Unit 11: Further Mechanical Principles and Applications

Unit code: Y/600/0261

QCF Level 3: BTEC National

Credit value: 10

Guided learning hours: 60

Aim and purpose

This unit gives learners the opportunity to extend their knowledge of mechanical principles and to apply them in the solution of engineering problems.

Unit introduction

All machines and mechanisms consist of interconnected parts working together to produce a desired output. Engineers involved in the design, testing and servicing of mechanical systems need to have a firm grasp of the underpinning principles in order to appreciate the choice of components, the forces acting on them and the way that they relate to each other.

The study of stationary structures and their components is often referred to as 'statics'. The first two learning outcomes cover the mechanical principles that underpin the design of framed structures, simply supported beams and structural components. The aim is to give learners the means to evaluate the integrity and safety of engineering structures and to lay the foundation for structural analysis at a higher level.

A great many engineering systems are designed to transmit motion and power. These include machine tools, motor vehicles, aircraft and a range of domestic appliances. The study of the motion in mechanical systems is known as 'kinematics' and the study of the forces at work and the power they transmit is known as 'dynamics'. Learning outcomes 3 and 4 aim to extend learners' knowledge of the mechanical principles associated with these studies. Learning outcome 3 aims to provide a basic knowledge of rotational motion and the effects of centripetal force in simple rotating systems. In learning outcome 4 learners are introduced to simple machines used as lifting devices. An understanding of the mechanical principles involved in the operation of these devices and mechanisms will provide a foundation for the analysis of more complex power transmission systems at a higher level of study.

Learning outcomes

On completion of this unit a learner should:

1 Be able to determine the forces acting in pin-jointed framed structures and simply supported beams

2 Be able to determine the stress in structural members and joints

3 Be able to determine the characteristics of rotating systems

4 Be able to determine the operating characteristics of simple lifting machines.

Unit content

1 Be able to determine the forces acting in pin-jointed framed structures and simply supported beams

Pin-jointed framed structures: solution eg graphical (such as use of Bow's notation, space and force diagram), analytical (such as resolution of joints, method of sections, resolution of forces in perpendicular directions ($F_x = F\cos\theta$, $F_y = F\sin\theta$), vector addition of forces, application of conditions for static equilibrium ($\Sigma F_x = 0$, $\Sigma F_y = 0$, $\Sigma M = 0$)

Forces: active forces eg concentrated loads; uniformly distributed loads; reactive forces eg support reactions, primary tensile and compressive force in structural members

Simply supported beams: distribution of shear force and bending moment for a loaded beam eg concentrated loads, uniformly distributed load (UDL); types of beam arrangement eg beam without overhang, beam with overhang and point of contraflexure

2 Be able to determine the stress in structural members and joints

Single and double shear joints: fastenings eg bolted or riveted joints in single and double shear; joint parameters eg rivet or bolt diameter, number of rivets or bolts, shear load, expressions for shear stress in joints subjected to single and double shear, factor of safety

Structural members: members eg plain struts and ties, series and parallel compound bars made from two different materials; loading eg expressions for direct stress and strain, thermal stress, factor of safety

3 Be able to determine the characteristics of rotating systems

Rotating systems with uniform angular acceleration: systems eg simple (such as rotating rim, flywheel, motor armature, pump or turbine rotor), complex (such as systems where combined linear and angular acceleration is present, hoist and vehicle on an inclined track); kinetic parameters eg angular displacement, angular velocity, angular acceleration, equations for uniform angular motion ($\omega_2 = \omega_1 \alpha t$, $\theta = \omega_1 t + \frac{1}{2}\alpha t^2$, $\omega_2^2 = \omega_1^2 + 2\alpha\theta$, $\theta = \frac{1}{2}(\omega_1 + \omega_2)t$); dynamic parameters eg radius of gyration, moment of inertia ($I = mk^2$), inertia torque ($T = I\alpha$), friction torque, application of D'Alembert's principle, mechanical work ($W = T\theta$), power ($Average\ Power = W/t$, $Instantaneous\ Power = T\omega$), rotational kinetic energy ($KE = \frac{1}{2}I\omega^2$), application of principle of conservation of energy

