MECHANICAL
ENGINEERING PRINCIPLES

John Bird & Carl Ross

THIRD EDITION

COMPANION WEBSITE

ROUTLEDGE

Mechanical Engineering Principles

Third Edition

John Bird BSc(Hons), CEng, CMath, CSci, FIMA, FIET, FCollT
Carl Ross BSc(Hons), PhD, DSc, CEng, FRINA, MSNAME

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Mechanical Engineering Principles

Third Edition

Why are competent engineers so vital?

Engineering is among the most important of all professions. It is the authors' opinions that engineers save more lives than medical doctors (physicians). For example, poor water, or the lack of it, is the second largest cause of human death in the world, and if engineers are given the 'tools', they can solve this problem. The largest cause of human death is caused by the malarial mosquito, and even death due to malaria can be decreased by engineers – by providing helicopters for spraying areas infected by the mosquito and making and designing medical syringes and pills to protect people against catching all sorts of diseases. Most medicines are produced by engineers! How does the engineer put 1 mg of 'medicine' precisely and individually into millions of pills, at an affordable price?

Moreover, one of the biggest contributions by humankind was the design of the agricultural tractor, which was designed and built by engineers to increase food production many-fold, for a human population which more-or-less quadruples every century! It is also interesting to note that the richest countries in the world are very heavily industrialized. Engineers create wealth! Most other professions don't!

Even in blue sky projects, engineers play a major role. For example, most rocket scientists are chartered engineers or their equivalents and Americans call their chartered engineers (and their equivalents), scientists. Astronomers are space scientists and not rocket scientists; they could not design a rocket to conquer outer space. Even modern theoretical physicists are mainly interested in astronomy and cosmology and also nuclear science. In general a theoretical physicist cannot, without special training, design a submarine structure to dive to the bottom of the Mariana Trench, which is 11.52 km or 7.16 miles deep, or design a very long bridge, a tall city skyscraper or a rocket to conquer outer space. It may be shown that the load on a submarine pressure hull of diameter 10 m and length 100 m is equivalent to carrying the total weight of about 7 million London double-decker buses!

This book presents a solid foundation for the reader in mechanical engineering principles, on which s/he can safely build tall buildings and long bridges that may last for a thousand years or more. It is the authors' experience that it is most unwise to attempt to build such structures on shaky foundations; they may come tumbling down – with disastrous consequences.

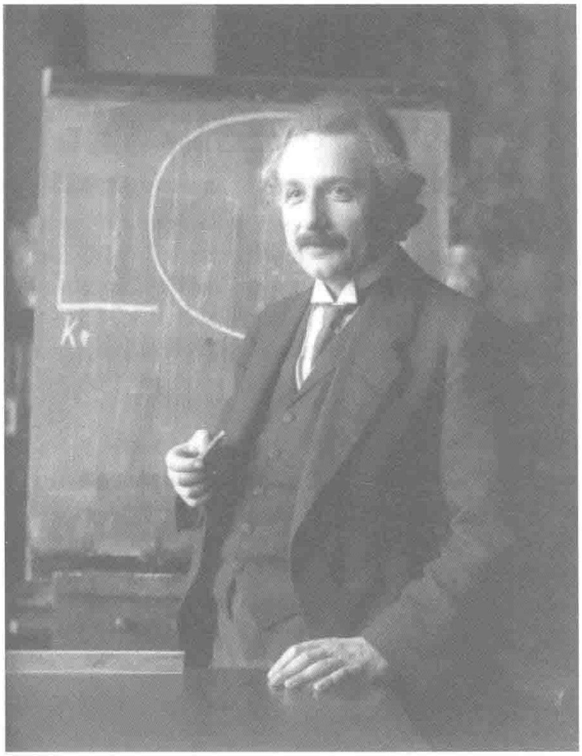
John Bird is the former Head of Applied Electronics in the Faculty of Technology at Highbury College, Portsmouth, U.K. More recently, he has combined freelance lecturing at the University of Portsmouth, with Examiner responsibilities for Advanced Mathematics with City and Guilds, and examining for the International Baccalaureate Organisation. He is the author of over 125 textbooks on engineering and mathematical subjects with worldwide sales of one million copies. He is currently a Senior Training Provider at the Defence School of Marine Engineering in the Defence College of Technical Training at H.M.S. Sultan, Gosport, Hampshire, U.K.

