MET IIA Paper 2. 2019

Crib

SECTION A
Question -1

Question-1 CRIB
i)

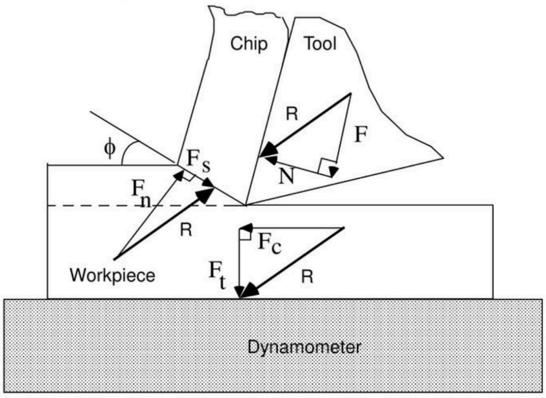
1. Power and torque requirements for cutting a wide range of materials have to be determined before a drive motor of suitable capacity can be chosen.
2. Cutting force data enables the selection of an appropriate design of the machine tool structure that avoids excessive distortion of the machine tool elements and maintains desired tolerances for the machined part.
3. Selection of appropriate jigs and fixtures for the workpiece so that they can withstand the cutting forces without excessive movement.
4. Cutting forces are usually the main sources for forced vibration between the work and the tool, and therefore their magnitudes are important for the analysis of machine tool dynamics.

ii)
A model of this sort is two-dimensional, and to be closely approximated by this ideal model, a machining process should satisfy the following assumptions:

- perfectly sharp tool,
- plane strain,
- constant depth of cut,
- constant and uniform cutting velocity,
- continuous chip formation,
- no built-up edge on tool,
- uniform shear and normal stress along shear plane and tool.

iii)
Forces in Orthogonal Cutting:

In orthogonal cutting, the resultant force R applied to the chip by the tool lies in a plane normal to the tool cutting edge. This force is usually determined, in experimental work, from the measurement of two orthogonal components: one in the direction of cutting velocity (referred to as the cutting force F_c), the other normal to the direction of cutting velocity (referred to as the thrust force F_t). The accurate measurement of these two forces is carried out with the use of dynamometers that measure the piezoelectric charges of quartz or the deflections (or strain) in elements supporting the cutting tools. These two components may be used to calculate many important variables in the process of chip formation. The resultant force can also be resolved into two components on the tool face: a friction force, F, along the tool–chip interface, and a normal force, N, perpendicular to the interface. The resultant force is balanced by an equal and opposite force along the shear plane and is resolved into a shear force, Fs , and a normal force F_n.



Free Body Diagram

b)

i) The shear stress can be determined by

$$\tau = \frac{F_s}{A}$$

Where A is the area of the shear plane. For a width of cut w and depth t_o,

$$A = \frac{wt_o}{\sin \emptyset}$$

Therefore

$$\tau = \frac{(F_c \cos \emptyset - F_t \sin \emptyset) \sin \emptyset}{wt_0}$$

ii)

Using the fist set of conditions, we need to determine the shear plane angle, ϕ. This can be achieved through the use of Merchant's approximation by first determining the friction coefficient, μ, then the friction angle, β. Thus, from the fact that

$$\mu = \frac{F}{N}$$

$$\mu = \frac{F_t + F_c \tan \alpha}{F_c - F_t \tan \alpha} = \mu = \frac{150 + 400 \tan 10}{400 - 150 \tan 10} = 0.59$$

Using Merchant's approximation for ϕ

$$\emptyset = 45 - \frac{\beta}{2} + \frac{\alpha}{2} = 45 - \frac{\tan^{-1} 0.59}{2} + \frac{10}{2} = 34.7^0$$

We can use the expression from part bi), which states that

$$\tau = \frac{(F_c \cos \emptyset - F_t \sin \emptyset)\sin \emptyset}{wt_0} = \frac{(400 \cos 34.7^0 - 150 \sin 34.7^0)\sin 34.7^0}{wt_0}$$

$$\tau = \frac{138.6}{wt_o}$$

** Under the second set of conditions. **Assuming the friction angle does not change with the rake angle**, we can calculate the new shear plane angle as follows

$$\emptyset = 45 - \frac{\beta}{2} + \frac{\alpha}{2} = 45 - \frac{\tan^{-1} 0.59}{2} + \frac{15}{2} = 37.2^0$$