Rotating systems with uniform centripetal acceleration: systems eg simple (such as concentrated mass rotating in a horizontal or vertical plane, vehicle on a hump-backed bridge, aircraft performing a loop), complex (such as centrifugal clutch, vehicle on a curved track); kinetic parameters eg expressions for centripetal acceleration ($a = \omega^2 r$, $a = v^2/r$); dynamic parameters eg expressions for centripetal force ($F_c = m\omega^2 r$, $F_c = mv^2/r$)

4 Be able to determine the operating characteristics of lifting machines

Parameters of lifting machines: kinetic parameters eg input motion, output motion, velocity or movement ratio, overhauling; dynamic parameters eg input effort, load raised, mechanical advantage or force ratio, law of a machine, efficiency, limiting efficiency

Lifting machines: lifting machines eg simple (such as inclined plane, screw jack, pulley blocks, wheel and axle, simple gear train winch), differential (such as differential wheel and axle, Weston differential pulley block, compound gear train winch)

Assessment and grading criteria

In order to pass this unit, the evidence that the learner presents for assessment needs to demonstrate that they can meet all the learning outcomes for the unit. The assessment criteria for a pass grade describe the level of achievement required to pass this unit.

Grading criteria		
To achieve a pass grade the evidence must show that the learner is able to:	**To achieve a merit grade the evidence must show that, in addition to the pass criteria, the learner is able to:**	**To achieve a distinction grade the evidence must show that, in addition to the pass and merit criteria, the learner is able to:**
P1 determine graphically the magnitude and nature of the support reactions and primary forces acting in the members of a framed structure with at least four pin-jointed members	**M1** analytically determine the magnitude and nature of the support reactions and primary forces acting in the members of a framed structure with at least four pin-jointed members	**D1** determine the induced stresses and dimensional changes that occur in the materials of a series connected compound bar and a parallel connected compound bar when subjected to direct loading
P2 determine the distribution of shear force and bending moment for a simply supported beam without overhang carrying at least three concentrated loads	**M2** determine the distribution of shear force and bending moment and locate a point of contraflexure for a simply supported beam with overhang carrying at least two concentrated loads and a continuous uniformly distributed load	**D2** evaluate the kinetic and dynamic parameters of operation of a differential lifting machine.
P3 determine the required parameters for a single shear lap joint and a double shear butt joint for given service conditions [IE1, IE4]	**M3** determine the applied torque, work done and power dissipated in a uniformly accelerated complex rotating system in which both linear and rotational motion is present, to overcome the effects of inertia, friction and gravity	
P4 determine the induced direct stress, dimensional change and factor of safety in operation for a rigidly held plain structural member when subjected to a combination of direct and thermal loading	**M4** determine the performance of a complex rotating system due to the effects of centripetal acceleration.	

Grading criteria			
To achieve a pass grade the evidence must show that the learner is able to:		**To achieve a merit grade the evidence must show that, in addition to the pass criteria, the learner is able to:**	**To achieve a distinction grade the evidence must show that, in addition to the pass and merit criteria, the learner is able to:**
P5	determine the applied torque, work done and power dissipated in a uniformly accelerated simple rotating system to overcome the effects of inertia and friction		
P6	determine centripetal acceleration and centripetal force in a simple rotating system		
P7	determine the kinetic and dynamic parameters of operation of two different simple lifting machines from given data.		

PLTS: This summary references where applicable, in the square brackets, the elements of the personal, learning and thinking skills applicable in the pass criteria. It identifies opportunities for learners to demonstrate effective application of the referenced elements of the skills.

Key	IE – independent enquirers	RL – reflective learners	SM – self-managers
	CT – creative thinkers	TW – team workers	EP – effective participators

Essential guidance for tutors

Delivery

There are close links between learning outcomes 1 and 2 of this unit, which are both concerned with static force systems. It is therefore likely that these learning outcomes will be delivered concurrently and with some degree of integration. Learning outcomes 3 and 4 are concerned with dynamic systems but the links are not so close and the order of delivery is a matter of centre preference. Wherever possible an investigative approach should be adopted in which the underpinning mechanical principles are consolidated in the solution of problems and laboratory investigations.

