

Lab 2d Torsional Second-Order System

OBJECTIVE

Warning: though the experiment has educational objectives (to learn about boiling heat transfer, etc.), these should not be included in your report.

- To measure and investigate the dynamic characteristics of a Torsional Second-Order system.
- To measure the inertia, spring, and damping constants of the plant.

EQUIPMENT

<i>Name</i>	<i>Model</i>	<i>S/N</i>
Experimental Control System	205	
DSP Based Controller / Data Acquisition Board		
Input /Output Electronics		
Electromechanical Plant		
System Interface Software (Executive Program)		

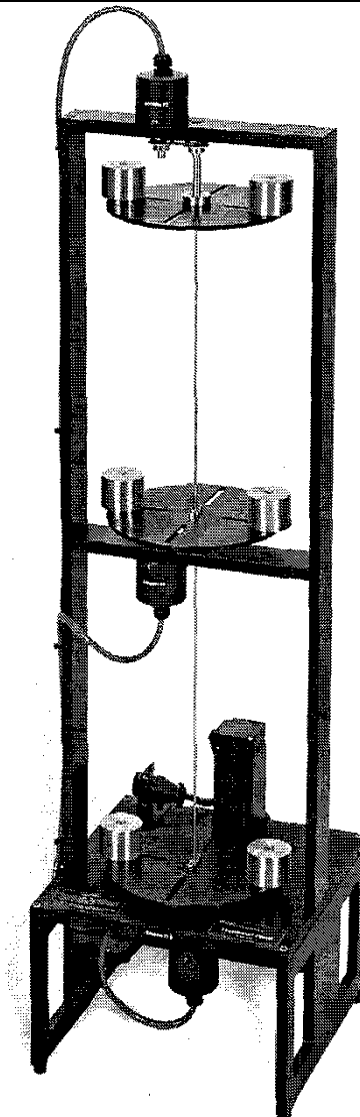


Figure 1: The Model 205
Torsional
Spring / Inertia Apparatus

The experimental system is comprised of the three subsystems. The first of these is the electromechanical plant which consists of the torsion mechanism, its actuator and sensors. The design features a brushless DC servo motor, high resolution encoders, adjustable inertias, and reconfigurable plant type.

The next subsystem is the real-time controller unit which contains the digital signal processor (DSP) based real-time controller, servo/actuator interfaces, servo amplifiers, and auxiliary power supplies. The DSP is capable of executing control laws at high sampling rates allowing the implementation to be modeled as continuous or discrete time. The controller also interprets trajectory commands and supports such functions as data acquisition, trajectory generation, and system health and safety checks. A logic gate array performs motor commutation and encoder pulse decoding. Two optional auxiliary digital-to-analog converters (DAC's) provide for real-time analog signal measurement. This controller is representative of modern industrial control implementation.

The third subsystem is the executive program which runs on a PC under Windows XP operating system. This menu-driven program is the user's interface to the system and supports controller specification, trajectory definition, data acquisition, plotting, system execution commands, and more. Controllers may assume a broad range of selectable block diagram topologies and dynamic order. The interface supports an assortment of features which provide a friendly yet powerful experimental environment.

REQUIRED READING

Reference [1] for the theory. See Attachment A for safety precautions. See Attachment B and Appendix C for ECP Executive Program Demonstration and unit description.

PRELAB QUESTION

- 1- What is damped frequency?
- 2- What is natural frequency?
- 3- What is damping ratio?
- 4- What is effective spring constant?
- 5- Read carefully the instructions in this write-up and describe how you will perform your measurements to obtain errors on the system parameters (spring constants and Damping ratio), as well as natural frequencies of the systems.

PROCEDURE

1. For Model 205a, clamp the center disk to put the mechanism in the configuration shown in Figure 1a using the 1/4" bolt, square nut, and clamp spacer. Only light torque on the bolt is necessary.

2. Secure four 500g masses on the upper and lower disks as shown in the figure. Verify that the masses are secured and that each is at a center distance of 9.0 cm (outermost ring) from the shaft center-line.
3. With the controller powered up, enter the Control Algorithm box via the Set-up menu and set $T_s = 0.00442$. Enter the Command menu, go to Trajectory and select Step, Set-up. Select Open Loop Step and input a step size of 0 (zero), a duration of 4000 ms and 1 repetition. Exit to the Background Screen by consecutively selecting OK. This puts the controller board in a mode for acquiring 8 sec of data on command but without driving the actuator. This procedure may be repeated and the duration adjusted to vary the data acquisition period.