** Under the second set of conditions. **Assuming the shear stress does not change with the rake angle** (since this is material dependent. * note better answers will comment on the fact that shear stress is a function of temperature, and a further assumption would be that the temperature of the shear zone remains constant) we can develop an expression relating the new cutting force and thrust force as follows,

$$\tau w t_0 = (F_c \cos 37.2^0 - F_t \sin 37.2^0)\sin 37.2^0 = 138.6 \ N$$

Also, given that, under the new conditions

$$\mu = \frac{F_t + F_c \tan 15}{F_c - F_t \tan 15} = 0.59$$

Using the last two equations we can solve for F_t and F_c

$$(F_c \cos 37.2^0 - F_t \sin 37.2^0)\sin 37.2^0 = 138.6$$
$$(0.796\, F_c - 0.604\, F_t)0.604 = 138.6$$
$$(0.480 F_c - 0.364\, F_t) = 138.6$$
$$F_c = \frac{138.6 + 0.364\, F_t}{0.480}$$

and…

$$\frac{F_t + F_c \tan 15}{F_c - F_t \tan 15} = 0.59$$

$$F_t + 0.267\, F_c = 0.59 F_c - 0.158\, F_t$$
$$1.158 F_t = 0.323 F_c$$
$$F_t = 0.278 F_c$$

therefore …

$$F_c = \frac{138.6 + 0.101\, F_c}{0.480}$$

giving

$$F_c = \frac{138.6}{0.379} = \mathbf{365.7}\ N$$

and

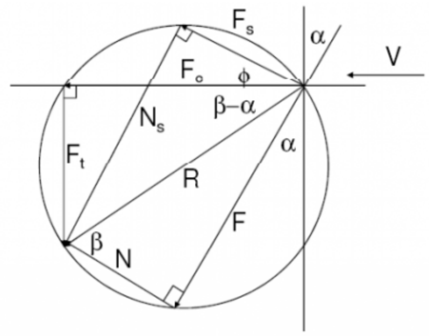
$$F_t = \mathbf{101.7}\ N$$

** Comment

In general, increasing the rake angle increases the shear angle and reduces the cutting force, since it reduces the amount of plastic deformation required to achieve the same removal rate.

c)

From the Merchant's circle at the cutting front,



we can show that that

$F_t = R \sin(\beta - \alpha)$ and $F_t = F_c \tan(\beta - \alpha)$

The sign of the thrust force, F_t, can be either positive or negative, depending on the relative magnitudes of the friction angle, β, and rake angle, α. When $\beta > \alpha$, the sign of F_t is positive (downward) and when $\beta < \alpha$, it is negative (upward). Therefore, in order to make the thrust force = 0, we make $\beta = \alpha$. This can be achieved by:

- Changing the rake angle of the tool, α.
- Changing the friction angle β by adding lubricant to the system.

Question-2 Crib

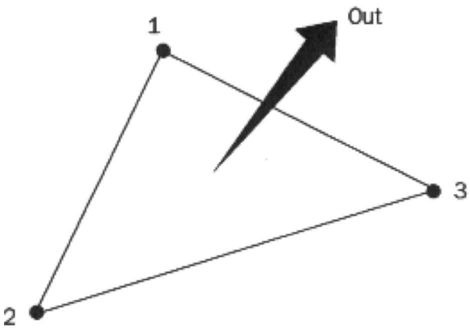
a)
This answer is best presented in a table. [**Note to examiner**: Good answers will give numerical information where appropriate.]

Attribute	**AM**	**CNC**
Materials	Limited, with properties below those of bulk materials	Nearly unlimited
Part size	< 600x900x500 mm	Large enough for aerospace parts
Part complexity	Unlimited. Major advantage	Limited
Accuracy	Typical range, 0.125 to 0.75 mm. Limited precision. Function of system.	Typical range, 0.0125 to 0.125 mm. Ultra precision.
Surface finish	2.5 – 15 microns Rz.	0.5 to 5 microns Rz
Lead-time	Short to moderate. From hours to days.	Moderate, from days to weeks, depends on part complexity and the need for jigs and fixtures.

b)
i) The STL file format provides two different ways of storing information about the triangular facets that tile the surface of a 3D object. These are called the ASCII encoding and the binary encoding. In both formats, the following information of each triangle is stored:

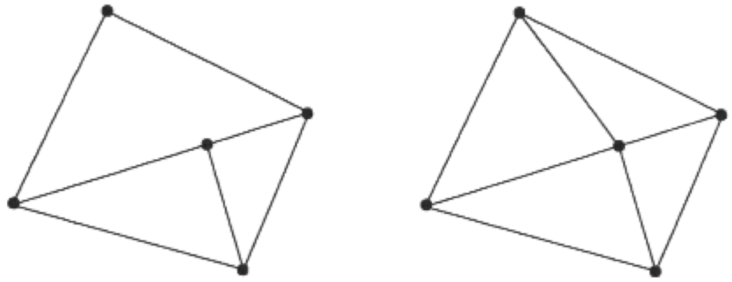
- The coordinates of the vertices.
- The components of the unit normal vector to the triangle.

