Model 220 Industrial Plant Emulator Experiments

1. Plant Identification. Identifies the plant inertias, spring constants, damping, gear ratios, and hardware gains. (similar to test series #1 in the Model 205 $ 210 Experiments)

2. Fundamentals Of Second Order Systems. This series of experiments and exercise is essentially identical to test series #2 in the Model 205 $ 210 Experiments (see also Figure 2).

3. Disturbance Attenuation. These tests are similar to series #3 in the Model 205 & 210 Experiments (see Figure 3) with the additional study of the effect of gear ratio in low and high frequency disturbance attenuation. (utilizes built-in secon-dary drive, does not require additional drive accessory)

4. Collocated Control With 2 DOF Plant. This experiment implements *collocated* (sensor & actuator at same location) closed loop control on the "Free-Free, 2-DOF" plant and shows that acceptable performance is achievable under high gain control at the collocation (drive), but an oscillatory response results at the noncollocation (load). The oscillations may be reduced under lower gain but reduced collocated performance and increased steady-state error result. See Figures 6 and 7a,b.

5. PID Plus Notch Filter Control. *Noncollocated* control is demonstrated using a notch filter to suppress the oscillatory plant dynamics. Similar to test series #5 in the Model 205 & 210 Experiments. See Figure 6c for tracking response.

6. Full State Feedback LQR Control. This experiment designs and implements an LQR controller for noncollocated control of the SIMO plant. Experimental results show the effectiveness of the scheme in dealing with structural flexibility. Similar to test series #6 in the Model 205 & 210 Experiments (see Figure 4). See Figure 6d for tracking response.

7. Practical Control Issues. This series of experiments addresses non-ideal conditions often present in real-world industrial plants.

a. Gear Ratio & Inertia. Shows by test and analysis the relationship between gear ratio, drive inertia, and load inertia and their affects on system gain. Demonstrates why most modern servo systems employ large gear ratios with minimal drive inertia.

b. Friction. Studies the effect of friction on steady state error and shows error reduction (for a given system bandwidth) with increased gear ratio and with noncollocated sensing when drive flexibility is present. Introduces the concept of *static servo stiffness*, and shows that this parameter becomes infinite (hence zero steady state error) when integral action is added.

c. Drive Saturation: Shows that drive saturation can lead to significant reduction in rise time, large following errors and limit cycle instability in extreme cases. (see Figure 8) Shows the effect of gear ratio on saturation and that saturation is increased when the gear ratio is either above or below some optimal value. The optimal value is obtained analytically.

d. Discrete Time Sampling: Examines the effect of sampling period, Ts, on instability and empirically obtains the maximum Ts before instability onset for low and high bandwidth systems (see Figure 8). A relationship is developed between continuous-time phase margin, crossover frequency, and sample-and-hold phase loss and is used to establish guidelines for maximum practical Ts for a given system.

