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Positioning Control of Drilling Tool Device for High Speed Performance

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Abstract: **Presently, there are good positioning systems for drilling tools but the challenging problem is that accuracy of positioning drops as the speed of operation of the system is increased. This paper obtained the dynamical model of the drilling tool positioning system. To improve positioning accuracy, a lead phase digital compensator was designed and added to the original plant or process to improve the transient response of the system in other to achieve a settling time of less than 12 seconds. The compensator parameters were obtained using MATLAB tuning tool and the entire design accomplished with the time domain analysis method. A digital controller with maximum overshoot less than 29%, a rise time of 1.59 seconds with a 2% criterion and a settling time of 8.8 seconds was obtained.**

Keywords: **positioning system, machine tools system, transfer function, digital compensator, and response.**

1. INTRODUCTION

Control of machine tools is a relatively new field that started in the early 1950s with the invention of the Numerically Controlled (NC) machine tool by John Parsons in Traverse City, MI, with subcontract to the MIT Servomechanism Laboratory [6].The major advance in NC occurred in the early 1970's with the introduction of Computer Numerical Control (CNC) in which a dedicated computer replaced most of the digital hardware control boards of the NC. Approximately at the same time, a few companies (e.g., Bendix [7]) started to develop adaptive control (AC) systems for machine tools. One of the early CNC/AC machines, developed by J. Tlusty and Y. Koren in 1973 [8], utilized an HP-2100 computer as the controller that runs both the conventional CNC and the AC programs.

Position control is needed in numerical control of machine tools. It is possible to programme a machine tool so that it will automatically drill a number of holes. Numerical control systems can be classified as position control (point-to-point [9]) or continuous contour. For example drilling, boring and tapping machine etc, require position control while machine tools including milling, routing machines etc, require continuous contour.

In this paper, a controller D(z) was designed to meet certain specifications for a numerically control machine that will automatically drill a number of holes. One of the techniques for designing a controller is the use of the Root Locus; and it has been used here to design the controller.

2. MACHINE TOOL SYSTEM ANALYSIS AND MODEL

Machine tools can be controlled automatically by the instruction recorded on punched cards or tapes. A schematic diagram of a typical position control machine tool system required to automatically drill a number of holes is shown in Figure 1.0. A feedback loop is introduced in the D/A (digital-to-analog) converter to obtain a more accurate conversion [2]. Given that the motor gain, k_m is 1 and the motor time constant, τ_m is 10 (obtainable from the process dynamic of a machine-tool system in [5]).

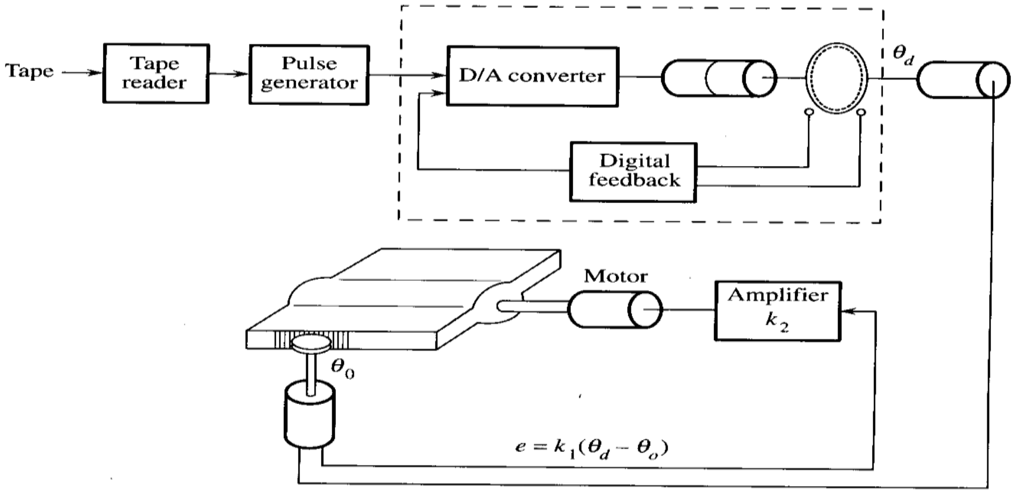

Fig: 1. Position Control Machine Tool System[2]

