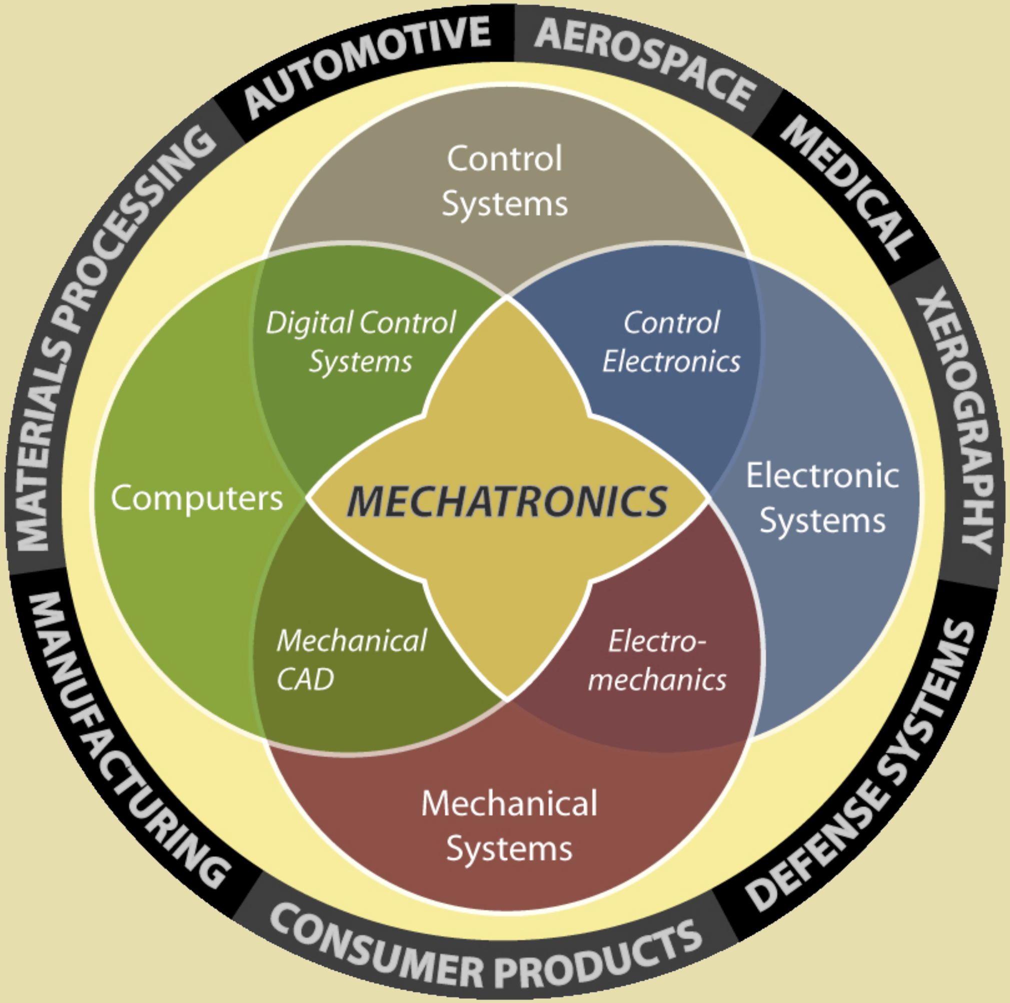
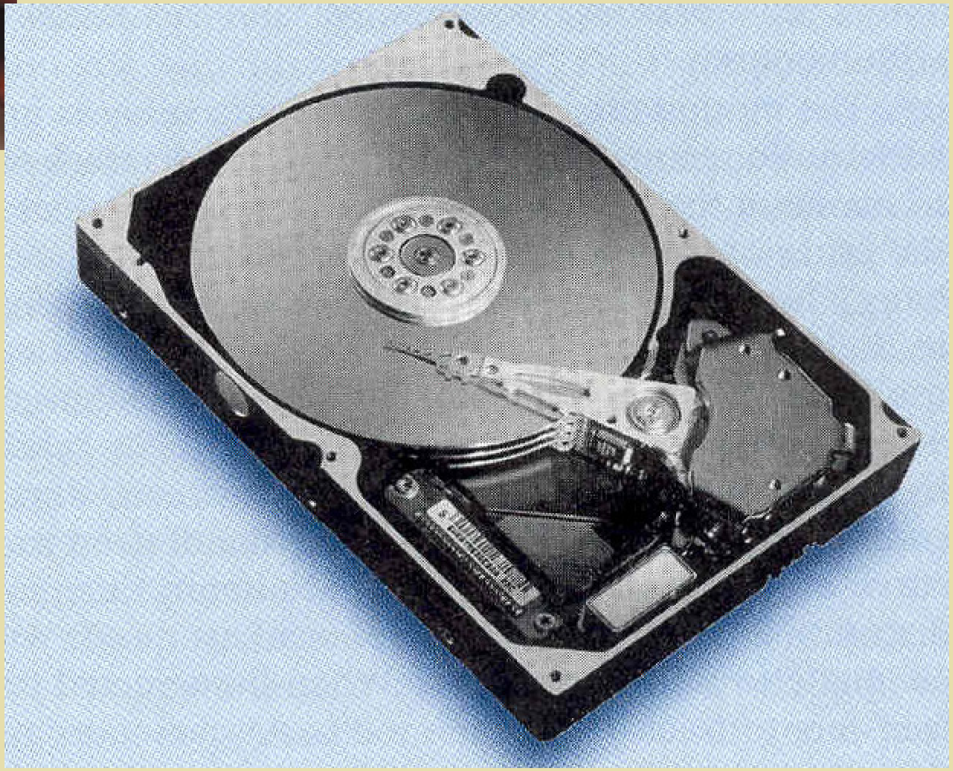
Computer Hard Disk Drive Case Study



100 GB
Hard-Disk Drive



Feedback Control System Design Procedure

- Control Engineering is an important part of the design process of most dynamic systems.
- The deliberate use of feedback can:
  - Stabilize an otherwise unstable system
  - Reduce the error due to disturbance inputs
  - Reduce the tracking error while following a command input
  - Reduce the sensitivity of a closed-loop transfer function to small variations in internal system parameters

- Remember that the purpose of control is to aid the product or process – the mechanism, the robot, the chemical plant, the aircraft, or whatever – to do its job.
- Engineers must take into account early in their plans the contribution of control to the design process! More and more systems are being designed so that they will not work without feedback!
- Control system design begins with a proposed product or process whose satisfactory dynamic performance depends on feedback for:
  - Stability
  - Disturbance Regulation
  - Tracking Accuracy
  - Reduction of the Effects of Parameter Variations

- Having a general step-by-step approach for feedback control system design serves two purposes:
  - It provides a useful starting point for any real-world controls problem.
  - It provides meaningful checkpoints once the design process is underway.

