

## **UNIT I- CONTROL SYSTEM MODELING**

### **What is meant by a system?**

It is an arrangement of physical components related in such a manner as to form an entire unit.

### **What is a command input?**

It is the excitation applied to a control system from an external source. It is also a motivating input signal to the system, which is independent of the output of the system.

### **Define output.**

It is the actual response obtained from a control system, which must be maintained at a prescribed value.

### **What is an actuating signal?**

It is the difference between the reference input and feedback signal. It is also called as actuating signal.

### **Define plant.**

It is the process/body/ machine, of which a particular quantity or condition is to be controlled.

### **List the two types of control systems?**

The two types of control system are, open loop systems and closed loop system.

### **What is an open loop system?**

The control system in which the output has no effect upon the input quantity, is known as open loop control system.

### **What is meant by a controller?**

It is the component required to generate the appropriate control signal applied to the plant.

### **Define manually controlled systems?**

Systems that involve continuous manual control by a human operator are called manually controlled system.

### **For what purpose feedback element is used?**

It is the component required to generate the appropriate control signal applied to the plant.

### **What is a closed loop system?**

A system in which output has some effect upon the input quantity, in such a manner as to maintain the desired output value.

### **What is feedback?**

The feedback is a control action, in which the output is sampled and a proportional signal is given to input for automatic correction of any changes in desired output.

### **Give the types of feedback?**

Negative feedback

Positive feedback.

### **What type of feedback is employed in control system?**

Negative type of feedback is employed in control system.

### **When will feedback exist in a system?**

Feedback is said to exist in a system, when a closed sequence, of cause and effect relations exist between system available.

### **Define transfer function[ Madras univ.apr 96]**

Transfer function of a given system is defined as the ratio of the laplace transform of output variable to laplace transform of input variables at zero input conditions.

### **Define order of the system.**

The highest power of the complex variables in the denominator of the transfer function determines the order of the system.

### **Define linear system.**

A system is said to be linear if it obeys the principle of superposition and homogeneity. The principle of superposition states that the response of the system to a weighted sum of the responses of the system to each individual input signals.

### **Give the important characteristics of open loop control system.**

Their ability to perform accurately is determined by their calibration, which implies to establish the input-output relation to obtain a desired system accuracy.

### **When will the system is said to be linear?**

The system is said to be linear, if it satisfies the following two properties:

- Adaptive property that is for any  $x$  and  $y$  belonging to the domain of the function  $f$ , we have  
$$F(x+y) = f(x) + f(y)$$
- Homogeneous property that is for any  $x$  belonging to the domain of the function  $f$  and for any scalar constant  $\alpha$  We have

$$F(\alpha x) = \alpha f(x)$$

These two properties together constitute a principle of superposition.

### **Why most of the systems are non-linear in nature?**

Most of the systems are non-linear in nature because of different non-linearities such as saturation, friction, dead zone etc. present in the system.

### **Give the classification of control system.**

Broadly control systems are classified as

Natural control systems, manmade control systems, combinational control systems, time varying and time-invariant systems, linear and non-linear systems, continuous time and discrete control systems, deterministic and stochastic control systems, single input single output (SISO) and multiple input multiple output systems, open loop and closed loop systems.

### **Give the advantages of open loop system.**

The advantages of open loop system are

1. Such systems are simple in construction.
2. Very much convenient when input is difficult to measure.
3. Such systems are easy for maintenance point of view.
4. Generally these are not troubled with problems of stability.
5. Such systems are simple to design and hence economical.

### **Give the disadvantages of open loop system.**

The disadvantages of open loop system are

1. Such systems are inaccurate and unreliable because accuracy of such systems are totally dependent on the accurate precalibration of the controller.
2. Such systems give inaccurate results if there are variation in the external environment i.e. systems cannot sense environmental changes.
3. Similarly they cannot sense internal disturbances in the system, after the controller stage.

### **Give the advantages of closed loop system.**

The advantages of closed loop system are:

1. accuracy of such system is always very high because controller modifies and manipulates the actuating signal such that error in the system will be zero.

2. Such systems sense environmental changes, as well as internal disturbances and accordingly modify the error.

4. In such system, there is reduced effect of non-linearities and distortions.

**Compare open loop system and closed loop system**

<b>OPEN LOOP SYSTEM</b>	<b>CLOSED LOOP SYSTEM</b>
Output measurement is not required for operation of the system.	Output measurement is necessary.
Highly affected by non-linearities	Reduced effect of non-linearities.
Highly sensitive to the disturbances and environmental changes	Less sensitive to disturbances and environmental changes.
Feedback element and error detector are absent	Feedback element and error detector are present
Generally stable in nature	Stability is the major consideration while designing.

**Give the difficulties associated with feed forward system.**

1. In some systems, the disturbance may not be measurable.

2. The feed forward compensation is an open loop technique and if actuator transfer function is not known accurately, then such compensation cannot be achieved.

**1.28 . Mention the basic elements of closed loop system {Madras univ.apr.98}**

Command input, reference transducer, error detector, controller, process to be controlled, feedback element.

**Define laplace transform.**

The laplace transform is defined as

Let  $f(t)$  be a real function of a variable  $t$  defined for  $t > 0$ , then

$$f(s) = L\{F(t)\} = \int_0^{\infty} f(t) e^{-st} dt.$$

### **For what purpose Laplace transform is used in control system?**

The output of any control system, for any input can be obtained by solving integro differential equations. Mathematically it is very difficult to solve such equations in time domain. The Laplace transform of such integro differential equations converts them into simple algebraic equations.

### **What is meant by modeling?**

The process of obtaining the desired mathematical description of the system is known as modeling.

### **Define differential equations.**

The basic models of dynamic physical systems are **differential equations**.

### **List the steps involved in obtaining the transfer function.**

- To write the differential equations governing the system.
- To laplace transform the equations i.e. to replace the terms involving  $d/dt$  by  $s$ , and integral of  $dt$  by  $1/s$ .
- To obtain the ratio of transformed output to the input variables.

### **Give the properties of transfer functions.**

The properties of transfer function are as follows:

- The transfer function of a system is the laplace transform of its impulse response. i.e. if the input to a system with transfer function  $P(s)$  is an impulse and all initial conditions are zero, the transform of the output is  $P(s)$ .
- The roots of the denominator are the system poles and the roots of the numerator are system zeros. The system stability can be described in terms of the location of the roots of the transfer function.

### **Give the advantages of transfer function.**

- It helps in the stability analysis of the system.
- It helps in determining the important information about the system Poles, zeros, characteristic equation etc.
- Once transfer function is known, output response for any type of reference input can be calculated.
- The system differential equation can be easily obtained by replacing variable 's' by  $d/dt$ .

### **Give the disadvantages of transfer function.**

The disadvantages of transfer function approach are:

- Only applicable to linear time invariant systems.
- It does not provide any information concerning the physical structure of the system. From transfer function, physical nature of the system, whether it is electrical, mechanical, thermal or hydraulic cannot be judged.
- Effects arising due to initial conditions are totally neglected. Hence initial conditions loose importance.

### **What is the other name for closed loop control system?**

The other name for closed loop control system is **feedback control system**.

### **Give the important features of feedback.**

- Reduced effects of non-linearities and distortion.
- Increased accuracy.
- Reduced sensitivity of the ratio of the output to input to variations in system characteristics.
- Tendency toward oscillation or instability.

### **What are the basic elements used for modeling mechanical translational system?**

The model of mechanical translational system can be obtained by using three basic elements mass spring and dashpot.

### **What is translational system?**

Consider a mechanical system in which motion is taking place along a straight line. Such systems are of translational type. These systems are characterized by displacement, linear velocity and linear acceleration.

### **Define torque.**

This is the motion about a fixed axis. In such systems, the force gets replaced by a moment about the fixed axis. I.e. {force x distance from fixed axis} which is called torque.

