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DIGITAL TRACKING CONTROL OF PRECISION MOTION SERVOSYSTEM

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Abstract: This paper presents model based digital tracking controller design for precision motion systems. As a demonstrating motion system is used geared permanent magnet DC motor with position sensor. Proposed controller consists of two parts. A feedback part allows tracking the reference signal and rejecting the plant disturbances and a feedforward part improves the tracking accuracy, especially in case of use time varying reference signal. Simulation results are presented.

1 Introduction

Motion systems are used in many different application areas, including industrial NC machines, hard disk drives in consumer electronics and so on. Typically the position or velocity of machines is controlled by using geared electric motors, pneumatic actuators or hydraulic actuators. Despite the large differences in application areas, these motion systems share a common aspect - control is essential for achieving speed and accuracy requirements. To fulfil these demands is commonly used combination of feedback and feedforward control (Figure 1), where the feedback controller C_1 allows tracking the reference signal and improves the disturbance rejection and the feedforward controller C_2 improves the tracking accuracy.

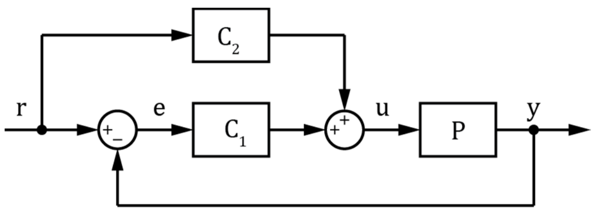

Figure 1 Two degree of freedom control architecture

The feedback controller works based on the difference between reference input *r* and output *y*. The most commonly used feedback controller in industry is PID controller in consideration of its stability and robustness against disturbances. However, the tracking error *e* cannot be avoided when only the feedback controller is used. To reduce the tracking error feedforward controller is used together with the feedback controller in order to make up for the feedback controller's disadvantage and enable a system to track the desired reference path. The feedforward controller is an open loop controller and generates the output with calculations based on the pre-specified system model. The reference input is directly fed forward to the plant *P* in the feedback control loop, which consequently improves response characteristics of the feedback loop. Transfer function from the reference to the controlled variable is

$$\frac{Y(z)}{R(z)}=\frac{C_1(z)P(z)+C_2(z)P(z)}{1+C_1(z)P(z)}. \tag{1}$$

Suppose that the desired output track the reference signal. In that case $Y(z)=R(z)$ is achieved and from the above equation we can derive feedforward controller as

$$C_2(z)=\frac{1}{P(z)}. \tag{2}$$

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By another point of view we can redraw mentioned controller into form shown in (Figure 2). After modifying the reference input by feedforward filter, the modified input is fed to the feedback control loop.

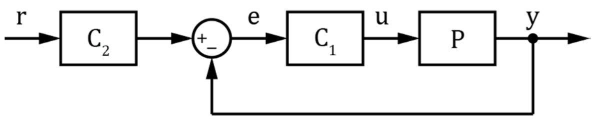

Figure 2 Alternative two degree of freedom control architecture

Transfer function from the reference signal to the controlled variable is

$$\frac{Y(z)}{R(z)} = C_2(z)\frac{C_1(z)P(z)}{1+C_1(z)P(z)}, \tag{3}$$

and the desired output track the reference signal when $Y(z) = R(z)$ is achieved. Feedforward controller in this case is

$$C_2(z) = \frac{1+C_1(z)P(z)}{C_1(z)P(z)}. \tag{4}$$

In this alternative architecture, the feedforward controller transfer function is more complex because there is also included transfer function of feedback controller. However, when the plant has unstable zeros, inverted plant transfer function yields to unstable feedforward controller and modification is necessary. In this case, the second type is more suitable than first. As a typical technique of this second type feedforward controller is ZPETC [1].

2 Plant dynamics

In this paper we are focused to the control of a geared permanent magnet DC motor with position sensor, which represents servomechanism. This servomechanism consists of electrical and mechanical part. As input to this system is voltage source v applied to the motor's armature, while the output is the angular position φ of the gearbox shaft.

