Effects of joints on stresses in thin shells	298
13.15	Rotating ring	301

Chapter 14 Mechanical Properties of Materials

14.1	Metals and alloys	305
14.2	Black mild steel in tension	306
14.3	Stress–strain curve	310
14.4	Modulus of elasticity	310
14.5	Specific modulus of elasticity	312
14.6	Black mild steel in compression: malleability	313
14.7	Bright drawn mild steel	313
14.8	Ductile metals	314
14.9	Proof stress	314
14.10	Brittle materials	315
14.11	Resilience and toughness	316
14.12	Mechanical properties of metals	316
14.13	Fatigue	319
14.14	Creep	320
14.15	Hardness	321
14.16	Polymers and plastics	323
14.17	Fibres	324
14.18	Fibre-reinforcement: composite materials	324
14.19	Non-destructive tests	325

Chapter 15 Shear and Torsion

15.1	Shear stress	327
15.2	Riveted joints	327
15.3	Shear strain	331
15.4	Relation between shear stress and shear strain: modulus of rigidity	332
15.5	Torsion of a thin tube	332
15.6	Twisting of solid shafts	334
15.7	Twisting of hollow shafts	335
15.8	Stiffness and strength	336
15.9	Power and torque	337

Chapter 16 Shear Force and Bending Moment

16.1	Shear force	341
16.2	Shear force diagram	341
16.3	Bending moment	342
16.4	Bending moment diagram	344
16.5	Calculation of beam reactions	345
16.6	Uniformly distributed loads	351
16.7	Combined loading	353
16.8	Condition for a maximum bending moment	357

Chapter 17 Bending of Beams

17.1	Pure bending of an elastic beam	362

17.2 Relation between curvature and strain 363
17.3 Position of the neutral axis 365
17.4 Moment of resistance 366
17.5 I of rectangular and circular sections 368
17.6 Strength of a beam in bending 372
17.7 Calculation of I for complex sections 373
17.8 Modulus of section 378

Chapter 18 Combined Bending and Direct Stress
18.1 Principle of superposition 380
18.2 Combined bending and direct stress of a loaded column 380
18.3 Further notes on factors of safety: limit-state design 388

Chapter 19 Fluid at Rest
19.1 Fluid 389
19.2 Pressure 389
19.3 Transmission of fluid pressure 390
19.4 Density; relative density; specific weight; specific gravity 391
19.5 Pressure in a liquid due to its own weight 392
19.6 Measurement of pressure 393
19.7 Measurement of gauge pressure 394
19.8 Measurement of pressure differences 395
19.9 Total thrust on a vertical plane surface 396
19.10 Centre of pressure 396
19.11 Inclined surface 403
19.12 Centre of pressure for inclined surface 404

Chapter 20 Fluid in Motion
20.1 Pressure energy 407
20.2 Potential energy 408
20.3 Kinetic energy 409
20.4 Interchange of pressure and kinetic energy 409
20.5 Bernoulli's equation (conservation of energy) 410
20.6 Pipe flow: equation of continuity 410
20.7 Flow rate 411
20.8 Variation in pressure head along a pipe 411
20.9 The flow of real fluids 415
20.10 Viscosity 415
20.11 Flow at low velocities 415
20.12 Onset of turbulence 416
20.13 Pressure loss in turbulent flow 417
20.14 Eddy formation 417
20.15 Energy of a liquid and pressure loss 418
20.16 Measurement of pipe flow rate: Venturi meter 420
20.17 Coefficient of discharge for a Venturi meter 421
20.18 Discharge through a small orifice 423
20.19 Coefficient of discharge for a small orifice 424

20.20	Coefficient of velocity	424
20.21	Vena contracta: coefficient of contraction	424
20.22	Relation between the coefficients	425
20.23	Power of a jet	425
20.24	Experimental determination of orifice coefficients	427
20.25	Impact of jets. Rotodynamic machinery	429

Chapter 21 Experimental Errors and the Adjustment of Data

21.1	Experiment	431
21.2	Error and discrepancy	431
21.3	Classification of errors	432
21.4	Justifiable accuracy	434
21.5	Possible errors	434
21.6	Propagation of error, or derived error	435
21.7	Region of uncertainty	435
21.8	Accepted value	435
21.9	Error derived from the sum of two quantities	435
21.10	Graphical methods	437
21.11	The straight line graph	438
21.12	Equation to a straight line	439
21.13	Equations which may be reduced to a straight line	441
21.14	Choice of axes	442

Index 445

Chapter 1

Statics

Statics is the study of forces on bodies *at rest* or in *steady motion*. The student at this stage should already be familiar with the elementary principles and theorems relating to forces in equilibrium and the following notes are intended as revision, but with an emphasis on the application of these principles to engineering problems.

