Paper 2

Section A

Q1 crib

a)

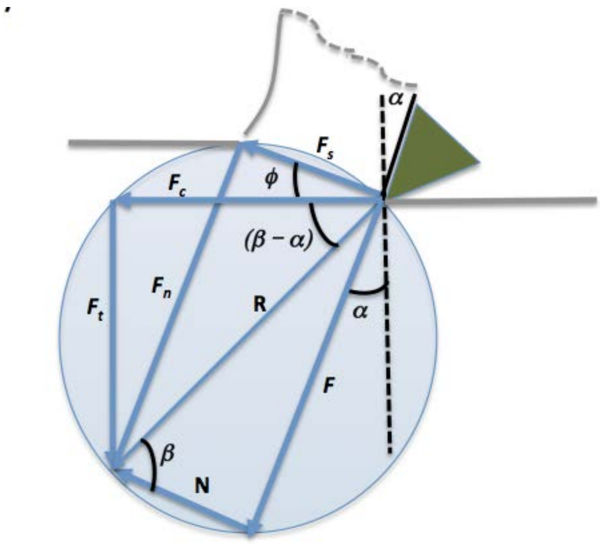
We need to determine the cutting forces in in machining operations for the following reasons

- Cutting forces involved in machining a range of materials allows the power consumption to be determined, which allows a machine to be specified in terms of motor size (kW).
- Knowing cutting forces allows the structural design of the machine tool to be determined, e.g – workpiece fixtures (holding force), tool-holder system (stiffness under load), machine dynamics (resonance and vibrations)
- Evaluation of role of the various machining parameters (tool material and geometry) on cutting forces to make machining process more efficient and economical.
- Knowing cutting forces allows the specification of condition monitoring of the cutting tools and machine tools.

Merchant made the following assumptions:

- Shear surface is a plane extending upwards from the cutting edge.
- The tool is perfectly sharp and there is no contact along the clearance face.
- The cutting edge is a straight line extending perpendicular to the direction of motion and generates a plane surface as the work moves past it.
- The chip doesn't flow to either side, that is chip width is constant.
- The depth of cut remains constant.
- Width of the tool is greater than that of the work.
- Work moves with uniform velocity relative tool tip.
- No-built up edge is formed.

b)



The range of cutting forces are largely determined by the strength of the material being machined. Specific cutting energies (J/mm^3) can range from ~ 0.4 for Al and its alloys to ~ 9 for hardened steels. For mild steels with cut depths of the order of a mm, a rake angle of around 15^0, a shear angle of around 25^0 and speeds of 100 mm/min, one can expect cutting forces of F_c ~ 300 N, thrust forces F_t of around ~ 200 N. Friction force F would be on the order of 270 N. The shear force Fs would be on the order of 187 N.

c)

We know that

$P_f = F \times V_c$

$P_s = F_s \times V_s$

Where F is the friction force, and Fs is the shear force.

Where.

V_c = the chip velocity

V_s = shear velocity

we have

$$\frac{W_f}{W_s} = \frac{F\ V_c}{F_s V_s}$$

Employing Merchant's force diagrams

we have

$$F = R \sin\beta$$

and

$$F_s = R\cos\big(\emptyset + (\beta - \alpha)\big)$$

giving

$$\frac{W_f}{W_s} = \frac{R \sin\beta \, V_c}{R \cos\big(\emptyset + (\beta - \alpha)\big) \, V_s}$$

$$\frac{W_f}{W_s} = \frac{\sin\beta \, V_c}{\cos\big(\emptyset + (\beta - \alpha)\big) \, V_s}$$

d)
i) The percentage of power can be expressed as

$$\frac{P_f}{P_t} = \frac{F \;\, V_c}{F_c V} = \frac{Fr}{F_c}$$

since from the velocity relationships. $Vt_o = V_c t_c$

where

$$r = t_o/t_c = 0.65$$

From Merchant's force circle

$$F = \; R \sin\beta$$

$$F_c = R \cos(\beta - \alpha)$$

and

$$R = \sqrt{F_t^2 + F_c^2} = \sqrt{25^2 + 125^2} = 127.47$$

thus

$$125 = 127.47 \cos(\beta - 10)$$

From which we find that

$\beta = 21.29$ and $F = 127.47 \sin 21.29 = 46.28$ N

Therefore the percentage of friction energy dissipation is calculated as

$$\frac{(46.28)(0.65)}{125} = 0.240 \; (24.0 \;\%)$$

Comment:
Good answers will point out that remainder of the energy is dissipated in the shear zone, assuming no loss of energy to the workpiece. Better answers will point out that this is never the case since thermal losses to the workpiece are usually around 5%.

