Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

8th International Conference
on Electrical Engineering

ICEENG 2012

USING PRECISE POSITION CONTROL IN MEASURING SYSTEMS

Walaa Eldeen Ahmed Ghadiry*, Mohamed Mohamed Sakr,PHD**

ABSTRACT

Motion control system is a system that has a special controller for controlling position, velocity or acceleration. In this paper the position control is concerned. A special application is introduced in detail which is the "gonio-photometer" laboratory which is used to measure the following:

a- Luminaire luminous intensity distribution.
b- Lamp luminous flux.

Position control of this application is concerned having a resolution angle (0.01 degree) with the aid of a dc servo motor system and PID controller in addition to the use of brakes for maintaining better results. Simulation and calculations of the system equations are held using Matlab program.
An alternative method is introduced for the position control of the application under study, which is the use of stepper motors instead of dc servo motors.

KEY WORDS: position control, servo motors, goniophotometers, gear ratio, encoders, PID, brakes, stepper motors.

1- INTRODUCTION

Motion control is typically considered to be the industrial automation field of controlling the position and/ or velocity of some type of actuator, usually an electric motor. Motion control is a very important component of robotics applications, but it is also used extensively in many other industrial applications where the motions are less complex. Non-robotic applications are often referred to as General Motion Control (GMC).

There are a number of design considerations for motion systems, as follows:

1- Speed: How fast does the controlled device have to move? This parameter is typically specified in rpm or inches per minute. It can also be expressed as the time it takes to get from point A to point B.
2- Torque: How hard does the motion control device have to work to move the load? This parameter is expressed in rotational units as a force through a lever arm, lb-ft, or lb-force for linear systems.
3- Accuracy: How close to the ideal motion path does the motion control system have to perform? How close does it have to be to the ideal command position ? When it is moving and/or when comes to rest? This parameter is often expressed as an error between actual and desired position. The error units are typically degrees in rotary systems and inches in linear systems.
4- Inertia. How much torque is required to change the speed of the moving parts? Inertia is a physical parameter that defines the resistance of all physical parts to changes in speed or direction. The smaller and lighter the parts, the easier it is to change the speed.

* Egyptian Armed Forces
** Chef of electric power department, Cairo University, Giza, Egypt.

A servomotor used in a position control system converts winding current to mechanical torque, producing the motion in a motion control system. A feedback device transmits motor shaft position to the comparator. From there, the position feedback is compared to the command position. The output from the comparator is the difference between the two and is called the position error. Continuing on, the servo-amplifier converts the comparator output (position error) to high current, which is then applied to the servomotor winding. The output of the servo amplifier is connected in such a way to cause the motor to rotate in the direction to minimize position error. Finally, a command generator provides the desired or command position signal that tells the motion control system how to move the servomotor and load.

If the command signal is changed to any position, the system would respond by moving the motor shaft accordingly. It's important to keep something in mind, though. Real-world servo motion control systems have certain limitations that do not yield the ideal performance.

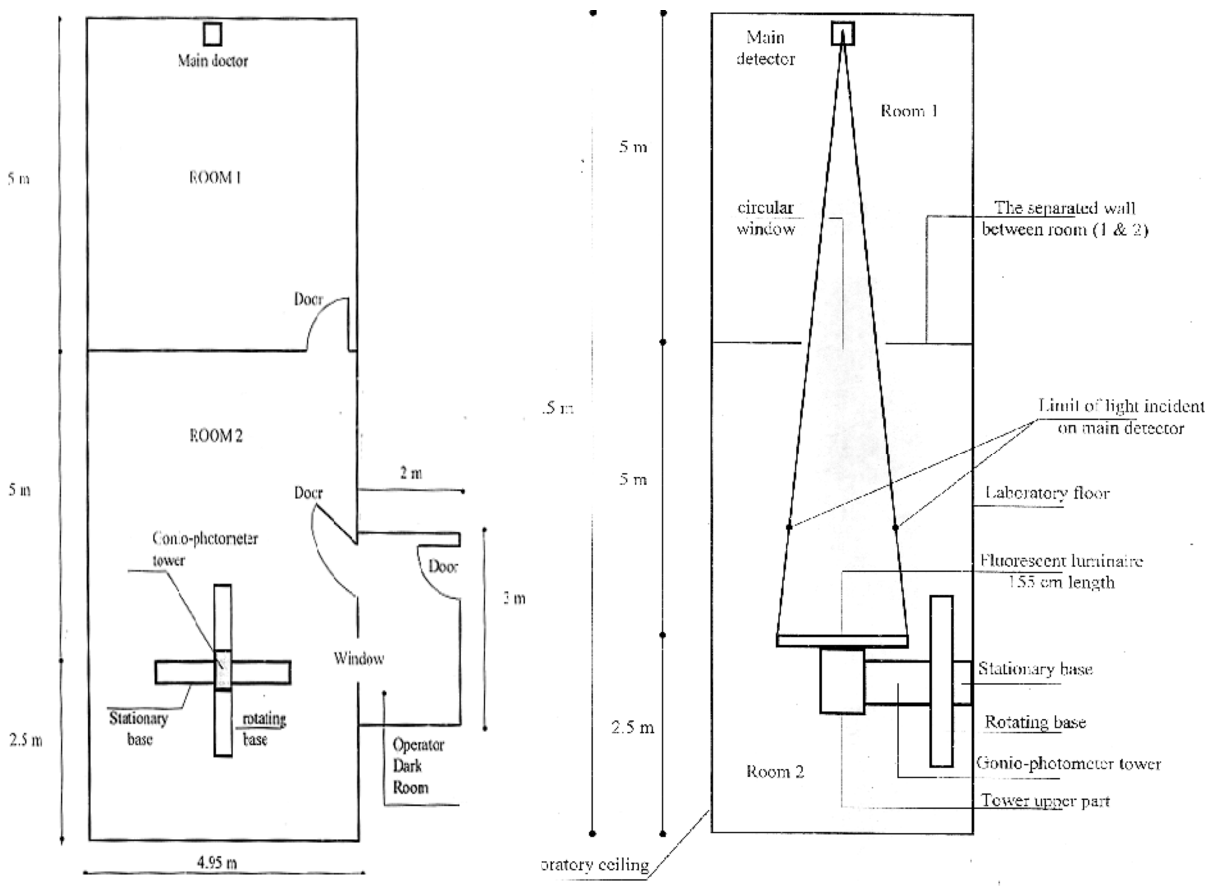
2- PROBLEM DESCRIPTION

A gonio photometer laboratory is a laboratory used for absolute measurements (CIE specifications) of the following:

1- Luminaire luminous intensity distribution.

2-Lamp luminous flux.

This laboratory is specified for (fluorescent, compact fluorescent and incandescent) lamps and the corresponding luminaries (lighting fixtures), Fig.1 (a,b).