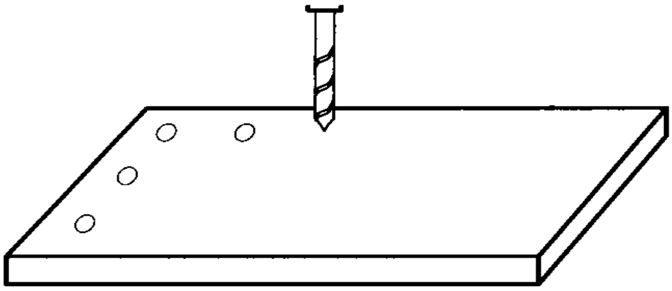

Fig: 2. Sample of number of holes drilled [2]

Given that the input voltage is applied to the armature circuit, an armature –controlled d.c. motor. Transfer functions are developed assuming the field current $i_f(t)$ is constant [3].

$$T(t) = k_t i_a(t) \qquad (1)$$

where $$T(t) = J\frac{d^2\theta_0(t)}{dt^2} + f\frac{d\theta_0(t)}{dt} \qquad (2)$$

T(t) is the torque, k_t is a constant.

When the motor is driving a load, a back e.m.f voltage v_b will be developed in the armature circuit to resist the applied voltage. The voltage $v_b(t)$ is linearly proportional to the angular velocity of the motor shaft:

$$v_b = k_b\frac{d\theta_0(t)}{dt} \qquad (3)$$

Thus the armature circuit can be described by

$$R_a i_a(t) + L_a\frac{di_a(t)}{dt} + v_b(t) = v_a(t) = u(t) \qquad (4)$$

$$\text{or } R_a i_a(t) + L_a\frac{di_a(t)}{dt} + k_b\frac{d\theta_0(t)}{dt} = u(t) \qquad (5)$$

Using (3), (4) and (5), a transfer function for the motor is developed. The substitution of (1) into (2) and the application of Laplace transform to (2) and (5) yield, assuming zero initial conditions.

$$k_t I_a(s) = Js^2\theta_0(s) + fs\theta_0(s) \qquad (6)$$

$$R_a I_a(s) + L_a s I_a(s) + k_b s\theta_0(s) = U(s) \qquad (7)$$

The elimination of I_a from these two equations yields

$$G(s) = \frac{\theta_0(s)}{U(S)} = \frac{k_t}{s[(Js+f)(R_a+L_a s)+k_t k_b]} \quad (8)$$

This is the transfer function from v_a=u to θ_0 of the armature controlled d.c.

Assuming the armature inductance L_a is set to zero as it is often done in application (i.e. the armature circuit inductance L_a is usually negligible [4]). In this case (8) reduces to

$$G(s) = \frac{\theta_0(s)}{U(S)} = \frac{k_t}{s(JR_a s+k_t k_b+fR_a)} = \frac{k_m}{s(\tau_m s+1)} \quad (9)$$

where $k_m = \frac{k_t}{k_t k_b+R_a}$, the motor gain (10)

and $\tau_m = \frac{JR_a}{k_t k_b+fR_a}$, the motor time constant. (11)

The time constant depends on the load as well as the armature. Equations (8) and (9) give the motor transfer function, which is also the transfer function of motor and load. The block diagram of the machine tool is shown in Figure 3