The normal vector should point outwards with respect to the 3D model, as shown below.

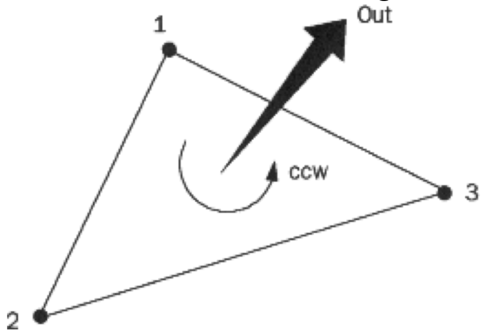



```
facet normal n_x n_y n_z
    outer loop
        vertex v1_x v1_y v1_z
        vertex v2_x v2_y v2_z
        vertex v3_x v3_y v3_z
    endloop
endfacet
```

There are three rules that must be followed.
1. The Vertex rule: The vertex rule states that each triangle must share two vertices with its neighbouring triangles.

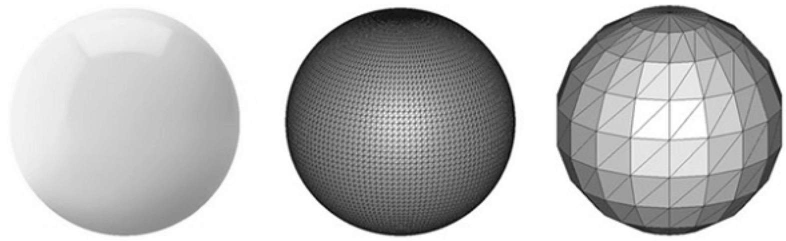


2. The orientation rule: The orientation rule says that the orientation of the facet (i.e. which way is “in” the 3D object and which way is“out”) must be specified in two ways. 1st, the direction of the normal should point outwards. 2nd, the vertices are listed I counter clockwise order when looking at the object from the outside (right-hand rule).



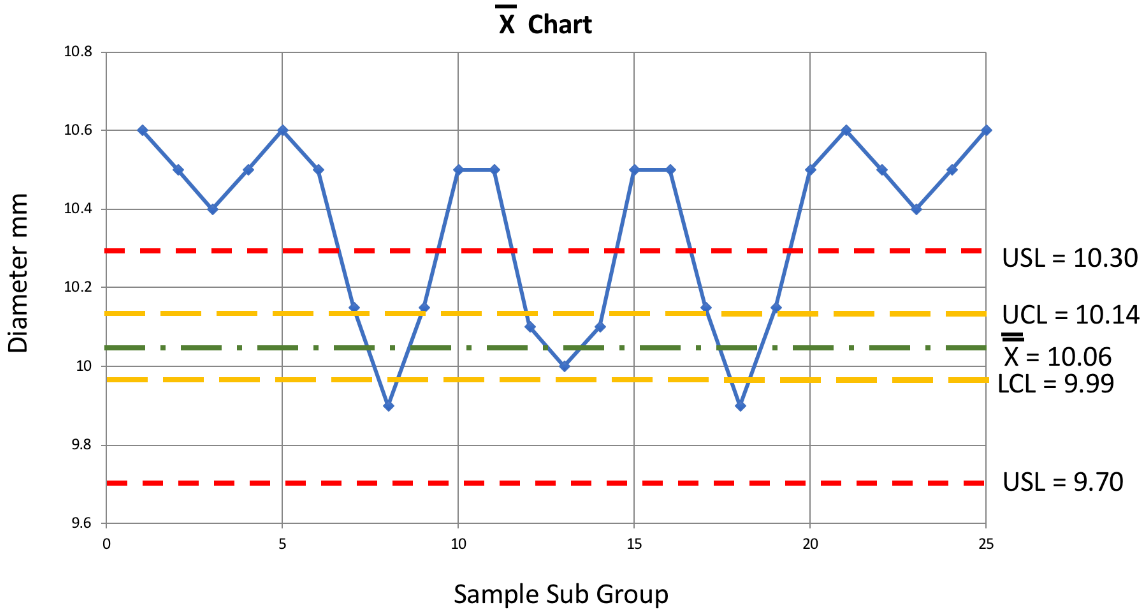
3. The all positive octant rule. The all positive octant rule says that the coordinates of the triangle vertices must all be positive. This implies that the 3D object lives in the all-positive octant of the 3D Cartesian coordinate system (and hence the name).