(a) Laboratory Space Details (Plan)

(b) Laboratory Space Details (Elevation)

Fig.1. Gonio-photometer Laboratory Space Details

2.1 Laboratory space

Laboratory space is divided into two rooms as shown in Fig.1 (a,b), which are as follows:
i) Main Detector Room (Room "1") , the complete structure of main detector is wall mounted in such a way that the detector is directly facing luminaire diffuser through a circular window.
ii) Gonio-Photometer Machine Room (Room "2"), Gonio-photometer machine should be installed such that the distance between luminaire diffuser and main detector sensitive plate is 10m.
As shown in fig., there is a circular window (0.5m radius) between the two rooms. The window allows all light rays (emitted from a luminaire equipped with 58w fluorescent lamps), to be incident on main detector. There is a door between the two rooms for main detector maintenance.
iii) Operator Dark Room (Room "3"), electrical control panel and computer are located in this room. Operator can observe the machine rotating through a small window. There is a door between this room and room no.2 for measurements preparation.

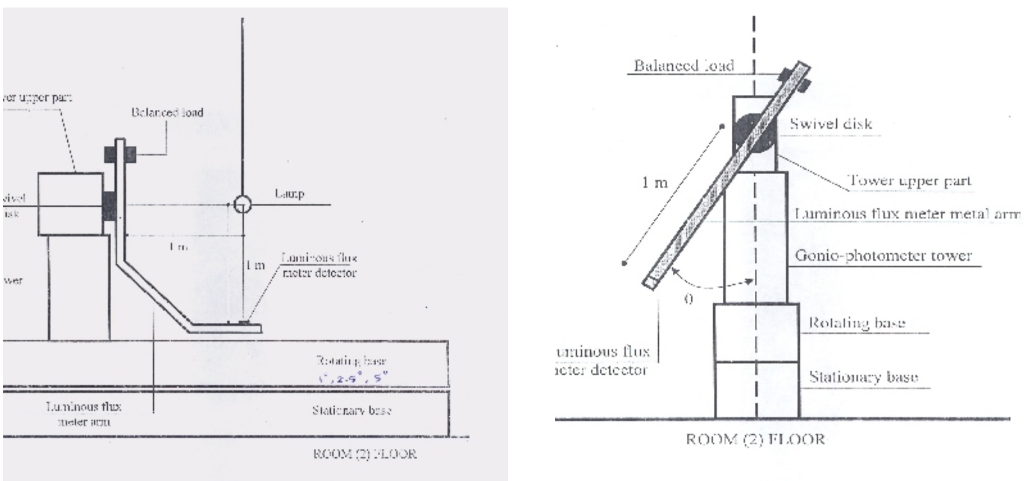
2.2 Laboratory Coating

Laboratory walls, ceiling and floor should be coated by "wall to wall" carpet, high thickness, long ripples, black color with matt finish with a reflection factor less than 0.05%
eflection factor = (lighting level due to reflected light)/ (incident lighting level).
Stationary and rotating bases and gonio-photometer tower should be coated with the same carpet.

2.3 Machine Description

2.3.1 Stationary Machine Base, Fig.2 (a,b)

a- Metal base, fixed on ground.
b- (AC/DC) motor, producing the horizontal machine rotation, embedded in
base at its center.
c- Approximate base dimensions:
length: 280 cm.
width: 35 cm.
height: (20-30) cm, according to the motor axial length.
d- (AC/Dc) motor is fully controlled by computer software to rotate its axis in
steps. The horizontal of each step can be adjusted by angle computer software (1, 2.5, 5degrees). Accurate measurements are achieved when the horizontal step angle becomes smaller. The accuracy degree of angle should not be greater than 0.01 degree. Mechanical loads and inertia of gonio-photometer and 30 kg fluorescent luminaire should be taken into account in the design of motor control system.



(a) Luminous Flux Meter (side) | (b) Luminous Flux Meter (front)

Fig.2. Gonio-photometer Machine Description

2.3.2 Rotating Machine Base, Fig.2 (a,b)

a- Metal base, coupled with stationary base motor.
b- When the stationary base motor rotates, the rotating base makes a horizontal rotation around its center.
c- Approximate base dimensions: (as those mentioned in the stationary base).
d- At the base center, gonio-photometer tower is fixed in its position by clamps. The tower can be linearly slided (to change its position) by the aid of two sided rails installed in rotating base.

2.3.3 Gonio-Photometer Tower, Fig.2 (a,b)

a- Metal tower fastened in its position by clamps. The horizontal level of its upper part can be adjusted by a 4 strong screws.
b- Horizontal axis (AC/DC) motor, producing the vertical luminaire rotation is installed at tower upper part.
c- (AC/DC) motor is fully controlled by computer software to rotate its axis a specified angle. The rotated angle is specified by computer software (10, 15, 30 degrees). The accuracy degree of the rotated angle should be not greater than 0.01 degree.
d- (AC/DC) motor is coupled with a metal swivel disk at which the luminaire is fastened to rotate
e- Mechanical loads and inertia of 30 kg fluorescent luminaire should be taken into account in the design of motor control system.
f- There is a circular mirror, located at the central point of metal swivel disk for laser beam adjustment.

3-POSITION CONTROL OF GONIOPHOTOMETER MOTORS

We will study the use of (AC/DC) motor for producing the horizontal machine rotation; the accuracy degree of angle should not be greater than 0.01 degree.

3.1 Servo Motors

A servo motor is a dc, ac, or brushless dc motor combined with a position sensing device (encoder), used in closed loop control systems. The digital servo motor controller directs operation of the servo motor by sending velocity command signals to the amplifier, which drives the servo motor. An integral feedback device (encoder or tachometer) is either incorporated within the servo motor or is remotely mounted, often on the load itself. This provides the servo motor's position and velocity feedback that the controller compares to its programmed motion profile and uses to alter its velocity or position signal.

3.1.1 AC Servo Motors

AC servo motors are used in ac servo mechanisms and computers which require rapid and accurate response characteristics. To obtain these characteristics, servo motors have small-diameter high-resistance rotors. The small diameter provides low inertia for fast starts, stops, and reversals, while the high resistance provides a nearly linear speed-torque relationship for accurate control. In an ideal servo motor, torque at any speed is directly proportional to control-winding voltage. In practice, however, this relationship exists only at zero speed because of the inherent inability of an induction motor to respond to voltage input changes under conditions of light load. The inherent damping of servo motors decreases as ratings increase and the motors have a reasonable efficiency at the sacrifice of speed-torque linearity.

3.1.2 DC Servo Motors

DC servo motors are normally used as prime movers in computers, numerically controlled machinery, or other applications where starts and stops are made quickly and accurately. Servo motors have lightweight, low-inertia armatures that respond quickly to excitation-voltage changes. In addition, very low armature inductance in these servo motors results in a low electrical time constant (typically 0.05 to 1.5 msec) that further sharpens servo motor response to command signals. For low speed, high smoothness, accurate position or velocity control, Low noise, and high efficiency, it is better to use DC servo or microstepping with stepper motors.
For the above comparison between ac and dc servomotors, it is clear that for our application (gonio-photometer) it is better to use the dc servo motor, for the fact that it is needs low speed, high smooth, accurate position control.