- Sequence of Steps for Feedback Control System Design

1. Understand the process and translate dynamic performance requirements into time, frequency, or pole-zero specifications.
    - The importance of understanding the process cannot be overemphasized!
    - Do not confuse the approximation with the reality!
    - You must be able to:
        - Use the simplified model for its intended purpose
        - Return to an accurate model or the actual physical system to really verify the design performance

2. Select the types and number of sensors considering location, technology, functional performance, physical properties, quality factors, and cost.
   - Which variables are important to control?
   - Which variables can physically be measured?
   - Select sensors that indirectly allow a good estimate to be made of the critical unmeasurable variables.
   - It is important to consider sensors for the disturbances, e.g., in chemical processes, it is often beneficial to sense a load disturbance directly because improved performance can be obtained if this information is fed forward to the controller.

3. Select the types and number of actuators considering location, technology, functional performance, physical properties, quality factors, and cost.
    - In order to control a dynamic system, you must be able to influence the response. The actuator does this.
    - Before choosing a specific actuator, consider which variables can be influenced.

4. Make a linear model of the process, actuator, and sensor.
   - Take the best choice for process, actuator, and sensor.
   - Identify the equilibrium point of interest.
   - Construct a small-signal dynamic model valid over the range of frequencies included in the performance specifications.
   - Validate this model with experimental measurements where possible.
   - Express the model in many forms: state-variable, pole-zero, and frequency response forms.
   - Simplify and reduce the order of the model, if necessary.
   - Quantify model uncertainty.

5. Make a simple trial design based on concepts of lead-lag compensation or PID control.
    - To form an initial estimate of the complexity of the design problem, sketch a frequency-response (Bode) plot and a root locus plot with respect to plant gain.
    - If the plant-actuator-sensor model is stable and minimum phase, the Bode plot will probably be the most useful; otherwise, the root locus shows very important information with respect to behavior in the right-half plane.
    - Try to meet specifications with a simple controller of the lead-lag, PID variety.
    - Do not overlook feedforward of the disturbances.
    - Consider the effect of sensor noise.

6. <u>Consider modifying the plant itself for improved closed-loop control</u>.
   - Based on the simple control design, evaluate the source of the undesirable characteristics of system performance.
   - Reevaluate the specifications, the physical configuration of the process, and the actuator and sensor selections in light of the preliminary design. Return to step 1 if improvement seems necessary or feasible.
   - It may be much easier to meet specifications by altering the process than to meet them by control strategies alone!
   - Consider all parts of the design, not only the control logic, to meet the specifications in the most cost-effective way.

7. Make a trial pole-placement design based on optimal control or other criteria.
   - If the trial-and-error compensators do not give entirely satisfactory performance, consider a design based on optimal control.
   - Select the location for your control poles that balance system performance and control effort.
   - Select the location for the estimator poles that represent a compromise between senor and process noise.
   - Plot the corresponding open-loop frequency response and the root locus to evaluate the stability margins of this design and its robustness to parameter changes.
   - Compare this optimal design with the transform-method design and select the better of the two.

8. Build a computer model and simulate the performance of the design.

- After reaching the best compromise among process modification, actuator and sensor selection, and controller design choice, run a simulation of the system.
- Include important nonlinearities, parasitic effects, and parameter variations you expect to find during operation.
- Design iterations should continue until the simulation confirms acceptable stability and robustness.
- As the design progresses, more complete and detailed models ("truth models") will be used.
- If the performance is not satisfactory, return to step 1 and repeat. Consider modifying the plant itself for improved closed-loop control.

9. Build a prototype and test it.
   - At this point you verify the quality of the model, discover unexpected effects, and consider ways to improve the design.
   - Implement the controller using an embedded software/hardware.
   - Tune the controller, if necessary.
   - After these tests, you may want to reconsider the sensor, actuator, and process and return to step 1.

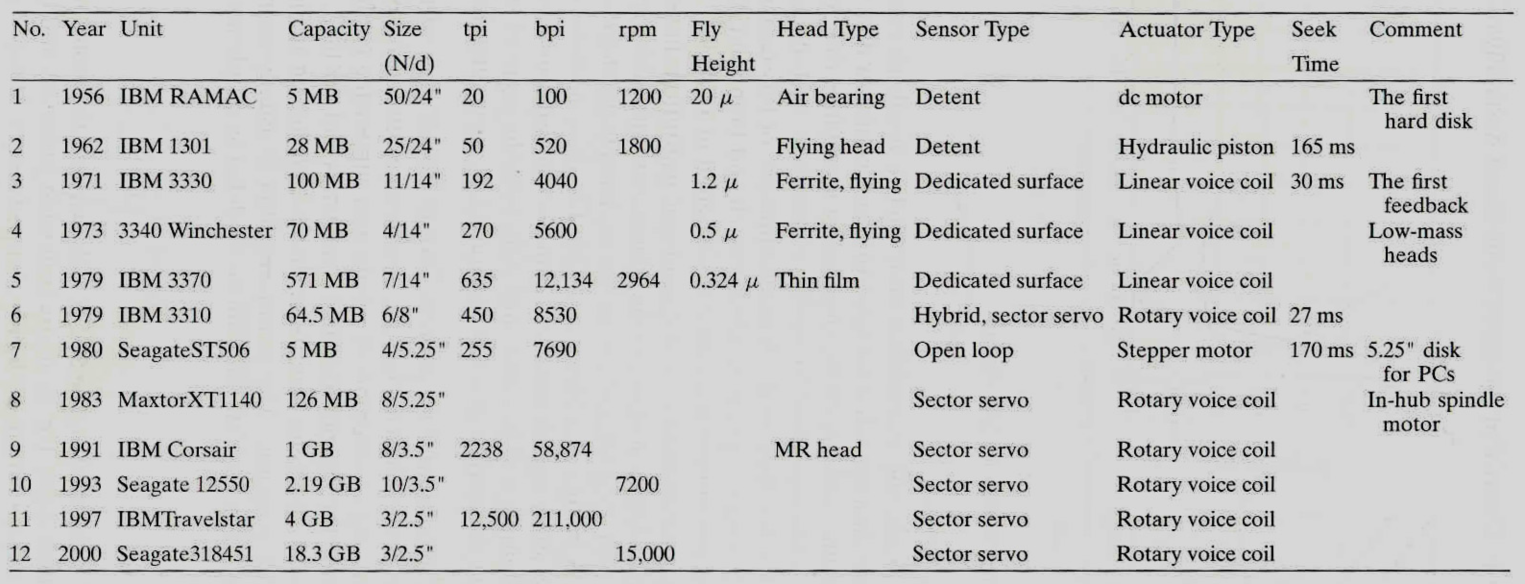
- This outline is an approximation of good practice.
- One very important consideration (Step 6) was for changing the plant itself to make the control problem easier and provide maximum closed-loop performance.
  - In many cases, proper plant modifications can provide additional damping or increase the stiffness, change in mode shapes, reduction of system response to disturbances, reduction of Coulomb friction, change in thermal capacity or conductivity, and so on.
  - Designing the system and “throwing it over the wall” to the control group is inefficient and flawed!
  - System design and control design must be done simultaneously!