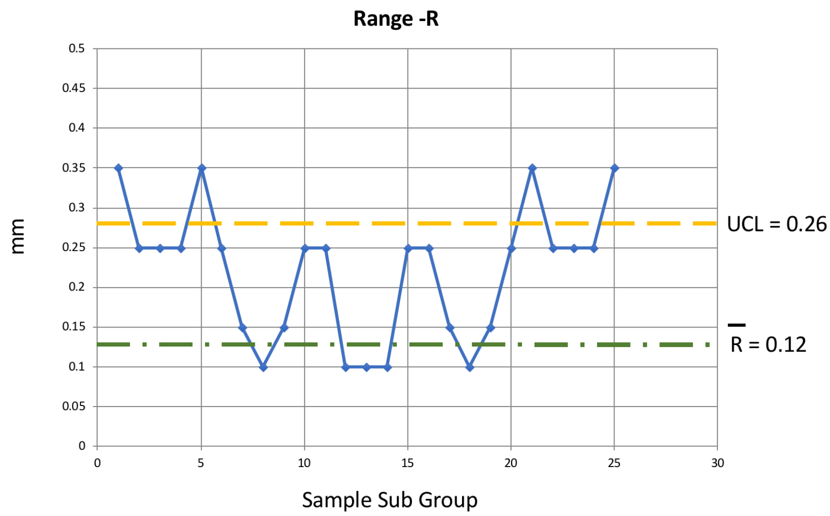
ii) The STL file format approximates the surface of a CAD model with triangles. The approximation is never perfect, and the facets introduce coarseness to the model as shown.



The perfect spherical surface on the left is approximated by tessellations. The figure on the right uses big triangles, resulting in a coarse model. The figure on the centre uses smaller triangles and achieves a smoother approximation. Hence STL file representations of a CAD model can greatly influence the resolution of the additively manufactured part.

C)
i)





Following the users trials, it is clear, for this particular task at least, that the machine is out of control and to a large degree, out of specification. From the R-chart, we see a very high level of dispersion, with data that is highly symmetric about subgroup 13. The high level of symmetry indicates that the machine is relatively stable, although there are clearly areas on the bed which perform better than others. This large spread of values in diameter indicate that the cylinders in certain locations are considerably ‘out of roundness’, notably at positions around the perimeter of the build platform. Cylinders produced at positions 7, 8, 9, 12, 13, 14, 17, 18 & 19, are produced in control and within tolerance and are exhibiting high levels of ‘roundness’.

ii)

The data provided by the manufacturer suggests that the machine was in control and operating within specification since,

$$Cp = \frac{USL - LSL}{6\sigma} = \frac{0.6}{0.3} = 2.0$$

$$Cpk_u = \frac{USL - \bar{\bar{X}}}{3\sigma} = \frac{0.24}{0.15} = 1.6$$

and

$$Cpk_l = \frac{\bar{\bar{X}} - LSL}{3\sigma} = \frac{0.36}{0.15} = 2.4$$

For the user's data in Table.1 we find that
$\bar{\bar{X}} = 10.35$, and $\sigma = 0.23$

In which case, $C_p = 0.43, Cpk_u = -0.07, and\ Cpk_l = 0.93$

<u>Comment:</u>

The manufacturer's data suggests that the machine is performing very well on the chosen build. A Cp value of 2 indicates that there is plenty of distance between the control limits and the specification limits. The Cpk values indicate that the spread of diameters is skewed towards the upper specification limit, with enough distance to keep the process in control.

The user's data of Table.1 tells a very different story. A Cp value of 0.43 suggests that the system is out of control by a considerable margin. The spread of the data is very large, again skewed beyond the upper specification limit.