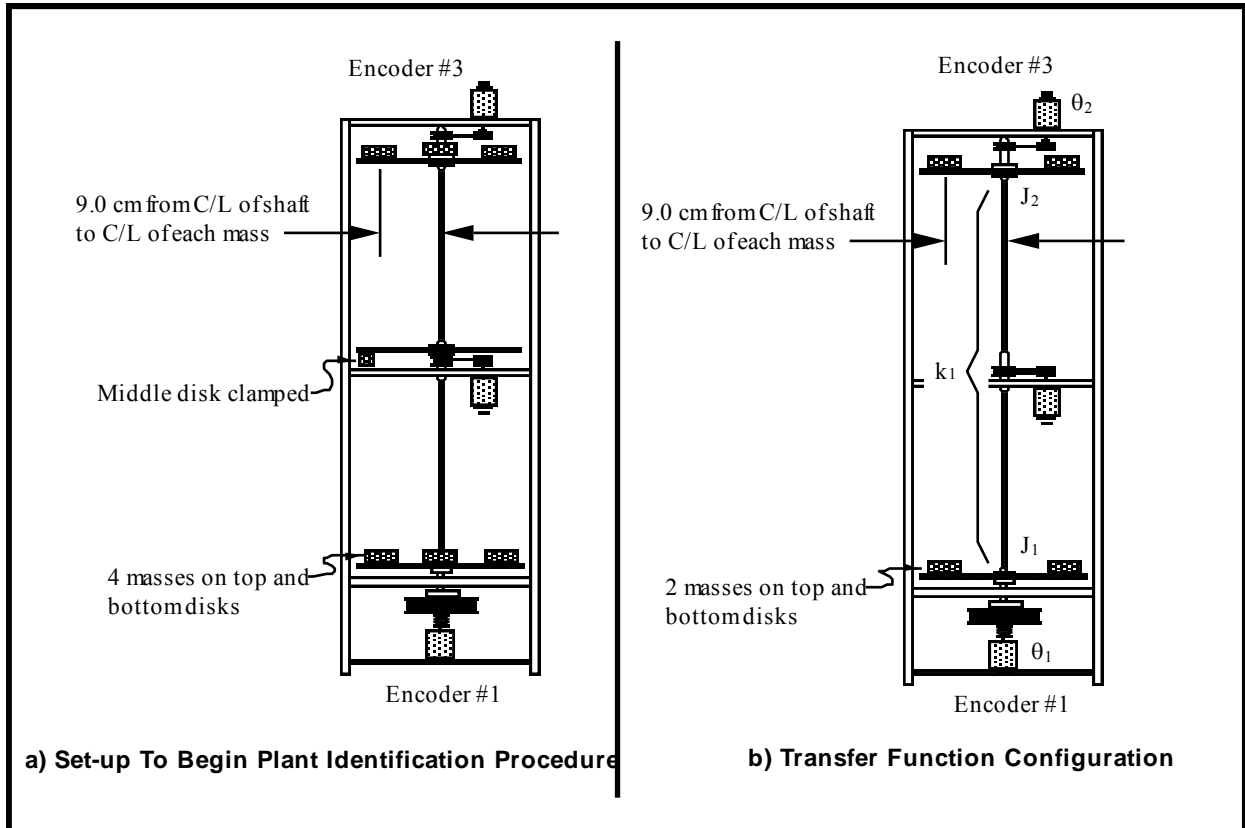


Figure 2 Configurations For Plant Identification (Model 205a shown)

4. Go to Set up Data Acquisition in the Data menu and select Encoder #1 and Encoder #3 as data to acquire and specify data sampling every 2 (two) servo cycles, i.e. every $2 T_s$'s. Select OK to exit. Select Zero Position from the Utility menu to zero the encoder positions.
5. Select Execute from the Command menu. Prepare to manually displace the upper disk approximately 20 deg. Exercise caution in displacing the inertia disk; displacements beyond 40 deg may damage and possibly break the flexible drive shaft. (Displacements beyond 25 deg will trip a software limit which disables the controller indicated by "Limit Exceeded" in the Controller Status box in the Background Screen. To reset, simply reselect Execute from the Command menu.) With the upper disk displaced approximately 20 deg (≤ 1000 encoder counts as read on the Background Screen display) in either direction, select Run from the Execute box and release the disk approximately 1 second later. The disk will oscillate and slowly attenuate while encoder data is collected to record this response. Select OK after data is uploaded.
6. Select Set-up Plot from the Plotting menu and choose Encoder #3 position; then select Plot Data from the Plotting menu. You will see the upper disk time response.
7. Choose several consecutive cycles (say 5 to 10) in the amplitude range between 100 and 1000 counts (This is representative of oscillation amplitudes during later closed loop control maneuvers. Much smaller amplitude responses become dominated by nonlinear friction effects and do not reflect the salient system dynamics) Divide the number of cycles by the time taken to complete them being sure to take beginning and end times from the same phase of the respective harmonic cycles.¹ Convert the resulting frequency in Hz to radians/sec. This *damped frequency*, ω_d , approximates the *natural frequency*, ω_n , according to:

$$\omega_{n_{d31}} = \frac{\omega_{d_{d31}}}{\sqrt{1-\zeta_{d31}^2}} = \omega_{d_{d31}} \quad (\text{for small } \zeta_{d31}) \quad (1)$$

where the "d31" subscript denotes disk #3, trial #1. (Close the graph window by clicking on the left button in the upper right hand corner of the graph. This will collapse the graph to icon form where it may later be brought back up by double-clicking on it.)

8. Remove the four masses from the third (upper) disk and repeat Steps 5 through 7 to obtain $\omega_{n_{d32}}$ for the unloaded disk. If necessary, repeat Step 3 to reduce the execution (data sampling) duration.

¹You may "zoom" the plot via Axis Scaling for more precise measurement in various areas. For an even greater precision, the data may be examined in tabular numerical form – see Export Raw Data, Section 2.1.7.3 of manual.

9. Measure the reduction from the initial cycle amplitude X_o to the last cycle amplitude X_n for the n cycles measured in Step #8. Using relationships associated with the *logarithmic decrement*:

$$\frac{\zeta_{d32}}{\sqrt{1-\zeta_{d32}^2}} = \frac{1}{2\pi n} \ln \frac{X_o}{X_n} \rightarrow \zeta_{d32} = \frac{1}{2\pi n} \ln \frac{X_o}{X_n} \quad (\text{for small } \zeta_{d32}) \quad (2)$$

find the damping ratio ζ_{d32} and show that for this small value the approximations of Eq's (1 and 2) are valid.

10. Repeat Steps 5 through 9 for the lower disk, disk #1. Here in Step 6 you will need to remove Encoder #3 position and add Encoder #1 position to the plot set-up. Hence obtain ω_{nd11} , ω_{nd12} and ζ_{d12} . How does this damping ratio compare with that for the upper disk?
11. Use the following information pertaining to each mass piece to calculate the portion of each disk's inertia attributable to the four masses for the "d31" and "d11" cases.

mass (incl. bolt & nut) = 500g (\pm 5g)
diameter = 5.00 cm (\pm 0.02 cm)

The moment of inertial of each cylindrical mass about its axis is $J_{cyl} = 0.5 * mass * radius^2$ where *radius* is the cylinder's radius and *mass* is a single piece's mass. From the parallel axis theorem, the moment of inertial of the mass rotating about an axis displaced from its own axis by a distance R is

$$J_{each\ mass} = J_{cyl} + mass * R^2$$

So J_m for the four masses combined would be

$$J_m = 4 * (0.5 * mass * radius^2 + mass * R^2)$$

if *mass* = 500 g, *radius* = 0.025 cm, and $R = 0.09$ cm then $J_m = 0.016825$ kg-m².

12. Using this inertia J_m (i.e. that associated with the four masses combined), use the following relationships to solve for the unloaded disk inertia J_{d3} , and upper torsional shaft spring k_{d3} .

$$k_{d3}/(J_m + J_{d3}) = (\omega_{nd31})^2 \quad (3)$$

$$k_{d3}/J_{d3} = (\omega_{nd32})^2 \quad (4)$$

Find the damping coefficient c_{d3} by equating the first order terms in the equation form:

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = s^2 + c/J_s + k/J \quad (5)$$

Repeat this for the lower unloaded disk inertia (this includes the reflected inertias of the motor, belt, and pulleys), spring and damping J_{d1} , c_{d1} and k_{d1} respectively.²

Now all dynamic parameters have been identified! Values for J_1 and J_2 for any configuration of masses may be found by adding the calculated inertia contribution of the masses to that of the unloaded disk³.