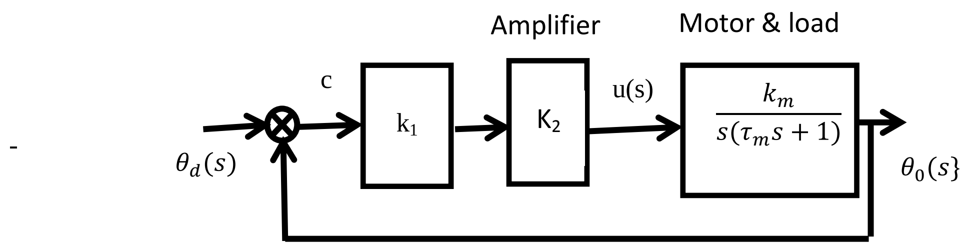

Fig: 3. Block Diagram of the Machine Tool

Where k_1 is the system gain and k_2 is the amplifier gain; $k_1 = k_2 = 1$

Substituting the values of k_m and τ_m into (9) yields

$$G(s) = \frac{1}{s(10s+1)} = \frac{0.1}{s(s+0.1)} \quad (12)$$

3. PROBLEM FORMULATION

The machine-tool system has the form shown in Fig.3 with [1]

$$G_p(s) = \frac{0.1}{s(s+0.1)}$$

The sampling rate is chosen as $T = 1s$. We desire the step response to have an overshoot of 29% or less and a settling time (with a 2% criterion) of 12seconds or less. Design a $D(z)$ to achieve these specifications.

3.1. Solution:

To configure the system, the block diagram model in Figure 4 is use to describe it. Initially, a continuous system is used to design $G_c(s)$ and then proceeds to obtain $D(z)$ from $G_c(s)$.

The next step is to introduce a lead compensator, so that $G_c(s) = K\frac{(S+a)}{S+b}$ (13)

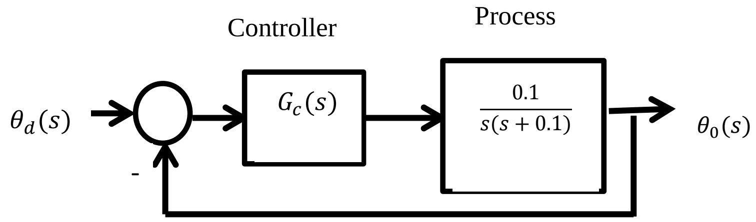

Fig.4. Model of the machine tool control for a machining process.

The control objective is to design a digital .

The control objective is to design a digital compensator, $D(z)$, so that the machine-tool process dynamic meets the stated specifications while achieving a proper positioning of the cutting tool on a work-piece.

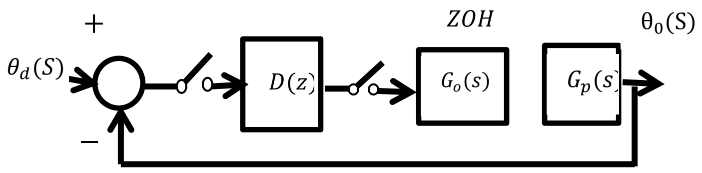

Fig. 5. Block diagram model with the D(z)

The controlled variable is $\theta_0(s)$

The design specifications are as follows:

Design Specifications

- Percent Overshoot, P.O. $\leq$ 29%; where P.O. is represented as M_p and it is chosen as 16%
- Settling time (with a 2% criterion),$T_s \leq 12s$

To obtain the damping ratio for the system,ζ, we use the Equation

$$e^{-\pi\zeta/\sqrt{1-\zeta^2}=M_p} \quad (14)$$

$$e^{-\pi\zeta/\sqrt{1-\zeta^2}=0.16}$$

$$-\frac{\pi\zeta}{\sqrt{1-\zeta^2}} = In0.16 \quad (15)$$

Solving Equation (15), yields $\zeta = 0.503$

$$T_s = \frac{4}{\zeta\omega_n} = 12s \quad (16)$$

Solving Equation (16), yields

$\zeta\omega_n = 0.33;\ \omega_n = 0.66$

$\omega_n\sqrt{1-\zeta^2} = 0.66\sqrt{1-0.503^2} = 0.66 \times 0.864 = 0.57$

The zero of the compensator is placed directly below the desired root location at $s = -z = -0.33$. The desired dominant root location is chosen as $r_1, \hat{r}_1 = -0.33 \pm j0.57$

The analytical method of obtaining the corresponding pole for the compensator is time consuming, as such MATLAB was used. By graphical tuning of the root locus, pole s =-3.66, and loop gain, K =20.3, an appreciable controller that meet the design specification was obtain.