Carl Ross gained his first degree in Naval Architecture, from King's College, Durham University; his PhD in Structural Engineering from the Victoria University of Manchester; and was awarded his DSc in Ocean Engineering from the CNAA, London. His research in the field of engineering led to advances in the design of submarine pressure hulls. His publications and guest lectures to date exceed some 290 papers and books, etc., and he is Professor of Structural Dynamics at the University of Portsmouth, UK.

See Carl Ross's website below, which has an enormous content on science, technology and education.

http://tiny.cc/6kvqhx

Some quotes from ***Albert Einstein*** (14 March 1879–18 April 1955)



'Scientists investigate that which already is; Engineers create that which has never been'

'Imagination is more important than knowledge. For knowledge is limited to all we now know and understand, while imagination embraces the entire world, and all there ever will be to know and understand'

'Everybody is a genius. But if you judge a fish by its ability to climb a tree, it will live its whole life believing that it is stupid'

'To stimulate creativity, one must develop the childlike inclination for play'

Preface

Mechanical Engineering Principles 3rd Edition aims to broaden the reader's knowledge of the basic principles that are fundamental to mechanical engineering design and the operation of mechanical systems.

Modern engineering systems and products still rely upon static and dynamic principles to make them work. Even systems that appear to be entirely electronic have a physical presence governed by the principles of statics.

In this third edition of *Mechanical Engineering Principles*, a further chapter has been added on revisionary mathematics; it is not possible to progress in engineering studies without a reasonable knowledge of mathematics, a fact that soon becomes obvious to both students and teachers alike. It is therefore hoped that this further chapter on mathematics revision will be helpful and make engineering studies more comprehensible. Minor modifications, some further worked problems, a glossary of terms and famous engineers' biographies have all been added to the text.

More has been added to the website for this new edition – such as full solutions being made available to both students and staff, and much more besides – see page x.

For clarity, the text is divided into **four sections**, these being:

Part 1 Revision of Mathematics
Part 2 Statics and Strength of Materials
Part 3 Dynamics
Part 4 Heat Transfer and Fluid Mechanics

***Mechanical Engineering Principles 3rd Edition* is suitable for the following:**

(i) National Certificate/Diploma courses in Mechanical Engineering
(ii) Undergraduate courses in Mechanical, Civil, Structural, Aeronautical & Marine Engineering, together with Naval Architecture
(iii) Any introductory/access/foundation course involving Mechanical Engineering Principles at University, and Colleges of Further and Higher education.

Although pre-requisites for the modules covered in this book include Foundation Certificate/diploma, or similar, in Mathematics and Science, **each topic considered in the text is presented in a way that assumes that the reader has little previous knowledge of that topic.**

Mechanical Engineering Principles 3rd Edition contains over **400 worked problems**, followed by over **700 further problems** (all **with answers**). The further problems are contained within some **150 Exercises**; each Exercise follows on directly from the relevant section of work, every few pages. In addition, the text contains **298 multiple-choice questions** (all **with answers**), and **260 short answer questions**, the answers for which can be determined from the preceding material in that particular chapter. Where at all possible, the problems mirror practical situations found in mechanical engineering. **387 line diagrams** enhance the understanding of the theory.

At regular intervals throughout the text are some **9 Revision Tests** to check understanding. For example, Revision Test 1 covers material contained in Chapter 1, Test 2 covers the material in Chapter 2, Test 3 covers the material in Chapters 3 to 6, and so on. No answers are given for the questions in the Revision Tests, but an **Instructor's guide** has been produced giving full solutions and suggested marking scheme. The guide is offered online free to lecturers/instructors – see below.

At the end of the text, a list of relevant **formulae** is included for easy reference, together with a **glossary of terms.**

'Learning by Example' is at the heart of *Mechanical Engineering Principles, 3rd Edition.*

JOHN BIRD
Defence College of Technical Training,
HMS Sultan, formerly
University of Portsmouth and
Highbury College, Portsmouth
CARL ROSS Professor, University of Portsmouth

Free Web downloads
The following support material is available from *http://www.routledge.com/cw/bird*

For Students:

1. Full worked solutions to all 700 further questions contained in the 150 Practice Exercises
2. A list of Essential Formulae
3. A full glossary of terms
4. Multiple-choice questions
5. Information on 20 Famous Engineers mentioned in the text
6. Video links to practical demonstrations by Professor Carl Ross **http://tiny.cc/6kvqhx**

For Lecturers/Instructors:

1– 6. As per students 1–6 above.

7. Full solutions and marking scheme for each of the 9 Revision Tests; also, each test may be downloaded for distribution to students.
8. All 387 illustrations used in the text may be downloaded for use in PowerPoint presentations.