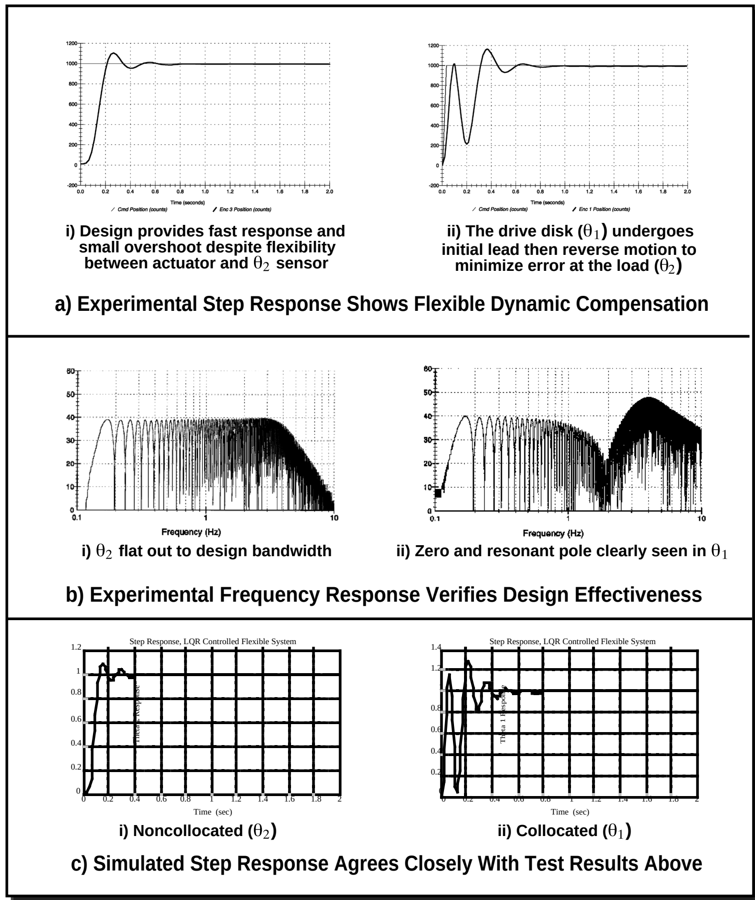


Figure 4. LQR Tests Demonstrate Effective Flexible Structure Control and Agreement of System With Dynamic Model

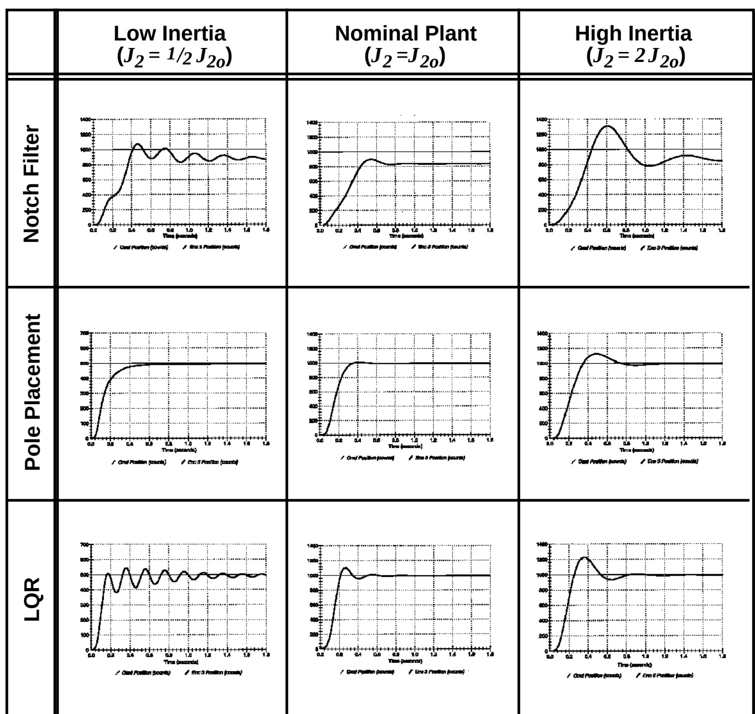


Figure 5. Robustness Tests Show Effect of Payload Changes On The Step Response of Various Control Systems

In the experiments, the frequency responses are also measured and stability margins studied

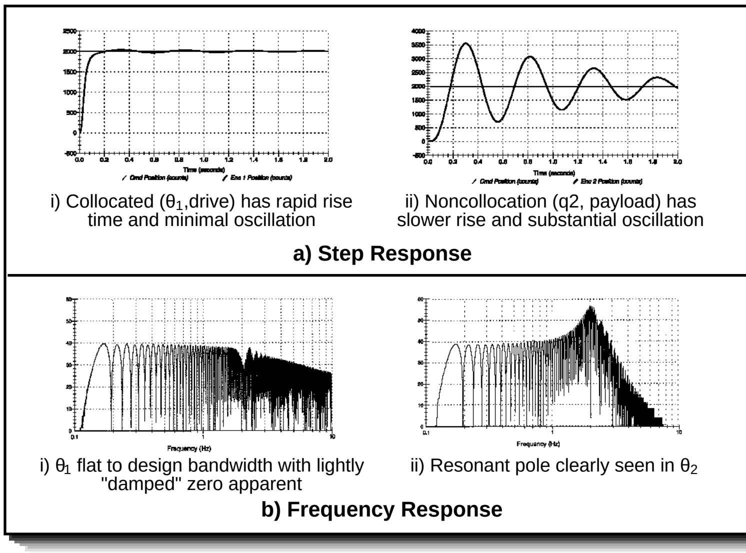
7. Practical Control Issues (contd.).