The controller, $G_c(s) = \frac{20.3(s+0.33)}{S+3.66}$ (17)

The root locus plot for the uncompensated system and the step response are shown in Fig. 6 and 7. The close loop transfer function,

$$G(s) = \frac{G_p(s)}{1+G_P(s)H(s)} = \frac{0.1}{s^2+0.1s+0.1} \quad (18)$$

And the characteristic equation,

$$q = s^2 + 0.1s + 0.1 \quad (19)$$

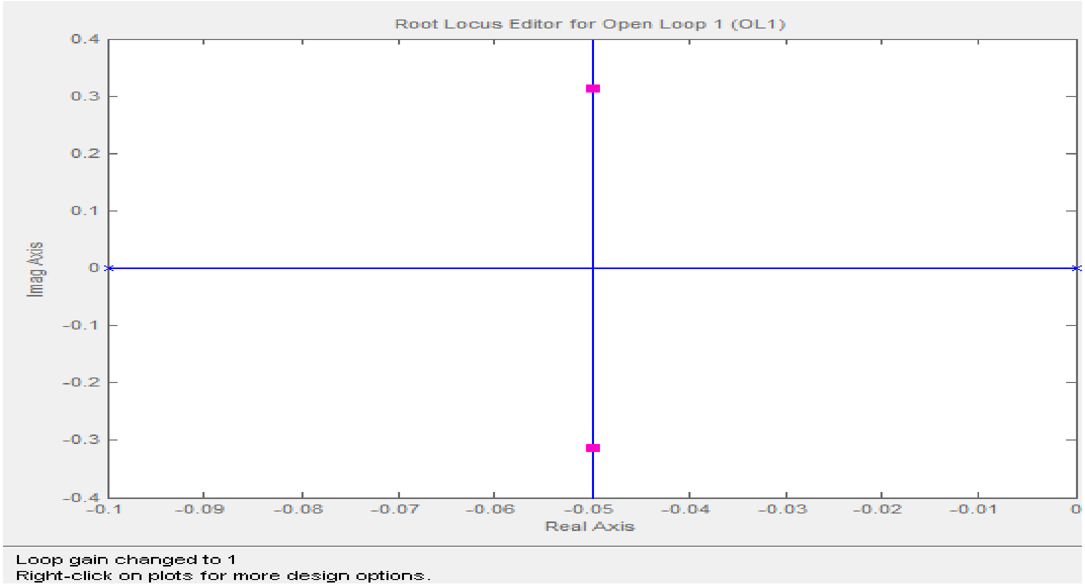

Fig: 6. Root Locus of the uncompensated system

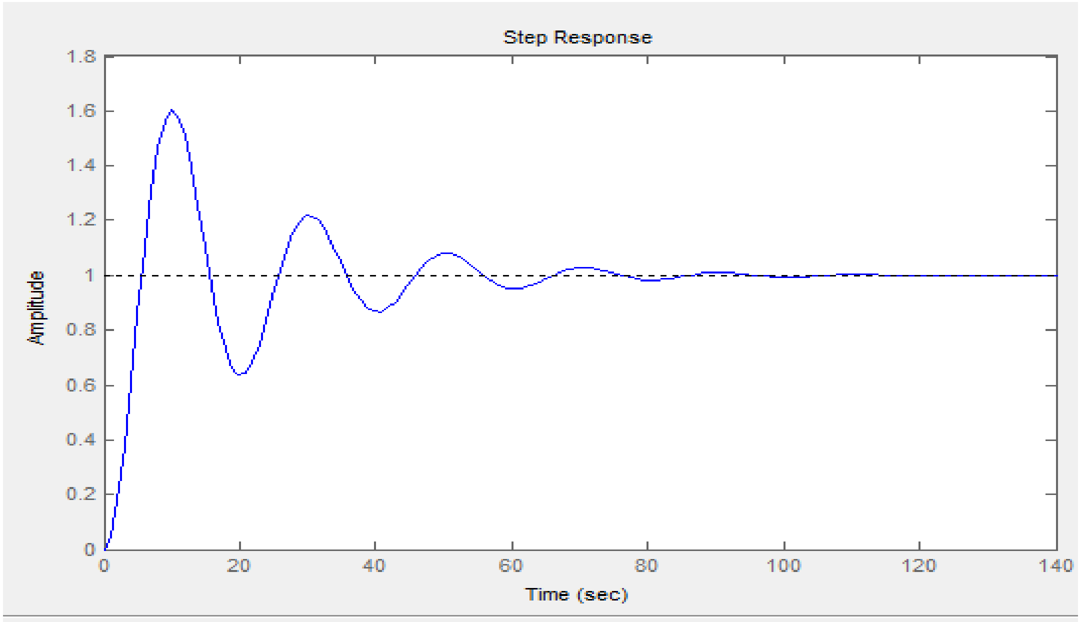

Fig. 7 Step response of the uncompensated system

From Fig. 6, the poles of the system are 0 and -0.1. Fig. 7 shows the characteristics of the system when uncompensated. The