Contents

Part One

Revision of Mathematics

Chapter 1

Revisionary mathematics

Why it is important to understand: Revisionary mathematics

Mathematics is a vital tool for professional and chartered engineers. It is used in mechanical & manufacturing engineering, in electrical & electronic engineering, in civil & structural engineering, in naval architecture & marine engineering and in aeronautical & rocket engineering. In these various branches of engineering, it is very often much cheaper and safer to design your artefact with the aid of mathematics – rather than through guesswork. 'Guesswork' may be reasonably satisfactory if you are designing an artefact similar to one that has already proven satisfactory; however, the classification societies will usually require you to provide the calculations proving that the artefact is safe and sound. Moreover, these calculations may not be readily available to you and you may have to provide fresh calculations, to prove that your artefact is 'roadworthy'. For example, if you design a tall building or a long bridge by 'guesswork', and the building or bridge do not prove to be structurally reliable, it could cost you a fortune to rectify the deficiencies. This cost may dwarf the initial estimate you made to construct these artefacts, and cause you to go bankrupt. Thus, without mathematics, the prospective professional or chartered engineer is very severely handicapped.

At the end of this chapter you should be able to:

- convert radians to degrees
- convert degrees to radians
- calculate sine, cosine and tangent for large and small angles
- calculate the sides of a right-angled triangle
- use Pythagoras' theorem
- use the sine and cosine rules for acute-angled triangles
- expand equations containing brackets
- be familiar with summing vulgar fractions
- understand and perform calculations with percentages
- understand and use the laws of indices
- solve simple simultaneous equations

1.1 Introduction

As highlighted above, it is not possible to understand aspects of mechanical engineering without a good knowledge of mathematics. This chapter highlights some areas of mathematics which will make the understanding of the engineering in the following chapters a little easier.

Mechanical Engineering Principles, Bird and Ross, ISBN 9780415517850

1.2 Radians and degrees

There are 2π radians or 360° in a complete circle, thus:

π **radians = 180°** from which,

$$\mathbf{1\ rad} = \frac{180°}{\pi} \quad \text{or} \quad \mathbf{1°} = \frac{\pi}{180}\ \mathbf{rad}$$

where π = 3.14159265358979323846 .... to 20 decimal places!

Problem 1. Convert the following angles to degrees correct to 3 decimal places:
(a) 0.1 rad (b) 0.2 rad (c) 0.3 rad

(a) $0.1\text{ rad} = 0.1\text{ rad} \times \frac{180°}{\pi\text{ rad}} = \mathbf{5.730°}$

(b) $0.2\text{ rad} = 0.2\text{ rad} \times \frac{180°}{\pi\text{ rad}} = \mathbf{11.459°}$

(c) $0.3\text{ rad} = 0.3\text{ rad} \times \frac{180°}{\pi\text{ rad}} = \mathbf{17.189°}$

Problem 2. Convert the following angles to radians correct to 4 decimal places:
(a) 5° (b) 10° (c) 30°

(a) $5° = 5° \times \frac{\pi\text{ rad}}{180°} = \frac{\pi}{36}\text{ rad} = \mathbf{0.0873\ rad}$

(b) $10° = 10° \times \frac{\pi\text{ rad}}{180°} = \frac{\pi}{18}\text{ rad} = \mathbf{0.1745\ rad}$

(c) $30° = 30° \times \frac{\pi\text{ rad}}{180°} = \frac{\pi}{6}\text{ rad} = \mathbf{0.5236\ rad}$

Now try the following Practice Exercise

Practice Exercise 1 Radians and degrees

1. Convert the following angles to degrees correct to 3 decimal places (where necessary):
   (a) 0.6 rad (b) 0.8 rad
   (c) 2 rad (d) 3.14159 rad
   [(a) 34.377° (b) 45.837°
   (c) 114.592° (d) 180°]
2. Convert the following angles to radians correct to 4 decimal places:
   (a) 45° (b) 90°
   (c) 120° (d) 180°
   [(a) $\frac{\pi}{4}$ rad or 0.7854 rad
   (b) $\frac{\pi}{2}$ rad or 1.5708 rad
   (c) $\frac{2\pi}{3}$ rad or 2.0944 rad
   (d) π rad or 3.1416 rad]

1.3 Measurement of angles

Angles are measured starting from the horizontal 'x' axis, in an **anticlockwise direction**, as shown by θ_1 to θ_4 in Figure 1.1. An angle can also be measured in a **clockwise direction**, as shown by θ_5 in Figure 1.1, but in this case the angle has a negative sign before it. If, for example, $\theta_4 = 300°$ then $\theta_5 = -60°$.