e. Sensor Quantization: Shows that with high bandwidth control terms, control effort quantization and hence noise propensity is inversely proportional to sensor resolution and Ts. This relationship is demonstrated for several control gains and sample periods.

f. Drive Flexibility: Studies various collocated and noncollocated control schemes, as described in 4 through 6 above to characterize and mitigate the effects of drive flexibility. A comparison of the various control schemes is shown in Figures 6 and 7. (see also Figures 4 and 5)

g. Backlash: Examines backlash effects in the context of collocated control in both tracking and regulation (including output disturbances). Then, implements a noncollocated scheme which significantly reduces the effect of backlash.

8. Any Topic You Choose! The versatility of the reconfigurable apparatus and interface software support the study of virtually any topic in control systems. The Model 220 apparatus is well suited to study a broad range of practical control problems. All experimental topics described on page 14 are applicable here.



i) Collocated (θ_1,drive) has rapid rise time and minimal oscillation

ii) Noncollocation (q2, payload) has slower rise and substantial oscillation

a) Step Response

i) θ_1 flat to design bandwidth with lightly "damped" zero apparent

ii) Resonant pole clearly seen in θ_2

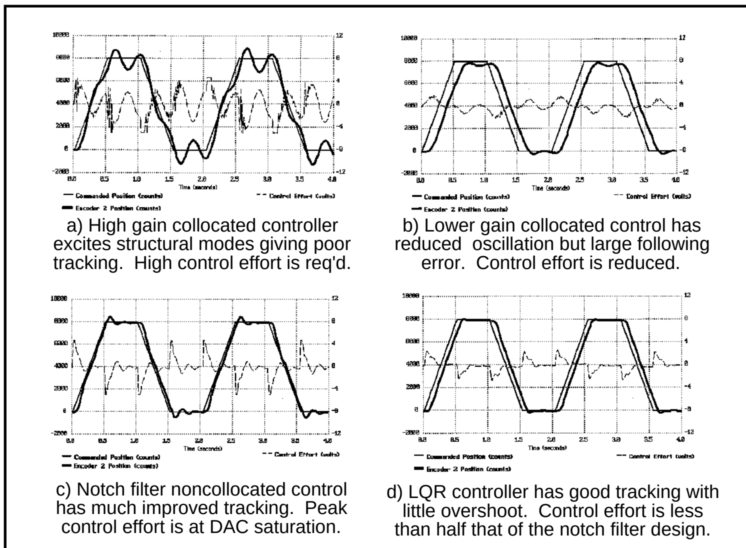
b) Frequency Response

Figure 6. 2DOF Collocated Design Gives Well-behaved Results at the Acuator But Oscillatory Response at the Load

Model 505, ECP Inverted Pendulum Experiments

1. Plant Identification. Identifies the plant parameters, and control gains using classical techniques and uses these to construct numerical plant models for control design.

2. Successive Loop Closure Design: This experiment first implements a high bandwidth control loop about x(s)/F(s) so that x(s)/c*(s) is nearly 1 through the control bandwidth. (Here c*(s) is the control effort in the subsequent outer loop). An outer loop is designed to meet certain performance requirements for the new "plant" θ(s)/x(s). (Pole placement technique is described in the manual, other methodologies are readily supported.) Typical test data are shown in Figure 9 where the characteristic nonminimum phase undershoot is obvious in both a step and ramp following closed loop responses. This approach is implemented in cases where θ(s)/x(s) is both stable and unstable. The implications of the open loop instability and right half plane zero to stability and performance of the closed loop system are investigated.



a) High gain collocated controller excites structural modes giving poor tracking. High control effort is req'd.

b) Lower gain collocated control has reduced oscillation but large following error. Control effort is reduced.

c) Notch filter noncollocated control has much improved tracking. Peak control effort is at DAC saturation.

d) LQR controller has good tracking with little overshoot. Control effort is less than half that of the notch filter design.

