Unit 18: Advanced Mechanical Principles and Applications

NQF Level 3: BTEC National

Guided learning hours: 60

Unit abstract

This unit will build upon learners' knowledge of underpinning mechanical principles and the way these 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 if costly breakdowns and accidents are to be avoided. Design engineers must thus be able to predict the stresses to which they are subjected and ensure that an appropriate factor of safety applies.

Learning outcomes 1 and 2 of this unit will broaden learners' knowledge of stress analysis to include stress due to bending, stress due to torsion and the effects of uniaxial and two-dimensional loading.

Learners sometimes have difficulty with the concepts of resultant and relative velocity. Learning outcome 3 seeks to clarify how they 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 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 learners' 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 diagram

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, velocity vector, determining 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

Grading grid

In order to pass this unit, the evidence that the learner presents for assessment needs to demonstrate that they can meet all of the learning outcomes for the unit. The 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 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 evaluate and 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	
	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.	

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:
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 P5 determine the output motion of a slider-crank mechanism and a four-bar linkage mechanism for given input conditions 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, natural frequency of vibration and the maximum velocity and acceleration for a mass-spring system and a simple pendulum with given parameters.		

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. These can then be extended to derive the expressions for strain and dimensional changes in the *x, y* and *z* directions for three-dimensional loading. Finally, the expression for volumetric strain can 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. This links directly with the integral calculus content in *Unit 4: Mathematics for Technicians*, where prior work 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 then 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.

Assessment

Evidence of achievement may be obtained from well-planned assignments and/or unseen tests. 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 and evaluate 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 slow-forward 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 can be given in the task.

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

This unit builds on the material covered in *Unit 6: Mechanical Principles and Applications* and *Unit 11: Further Mechanical Principles and Applications* and lays the foundation for further study at BTEC Higher National Certificate/Diploma level.

The unit also has links with *Unit 4: Mathematics for Technicians* in the application of differential and integral calculus.

The 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

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.

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 National Option Units* (Newnes, 2003) ISBN 0750657618

Tooley M and Dingle L — *BTEC National Engineering* (Newnes, 2002) ISBN 0750651660

Key skills

Achievement of key skills is not a requirement of this qualification but it is encouraged. Suggestions of opportunities for the generation of Level 3 key skill evidence are given here. Staff should check that learners have produced all the evidence required by part B of the key skills specifications when assessing this evidence. Learners may need to develop additional evidence elsewhere to fully meet the requirements of the key skills specifications.

Application of number Level 3	
When learners are:	**They should be able to develop the following key skills evidence:**
• determining 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 • determining the maximum shear stress, factor of safety in operation and angle of twist for a mechanical power transmission shaft for given operating conditions.	N3.1 Plan an activity and get relevant information from relevant sources. N3.2 Use this information to carry out multi-stage calculations to do with: a amounts or sizes b scales or proportion c handling statistics d using formulae. N3.3 Interpret the results of your calculations, present your findings and justify your methods.
Problem solving Level 3	
When learners are:	**They should be able to develop the following key skills evidence:**
• determining the output motion of a slider-crank and a four-bar linkage mechanism for given input conditions.	PS3.1 Explore a problem and identify different ways of tackling it. PS3.2 Plan and implement at least one way of solving the problem. PS3.3 Check if the problem has been solved and review your approach to problem solving.