ii) <u>Shear stress.</u>

The average shear stress in the shear plane is given by

$$\tau = \frac{F_s}{A_s} = \frac{\sin \emptyset \, (F_c \cos \emptyset - F_t \sin \emptyset)}{w t_o}$$

we know that

$$\tan \emptyset = \frac{r \cos \alpha}{1 - r \sin \alpha}$$

$$\tan \emptyset = \frac{0.65 \cos 10}{1 - 0.65 \sin 10}$$

$$\emptyset = 35.80$$

therefore

$$\tau = \frac{F_s}{A_s} = \frac{0.585 \times (125 \ \times \cos 35.80 - 25 \times \ \sin 35.80)}{3.0 \ \times \ 0.13}$$

$$\tau = \frac{F_s}{A_s} = \frac{50.75}{0.39}$$

$$\tau = \frac{F_s}{A_s} = 130.13 \ N/mm^2$$

<u>Shear Strain:</u>

we know that

$$S = \cot \emptyset + \tan(\emptyset - \alpha)$$

$$S = \cot 35.8 + \tan(35.8 - 10)$$

$$S = 1.387 + 0.483 = \ 1.87$$

comment:

Large shear strains are associated with low shear angles and low or negative rake angles. Shear strains of 5 or higher have been observed and the value shown here is typical in metal cutting operations.

<u>Examiners Comments</u>

This question related to Merchant's cutting model, which is a major component of the course. Part a) was answered very well with all candidates able to discuss basic elements and benefits of the model, although some were less clear on the underlying assumptions. Part b) most candidates were able to describe the relationships between the various forces acting in an orthogonal cutting process, although few were able to site the range of values for the forces that one would expect to find in general operating conditions. The derivation in Part c) was delivered well by most candidates. Part d) delivered a mixed bag of performance, with many candidates unable to develop a route to calculate shear stress and strain in Part c) ii. Overall, performance was good, with a number of candidates delivering an exceptional performance.

Q2 Crib

a)

i) Statistical Process Control (SPC) is an industry-standard technique that is used in manufacturing to monitor and control output. SPC is a system of quality measurement and control by monitoring the production process. SPC is a commonly used consistency method. In a manufactured commodity, it is a way of regulating variance. Manufacturing is all about accuracy and predictability; the reverse of it is variance. If a product is to meet or exceed customer expectations, generally is should be produced by a process that is stable or repeatable. More precisely, the process must be capable of operating with little variability around target or nominal dimensions of the products quality characteristic. SPC is a powerful collection of problem-solving tools useful in achieving process stability and improving capability through the reduction of variability.

ii) Variation in quality of manufactured product in the respective process in industry is inherent & evitable. These variations are broadly classified as-

Chance/ Non assignable causes and **Assignable** causes

Chance Causes:
In any manufacturing process, it is not possible to produce goods of exactly the same quality. Variation is inevitable. Certain small variation is natural to the process, being due to chance causes and cannot be prevented. This variation is therefore called *allowable*.

Assignable Causes:
This type of variation attributed to any production process is due to non-random or so called assignable causes and is termed as *preventable variation*.
Assignable causes may creep in at any stage of the process, right from the arrival of the raw materials to the final delivery of goods.
Some of the important factors of assignable causes of variation **are**-
i) Substandard or defective raw materials
ii) New techniques or operation
iii) Negligence of the operators
iv) Wrong or improper handling of machines
v) Faulty equipment
vi) Unskilled or inexperienced technical staff and so on.
These causes can be identified and eliminated and are to discovered in a production process before the production becomes defective.

b)
i)

There are two main types of control charts that can used. **Attribute** control charts and **Variable.**

Attribute control charts:
Attribute charts are usually easier and more cost effective to create; however, the detail and amount of information is less than continuous data charts. Larger sample sizes are needed and indicate a change in the rate of defects or defective units.

An attribute control chart is a way to track the production of defective items. The chart doesn't tell you *why* the defects happened, but it does give you the total or **average** counts per unit.

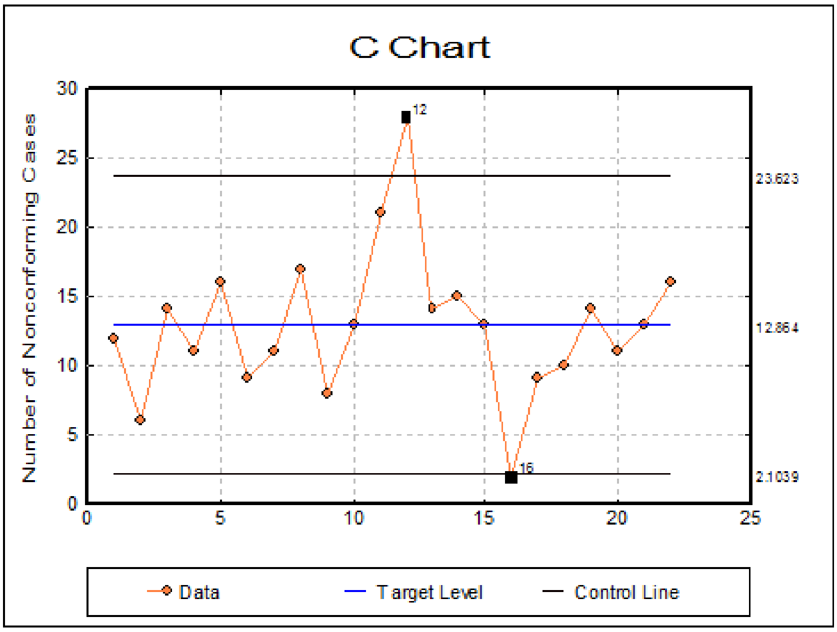
An *attribute* is a count or discrete data like conforming/non-conforming, pass/fail or yes/no. Attributes are **qualitative**, as opposed to variables (e.g. physical dimensions) which are **quantitative**.