Day 2 Procedure

- 1) Read and follow the safety precautions in Attachment A at the end of this write-up. Note: All users must read and understand Attachment A (Ecp Manual Section 2.3, Safety) before performing any procedures described in this chapter.
- 2) Read through the unit description in Appendix C if you have not done this already.
- 3) Work through the ECP Executive Program Demonstration in Attachment B at the end of this writeup. However, instead of using the “default.cfg” in the handout use the one created for this lab, “lab2d_default.cfg”. Go through the procedures in Attachment B; it uses no masses on the disks and all disks are free to rotate so remove any bolts fixing the discs. Familiarize yourself with the operation of the ECP Executive program by completing the demonstration of the ECP Executive program. Note also the control settings may be different than the Attachment B values (the gains discussed in step 2 in Attachment B); record these in your logbooks. At the end of the demo you should have a good understanding of: loading configuration files, using the trajectory settings, executing a trajectory, and plotting data.
- 4) Use the "Export Raw Data" function under the "Data" menu to export acquired data, and then bring the data into the Excel program. This will be useful in storing data if you need. Learn how to export and plot data. Consult the TA or manual for assistance if needed.
- 5) Abort the control algorithm, just in case it is still active, since you should not added or remove masses with the control program activated. Measure the mass of two masses and position them 9 cm. from the shaft center line on encoder plate 2. Measure their distance to have an accurate number for this distance and an uncertainty estimate. Fix or lock disk 3 to prevent its rotational movement using the spacer, bolt and nut.

²Steps 11 and 12 may be done later, away from the laboratory, if necessary.

³In plant configurations where a disk is used in the center location, the inertia and damping parameters may be assumed to be the same as for the upper disk.

- 6) Using what you have learned in step 3) above, load the configuration file "lab2d_step.cfg". Go to the algorithm settings and record them. Go to the trajectory settings menu and record them. Return to the Setup Control Algorithm menu and implement the algorithm. Setup a plot of the encoder 1 and 2 position output. Execute the trajectory. Observe the plot of the data and do not delete this plot. Export the data to a file and determine the frequency of the oscillations at encoder 2. Using Equation (6) determine the effective spring constant $k_{effective}$ for both shafts attached in this configuration

$$k_{effective}/(J_m+J_d) = (\omega_n)^2 \quad (6)$$

where J_m is for two masses (about 0.0084 kg-m²), for J_d use the inertia found for disk 3 in Day 1 for disk 2, and use the measured natural frequency for ω_n . Drive the system again using the configuration file "lab2d_step.cfg", plot the data from the encoders 2 to determine the frequency of the oscillations determining again. Determine the torsional spring constant parameter value for the shafts again. Compare this spring constant to what you found for the individual shafts on day 1 (one between encoders 1 and 2, and the other between encoders 2 and 3). Repeat this several times and estimate a repeatability error for $k_{effective}$.

- 7) Press the "Abort Control" button. Move the masses to a position 5 cm from the shaft centerline. Implement the algorithm/configuration file "lab2d_step.cfg" again, and execute the trajectory. Export the data to a file and determine and record the natural frequency. Determine the torsional spring constant parameter value $k_{effective}$ once more from the measured natural frequency and the new rotational inertia at the 5 cm position. Repeat this several times and estimate a repeatability error. Does the value of $k_{effective}$ change, and why should it or should it not change?
- 8) Press the "Abort Control" button. Add two more masses to the remaining slots on the plate of encoder 2. Place all masses 9 cm from the shaft centerline also. Load the configuration file "lab2d_step.cfg". Implement the algorithm and execute the trajectory again. Export the data to a file and determine the natural frequency. Find the torsional spring constant parameter value again from the measured natural frequency. Repeat this several times and estimate a repeatability error. Does the value of $k_{effective}$ change from that in step 6) or 7), and why should it or should it not change?
- 9) This step can be done outside of lab, if desired. Report on and discuss the effect of mass and radial position on natural frequency and polar moment of inertia for the torsional vibration system. Determine whether the dependence is linear or non-linear. Plot the natural frequency and polar moment of inertia versus mass and position from shaft centerline. Is the damping Coulomb- or viscous-type damping?

- 10) Press the "Abort Control" button. Load the configuration file "lab2d_sine_low.cfg". Record the control and trajectory settings. Implement the algorithm and execute the sine input trajectory. Observe the data plot of the two encoder positions. Is the system response at encoder 2 over- or under-damped relative to the motion input at encoder 1? Record the amplitude and frequency data, and note the steady state time-delay between the two encoders. This time delay can be used to determine the phase shift.
- 11) Repeat the steps in 10) by loading, and running each of the following configuration files:
 "lab2d_sine_transmission.cfg"
 "lab2d_sine_resonance.cfg"
 "lab2d_sinefilter1.cfg"
 "lab2d_sinefilter2.cfg".

Record the amplitude and frequency data for each file run, and note the steady state time-delay between the two encoders for each case. This time delay can be used to determine the phase shift in the next step that you will complete outside the lab.

- 12) Outside of lab, make your own frequency response plots like Figure 3.16 and 3.17 in your text for Magnitude ratio and Phase shift, respectively (see plots repeated below). However, your plots should have one theoretical curve corresponding the damping ratio you estimate best fits all of your data, and five experimental data points corresponding to the five frequency ratios (ω/ω_n) executed in steps 10) and 11). Use ω_n determine for the four masses on plate 2 in step 8).