3.2 Controller

The PID controller is the most common form of feedback. It was an essential element of early governors and it became the standard tool when process control emerged in the 1940s. In process control today, more than 95% of the control loops are of PID type, most loops are actually PI control. PID controllers are today found in all areas where control is used. PID stands for Proportional Integral Derivative. It is a basic filter mechanism used to control some output based upon the aggregate function of factors. PID control is often combined with logic, sequential functions, selectors, and simple function blocks to build the complicated automation systems used for energy reduction, transportation, and manufacturing. Many sophisticated control strategies, such as model predictive control, are also organized hierarchically. The PID controller can thus be said to be the “bread and butter’’ of control engineering. It is an important component in every control engineer’s tool box. PID controllers have survived many changes in technology, from mechanics and pneumatics to microprocessors via electronic tubes, transistors, integrated circuits. The microprocessor has had a dramatic influence on the PID controller. Practically all PID controllers made today are based on microprocessors. This has given opportunities to provide additional features like automatic tuning, gain scheduling, and continuous adaptation.

3.2.1 PID Formula Fig.3

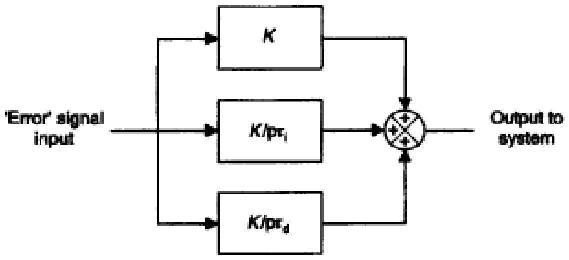


Fig.3. PID Controller

The major simplification is to perform the algorithm at a fixed time rate. Then, everything having to do with time gets rolled up into the constants. Now the basic formula becomes:

$$\text{PID: } K(1 + 1/p\tau_i + p\tau_d) = \frac{K(1 + p\tau_i + p^2\tau_i\tau_d)}{p\tau_i}$$

$$\text{PI: } K(1 + 1/p\tau_i) = \frac{K(1 + p\tau_i)}{p\tau_i}$$

Where K is the proportional coefficient; 'p' is the Laplace operator; τi is the integral time constant and τd is the derivative time constant.
Figure 3.12 shows the three terms of the PID controller: the first is proportional to the 'error' signal, which is the difference between reference (demanded) input and feedback of the measured output; the second and third are the integral and derivative of the 'error' signal respectively.

4 PROBLEM SIMULATION AND CALCULATIONS

We will simulate a dc servo motor using Matlab, use a PID controller to control this motor to obtain a precise position control not exceeding 0.01 degree and finally obtaining the corresponding calculations with a discussion of the results.

4.1 Simulation of a DC Servo Motor

The Matlab representation and modeling of DC motor is as shown in Fig.4.1

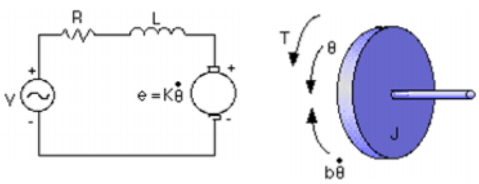


Fig. 4.1 Modeling Of A DC Motor

For our example, we will assume the following values for the physical parameters. These values were derived by experiment from an actual motor:

1- moment of inertia of the rotor (J) = 3.2284E-6 kg.m^2/s^2
2- damping ratio of the mechanical system (b) = 3.5077E-6 Nms
3-electromotive force constant (K=Ke=Kt) = 0.0274 Nm/Amp
4- electric resistance (R) = 4 ohm
5- electric inductance (L) = 2.75E-6 H
6- input (V): Source Voltage
7- output (theta): position of shaft
8- The rotor and shaft are assumed to be rigid.

System Equations:

$$T = K_t i$$

$$e = K_e \dot{\theta}$$

From (fig. 4.1) we can write the following equations based on Newton's law combined with Kirchhoff's law:

$$J\ddot{\theta} + b\dot{\theta} = Ki$$

$$L\frac{di}{dt} + Ri = V - K\dot{\theta}$$

Transfer Function is given by: $$\frac{\theta}{V} = \frac{K}{s((Js+b)(Ls+R)+K^2)}$$

Having motor speed = 1500 rpm,
Gear ratio (N) = 1500:6
= 250:1

Assuming that the mechanical loads of gonio-photometer and 30 kg fluorescent luminaire = 100 kg, having a shape of a cylinder with 1m radius will have an inertia equals;
Jl = ½(100) (1)2 = 50kg m2.
Jeq = Jm + Jl / N2.
= 3.2284E-6 + 50/ (250)2
= 0.8032284E-3 kg m2

4.2 Using PID Controller

For maintaining resolution = 0.01 degrees. (Steady state error), we will try to use PID controller to achieve this resolution. Let's try a PI controller to get rid of the steady state error (0.01 rad) using Matlab:
Neglecting damping ratio of the load, using Matlab:
Using PID controller:

```
J=0.8032284E-3;
b=3.5077E-6;
K=0.0274;
R=4;
L=2.75E-6;
num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
Kp=0.5;
Ki=0.5;
Kd=1;
numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:4;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
maxovershoot =  0.0594
s=401;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
settlingtime=(s-1)*0.01
settlingtime= 3.890
```

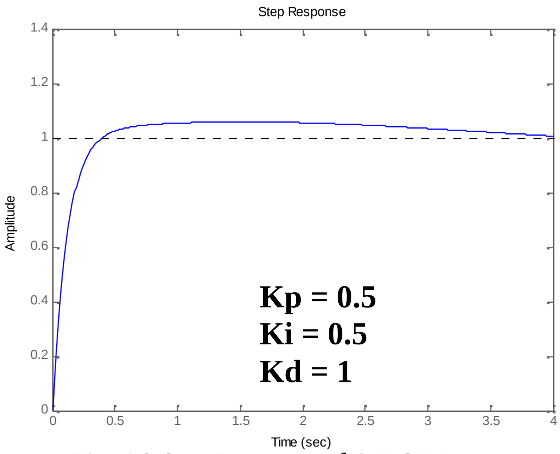


Fig. 4.2 Step Response of A DC Motor Using PID Controller (Kp=0.5,Ki=0.5,Kd=1)

Tuning Kp , Ki , Kd :

```
J=0.8032284E-3;
b=3.5077E-6;
K=0.0274;
```

```
R=4;
L=2.75E-6;
num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
Kp=0.5;
Ki=0.5;
Kd=5;
numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:5;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
maxovershoot =    -0.0030
s=21;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
settlingtime=(s-1)*0.01
settlingtime=  0.1100
```

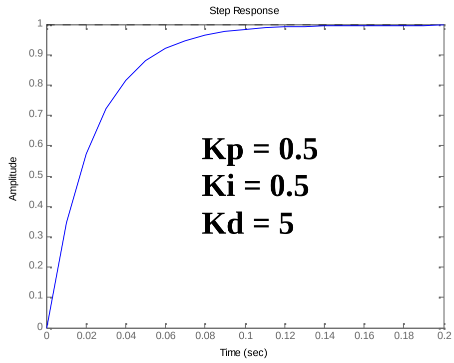


Fig. 4.3 Step Response of A DC Motor Using PID Controller (Kp=0.5,Ki=0.5,Kd=5)