Types of Attribute Control chart

A **P chart** or **NP Chart** tracks the number of defects in the process. The difference between the two is that an NP chart plots actual counts while the p-chart plots proportions. Both of these charts are based on the **binomial distribution** and track counts of pass/fail or similar attributes.

C Charts and **U charts** are based on the **Poisson distribution.** While they also track defects, they are used with constraints. For example, a television screen might be defective if there are more than three non-working pixels. Screens with zero, one, or two pixels are acceptable. The difference between the C and U chart is that a C chart controls *counts* of defects per unit, while the u chart controls the *average* number of defects per unit.

An example of a C chart is given below.



Variable Control Charts:

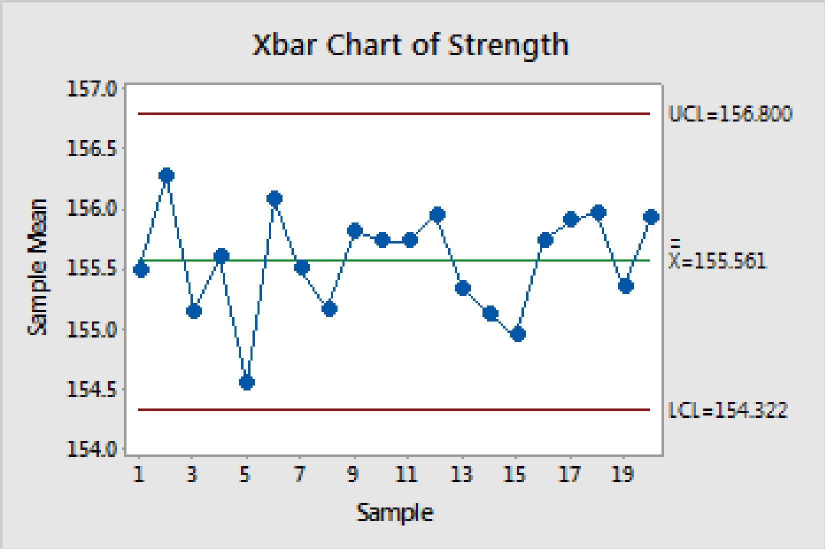
In evaluating the output from a process, you could measure a key characteristic using a continuous scale. This produces variable (continuous) data.

Variables control charts are used to evaluate variation in a process where the measurement is a variable--i.e. the variable can be measured on a continuous scale (e.g. height, weight, length, concentration). There are two main types of variables control charts. One (e.g. x-bar chart) evaluates variation between samples. Non-random patterns in the data on these charts would indicate a possible change in central tendency from one sampling period to the next. One way of thinking about the use of a **variables control chart** is that you are testing the hypothesis that a particular sample mean came from the population of sample means represented by the control limits of the process. If the particular sample mean is within the control limits, your conclusion is that it does come from that population. If the particular sample mean is outside the control limits, you conclusion is that it may have come from some other distribution.

The other type of variables control chart (e.g. R-chart, S-chart, Moving Range chart) evaluates variation within samples. Non-random patterns (signals) in the data on these charts would indicate a possible change in the variation within the samples.

Non-random patterns in the data plotted on the control charts provide evidence of the process being **in-control** (only common cause variation present; predictable) or **out-of-control** (common cause and assignable cause variation present; unpredictable). Adjusting a process which is in-control will result in increased variation. Failing to adjust a process which is out-of-control results in a loss of predictability. Control charts help a machine operator or manager to decide when it is appropriate to make an adjustment and when it is better to leave the process alone.

An example control chart is shown below.



c)
In this case we will apply a P-chart.

The performance average is given by

$\bar{P}$ = total defectives/total sample observations = 100/(10x100) = 0.1

Next we compute the control limits assuming Z = 3.

Upper control limit

$$UCL \ = \ \bar{P} + \ z\sqrt{\frac{\bar{P}(1-\bar{P}}{n}} = 0.1 + 3\sqrt{\frac{0.1(1-0.1)}{100}}$$

