Unit 6: Mechanical Principles and Applications

NQF level 3: BTEC National

Guided learning hours: 60

Unit abstract

The use and application of mechanical systems is an essential part of modern life. The design, manufacture and maintenance of these systems are the concern of engineers and technicians who must be able to apply a blend of practical and theoretical knowledge to ensure that systems work safely and efficiently. Science underpins all aspects of engineering and a sound understanding of its principles is essential for anyone seeking to become an engineer.

The selection and use of engineering materials builds on the principles laid down by the scientists Hooke and Young. The laws of motion, put forward by Sir Isaac Newton, underpin the design of dynamic engineering systems ranging from domestic appliances through motor vehicles to spacecraft. Similarly, the design of internal combustion engines and gas turbines is based on the principles and laws that were first put forward by Boyle, Charles and Joule.

This unit aims to build upon learners' knowledge gained at GCSE and BTEC First Diploma level. Learning outcome 1 will introduce learners to the behaviour of loaded engineering materials and the analysis of a range of static engineering systems that will include Hooke's Law and Young's modulus. Learning outcome 2 will extend learners' knowledge of dynamic systems through the application of Newtonian mechanics. It will also consider the storage and transfer of energy which is often involved in the operation of mechanical systems. Learning outcomes 3 and 4 seek to lay the foundation for future work in applied thermodynamics and fluid mechanics. In particular, they will deal with the effects of heat transfer, the expansion and compression of gases and hydrostatic forces using the work of Boyle, Charles and Joule.

This unit provides a basis for further work in the areas of mechanical principles, engineering thermodynamics, fluid mechanics and other related engineering applications of science.

Learning outcomes

On completion of this unit a learner should:

1 Be able to determine the effects of loading in static engineering systems

2 Be able to determine work, power and energy transfer in dynamic engineering systems

3 Be able to determine the parameters of fluid systems

4 Be able to determine the effects of energy transfer in thermodynamic systems.

Unit content

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1 Be able to determine the effects of loading in static engineering systems

Non-concurrent coplanar force systems: graphical representation eg space and free body diagrams; resolution of forces in perpendicular directions eg $F_x = F \cos\theta$, $F_y = F \sin\theta$, vector addition of forces, conditions for static equilibrium ($\Sigma F_x = 0$), ($\Sigma F_y = 0$, ($\Sigma M = 0$), resultant, equilibrant, line of action

Simply supported beams: conditions for static equilibrium; loading (concentrated loads, uniformly distributed loads, support reactions)

Loaded components: elastic constants (modulus of elasticity, shear modulus); loading (uniaxial loading, shear loading); effects eg direct stress and strain including dimensional change, shear stress and strain, factor of safety

2 Be able to determine work, power and energy transfer in dynamic engineering systems

Kinetic principles: equations for linear motion with uniform acceleration ($v = u + at$, $s = ut + ½at^2$, $v^2 = u^2 + 2as$, $s = ½(u + v)t$)

Kinetic parameters: eg displacement (s), initial velocity (u), final velocity (v), uniform linear acceleration (a)

Dynamic principles: D'Alembert, principle of conservation of momentum, principle of conservation of energy

Dynamics parameters: eg tractive effort, braking force, inertia, frictional resistance, gravity, mechanical work (W = Fs), power dissipation (Average Power = W/t, Instantaneous Power = Fv), gravitational potential energy (PE = mgh), kinetic energy ($KE = ½mv^2$)

3 Be able to determine the parameters of fluid systems

Thrust on a submerged surface: hydrostatic pressure, hydrostatic thrust on an immersed plane surface ($F = \rho gAh$); centre of pressure of a rectangular retaining surface with one edge in the free surface of a liquid

Immersed bodies: Archimedes' principle; fluid eg liquid, gas; immersion of a body eg fully immersed, partly immersed, determination of density using floatation and specific gravity bottle

Design characteristics of a gradually tapering pipe: eg volume flow rate, mass flow rate, input and output flow velocities, input and output diameters, continuity of volume and mass for incompressible fluid flow