### **Define friction.**

Whenever there is a motion, there exists a friction. Friction may be between moving element and fixed support or between two moving surfaces. Friction is also non-linear in nature.

**Give the types of friction.**

Friction can be divided into three types. They are

- Viscous friction.
- Static friction.
- Coulomb friction.

**Name the two types of electrical analogous for mechanical system.**

The two types of analogies for mechanical system are force-voltage analogy and force-current analogy.

**What are analogous systems?**

Systems whose differential equations are identical form are called analogous systems.

**Give two types of variables in physical system.**

The two variables in physical systems are through variables and across variable. Through variables refer to a point, the across variable is measured between two points.

**Give the other names for force voltage analogy, force current analogy.**

The other names for force voltage analogy and force current analogy are

Force voltage analogy- Loop analysis.

Force current analogy- nodal analysis.

**What is block diagram?**

A block diagram of a system is a pictorial representation of the functions performed by each component of the system and shows the flow of signals.

**What are the basic components of block diagram?**

The basic components of block diagram are block, branch point, summing point, arrows.

The connection between the blocks is shown by lines called **branches**.

The signal can travel along the direction of **arrow** only.

**What is the need for block diagram reduction?**

Block diagrams of some of the control systems turn out to be complex. Such that the evaluation of their performance requires simplification(or reduction) of block diagrams which is carried out by block diagram rearrangements.

**List the advantages of block diagram.**

- Individual as well as overall performance of the system can be studied by using transfer functions shown in the block diagram.

- Overall closed loop transfer function can be easily calculated by using block diagram rules.
- The function of individual elements can be visualized from the block diagram.
- Very simple to construct the block diagram for complicated systems.

**List the disadvantages of block diagram.**

- Source of energy is generally not shown in the block diagram. So block diagram for given system is not unique.
- Block diagram does not include any information about physical construction of the system.
- Block diagram reduction technique is time consuming process for complicated systems(higher order systems).

**List the steps to reduce the block diagram.**

- Reduce the series blocks.
- Reduce the parallel blocks.
- Reduce minor feedback loops.
- 
- As far as possible shift summing point to the left and take-off point to the right.
- Repeat the above steps till canonical form is obtained.

**What is signal flow graph?**

The graphical representation of the variables of a set of linear algebraic equations representing the system is called signal flow graph.

**Give the properties of signal flow graph?**

- The signal in the system flows along the branches and along the arrows associated with the branches.
- The value of variable represented by any node is an algebraic sum of all the signals entering at the node.
- The signals gets multiplied by the branch gain or branch transmittance when it travels along it.
- Applicable only to linear time invariant systems.
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### **What is the need for signal flow graph?**

Block diagrams are very successful for representing control systems, but for complicated systems, the block diagram reduction process is tedious and time consuming. So signal flow graphs are needed which does not require any reduction process because of availability of a flow graph formula, which relates the input and output system variables.

### **What is transmittance?**

The transmittance is the gain acquired by the signal when travels from one node to another node in the signal flow graph.

### **What do you mean by a node in signal flow graph?**

It represents a system variable, which is equal to the sum of all incoming signals at the node, outgoing signals from the node do not affect the value of the node variable.

### **What do you mean by a branch in signal flow graph?**

A signal travels along a branch from one node to another in the direction indicated by the branch arrow and in the process gets multiplied by the gain or transmittance of the branch.

### **Define chain node.**

A node having incoming and outgoing branches is known as chain node.

### **Define self loop.**

A feedback loop consisting of only one node is called self loop.

### **Define Loop gain.**

The product of all the gains of the branches forming a loop is called loop gain.

### **Define forward path.**

A path from the input to output node is defined as forward path.

### **List the advantages and disadvantages of feedback systems.**

- Increased accuracy.
- Reduced sensitivity.
- Reduced effects of non-linearities and distortion.
- Increased bandwidth.
- Tendency towards oscillation or instability.

## **UNIT II – TIME RESPONSE ANALYSIS**

### **What are the standard test signals employed for time domain studies?**

The standard test signals employed for time domain studies are 1. step signal, ramp signal, parabolic signal, impulse signal.

### **What are time domain specifications?**

The time domain specifications are 1. Delay time, 2. Rise time, 3. Peak time, 4. Maximum peak overshoot, 5. settling time.

### **What is the difference between type and order of a system?**

Type number of a system indicates the number of poles at the origin whereas the order of the system indicates the **order** of the differential equation governing the dynamics of a system. (or highest degree of denominator polynomial of the transfer function.

### **Define settling time.**

Settling time is defined as the time taken by the response to reach and stay within a specified tolerance band of its final value.

### **Define peak overshoot.**

It is defined as the difference between the peak value of step response and the steady output.

### **What is time response?**

The time response is the output of a closed loop system as a function of a time. It is denoted by  $c(t)$ . It is given by the inverse Laplace transform of the product of input and transfer function of a system.

### **What is transient response.**

The output variation during the time, it takes to achieve its final value is known as transient response. The time required to achieve the final value is called transient response.

### **What is steady state response?**

It is that part of the time response which remains after complete transient response vanishes from the system output.

### **What is meant by transient period?**

The time required to achieve the final value is called transient period.

The transient response may be **oscillatory or exponential** in nature.

### **Give the expression for total time response $c(t)$ .**

$C(t) = C_{ss}(t) + C_t(t)$  where  $C_{ss}(t)$  = steady state output,  $C_t(t)$  = transient state output.

**Give the mathematical expression for stable operating systems.**

Lt.  $Ct(t) = 0 \text{ t} \alpha \alpha$

**What is meant by stable system?**

To get the desired output, system must pass through transient period. Transient response must vanish after some time to get the final value closer to the desired value. Such systems in which transient response dies out after some time is called stable systems.

**Define steady state error.**

The difference between the desired output and the actual output of the system is called steady state error, which indicates the accuracy and plays an important role in designing the system.

**For what purpose standard test signals are used?**

While analyzing the systems it is highly impossible to each one of it as an study the response. Hence the analysis points of view, those signals, which are most commonly used as reference inputs, are called as standard test signals.

**Define step signal.**

It is the sudden application of the input at a specified time.

Mathematically it can be expressed as

$$R(t) = A \text{ for } t > 0$$

$$R(t) = 0 \text{ for } t < 0.$$

If  $A = 1$ , then it is called unit step function denoted by  $u(t)$

**Define ramp signal.**

It is the constant rate of change in input. I.e. gradual application of the input.

Magnitude of ramp input is nothing but its slope.

Mathematically it can be expressed as

$$R(t) = At \text{ for } t > 0$$

$$R(t) = 0 \text{ for } t < 0.$$

If  $A = 1$ , then it is called unit ramp function.

**Define parabolic signal.**

It is a signal, in which the instantaneous value varies as square of time from an initial value of zero at  $t = 0$ .

Mathematically it can be expressed as

$$R(t) = A t^2 \text{ for } t > 0$$

$R(t) = 0$  for  $t < 0$ .

If  $A = 1$ , then it is called unit parabolic function.

### **What is positional error coefficient?**

Steady state error of the system for a step input is  $1/(1 + K_p)$ . where  $K_p$  is the positional error coefficient. The positional error coefficient is given by

$$K_p = \lim_{s \rightarrow 0} G(s)H(s)$$

### **What is velocity error coefficient?**

Steady state error of the system for a ramp input is  $1/K_v$ . where  $K_v$  is the velocity error coefficient. The velocity error coefficient is given by

$$K_v = \lim_{s \rightarrow 0} sG(s)H(s)$$

### **What is acceleration error coefficient?**

Steady state error of the system for a step input is  $1/K_a$ . where  $K_a$  is the acceleration error coefficient. The acceleration error coefficient is given by

$$K_a = \lim_{s \rightarrow 0} s^2 G(s)H(s)$$

### **How are control systems classified in accordance with the number of integrations in the open loop transfer function?**

Control systems are classified in accordance with the number of integrations in the open-loop transfer function as

- Type - 0 system.
- Type - 1 system.
- Type - 2 system.