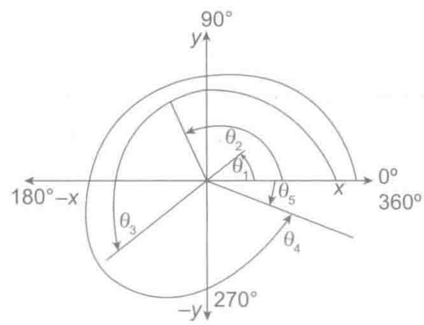


Figure 1.1

Problem 3. Use a calculator to determine the cosine, sine and tangent of the following angles, each measured anticlockwise from the horizontal 'x' axis, each correct to 4 decimal places:
(a) 30° (b) 120° (c) 250°
(d) 320° (e) 390° (f) 480°

(a) cos 30° = **0.8660** sin 30° = **0.5000**
tan 30° = **0.5774**

(b) cos 120° = **– 0.5000** sin 120° = **0.8660**
tan 120° = **– 1.7321**

(c) cos 250° = **– 0.3420** sin 250° = **– 0.9397**
tan 250° = **2.7475**

(d) cos 320° = **0.7660** sin 320° = **– 0.6428**
tan 320° = **– 0.8391**

(e) $\cos 390° = \mathbf{0.8660}$ $\sin 390° = \mathbf{0.5000}$
$\tan 390° = \mathbf{0.5774}$

(f) $\cos 480° = \mathbf{-0.5000}$ $\sin 480° = \mathbf{0.8660}$
$\tan 480° = \mathbf{-1.7321}$

These angles are now drawn in Figure 1.2. Note that cosine and sine always lie between –1 and +1 but that tangent can be >1 and <1

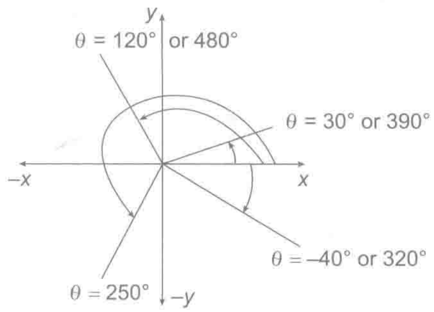


Figure 1.2

Note from Figure 1.2 that $\theta = 30°$ is the same as $\theta = 390°$ and so are their cosines, sines and tangents. Similarly, note that $\theta = 120°$ is the same as $\theta = 480°$ and so are their cosines, sines and tangents. Also, note that $\theta = -40°$ is the same as $\theta = +320°$ and so are their cosines, sines and tangents.
It is noted from above that

- in the **first quadrant**, i.e. where θ varies from 0° to 90°, all (A) values of cosine, sine and tangent are positive
- in the **second quadrant**, i.e. where θ varies from 90° to 180°, only values of sine (S) are positive
- in the **third quadrant**, i.e. where θ varies from 180° to 270°, only values of tangent (T) are positive
- in the **fourth quadrant**, i.e. where θ varies from 270° to 360°, only values of cosine (C) are positive

These positive signs, A, S, T and C are shown in Figure 1.3.

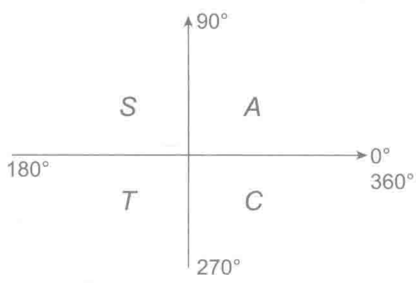


Figure 1.3

Now try the following Practice Exercise

Practice Exercise 2 Measurement of angles

1. Find the cosine, sine and tangent of the following angles, where appropriate each correct to 4 decimal places:
(a) 60° (b) 90° (c) 150°
(d) 180° (e) 210° (f) 270°
(g) 330° (h) – 30° (i) 420°
(j) 450° (k) 510°

[(a) 0.5, 0.8660, 1.7321
(b) 0, 1, ∞
(c) – 0.8660, 0.5, – 0.5774
(d) –1, 0, 0
(e) – 0.8660, – 0.5, 0.5774
(f) 0, –1, – ∞
(g) 0.8660, – 0.5000, – 0.5774
(h) 0.8660, – 0.5000, – 0.5774
(i) 0.5, 0.8660, 1.7321
(j) 0, 1, ∞
(k) – 0.8660, 0.5, – 0.5774]