Revision of previous work may be needed at the start of learning outcome 1. In particular, learners will need a clear understanding of vector addition and the resolution of forces. In the solution of pin-jointed framed structures, a maximum of four members will give sufficient depth of treatment. With larger numbers, the process becomes repetitive and time consuming. Appropriate use should be made of Bow's notation in the construction of space and vector diagrams. The calculation of stress in structural members and fastenings can proceed directly from determination of the primary forces present in struts and ties.

Learners will already have encountered the calculation of beam reactions in *Unit 6: Mechanical Principles and Applications*. This knowledge can now be extended to cover distribution of shear force and bending moment in beams carrying a combination of concentrated and uniformly distributed loads. An appropriate and coherent sign convention should be adopted that can be extended at a higher level to the determination of slope and deflection.

The significance of points of contraflexure in the design of fabricated beams should be explained together with the relationship between shear force and bending moment. This will give a firm foundation for beam analysis at a higher level. If available, the use of CAD packages can be useful in confirming the analysis of static force systems.

Learning outcome 3 will extend learners' knowledge of kinematics and dynamics to cover uniform rotational motion. The use of both D'Alembert's principle and the principle of conservation of energy should be encouraged when problem solving. The application of D'Alembert's principle is in effect the application of Newton's second and third laws of motion with the inertial reaction ma or $I\alpha$, considered as an external force or torque. It enables a free body diagram to be drawn which aids the mathematical modelling of a dynamic system. For a linear motion system the diagram might also contain frictional resistance F_f and weight mg, or some component of weight $mg \sin\theta$, if the body is on an incline. The resultant force F (tractive effort or braking force) is then the vector sum of these three, ie $F = ma + F_f + mg \sin\theta$.

The same applies to rigid body rotation where the resultant tractive or braking torque T is the vector sum of the inertial resistance $I\alpha$, which is again imagined to be an external torque, and the friction torque T_f, ie, $T = I\alpha + T_f$.

Laboratory investigation of moment of inertia and radius of gyration of a rotor will help reinforce delivery. An explanation of vector subtraction may be necessary prior to derivation of the expressions for centripetal acceleration and centripetal force. The expressions may be verified experimentally using turntable apparatus if available. A range of simple and complex applications should be considered when problem solving.

The lifting machines listed as examples for learning outcome 4 have many practical applications and the underpinning theory is highly relevant to machine design. The topic lends itself to practical investigations, which may be incorporated into the assessment strategy.

Note that the use of 'eg' in the content is to give an indication and illustration of the breadth and depth of the area or topic. As such, not all content that follows an 'eg' needs to be taught or assessed.

Outline learning plan

The outline learning plan has been included in this unit as guidance and can be used in conjunction with the programme of suggested assignments.

The outline learning plan demonstrates one way in planning the delivery and assessment of this unit.

Topic and suggested assignments/activities and/assessment
Whole-class teaching: • introduction to unit content • revise Bow's notation and demonstrate graphical solution of a simple pin-jointed framed structure • revise resolution of forces and demonstrate analytical solution of a simple framed structure by resolution of forces acting at the joints and by method of sections. *Individual activity*: • graphical and analytical solution of simple pin-jointed framed structures.
Whole-class teaching: • define shear force and bending moment and explain sign conventions • demonstrate calculation and diagrammatic distribution of shear force and bending moment for simple cantilevers and simply supported beams carrying concentrated loads • demonstrate calculation and diagrammatic distribution of shear force and bending moment for simple cantilevers and simply supported beams carrying a combination of uniformly distributed and concentrated loads • explain relationship between shear force and bending moment diagrams and the significance of points of contraflexure. *Individual activity*: • determination of shear force and bending moment distribution in simple cantilevers and simply supported beams.
Preparation for and carrying out **Assignment 1: Forces and Moments in Static Systems** (P1, P2, M1, M2).
Whole-class teaching: • revise calculation of direct stress and strain, modulus of elasticity and factor of safety • describe series connected compound bars and demonstrate the calculation of stress and dimensional change due to direct loading • describe parallel connected compound bars and demonstrate the calculation of stress and dimensional change due to direct loading. *Individual activity*: • solve problems to determine induced stresses and dimensional changes in series and parallel connected compound bars due to direct loading.