Physical System

- Background
  - In the year 2000, a hard-disk drive memory for a portable laptop computer consists of three disks each 2.5 inches in diameter rotating at 15,000 rpm.
  - The device could hold 18,350 megabytes of data.
  - The read / write assembly consisted of a single arm moving a comb of heads, one per surface, in a rotary motion to move the heads from track to track.
  - The heads are mountable on a gimbal at the end of the arm and fly above the surfaces of the disks.

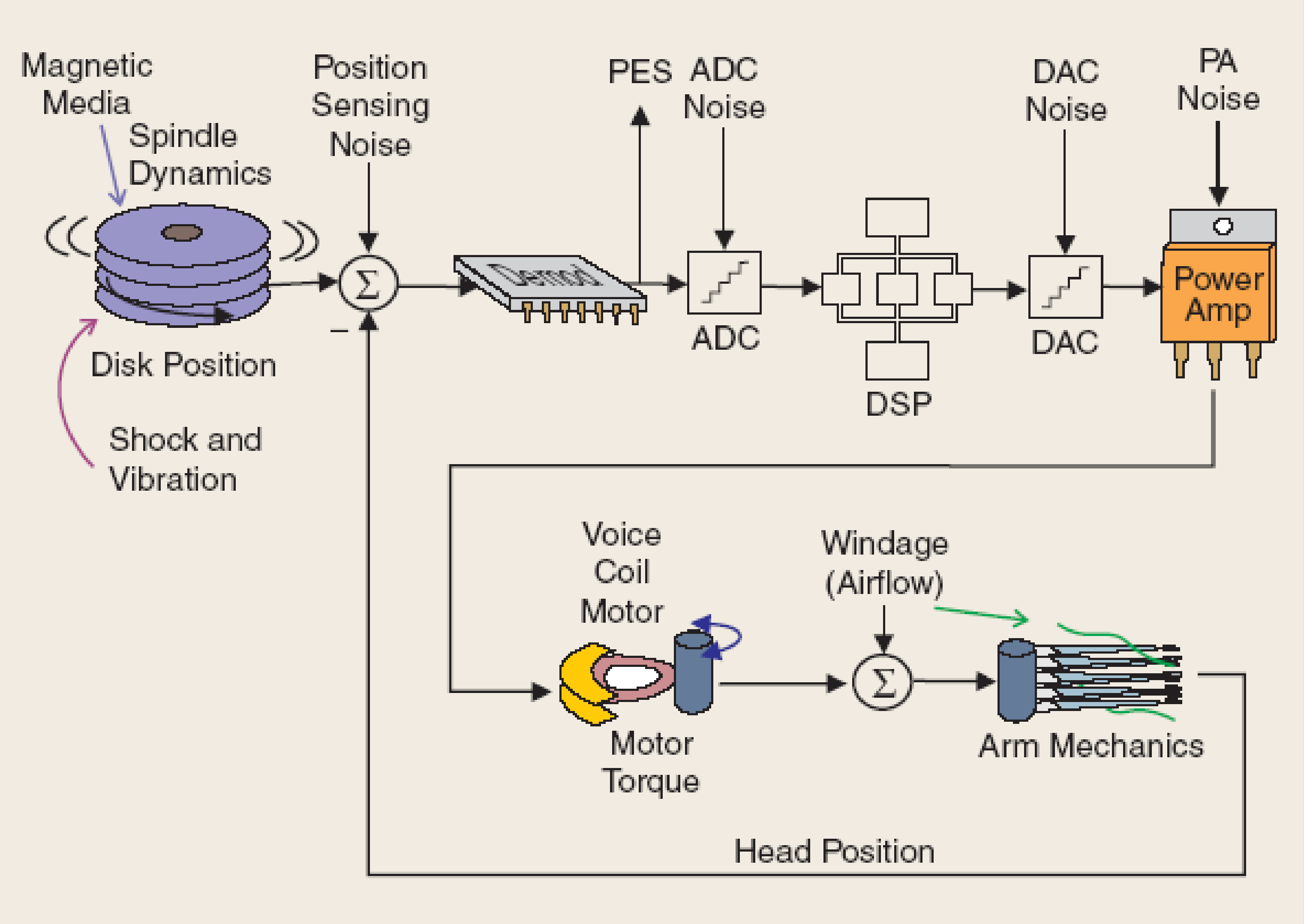
- To follow a track, the assembly is under active feedback control using samples of position data recorded between the sectors of user data around each track.
- The cost of a modern drive is less than $ 0.01 per megabyte. In 1956, the cost of the first drive was about $ 10,000 per megabyte!