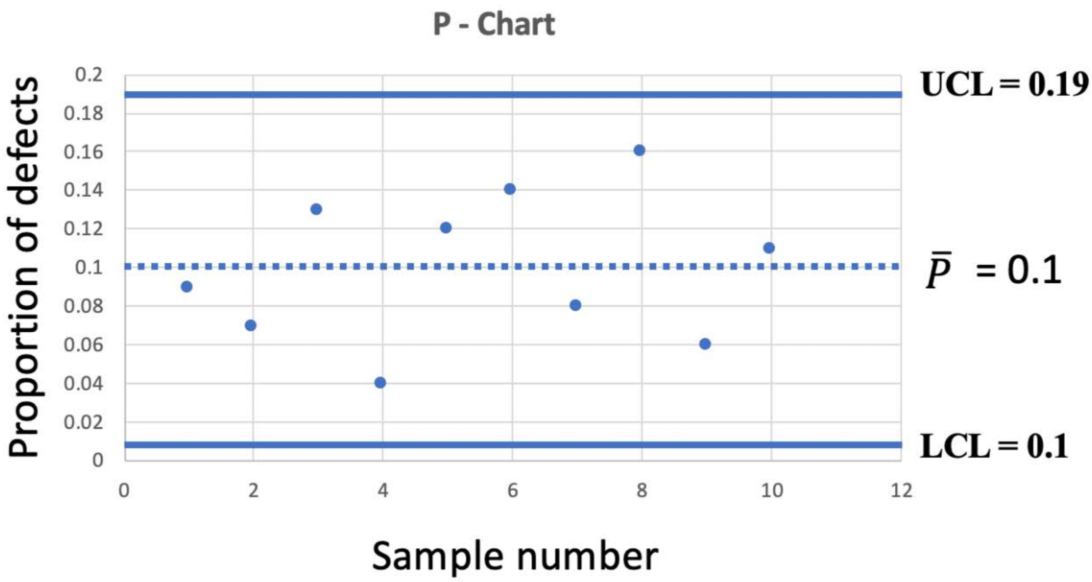
UCL =0.19

Lower control limit

$$UCL \ = \ \bar{P} - \ z\sqrt{\frac{\bar{P}(1-\bar{P}}{n}} = 0.1 - 3\sqrt{\frac{0.1(1-0.1)}{100}}$$

LCL = 0.01

The P- Chart for this case is given below. **In this case the process is in control.**



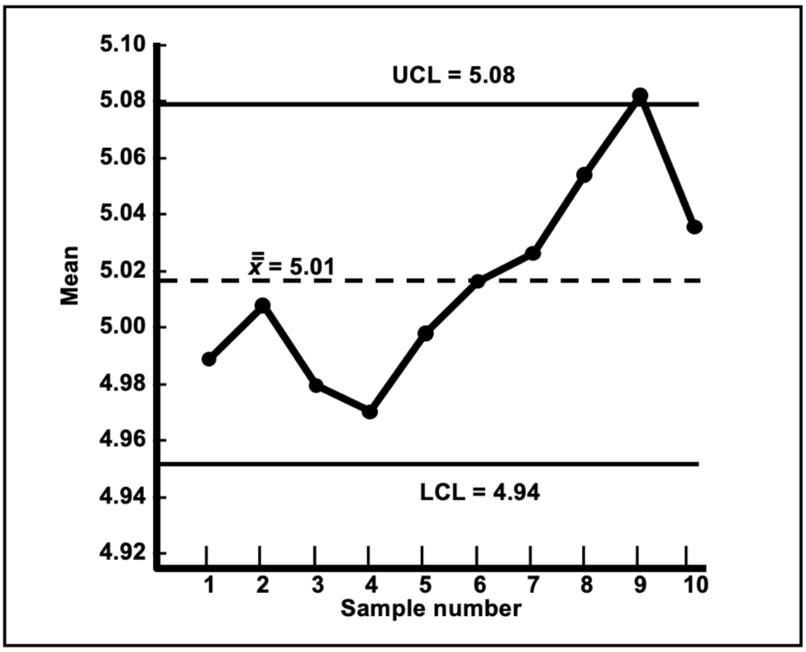
Whilst the process here is shown to be in control, there is still room for improvement. The engineering team should examine the manufacturing processes and employ further control charts to identify the root causes of failure.

d)
For the X-bar chart.