The above graph shows a very fast response which may be not desired, by re adjusting PID coefficients we can get :

```
J=0.8032284E-3;
b=3.5077E-6;
K=0.0274;
R=4;
L=2.75E-6;
num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
Kp=0.5;
Ki=0.1;
Kd=0.3;
numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:5;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
maxovershoot =   0.2205
s=501;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
settlingtime=(s-1)*0.01
settlingtime= 3.8000
```

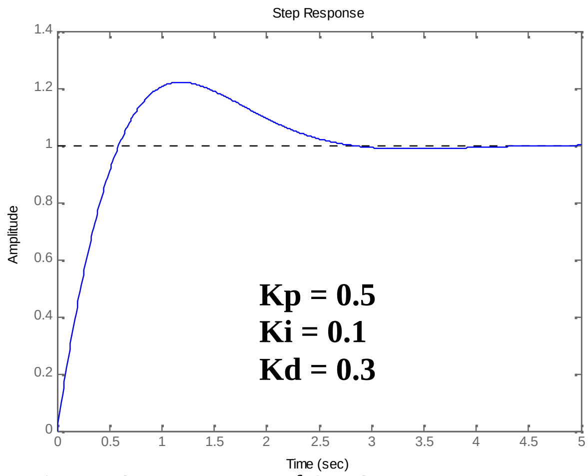


Fig. 4.4 Step Response of A DC Motor

Using PID Controller (Kp=0.5,Ki=0.1,Kd=0.3)

If we want a faster response we can use brakes to stop the motor at an earlier position, the tangent to the curve represent the speed of the motor

The consumed energy due to friction of plates = kinetic energy of the motor at that point = ½ (100) (0.99/0.58)2 = 145.675 joules.

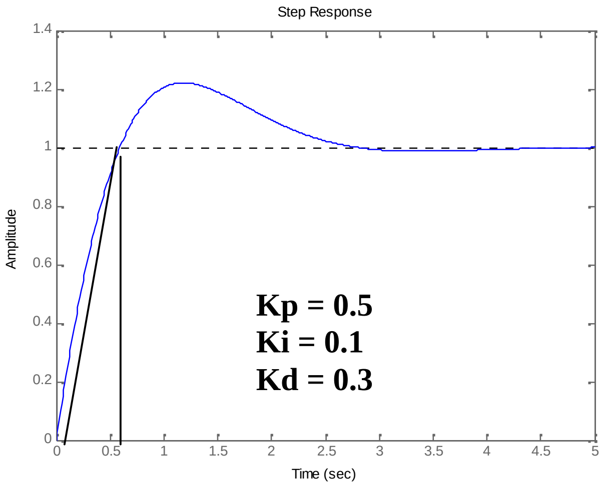


Fig. 4.5 Step Response of A DC Motor
Using PID Controller (Kp=0.5,Ki=0.1,Kd=0.3) and Brakes

Thus we can use brakes having higher power than the calculated energy consumed for obtaining a faster response.

4.3 The Effect of Varying Moment Of Inertia

For studying the effect of varying the total equivalent moment of inertia, the other parameters will be kept unchanged while increasing and decreasing the equivalent moment of inertia and retuning the PID parameters for obtaining best results.

4.3.1 The Effect of Increasing Moment Of Inertia

By multiplying the equivalent moment of inertia by 10 thus the result will be as shown:

```
J=0.8032284E-2;
b=3.5077E-6;
K=0.0274;
R=4;
L=2.75E-6;
num=K;
```

```
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
Kp=0.5;
Ki=0.1;
Kd=0.3;
numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:50;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
```

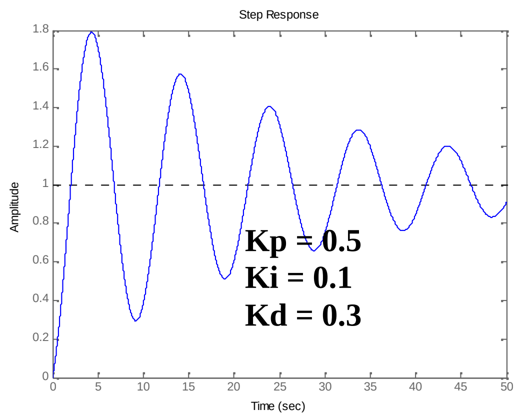


Fig. 4.6 Step Response of A DC Motor Using PID Controller (Kp=0.5,Ki=0.1,Kd=0.3)

```
maxovershoot =  0.7918
s=5001;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
settlingtime=(s-1)*0.01
settlingtime= 50
```

Thus PID parameters should be retuned:

```
J=0.8032284E-2;
b=3.5077E-6;
K=0.0274;
R=4;
L=2.75E-6;
num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
 Kp=3;
 Ki=0.1;
 Kd=3;
 numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:5;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
maxovershoot =  0.1788
s=501;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
 settlingtime=(s-1)*0.01
settlingtime =   3.5000
```

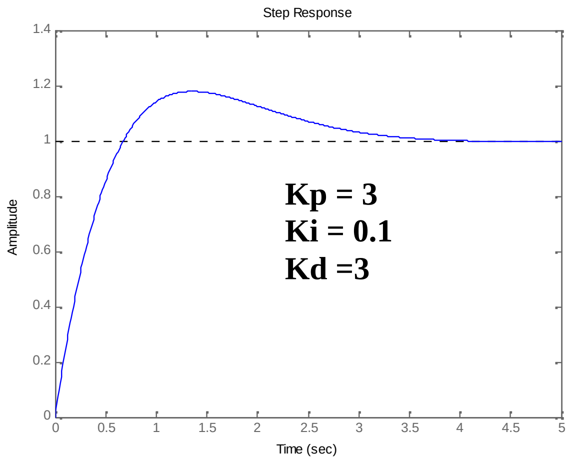


Fig. 4.7 Step Response of A DC Motor Using PID Controller (Kp=3,Ki=0.1,Kd=3)

4.3.2 The Effect of Decreasing Moment Of Inertia

By dividing the equivalent moment of inertia by 10 thus the result will be as shown:

```
J=0.8032284E-4;
b=3.5077E-6;
K=0.0274;
R=4;
```

```
L=2.75E-6;
num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
Kp=0.5;
Ki=0.1;
Kd=0.3;
numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:5;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
maxovershoot =
    0.0079
s=501;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
 settlingtime=(s-1)*0.01
settlingtime =
    0.4800
```

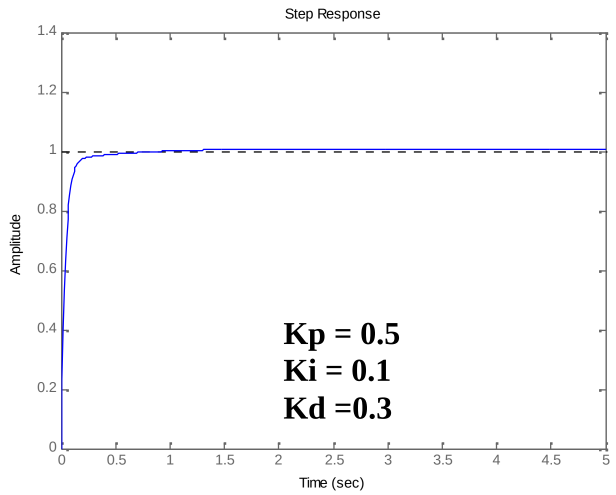


Fig. 4.8 Step Response of A DC Motor Using PID Controller (Kp=0.5,Ki=0.1,Kd=0.3)

4.4 The Effect of Varying Damping Ratio

For studying the effect of varying the damping ratio, the other parameters will be kept unchanged while increasing and decreasing the damping ratio and retuning the PID parameters for obtaining best results.