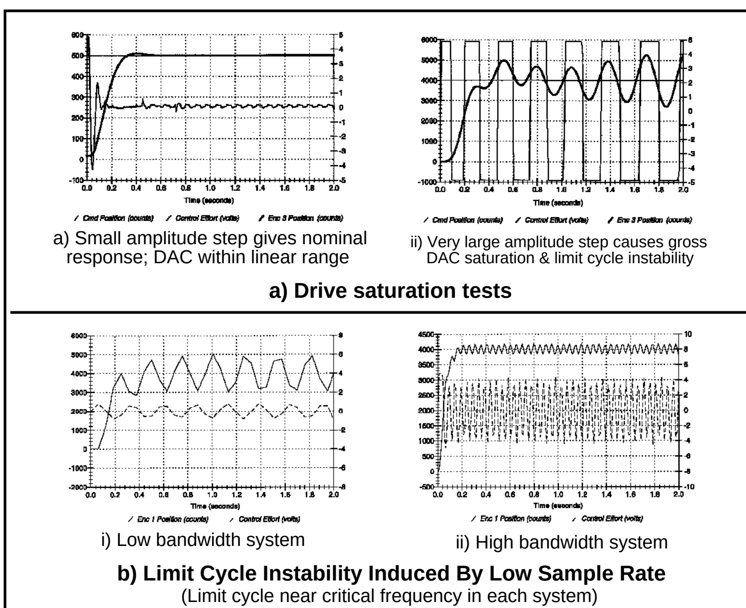
Figure 7. Tracking Tests Show Large Differences In System Performance

3. Dynamic Filter Controller Augmentation: A method for augmenting control with cascaded dynamic filters is given. It is used to implement a low pass filter for noise suppression in the controllers described above.

4. LQR Control Design: LQR synthesis is employed where the states are the pendulum and balance rod positions and rates and with the error weighting exclusively on the state of the pendulum rod angle. Controllers are designed for a spectrum of control effort weights and well-behaved control of this dynamically complex system is demonstrated for a range of gains. An optional exercise involves experimental determination of gain margin.

5. Tracking Control: Various trajectories are executed on systems using the above controllers. Reduction of following error and peak control effort through use of higher order input trajectory is demonstrated. The phase and gain characteristics are studied via sine sweep responses where the extra phase lag due to the nonminimum phase zero is apparent.

6. Additional Topics: Many more experiments are readily performed. In general, those described on page 14 are applicable.



a) Small amplitude step gives nominal response; DAC within linear range

ii) Very large amplitude step causes gross DAC saturation & limit cycle instability

a) Drive saturation tests

i) Low bandwidth system

ii) High bandwidth system

b) Limit Cycle Instability Induced By Low Sample Rate
(Limit cycle near critical frequency in each system)

Figure 8. Practical Control Tests Demonstrsate Important Issues

Model 730, Magnetic Levitator Experiments

The MagLev apparatus incorporates a variety of features that let you easily perform SISO, SIMO, and MIMO experiments, on nonlinear or linearized plants in open loop stable and unstable forms and apply programmable disturbances to the SISO and MIMO configurations.

1. Plant Identification. Identifies the plant parameters, nonlinear magnetic field characteristic, and control gains and constructs numerical plant models for control design.

2. Nonlinear Plant Control: Demonstrates that the linearized model of the system is valid for small excursions about the operating point but yields anomalous behavior for large excursions. As seen in Figure 10a, the large amplitude step response is grossly asymmetric, exhibiting high gain (high damping ratio, low steady-state error) in the negative direction and low gain in the positive direction. It is shown that large negative motion can result in instability. These tests are conducted on both the open loop stable (repulsive levitation) and unstable (attractive levitation) plant configurations.

3. Nonlinear Plant Compensation: The strong nonlinearity measured in the plant identification experiments is inverted in the real-time algorithm, and a linear controller is designed for the combined linear pseudo-plant. As seen in Figure 10b, the resulting system exhibits linear response characteristics and relatively high performance.