$$\bar{\bar{x}} = \frac{\sum \bar{x}}{k} = \frac{50.09}{10} = 5.01 \text{ cm}$$

$$UCL = \bar{\bar{x}} + A_2\bar{R} = 5.01 + (0.58)(0.115) = 5.08$$

$$LCL = \bar{\bar{x}} - A_2\bar{R} = 5.01 - (0.58)(0.115) = 4.94$$



For the R chart

$$UCL = D_4\bar{R} \qquad LCL = D_3\bar{R}$$

$$\bar{R} = \frac{\sum R}{k}$$

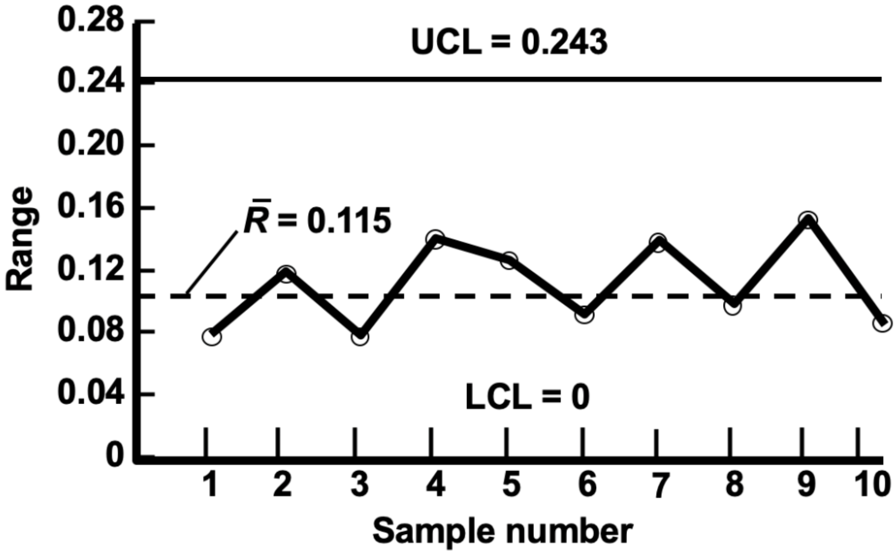
where

$\bar{R}$ **= range of each sample**
k **= number of samples**

$$R = \frac{\sum R}{k} = \frac{1.15}{10} = 0.115 \qquad \begin{array}{l} UCL = D_4R = 2.11(0.115) = 0.243 \\ LCL = D_3R = 0(0.115) = 0 \end{array}$$

Using Factor Values D_3 and D_4

R- Chart



In this case, the sample mean is shifting upward and the range (dispersion) is consistent. This suggests an assignable cause of change which must be investigated further. In order to make a confident purchase, one would need to know the specification limits of the design since these should fall outside of the control limits and hence render the machine suitable for use.

<u>Examiners Comments</u>

This question related to Statistical Process Control (SPC). Part a) was answered well in most cases, with candidates demonstrating their understanding and value of SPC in manufacturing operations. Part b) delivered a mixed response with higher performing candidates providing greater detail on the elements of Attribute and Variable control charts. Very few candidates mentioned the role that specification limits have in control chart development and interpretation. Part c) required candidates to assess the performance of a manufacturing operation using an Attribute control chart generated from the supplied data. Most candidates did well here, although marks were often lost due to lack of discussion relating to the further actions that could be taken as a result of their findings. Part d) focused on X-bar and R charts. Most candidates demonstrated a good level of knowledge. Some candidates lost marks for not providing sketches, choosing instead to rely on limited calculations of LCL and UCL levels etc. Higher performing candidates gave detailed discussions of the further information/steps that would be required to make an informed purchase decision.

SECTION B

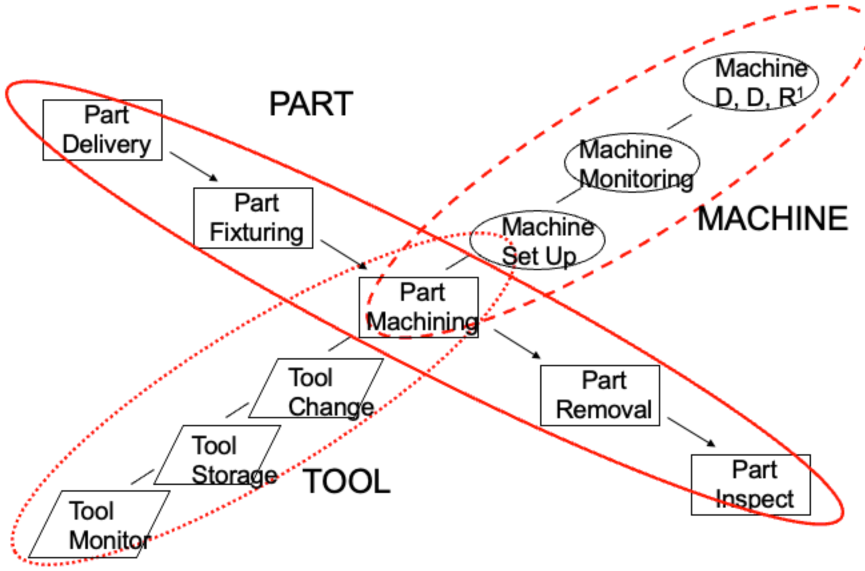
Q3. Machine Tool Vibration Control

a) Machine tools play a central role in many manufacturing operations, and are often required to operate in a fully automated, unattended manner on a regular basis. Discuss the different issues that need to be considered in preparing a machine tool to operate in this manner and the support approaches typically used.