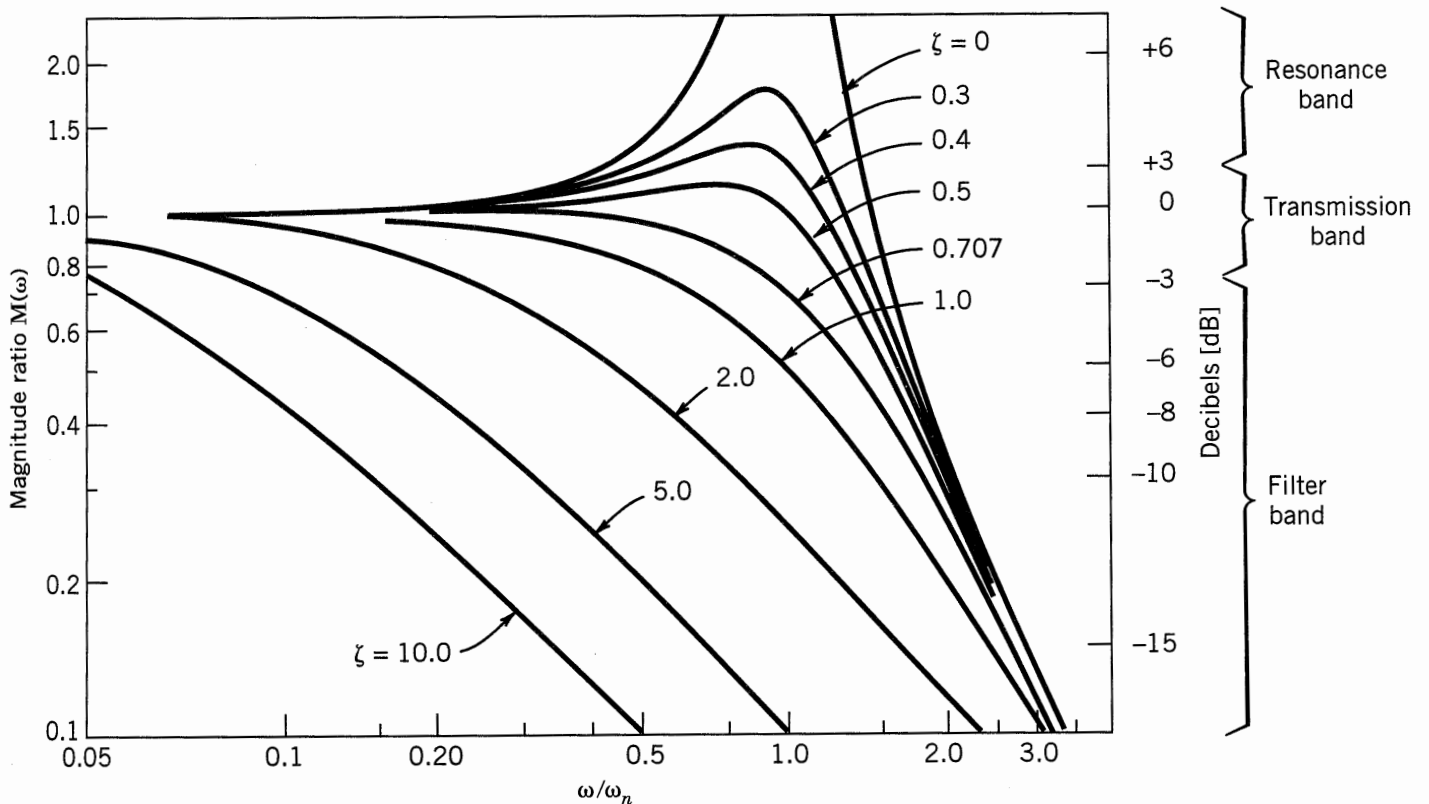


Figure 3.16 Second-order system frequency response: magnitude ratio.

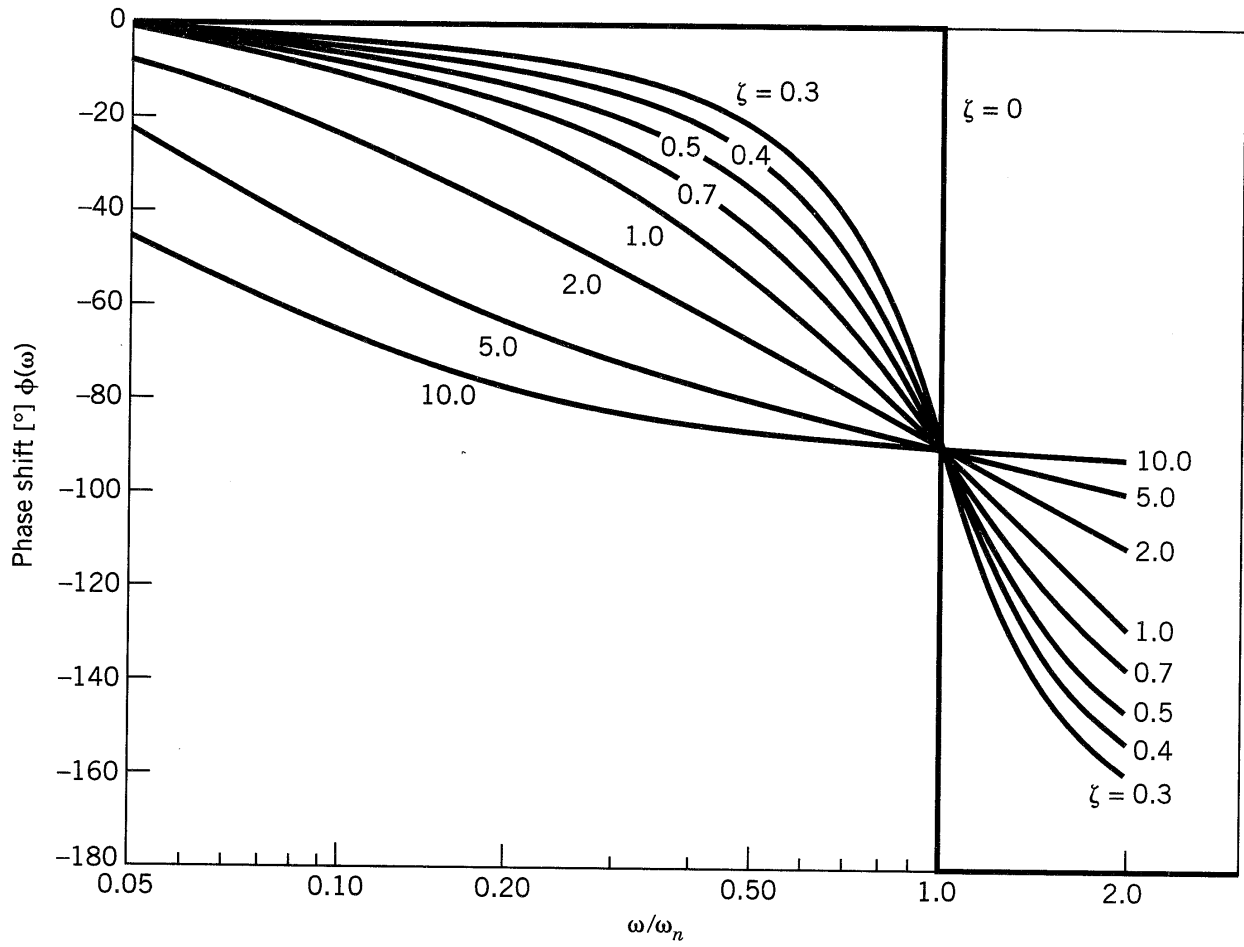


Figure 3.17 Second-order system frequency response: phase shift.