### **Why the zeros on the real axis near the origin are generally avoided in design?**

The closer the zero at the origin, the more pronounced is the peaking phenomenon. Hence the zeros on the real axis near the origin are generally avoided in design.

### **State various time domain specifications.**

The time domain specifications are:

- Delay time.
- Rise time.
- Settling time.

- Maximum over shoot.
- Peak time.

### **How the system is classified n the basis of damping?**

Depending on the value of damping, the system is classified into four cases:

- Case 1: Undamped system, (damping ratio = 0)
- Case 2: under damped system (  $0 < \text{damping ratio} < 1$  )
- Case 3: Critically damped system ((damping ratio = 1)
- Case 4: Over damped system (damping ratio  $> 1$ )

An increase in damping ratio increase rise time.

### **When will the concept of Kp, Kv, Ka applicable?**

The concept of Kp, Kv, Ka is applicable only if the system is represented in its simple form, and only when the system is stable.

### **What is meant by type number of the system? What is its significance?**

The type number is given by number of poles of loop transfer function at the origin. The type number of the system decides the steady state error.

### **List the disadvantages of static error coefficients.**

The disadvantages of static error coefficients are:

- Method does not provide variation of error with respect to time, which will be otherwise very useful from design point of view.
- Method cannot give the error if inputs are other than standard inputs.
- Most of the times, method gives mathematical answer of the precise value of the error.
- The method is applicable only to stable system.

### **Define damping ratio.**

The damping ratio is defined as the ratio of actual damping to critical damping.

### **Define damping.**

Every system has the tendency to oppose the oscillatory behavior of the system, which is called damping.

### **Define sensitivity of the control system.**

An effect in the system performance due to parameter variations can be studied mathematically defining the term sensitivity of a control system. The change in a particular variable, due to parameter can be expressed in terms of sensitivity.

**Define natural frequency.**

The frequency of oscillations under damping ratio =0 condition is called natural frequency.

**2.33.What will happen to the stability of the system, if closed loop poles moves in the left half way from imaginary axis?**

As closed loop poles moves in the left half way from imaginary axis in the s-plane, transients die out more quickly, making system more stable.

**2.34.What happens to damping ratio and rise time if bandwidth is increased?**

A large bandwidth corresponds to a small rise time, or fast response. So bandwidth varies inversely proportional to the speed of response. So as bandwidth is increased, the damping ratio and rise time both reduces.

**2.35.A system is critically damped. How will the system behave, if the gain of the system is increased?**

A system is critically damped means, gain is at its marginal value and system closed loop poles are on the imaginary axis. If gain is increased beyond this marginal value, the closed loop poles on the imaginary axis gets shifted in the right half of the s-plane making the system unstable in nature.

**List the advantages of generalized error coefficients.**

- It gives error signal as a function of time.
- It can be used to determine

**What is the order of the system?**

The order of the system is given by the order of the differential equation, governing the system. It is also given by the maximum power of S in the denominator polynomial of the transfer function. The maximum power of S also gives number of poles of the system and so the order of the system is also given by number of poles of the transfer function.

**What is called a proportional plus integral controller?**

In an integral error compensation scheme, the output response depends in some manner upon the integral of the actuating which produces an output signal of two terms, one proportional to the

actuating signal and the other proportional to its integral. Such a controller is called proportional plus integral controller.

**What is called a PID controller?**

To increase the damping factor of the dominant poles of a PI controlled system, it is combined with a derivative error scheme. Such a controller is called a PID controller.

**What is the advantage of PD controller?**

The advantage of PD controller is that as the damping increases due to compensation, with  $\zeta$  remaining fixed, the system settling time reduces.

**What is the effect of PD controller on the system performance?**

The effect of PD controller is to increase the damping ratio of the system and so peak overshoot is reduced.

**What is the effect of PI controller on the system performance?**

The PI controller increases the order of the system by one, which results in reducing the steady state error. But the system becomes less stable than the original system.

**Why derivative controller is not used alone in control systems?**

The derivative controller produces a control action based on the rate of change of error signal, and it does not produce corrective measures for any constant error. Hence derivative controller is not used alone in the control system.

## UNIT –III FREQUENCY RESPONSE ANALYSIS

### **Define cut-off rate.**

The slope of the resultant magnitude curve near the cut-off frequency is called cut-off rate.

### **Define resonant peak(Mr)**

It is the maximum value of magnitude of the closed loop frequency response. Larger the value of the resonant peak, more is the value of the peak overshoot of system for step input. It is a measure of relative stability of the system.

### **Define gain-cross over frequency. ( $\omega_{gc}$ ).**

The frequency at which magnitude of  $G(j\omega)H(j\omega)$  is unity. I.e. 1 is called gain cross over frequency.

### **Define phase-cross over frequency. ( $\omega_{pc}$ ).**

The frequency at which phase angle of  $G(j\omega)H(j\omega)$  is  $-180^\circ$ . is called phase cross over frequency.

### **Define gain margin G.M. in bode plot.**

In root locus gain K is increased, the system stability reduces and for a certain value of K, it becomes marginally stable. (Except first and second order systems). So gain margin is defined as the margin in gain allowable by which gain can be increased till system on the verge of instability.

### **Define phase margin.**

Phase margin is similar to the gain, it is possible to introduce phase lag in the system. I.e. negative angles without affecting magnitude plot of  $G(j\omega)H(j\omega)$ . The amount of additional phase lag, which can be introduced in the system till the system reaches on the verge of instability is called phase margin P.M.

### **How the gain margin and phase margin be improved?**

The easiest way to improve G.M. and P.M. is to reduce the gain. However this increases steady state error and makes the system sluggish. Better methods are available. These methods are adding compensating networks are compensators.

### **Define bandwidth.**

It is defined as the range of frequencies over which the system will respond satisfactorily. It can also be defined as range of frequencies in which the magnitude response is also flat in nature. So it is defined as range of frequencies over the magnitude of closed loop response. I.e

$|c(j\omega)/R(j\omega)|$  does not drop by more than 3db. From its zero frequency value.



**List the advantages of bode plots.**

- Transfer function of system can be obtained from bode plot.
- Data for constructing complicated polar and nyquist plots can be easily obtained from bode plot.
- It indicates how system should be compensated to get desired response.
- Relative stability of system can be studied by calculating G.M. and P.M. from bode plot.

**What is meant by the term corner frequency?**

The frequency at which change of slope from 0 db to  $-20$ db occurs is called corner frequency, denoted by  $\omega_c$

$$\omega_c = (1/T)$$

hence asymptotic i.e. approximate magnitude plot for such factor is 0 db line upto

$$\omega_c = (1/T) \text{ and line of slope } -20 \text{ db /dec. when } \omega > \omega_c \text{ i.e. above } \omega_c = (1/T)$$

**Write short notes on the correlation between the time and frequency response.**

There exist a correlation between time and frequency response of first or second order systems. The frequency domain specifications can be expressed in terms of the time domain, there is a corresponding resonant peak in frequency domain. For higher order systems there is no explicit correlation between time and frequency response. But if there is a pair of dominant complex conjugate poles, then the system can be approximated to second order system and the correlation between time and frequency response can be eliminated.

**What are minimum phase systems?**

The minimum phase systems are systems with minimum phase transfer functions. In minimum phase transfer functions, all poles and zero will lie on the left half of S-plane.

**What is all pass system?**

All pass systems are systems with all pass transfer functions. In some systems, the property of unit magnitude at all frequencies applies to all transfer functions with this property are called all-pass systems. Antisymmetric pole-zero pattern for every pole in the left half of S-plane, there is a zero in the mirror image position with respect to imaginary axis.

**Define non-minimum phase transfer function?**

A transfer function which has one or more zeros in the right half of the S-plane is known as non-minimum phase transfer function.

