SQA Advanced Unit Specification

General information for centres

Unit title: Control Systems Behaviour

Unit code: HV51 48

Unit purpose: This unit is designed to enable candidates to develop their knowledge and understanding of closed-loop control systems. It allows candidates to develop knowledge and skills that will enable them to model and analyse closed-loop control systems. The unit also provides candidates with the knowledge and skills to allow them to understand how controllers can be used to suitably modify the behaviour of closed-loop systems. The unit also provides the candidates with the opportunity to apply simulation software as a tool to analyse and predict the behaviour of control systems.

On completion of the unit the candidate should be able to:

1 demonstrate the modelling of closed-loop systems
2 predict the transient and steady-state behaviour of closed-loop systems
3 apply frequency response methods to the analysis of control systems
4 apply three term controllers to closed-loop control systems

Credit points and level: 1 SQA Advanced Credit at SCQF level 8: (8 SCQF credit points at SCQF level 8*)

**SCQF credit points are used to allocate credit to qualifications in the Scottish Credit and Qualifications Framework (SCQF). Each qualification in the Framework is allocated a number of SCQF credit points at an SCQF level. There are 12 SCQF levels, ranging from National 1 to Doctorates.*

Recommended prior knowledge and skills: Candidates should possess a broad knowledge and understanding of open and closed-loop systems. This may be evidenced by the possession of SQA Advanced Unit HT1R 47 Fundamentals of Control Systems and Transducers or any other relevant qualification or experience. It would also be beneficial if candidates were familiar with algebraic manipulation and simple differential equations. This may be evidenced by the possession of the following SQA Advanced Units: HP48 46 Engineering Mathematics 1. A knowledge of basic operational amplifier circuits would be beneficial. However, entry requirements are at the discretion of the centre.

Core skills: There may be opportunities to gather evidence towards the following core skills or core skills components in this unit, although there is no automatic certification of core skills or core skills components:

- Written Communication (reading) at SCQF level 6
- Written Communication (writing) at SCQF level 6
- Numeracy at SCQF level 6
- Using Information Technology at SCQF level 6
- Critical Thinking at SCQF level 6
- Reviewing and Evaluating at SCQF level 6

Context for delivery: This unit was developed for the SQA Advanced Diploma in Electrical Engineering. If this unit is delivered as part of a group award, it is recommended that it should be taught and assessed within the subject area of the group award to which it contributes.

Assessment: The assessment for Outcome 1 in this unit should be a written assessment. The assessment paper should be composed of an appropriate balance of short answer, restricted response and structured questions. The assessment event should last one hour.

The assessment for Outcomes 2, 3 and 4 of this unit is combined together into one assignment. The simulation content of the assignment should be conducted under supervised, open-book conditions and it is suggested that it should be completed within six hours. The analysis of simulation printouts, calculations and report writing sections of the assignment may be undertaken outwith the centre. The assessor should observe the candidates to ensure that they are individually able to use the simulation package. Candidates should submit a report containing a hard copy of the appropriate files created during the use of the simulation package along with all analysis and calculations required. The candidate should answer all questions and carry out all tasks set in the assignment.

SQA Advanced Unit Specification: statement of standards

Unit title: Control Systems Behaviour

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The sections of the unit stating the outcomes, knowledge and/or skills, and evidence requirements are mandatory.

Where evidence for outcomes is assessed on a sample basis, the whole of the content listed in the knowledge and/or skills section must be taught and available for assessment. Candidates should not know in advance the items on which they will be assessed and different items should be sampled on each assessment occasion.

Outcome 1

Demonstrate the modelling of closed-loop systems

Knowledge and/or skills

- ♦ Representation of system components by transfer functions
- ♦ Representation of systems in block diagram form
- ♦ Acquisition of open and closed-loop transfer functions from block diagrams

Evidence requirements for Outcome 1

All knowledge and/or skills items in Outcome 1 should all be assessed. The evidence should be provided in response to specific questions presented in a written paper. Each candidate will need to demonstrate that he/she can answer all questions satisfactory.