A complete list of automation requirements for stand alone operation is:

- Providing instructions for start, operation, finish
- Auxiliary Support
- Automation of basic operations
- Automation of operation sequence
- Automation of part handling
- Automation of operation variety management
- Automation of monitoring, maintenance functions

Further the diagram below identifies all the issues associated with tool, part and machine monitoring. Students might use a diagram such as this to orient the different auxiliary tasks being described.



b) *The management of vibrations is critical for effective machine tool performance. Discuss three approaches taken in the design of a machine tool to ensure the vibrations that occur during its operation are minimised.*

Approaches discussed in lectures for minijmising the vibration problem in the design phase include:

- Remove/isolate forcing element
- Increase damping
- Increase stiffness
- Improved mass distribution

c) *An upgraded position control system for a machine tool is being considered, where the original proportional controller, denoted K_1, is being replaced by a new proportional, derivative controller K_2. A simplified model, G, of the cutting tool dynamics (from cutting force to end effector position) and the two controllers and are given below:*

$$G = \frac{1}{1 + 2c\, s/w_N + s^2/{w_N}^2}$$

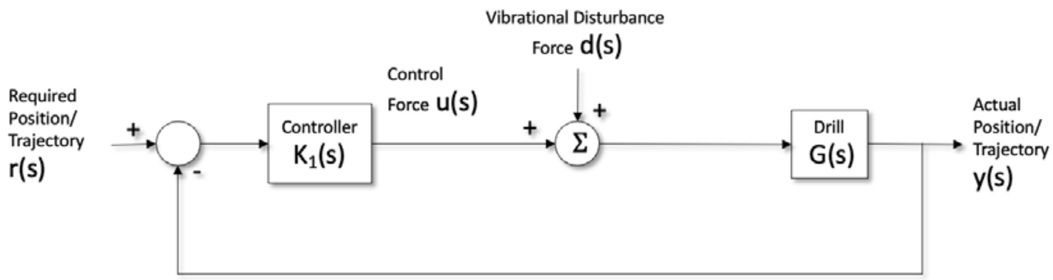
;

$$K_1 = k_{P;}$$

$$K_2 = k_P + s k_{D.}$$

where $c = 0.2,\ w_N = 500\ r/s, k_P = 0.44\ , k_D = 1.6 \times 10^{-3}$.

(i) Draw an appropriate feedback diagram for the closed loop system involving the machine tool and the original controller K_1 showing the reference signal, r, position output, y, and a vibration disturbance, d, at the input to the machine tool. Clearly label your diagram.



where the closed loop transfer function from *d(s)* to *y(s)* is given by

$$\frac{y(s)}{d(s)}\ (closed\ loop) = \frac{G}{1+GK_1}$$

(ii) *If the most damaging vibrations experienced by the machine tool were at 400 rad/sec, determine the % improvement (in terms of vibration reduction) achieved with the new controller K_2 replacing K_1 .*

This problem reduces to determining the resulting damping and natural frequency of the closed loop systems involving K_1 *and* K_2.

$$K_1:\ \frac{G}{1+GK_1} = \frac{1}{1+2cs/\omega_n + s^2/\omega_n^2 + k_p}$$

$$Dr:\ (k_p+1) + 2cs/\omega_n + s^2/\omega_n^2 = 0$$

$$\omega_{n_1}^2 = (1+k_p)\,\omega_n^2$$

$$\omega_{n_1} = \left[1.44 \times (500)^2\right]^{1/2}$$

$$= 600\ r/s.$$

Also

$$2c_1\omega_{n_1} = 2c\omega_n$$

$$\Rightarrow c_1 = c\cdot\frac{\omega_n}{\omega_{n_1}} = 0.2\times\frac{5}{6}$$

$$= \frac{1}{6}\ \text{or}\ 0.166$$

$$K_2:\ \frac{G}{1+GK_2} = \frac{1}{1+2cs/\omega_n + s^2/\omega_n^2 + K_p + K_D s}$$

$$Dr = 0 \Rightarrow (K_p+1)\,\omega_n^2 + (2c\omega_n + K_d\omega_n^2)s + s^2 = 0$$

$$\Rightarrow \omega_{n_2}^2 = \omega_{n_1}^2 = 600\ r/s.$$

But

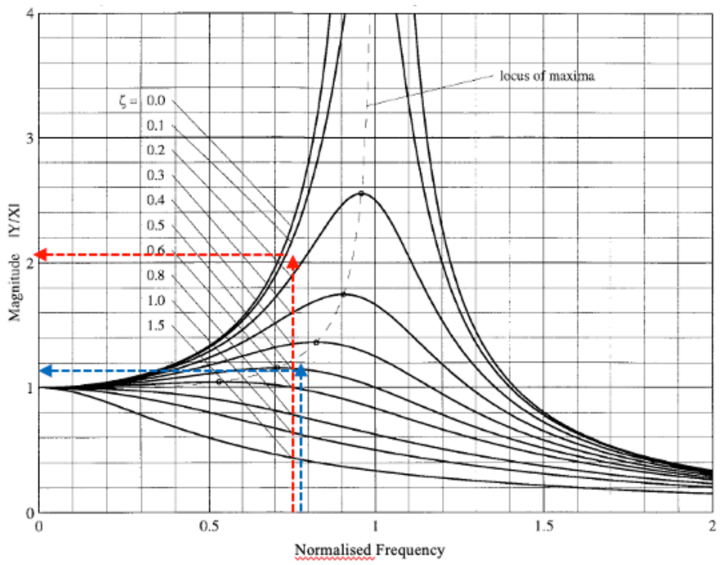
$$2c_2\omega_{n_2} = 2c\omega_n + k_D\omega_n^2$$

$$c_2 = c\frac{\omega_n}{\omega_{n_2}} + \frac{k_D\omega_n^2}{2\omega_{n_2}}$$

$$= 0.1666 + 0.333$$

$$= 0.5$$

with identical natural frequency in each case, the different damping factors determine the different levels of overshoot as can be determined from the mechanics data book:



For K_1 the overshoot (i.e. essentially the maximum vibration amplitude) is approximately *105%* and K_2 approximately *15%* so a 7 fold reduction in oscillation. The percentage reduction in overshoot is approximately 85%. It is noted that there are different ways to present this level of reduction and these will be accepted during marking.

