Unit 18: Advanced Mechanical Principles and Applications

Unit code: F/600/0268

QCF Level 3: BTEC National

Credit value: 10

Guided learning hours: 60

Aim and purpose

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

Unit introduction

This unit will build on the learner's knowledge of underpinning mechanical principles and the way they affect the design, operation, testing and servicing of machines and mechanisms.

The component parts of a mechanical system are very often subjected to loads and may be used to transmit force. It is essential that they are fit for purpose so that costly breakdowns and accidents are avoided. Design engineers must be able to predict the stresses to which engineering components will be subjected and ensure an appropriate level of safety.

Learning outcomes 1 and 2 will broaden the learner's knowledge of stress analysis to include stress due to bending, stress due to torsion and the effects of two-dimensional and three dimensional loading.

Learners sometimes have difficulty with the concepts of resultant and relative velocity. Learning outcome 3 seeks to clarify how these concepts are determined through the techniques of vector addition and vector subtraction. These are then applied to the operation of plane linkage mechanisms to determine the output characteristics for given input conditions.

The aim of learning outcome 4 is to give an understanding of mechanical oscillations in engineering systems. The concept of simple harmonic motion is introduced and expressions are derived for its parameters. These are then applied to freely vibrating systems such as mass-spring systems and the simple pendulum.

The unit as a whole provides an opportunity for investigative, relevant and active study that will enhance the learner's ability to solve engineering problems.

Learning outcomes

On completion of this unit a learner should:

1. Be able to determine the effects of uniaxial and complex loading on engineering components
2. Be able to determine the stress due to bending in beams and torsion in power transmission shafts
3. Be able to determine relative and resultant velocity in engineering systems
4. Be able to determine the characteristics of simple harmonic motion in engineering systems.

Unit content

1 Be able to determine the effects of uniaxial and complex loading on engineering components

Uniaxial loading: expressions for longitudinal and transverse strain; application of Poisson's ratio; determination of dimensional changes in plain struts and ties

Complex loading: expressions eg strain in x and y directions due to 2D loading, strain in x, y and z directions due to 3D loading; changes eg dimensional in rectangular plates, dimensional and volume for cubic elements

2 Be able to determine the stress due to bending in beams and torsion in power transmission shafts

Direct stress due to bending: expressions for second moment of area of solid and hollow rectangular and circular beam sections; application of bending equation ($\sigma/y = M/I = E/R$) to determine stress due to bending and radius of curvature at a beam section; determination of factor of safety in operation

Shear stress due to torsion: expressions for polar second moment of area of solid and hollow circular transmission shaft sections; application of torsion equation ($\tau/r = T/J = G\theta/l$) and expression for power transmitted ($Power = T\omega$) to determine induced shear stress and angle of twist; determination of factor of safety in operation

3 Be able to determine relative and resultant velocity in engineering systems

Resultant and relative velocity: vector addition of velocities; resultant velocity of a body with simultaneous velocities in different directions; vector subtraction of velocities; relative velocity between objects moving simultaneously in different directions; construction of space diagrams and velocity vector diagrams

Plane mechanisms: eg slider-crank and inversions, four-bar linkage and inversions, slotted link quick return mechanism, Whitworth quick-return mechanism; construction of diagrams eg space diagram, velocity vector diagram, determination of output motion

4 Be able to determine the characteristics of simple harmonic motion in engineering systems

Simple harmonic motion generation: general equations for simple harmonic motion derived from a consideration of uniform circular motion eg expressions for circular frequency, displacement with time, velocity with time, velocity with displacement, acceleration with time, acceleration with displacement, periodic time, frequency of vibration; application to mechanical systems where output simple harmonic motion is generated by input uniform circular motion eg scotch yoke mechanism; parameters to be determined eg frequency of vibration, periodic time, displacement, velocity and acceleration at a given instant

Vibrating mechanical systems: systems (mass-spring, simple pendulum); expressions for circular frequency in terms of system parameters; application of general equations for simple harmonic motion eg natural frequency of vibration, periodic time, velocity and acceleration at a given instant

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.