4. Fundamentals Of Second Order Systems. These experiments and exercises utilize the nonlinear compensation routine above to effect a simple second order system. These experiments parallel those described in test series #2 in the Model 205 $ 210 Experiments (see Figure 2).

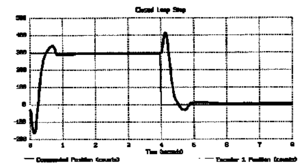
5 Disturbance Attenuation. These tests use the second actuator coil to apply disturbances to an SISO configuration with several controllers. These experiments parallel those described in test series #3 in the Model 205 $ 210 Experiments (see Figure 3).

6. Collocated SIMO Design: This experiment uses two magnets oriented in an inter-magnet repulsive configuration and implements collocated control about the first magnet. The resulting system has relatively well-behaved performance characteristics at the collocated (proximal) magnet, but is highly oscillatory at the noncollocated (distal) one. These results are similar to those seen in Figure 6.

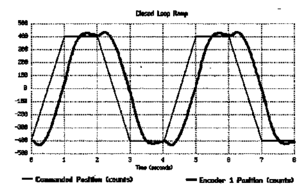
7. Noncollocated SIMO Design For the same configuration as in #6, a successive loop, pole placement scheme is employed for noncollocated control of the second magnet. This is shown to provide tight tracking and improved disturbance rejection over the collocated approach. Step and frequency responses are similar to those of Figure 4.

8. MIMO Design These tests use two magnets and two actuators with force interaction between each magnet and both actuators and the other magnet. Independent controllers are first implemented and are shown to have significant coupling in the outputs as seen in Figure 11a. Full multivariable control synthesis is then employed which yields effective independent control of the outputs (Figure 11b). The the closed loop system is characterized via experimental singular value plots as shown in Figure 12.

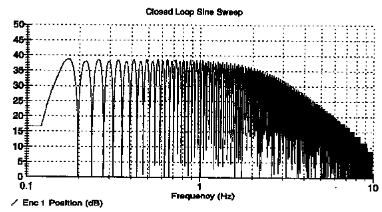
9. Any Topic You Choose! The versatility of the reconfigurable apparatus and interface software support the study of virtually any topic in control systems. All experimental topics described on page 14 are applicable here.



a) Step response of successive loop controlled system shows characteristic nonminimum phase undershoot

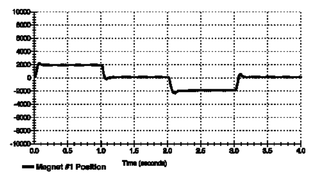


b) Ramp tracking has reduced undershoot and overshoot relative to step

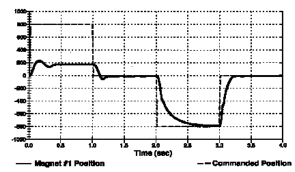


c) Frequency response agrees well with design goal (3rd order Butterworth polynomial, 1 Hz). Attainable closed loop bandwidth is bounded from below by RHP poles, and from above by RHP zeros

Figure 9. Inverted Pendulum Test Results Show Nonmimimum Phase and Bandwidth Limitations Inherent In Plant

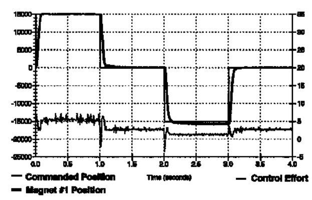


i) For small motions, bipolar step response is roughly symmetrical

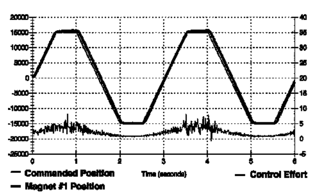


ii) Large motion response grossly asymmetrical: low gain in positive direction, high gain in negative

a) Response Of Nonlinear System Varies With Amplitude



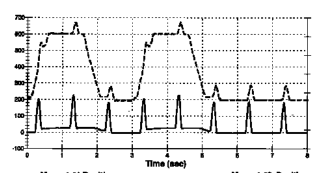
i) Large amplitude bipolar step is symmetrical and exhibits relatively high performance, control effort is asymmetric