4.4.1 The Effect of Increasing Damping Ratio

By multiplying the damping ratio by 1000 thus the result will be as shown:

```
J=0.8032284E-3;
b=3.5077E-3;
K=0.0274;
R=4;
L=2.75E-6;
num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
Kp=0.5;
Ki=0.1;
Kd=0.3;
numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:5;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
maxovershoot =   0.1093
s=501;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
settlingtime=(s-1)*0.01
settlingtime= 5
```

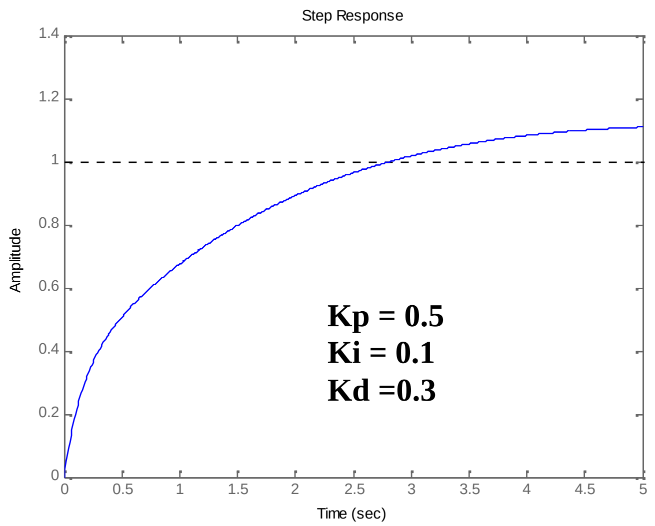


Fig. 4.9 Step Response of A DC Motor
Using PID Controller (Kp=0.5,Ki=0.1,Kd=0.3)

Thus PID parameters should be retuned:

```
J=0.8032284E-3;
b=3.5077E-3;
K=0.0274;
R=4;
L=2.75E-6;
num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
Kp=10;
Ki=0.1;
Kd=3;
numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:5;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
maxovershoot =
  5.2446e-004
s=501;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
settlingtime=(s-1)*0.01
settlingtime =     0.5500
```

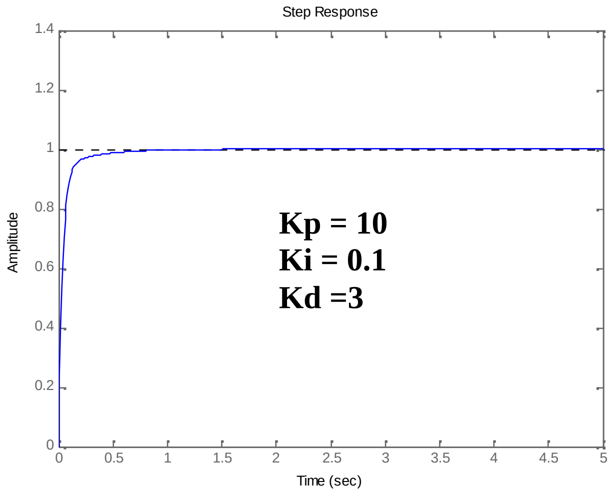


Fig. 4.10 Step Response of A DC Motor
Using PID Controller (Kp=10,Ki=0.1,Kd=3)

4.4.2 The Effect of Decreasing Damping Ratio

By dividing the damping ratio by 1000 thus the result will be as shown:

```
J=0.8032284E-3;
b=3.5077E-9;
K=0.0274;
R=4;
L=2.75E-6;
num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];
Kp=0.5;
Ki=0.1;
Kd=0.3;
numcf=[Kd Kp Ki];
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);
[numc,denc]=cloop(numf,denf,-1);
t=0:0.01:5;
step(numc,denc,t)
[y,x,t]=step(numc,denc,t);
[ymax,t]=max(y);
maxovershoot=ymax-1
maxovershoot =  0.2214
s=501;while y(s)>0.99 & y(s)<1.01;s=s-1;end;
settlingtime=(s-1)*0.01
settlingtime=
3.8200
```

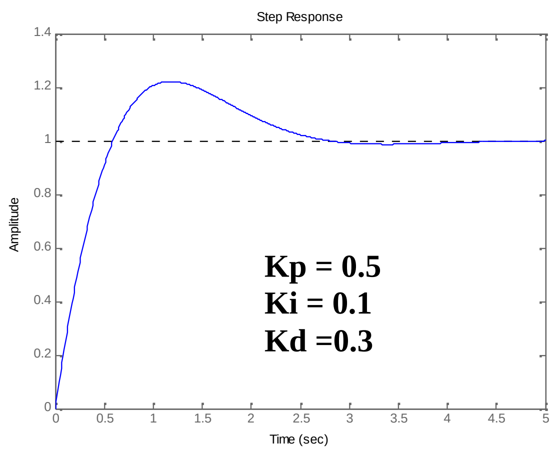


Fig. 4.11 Step Response of A DC Motor
Using PID Controller (Kp=0.5,Ki=0.1,Kd=0.3)

4.4.3 Comments on Step Response Curves

1- Referring to the previous curves, it is clear that the considered resolution (0.01 degrees) could be achieved using the PID controller, and using the brakes enhanced the results and improved it by decreasing the time needed to reach the final precise position.

2- Referring to the previous curves, it is clear that for varying the moment of inertia as well as the damping ratio, the considered resolution (0.01 degrees) could be achieved by varying the PD coefficients as indicated in each curve.

5- POSITION CONTROL OF STEPPER MOTORS AS AN ALTERNATIVE METHOD

5.1 General

Positioning systems have been traditionally implemented using DC motors due to the relative ease in controlling them. This ease of control is due to the fact that the system equations describing a (separately excited) DC motor are linear. However, there are still disadvantages in using such motors for positioning systems. In particular, for high speed repetitive motion, the brushes are subject to excessive mechanical wear and consequently lead to a decrease in performance. Also, due to repetitive motion is the problem of overheating of the armature windings. Since the windings are on the rotor, the heat does not have a direct path to the outside environment, but instead must be dissipated through the stator. Finally, the torque to inertia ratio is relatively low, again due to having the armature windings on the rotor. For the reasons just enumerated, positioning systems are now being implemented using stepper motors. Originally, stepper motors were designed to provide precise positioning control within an integer number of steps (e.g., 200 steps for a resolution of 1.8”) without using sensors. That is, they are open-loop stable to any step position, and consequently no feedback is needed to control them. Furthermore, by a more precise control of the phase currents, microstepping can be achieved in which there are 2000 steps or a resolution of 0.18’. (This is the resolution limit of a typical position transducer such as an optical encoder) [6].