peak amplitude is 1.6 and the overshoot is 60.4%; the rise time and settling time are 3.74s and 73.1s; and with a final value of 1.

3.2. The compensated system Parameters in continuous time domain:

The open loop transfer function,

$$L(s) = G_c(s) \times G_p(s) = \frac{2.03(s+0.33)}{s(s+3.66)(s+0.1)} \qquad (20)$$

The closed loop transfer function,

$$T(s) = \frac{L(s)}{1+L(s)H(s)} = \frac{2.03S+0.6699}{S^3+3.7595S^2+2.3957S+0.6699} \qquad (21)$$

The root locus for the compensated system and the step response are shown in Fig. 8. and 9.

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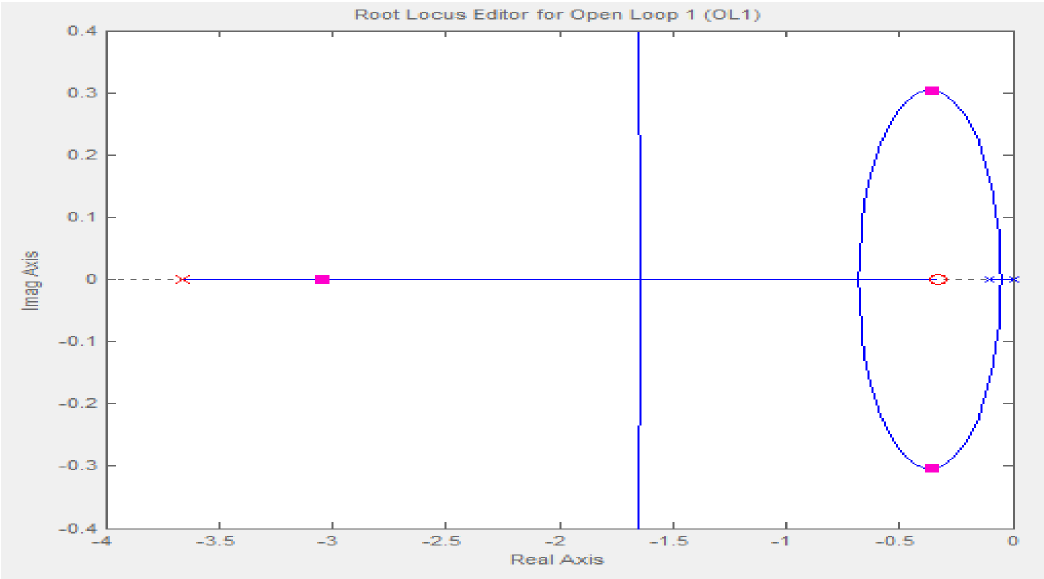