A candidate’s response can be judged to be satisfactory where evidence is provided to meet the minimum requirements for each item by showing that the candidate is able to:

- ♦ Represent system components by transfer functions

  Given a schematic diagram representing a particular control system, the various system components with their transfer functions should be identified

- ♦ Represent systems in block diagram form

  The equivalent block diagram for the schematic diagram given above, should be drawn representing the system components with their transfer functions

- ♦ Acquire open and closed-loop transfer functions from block diagrams

  The forward path open-loop and the closed-loop transfer functions should be determined for the system given above.

Evidence should be generated through assessment undertaken in controlled, supervised conditions. Assessment should be conducted under closed-book conditions and as such candidates may not bring any textbooks, handouts, manuals or notes to the assessment.

Assessment guidelines for Outcome 1

The assessment paper for this outcome should last one hour and be carried out under supervised, controlled conditions. Such a paper should be composed of an appropriate balance of short answer, restricted response and structured questions. This assessment should be carried out at the end of the delivery of Outcome 1. Students should be provided with a formula sheet containing component transfer functions that can be used in the assessment.

Outcome 2

Predict the transient and steady-state behaviour of closed-loop systems

Knowledge and/or skills

- Calculation of transient and steady-state values from the closed-loop transfer function of the system
- Use of simulation software to determine system transient and steady-state characteristics
- Use of simulation software to demonstrate the response of high order systems and second order approximation.

Outcome 3

Apply frequency response methods to the analysis of control systems

Knowledge and/or skills

- Application of the open-loop frequency response using Nyquist criteria for stability to predict and explain closed-loop behaviour
- Operation of open-loop frequency response to plot on a Nichols Chart
- Use of simulation software to produce frequency response graphs for closed-loop analysis

Outcome 4

Apply three term controllers to closed-loop control systems

Knowledge and/or skills

- Requirement for proportional integral and derivative (PID) control
- The effect of each term of a three term controller on closed-loop behaviour
- Description of circuits realising three term control
- Use of simulation software to determine controller setting

Evidence requirements for Outcomes 2 to 4

All parts of the knowledge and/or skills listed in Outcome 2, 3 and 4 shall be assessed. Evidence will be provided in the form of a written assignment. The candidate's response will be judged to be satisfactory where evidence provided is sufficient to meet the requirements for each item by showing that the candidate is able to:

Outcome 2

- calculate transient and steady-state values from the closed-loop transfer function of the system

  Presented with a second order closed-loop transfer function, the following system characteristics should be calculated: damping ratio, peak overshoot, time to peak, frequency of oscillation, time constant, settling time, steady-state value, offset error and steady-state error.
  The response to a step input should be sketched using the above calculated characteristics.

- use simulation software to determine system transient and steady-state characteristics

  Enter plant transfer function into software package and plot out a time response for a step input under proportional control. Note the effect on system characteristics for different values of gain.

- use simulation software to demonstrate the response of high order systems

  Plot time response and note system characteristics.

Outcome 3

- Apply the open-loop frequency response using Nyquist criteria for stability to predict and explain closed-loop behaviour

  Explain how an open-loop frequency response can be used to predict closed-loop behaviour.

- Analyse the operation of open-loop frequency response to plot on a Nichols Chart

  Determine gain margin and phase margin for a given frequency plot and comment on the absolute and relative stability for a given system.

- Use simulation software to produce frequency response graphs for closed-loop analysis.

  Measure M_p (peak magnification factor) and ω_r (resonant frequency) from frequency plots and estimate the closed-loop transient performance. Compare the estimated and measured transient performances.

  Use the above, or similar technique, to approximate the transfer function of a higher order system to that of a second order one by using M_p and ω_{r} to calculate ξ (system damping factor) and ω_n (undamped natural frequency of oscillation).

Compare transient performances of the approximated second order to that of the higher order.

Outcome 4

- Explain the requirement for proportional, integral and derivative (PID) control

  State that the main advantage of PID control is that system response can be tailored to meet a particular control specification.