4 **Be able to determine the effects of energy transfer in thermodynamic systems**

Heat transfer: heat transfer parameters eg temperature, pressure, mass, linear dimensions, time, specific heat capacity, specific latent heat of fusion, specific latent heat of vaporisation, thermal efficiency, power rating, linear expansivity; heat transfer principles eg sensible and latent heat transfer, linear expansion; phase eg solid, liquid, gas

Thermodynamic process equations: Boyle's law ($pV = Constant$), Charles' law ($V/T = Constant$), general gas equation ($pV/T = Constant$), characteristic gas equation ($pV = mRT$); process parameters eg absolute temperature, absolute pressure, volume, mass, density

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 describes 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	calculate the magnitude, direction and position of the line of action of the resultant and equilibrant of a non-concurrent coplanar force system containing a minimum of four forces acting in different directions	M1	calculate the factor of safety in operation for a component subjected to combined direct and shear loading against given failure criteria	D1	compare and contrast the use of D'Alembert's principle with the principle of conservation of energy to solve an engineering problem
P2	calculate the support reactions of a simply supported beam carrying at least two concentrated loads and a uniformly distributed load	M2	determine the retarding force on a freely falling body when it impacts upon a stationary object and is brought to rest without rebound, in a given distance	D2	evaluate the methods that might be used to determine the density of a solid material and the density of a liquid.
P3	calculate the induced direct stress, strain and dimensional change in a component subjected to direct uniaxial loading and the shear stress and strain in a component subjected to shear loading	M3	determine the thermal efficiency of a heat transfer process from given values of flow rate, temperature change and input power		
		M4	determine the force induced in a rigidly held component that undergoes a change in temperature.		

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 solve three or more problems that require the application of kinetic and dynamic principles to determine unknown system parameters P5 calculate the resultant thrust and overturning moment on a vertical rectangular retaining surface with one edge in the free surface of a liquid P6 determine the up-thrust on an immersed body P7 use the continuity of volume and mass flow for an incompressible fluid to determine the design characteristics of a gradually tapering pipe P8 calculate dimensional change when a solid material undergoes a change in temperature and the heat transfer that accompanies a change of temperature and phase P9 solve two or more problems that require application of thermodynamic process equations for a perfect gas to determine unknown parameters of the problems.		

Essential guidance for tutors

Delivery

Although the unit content can be delivered in any order, it might be advisable to follow the order of the learning outcomes. Revision of previous work on the parallelogram and triangle of forces may be necessary in learning outcome 1 before applying the principles of vector addition and force resolution to non-concurrent coplanar force systems. Likewise, the conditions for static equilibrium may need to be revised before applying them to the calculation of simply supported beam reactions. Practical demonstrations using force boards and balanced beam apparatus could be used to support the theoretical concepts.

After defining elasticity, the validity of Hooke's law might also be demonstrated as a practical exercise before introducing learners to the concepts of stress, strain and the elastic constants. If available, use should be made of tensile testing equipment and a suitable extensometer to determine modulus of elasticity and tensile strength. Where appropriate, the calculation of stress should be accompanied by determination of the factor of safety in operation. However, learners should be made aware that the presence of stress concentrations could affect its validity.

Revision of the parameters of motion with uniform acceleration should be followed by derivation of the equations for uniform motion using distance versus time and velocity versus time graphs. Although Newton's laws of motion are not specifically referred to in the unit content, they are implicit in the consideration of momentum, inertia and the application of D'Alembert's principle. In its simplest form, D'Alembert's principle states that if the internal inertial reaction to the acceleration or retardation of a body (ie *ma* given by Newton's second law) is imagined to be an external force, then the body can be treated as though it were in static equilibrium under the action of a system of forces. A free body diagram can then be drawn to aid the solution of a dynamic problem. The diagram might also contain frictional resistance F_f and 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 application of D'Alembert's principle is thus the application of Newton's second and third laws of motion with the inertial reaction *ma*, considered as an external force. Problems should be set which involve consideration of inertia, friction and gravity when calculating tractive effort, braking force, work and power. These might include the motion of a vehicle on an incline, the operation of a lift or hoist, or the motion of a machine slide or worktable.