REFERENCE

- [1] Figliola, Richard S., and Donald E. Beasley.” Theory and Design for Mechanical Measurements” 5th Ed. ,Wiley, 2011.

Appendix A: Safety

The following are safety features of the system and cautions regarding its operation. This section must be read and understood by all users prior to operating the system. If any material in this section is not clear to the reader, contact ECP for clarification before operating the system.

Important Notice: In the event of an emergency, control effort should be immediately discontinued by pressing the red "OFF" button on front of the control box.

A.1 Hardware

A relay circuit is installed within the Control Box which automatically turns off power to the Box whenever the real-time Controller (within the PC) is turned on or off. Thus for the PC bus version⁴ of the real-time Controller the user should turn on the computer prior to pressing on the black ON switch. This feature is implemented to prevent uncontrolled motor response during the transient power on/off periods. The power to the Control Box may be turned off at any time by pressing the red OFF switch.

Although not recommended, it will not damage the hardware to apply power to the Control-Box even when the PC is turned off. However, doing so does not result in motor activation as the motor current amplifier will be disabled. The *amplifier enable* signal input to the Control Box is connected to the real-time Controller via the 60-pin flat ribbon cable. This input operates in a normally closed mode. When power to the real-time Controller is off, this input becomes open which in turn disables the motor amplifier.

The recommended procedure for **start up** is as follows:

First : Turn on the PC with the real-time Controller installed in it.

Second: Turn on the power to Control Box (press on the black switch).

The recommended **shut down** procedure is:

First: Turn off the power to the Control Box.

Second: Turn off the PC..

FUSES: There are two 3.0A 120V slow blow fuses within the Control Box. One of them is housed at the back of the Control Box next to the power cord plug. The second one is inside the box next to the large blue colored capacitor.

⁴The majority of this section pertains to the PC bus installation of the real-time controller. For the controller box/RS-232 version, the control box should generally be powered on before entering the executive software.

A.2 Software

The Limit Exceeded indicator of the Controller Status display indicates either one or more of the following conditions have occurred:

- Over speed of the motor
- Excessive deflection (twisting) of the torsion shaft
- Excessive drive motor power

The real-time Controller continuously monitors the above limiting conditions in its background routine (intervals of time in-between higher priority tasks). When one of these conditions occurs, the real-time Controller opens up the control loop with a zero torque command sent to the actuator. The Limit Exceeded indicator stays on until a new set of (stabilizing) control gains are downloaded to the real-time Controller via the Implement Algorithm button of the Setup Control Algorithm dialog box, or a new trajectory is executed via the Command menu. Obviously the new trajectory must have parameters that do not cause the Limit Exceeded condition.

The Limit Exceeded indicator of the Disturbance Motor Status display indicates either one or both of the following conditions have occurred:

- Over speed of the disturbance motor.
- Excessive disturbance motor power

Also included is a *watch-dog timer*. This subsystem provides a fail-safe shutdown to guard against software malfunction and under-voltage conditions. The use of the watch-dog timer is transparent to the user. This shutdown condition turns on the red LED on the real-time Controller card, and will cause the control box to power down automatically. You may need to cycle the power to the PC in order to reinitialize the real-time Controller should a watch-dog timer shutdown occur.

A.3 Safety Checking The Controller

While it should generally be avoided, in some cases it is instructive or necessary to manually contact the mechanism when a controller is active. This should always be done with caution and never in such a way that clothing or hair may be caught in the apparatus. By staying clear of the mechanism when it is moving or when a trajectory has been commanded, the risk of injury is greatly reduced. Being motionless, however, is not sufficient to assure the system is safe to contact. In some cases an unstable controller may have been implemented but the system may remain motionless until perturbed – then it could react violently.

In order to eliminate the risk of injury in such an event, you should always safety check the controller prior to physically contacting the system. This is done by lightly grasping a slender, light object with no sharp edges (e.g. a ruler without sharp edges or an unsharpened pencil) and using it to slowly move either the load or drive disk from side to side. Keep hands clear of the mechanism while doing this and apply only light force to the disk. If the disk does not spin up or oscillate then it may be manually contacted – but with caution. This procedure must be repeated whenever any user interaction with the system occurs (either via the Executive Program or the Controller Box) if the mechanism is to be physically contacted again.

A.4 Warnings

WARNING #1: Stay clear of and do not touch any part of the mechanism while it is moving, while a trajectory has been commanded (via Execute, Command menu), or before the active controller has been safety checked – see Section A.3.

WARNING #2: The following apply at all times except when motor drive power is disconnected (consult ECP if uncertain as to how to disconnect drive power):

- a) Stay clear of the mechanism while wearing loose clothing (e.g. ties, scarves and loose sleeves) and when hair is not kept close to the head.
- b) Keep head and face well clear of the mechanism.

WARNING #3: Verify that the masses and inertia disks are secured prior to powering up the Control Box or transporting the mechanism.

WARNING #4: Do not take the cover off or physically touch the interior of the Control Box unless its power cord is unplugged (first press the "Off" button on the front panel) and the PC is unpowered or disconnected.

WARNING #5: The power cord must be removed from the Control box prior to the replacement of any fuses.

Attachment B: Demonstration of ECP Executive Program

This section walks the user through the functions of the system. By following the instructions below you will actually implement a controller, maneuver the system through various trajectories, and acquire and plot data.

Step 1: Loading A Configuration File. With the power to the Control box turned off, enter the ECP Executive program. You should see the Background Display. Turn on power to the Control Box (press on the black button). Now enter the File menu, choose Load Setting and select the file `default.cfg`. In fact, it would have been loaded into the Executive automatically upon startup. This particular `default.cfg` file contains the controller gain parameters and other trajectory, data gathering and plotting parameters specifically saved for the activities within this section.

Note again that this file has been created to operate with a plant with three disks with no extra (brass) weights attached.

Step 2: Implementing The Controller. Now enter the Setup menu and choose Setup Control Algorithm. You should see the sampling time $T_s = 0.004420$ seconds, Discrete Time control type, and State Feedback control selected. Select Setup Algorithm; you should see for Model 205a the following gains: $k_{pf}=0.935$, $k_1=1.0074$, $k_2=4.9957$, $k_3=-0.07867$, $k_4= 5.27106$, $k_5=0.00533$ and $k_6=5.510$. This controller was designed using linear quadratic regulator (LQR) synthesis techniques with all error weighting on encoder 3.