Assessment and 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 the dimensional effects of uniaxial loading on a plain structural component and two-dimensional loading on a rectangular plate	**M1**	determine the dimensional effects and change in volume for a given element of an engineering component when subjected to three-dimensional loading	**D1**	compare the saving in weight and the reduced torque transmission capacity for a hollow power transmission shaft as its internal diameter is increased
P2	determine the maximum stress due to bending, factor of safety in operation and minimum radius of curvature for a simply supported beam carrying a given concentrated load and a uniformly distributed load	**M2**	compare the effects on a rectangular section beam's load-carrying capacity of increasing the breadth and increasing the depth by given amounts	**D2**	determine from test data the effective contributory mass of the spring in an oscillating mass-spring system.
P3	determine the maximum shear stress, factor of safety in operation and angle of twist for a mechanical power transmission shaft when transmitting given power at a given speed	**M3**	determine the output velocity of a given quick-return mechanism for given input conditions		
P4	determine the resultant velocity of an object when moving simultaneously with velocities in two different directions and its velocity relative to a second object moving in the same plane in a third direction [IE]	**M4**	evaluate the output motion of the slider in a slider-crank mechanism with uniform input motion of the crank, for compliance with the conditions necessary for it to describe simple harmonic motion.		
P5	determine the output motion of a slider-crank mechanism and a four-bar linkage mechanism for given input conditions				

Assessment and 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:**
P6 determine the periodic time and the displacement, velocity and acceleration at a given instant of the simple harmonic motion generated by circular motion of given parameters		
P7 determine the circular frequency, the natural frequency of vibration and the maximum velocity and acceleration for a mass-spring system and a simple pendulum with given parameters.		

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

The delivery strategy for learning outcome 1 should progress in logical stages, beginning with the definition of Poisson's ratio. Calculation of longitudinal and transverse strain for uniaxial loading can follow, together with the associated dimensional changes. This can lead on to development of the expressions for strain and dimensional changes in the x and y directions for two-dimensional loading, and be extended to derive the expressions for strain and dimensional changes in the x, y and z directions for three-dimensional loading. The expression for volumetric strain due to three-dimensional loading can then be developed and applied to determine change in volume. Although not essential, it might be appropriate at this stage to put forward the concept of bulk modulus in preparation for work at a higher level.

A recap of previous work on bending moment distribution in simply supported beams may be beneficial as an introduction to learning outcome 2. After explaining the assumptions made in bending theory, an expression can be derived for bending stress in terms of radius of curvature and modulus of elasticity. This can then be used in the development of an expression for bending stress in terms of bending moment and second moment of area of the beam section. Examination of the expressions will indicate that stress due to bending is proportional to distance from the neutral axis.

After combining the expressions to give the full bending equation, proof should be given that the neutral axis of bending passes through the centroid of the beam section. Time can then be devoted to determination of the second moment of area of solid and hollow rectangular and circular section beams about a plane axis through the centroid. This links directly with the integral calculus content in *Unit 4: Mathematics for Engineering Technicians*, where prior liaison might ensure that the topic is covered in preparation for its application in stress analysis and fluid mechanics. Problem solving should involve determination of second moment of area, maximum stress due to bending, factor of safety and radius of curvature for a range of simply supported beam sections and loading. The significance of second moment of area and modulus of elasticity in determining resistance to bending should be stressed.

If time permits and beam apparatus is available, a practical investigation can be included to determine the modulus of elasticity of a beam that is symmetrically loaded outside its supports. The modulus of elasticity can be obtained from the bending equation after calculation of the applied bending moment and the radius of curvature between the supports. These can be obtained from the applied loads, the distance between the supports, the overhang and the central deflection.

After explaining the assumptions made in torsion theory, the torsion equation may also be derived in two stages, ie shear stress in terms of angle of twist, shaft length and shear modulus and shear stress in terms of applied torque and polar second moment of area. These can then be combined to give the full torsion equation, examination of which will indicate that shear stress due to torsion increases uniformly with radius. The expression for polar second moment of area may be derived by integration, or by applying the perpendicular axis theorem to the expression derived in the bending theory for second moment of area of a circular section beam about a diameter. Stationary torsion bars and power transmission shafts may be considered when problem solving, together with the twin-design criteria of allowable shear stress and allowable angle of twist.

If torsion apparatus is available, a practical investigation can be carried out to determine the shear modulus of a shaft material from measurements of applied torque, shaft length and angle of twist.

Delivery of learning outcome 3 could begin with the graphical or analytical solution of simple problems to determine the resultant velocity of a body with simultaneous velocities in different directions. This will demonstrate the vector addition of velocities. Further problems to determine the relative velocity between bodies moving in different directions will demonstrate the vector subtraction principle. With this knowledge in place, learners can be introduced to the analysis of plane linkage mechanisms. The operation and applications of the slider-crank, four-bar linkage and quick-return mechanisms should be described, and if possible also demonstrated. Vector addition and subtraction techniques may then be applied to determine output motion for given input conditions.