**Define minimum phase transfer function.**

A transfer function which has least (minimum) phase angle range for a given magnitude curve is called a minimum phase transfer function.

**For a stable system the gain cross over occurs earlier than phase cross over. Justify your answer.**

System is said to be stable when P.M. and G.M. are positive, while system is said to be unstable when both P.M. and G.M. are negative. Now when system is on the verge of instability, i.e. marginally stable in nature, then G.M and P.M. both are zero. This is possible when  $\phi_{gc} = \phi_{pc}$ . This condition  $\phi_{gc} = \phi_{pc}$  is useful to design the marginally stable systems. For P.M. and G.M. are positive i.e. for stable system  $\phi_{gc} < \phi_{pc}$ . While for P.M. and G.M. negative i.e. for unstable system  $\phi_{gc} > \phi_{pc}$ . In some absolutely stable system G.M. may be obtained as  $+$   $\phi$ , while for inherently unstable system G.M. may be obtained as  $-\phi$ ,

**What is meant by frequency response of system?**

The magnitude and phase relationship between the sinusoidal input and the steady state output of a system is termed as the frequency response. In linear time invariant systems, the frequency response is independent of the amplitude and phase of the input signal.

**List the frequency domain methods to find the stability of the system.**

The commonly used frequency domain methods to sketch the frequency response of the systems are

- Bode plot
- Polar plot
- Nyquist plot
- Nichol's chart

**Define an octave.**

The range of frequencies  $\omega_2 = 2\omega_1$  is called an octave.

**What are frequency domain specifications?**

The frequency domain specification indicates the performance of the system in frequency domain. And they are

- (i) Resonant peak
- (ii) Cut-off rate
- (iii) Resonant frequency

(iv) Gain margin

(v) Phase margin

### **What are the advantages of frequency response analysis?**

- Without the knowledge of the transfer function, the frequency response of stable open-loop system can be obtained experimentally.
- For difficult cases, such as conditionally stable systems, nyquist plot is probably the only method to analyze stability.
- Frequency response can be precisely applied to the systems those do not have rational transfer function. I.e. e-TS etc.
- It can be extended to certain non-linear systems.

The apparatus required for obtaining frequency response is simple and inexpensive and easy to use.

### **Give the limitations of frequency response analysis.**

- The methods considered some what “old” and outdated in view of extensive methods developed for digital computer simulation and modelling.
- Obtaining frequency response practically is fairly time consuming.
- For an existing system, obtaining frequency response is possible only if the time constants are upto few minutes.

### **What is bode plot?**

The transfer function is represented as a lograthimic plot which consists of two graphs, one giving the logarithm of  $|G(j\omega)|$  both plotted against frequency in logarithm scale. These plots are called bode plots.

### **Define a decade in bode plot.**

$$20 \log |G(j\omega)| = -20 \log |T|$$

$$= -20 \log \omega - 20 \log T$$

The plot of above equation is straight line with a slope  $-20\text{db}$  per unit change in  $\log \omega$ . A unit change in  $20 \log \omega$  means

$$\text{Log}(\omega_2/\omega_1) = 1$$

Or  $\omega_2 = 10\omega_1$  this range of frequency is called a decade.

### **How static error coefficients can be determined in bode plots?**

The steady state error of a closed loop system depends on the system type and gain. The static error coefficients can be determined by these two characteristics viz. type and gain. For any given log magnitude curve, the system type and gain can be determined

Positional error coefficient is determined by **type 0** system

Velocity error coefficient is determined by **type 1** system

Accelerational error coefficient is determined by **type 2** system.

### **Give the factors of $G(j\omega)$ used in the construction of bode plots.**

The factors of  $G(j\omega)$  used in the construction of bode plot are:

Constant gain  $K$

Poles at the origin

Poles on the real axis

Zero on the real axis

Complex conjugate poles, zeros.

### **What is approximate bode plot?**

In approx. bode plot the magnitude plot of first and second order factors are approximated by two straight lines, which are asymptotes to exact plot. One straight line is at 0db, for the frequency. For the frequency range 0 to  $\omega_c$  and the other straight line is drawn with a slope of 20db/dec for frequency range  $\omega_c$  of  $10^{\infty}$ . Here  $\omega_c$  is corner frequency.

### **What is sensitivity?**

All physical elements have properties that change with environment and age. A good control system should be very sensitive to these parameters variations while being able to follow the command responsively. This is called sensitivity.

### **What is a polar plot?**

The sinusoidal transfer function  $G(j\omega) = \text{Re}[G(j\omega)] + j\text{Im}[G(j\omega)]$

$$G(j\omega) = M \angle \phi \quad G(j\omega) = M \angle \phi$$

From the above equations it is seen that  $G(j\omega)$  may be represented as a phasor of magnitude  $M$  and phase angle  $\phi$ . As the input frequency  $\omega$  is varied from 0 to  $\infty$ , the magnitude  $M$  and phase angle  $\phi$  change and hence the tip of the phasor  $G(j\omega)$  trace a locus in the complex plane. The locus thus obtained is known as polar plot.

### **Discuss relative stability in frequency domain.**

The relative stability indicates the closeness of the system to stable region. It is an indication of the strength or degree of stability of the system .

In frequency domain the relative stability of a system can be studied from Nyquist plot. The relative stability of the system is given by closeness of the polar plot to  $-1+j0$  point, as the polar plot gets closer to  $-1+j0$  point the system move towards instability.

### **Why polar plots are preferred over bode plots?**

A major disadvantage of bode plots is that we have two separate curves showing the variation of the gain and phase shift with frequency. A method of combining these two values in a single plot is referred to as the polar plot. For this purpose only, we prefer polar plots over bode plots. Polar plots are very useful for determining the stability of a closed loop system from its open loop frequency response.

### **Give the advantages of polar plots?**

The polar plot usually requires more computation than bode plot. But it has the advantage of simultaneously providing information about gain as well as phase shift.

### **Define pure delay or transport lag.**

In systems like electrical, mechanical, pneumatic systems, there is a time delay between the application of the input and its effect on the output. This is often called “transport lag” or pure delay”.

### **List the procedure to sketch the polar plot of a given function.**

Let  $G(s)$  be the given transfer function

- Put  $s=j\omega$  in the given transfer function  $G(S)$  to obtain  $G(j\omega)$
- Evaluate  $\angle G(j\omega)$  and  $|G(j\omega)|$
- At  $\omega = 0$  evaluate  $\angle G(j\omega)$  and  $|G(j\omega)|$
- At  $\omega = \infty$  evaluate  $\angle G(j\omega)$  and  $|G(j\omega)|$

With these values of  $\angle G(j\omega)$  and  $|G(j\omega)|$  obtained for different values of  $\omega$ , sketch the polar plot in polar graph paper.

### **What is Nichol's chart?**

N.B Nichols transformed the constant M and N circles to log magnitude and the phase angle coordinates and the resulting chart is known as Nichols chart. The Nichols chart consists of M and N superimposed on ordinary paths.

### **What are the advantages of Nichols chart?**

It is used to find closed loop frequency response from open loop frequency response.

The frequency domain specifications can be determined from Nichols chart.

The gain of the system can be adjusted to satisfy the given specifications.

### **Give the uses of Nichols chart.**

The complete closed loop frequency response can be obtained.

The 3db B.W. of the closed loop system can be obtained.

To design the value of K for the given  $N_r$ .

The frequency  $W_r$  corresponding to the  $N_r$  for the closed loop system can be obtained.

Once  $M_r$  and  $W_r$  are known the various other frequency and time domain specifications can be obtained.

### **How the closed loop frequency response is determined from the open loop frequency response?**

The  $G(j\omega)$  locus or the Nichols plot is sketched on the standard Nichols chart. The meeting point of M contour with  $G(j\omega)$  locus gives the magnitude of the closed loop system and the meeting point with N circle gives the argument or phase of the closed loop system.