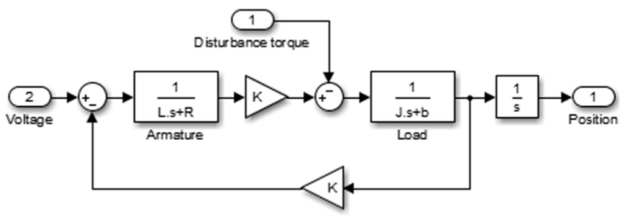

Figure 3 Model of permanent magnet DC motor with gearbox and position sensor

In order to model of servomechanism shown in (Figure 3), the parameters and variables are defined as follows:

- L - armature winding inductance
- R - armature winding resistance
- K - torque; electrical constant
- J - overall inertia at output shaft
- b - overall damping at output shaft

Continuous-time transfer function of the servomechanism's velocity loop is

$$\frac{\dot{\Phi}(s)}{V(s)} = \frac{K}{(Ls+R)(Js+b)+K^2}. \tag{5}$$

Table 1 Parameters of servomechanism

L	0.001	[H]
R	2.4	[Ω]
K	3.8	[Nm/A; Vs/rad]
J	0.5	[kgm^2]
b	0.001	[Nms/rad]

For the purpose of design of a digital control system we need to create a sampled model of the servomechanism. It is necessary to choose a frequency with which the continuous-time plant is sampled. Sampling frequency must be fast compared to the dynamics of the system in order that the sampled output of the system captures the system's full behaviour. It is appropriate to relate the sampling rate to the bandwidth.

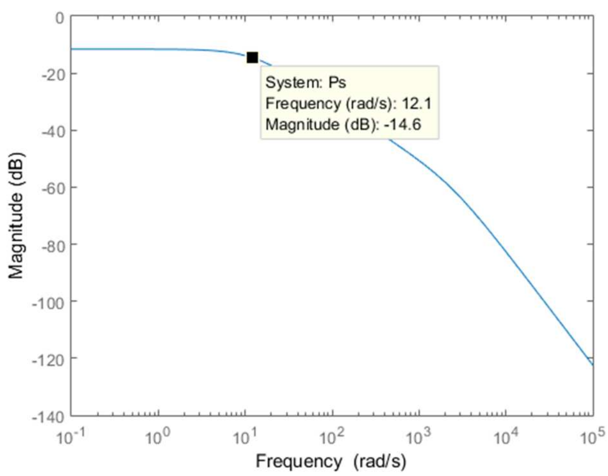

Figure 4 Bode plot of the servomechanism's velocity loop

The resulting -3dB bandwidth f_{BW} of the servomechanism is 1.92 Hz. As a general rule of thumb, the sampling period T should be chosen in the range

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$$\frac{1}{40 f_{BW}} < T < \frac{1}{10 f_{BW}}. \tag{6}$$

With respect to this rule the sampling period was chosen as T = 0.05 s. Next step is to convert the continuous-time transfer function of the servomechanism's velocity loop to the discrete z-domain. As a type of hold circuit we will choose a zero-order hold method. Discrete-time transfer function of the velocity's loop is then

$$\frac{\dot{\Phi}(z)}{V(z)} = \frac{0.1187z + 0.0007}{z(z - 0.5462)}. \tag{7}$$

3 Controller design

Controller of the velocity's loop consist of a feedback and a feedforward part. A feedback part allows tracking the reference signal and rejetcing the plant disturbance and a feedforward part imptroves the tracking accuracy.

3.1 Feedback

As a feedback compensator is used PI controller, where the proportional control P have the effect of reducing the rise time and the steady-state error and integral control I have the effect of eliminating the steady-state error for a constant input. Transfer function of a PI controlles is

$$C_1(s) = P + \frac{I}{s}. \tag{8}$$

Discretizing the above continuous-time transfer function of PI controler by using zero order hold method we achieve digital PI controller form as

$$C_1(z) = \frac{Pz - P + IT}{z - 1}. \tag{9}$$

The required step response of servomechanism's velocity loop is achieved by choosing proportional gain as P = 4 and integral gain as I = 35. Digital PI controller's transfer function then takes form

$$C_1(z) = \frac{4z - 2.25}{z - 1}. \tag{10}$$

3.2 Feedforward

Feedforward control requires integration of the mathematical model into the control algorithm such that it is used to determine the control actions based on what is known about the system being controlled. Reference signal is, according to knowledge of behaviour of the system, at first modified and modified input signal is then fed to servomechanism's feedback control loop. Servomechanism's velocity feedforward is based on minimal realization of inverse of velocity's feedback control loop as

$$C_2(z) = \frac{z^2 - 1.131z + 0.2877}{0.4412z^2 - 0.2832z - 0.0016}. \tag{11}$$

Pole-zero map of the above discrete-time transfer function shows that all poles and zeros are inside the unit circle what means that designed feedforward controller is causal and stable.