Exit this dialog box and select Implement Algorithm. The control law is now downloaded to the real-time Controller. Use a ruler to verify that control action is in effect on the lower disk. If you do not notice any motor power, click on the Implement Algorithm button again until you notice the servo loop closed. Now select Upload Algorithm, then General Form and Setup Algorithm. You should see the general form of the real-time algorithm with some non-zero coefficients. These coefficients correspond to the state feedback gains mapped to a form suitable for execution via the general form algorithm. Note that the general form algorithm is the only structure that actually runs in real-time. All other structures (e.g. PID, dynamic filters, etc.) are translated to the general form by the Executive prior to implementation.

Step 3: Setting Up Data Acquisition. Enter the Data menu and select Setup Data Acquisition. In this box make sure that the following four items are selected: Commanded Position and Encoders 1,2, & 3. *Data sample period* should be 2 which means that data will be collected every second servo cycle (in this case every $2*0.00442=0.00884$ seconds).

Step 4: Executing A Step Input Trajectory & Plotting. Enter the Command menu and select Trajectory. In this box select Step and then Setup. You should see *step size* = 1000, *dwell time* =1000 ms and *no. of repetitions* = 1. If not, change the values to correspond to this parameter set. Exit this box and go to the Command menu. This time select Execute and with the Sample Data check box checked run the trajectory. You should have noticed a step move of 1000 counts, a dwell of 1 second and a return step move. Wait for the data to be uploaded from the real-time Controller to the Executive program running on the PC. Now enter the Plotting menu and choose Setup Plot. Select Encoder 3 and Commanded Position for plotting (left axis) and select Plot Data.

You should see a plot similar to the one shown in Figure 5. Replace Encoder 3 with 2 via the Setup Plot box and then with Encoder 1, plotting the data each time. Similar plots to the ones shown in Figures 6 and 7 should be seen. Note that all plot screens may be repositioned by dragging the plot frame bar using the mouse. A plot screen may be minimized or "shrunk" by clicking on the left most button on the top right hand corner. By double clicking on a minimized plot screen it may be expanded again. In general, to limit the program memory usage, one should avoid minimizing more than 8 to 10 plot screens on the Background screen. It is best to close unwanted plot screens rather than minimize them. You can re-size the plots using the cursor to "drag" any edge of the plot frame (position cursor at corner and begin "dragging" when cursor becomes double arrow).