- Explain the effect of each term of a three term controller on closed-loop behaviour

  State the effect each mode of a PID controller has on system characteristics and compare with simulated responses.

- Describe circuits realising three term control

  Draw an operational amplifier based circuit diagram, with calculated component values, to realise PID controller settings.

- Use simulation software to determine controller settings

  Use an appropriate PID tuning method (for example Ziegler and Nichols) to initially tune the controller and then fine tune to meet a given specification.

Assessment guidelines for Outcomes 2 to 4

It is recommended that Outcome 2, Outcome 3 and Outcome 4 of this unit be combined together into one assignment to be carried out at the end of the unit delivery.

It is suggested that the assignment could commence with the candidate being given a fourth order transfer function of a plant under proportional control. The candidate would be expected, through the use of a control simulation software package such as Codas, to predict its closed-loop behaviour from the analysis of its frequency response. Software analysis and calculation should allow the candidate to determine transient and steady-state values from which a second order approximation of the system can be determined. This second order response is compared with the higher order response.

PID control can then be applied to the plant to meet a given control specification. Candidates should draw the circuit diagram, with calculated component values, to realise the PID controller.

Candidates should submit a report containing a hard copy of the appropriate files created during the use of the simulation package. The candidate should answer all questions and tasks set in the assignment.

Use of the software package to simulate and produce graphs etc should be conducted under supervised open-book conditions and it is suggested that it should be completed within three hours. The assessor should observe the candidates to ensure that they are individually able to use the simulation package.

Analysis of simulation printouts, answering set questions covering the describe-and-explain elements, and report writing can be conducted open-book outside the centre in their own study time.

Administrative information

Unit code:	HV51 48
Unit title:	Control Systems Behaviour
Superclass category:	VE
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SQA acknowledges the valuable contribution that Scotland's colleges have made to the development of SQA Advanced qualifications.

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SQA Advanced Unit Specification: support notes

Unit title: Control Systems Behaviour

This part of the unit specification is offered as guidance. The support notes are not mandatory.

While the exact time allocated to this unit is at the discretion of the centre, the notional design length is 40 hours.

Guidance on the content and context for this unit

This unit has been written in order to allow candidates to develop knowledge, understanding and skills in the following areas:

1 modelling of systems under closed-loop control
2 prediction of transient and steady-state behaviour of closed-loop control
3 analysis of control systems using frequency response methods
4 proportional, integral and derivative (PID) control

This unit is at SCQF level 8 and has been devised as an optional unit within the new SQA Advanced Diploma in Electrical Engineering. However it does not preclude the use of this unit in other awards where award designers feel this to be appropriate.

In designing this unit, the writer has identified the range of topics expected to be covered by lecturers. The writer has also given recommendations as to how much time should be spent on each outcome. This has been done to allow lecturers to decide what depth of treatment should be given to the topics attached to each of the outcomes.

A list of topics for each outcome is given below. Lecturers are advised to study this list so that they can get a clear indication of the standard of achievement expected of candidates in this unit.

1 Demonstrate the modelling of closed-loop systems (5 hours).

The candidate should be made aware how a first order transfer function for a system component can be determined eg DC motor, potentiometer, tachogenerator etc.

This should be used to represent a given control system in block diagram form from a given schematic diagram. Systems such as a remote position control, motor speed control and the temperature control of an oven can be used. The forward path transfer function G(s) and the feedback path transfer function H(s) of the system can then be determined and used to calculate the closed-loop transfer function of the system using:

$$F(s) = \frac{G(s)}{1 + G(s)H(s)}$$

2 Predict the transient and steady-state behaviour of closed-loop systems (8 hours).

By relating the closed-loop transfer function of a system to the generalised second order closed-loop transfer function:

$$F(s) = \frac{K_{DC}\omega_n^{\ 2}}{s^2 + 2\xi\omega_n s + \omega_n^{\ 2}}$$

Where	ω_n	undamped natural frequency of oscillation
	K_{DC}	DC gain giving the relationship between the steady-state output and the steady-state input. This is the DC value of the overall system gain, whether open-loop or closed-loop. It is a function of the individual gains, whether within the loop or outwith. The individual gains within a closed-loop system can affect the closed-loop transient behaviour (ω and τ).
	ξ	damping factor

We can extract the damping factor ξ, the natural frequency of oscillation ω_n and the DC gain K_{DC}. Using the following set equations, these parameters can be used to calculate the remaining characteristics and allow one to sketch the closed-loop system response.