1.4 Triangle calculations

(a) Sine, cosine and tangent

From Figure 1.4, $\sin\theta = \frac{bc}{ac}$ $\cos\theta = \frac{ab}{ac}$

$$\tan\theta = \frac{bc}{ab}$$

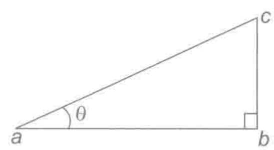


Figure 1.4

Problem 4. In Figure 1.4, if $ab = 2$ and $ac = 3$, determine the angle θ.

It is convenient to use the expression for $\cos\theta$, since 'ab' and 'ac' are given.

Hence, $\cos\theta = \frac{ab}{ac} = \frac{2}{3} = 0.66667$

from which, $\theta = \cos^{-1}(0.66667) = \mathbf{48.19°}$

Problem 5. In Figure 1.4, if $bc = 1.5$ and $ac = 2.2$, determine the angle θ.

It is convenient to use the expression for sin θ, since 'bc' and 'ac' are given.

Hence, $\sin\theta = \frac{bc}{ac} = \frac{1.5}{2.2} = 0.68182$

from which, $\theta = \sin^{-1}(0.68182) = \mathbf{42.99°}$

Problem 6. In Figure 1.4, if $bc = 8$ and $ab = 1.3$, determine the angle θ.

It is convenient to use the expression for tan θ, since 'bc' and 'ab' are given.

Hence, $\tan\theta = \frac{bc}{ab} = \frac{8}{1.3} = 6.1538$

from which, $\theta = \tan^{-1}(6.1538) = \mathbf{80.77°}$

(b) Pythagoras' theorem

Pythagoras' theorem* states that:
$(\text{hypotenuse})^2 = (\text{adjacent side})^2 + (\text{opposite side})^2$
i.e. in the triangle of Figure 1.5,

$$\mathbf{ac^2 = ab^2 + bc^2}$$

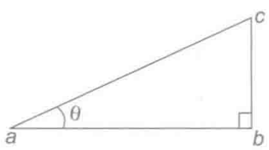


Figure 1.5

Problem 7. In Figure 1.5, if $ab = 5.1$ m and $bc = 6.7$ m, determine the length of the hypotenuse, ac.

From Pythagoras, $ac^2 = ab^2 + bc^2$

$= 5.1^2 + 6.7^2 = 26.01 + 44.89$

$= 70.90$

from which, $ac = \sqrt{70.90} = \mathbf{8.42\ m}$

Now try the following Practice Exercise

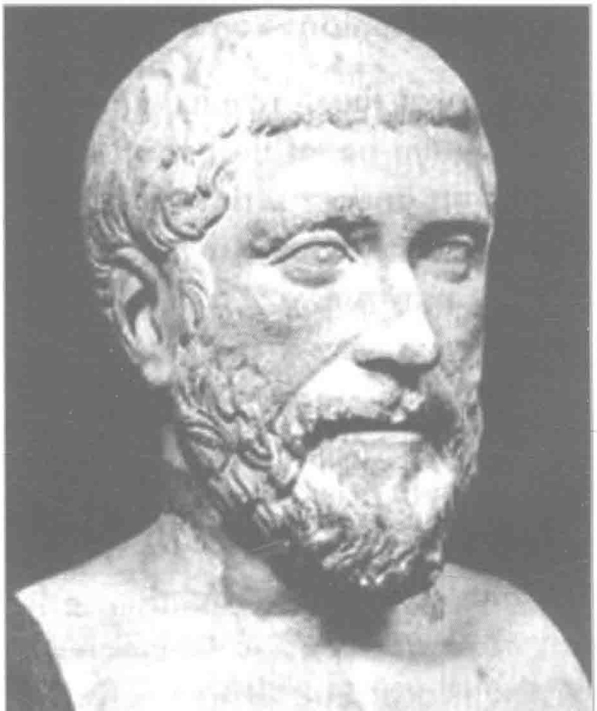
Practice Exercise 3 Sines, cosines and tangents and Pythagoras' theorem

In problems 1 to 5, refer to Figure 1.5.