Fig. 8. Root Locus plot of the compensated system

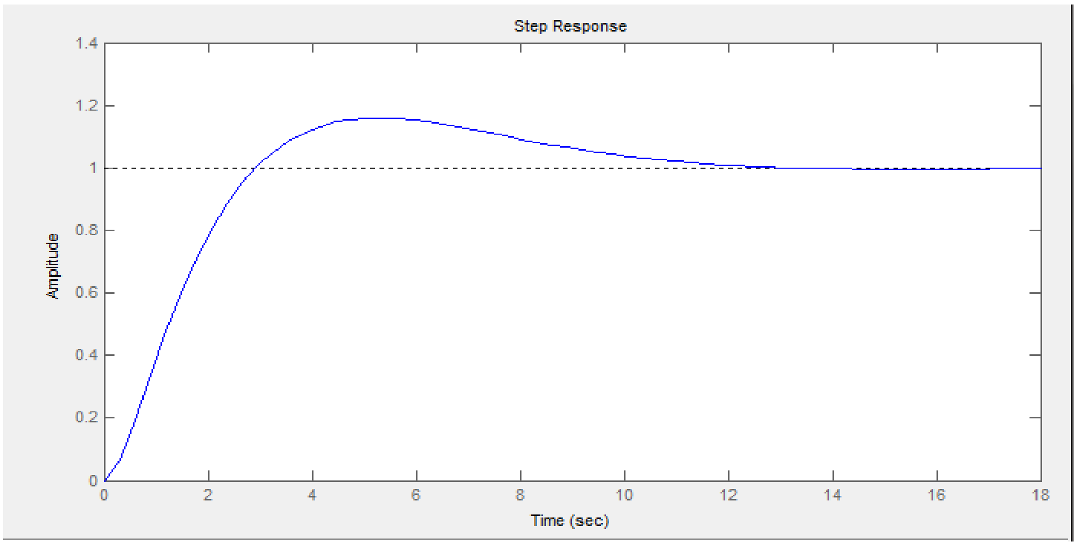

Fig .9. Step response of the compensated system

The step response plot of Fig. 9 shows an improved performance characteristics of the system. which compares moderately well with the stated specifications. The peak amplitude is 1.16 and overshoot is 16%; a rise time of 2.06s (with 2% criterion) and a settling time of 11s. The steady state value is 1.

3.3. Design of the controller, D(z)

Tustin rule is used to convert $G_c(s)\ to\ D(z)$. It states that:

$$s = \frac{2(z-1)}{T(z+1)}, where\ T = 1s$$

$$D(z) = \frac{20.3[\frac{2(z-1)}{T(z+1)}+0.33]}{\frac{2(z-1)}{T(z+1)}+3.66} = \frac{8.3567(z-0.7167)}{z+0.2933} \qquad (22)$$

Open-loop transfer function, $L(z) = D(z) \times G(z)$

$$G(z) = G_o(s) \times G_p(s) = \left(\frac{1-e^{-Ts}}{s}\right)\left\{\frac{0.1}{s(s+0.1)}\right\} = \frac{0.04837z+0.04679}{z^2-1.905+0.9048} \qquad (23)$$

$where\ T = 1s$

Hence,

$$L(z) = \frac{8.3567(z-0.7167)}{z+0.2933} \times \frac{0.04837z+0.04679}{z^2-1.905z+0.9048} = \frac{0.4025(z-0.7167)(z+0.9672)}{(z+0.2933)(z-0.9048)(z-1)} \quad (24)$$

Closed-loop transfer function,

$$T(z) = \frac{L(z)}{1+L(z)H(z)} = \frac{0.4025(z+0.9672)(z-0.7167)}{(z-0.03676)(z^2-1.171z+0.4044)} \quad (25)$$

The root locus and the step response of the system in discrete time are shown in Fig. 10 and 11.