$\omega_d = \omega_n \sqrt{(1-\xi^2)}$		ω_d = damped frequency of oscillation
$V_{ss} = K_{DC} \times \text{input}$		Vss = steady-state value
$\% \text{ os} = 100e^x$	where $x = \dfrac{-\xi\pi}{\sqrt{(1-\xi^2)}}$	%os = peak percentage overshoot
$\tau = \dfrac{1}{\xi\omega_n}$		τ = time constant
$T_s \cong 5\tau$		T_s = time to settle

For a Second Order System, the settling time tells us the time for the transient to die away to within some tolerance band. For an underdamped system this transient response takes the form of an exponential envelope. The response must not only reach but also stay within the band. A typical tolerance band would be +0.5% to –0.5% of the steady-state value, this approximates to 5 time constants as with first order systems.

This calculated response can be verified using a computer simulation package.

3 Apply frequency response methods to the analysis of control systems (10 hours)

Various open-loop frequency response methods can be used to predict how a system will behave under closed-loop control. This can be used to prevent possible system damage, due to excessive overshoot for example, when the closed-loop control is applied. A convenient way of predicting closed-loop behaviour without actually having to connect the feedback path is to obtain the open-loop frequency response of the system (either by calculation or measurement) and then presenting the information graphically. Nichols frequency response method is recommended as it is the most informative and user friendly. We can make use of a computer simulation package to produce a Nichols plot from which the gain and phase margins can be measured. Examination of the gain and phase margins allows one to determine whether a system will be stable or not, absolute stability. It also can give an indication just how stable a system is, relative stability ie if the gain margin is between 8 and 12 dBs AND the phase margin is between 45 and 50 degrees.

Using gain and phase margins as measures of relative stability gives an idea of the type of response, but it is not possible to use open-loop data to quantify closed-loop behaviour. What we need is closed-loop frequency response data. In the time domain, the step responses of underdamped second order systems exhibit an overshoot when the damping ratio is less than unity. In the frequency domain there is an analogous situation where the system exhibits resonance for damping ratios less than $1/\sqrt{2}$ where the gain reaches a peak value, M_p, greater than unity. The peak gain is referred to as the peak magnification factor, hence the use of the letter M. For design purposes, one requires loci of constant closed-loop gain which are termed M-contours. These loci are curves superimposed on the open-loop plot, on which the closed-loop magnification factor is constant. A good measure of the damped natural frequency of the closed-loop system is its resonant frequency, ω_r. This frequency can be found by locating the frequency at which the open-loop frequency response locus is tangential to the smallest M-contour.

The simulation package can also allow the M_p and the resonant angular frequency ω_r to be determined from examination of the Nichols or Bode Gain plots. These parameters allow the system damping factor ξ and natural frequency of oscillation ω_n to be calculated using the following formulae:

$$M_p = \frac{1}{2\xi\sqrt{(1-\xi^2)}}$$

$$\omega_r = \omega_n\sqrt{(1-2\xi^2)}$$

This can be used to determine the second order closed-loop transfer function of a system using the generalised equation:

$$F(s) = \frac{K_{DC}\omega_n^{\ 2}}{s^2 + 2\xi\omega_n s + \omega_n^{\ 2}}$$

This technique can be used to determine the approximate second order transfer function of a higher order system from the examination of its frequency response plots and extracting the above parameters.