Topic and suggested assignments/activities and/assessment
Whole-class teaching: • revise linear expansivity and expression for stress due to thermal loading • demonstrate solution of problems involving plain struts and ties subjected to a combination of direct and thermal loading • demonstrate solution of problems involving series and parallel connected compound bars subjected to a combination of direct loading. *Individual activity*: • solve problems to determine induced stresses and dimensional changes in series and parallel connected compound bars due to direct loading.
Whole-class teaching: • revise shear loading and calculation of shear stress • discuss the applications of riveted and bolted lap joints and butt joints • derive expressions for shear stress in bolts and rivets subjected to single and double shear • demonstrate solution of problems involving riveted and bolted joints subjected to single and double shear. *Individual activity*: • solve problems involving riveted and bolted lap joints and butt joints.
Preparation for and carrying out **Assignment 2: Stress in Static System Component** (P3, P4, D1).
Whole-class teaching: • revise equations for uniform linear motion and derive corresponding equations for uniform angular motion • derive linear-angular motion conversion formulae and expressions for rotational work and power • derive expression for torque required to overcome the inertia of a rotating body and define mass moment of inertia and radius of gyration • derive expressions for moment of inertia of a rotating rim and a rotating disc about polar axes • demonstrate application of D'Alembert's principle to solve dynamic problems on the range of simple and complex rotating systems. *Individual activity*: • solve dynamic problems on the range of simple and complex rotating systems involving using equations of motion and D'Alembert's principle.
Whole-class teaching: • revise linear kinetic energy and gravitational potential energy • derive expression for rotational kinetic energy • demonstrate application of the principle of conservation of energy to solve dynamic problems on the range of rotating systems. *Individual or small-group activity*: • solve dynamic problems on the range of simple and complex rotating systems using the principle of conservation of energy.

Topic and suggested assignments/activities and/assessment
Whole-class teaching: • derive expressions for centripetal acceleration and centripetal force • describe the construction and operation of a centrifugal clutch and derive expressions for engagement speed and for torque and power transmitted • describe and discuss the stability of a vehicle on an unbanked curve and derive expressions for maximum safe speed • derive expression for banking angle required for no side-slip tendency at a given speed • demonstrate solution of dynamic problems involving the range simple and complex rotating systems. *Individual or small-group activity*: • solve dynamic problems involving the range simple and complex rotating systems.
Preparation for and carrying out **Assignment 3: Dynamic Systems** (P5, P6, M3, M4).
Whole-class teaching: • describe the range of simple and differential lifting machines and their parameters • derive expressions for velocity ratio for the range of lifting machines • explain the law of a machine and derive the expression for limiting efficiency • demonstrate the solution of system problems for simple and differential lifting machines. *Individual activity*: • solve system problems on simple and differential lifting machines.
Preparation for and carrying out **Assignment 4: Lifting Machines** (P7, D2).
Feedback on assessment and unit review.

Assessment

Ideally, assessment of this unit will be achieved through application of the mechanical principles covered to the relevant engineering settings. This could be achieved through integration with other engineering principles units, practical work that provides learners with opportunities to produce individual evidence for assessment against the criteria, and individual project/assignment tasks. Whichever approach is taken it is important to ensure that the criteria are achieved autonomously. Where centres consider a test/examination is necessary to achieve authentic evidence then they need to ensure that the test items are set in a way to enable the criteria to be met in full. Centres also need to consider how such an assessment will provide opportunities to meet the merit and distinction criteria and how to provide learners with further learning and assessment should they initially fail to achieve in the test/examination.

If learners make an arithmetic error within the solution to a problem, it is for the centre to decide the significance of such an error, assess the work accordingly and provide suitable feedback. For example, if a learner has chosen the correct approach and manipulated the necessary formulae and data correctly but has made and carried through a minor arithmetic error, then the final 'inaccurate' solution to the problem may be deemed to be good enough to meet the criterion. However, if the final solution to the problem is so obviously wrong that it should have prompted further checks for accuracy, then the solution could be deemed to be unacceptable and reassessment considered. The incorrect application of units and/or dimensions are a typical cause of such major errors, which can lead to relatively large scale errors of the magnitude 10^3 or greater.