A stepper motor is an electromechanical device which converts electrical pulses into discrete mechanical movements. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence. The motors rotation has several direct relationships to these applied input pulses. The sequence of the applied pulses is directly related to the direction of motor shafts rotation. The speed of the motor shaft rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied.

5.2 Open-Loop and Closed-Loop Control

One of the principal merits of stepper motors is their ability to operate as control devices in an open-loop mode. The precision of control in open-loop is the angular step of the motor. Angular steps of hybrid steppers are commonly 1.8 degree. Finer steps can be achieved by a process known as microstepping, but this requires considerably more logic circuitry in the controller. The control of stepper motors in open-loop is generally simpler than the control required for competitive systems (usually closed-loop systems) such as servomotor and brushless dc motor systems. In open-loop, stepper motors are usually controlled by digital systems, in which the count of clock pulses or transistor pulses is available. The fixed relationship between count and angular or linear step gives a precise control of the motor output position and velocity. In general, there is no error between the pulse count and the position change of the motor output, provided of course that the motor develops

sufficient torque to overcome system friction, inertia, and load. Using the proper conversion factors, the same may be said for the relationship between counts per second and motor velocity.
However, as in all physical systems, there are situations that may negate this relationship between pulse count and position. Discounting the obvious physical problems, such as bad bearings or some interference in the load side of the system or “glitches” in the counting system, the principal source of error is motor instability, especially at low speeds. A step motor is operated in a transient mode during each pulse, in contrast to conventional continuously excited motors that operate in a steady-state mode. Motor shaft oscillation can be caused by both electrical and mechanical time constants in the systems and cause the motor to “slip a pole” or in some other manner get out of synchronism with the input pulse rate. Demands for rapid acceleration may also cause inaccuracies between pulse count and output position or velocity. For this reason most stepper systems have a “slew rating,” which is the maximum number of steps that the system can make in a given time interval; this rating is a function of both the motor and controller parameters. There may also be problems between the pulse count and position in operations requiring frequent stop-start, reversing, or pause operations. These errors can be corrected, in general, by the logic system, but may require some sort of a position feedback signal or another counting system to count the mechanical steps [3].

5.3 Microstepping

It appears that microstepping was invented in 1974 by Larry Durkos, who was working as a mechanical engineer for American Monitor Corporation. The company was a medical equipment vendor, and they were using a large Superior Electric 1.8 degree per step stepping motors to directly drive the 20 inch diameter turntable of their Kinetic Discrete Analyzer. The turntable was used to bring each of 100 blood samples into position for analysis. That is 2 steps per sample, and the motion was so abrupt that the samples tended to spill. The system was controlled by a minicomputer (today, we would use a microcontroller), and Durkos worked out how to do computer-controlled sine-cosine microstepping in order to solve this problem. The solution was published in the technical service manuals for the KDA analyzer, but it was never patented. Representatives of Superior Electric learned of microstepping from Durkos, and that company was the first to market a microstepping controller.

The regular stepwise of a conventional stepping motor, which is normally not less than 0.5o per step, is sometimes too large for some applications such as printers, plotters, robot arms, machine tool feed drives, and so on. The required positioning resolution in such cases is usually reached by use of gearing. Sensitivity of step motors to load inertia is well known which leads to a limitation. Furthermore, with a regular stepping operation, we have large overshoot and resonance problems which have plagued this motor for a long time. In this case, the microstepping control is an efficient solution to overcome these problems. It consists of dividing artificially the motor step-angle into smaller steps called microsteps. Hence, the motor positioning resolution will be improved by a high factor. As a result, gearing and its associated backlash problems can be avoided when improved resolution is required. Some dynamic problems of motor are also minimized by using such technique [2].
Microstepping is a way to make small steps even smaller. The smaller the step is the higher the resolution and the better the vibration characteristics. In microstepping, a phase is not fully on or fully off. It is partially on. Sine waves are applied to both phase A and phase B, 90° apart. When the maximum power is in phase A, phase B is at zero. The rotor will line up with phase A. As the current to phase A decreases, it is increasing to phase B. The rotor will take tiny steps toward phase B until phase B is at its max and phase A is at zero. The process continues around the other phases and we have microstepping. There are some problems associated with microstepping, mostly accuracy and torque.

Then why microstepping? There are still compelling reasons other than high resolution for microstepping. They include reducing mechanical noise, gentler mechanical actuation, and reducing resonance problems [1].

Microstepping serves two purposes. First, it allows a stepping motor to stop and hold a position between the full or half-step positions; second, it largely eliminates the jerky character of low-speed stepping-motor operation and the noise at intermediate speeds; and third, it reduces problems with resonance [5].

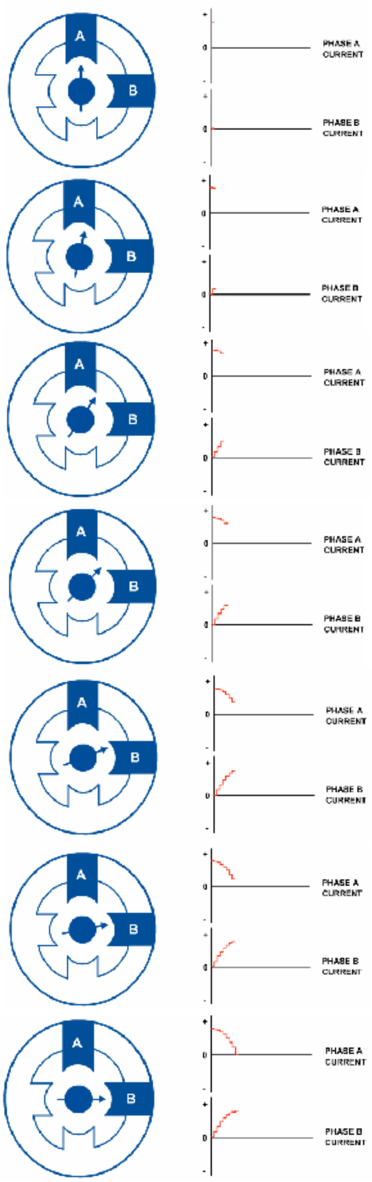


Fig. 5.1 Microstepping (Simplified)

5. 4 Torque Phasor Diagram

Let's now look at what current ratios are needed to produce a particular step angle. The Microstep angle can be graphically represented with a Phasor Diagram. (Fig. 5.12) The X and Y axis indicate the current level in two respective coils A, B. A vector (ray from origin to coordinate X, Y) shows the resultant angle and Torque (magnitude of the vector) when some current is applied to both coils. This diagram shows the 'sub-angle' between natural whole steps (poles) of the motors. On a typical 200 steps per revolution motor this is 1.8 degrees. The graph below is a representation of how that angle can be further sub-divided.