Disk-Drive Parameters Over Time



No.	Year	Unit	Capacity	Size (N/d)	tpi	bpi	rpm	Fly Height	Head Type	Sensor Type	Actuator Type	Seek Time	Comment
1	1956	IBM RAMAC	5 MB	50/24"	20	100	1200	20 μ	Air bearing	Detent	dc motor		The first hard disk
2	1962	IBM 1301	28 MB	25/24"	50	520	1800		Flying head	Detent	Hydraulic piston	165 ms	
3	1971	IBM 3330	100 MB	11/14"	192	4040		1.2 μ	Ferrite, flying	Dedicated surface	Linear voice coil	30 ms	The first feedback
4	1973	3340 Winchester	70 MB	4/14"	270	5600		0.5 μ	Ferrite, flying	Dedicated surface	Linear voice coil		Low-mass heads
5	1979	IBM 3370	571 MB	7/14"	635	12,134	2964	0.324 μ	Thin film	Dedicated surface	Linear voice coil		
6	1979	IBM 3310	64.5 MB	6/8"	450	8530				Hybrid, sector servo	Rotary voice coil	27 ms	
7	1980	SeagateST506	5 MB	4/5.25"	255	7690				Open loop	Stepper motor	170 ms	5.25" disk for PCs
8	1983	MaxtorXT1140	126 MB	8/5.25"						Sector servo	Rotary voice coil		In-hub spindle motor
9	1991	IBM Corsair	1 GB	8/3.5"	2238	58,874			MR head	Sector servo	Rotary voice coil		
10	1993	Seagate 12550	2.19 GB	10/3.5"			7200			Sector servo	Rotary voice coil		
11	1997	IBMTravelstar	4 GB	3/2.5"	12,500	211,000				Sector servo	Rotary voice coil		
12	2000	Seagate318451	18.3 GB	3/2.5"			15,000			Sector servo	Rotary voice coil		

- <u>Physical System Description</u>

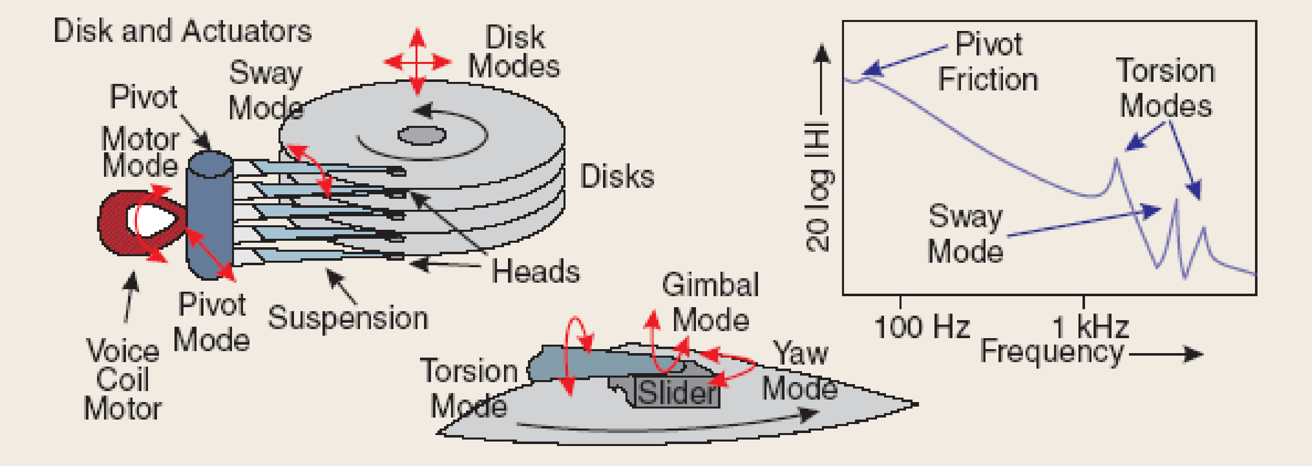


- The mechanism consists of a rotary voice-coil motor moving an assembly of a light arm supporting gimbal-mounted sliders that include the magnetoresistive read heads and the light, thin-film inductive write heads.
- The slider flies above the disk surface on an air bearing produced by the disk rotation.
- The power amplifier is usually connected as a current amplifier so the basic motion can be modeled as a simple inertia:

$$G(s) = \frac{A}{Js^2}$$

- J is the total inertia and A includes both the motor torque constant and the amplifier gain.

- The structure is flexible, however, and the detailed motion is very complex with many lightly damped modes.
- Shown below is a pictorial view of hard disks and actuators, as well as their modes.



- It is also subject to buffeting from the air flow and from vibration caused by housing motion.

- For purposes of control design, a single resonant mode will be included, where the vibration frequency ω_1 and the damping ratio ζ are known only within bounds.

$$G(s) = \frac{A}{Js^2} \frac{\left(2\zeta \frac{s}{\omega_1} + 1\right)}{\left(\frac{s^2}{\omega_1^2} + 2\zeta \frac{s}{\omega_1} + 1\right)}$$

- The motion control of the head assembly is in two modes, which are the seek motion to move the head from track to track and the track-follow motion to maintain the heads over the center of the selected track.

- In the seek mode the criterion is minimum time and theory would call for on-off or bang-bang control, i.e., the control is saturated with one polarity for half the time, then reversed for the remaining half.
- To use the same controller for many units, which differ in the maximum torque available and other critical parameters, the method used in disk drives is a bang-curve-follow technique in which the assembly is accelerated under full torque until the velocity reaches a torque reversal curve based on the distance to the desired track, and deceleration is under feedback control to follow this curve to reach the desired track with zero velocity.
- When the selected track is reached, the control transfers to track-following mode.

- Over the years, disks have become smaller and thus stiffer and smoother. As the arm assembly has become smaller, it has less inertia to the extent that for very small motions as in a one- or two-track transfer, friction is more important than inertia. For recent drives, the width of a track is on the order of 0.2 micron, a value comparable to the feature dimensions on a modern integrated circuit chip!
- To counter this trend, research is exploring ways to add a second actuator either on the arm or on the gimbal to make small moves much as the wrist acts on the end of a robot arm.
- Because of the difficulty of controlling a very lightly damped flexibility, consideration is also given to adding a coating to the arm to increase the damping of the principal modes of vibration.