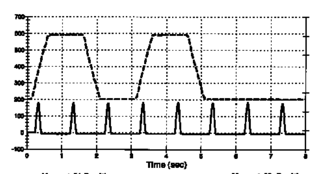
ii) Relatively close tracking is obtained. Control effort is asymmetric as nonlinearity is compensated

b) Nonlinear Compensation Effective In Inverting Nonlinearity

Figure 10. Tests Show Nonlinear Magnetic Field Characteristic and Effective Compensation



a) Independent SISO control of each magnet yields substantial output coupling



b) Full multivariable controller provides independent output control

Figure 11. MIMO Tests Show High Performance Multivariable Control

Model 750, Control Moment Gyroscope Experiments

The Control Moment Gyroscope is a dynamically rich platform that you can easily transform into a variety of linear and nonlinear SISO, SIMO, and MIMO plants, for experiments ranging from elementary to highly complex. (See Model 750 apparatus description for axis definitions used below.)

1. Plant Identification. Identifies the plant parameters through physical measurements involving conservation of angular momentum and the gyroscopic properties of nutation and precession.

2. Gyroscopic Dynamics: Nutation & Precession: Students measure the nutation frequency and mode shape at various values of angular momentum (rotor speed). The mode-shape, seen in the upper plot of Figure 13a, shows Axes 2 and 4 to be 90 deg. out of phase (unlike the more typical 180 deg.), which leads to complex eigenvectors. The nutation frequency is shown to vary linearly with angular momentum. The mode is effectively damped (lower plot in Figure 13a) by applying rate feedback at Axis 2. Precession (ω) is measured by applying a step torque input (T) transverse to the rotor momentum (H) according to the gyroscopic cross product $T = \omega x H$ (Figure 13B).

3. Reaction Torque Control: The large inertia of the rotor is used as a reactive body for control of the inner gimbal assembly about Axis 3. A typical step response, shown in Figure 14a, shows the rotor speed is the integral of control effort according to conservation of angular momentum.

4. Fundamentals Of Second Order Systems. The configuration studied in #3 behaves as a second order system about Axis 3 and therefore serves as a testbed for this important fundamental topic. These experiments parallel those described in test series #2 in the Model 205 $ 210 Experiments (see Figure 2).

5 Gyroscopic Control – Successive Loop SIMO: An inner loop controls the transverse rotor rate about Axis 2 and an outer loop controls the position of the assembly about axis 4 using using torque produced via the gyroscopic cross product. As seen in Figure 14b, the Axis 2 rate has the same shape as conventional control effort (e.g. torque) does in a rigid body system.

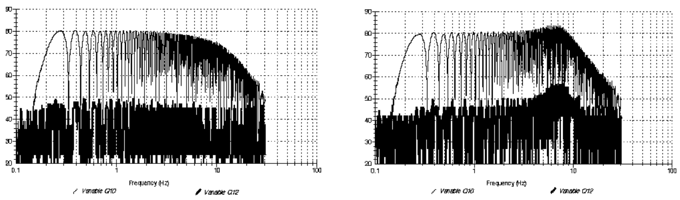
6. Gyroscopic Control – Pole Placement SISO: Control is implemented using only the Axis 4 sensor signal. The diophantine equation is solved to place the closed loop poles in a 5th order Butterworth pattern and the resulting system is characterized and shown to behave according to its design.

7. Gyroscopic Control – LQR. Full state feedback LQR methodology is utilized to produce high performance control. The three gyroscopic control methodologies are compared for various figures of merit as measured and analyzed in these tests.

8. Combined Reactive & Gyroscopic Control Axes 3 and 4 are controlled by independent reactive and gyroscopic loops. As seen in Figure 15a, this approach is shown to be effective when gimbal angles are zero (no nominal cross-coupling) but experiences gross output coupling for large off-nominal gimbal positions (Figure 15b).