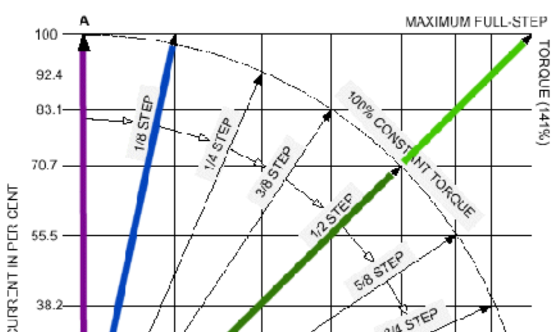


Fig. 5.2 Torque Phasor Diagram

RED

Full current to coil B, only. Rotor points to a natural 'pole' at a whole step position.

PURPLE

Full current to coil A only. Rotor points to a natural 'pole' also at a whole step position.

GREEN (LIGHT GREEN)

The green vectors are the most important to grasp. The light green vector shows what happens when you take a 'half' step with an ordinary (non-microstepping) controller by fully activating both coils. The angle is correct,since rotor points midway between the natural poles, but the magnitude (torque) is greater than at the whole step positions (Red and Purple vectors.).The magnitude is 1.414 times (square root of two) greater. The result is uneven torque, with resultant surges in current usage with each half step.

GREEN (DARK GREEN)

Now consider the Dark Green Vector. The angle is the same as the light green (rotor points midway between the natural poles) but the torque is now the same magnitude as the whole step positions. This was achieved by reducing the current by .707 (one half the square root of 2) in each coil. The result is even torque at the half step positions, precisely what we want.

BLUE

Now carry this concept one step further and look at the blue (1/8 step) vector. The current in the coils is precisely proportioned to achieve an eighth step between the whole step positions, with equivalent torque. We can see that the torque is equivalent since the magnitude (length) of this ray is the same as the whole step vectors. All the microstep vectors have the same magnitude!

Once we understand the phasor diagram, we can see how the Microstepping controller uses the current levels in each of the 2 coils to achieve the desired sub-angle. What are the limits? How small a step angle can you take? This depends on the precision of the motor and the Microstep driver. Generally speaking, 1/8th to 1/16th steps is a good compromise that can be achieved with ordinary motors and a good controller. Let's look at the current ratios needed to achieve a particular 1/8 step angle.

Step Series	Current Phase A	Current Phase B	Step Position
0	100.0%	0.0%	full step
1	98.1%	19.5%	1/8 step
2	92.4%	38.2%	1/4 step
3	83.1%	55.5%	3/8 step
4	70.7%	70.7%	1/2 step
5	55.5%	83.1%	5/8 step
6	38.2%	92.4%	3/4 step

Table 5.1 1/8th- Step subdivisions current ratios

5.5 Torque vs, Angle Characteristics

The torque vs. angle characteristics of a stepper motor is the relationship between the displacement of the rotor and the torque which is applied to the rotor shaft when the stepper motor is energized at its rated voltage. An ideal stepper motor has a sinusoidal torque vs. displacement characteristic as shown in next figure. Positions A and C represent stable equilibrium points when no external force or load is applied to the rotor shaft. When you apply an external force Ta to the motor shaft you in essence create an angular displacement, Θa. This angular displacement, Θa, is referred to as a lead or lag angle depending on whether the motor is actively accelerating or decelerating. When the rotor stops with an applied load it will come to rest at the position defined by this displacement angle. The motor develops a torque, Ta, in opposition to the applied external force in order to balance the load. As the load is increased the displacement angle also increases until it reaches the maximum holding torque, TH, of the motor. Once TH is exceeded the motor enters an unstable region. In this region a torque is the opposite direction is created and the rotor jumps over the unstable point to the next stable point.

The displacement angle is determined by the following relationship:
X = (Z / 2 π) x sin (Ta / TH) where:
Z = rotor tooth pitch
Ta = Load torque
TH = Motors rated holding torque
X = Displacement angle.

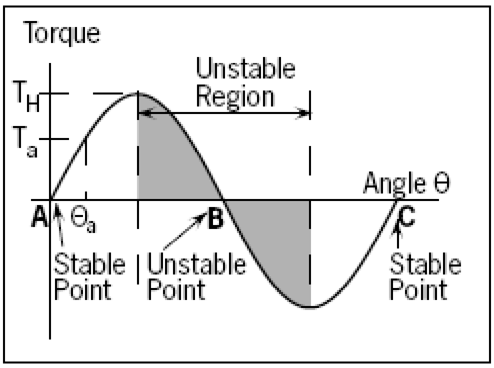


Fig. 5.3 Torque vs. Rotor Angular Positions

5.6 Torque vs, Speed Characteristics

The torque vs. speed characteristics are the key to selecting the right motor and drive method for a specific application. These characteristics are dependent upon (change with) the motor, excitation mode and type of driver or drive method. A typical "speed – torque curve" is shown in the next figure. To get a better understanding of this curve it is useful to define the different aspect of this curve.

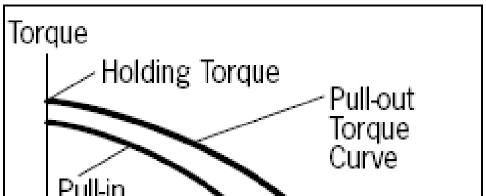


Fig. 5.4 Torque vs. Speed Characteristics Of A Stepper Motor

Holding torque

The maximum torque produced by the motor at standstill. Normally, the holding torque is higher than the running torque and, thus, acts as a strong brake in holding a load. Since deflection varies with load, the higher the holding torque the more accurate the position will be held.

Residual Torque

The non-energized detent torque of a permanent magnet Stepper motor is called residual torque. A result of the permanent magnet flux and bearing friction, it has a value of approximately 1/10 the holding torque. This characteristic of PM steppers is useful in holding a load in the proper position even when the motor is de-energized. The position, however, will not be held as accurately as when the motor is energized.

Pull-In Curve

The pull-in curve defines an area referred to as the start stop region. This is the maximum frequency at which the motor can start/stop instantaneously, with a load applied, without loss of synchronism. (Use the PULL IN curve if the control circuit provides no acceleration and the load is frictional only).

The pull-in characteristics vary also depending on the load. The larger the load inertia is the smaller the pull-in area. We can see from the shape of the curve that the step rate affects the torque output capability of stepper motor The decreasing torque output as the speed increases is caused by the fact that at high speeds the inductance of the motor is the dominant circuit element. The shape of the speed – torque curve can change quite dramatically depending on the type of driver used. Most motor manufacturers provide these speeds - torque curves for their motors. It is important to understand what driver type or drive method the motor manufacturer used in developing their curves as the torque vs. speed characteristics of a given motor can vary significantly depending on the drive method used.

Maximum Start Rate

The maximum starting step frequency with no load applied.

Pull-Out Curve

The pull-out curve defines an area referred to as the slew region. It defines the maximum frequency at which the motor can operate without losing synchronism. Since this region is outside the pull-in area the motor must be ramped (accelerated or decelerated) into this region.(Use the PULL OUT curve, in conjunction with a Torque = Inertia x Acceleration equation ($T= J\alpha$), when the load is inertial and/or acceleration control is provided).