- Other proposals include adding sensors on the arm to allow extra feedback to control the flexibility.
- Here, we will assume a single voice-coil actuator and that the flexibility is described as shown below where $\omega_1 \geq (2500)(2\pi)$ and $\zeta \geq 0.05$. Because the details of the actual resonance are not well known, the resonance will need to be gain stabilized.

$$G(s) = \frac{A}{Js^2} \frac{\left(2\zeta \frac{s}{\omega_1} + 1\right)}{\left(\frac{s^2}{\omega_1^2} + 2\zeta \frac{s}{\omega_1} + 1\right)}$$

- Sensors
  - The track position information in modern disks is recorded on each track in a gap between the sectors of user data. Controls based on this information are called sector servos, and the data are of necessity sampled.
  - There is a conflict between the desire to record large amounts of data, which calls for fewer and larger sectors, and the control requirement to have a high sample rate which calls for smaller sectors.
  - Each case is a compromise between these conflicting demands.
  - Because the position data are sampled, the controllers are digital devices to make the best possible use of the position data. Here we will design an analog controller.

- The position information extracted from data recorded on the disk is subject to errors caused by run-out in the track path, which means that the radius of the track is not constant. In general, there is a repeatable component in each trip around the track; this element can be estimated, often harmonic by harmonic, and a signal can be used as feedforward to the motor to cancel it out.
- The position error signal (PES) also contains random noise from many sources. These include buffeting by the air flow over the slider, wobble and vibration of the disks, noise from the power amplifier used to provide torque to the motor, and errors caused by the analog to digital converters needed in the process.

- Actuators
  - The first feedback control of the head position was introduced in 1971 and the actuator was a linear-motion voice-coil motor. In 1979 a rotary voice-coil motor was introduced and today almost all hard disk drives use a rotary motion actuator.
  - The power amplifier is usually connected as a current amplifier to simplify the dynamics.
  - The feedback from the current-sensing resistor to the amplifier constitutes a torque loop that is designed separately and carefully so the dynamics of the motor can be ignored most of the time in considering the outer loop position control in track following.

- Linear Model
  - The linear model has one flexible mode:

$$G(s) = \frac{A}{Js^2} \frac{\left(2\zeta \frac{s}{\omega_1} + 1\right)}{\left(\frac{s^2}{\omega_1^2} + 2\zeta \frac{s}{\omega_1} + 1\right)}$$

  - We will take $\zeta = 0.05$ and $\omega_1 = 2.5$, corresponding to measuring time in milliseconds rather than seconds.
  - The gain A and the inertia J will be absorbed in the gain of the compensator.
  - The power amplifier is thus assumed to be an ideal current amplifier.
  - Also, we are considering only track following, and not seek.

- PID or Lead-Lag Design
  - Because the nominal model is so simple, the first design will be a lead compensation with the objective to achieve the greatest possible bandwidth subject to having a phase margin of 50° and such that it will gain stabilize the resonance with a gain margin of at least 4.
  - Reducing the gain at high frequency is called gain stabilization.
  - We will try two designs and compare them for bandwidth and the quality of their step responses.
  - In the first case we will use a simple lead compensation, selected to give 50° phase margin and a factor of 4 gain margin.

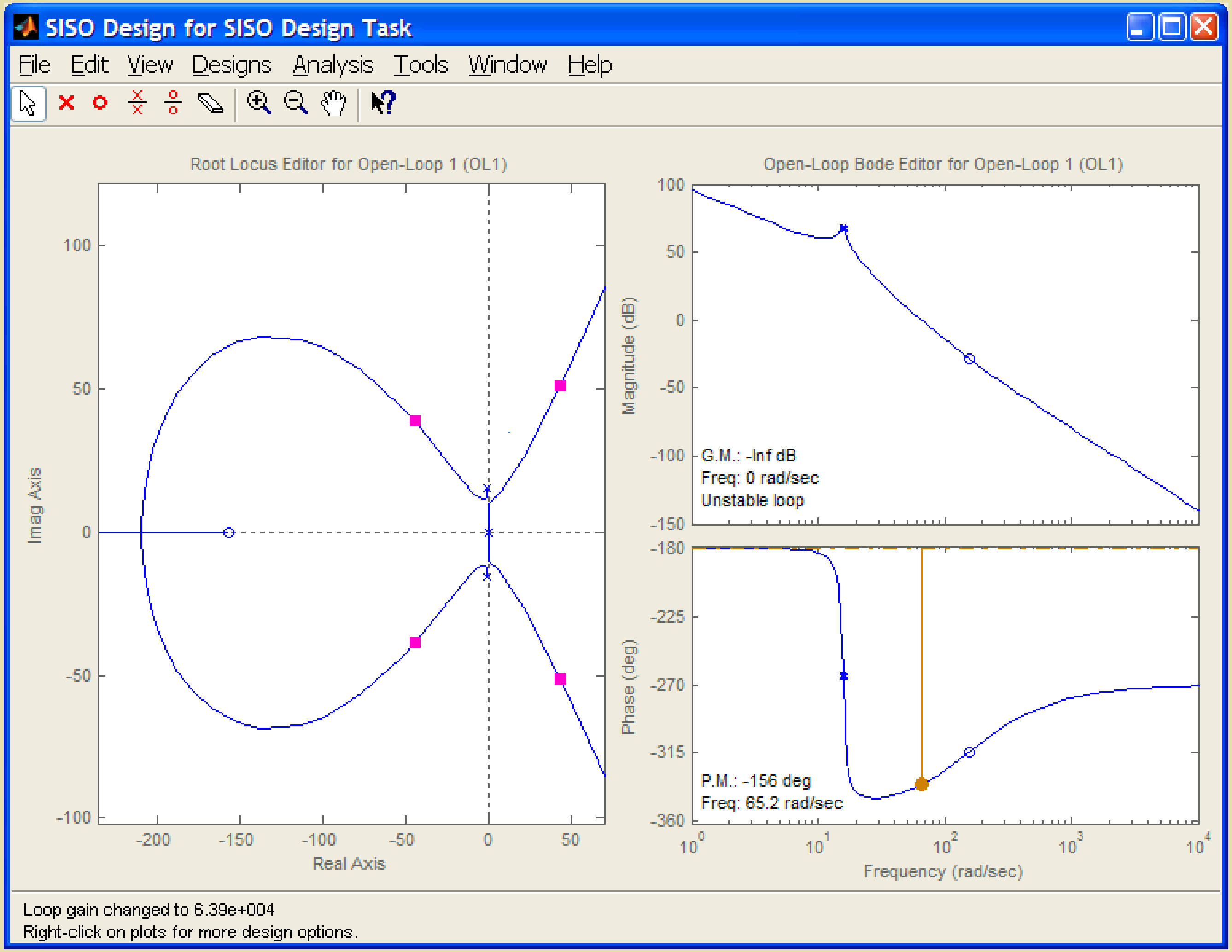
- The lead compensation has a transfer function of:

$$D(s) = \frac{Ts+1}{\alpha Ts+1} \quad \text{where } \alpha < 1$$

- 1/α is the ratio between the pole-zero breakpoint frequencies. The lead will be designed with an α = 0.1 to get the desired phase margin and the crossover frequency will be placed as high as possible while keeping a gain margin of 4 at the resonance.
- The resulting lead transfer function is:

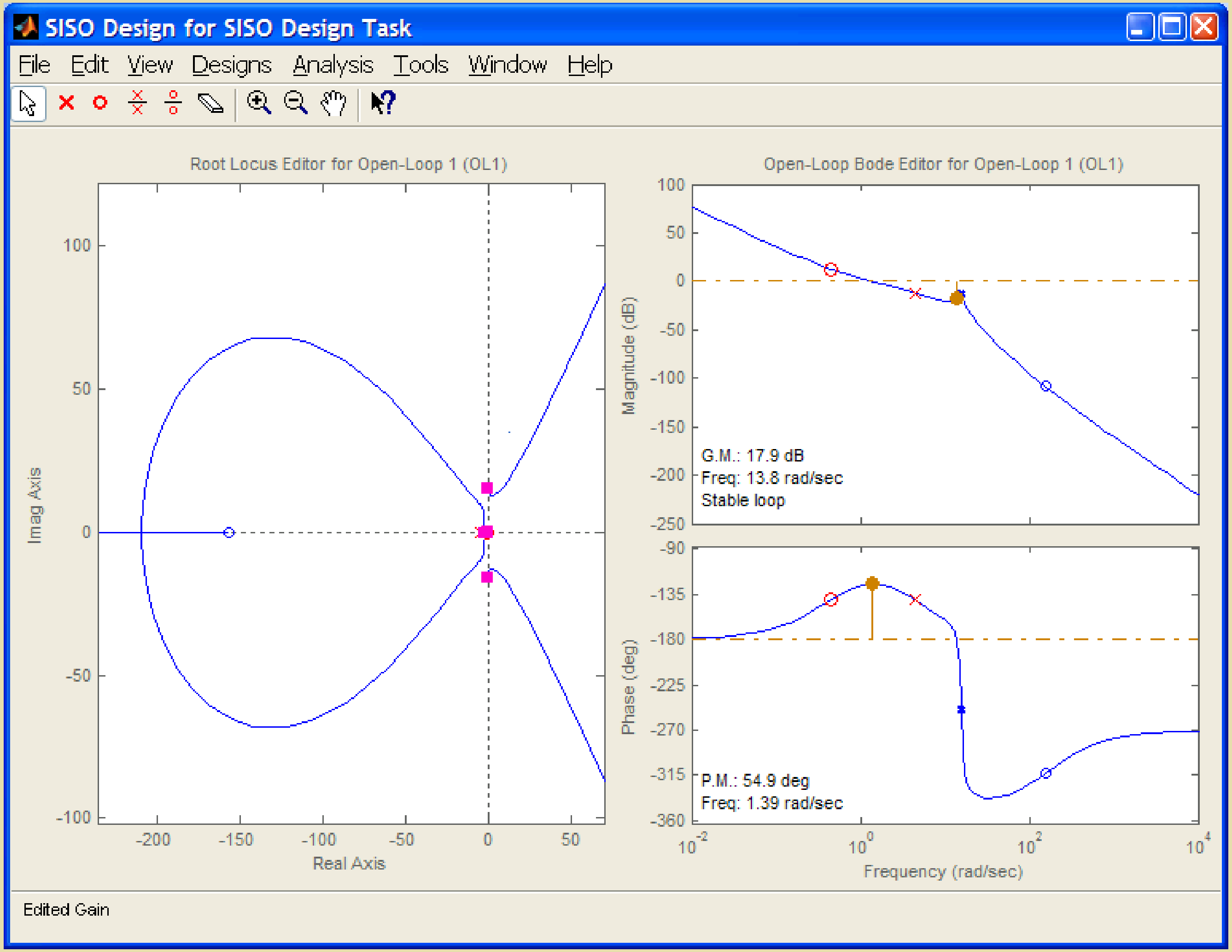
$$D(s) = 0.617\frac{(2.22s+1)}{(0.222s+1)}$$

– Uncompensated transfer function:



Loop gain changed to 6.39e+004
Right-click on plots for more design options.

– Compensated transfer function:

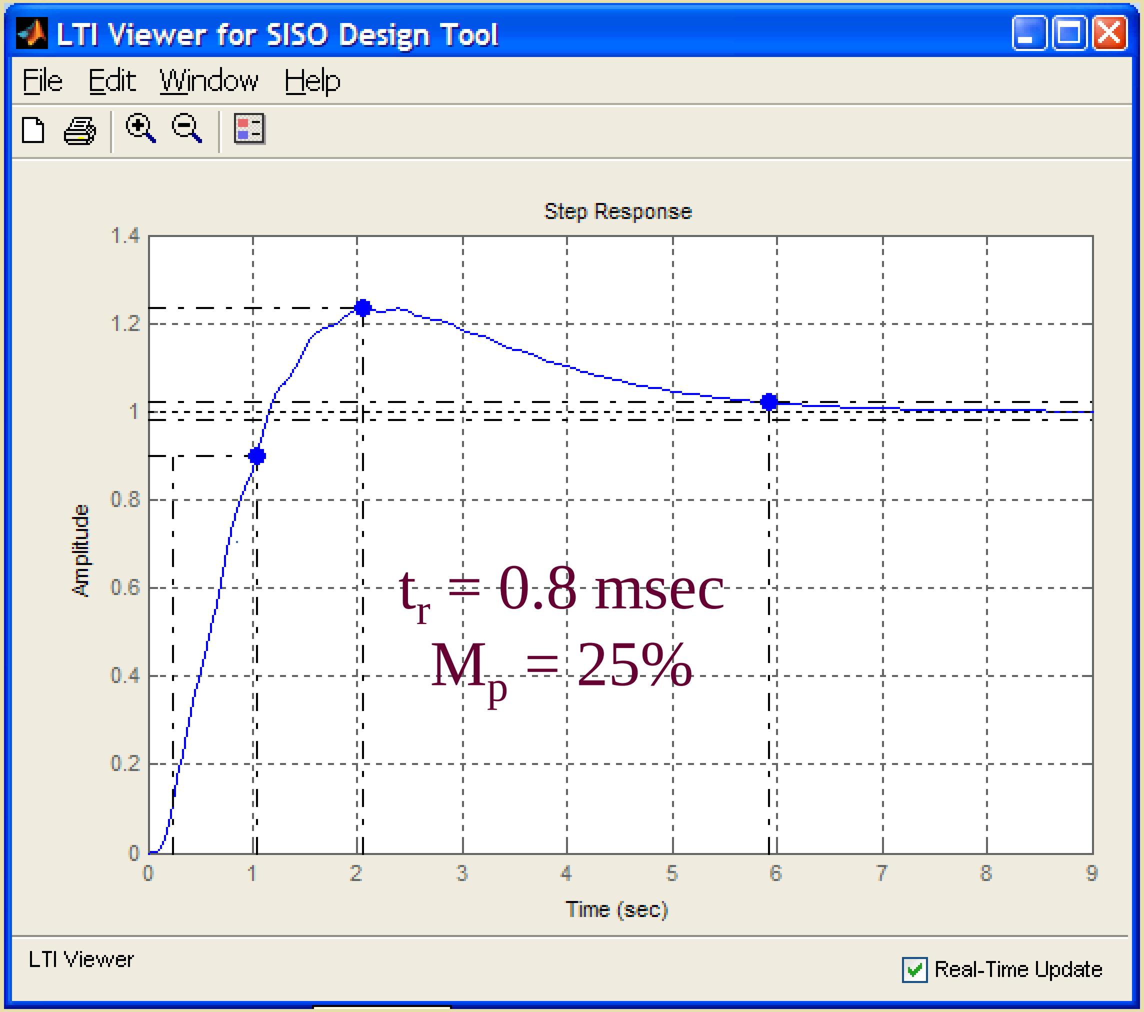


G.M.: 17.9 dB
Freq: 13.8 rad/sec
Stable loop

P.M.: 54.9 deg
Freq: 1.39 rad/sec

Edited Gain

– Step response for compensated system:



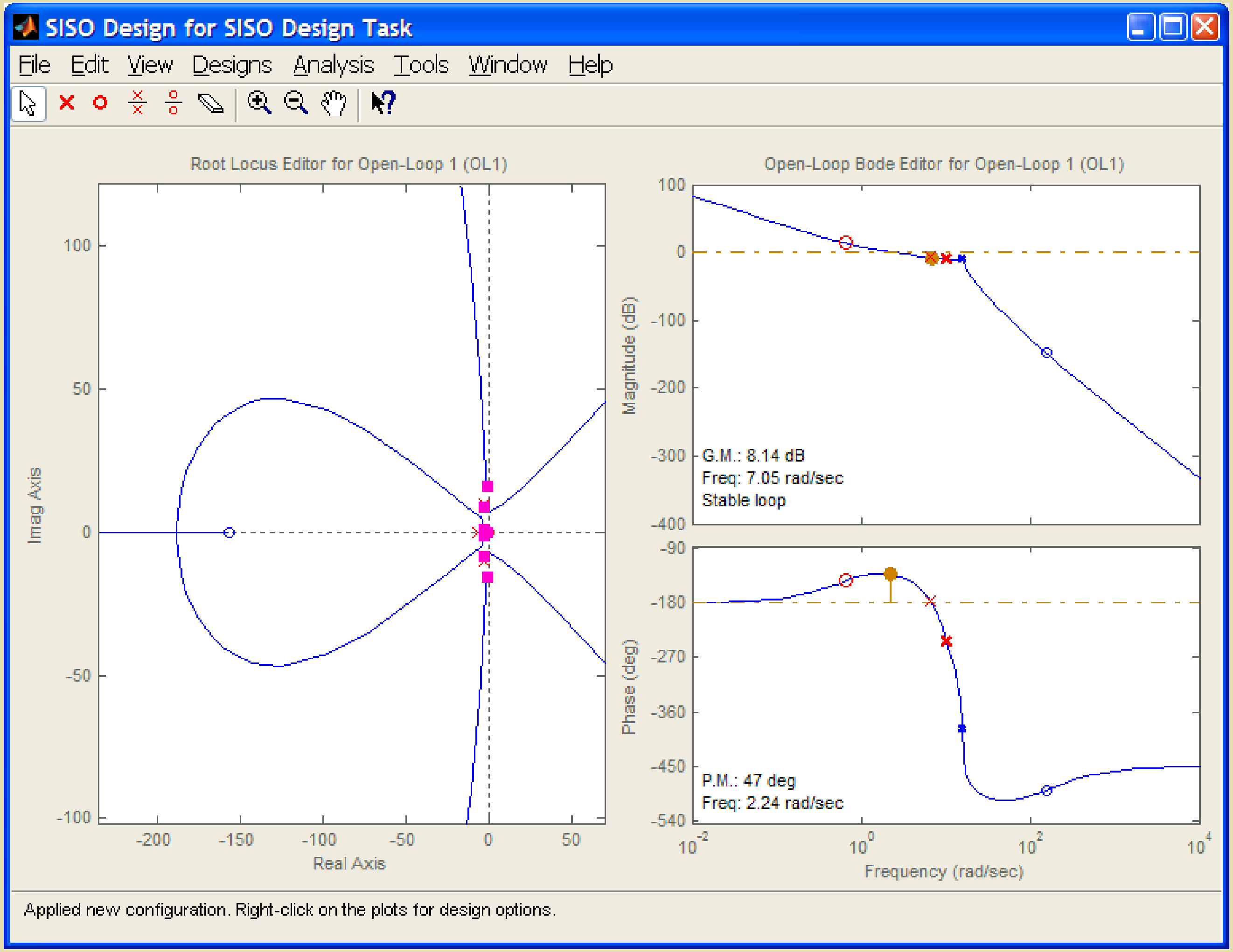
$t_r = 0.8$ msec

$M_p = 25\%$

- As a second design, a roll-off filter is to be added to try to suppress the resonance peak in order to gain a bit in speed of response and bandwidth. The idea is to put the filter cutoff frequency between the crossover frequency and the resonance frequency and to give it a damping ratio low enough that it does not reduce the phase margin too much but high enough that it does not interfere with the gain margin.
- After some experimentation, the following design is proposed:

$$D(s) = 1.44\frac{(1.48s+1)}{(0.148s+1)} \qquad F(s) = \frac{1}{\dfrac{s^2}{(10.3)^2} + \dfrac{2(0.3)}{(10.3)}s + 1}$$

– Compensated transfer function:

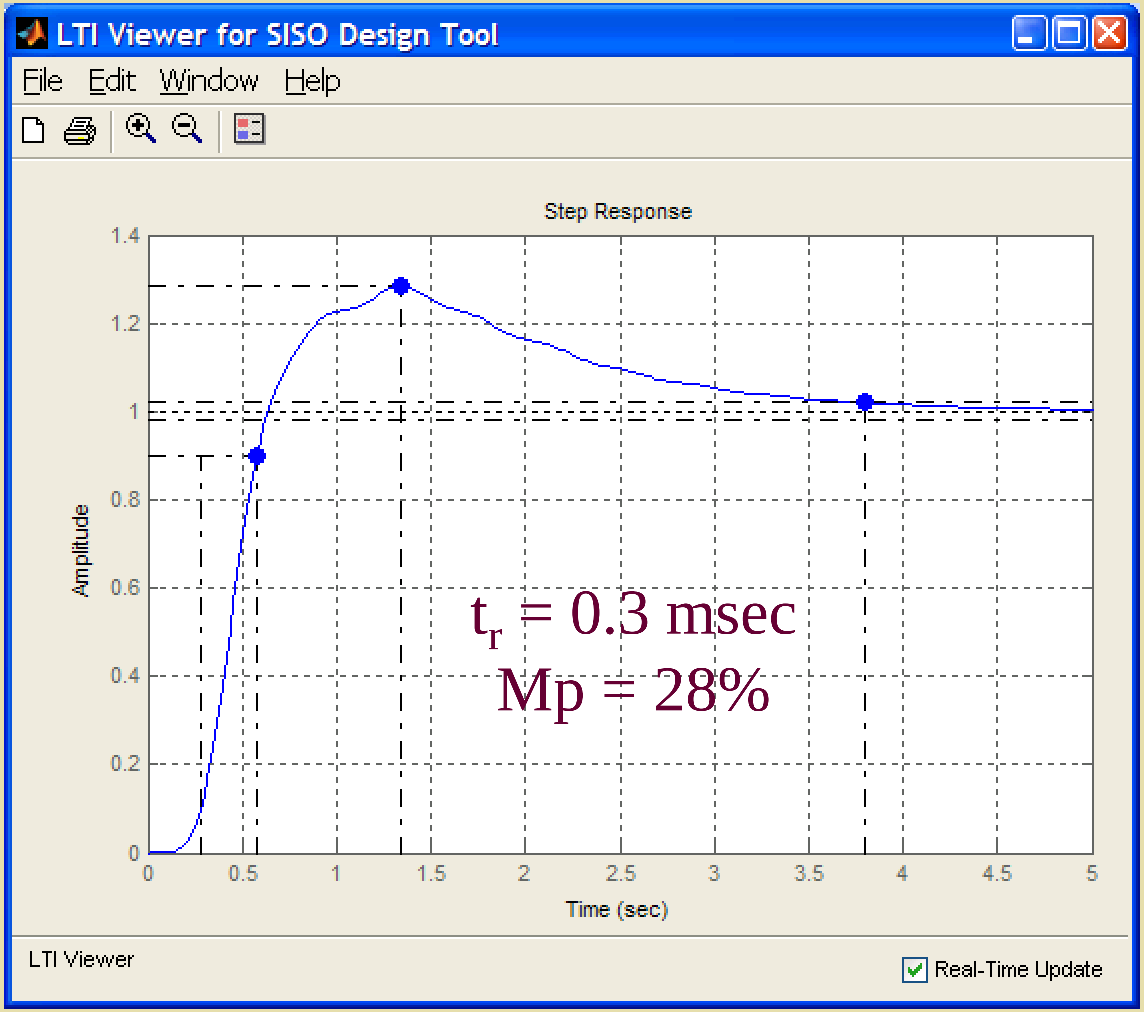


G.M.: 8.14 dB
Freq: 7.05 rad/sec
Stable loop

P.M.: 47 deg
Freq: 2.24 rad/sec

Applied new configuration. Right-click on the plots for design options.

– Step response of compensated system:



t_r = 0.3 msec

Mp = 28%

- The step response rise time is 0.3 msec, a 60% reduction from the case without the roll-off filter. The overshoot is a bit higher in this case.
- Further possibilities for the control compensation might include a notch filter rather than a low-pass filter. A notch might be able to further suppress the resonance and permit further increase in bandwidth. A great deal depends on the degree of understanding of the resonance and how much uncertainty surrounds its behavior.

- Evaluate / Modify the Plant
  - Possible changes to the process that involve major design changes were previously discussed. Once the major parameters of the design have been selected, the remaining possibilities for improvement might include a change in the fabrication of the arm to add stiffness which will raise the frequency of vibration and to add a damping coating to the arm to increase the damping ratio of the flexibility.
  - Other possibilities for improvement concern changes in the PES decoding methodology to reduce the noise.

- Try an Optimal Controller or Adaptive Controller
  - These advance approaches could be tried next.
- Simulate the Design and Compare the Alternatives
  - Usually done in parallel with the design.
- Build a Prototype
  - Done early in the design process as a bench model so trial schemes can be tested on hardware as designed.