(iii) What additional precautions could be taken to ensure the control system minimises these vibrations and manages the level of control force used?

Further control measures include so called *advanced control* for machining is defined as the on-line adjustment of process parameters for the purpose of

- optimising production rate [using feed rate, speed]
- optimising quality [force, speed]
- minimising cost of materials and components [force, speed]
- Protecting machine [force, torque, power]

One form of advanced control is Adaptive Control Constrained (ACC) which puts upper limirs on allowable forces to protect the machine as well as work piece.

- Places a constraint on a process variable
- E.g., if the thrust force and the cutting force is excessive, the AC system will changing the cutting speed or feed to lower the cutting force
- Most common form of AC

Additionally some students might note that it is possible to use the feedback controller to alter the overall natural frequency of the closed loop and hence steer the system further away from the vibration frequency.

Examiners Comments

The question related to the monitoring and control of machine tools and particularly focussed on vibration management.

The first section of the question focussed on approaches to supporting a machine tool being prepared for continuous, automated operation and students managed this well capturing issues associated with work piece, tool and machine monitoring and the necessary preparation required.

The second and third sections were specifically associated with the management of vibration in machine tool. A broad question of design preparation for good vibration management was managed pretty well with good students understanding the role of damping and stiffness as well as isolation as design options. The third section then focussed on the dynamic control of the machine tool in the face of a vibration disturbance. Most students were able to sketch feedback diagrams and closed loop systems well. The comparison of two controllers for this problem was the most challenging and some students struggled with this calculation.

A final section on extensions and improvements for the control system was generally done well by those who attempted it.

Q4 Petri Net Modelling

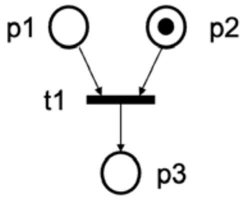
a) Explain what is meant by the following terms used in relation to Petri Net models

(i) The *marking* of a Petri Net?

To set the PN operating, we also require an **initial marking**, M_0, assigning tokens to specific places.

M_0: P → J+

A **marked PN** is described by <N, M_0> and M_0 is a 1 x N vector



e.g. M_0 = (0,1,0)
=> 1 token in place p2

(ii) The *enabling* and *firing* of a transition?

The availability of the required no. of tokens for a transition enables the transition. However

ENABLED ≠ FIRED

i.e. Firing **may** require external trigger

When fired, a transition

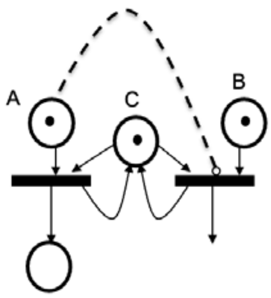
- removes requisite INPUT tokens (according to the weight)
- adds requisite OUTPUT tokens (according to the weight)

(iii) The *weight* on an arc?

The wieght on an arc determines the number of tokens associated with the operation of the arc. The default is 1.

(iv) An *inhibitor arc*?

An inhibitor arc is used to ensure one transition fires in preference to another. In the situation below the left hand transition has priority and can command resource C.



b) A simplified model for operations on a drilling machine is illustrated in Fig 1.

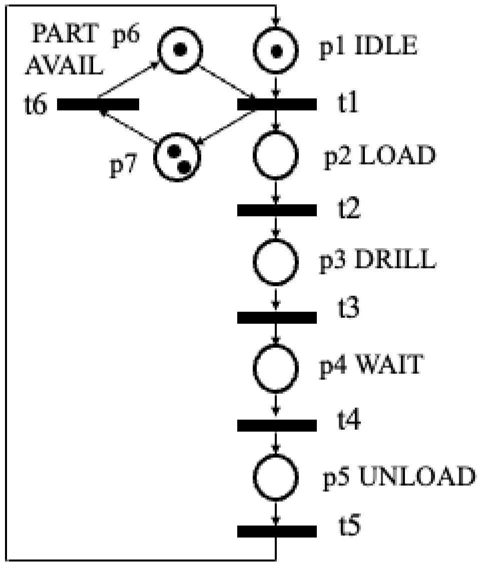


Figure 1 Petri Net of Drilling Operation

(i) What is the initial marking of this system? What is the marking of the model after transition t_1 has fired?

The initial marking M0 is (1,0,0,0,0,1,2), and after firing t1 the marking M1 is (0,1,0,0,0,0,3) although student who assume t6 also fires and give M1 as (0,1,0,0,0,1,2) should not be penalised.