It is possible to assess the criteria P1, P2, M1 and M2 through an assignment requiring the graphical and analytical solution of a given pin-jointed framed structure and the analysis of given simply supported beams. The magnitude and nature of the framed structure support reactions and internal forces may be determined graphically (P1) and confirmed analytically (M1). Learners should make use of Bow's notation in their analysis.

The simply supported beam for P2 should contain at least three concentrated loads and be supported at its free ends. The simply supported beam for M2 should overhang one of its supports and contain at least two concentrated loads and a continuous uniformly distributed load. Learners should be required to adopt an analytical approach to locate the point of contraflexure.

A second assignment could assess the criteria P3, P4 and D1. The first task might be to determine the parameters for a single shear lap joint and for a double shear butt joint (P3) for given service conditions. This might involve calculation of the rivet/bolt diameter required for a given load or the safe working load for a particular joint. The joints should contain at least three rivets/bolts (six in total for the butt joint).

A second task might be to calculate the direct stress induced in a rigidly fixed member due to direct loading and temperature change (P4). A further task could involve evaluation of the stresses and dimensional changes occurring in series and parallel connected compound bars (D1) when subjected to direct loading.

A third assignment could be used to assess the criteria P5, P6, M3 and M4. The first task might involve consideration of a simple rotating system, such as a flywheel, which is accelerated against the effects of inertia and friction (P5). A second task might involve consideration of a more complex system such as a hoist or a vehicle on an incline in which both linear and angular motion is present (M3). The third task might be to determine the centripetal acceleration and centripetal force present in a simple rotating system (P6). A final task would require learners to determine effects of centripetal acceleration and force in a more complex rotating system (M4). This might involve determining the speed of engagement and power transmitted by a centrifugal clutch. Alternatively, learners could evaluate the active and reactive forces on a vehicle travelling round a curved level track, maximum safe speed and the banking angle required for no tendency to side-slip at a given speed. The term performance in the criterion is therefore relevant to the particular rotating system given/used.

A final assignment containing two tasks could be used to achieve the P7 and D2 criteria. The first task would involve determination of velocity ratio, mechanical advantage and efficiency of two simple lifting machines for given input conditions (P7). Exemplar machines are ranged in the unit content.

In a second task the D2 distinction criterion could be achieved by means of a practical or simulated investigation of a differential lifting device. This should involve the determination of velocity ratio and the gathering of a sufficiently wide range of load and effort values for analysis of the machine performance. Graphs of load versus effort and load versus efficiency can then be plotted from the manipulated and tabulated test data. The law of the machine can be derived from the load versus effort graph and the theoretical value of the limiting efficiency obtained. An evaluation of this limiting value can then be made by comparison with that indicated on the load versus efficiency graph. An evaluation can also be made as to the likelihood of overhauling. Again, exemplar machines for this task are ranged in the unit content.

Programme of suggested assignments

The table below shows a programme of suggested assignments that cover the pass, merit and distinction criteria in the assessment and grading grid. This is for guidance and it is recommended that centres either write their own assignments or adapt any Edexcel assignments to meet local needs and resources.

Criteria covered	Assignment title	Scenario	Assessment method
P1, P2, M1, M2	Forces and Moments in Static Systems	Analysis of pin-jointed framed structures and simply supported beams.	A written report containing required graphics and an appropriate introductory explanation to each step in the sequence of calculations and findings.
P3, P4, D1	Stress in Static System Components	Determination of parameters for riveted joints and determination of stress in plain and compound structural members.	A written report containing an appropriate introductory explanation to each step in the sequence of calculations and findings.
P5, P6, M3, M4	Dynamic Systems	Determination of dynamic system parameters and performance.	A written report containing an appropriate introductory explanation to each step in the sequence of calculations and findings.
P7, D2	Lifting Machines	Determination of the parameters and performance of simple lifting machines.	A written report containing an appropriate introductory explanation to each step in the sequence of calculations and findings.