The relationship between work done and the form of energy stored should be clearly explained when deriving expressions for gravitational potential energy and kinetic energy. A clear distinction should be made between the principle of conservation of momentum and the principle of conservation of energy together with their applications. If time and facilities permit, the use of dynamics trolleys and timers can be used to demonstrate the principle of conservation of momentum. Problems involving bodies in collision, separation of space vehicles and the operation of pile drivers and drop hammers might be used to illustrate application of the two principles. Dynamics problems that have been previously solved using the equations of motion, D'Alembert's principle and Newton's laws might be revisited and solved using energy considerations. Learners will then be aware that this is an alternative and equally valid approach to the solution of dynamics problems and will be able to compare and evaluate the two methods.

On starting learning outcome 3, revision of previous work on hydrostatic pressure will lead to calculation of thrust on immersed plane surfaces. The depth of the centre of pressure for a rectangular retaining wall with one edge in the free surface of the liquid should be derived from first principles using integration. This can then be applied in the solution of problems such as those involving retaining walls, sluice gates and lock gates. Knowledge of the second moment of area is not required for this level of problem. This could be followed by an explanation of Archimedes' principle and calculation of up-thrust on immersed bodies. The determination of density by floatation and use of a specific gravity bottle should be explained and if possible, demonstrated. Steady incompressible flow through tapering pipes can then be considered with problems to determine flow velocities, flow rates and pipe dimensions using the equations for continuity of volume and mass flow.

It will be beneficial to revise and define the Celsius and absolute scales of temperature and the concept of absolute zero of temperature before starting the heat transfer unit content of learning outcome 4. This could begin with the definition of linear expansivity and the calculation of dimensional change that accompanies a change in temperature for a substance whose movement is unrestricted. Learners should be made aware that thermal stress would be induced where a body is restricted in some way. If time and facilities exist it may be beneficial to include a practical investigation to determine the linear expansivity of a material. The definition of specific heat capacity and specific latent heat of fusion and vaporisation could follow, with the solution of problems involving the calculation of sensible and latent heat transfer and transfer rates.

The remaining unit content of learning outcome 4 is concerned with the expansion and compression of gases. This essentially involves an explanation of the gas laws and, if possible, their experimental verification. The general gas equation $pV/T = constant$, can be derived from a consideration of expansion according to Boyle's and Charles' laws leading to statement of the characteristic gas equation $pV = mRT$. Learners should also be made aware that this could be manipulated to give expressions for the density and specific volume of a gas. It is sufficient at this stage to quote the value of the characteristic gas constant R for a given gas without reference to the universal gas constant or the specific heat capacities of the gas.

Learners should be made aware of the limitations of the gas equations when applied to real gases and particularly to vapours. Problems might include the expansion and compression of a gas in an engine cylinder bringing in the calculation of initial and final volumes from bore, stroke and compression ratio data, making use of all of the ranged equations.

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

Ideally, the assessment of this unit will be achieved through application of the mechanical science covered within 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.

The criterion P1 requires the solution of a single non-concurrent force system that contains a minimum of four active forces. It will be expected that two of these forces will be set to act in directions other than the horizontal and vertical. This will necessitate the resolution of forces in perpendicular directions, eg the use of $F_x = F \, Cos\theta$ and $F_y = F \, Sin\theta$, as the first step in the solution to the problem. A typical problem might be an engineering component under the action of at least four non-concurrent forces whose magnitudes and directions are given. One of the forces might be its own weight but at least two of them should act in directions other than the horizontal and vertical. Learners would be expected to produce space and free body diagrams, resolve forces horizontally and vertically and take moments of the forces about some suitable reference point. The magnitude and direction of the resultant force and the position of its line of action could then be found through vector addition, application of Pythagoras' theorem and consideration of the resultant turning moment.