Maximum Slew Rate

The maximum operating frequency of the motor with no load applied.

5.6 Single Step Response

The single-step response characteristic of a stepper motor is shown in the fig. 5.15 When one step pulse is applied to a stepper motor the rotor behaves in a manner as defined by the next curve. The step time t is the time it takes the motor shaft to rotate one step angle once the first step pulse is applied. This step time is highly dependent on the ratio of torque to inertia (load) as well as the type of driver used. Since the torque is a function of the displacement it follows that the acceleration will also be. Therefore, when moving in large step increments, a high torque is developed and consequently a high acceleration. This can cause overshoots and ringing as shown.

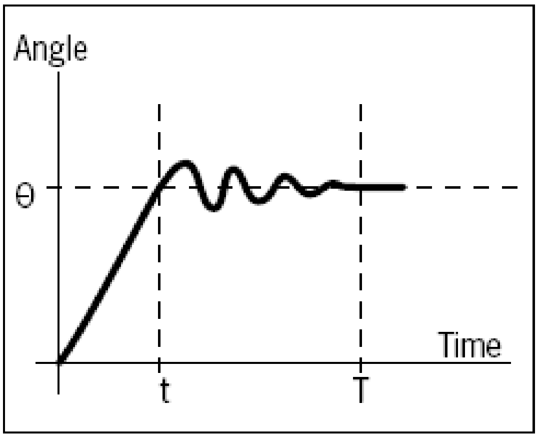


Fig. 5.5 Single Step Response vs. Time

The settling time T is the time it takes these oscillations or ringing to cease. In certain applications this phenomena can be undesirable. It is possible to reduce or eliminate this behavior by increasing the frictional load or adding external damping can thus modify this response, if it is required. Mechanical dampers (e.g., slip pads or plates), or devices such as a fluid coupled flywheel can be used, but add to system cost and complexity. Electronic damping also can be accomplished. Step sequencing is altered to cause braking of the rotor, thus minimizing overshoot; another method is by microstepping the stepper motor.

5.7 Resonance

It is a phenomenon known as mid frequency resonance occurs in step motors operated in the open-loop mode. When this frequency range is reached, the motor develops velocity perturbations about the nominal drive velocity which reaches catastrophic proportions, resulting in the loss of synchronism. The motor stalls as a result. If proper damping is used, it is possible to get through this region and operate above the resonant point [5].

Resonance is inherent in the design and operation of all stepping motors. Slow stepping rates combined with high rotor inertia and elevated torque produce ringing as the rotor overshoots its desired angular displacement and is pulled back into position. Resonance arises when the step rate coincides with rotor ringing, typically about 100 to 200 steps/sec. Unable to overcome the combined effects of both load inertia and ringing, the motor skips steps and loses torque and synchronization. Changing any one of the three parameters - inertia load, step rate, or torque - will reduce or eliminate resonance. As a practical matter, only torque is the easiest to change using microstepping. Microstepping applies power to the stator windings of the motor in incremental steps. Torque builds slowly reducing overshoot and canceling resonance [4].

6-CONCLUSION AND DISCUSSION

6.1 FIRST POINT

For a precision position control we can consider which is more appropriate:
a-Servo Motors
b-Stepper Motors

First, a system that requires high power or torque will be a slow-speed system. Second, a very precise or accurate system will typically run more slowly and be low torque. Finally, a system that is required to perform complex motion also requires more engineering expertise to design.

For our application (gonio-photometer) we used the dc servo motor, for the fact that it needs low speed, high smooth, accurate position control. Servo motors actually have to sense position of the motor and control accordingly. This will lead to the use of the following components:
1-Dc motor.
2- A gear reduction drive for torque increase.
3- An electronic shaft position sensing (Encoder).
4- Control circuit.
5- Brakes (if needed).
Using the above components we could achieve the desired accuracy as it was discussed before.

6.2 SECOND POINT

Using a stepper motor in obtaining the precise position control accuracy faces some problems however it has many advantages. One of the most significant advantages of a stepper motor is its ability to be accurately controlled in an open loop system. Open loop control means no feedback information about position is needed. This type of control eliminates the need for expensive sensing and feedback devices such as optical encoders. Your position is known simply by keeping track of the input step pulses. However overloading a stepper motor may cause it to not arrive at the desired position. There are many advantages resulting from using stepper motors as discussed before in the thesis, we can revise these advantages and also the disadvantages once more.

Advantages
1. The rotation angle of the motor is proportional to the input pulse.
2. The motor has full torque at standstill (if the windings are energized).
3. Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 – 5% of a step and this error is non cumulative from one step to the next.
4. Excellent response to starting/stopping/reversing.
5. Very reliable since there are no contact brushes in the motor, therefore the life of the motor is simply dependant on the life of the bearing.
6. The motors response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.
7. It is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
8. A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.

Disadvantages
1. Resonances can occur if not properly controlled.
2. Not easy to operate at extremely high speeds. (Not in our application).

There are some problems associated with stepper motors, mostly accuracy and torque. Because the phases are only partially energized, the motor torque is reduced, usually by about 30%. Since the torque is a function of the displacement it follows that the acceleration will also be. Therefore, when moving in large step increments, a high torque is developed and consequently a high acceleration. This can cause overshoots and ringing as discussed before. It is possible to reduce or eliminate this behavior by increasing the frictional load or adding external damping can thus modify this response, if it is required. Mechanical dampers (e.g., slip pads or plates), or devices such as a fluid coupled flywheel can be used, but add to system cost and complexity. Electronic damping also can be accomplished. Step sequencing is altered to cause braking of the rotor, thus minimizing overshoot; another method is by microstepping the stepper motor.

In summary, step motors are excellent for positioning applications. Step motors can be precisely controlled in terms of both distance and speed simply by varying the number of pulses and their frequency. Their high pole count gives them accuracy while at the same time they run open loop. If sized properly for the application, a step motor will never miss a step. And because they don't need positional feedback, they are very cost effective however, in some cases it is necessary to close the loop with encoders which adds to the price.

REFERENCES

[1] Beauchemin, George; Budimir, Miles, Machine Design, 10/9/2003, Vol. 75 Issue 19, p86-86, EBSCO Publishing

[2] Boujemaˆ A Ben Salah and Mohamed Ben Rejeb, Systems Analysis Modelling Simulation, Vol. 43, No. 2, February 2003, p189–200,Taylor and Francis Ltd

[3] Hamid A. Toliyat, Gerald B. Kliman “Handbook of Electric Motors”, CRC, 2004

[4] Mike Lefebvre, Machine Design, Feb 2005, 2005, Vol. 77; No. 4, p140-143

[5] W. H. Yeadon and A. W. Yeadon **“**Handbook of Small Electric Motors”, McGraw-Hill, 2001

[6] Zribi, M.; Chiasson, J.; Automatic Control, IEEE Transactions on Volume 36, Issue 5, May 1991 Page(s):620 - 625 Digital Object Identifier 10.1109/9.76368, IEEE Transactions on Automatic Control, Vol. 36, No.5, May 1991