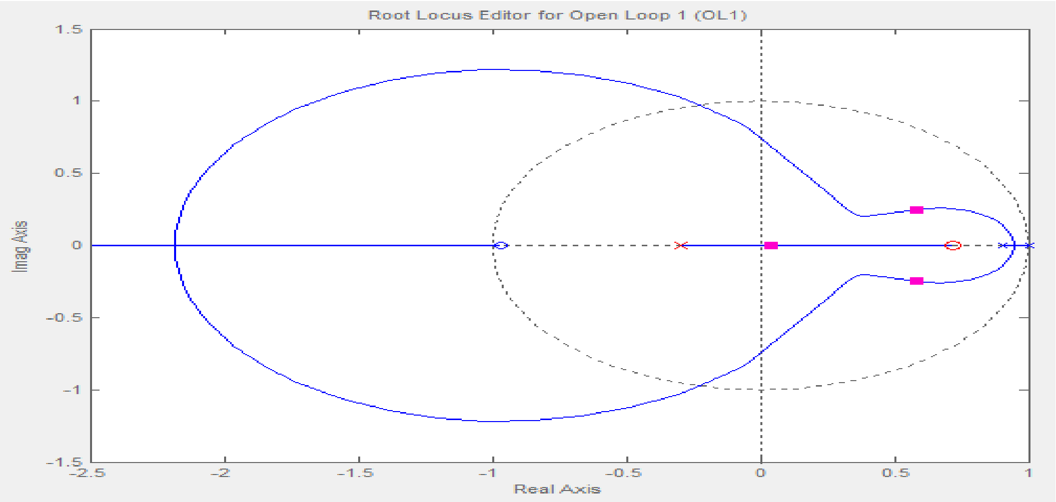

Fig.10. Root Locus plot of the compensated system

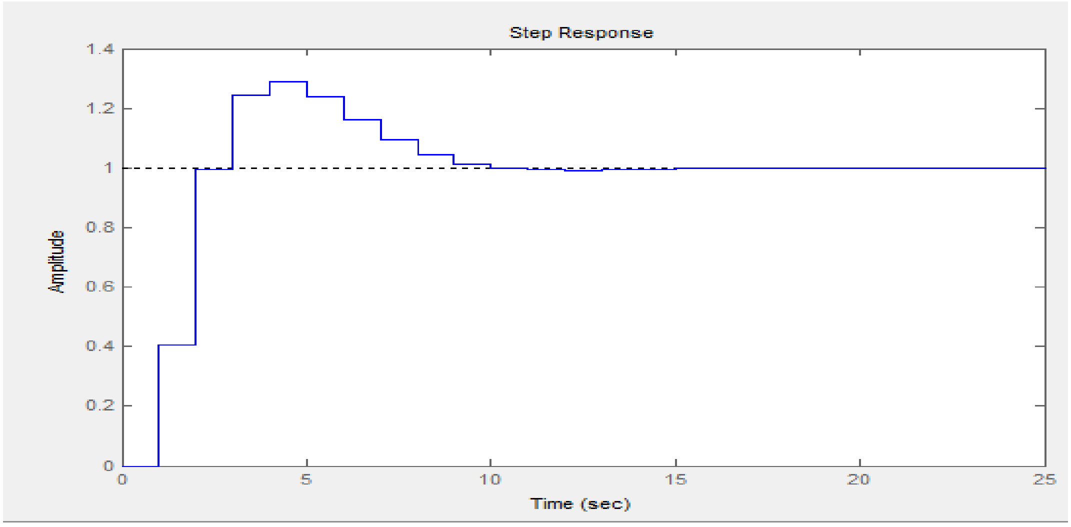

Fig.11. Step response of the system in discrete time

In Fig.10, the poles of the closed loop system, 0.0368 and 0.585± 0249i lie in the unit circle. This indicates that the system is stable. In Fig.11, the step response has an overshoot of 28.9%, rise time of 1.59s, and a settling time of 8.8s.

4. DISCUSSION AND CONCLUSION

The specifications for the transient response of this system were originally expressed in terms of the overshoot, and the settling time. These specifications were translated, on the basis of an approximation of the system by a second-order system, to an equivalent ζ *and* ω_n and therefore a desired root location.

The step response of the uncompensated system in Fig.7 shows that using the drilling tool, it will take a long time for it to reach a steady state so that drilling can commence and the accuracy of positioning will drop as speed is increased due to cycling experienced during the transient period. The delay in the system will reduce the number of holes that can be drilled at a time. This effect has been taken care of by the controller which greatly improved the system such that transient response of the system is now faster and as such the steady state is attained at a reduced time. Invariably more holes can be drilled at any given time owing to achieved fast response and reduced settling time.

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