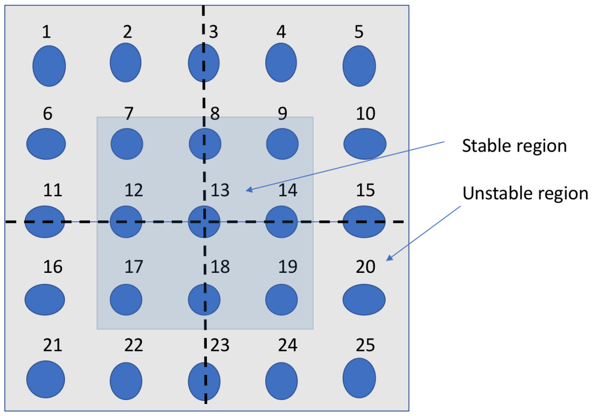
iii) Possible Causes for the variations observed

- The production of the cylinders is produced at various points on the bed. It is likely that there is a problem with the optical train given that the centre of the bed, near to the optical axis, is performing in control and within specification. This could be due to optical misalignment or a damaged imaging system (less likely since the symmetric about the bed).
- Operator mistakes or set-up conditions may change process mean. The manufacturer may have only built cylinders in the middle of the machine, which may explain their data compliance.
- It is important that all STL file code elements are the same for each cylinder, i.e equal number of tessellations across the part. Curved surfaces such as cylinder walls are particularly susceptible to low resolution STL files. Was this the case?
- Are there material variations across the bed?
- There may be powder level variations across the bed which will change the melt response of the material. Is the levelling arm working consistently across the bed? Has it been calibrated? Is it damaged?

Corrective actions

- Make at better assessment of the optical characteristics of the laser system. Repeat the validation trials using only positions, 7, 8, 9, 12, 13, 14, 17, 18 & 19. Looking at the

charts, it is likely this will result in better compliance. If so, only operate the machine in these locations. This will reduce the build rates and increase costs.
[**Note to examiner**: Better answers will show that an imaging system used in this case has variations in performance (beam diameter variation) across the bed due to the change in distance the beam has to travel from the optical axis, as shown below]



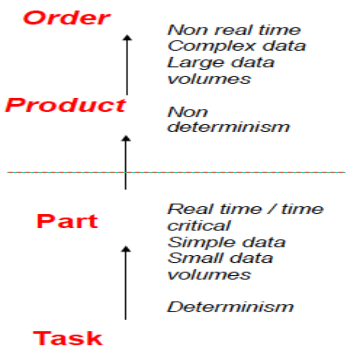
- Take precautions against low resolution STL files. Increase the resolution and repeat the trials.

SECTION B Crib

Question – 3

a)

i) The responses for this question might refer to a diagram like the one below which was used as the basis for these discussions in the lectures. A good response will discuss the varying requirements for data in terms of timeliness, volume and complexity as the control focus shifts from task to part to product and to order. The hierarchy is important because the higher layer will aggregate data from the lower layers which keeps the communication and computing system manageable. Good students will also mention the determinisitic constraints on lower level operations where real time control required guarantees of control system performance.



(ii)

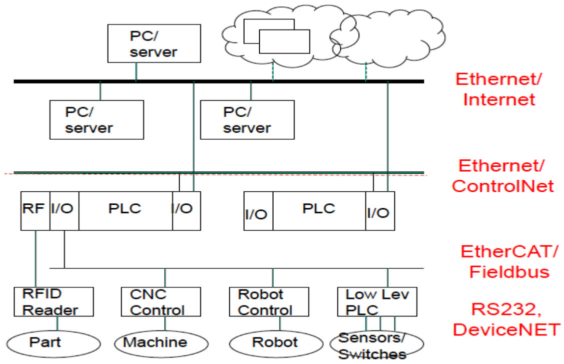
The figure below outlines the different communication and computing system required for a factory control environment. The systems reflect the properties mentioned in the previous question

Computing

- PC/Server/Cloud – low cost, high volume data storage
- PLC – lower data capacity, time guarantees, electrical isolation,

Communications

- serial, device NET – deterministic, high speed, low volumes
- etherCAT, fieldbus – deterministic, higher data volumes
- Ethernet, internet – non deterministic, efficient for high volumes



(iii)

Students are likely to chose from the following issues discussed in lectures and explain what they are and how they impact on automation and the decision hierarchy:

Tech Development	*Description*	*Effect on Automation*	*Influence on Comms / Computing Hierarchy*
Internet of things	Connecting sensors and actuators to networked servers typically using wifi	Direct link of sensor to server – low cost, external method for adding new sensors	Bypassing of the multi layer hierarchy Integration of non production data
Industry 4.0	Connectivity and optimization in vertical, horizontal and value chain directions	Similar to IoT and also greater levels of processing at lower parts of hierarchy plus ability of higher levels to access RT data	General flattening of the hierarchy and also integration of customers and suppliers within real time operations
Digital Twins	Dynamic (live) model based replication of products or processes with sensor integration	Digital twin actively driving the production of a particular product	Hierarchy doesn't consider products having an active role in product process
AI/Multi Agent Control	Machines, devices, parts with their own ability to interact and reason	Introduce AI based reasoning into some or all of the decision hierarchy	Alternative model to hierarchical control – decisions made by the machines!
Augmented Reality	Overlaying of advisory information onto image of an item	Use in quality control, condition monitoring, fault diagnosis, maintenance	Limited influence but AR would need to access communications at the different levels