Delivery of learning outcome 4 should start with the definition of simple harmonic motion and examples of its occurrence in mechanical systems. Learners will realise that, because acceleration in the system is changing, new expressions need to be derived for displacement, velocity and acceleration at any given instant. This is traditionally achieved by a consideration of circular motion with uniform angular velocity, and the application of differential calculus. The expressions derived can be applied in the solution of general problems on simple harmonic motion. Finally, consideration can be given to simple harmonic motion in a mass-spring system and simple pendulum. Derivation of the expressions for circular frequency should be followed by problem solving and practical investigations. In the case of a mass-spring system the influence of the mass of the spring on the frequency of vibration might be investigated.

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 expressions for direct stress and strain and modulus of elasticity • define Poisson's ratio and demonstrate calculation of longitudinal and transverse dimensional changes due to uniaxial loading • derive expressions for strain in x and y directions due to two dimensional loading and demonstrate calculation of resulting dimensional changes • derive expressions for strain in x, y and z directions due to three dimensional loading and demonstrate calculation of resulting dimensional and volumetric changes. *Individual activity*: • solve problems involving uniaxial, two dimensional and three dimensional loading.
Preparation for carrying out **Assignment 1: Uniaxial and Complex Loading** (P1, M1).

Topic and suggested assignments/activities and/assessment
Whole-class teaching: • revise calculation of support reactions and distribution of shear force and bending moment in simply supported beams • list and discuss assumptions made in deriving expressions for stress due to bending • derive expressions for stress due to bending in terms of radius of curvature and modulus of elasticity of beam material • derive expressions for stress due to bending in terms of bending moment and second moment of area of beam cross-section • derive expressions for second moment of area of solid and hollow rectangular and circular beam sections about an axis through the centroid • show that the neutral axis of bending passes through the centroid of a beam section and discuss factors that affect beam stiffness • demonstrate calculation of stress and radius of curvature due to bending. *Individual activity*: • solve problems on simply supported beams and cantilevers involving the calculation of stress and curvature due to bending. *Small-group activity*: • carry out a practical investigation on a simply supported beam to determine the modulus of elasticity of the beam material.
Whole-class teaching: • revise calculation of shear stress, shear strain, shear modulus and shaft power transmission • list and discuss assumptions made in deriving expressions for shear stress due to torsion • derive expressions for shear stress due to torsion in terms of angle of twist and shear modulus of shaft material • derive expressions for shear stress due to torsion in terms of applied torque and polar second moment of area of shaft cross-section • derive expressions for second moment of area of solid and hollow circular sections about a polar axis and discuss factors that affect shaft stiffness and power transmission capacity • demonstrate calculation of shear stress and angle of twist due to torsion. *Individual activity*: • solve problems on torsion bars and power transmission shafts and involving the calculation of shear stress and angle of twist. *Small-group activity*: • carry out a practical investigation on a shaft subjected to torsion to determine its shear modulus.
Preparation for and carrying out **Assignment 2: Bending and Torsion** (P2, P3, M2, D1).

Topic and suggested assignments/activities and/assessment
Whole-class teaching: • recap vector addition and subtraction techniques • demonstrate graphical and analytical determination of resultant velocity and relative velocity • describe and discuss applications of slider-crank and four-bar linkage mechanisms and their inversions • demonstrate construction of space and velocity vector diagrams to determine output motion of slider-crank and four-bar linkage mechanisms • describe and discuss applications of slotted link and Whitworth quick-return mechanisms • demonstrate construction of space and velocity vector diagrams to determine output motion of slotted link and Whitworth quick-return mechanisms. *Individual activity*: • solve problems to determine resultant velocity of a moving body, the relative velocity between moving bodies and the output motion of linkage mechanisms.
Preparation for and carrying out **Assignment 3: Resultant and Relative Velocity** (P4, P5, M3).
Whole-class teaching: • define simple harmonic motion and discuss its parameters • derive the general equations for simple harmonic motion from a consideration of uniform circular motion • describe and discuss mechanisms that can produce simple harmonic motion in engineering systems eg scotch yoke mechanism and simple harmonic motion cams • demonstrate the calculation of system parameters from given data • develop proof that a disturbed mass-spring system vibrates with simple harmonic motion and derive expressions for circular frequency, periodic time and natural frequency of vibration • develop proof that a simple pendulum bob moves with simple harmonic motion for small displacements and derive expressions for circular frequency, periodic time and natural frequency of vibration • demonstrate solution of problems on the range of systems where simple harmonic motion is present. *Individual activity*: • solve dynamic problems on the range of systems where simple harmonic motion is present. *Small-group activity*: • carry out practical investigations on a mass spring system and a simple pendulum to verify the occurrence of simple harmonic motion.
Preparation for and carrying out **Assignment 4: Simple Harmonic Motion** (P6, P7, M4, D2).
Feedback and unit evaluation.