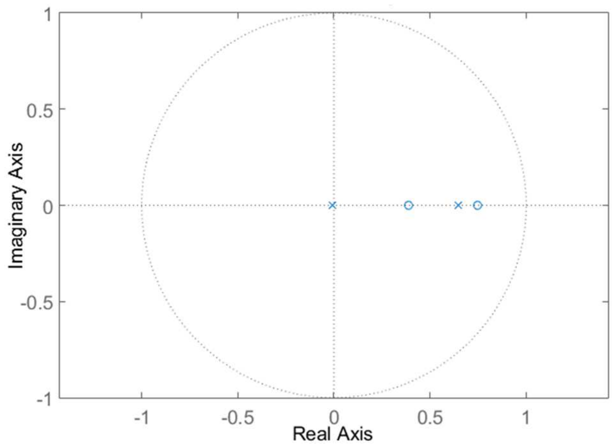

Figure 5 Pole-zero map of feedforward controller C_2

Servomechanism's position controller consist of cascaded position and velocity loop with feedforward. Feedforward path speeds the response of controller by taking the command around the slower position loop directly to the velocity loop which improves the dynamics of the servomechanism.

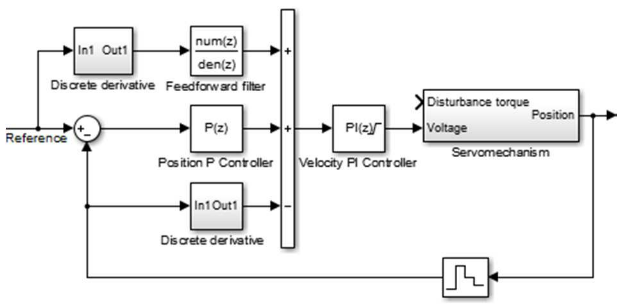

Figure 6 Cascaded position and velocity loop with feedforward

4 Simulations and analysis

Simulation results of servomechanism ability to track the reference signal with and without feedforward controller path are shown in (Figure 7). As a testing referecne input was chosen sine signal with frequency of 1 rad/s. Ability of servomechanism to track the reference signal without feedforward controller is not enough sufficient considering to significant phase shift between referecne signal and servomechanism's output. Observed phase shift cause to significant error between reference and output signal, which is in precision motion systems inappropriate. Addying feedforward path to servomechanism's controller yields to better behaviour of servomechanism's output.

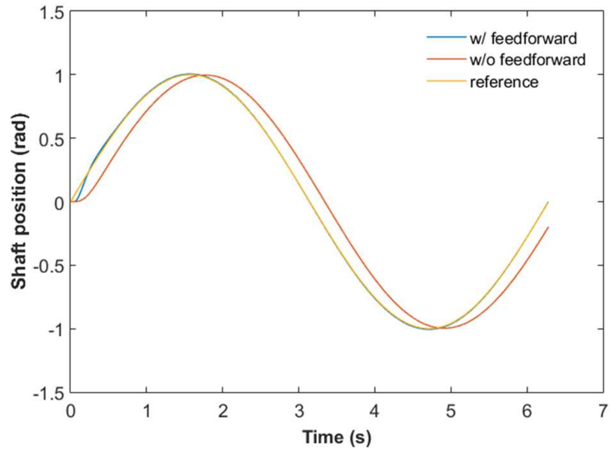

Figure 7 Reference trajectory tracking with and without velocity feedforward

By adding of feedforward path to the controller the ability of servomechanism to track the reference signal is significantly improved.

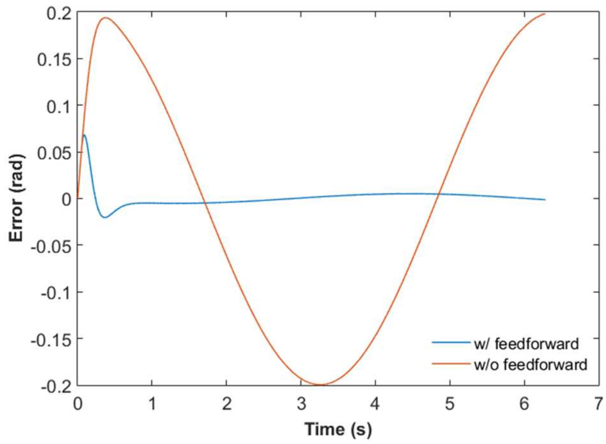

Figure 8 Tracking error with and without velocity feedforward

5 Conclusion

Controller design and simulation results of precision motion servomechanism are presented. The proposed controller based on combination of feedback and feedforward control loop shows that it can be provided impressive tracking performance by adding of feedforward path to controller. Result of adding of feedforward path to controller is significant reduction of error between reference signal and servomechanism's output.

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