### **What are the M and N circles?**

The magnitude, M of the closed loop transfer function section with unity feedback will be in the form of circles in complex plane for each constant value of M. The family of these circles are called M circles.

Let  $N = \tan \alpha$  where  $\alpha$  is the phase of closed loop transfer function with unity feed back. For each constant of N, a circle can be drawn in the complex plane the family of these circles are called N circles.

### **What happens to the damping ratio and rise time if the band width is increased?**

A large BW corresponds to a small rise time or fast response so BW is inversely proportional to the speed of response, so as BW is increased damping ratio and rise time both reduces.

**If the very low frequency asymptote magnitude plot of an unity feedback system has a slope of -40db/decade, find the standard input or inputs it can follow with any steady state errors:** At very low frequency, the magnitude plot slope is -40db/decade i.e. there are two poles at the origin and hence the system is Type 2 system. Type 2 system follows parabolic input with some error but it can follow ramp type standard inputs without any steady state errors.

**For a stable system the gain margin and phase margin should be positive. Justify answer.**

- The gain margin indicates the amount of the gain which can be introduced in the system till system reaches on the verge of instability. Here positive gain margin indicates that such a gain introduction is possible till system becomes unstable i.e. system is basically stable.
- Similarly margin is the amount of the lag which can be introduced till system reaches on the verge of instability so positive phase margin indicates that such a introduction possible and the system is stable. The negative gain margin and the phase margin indicates that there is no chance to introduce gain or phase lag as the system is already unstable.

**What are compensators?**

In control systems design, under certain circumstances it is necessary to introduce some kind of corrective subsystems to force the chosen plant to meet the given specifications. These subsystems are known as compensators and their job is to compensate for the deficiency in the performance of the plant.

**What are the two methods of specifying the performance of control system?**

By a set of specifications in time domain or in frequency domain such as peak overshoot, setting time, gain margin, phase margin, steady state error etc.

By optimality of certain function e.g. en internal function.

**Give the two approaches to the control system design problem.**

There are basically two approaches to the control system design problem:

We select the configuration of the overall system by introducing compensators and then choose the parameters of the compensators to meet the given plant, we find an overall system that meets the given specifications and then compute the necessary compensations.

**What are the two types of compensation techniques write short notes on them?**

- i. Cascade or series compensation.
- ii. Feedback compensation.

In cascade or series, the compensator transfer function is placed in cascade with the plant transfer function.

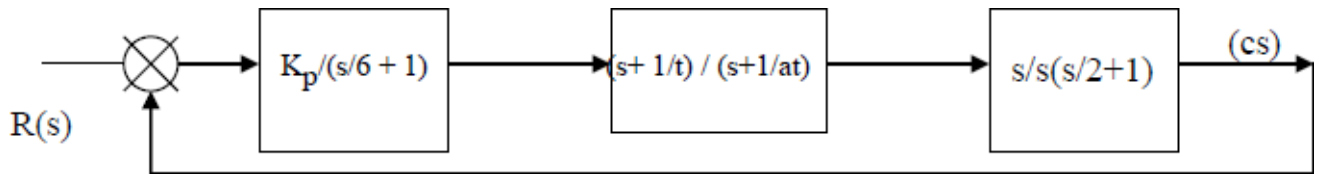
In feedback compensation, the compensator is placed in the feedback path.

**Define Lead compensator.**

$$G_c(s) = (s+Z_c) / (s + P_c) = (s+1/\gamma) / (s+ 1/at), \text{ where } a = Z_c/P_c < 1, t > 0,$$

$a < 1$  ensures that the pole is located to the left of the zero. The compensator having a transfer of the form given above is known as a lead compensator. A lead compensator speeds up the transient response and increases the margin of stability of the system. It also helps to increase the system error constant though to a limited extent.

**Draw the block diagram of the system with lead compensation.**



**What is a lag compensator?**

$$G_c(s) = (s+Z_c) / (s + P_c) \text{ where } b = Z_c/P_c > 1.$$

$b > 1$  ensures that pole is to the right of zero, i.e. Nearer to the origin than zero. The compensator having a transfer function of the form given above is called a lag compensator. A lag compensator improves the steady state behavior of the system while nearly preserving its transient response.

**What is a lag lead compensator?**

When both the transient and steady state response require improvement lag lead compensator is required. This is basically a lag lead compensator connected in series.

**What are the two situations in which compensation is required?**

There are two situations in which compensation is required:

- i. The system is absolutely unstable and the compensation is required to stabilize it as well as to achieve a specified performance.
- ii. The system is stable but the compensation is required to obtain the desired performance.

**What are the different components by which compensators are realized?**

- i. Electrical components
- ii. Mechanical components
- iii. Pneumatic components
- iv. Hydraulic or other components.



**Give the sinusoidal transfer function of the lead compensator.** The

Sinusoidal transfer function of the lead compensator is given by  $G_c(j\omega) = (1+j\omega a) / (1+j\omega b)$ ,  $a < b$

Since  $a < b$  the network output leads the sinusoidal input under steady state and hence the name lead compensator.

**Why lag compensator is called so?**

The sinusoidal transfer function of the lag network is given by  $G_c(j\omega) = (1+j\omega a) / (1+j\omega b)$ , since  $b > a$  the steady state output has a lagging phase angle with respect to sinusoidal input and hence the name lag network.

**List the types of compensation.**

- Series Compensation
- Parallel compensation
- Series-parallel compensation

**What is meant by compensation?**

All the control systems are designed to achieve specific objectives. The certain requirements are defined for the control system. If a system is to be redesigned so as to meet the required specifications, it is necessary to alter the system by adding an external device to it. Such a redesign of a system using an additional device is called compensation.

**What is series compensation?**

The compensator is a physical device whose transfer function is denoted as  $G_c(s)$ . If the compensator is placed in series with the forward path transfer function of the plant, the scheme is called series compensation.

**What is parallel compensation?**

In some cases, the feedback is taken from some internal element and compensator is introduced in such a feedback path to provide an additional feedback loop. Such compensation is called feedback or parallel compensation.

**What is series-parallel compensation?**

In some cases, it is necessary to provide both types of compensation, series as well as feedback. Such a scheme is called series-parallel compensation.

### **What are compensating networks?**

The compensator is a physical device. It may be an electrical network, mechanical unit, pneumatic, hydraulic or combinations of various types. The commonly used electrical compensating networks are

- Lead network or Lead compensator
- Lag network or Lag compensator
- Lag-Lead network or Lag-Lead compensator.

### **What are the observations that are made from the Bode's plot of the lag compensated system?**

The cross over frequency is reduced. The high frequency end of the lag-magnitude plot has been raised up by a dB gain of  $20\log(1/a)$ .

**What is the effect of lead compensator and lag compensator on system bandwidth?** Lead compensator increases the system bandwidth whereas Lag compensator reduces the system bandwidth.

### **Distinguish between lead compensator and lag compensator.**

Lead compensator    Lag compensator

1. Increases system bandwidth    Reduces system bandwidth
2. Increases speed of response    slows down speed of response

### **What are the forms in which frequency domain specification are given in cascade compensation?**

- Phase margin  $\Phi_{pm}$  or resonant peak  $M_r$  – indicative of relative stability.
- Bandwidth  $\omega_0$  or resonant frequency  $\omega_r$  - indicative of rise time and settling time.
- Error constant – indicative of steady state error.

### **How is the cascade compensation carried out in frequency domain?**

The frequency domain compensation may be carried out using Nyquist plots, Bode plots or Nichol's chart. The advantages of the Bode plots are that they are easier to draw and modify.

### **Give the effects of Lead compensation.**

- The lead compensator adds dominant zero and a pole. This increases the damping of the closed loop system.