1. If ab = 2.1 m and bc = 1.5 m, determine angle θ. [35.54°]
2. If ab = 2.3 m and ac = 5.0 m, determine angle θ. [62.61°]
3. If bc = 3.1 m and ac = 6.4 m, determine angle θ. [28.97°]
4. If ab = 5.7 cm and bc = 4.2 cm, determine the length ac [7.08 cm]
5. If ab = 4.1 m and ac = 6.2 m, determine length bc. [4.65 m]

(c) The sine and cosine rules

For the triangle ABC shown in Figure 1.6,



*Pythagoras of Samos (born approximately 570BC and died around 495BC) was an Ionian Greek philosopher and mathematician, best known for the Pythagorean Theorem. To find out more go to www.routledge.com/cw/bird

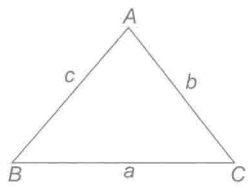


Figure 1.6

the sine rule states: $\dfrac{a}{\sin A} = \dfrac{b}{\sin B} = \dfrac{c}{\sin C}$

and the cosine rule states: $a^2 = b^2 + c^2 - 2bc\cos A$

Problem 8. In Figure 1.6, if $a = 3$ m, $A = 20°$ and $B = 120°$, determine lengths b, c and angle C.

Using the sine rule, $\dfrac{a}{\sin A} = \dfrac{b}{\sin B}$

i.e. $\dfrac{3}{\sin 20°} = \dfrac{b}{\sin 120°}$

from which, $b = \dfrac{3\sin 120°}{\sin 20°} = \dfrac{3 \times 0.8660}{0.3420}$

$= \mathbf{7.596\ m}$

Angle, $C = 180° - 20° - 120° = \mathbf{40°}$

Using the sine rule again gives: $\dfrac{c}{\sin C} = \dfrac{a}{\sin A}$

i.e. $c = \dfrac{a\sin C}{\sin A} = \dfrac{3 \times \sin 40°}{\sin 20°}$

$= \mathbf{5.638\ m}$

Problem 9. In Figure 1.6, if $b = 8.2$ cm. $c = 5.1$ cm and $A = 70°$, determine the length a and angles B and C.

From the cosine rule,

$$a^2 = b^2 + c^2 - 2bc\cos A$$
$$= 8.2^2 + 5.1^2 - 2 \times 8.2 \times 5.1 \times \cos 70°$$
$$= 67.24 + 26.01 - 2(8.2)(5.1)\cos 70°$$
$$= 64.643$$

Hence, **length,** $a = \sqrt{64.643} = \mathbf{8.04\ cm}$

Using the sine rule: $\dfrac{a}{\sin A} = \dfrac{b}{\sin B}$

i.e. $\dfrac{8.04}{\sin 70°} = \dfrac{8.2}{\sin B}$

from which, $8.04 \sin B = 8.2 \sin 70°$

and $\sin B = \dfrac{8.2\sin 70°}{8.04} = 0.95839$

and $B = \sin^{-1}(0.95839) = \mathbf{73.41°}$

Since $A + B + C = 180°$, then

$C = 180° - A - B = 180° - 70° - 73.41° = \mathbf{36.59°}$

Now try the following Practice Exercise

Practice Exercise 4 Sine and cosine rules

In problems 1 to 4, refer to Figure 1.6.

1. If $b = 6$ m, $c = 4$ m and $B = 100°$, determine angles A and C and length a. [$A = 38.96°$, $C = 41.04°$, $a = 3.83$ m]
2. If $a = 15$ m, $c = 23$ m and $B = 67°$, determine length b and angles A and C. [$b = 22.01$ m, $A = 38.86°$, $C = 74.14°$]
3. If $a = 4$ m, $b = 8$ m and $c = 6$ m, determine angle A. [28.96°]
4. If $a = 10.0$ cm, $b = 8.0$ cm and $c = 7.0$ cm, determine angles A, B and C. [$A = 83.33°$, $B = 52.62°$, $C = 44.05°$]
5. In Figure 1.7, PR represents the inclined jib of a crane and is 10.0 m long. PQ is 4.0 m long. Determine the inclination of the jib to the vertical (i.e. angle P) and the length of tie QR.

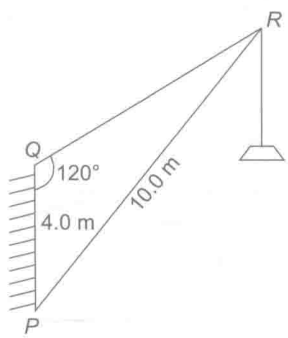


Figure 1.7

[$P = 39.73°$, $QR = 7.38$ m]