Links to National Occupational Standards, other BTEC units, other BTEC qualifications and other relevant units and qualifications

This unit forms part of the BTEC Engineering sector suite. This unit has particular links with the following unit titles in the Engineering suite:

Level 1	Level 2	Level 3
	Applied Electrical and Mechanical science for Technicians	Mechanical Principles and Applications
		Applications of Mechanical Systems and Technology
		Advanced Mechanical Principles and Applications

This unit provides some of the underpinning knowledge for the SEMTA Level 3 NVQ in Mechanical Manufacture, Level 3 NVQ in Engineering Maintenance and Level 3 NVQ in Engineering Technical Support.

Essential resources

There are no essential resources required for this unit. However centres should try to provide access to laboratory facilities with a range of equipment for investigation and demonstration purposes wherever possible. In particular, flywheels or other rotor systems for the determination of moment of inertia and radius of gyration, turntable apparatus for the investigation of centripetal acceleration and force and a range of simple lifting machines.

Employer engagement and vocational contexts

Some of the work for this unit can be set in the context of learners' work placements or be based on case studies of local employers. Industrial visits will enhance delivery of the unit. Engineering companies with design, testing and development departments will be able to explain the relevance of mechanical science to their work.

There are a range of organisations that may be able help centres engage and involve local employers in the delivery of this unit, for example:

- Work Experience/Workplace learning frameworks – Centre for Education and Industry (CEI, University of Warwick) – www.warwick.ac.uk/wie/cei
- Learning and Skills Network – www.vocationallearning.org.uk
- Network for Science, Technology, Engineering and Maths Network Ambassadors Scheme – www.stemnet.org.uk
- National Education and Business Partnership Network – www.nebpn.org
- Local, regional Business links – www.businesslink.gov.uk
- Work-based learning guidance – www.aimhighersw.ac.uk/wbl.htm

Indicative reading for learners

Textbooks

Bird J – *Science for Engineering* (Newnes, 2003) ISBN 0750657774

Bolton W – *Engineering Science* (Newnes, 2001) ISBN 0750652594

Darbyshire A – *Mechanical Engineering BTEC Optional Units* (Newnes, 2003) ISBN 0750657618

Tooley M and Dingle L – *BTEC National Engineering* (Newnes, 2007) ISBN 9780750685214

Delivery of personal, learning and thinking skills

The table below identifies the opportunities for personal, learning and thinking skills (PLTS) that have been included within the pass assessment criteria of this unit.

Skill	When learners are ...
Independent enquirers	determining the required parameters for a single shear lap joint and a double shear butt joint for given service conditions.

Although PLTS are identified within this unit as an inherent part of the assessment criteria, there are further opportunities to develop a range of PLTS through various approaches to teaching and learning.

Skill	When learners are ...
Creative thinkers	trying out alternative solutions to problems
Reflective learners	inviting feedback and dealing positively with praise, setbacks and criticism
Self-managers	organising their time and resources and prioritising actions when solving problems.

Functional Skills – Level 2

Skill	When learners are ...
ICT – Develop, present and communicate information	
Enter, develop and format information independently to suit its meaning and purpose including: • text and tables • images • numbers • records	presenting calculations and findings for set assignments
Mathematics	
Understand routine and non-routine problems in a wide range of familiar and unfamiliar contexts and situations	understanding the settings and contexts of mechanical system problems
Identify the situation or problem and the mathematical methods needed to tackle it	identifying relevant data and calculating system parameters
Select and apply a range of skills to find solutions	selecting and applying appropriate methods and procedures to solve mechanical system problems
Use appropriate checking procedures and evaluate their effectiveness at each stage	checking the validity of calculations and findings
Interpret and communicate solutions to practical problems in familiar and unfamiliar routine contexts and situations	presenting calculations in a logical sequence with statements of intent and correctly stated units
Draw conclusions and provide mathematical justifications	justifying selection and use of formulae and presenting findings and conclusions
English	
Writing – write documents, including extended writing pieces, communicating information, ideas and opinions, effectively and persuasively	presenting solutions to problems, justifying of methods used and communicating findings and conclusions.