Assessment

Ideally, assessment of this unit will be achieved through applying the mechanical principles covered to 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 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, 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 is a typical cause of such major errors, which can lead to relatively large scale errors of the magnitude 103 or greater.

Assuming that the unit is delivered in the order of the learning outcomes, a first assignment could provide an opportunity to achieve the pass criterion P1 by means of tasks to determine the dimensional effects of uniaxial and two-dimensional loading. These could be followed by a task to determine the dimensional effects of three-dimensional loading and corresponding change in volume for achievement of the M1.

A second assignment might contain a task to determine the stress and curvature in a loaded beam (P2) and a task to determine the shear stress and angle of twist in a power-transmission shaft for given operating conditions (P3). A third task, to achieve criterion M2, could be to examine the effects of increasing the breadth and depth of a rectangular beam section on its second moment of area and hence also on its load-carrying capacity. A fourth task to achieve D1 might be to compare the saving in weight and the reduction in torque transmission capacity as the internal diameter of a hollow transmission shaft is increased.

P4 and P5 could be assessed through an assignment containing a task to determine resultant and relative velocities in a system of moving bodies and a task to determine the output motion of plain mechanisms for given input conditions. Both a slider-crank and four-bar chain should be considered, whilst a third task to achieve M3 could be to determine the output velocity of a quick-return mechanism. In all three criteria there is an expectation that the response will involve the construction of diagrams to help determine the solution.

A final assignment for P6 and P7 should contain tasks to determine the parameters of simple harmonic motion for a system generated by uniform circular motion, a mass-spring system and a simple pendulum. These could be followed by a task to evaluate the output motion of a slider-crank mechanism for uniform input rotation of the crank to achieve merit criterion M4. The evaluation should conclude that the motion is not simple harmonic but that it may be approached be lengthening the connecting link. A final task to achieve distinction criterion D2 could involve the gathering and analysis of test data to determine the contributory effect of spring mass on the periodic time of a vibrating mass-spring system. The test data may be given in the absence of practical test facilities.

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, M1	Uniaxial and Complex Loading	Problems involving engineering components subjected to uniaxial loading, two-dimensional and three-dimensional loading.	A written report containing an explanation to each step in the sequence of calculations and findings.
P2, P3, M2, D1	Bending and Torsion	Problem on a simply supported beam and problem on a power transmission shaft Evaluation of load-carrying capacity and power-transmission capacity.	A written report containing an introductory explanation to each step in the sequence of calculations and findings. A written evaluation of the load-carrying capacity of a beam and the power-transmission capacity of a shaft.
P4, P5, M3	Resultant and Relative Velocity	Problems involving resultant and relative velocity of moving bodies and motion in plane mechanisms.	A written report containing an introductory explanation to each step in the sequence of graphics and calculations.
P6, P7, M4, D2	Simple Harmonic Motion	Problems involving simple harmonic motion in engineering systems. Evaluation of the output motion of the slider-crank mechanism and analysis of test data for a mass-spring system.	A written report containing an explanation to each step in the sequence of calculations and findings. A written evaluation of the output motion of a slider-crank mechanism. Analysis of test data for a mass-spring system to determine the contributory mass of the spring.

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	Mathematics for Engineering Technicians
		Mechanical Principles and Applications
		Further Mechanical Principles and Applications
		Applications of Mechanical Systems in Engineering

Essential resources

Centres should have access to investigation and demonstration equipment, such as simply supported beam apparatus, torsion test apparatus and apparatus for the investigation of simple harmonic motion.

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 9780750657778

Bolton W – *Engineering Science* (Newnes, 2006) ISBN 9780750680837

Darbyshire A – *Mechanical Engineering BTEC National Option Units* (Newnes, 2008) ISBN 9780750686570

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 resultant velocity of an object when moving simultaneously with velocities in two different directions and its velocity relative to a second object moving in the same plane in a third direction.

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, evaluations and conclusions.