- It improves the phase margin of the closed loop system.
- The steady state error does not get affected.
- It increases bandwidth of the closed loop system. More the bandwidth the faster is the response.
- The increased damping means less rise time and less settling time. Thus there is improvement in the transient response.

**Give the effects and limitations of lag compensator.**

- Lag compensator allows high gain at low frequencies, thus it is basically a low pass filter. Hence it improves steady state performance.

**Explain how the lead compensation is done using Bode plots.**

The lead compensation on Bode's plot proceeds by adjusting the system error constant to the desired value. The phase margin of the uncompensated system is then checked, if found satisfactory, the lead compensation is designed to meet the specified phase margin.

**What are the observations that are made from the Bode plots of the lag compensated system?**

**1.** The phase cross over frequency is reduced. **2.** The high frequency end of the log-magnitude plot has been raised up by a dB-gain of  $20\log(1/a)$ .

## UNIT-IV STABILITY ANALYSIS

### **Define parameter variations.**

The parameters of any control system cannot be constant through its entire life. There are always changes in the parameters due to environmental changes and other disturbances. These changes are called parameter variations.

### **Define sensitivity of a control system.**

An effect in the system performance due to parameter variations can be studied mathematically defining the term sensitivity of a control system. The change in particular variable due to parameter can be expressed in terms of sensitivity.

### **State Routh's criterion for stability.**

**Routh's criterion** states that, the necessary and sufficient condition for the stability is that, all the elements in the first column of the **Routh's array** be positive. If the condition is not met, the system is unstable, and the number of sign changes in the elements of the first column of **Routh's array** corresponds to the number of roots of characteristic equation in the right half of the S-plane.

### **What are the conditions for a linear time invariant system to be stable?**

A linear time- invariant system is stable if the following two notions of system stability are satisfied.

1. When the system is by a bounded input, the output is bounded.
2. In the absence of the input, the output tends towards zero irrespective of initial conditions.

**4.5. What do you mean by asymptotic stability?** In the absence of the input, the output tends towards zero (the equilibrium state of the systems) irrespective of initial conditions. This stability is known as asymptotic stability.

### **How the system is classified based on stability?**

Based on the stability, the system can be classified as

Absolute stable system.  Conditionally stable system.  Unstable system.

Marginally stable or critically stable system.

**Define BIBO stability.**

A linear relaxed system is said to have BIBO stability if every bounded (finite) input results in a bounded (finite) output.

**What is meant by unstable system?**

A linear time invariant system is said to be unstable if

- The system produces unbounded output for a bounded input.
- In absence of the input, output may not be returning to zero.

**What is meant by critically or marginally stable system?**

A linear time invariant system is said to be critically or marginally stable, if for a bounded input, its output oscillates with constant frequency and amplitude. Such oscillations of output are called undamped oscillations or sustained oscillations.

**What is the necessary condition for stability?**

The necessary condition for the stability is that all the co-efficient of the characteristic polynomial be positive.

**State the requirement for BIBO stability.**

The requirement for BIBO stability is that

$$\int m(\tau) d\tau < \alpha$$

Where  $m(\tau)$  is the impulse response of the system.

**State Hurwitz criterion.**

The necessary and sufficient conditions to have all roots of the characteristic equation in left half of the s-plane is that, the sub-determinants  $D_k$ ,  $k = 1, 2, \dots, m$  obtained from Hurwitz's determinant must be positive.

**Define absolute stable.**

Absolutely stable with respect to a parameter of the system, if it is stable for all values of this parameter.

**What do you mean by relative stability?**

Relative stability is a quantitative of how fast the transients die out in the system. If it is stable for all values of this parameter.

**What does the positive ness of the coefficients of characteristic equation indicate?**

- The positive ness of the coefficients of characteristic equation is necessary as well as sufficient condition for stability of system of first and second order.
- The positive ness of the coefficients of the characteristic equation ensures the negative ness of the real parts of the complex roots for third and higher order systems.

**State the conditions under which the coefficients can be zero or negative.**

- One or more roots have positive real parts.
- A root (or roots) at origin i.e.  $S_K = 0$  and hence  $a_n = 0$ .
- $S_l = 0$  for some  $l$ , which implies the presence of roots on the  $j\omega$  axis.

**How the roots of characteristic equation are related to stability?**

If the roots of characteristic equation has positive real part then the impulse response of the system is not bounded (the impulse response will be finite as  $t$  tends to infinity.) hence the system will be unstable. If the roots have negative real parts then impulse response is bounded. ( the impulse response becomes zero as  $t$  tends to infinity). Hence the system will be stable.

**What is the relation between stability and coefficient of characteristic polynomial?**

If the coefficients of characteristic polynomial are negative or zero, then some of the roots lie on the right half of the  $S$ -plane. Hence the system is unstable. If the coefficients  $k$  of characteristic polynomial are positive and if no coefficient is zero, then there is a possibility of the system to be stable, provided all the roots are lying on left half of  $S$ -plane.

**What will be the nature of impulse response when the roots of characteristic equation are lying on imaginary axis?**

If the roots of characteristic equation lie on imaginary axis, then the impulse response is oscillatory.

**What will be the nature of impulse response when the roots of characteristic equation are lying on right half of the  $S$ -plane?**

When the roots are lying on the real axis, i.e on the right half of the  $S$ -plane, the response is exponentially increasing. When the roots are complex conjugate and lying on the right half of the  $S$ -plane, the response is oscillatory with exponentially increasing amplitude.

### **What is ROUTH stability criterion?**

ROUTH stability criterion states that, the necessary and sufficient condition for stability is that all of the elements in the first column of the Routh's array be positive. If this condition is not met, then the system is unstable, and the number of sign changes in the elements of the first column corresponds to the number of roots of characteristic equation in the right half of the S-plane.

### **What is auxiliary polynomial?**

In the construction of the Routh array, a row of all zero indicates the existence of an even polynomial as a factor of the given characteristic equation. In an even polynomial, the coefficients of auxiliary polynomial are given by the elements of the row just above the row of all zeros.

### **What is quadrantal symmetry?**

The symmetry of roots with respect to both real and imaginary axis is called quadrantal symmetry.

### **Give an application of Routh Stability criterion,**

The Routh Stability criterion is frequently used for the determination of the condition of stability of linear feedback control systems.

### **The Routh-Hurwitz criteria gives absolute stability. Justify your answer.**

Basically Routh-Hurwitz is a time domain method. It only gives the indication about the locations of the roots of the characteristic equation in the S-plane. It does not give the information about the actual locations and the types of roots. As the actual locations of the roots are unknown, it is impossible to calculate the parameters required for the prediction of the relative stability. I.e. gain margin, phase margin etc.

### **The addition of a pole will make a system more stable. Justify your answer.**

This is a false statement. When the pole is added to the system, it drives the root locus towards the imaginary axis, they become dominant and hence the relative stability of the system decreases. It makes the system more oscillatory. So addition of pole makes the system unstable and not stable.

### **What do you mean by root locus technique?**

Root locus technique provides a graphical method of plotting the locus of the roots in the S-plane as a given system parameter is varied over the complete range of values (may be from zero to infinity). The roots corresponding to a particular value of the system parameter can then be located on the locus or the value of the parameter for a desired root location can be determined from the locus.

**In the routh array what conclusion you can make when there is a row of all zeros?**

All zero row in routh array indicates the existence of an even polynomial as a factor of the given characteristic equation. The even polynomial may have roots on imaginary axis.

**What is limitedly stable system?**

For a bounded input signal, if the output has constant amplitude oscillations, then the system may be stable or unstable, under some limited constraints. Such a system is called limitedly stable system.

**How will you find the root locus on real axis?**

To find the root locus on real axis, choose a test point on the real axis. If the total number of poles and zeros on the real axis to the right of this test point is odd number, then the test point lies on the root locus. If it is even number means, then the test point does not lie on the root locus.