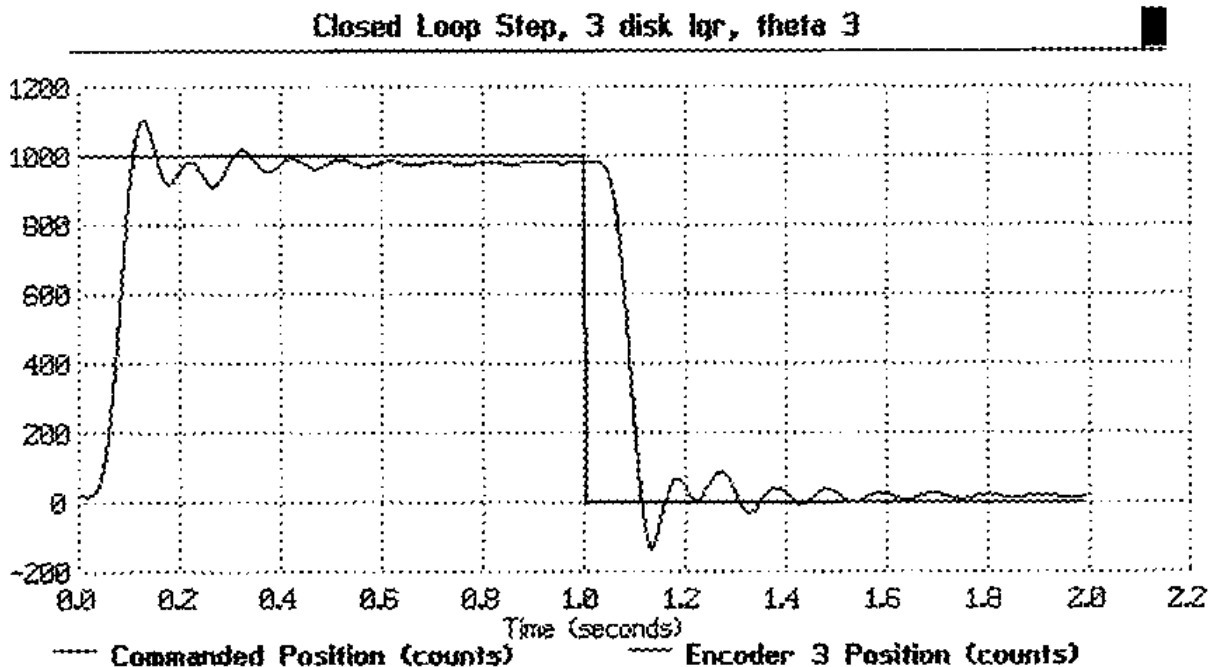


Figure 5 Step Response at Encoder 3

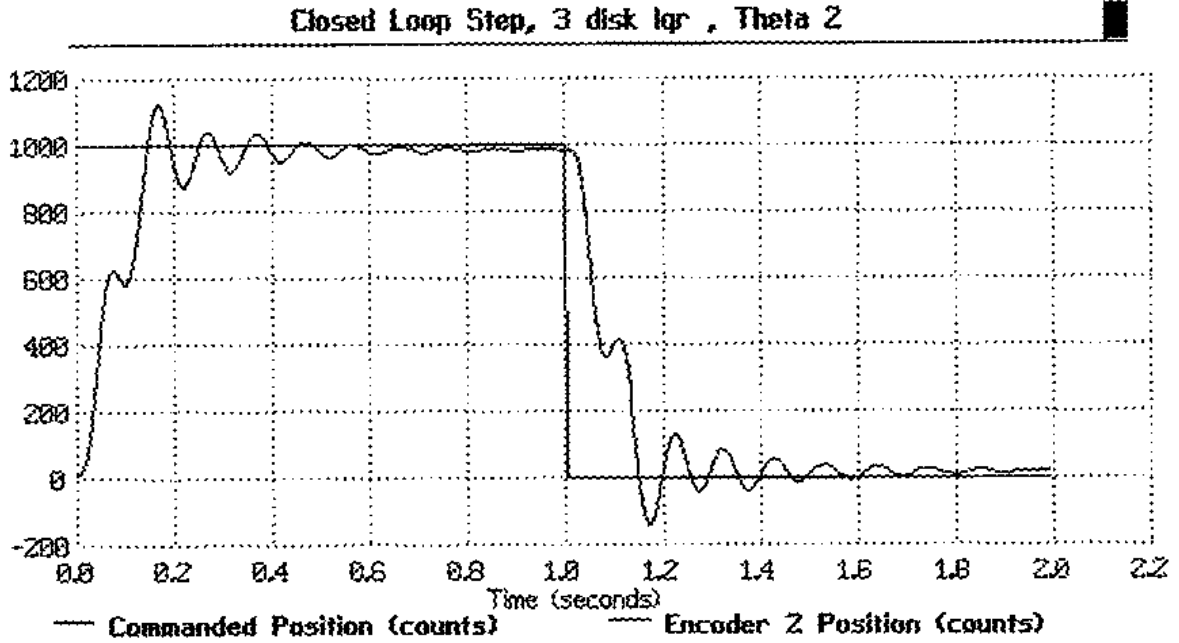


Figure 6 Step Response at Encoder 2

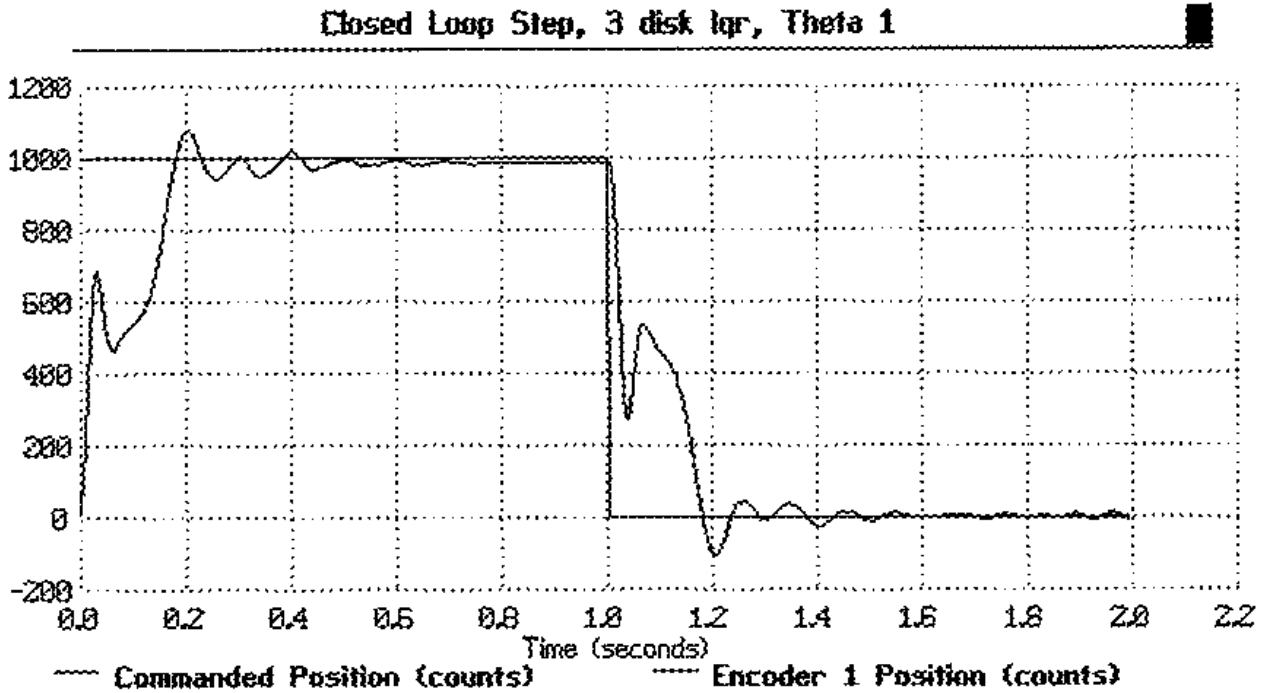


Figure 7 Step Response at Encoder 1

Appendix C: Electromechanical Plant

C.1 Design Description

The plant, shown in Figure 8, three (Model 205a) disks supported by a torsionally flexible shaft which is suspended vertically on anti-friction ball bearings. The shaft is driven by a brushless servo motor connected via a rigid belt (negligible tensile flexibility) and pulley system with a 3:1 speed reduction ratio. As shown in Figure 8 there is an encoder at each disk location. An encoder located on the base of the shaft measures the angular displacement, θ_1 of the first disk, J_1 . The second and third disk is connected to its encoder by a rigid belt / pulley with a 1:1 speed ratio.

Figure 9 also shows the variety of plant types that are supported by each model. Mathematical modeling and parameter identification of these plants are given in the Unit Manual, Chapters 5 and 6.