1.1 Mass, force and weight

The *mass* of a body is the quantity of matter it contains.

A *force* is simply a push or a pull and may be measured by its effect on a body. A force may change or tend to change the shape or size of a body; if applied to a body at rest the force will move or tend to move it; if applied to a body already moving the force will change the motion.

A particular force is that due to the effect of gravity on a body, i.e. the *weight* of a body.

These three quantities – mass, force and weight – are dealt with fully in Chapter 5, but it is necessary here to specify the units and the essential relationship between mass and weight.

The base SI unit of mass is the *kilogram* (kg); other units of mass are:

$$\begin{aligned} 1 \textit{ megagram} \text{ (Mg) or } \textit{tonne} \text{ (t)} &= 10^3 \text{ kg} \\ 1 \textit{ gram} &= 10^{-3} \text{ kg} \\ 1 \textit{ milligram} \text{ (mg)} &= 10^{-6} \text{ kg} \end{aligned}$$

The derived SI unit of force is the *newton* (N) defined as *that force which, when applied to a body having a mass of one kilogram, gives it an acceleration of one metre per second squared*. From Newton's second law of motion (*see* page 81) we have

$$\text{force} = \text{mass} \times \text{acceleration}$$

i.e. $$F = ma$$

where F is the applied force, m the mass of a body and a the acceleration produced in the body. Thus, in SI units, $F = 1$ N, $m = 1$ kg and $a = 1$ m/s^2,

i.e. $1(\text{N}) = 1(\text{kg}) \times 1(\text{m/s}^2)$

Other units of force used are:

1 *kilonewton* (kN) = 10^3 N
1 *meganewton* (MN) = 10^6 N
1 *giganewton* (GN) = 10^9 N

The acceleration of any body towards earth in free fall is $g = 9.8$ m/s^2, hence the weight W of a body of mass m is:

force = mass × acceleration

i.e. $W = mg$

If the mass m is in kilograms, then

$$W = m \times 9.8 \text{ N}$$

If the mass m is in megagrams (tonnes), then

$$W = m \times 1000 \times 9.8 \text{ N}$$
$$= m \times 9.8 \text{ kN}$$

(Figure 5.5, Chapter 5, shows the relationship between the weight W of a body and its mass m.)

Although defined in dynamic terms, a force may also be measured statically by the weight of the mass it will just support or by comparing its effect with the weight of a standard mass. Thus, if a mass m is suspended from a spring (Fig. 1.1) the extension is due to the force of gravity on the mass, i.e. to its weight $W = mg$. If y is the extension produced by this force W and a force F on the same spring produces an extension x then the value of F is measured in terms of W by simple proportion: thus

$$\frac{F}{W} = \frac{x}{y}$$

Proper specification of a force requires knowledge of three quantities:

- its magnitude
- its point of application
- its line of action

Since a force has magnitude, direction and sense, it is a *vector quantity* and may be represented by a straight line of definite length and direction.

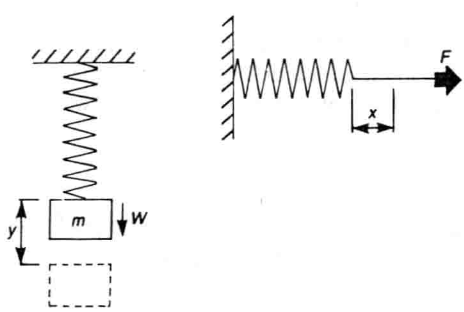

Fig. 1.1

Dead loads

In statics the vertically downward force due to the weight of 'dead loads' must always be taken into account, and this force of gravity acts through the centre of gravity of the load. In a structure such as a bridge, the dead load is the weight of the bridge framework itself plus the cladding and rail track or road surface. (Note that a train travelling over the bridge is a 'live' load.) A load may be given in force units, i.e. N, kN, MN or GN. A 'load' may also be specified in mass units, i.e. kg or Mg (tonne), and in this case the corresponding *weight* of the mass must be found before carrying out calculations involving forces.