(b)

The discussion under each of these categories should include issues such as:

i)
Physical systems and choices made in selecting:

- robots: end effectors, fixtures
- machine tool: part delivery, fixturing, tool management
- cell operations: automated part flow, part storage

ii)
Information and Control systems – hardware, software and programming of

- machines / robots: programming of sequences for each machine
- cell: PLC programming of cell logic – planning, programming, testing

iii)

Interfaces – design/specification and properties of different

- sensors: part presences, machine properties
- actuators: control signals for part movement,
- communications networks between physical and control systems
- communications between cell and factory computing

Other Issues that are required to complete a successful integrated cell

- testing
- commissioning

Question – 4 Crib

a)

(i) P – simple, easy to tune, good for adjusting loop speed, no ss error guarantees, nor damping adjustment. In a machining context this may not be sufficient to ensure accurate machining of a profile
(ii) PI – more complex to set up and tune than P (two parameters) but in addition to P benefits are that integral action can ensure no SS error which should ensure accurate machining of a profile provided there is sufficient damping in the original system already
(iii) PID – yet more complex (three parameters) but in addition to PI benefits allow for the adjustment of c/l damping which ensures little or no overshoot in position control which in a machining context may lead to internally generated chatter.

Hence PD control allows for simultaneous speed and damping adjustment which restricts the level of oscillation in closed loop. Use when open loop system is lightly damped and/or tight constraint on level of oscillation in c/l. Steady state accuracy of the machined profile might be less important than other properties.

b)

(i) For a standard block diagram with feedback control the closed loop transfer function then becomes

$$CLTF = \frac{GK}{1+GK} = \frac{\frac{\omega_n{}^2}{s^2+2\zeta\omega_n s+\omega_n{}^2}\times(K_P+K_D s)}{1+\frac{\omega_n{}^2}{s^2+2\zeta\omega_n s+\omega_n{}^2}\times(K_P+K_D s)}$$

$$= \frac{\omega_n{}^2\times(K_P+K_D s)}{s^2+2\zeta\omega_n s+\omega_n{}^2+\omega_n{}^2\times(K_P+K_D s)}$$

$$= \frac{\omega_n{}^2\times(K_P+K_D s)}{s^2+(2\zeta\omega_n+\omega_n{}^2 K_D)s+\omega_n{}^2+\omega_n{}^2\times(K_P+1)}$$

Hence, using * to denote revised closed loop values

$$\omega^*{}_n{}^2 = \omega_n{}^2 \times (K_P + 1)$$

and

$$2\,\zeta^*\omega^*{}_n = 2\zeta\omega_n+\omega_n{}^2 K_D.$$

Hence,

$$\zeta^* = \frac{2\zeta\omega_n+\omega_n{}^2 K_D.}{2\omega_n\ \sqrt{K_P+1}} = \frac{2\times0.15+2}{2\sqrt{(1+8)}} = \frac{2.3}{6} = 0.38$$

(ii) Increasing K_D will directly increase the closed loop damping independent of the closed loop speed which is separately set by K_P. This improves the ability of the system to suppress vibrations and can also improve tracking bandwidth and accuracy. Good answers might for example examine the sensitivity of a % change in K_D on damping.

c) How might you use adaptive control in the context of the machining control system introduced in b)? Justify your approach.

[30%]

Two types of adaptive control

1 Adaptive Control Constrained (ACC): Places a constraint on a process variable

e.g. In this system for example if the thrust force and the cutting force is excessive, the
AC system will reduce the cutting speed or feedrate to lower the force applied. ACC is relatively simple to implement and often part of the machine tools basic functions.

2 Adaptive Control Optimised (ACO): Allows features of ACC but also adds systems that optimise the speed or efficiency of operations.
e.g. in this system speed could be adjusted / increased for maximising removal rate while still staying with constraints of force limits. ACO is more complex to implement and tune than ACC

The diagram below shows the benefit of ACO in terms of cutting time, where federate per tooth is increased during low force operations.