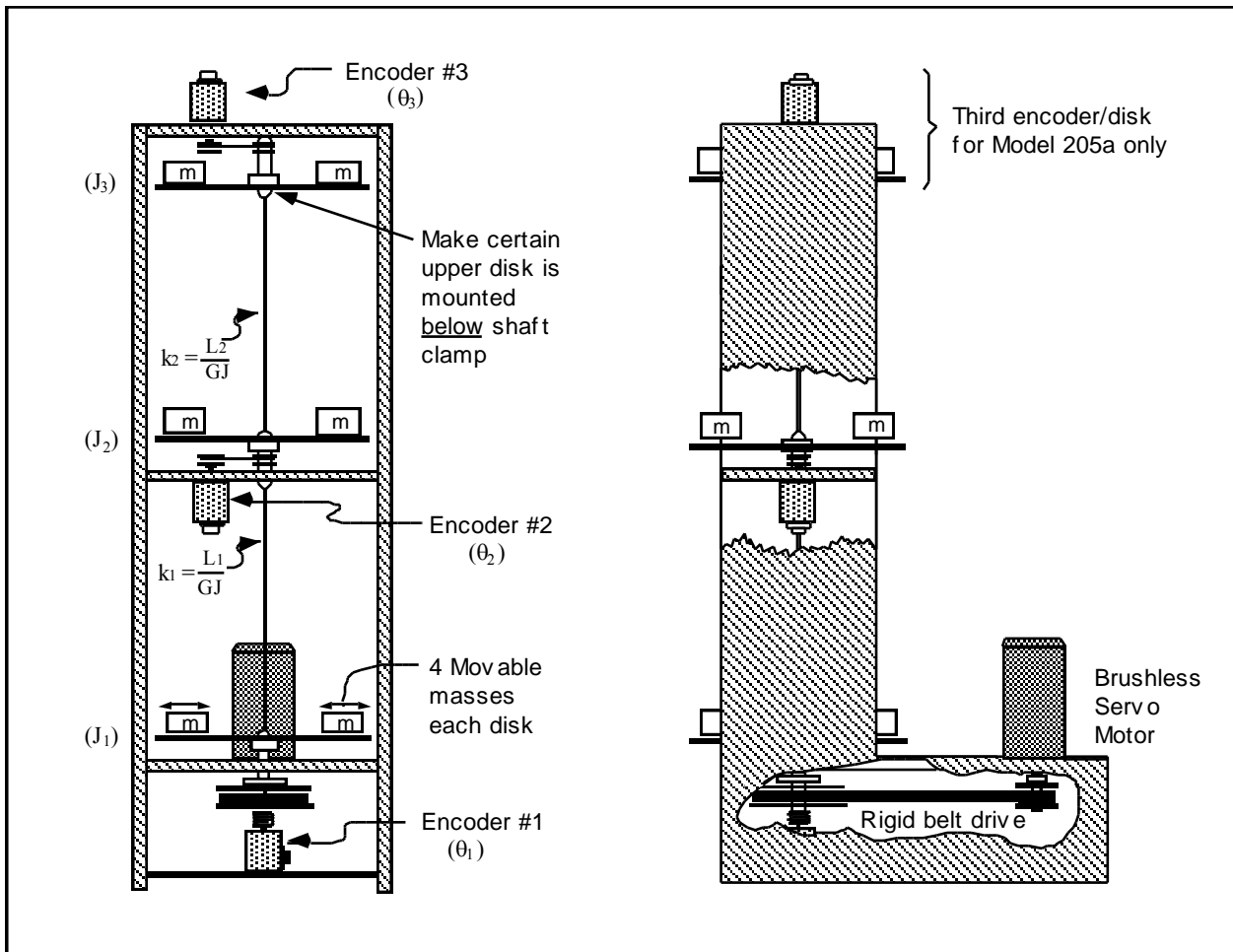


Figure 8 Torsion Spring / Inertia Apparatus

Spring / Inertia / Encoder Configurations			DIR		
Plant Model					

Figure 9 Plant configurations

C.2 Changing Plant Configurations and Parameter Values

As shown in Figure 9, the plant may be placed in a variety of free and clamped configurations with 1, 2, and 3 (Model 205a) degrees of freedom (DOF). Changing configurations often requires removing or replacing inertia disks. It is important to keep each pair of half-disks together in matched sets (see inscribed letters on disk edges). By aligning the concentric markings, the proper relative alignment of the two halves is assured. For operating safety, be sure to firmly tighten (but not excessively so) the bolts that fasten the disks to the shaft clamps.

The user may change inertia values by changing the number of masses and/or their location on a given disk. Figure 10 gives instructions for physically changing inertias.

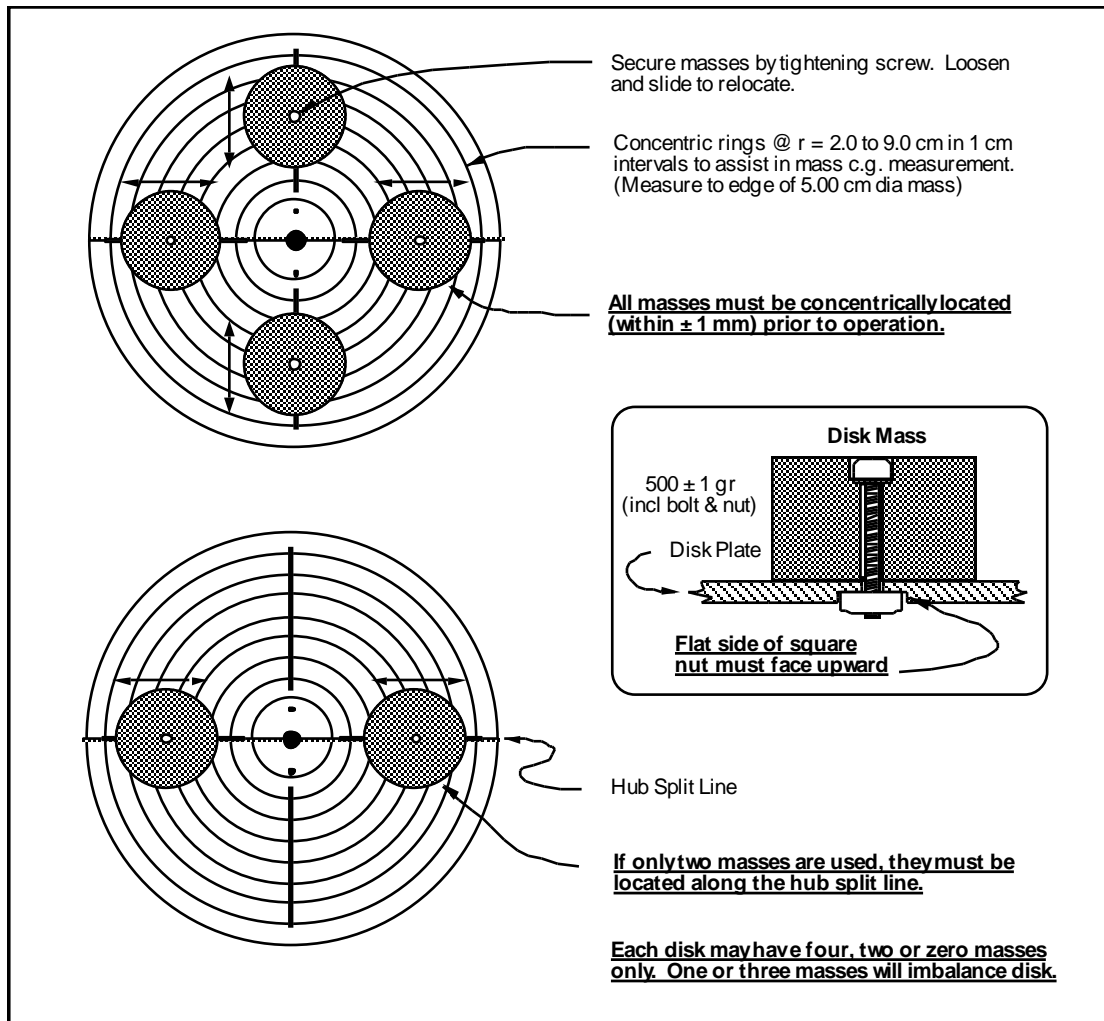


Figure 10 Guidelines For Changing Or Adjusting Disk Masses

The user should verify that the disks, belts, and pulleys are properly aligned and secured and rotate freely prior to operation.