P2 will use similar skills as those required for P1 but in this case they will be applied to a simply supported beam carrying two point loads, as a minimum, and a uniformly distributed load. This level of loading will provide centres with a considerable variety of beams to use for assessment. During the delivery phase for this part of the unit a greater range of loading may be considered but centres need only work with the minimum for assessment purposes. Neither the content or criteria stipulate that the point loads should be anything other than perpendicular to the beam. Again, for delivery it may be useful to get learners to resolve forces applied at an angle to the beam, but as this is covered for assessment by P1 it does not need to be covered again in P2.

The assessment for criterion P3 will involve the consideration of a directly loaded component requiring the calculation of direct stress, direct strain and the accompanying dimensional change. It would also separately involve the calculation of shear stress and shear strain in a component or material subjected to shear loading. Centres should consider how the task set for P3 could be extended to incorporate an opportunity to achieve M1. This might involve consideration of the factor of safety in operation for an angled joint that is bolted or riveted such that the fastenings are subjected to both tensile and shearing forces.

P4 will require at least three dynamic system problems to be set to ensure that the range of kinetic and dynamic principles to achieve P4 are covered. If one or two more problems are required then centres should not fragment the application of kinetic and dynamic principles to the extent that they over simplify the problems. It is the interrelationships between the kinetic and dynamics principles that are as important as the use of any single equation. The principles applied in P4 can be directly linked to M2, although achievement of M2 will require a further task to be set to consider the impact of a freely falling body. Suitable examples of this type of problem are listed above in the delivery section of the guidance. A final task to achieve the distinction criterion D1 would be required to enable learners to consider and solve an engineering problem using the two alternative approaches (ie D'Alembert's principle and the principle of conservation of energy) and compare the two methods.

The criteria P5 and P6 can be linked together as they consider applications of hydrostatics. P5 may be achieved by calculating resultant thrust and overturning moment on a rectangular retaining surface, examples of which are listed in the delivery section. P6 may be achieved by calculating the up-thrust on a totally immersed body using Archimedes' principle. There are no links to the merit criteria from these two areas of the unit but the skills and understanding of fluids and solids are used again for D2, which examines learners' understanding of the methods used to determine the density of solids and liquids. P7 continues this theme with fluids but this time examines learners' understanding of fluid flow. This criterion may be achieved by considering the design of a gradually tapering pipe to suit given dimensional and flow constraints.

Finally, P8 and P9 have been designed to assess the thermodynamics aspects of the unit and each criterion will require a separate task. In particular, P9 will require at least two tasks to be able to provide full coverage of the content requirements for this criterion. The area of work covered by P8 — the effects of heat transfer — is extended in the merit criteria M3 and M4.

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

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.

The unit builds on the material covered in the BTEC First Diploma *Unit 3: Applied Electrical and Mechanical Science for Technicians.*

It lays the foundation for further study in *Unit 11: Further Mechanical Principles and Applications, Unit 12: Applications of Mechanical Systems and Technology, Unit 13: Principles and Applications of Fluid Mechanics*, *Unit 14: Principles and Applications of Thermodynamics* and *Unit 18: Advanced Mechanical Principles and Applications.*

Essential resources

There are no essential resources required for this unit. However, centres should consider providing learners with access to laboratory facilities that provide a sufficient range of investigation and demonstration equipment. In particular, tensile testing equipment, dynamics trolleys, linear expansivity apparatus, apparatus to determine density and apparatus for verification of Boyle's and Charles' laws would be of significant value.

Indicative reading for learners

Textbooks

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

Bolton W — *Engineering Science* (Newnes, 2006) ISBN 0750680830

Darbyshire A — *Mechanical Engineering BTEC National Option Units* (Newnes, 2003) ISBN 0750657618

Tooley M and Dingle L — *BTEC National Engineering* (Butterworth–Heinemann, 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. Tutors 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 induced stress, strain and dimensional change in a component subjected to direct uniaxial loading and the shear stress and strain in a component subjected to shear loading.	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:**
• using kinetic and dynamic principles to determine the applied force, work done and power dissipated in a uniformly accelerated engineering system to overcome the effects of inertia, friction and gravity.	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.