4 Apply three term controllers to closed-loop control systems (10 hours)

A three term controller can be used to meet most control specifications. The three modes of control PID, proportional integral and derivative, are applied to the error signal from the error detector. Each mode of the PID controller can be adjusted independently by altering the gain, integral action time and derivative action time settings respectively. Software simulation can be used to find the controller settings for each mode in order to meet the control specification. A systems closed-loop response can be made acceptable by tuning a two or three term controller. However, attempting to tune the controller purely by trial and error can be tedious and sometimes misleading. Systematic tuning methods such as Ziegler and Nichols may be employed. The Ziegler and Nichols method is adopted to initially roughly tune the controller settings after which fine adjustments can be made to meet a given control specification. Operational amplifier, integrator and derivative circuits can be used to realise each mode of the controller with component values calculated from the controller setting of gain, integral and derivative action times.

Unit Assessment

Written paper	1 hour	(Outcome 1)
Practically based assignment	3 hours	(Outcomes 2, 3 & 4 supervised use of software package to produce simulation printouts)
	3 hours	Analysis, set questions and report

Guidance on the delivery and assessment of this unit

It is intended that this unit be presented at all times referring to the specific simulation package available, and that user guides for the software package are available to the candidate.
In the delivery of this unit, candidates should be provided with the opportunity to gain as much 'hands on' experience as possible.

Details on approaches to assessment are given under evidence requirements and assessment guidelines under each outcome in the SQA Advanced Unit Specification: statement of standards section. It is recommended that these sections be read carefully before proceeding with assessment of candidates.

Open learning

This unit could be delivered by distance learning, which may incorporate some degree of online support. Candidates will require access to appropriate simulation software, which could be supported at the centre. With regard to assessment, planning would be required by the centre concerned to ensure the sufficiency and authenticity of candidate evidence. Arrangements would be required to ensure that the evidence was conducted under controlled, supervised conditions.

Equality and inclusion

This unit specification has been designed to ensure that there are no unnecessary barriers to learning or assessment. The individual needs of learners should be taken into account when planning learning experiences, selecting assessment methods or considering alternative evidence.

Further advice can be found on our website www.sqa.org.uk/assessmentarrangements.

General information for candidates

Unit title: Control Systems Behaviour

This unit has been designed to allow you to develop knowledge, understanding and skills associated with control systems.

Outcomes 1 and 2 of the unit will introduce you to control systems modelling which allows the control engineer to predict the closed-loop behaviour of a control system from calculations.

Outcome 3 of the unit will provide you with the opportunity to use a simulation software package to predict the closed-loop behaviour from the analysis of the open-loop frequency response.

Outcome 4 will introduce you to proportional, integral and derivative (PID) control, sometimes referred to three term control. This will allow you to tailor the response of a system to meet a particular control design specification.

The assessment for Outcome 1 will consist of a one hour written paper to be carried out under supervised, closed-book conditions. Candidates will be issued a formula sheet containing component transfer functions that can be used in the assessment. This assessment paper will be presented to you at the end of delivery for Outcome 1.

The assessment for Outcome 2, Outcome 3 and Outcome 4 of this unit is combined together into one assignment. This assignment will be issued towards the end of the unit after all relevant theory, concepts and practice using simulation software, has been completed. This assignment will consist of a number of tasks that all have to be completed. The assignment tasks will be generally divided up into two areas, use of the simulation software and analysis of results. The simulation content of the assignment will be conducted under supervised open-book conditions and should be completed within six hours. Analysis of results, required calculations and report preparation can take place outside the centre. You may be given a third or higher order transfer function of a plant from which you are expected to predict its closed-loop behaviour, under proportional control. This can be achieved from the analysis of its frequency response. Software analysis should allow you to determine transient and steady-state values from which a second order approximation of the system can be determined and compared with the higher order response. Using the software package you will then be required to apply PID control to the plant to meet a given control specification. You will then be expected to draw the circuit diagram, with calculated component values, to realise the PID controller. You are expected to submit a report containing a hard copy of the appropriate files created during the use of the simulation package. The candidate should answer all questions and carry out all tasks set in the assignment.