**The root locus gives the bird's eye view of the stability of the systems. Justify your answer.**

The above statement is false. The root locus gives the locus of the characteristic equation as gain  $K$  is varied from zero to infinity. So from root locus we can get the exact locations of roots for any value of  $k$ . Similarly for any value of  $K$ , the nature of the roots were real complex conjugates can be predicted. From this we get the idea about transient response nature of the system, including the settling time of the system. It can give range of values of  $K$  for which system remains stable. Thus root locus gives total information about the stability of the system. Hence it is said that root locus gives inside analysis of the stability and not the birds eye view of the stability.

**Whether root locus gives the idea about the steady state error?**

The root locus gives the information about the nature of the roots of the characteristic equation. So from it, root locus gives the idea about the overall stability of the system and the nature of the transient response. But it cannot give idea about the steady state errors. The steady state error depends partly on the system gain  $K$ , hence we may say that root locus gives the partly information about steady state errors.

**What is centroid? How the centroid is calculated?**

The meeting point of asymptotes with real axis is called centroid. The centroid is given by

Centroid ( $\sigma$ ) = sum of real parts of poles – sum of real parts of zeros



P-Z

Where P= number of poles

Z = number of zeros.

**The roots of characteristic equation will be real and equal for a system. Justify your answer.**

The above statement is false, because the underdamped system is the one having exponential decaying. It oscillates with decreasing amplitude and settles down. For the real and equal roots, the response is exponential but fast and without any oscillations. It is called critically damped. So real and equal roots does not represent underdamped system.

**The root locus gives the idea about the transient response of the system. Justify your answer.**

The root locus is the locus of the roots of the characteristic equation as K (gain) varies from 0 to infinity. The transient response is totally dependent on the nature of the roots of the characteristic equation, real -negative roots give exponentially decaying. Real- positive roots gives exponentially increasing., complex with negative real parts give decaying oscillatory transient response. The information about nature of roots is provided by root locus. Hence it gives idea about the transient response of the system.

**A system having repeated roots of characteristic equation on imaginary axis is stable. State true or false.**

**Answer: False.**

Because when there are repeated roots on the imaginary axis, the output contains a term like  $t e^{-at}$  and  $t$  tends to  $\infty$ , such term makes the system output uncontrollable. Hence such system is unstable.

**What are asymptotes? Give the formula to calculate the angle of asymptotes.** Asymptotes are straight lines, which are parallel to root locus going to infinity and meet the root locus at infinity.

Angle of asymptotes =  $+(2q+1) 180^\circ$  where P- no. of poles, Z- no. of zeros

P-Z.

**What are breakaway points?**

Points at which multiple roots of the characteristic equation occur are called breakaway points. A breakaway point may involve two or more than two branches.

**State the rule for obtaining breakaway point.**

- Construct the characteristic equation  $1 + G(s)H(s) = 0$  of the system.
- From this equation, separate the terms involving K and terms involving S. Write the value of K in terms of S. i.e.  $K = f(s)$
- Differentiate the above equation with respect to S. equate it to zero. I.e.  $dK/ds = 0$ .
- Roots of the equation  $dK/ds = 0$  gives us the breakaway points.

**How do you find the crossing point of root locus in imaginary axis?**

Method (i) by routh hurwitz criterion.

Method (ii) By letting  $S = j\omega$ . In the characteristic equation and separate the real and imaginary part. These two equations are equated to zero. Solve the two equations for  $\omega$  and K. the value of  $\omega$  gives the point where the root locus crosses the imaginary axis and the value of K is the gain corresponding to the crossing point.

If a system is having complex conjugate with positive real point, then the system is said to be **unstable**.

If a system is having complex conjugate with negative real point, then the system is said to be **absolute stable**.

**Give the formula for finding angle of departure at complex pole.**

$$\phi_d = 180^\circ - \phi_p$$

where  $\phi_p = \sum \phi_p - \sum \phi_z$

$\sum \phi_p$  = contributions by the angles made by remaining poles at the pole at which  $\phi_d$  is to be calculated.

$\sum \phi_z$  = contributions by the angles made by remaining zeros at the pole at which  $\phi_d$  is to be calculated.

**Give the formula for finding angle of arrival at complex pole.**

$$\phi_a = 180^\circ + \phi_p$$

where  $\phi_p = \sum \phi_p - \sum \phi_z$

**What is magnitude criterion of root locus?**

The magnitude condition states that  $S = S_a$ , will be a point on the root locus, if for that value of S, magnitude of  $G(s)H(s)$  is equal to 1 (i.e.  $|G(s)H(s)| = 1$ .)

$$\text{Let } G(s)H(s) = K (S+Z1)(S+Z2) (S+Z3) \dots\dots\dots$$

$(S+P1)(S+P2)(S+P3)\dots$

for  $S = S_a$  be point in root locus.

$G(s)H(s) = K \frac{(S+Z1)(S+Z2)(S+Z3)\dots}{(S+P1)(S+P2)(S+P3)\dots}$

$K = \frac{\text{product of length of vectors from open loop zero to the point } S_a}{\text{product of length of vectors from open loop poles to the point } S_a}$

### **What is angle criterion of root locus?**

The angle criterion of root locus states that  $S = S_a$  will be a point on root locus if for that value of  $S$ , the argument or phase of  $G(S)H(S)$  is equal to an odd multiple of  $180^\circ$

### **What is dominant pole?**

The dominant pole is a pair of complex conjugate pole which decides transient response of the system. In higher order systems, the dominant poles are very close to origin and all other poles of the system are widely separated and so they have less effect on transient response of the system.

### **How will you find the gain K at a point on the root locus?**

The gain  $K$  at a point  $S = S_a$  on root locus is given by

$K = \frac{\text{product of length of vectors from open loop zero to the point } S_a}{\text{product of length of vectors from open loop poles to the point } S_a}$

### **Give the effect of addition of poles on the root locus.**

- Root locus shift towards imaginary axis.
- System stability relatively decreases.
- System becomes more oscillatory in nature.
- Range of operating value of  $K$  for system stability decreases.

### **Give the effect of addition of zero on the root locus.**

- Root locus shift to left away from imaginary axis.
- Relative stability of the system increases.
- System becomes less oscillatory in nature.
- Range of operating value of  $K$  for system stability increases.

### **State the advantages of root locus method.**

- Root locus analysis helps in deciding the stability of the control systems with time delay.
- Information about settling time of the system also can be determined from the root locus.

□ The absolute stability of the system can be predicted from the location of the roots in the S-plane.

**Define gain margin in Nyquist plot.**

Gain margin is the amount of gain in decibels(db) that is allowed to be increased in the loop before the closed loop system reaches stability.

**Define phase margin in Nyquist plot.**

Phase margin may be defined as the angle in degrees through which the  $G(j\omega)H(j\omega)$  plot must rotate about origin in order that the gain cross over point on the locus passes through the point  $(-1+j0)$

**What are the observations that are made from the polar plot?**

- Addition of a pole at the origin to a transfer function rotates the polar plot at zero and infinite frequencies by a further angle of  $-90^\circ$
- Addition of a non zero pole to a transfer function results in further rotation of the polar plot through angle of  $-90^\circ$  as  $\omega \rightarrow \infty$

**On what theorem the Nyquist stability criterion is based on?**

The Nyquist stability criterion is based on Cauchy's residue theorem of complex variables which is referred to as the principle of argument.

**State the principle of argument.**

The principle of argument can be stated as follows:

Let  $G(s)$  be a single valued function that has finite poles in the S-plane. Suppose that an arbitrary closed path  $T_a$  is chosen in the S-plane so that the path does not go through any one of the poles or the zeros of  $Q(s)$ ; the corresponding locus mapped in the  $Q(s)$  plane will encircle the origin as many times as the difference between the number of the zeros and the number of poles of  $Q(s)$  that are encircled by the S-plane locus  $T_a$ .