1.2 Forces in equilibrium: triangle of forces

Statics is the study of forces *in equilibrium* ('in balance'). A single force cannot exist alone and is unbalanced. For equilibrium it must be balanced by an equal and opposite force acting along the same straight line. Thus in Fig. 1.2 the load of 1 kN *on* the tie is balanced at the joint O by an equal and opposite force of 1 kN exerted *by* the joint *on* the tie. Thus forces may be said to exist in pairs. Nevertheless, a single force may also be balanced by any number of other forces.

For three forces in the same plane to be in equilibrium:

- They must have their lines of action all passing through one point, i.e. they must be *concurrent*.
- They may be represented in magnitude and direction by the three sides of a triangle *taken in order*, i.e. by a *triangle of forces*.

The condition that all three forces must pass through one point is particularly useful in solving mechanics problems. For example, the light jib crane shown in Fig. 1.3(a) is in equilibrium under the action of three forces. The jib carries a load W at A; the free end is supported by a cable in which the tension is T; the end C is pinned to the wall by a joint which allows free rotation of the jib at C. The reaction F of the joint on the jib is completely unknown; the magnitude of T is unknown but its direction must be that of the cable. Since the three forces are in balance their lines of action must pass through one point, i.e. where the lines of action of W and T intersect (point Z, Fig. 1.3(a)). The line of action of F is therefore found by joining C to Z.

Since the magnitude of W is known and the directions of the three forces have been determined, the triangle of forces can now be drawn, Fig. 1.3(b). The sense of the forces T and F are determined by taking the sides of the triangle *in order*, i.e. by

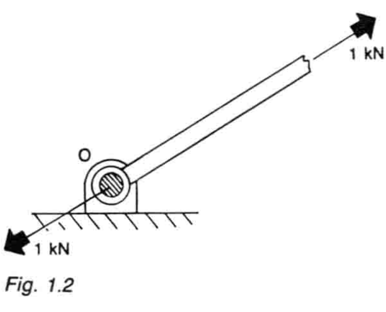

Fig. 1.2

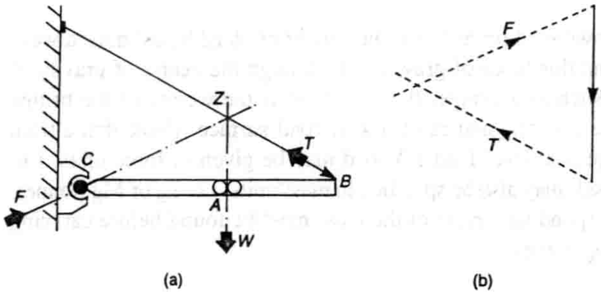

Fig. 1.3

going round the triangle showing the vectors 'head to tail', starting with the known sense of the load W, vertically downwards.

1.3 Resultant and equilibrant: parallelogram of forces

The forces W and T of Fig. 1.3 may also be represented by the two sides **ab** and **ad**, respectively, of the parallelogram **abcd** (Fig. 1.4). The diagonal **ac**, taken in the sense **a** to **c**, is the *resultant* R of the two forces W and T acting together. This resultant force is equivalent to, and may replace completely, these two forces. The resultant **ac** may be balanced by an equal and opposite force **ca** called the *equilibrant*. This is in fact the force F at the pin-joint, Fig. 1.3(a). This construction, by which two forces are replaced by a single equivalent force, is known as the *parallelogram of forces*. It can only be used if the two forces are specified in both magnitude *and* direction.

1.4 Resolution of forces

Since the forces represented by **ab** and **ad** in Fig. 1.4 may be replaced completely by a single force **ac**, it is often useful to carry out the reverse process, i.e. to replace a single force by two other forces in any two convenient directions. These two forces are then known as the *components* of the single force. Physically this is equivalent to finding the effects of the single force in the two chosen directions.

The most convenient choice of directions in which to *resolve* a force is in two directions at right angles. Figure 1.5 shows a force R = **ac** resolved into forces X

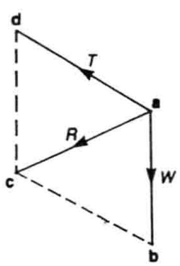

Fig. 1.4

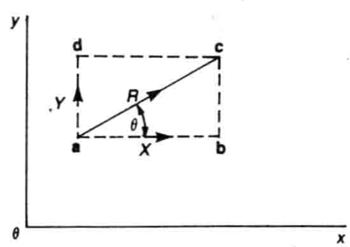

Fig. 1.5