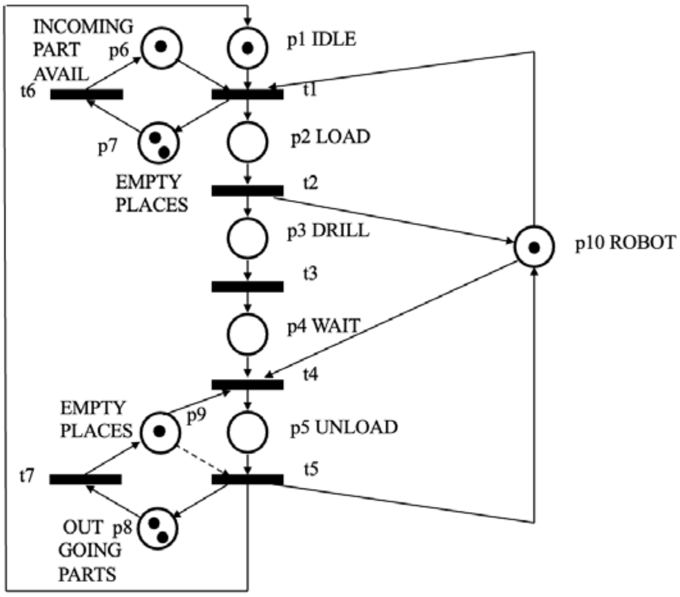
(ii) Place p_6 indicates whether a part is available for drilling. What is the role of p_7?

Place p7 indicates the number of empty places in the incoming parts buffer. The total number of places in the buffer is 3 and hen ce initially there are 2 spare places available for additional incoming parts.

(iii) The drilling operation modelled in Fig 1 is to be integrated into a simple automated production cell illustrated in Fig 2. A single robot moves incoming parts to the drilling station and also removes completed parts to an outgoing parts station. Stating any assumptions you are making, extend the Petri Net given in Fig 1. to integrate the robot and the outgoing parts station which can hold three completed parts at a time.

Assumptions

Approach



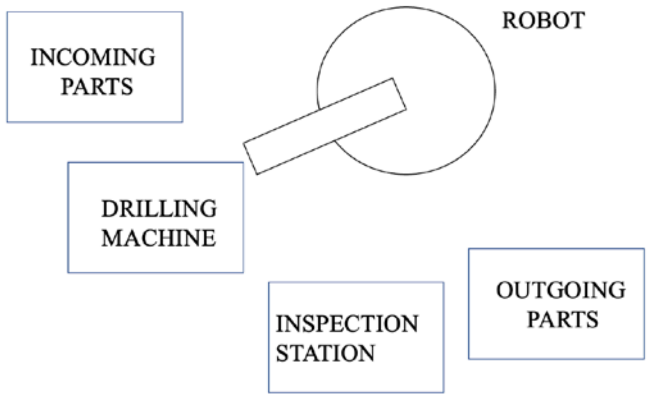
(iv) Referring to your extended Petri Net, explain how your proposed approach can ensure the system is able to operate in a safe and deadlock free manner.

The following additional measures could be included:

1. Handshaking: Most machines are equipped with an operational signal which can be incorporated as a confirmation flag for the cell controller (typically a PLC).
This introduces an additional state into the controller operation but greatly enhances reliability and diagnostic capability.
2. Deadlock Avoidance: Ensuring the robot doesnt attempt to load or unload without a place being available. For outgoing parts the dotted line indicates an unsafe pathway from p9 while the full line indicates a safe pathway
3. Robot priority: The robot operations could be prioritised so that unloading is always completed before any loading commences. An inhibitor arc or similar mechanisms can be used.

Beyond this the buffer control mechanisms stop the chance of overloading of the storgae zones/

c) It is proposed that an inspection station be introduced into the cell described in part b) such that one in every three drilled parts is inspected for drilling quality prior to moving to the outgoing parts station. Briefly explain how this inspection process could be described using a Petri Net model.



There are numerous ways to do this. The simplest approach would be to include a mechanism similar to that used for buffer management in which a token is added each time a part is completed. When three parts are complete the place would fire an arc weighted with 3 and the resulting transition would be given a priority to move to inspection rather than directly to the outgoing collection point. A description is satisfactory for this question although a petri net of the routing process would be advantageous.

Examiners Comments.

This question related to the use of petri nets in the development of automated production operations.

Section a) – requiring students to explain some fundamental properties of petri nets was generally done very well.

Section b) was based around a petri net of the automation logic for a drilling operation. In parts i), ii) most students were able to analyse and describe the petri net provided very well. Part iii) required an extension of the petri net provided in the question to accommodate a robot and an output product station. There was a range of responses to this section with very good students managing to integrate robot and output product station quite simply - the latter mirroring the input product station. Part iv) relating to safety and deadlock avoidance for this system was generally done well.

In Section c) students were asked to consider a further extension and to describe how an inspection station might be included. This was quite a demanding section and quite a range of responses were produced.