9. Multi-variable Control Full multi-variable control is developed and implemented and is shown to provide largely decoupled output for large gimbal angles as seen in Figure 15b. Practical issues such as the large difference in control authority between gyroscopic and reactive actuation and the need for balancing the coupled system design are addressed.

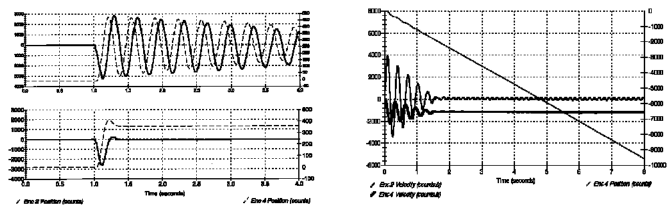
10. Any Topic You Choose! The versatility of the reconfigurable apparatus and interface software support the study of a broad range of control topics. All experimental topics described on page 14 are applicable here.



a) Sine sweep @ Input #1 shows flat response to design bandwidth in output #1 and virtually no response in output #2

b) Increased gain causes pole pair to approach imaginary axis resulting in resonance in both outputs

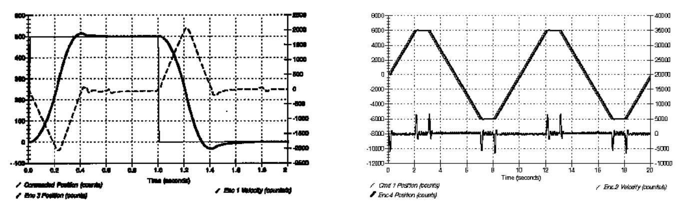
Figure 12. ECP's Experimental Singular Value Plot Function Shows Multivariable Frequency Domain Behavior



a) Upper plot: Nutation mode, 90 deg. phase between q_2 and q_4. Lower plot: effective nutation damping by q_2 rate feedback

b) Precession seen as constant slope in q_4. Transient excited by discontinuous step torque input

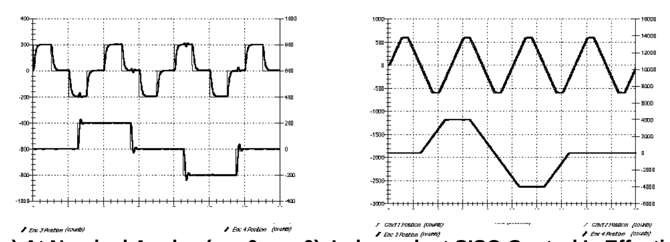
Figure 13. Dynamic Tests Show Nutation & Gyroscopic Precession



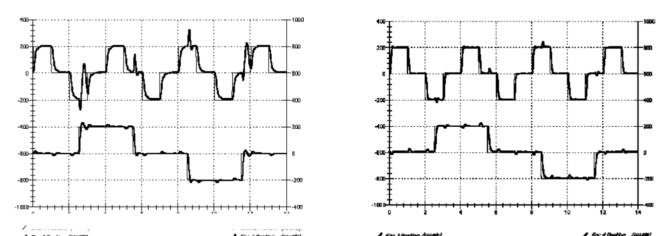
a) Reaction torque step response shows effective control of q_3, while uncontrolled rotor speed is integral of control effort

b) Gyroscopic control in ramp tracking: gimbal rate, ω_2 seen to act same as conventional control effort

Figure 14. SISO Data From Reactive & Gyroscopic Control Experiments Show Characteristic Properties



a) At Nominal Angles (q_2=0, q_3=0), Independent SISO Control Is Effective



i) Gross output coupling in independent SISO controlled system

ii) Multivariable control yields small output coupling

b) At Off-nominal Gimbal Angles (q_2=30°, q_3=30°), Multivariable Control Required To Minimize Output Coupling

Figure 15. MIMO Plant Tests Show Need For Multivariable Controller

- High speed processing
- Data acquisition
- Trajectory generation
- Safety limits

- Servo amplifier(s)
- Power supplies
- Analog signal out

- Operating instructions
- Theory
- Experiments with solutions
- Control software routines

- Servo actuator(s)
- Encoder feedback
- Adjustable dynamics

- Controller specification
- System commands
- Plotting
- Data import/export