**Discuss Nyquist stability criterion.**

Nyquist has used the mapping theorem or the principle of argument effectively to develop a criterion to study the stability of control system in the frequency domain. He has suggested to select a single valued function  $F(s)$  as  $1+G(s)H(s)$ , where  $G(s)H(s)$  is open loop transfer function of the system.  $F(s) = 1+G(s)H(s)$

Poles of  $1+G(s)H(s) =$  poles of  $G(s)H(s) =$  open loops poles.

They are known to us, but the zeros of  $1+G(s)H(s)$  are unknown to us

For stability all the zeros of  $1+G(s)H(s)$  must be in left half of s-plane. Instead of analyzing whether all the zeros are located in the left half of the s-plane, it is better to the presence of any one zero of  $1+G(s)H(s)$  in the right half of the s-plane making system unstable.

So Nyquist has suggested to select a  $T(s)$  path which will encircle the entire half of the s-plane.

This path is called Nyquist path and should not be changed except small modifications.

**List the steps to solve problems by Nyquist criterion.**

Step1: count how many no. of poles of  $G(s)H(s)$  are in the right half of the s-plane i.e, with the positive real part. This is the value of p.

Step2: Decide the stability criterion as  $N= (-P)$  i.e., how many times Nyquist plot should encircle  $-1+j0$  point for absolute stability.

Step3: select Nyquist path as per the function  $G(s)H(s)$ .

Step4: Analyse the sections as starting point and terminating point. Last section analysis not required.

Step5: Mathematically find out  $W_{pc}$  and the intersection of Nyquist plot with negative real axis by rationalizing  $G(j\omega)H(j\omega)$ .

Step6: With the number of encirclements  $N$  of  $-1+j0$  by Nyquist plot. If this matches with the criterion decided in step 2 system is stable, otherwise the system is unstable.

**List the advantages of Nyquist plot.**

It gives same information about absolute stability as provided by rouths criterion.

Useful for determining the stability of the closed loop system from open loop transfer function without knowing the roots of characteristic equation.

Information regarding frequency response can be obtained.

Very useful for analyzing conditionally stable systems.

It also indicates relative stability giving the values of G.M. and P.M.

**Define phase cross over frequency in nyquist plot.**

The phase cross over frequency  $\omega_{pc}$  is the frequency at which phase cross over point or where  $\angle G(j\omega)H(j\omega) = 180^\circ$

**Define phase cross over point in nyquist plot.**

It is the point in the  $G(j\omega)$  plane at which the nyquist plot  $G(j\omega)H(j\omega)$  intersects the negative real axis.

## UNIT-V

### STATE VARIABLE ANALYSIS AND DIGITAL CONTROL SYSTEM

#### **What is state?**

The state of dynamic system is defined as a minimal set of variables such that the knowledge of these variables at  $t = t_0$  together with the knowledge of inputs  $t > 0$  completely determine the behavior of the system for  $t > t_0$ .

#### **What is state variable?**

The variables involved in determining the state of dynamic system are called state variables. Generally  $x_1(t), x_2(t), x_3(t), \dots, x_n(t)$  are called state variables.

#### **What is state vector?**

The state vector  $x(t)$  is the vector sum of all the state variables.

#### **What is state space?**

The space whose coordinate axes are nothing but the 'n' state variables with time as the implicit variable is called state space.

#### **What is controllability?**

A general nth order multi-input linear time invariant system

.

$\dot{X} = AX + Bu$ . Is completely controllable if and only if the rank of the composite matrix  $Q_c = [B:AB:A^2B:\dots:A^{n-1}B]$  is n

#### **What is observability?**

A general nth order multi-input multiple output linear time invariant system

.

$\dot{X} = AX + Bu$ .

$Y = CX$  is completely observable

if rank of the composite matrix  $Q_o = [C:ATCT:\dots:(AT)^{n-1}C]$  is n

#### **What is the condition to be satisfied for a sampled data system to be stable?**

The poles of the pulse transfer function  $H(z)$  must lie inside z-plane unit circle.

#### **What is the characteristic equation of a sampled data system?**

The denominator polynomial of a closed loop pulse transfer function  $H(z)$  is known as the characteristic equation.

**List the methods used to test the stability of discrete time system.**

- Jury’s stability test.
- Bilinear transformation.
- Root locus technique.

**Define sampled data system.**

In a control system, if the signals in any part/point of the system is discrete ( digital or sampled) then the entire system is said to be sampled data system.

**When a control system can be called as sampled data control system?**

Any control system can be called as sampled data control system, when ever,

- A digital system (computer/ microprocessor/microcontroller) becomes part of control system.
- Control components are on the time sharing mode.
- Control signals are discrete or digital signals.

**Distinguish between sampled data systems and continuous-time systems.**

Control system components of sampled data control system are able to handle discrete (digital) signals. On the other hand, continuous time system components can handle analog signals. Similarly output signals of sampled data system components are discrete (digital) signals.

**5.13 List the advantages and disadvantages of sampled data control system.**

Advantages	Disadvantages
Accuracy increased while compared with analog system	Digital conversion and reconstruction may introduce noise.
Speed increased and flexibility improved.	Improper selection of sampling period may leads to instability.
Digital transducers have better resolution.	
Highly immune to noise.	
Linearizable becomes simple.	
Free from transmission noise.	
Complex algorithms can easily be implemented.	

**What are sampling and sampler?**

Sampling of a signal is a process by which analog signals are sampled at predetermined intervals to convert into discrete time signals. The device used to perform sampling is called sampler.

**What is periodic sampling?**

Sampling of a signal at uniform equal intervals is called periodic sampling. The uniform equal interval  $T$  is called period.

**What is quantization?**

The process of approximating a discrete time continuous valued signal into a discrete valued signal is called quantization. If the sampled analog value lies in between two digital adjacent values then the sampled analog value will be represented by a digital value which is nearer to the analog value than the other. This process of approximation is called quantization.

**What is coding?**

Representation of sampled data by  $n$  bit binary number is called coding.

**What is hold circuit?**

A device used to convert digital signal into analog signal.

**What is zero-order hold?**

It is a hold circuit. The output of the hold circuit is analog signal whose magnitude equal to latest sampled value till next sample occurs.

**What is first order hold?**

The output of the first order hold is constructed from latest two samples (current and previous samples). The slope of the output signal is determined by this current and previous sample.

**What is acquisition time?**

Time taken by an analog to digital converter to sample the signal, to quantize it and to code it is known as acquisition time.

**Define aperture time.**

It is the duration of sampling of analog signal.

**What is settling time?**

It is the time taken by a digital to analog converter to convert the given digital signal into analog signal magnitude and be remain within the tolerance is called settling time.



### **What is hold mode droop?**

There is no droop in an ideal hold circuit. The change in signal magnitude during hold mode of a hold circuit is called hold mode droop.

### **What are the problems that may occur in a practical hold circuit?**

- Hold mode droop may occur.
- Nonlinear variation during sampling aperture.
- Error in the periodicity of sampling.

### **How the high frequency noise in the output hold circuits can be filtered?**

The control system components act as low pass filter. Hence the high frequency signals are automatically filtered.

### **What is discrete signal sequence $f(k)$ ?**

A discrete signal sequence or discrete time signal  $f(k)$  is function of independent variable  $k$  is an integer.

### **What is impulse response?**

The output (response) of a system when the input is impulse signal is known as impulse response.

### **What is weighting sequence?**

The impulse response of a linear discrete time system is called weighting sequence.

### **What is pulse transfer function?**

It is the mathematical model of discrete time system. It is the impulse response of the system represented in the  $z$ -domain. It is also defined as the ratio of  $z$ -transform of output signal to the  $z$ -transform of input signal of the system.

### **What is pulse transfer function?**

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Pulse transfer function  $H(z) = C(z)/R(z)$ .

Where  $C(z)$  is  $z$ -transform of output signal.

$R(z)$  is  $z$ -transform of input signal.