Control Challenges and Techniques for Hard Disk Drives

Matthew T. White
IBM Corporation
Almaden Research Center
San Jose, CA

Advances in Servo Technology
"Keeping Areal Density on Track"
Santa Clara University IIST Symposium
July 17, 2000

Summary

- HDDs include a wide variety of engineering disciplines. The servo system is a significant component of the overall system.
- HDD capacities and performance are increasing rapidly, but with tight price pressures
- As technology improves, exciting new applications for HDDs are being found with a wide range of performance requirements
- With these advancements, significant challenges face the HDD servo engineer in the form of external disturbances, limited sampling frequency, position signal generation, ...
- HDDs have been a popular area for controls research, in industry and universities. As it gets harder to achieve the required capacities with the current control schemes, more of these research ideas will start to appear in products

HDD Servo Research (cont'd)

- Repetitive control (Guo, *Trans Mechatronics* 1997; Kempf et al., *IEEE Ctrl Sys* 1993)
  - Remove errors synchronized with the spindle rotation
- Bias modeling and compensation (Eddy & Messner, 1995 *IMECE*; Huang & Messner, *Trans Mag* 1998)
  - Bias value a function of seek length, target track, and seek history
  - Minimize settling time by adding a constant feedforward term to offset bias
  - Optimal value turns out not to be exact cancellation
- Multi-rate control (Semba, *Intermag 2000*; Baek & Lee, 1999 *ACC*)
  - Run estimator/controller at a higher rate than the sampling frequency
  - Inter-sample estimation is open loop
  - Requires more computations, but improves performance
- Plus applications of many other control design techniques: H-infinity, fuzzy, 2DOF, ...

HDD Servo Research

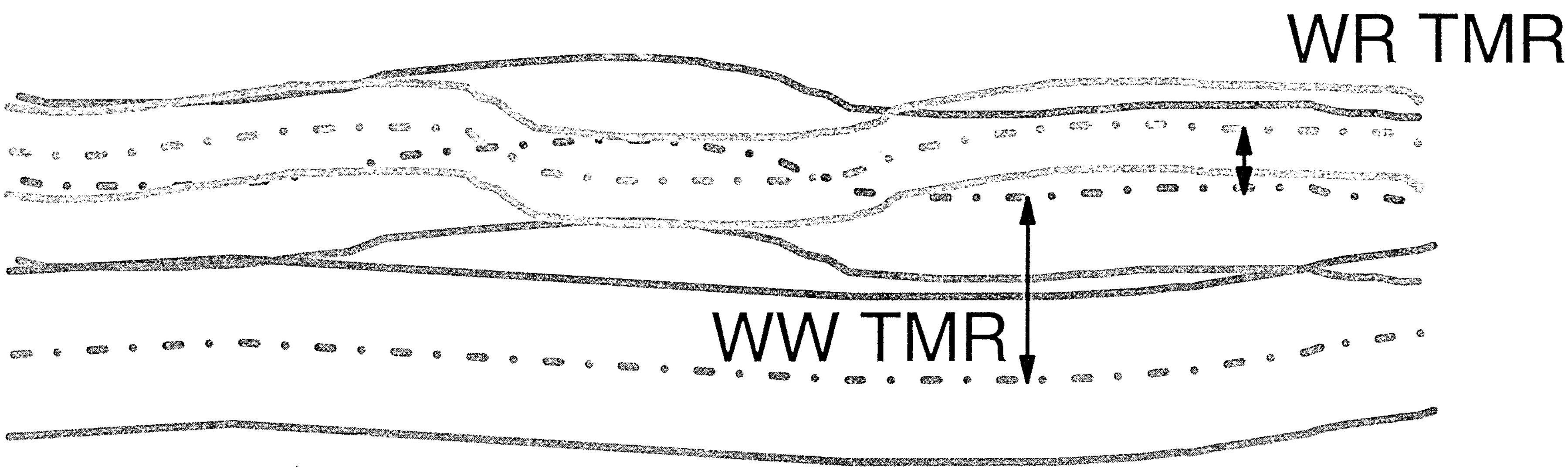
- Active damping (IBM white paper 1999)
  - Uses additional information about the actuator in a secondary feedback loop
  - Improves plant dynamics for control, leading to increased bandwidth
- MEMs microactuator (Fan et al., *Trans Mag* 1999)
  - Microactuator placed between suspension and slider is more nearly collocated
  - First resonance is extremely high, leading to much higher possible bandwidths
- Piezo milliactuator (Bennin, *IDEMA Insight* 1999)
  - Piezo 'motor' on suspension
  - Easier integration than MEMs, but dynamics not quite as clean
- Acceleration feedforward (White & Tomizuka, *Ctrl Eng Prac* 1997)
  - Measure the external disturbance with an accelerometer
  - Input the acceleration to an adaptive filter to compensate for the disturbance
- Disturbance observer (White, Tomizuka & Smith, 1999 *ACC*)
  - Estimate vibration or shock disturbance from control signal, PES and plant model
  - Feed estimate back into control signal to offset disturbance

PES Sources

- Repeatable RunOut (RRO)
  - synchronized to spindle rotation
  - due to disk slip, thermal motion, drive induced vibration, STW NRRO
  - compensation techniques include peak filter and feedforward
- Non Repeatable RunOut (NRRO)
  - external shock and vibration (other spindles)
  - spindle bearing runout (periodic but not synchronous)
  - air turbulence: disk vibration/flutter, actuator windage
  - actuator pivot and flex cable bias
- PES and quantization noise
- Servo's job is getting harder
  - PES noise used to be dominant, but scaled with SNR
  - Now disk motion is dominant (scales with form factor?)

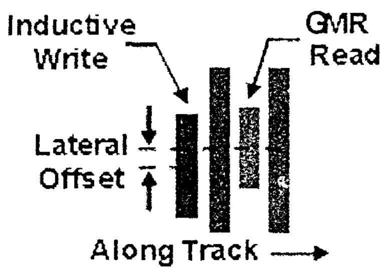
Track Misregistration (TMR)

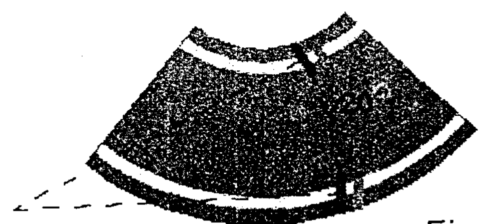
- Real tracks aren't perfect circles!
- Statistics of written and read track positions are called TMR
  - write-to-read TMR is the difference of two passes over the same track
  - write-to-write TMR is the difference of two adjacent tracks
- Write head is slightly less (~80%) than one track width



Magnetic Sensor (Head)

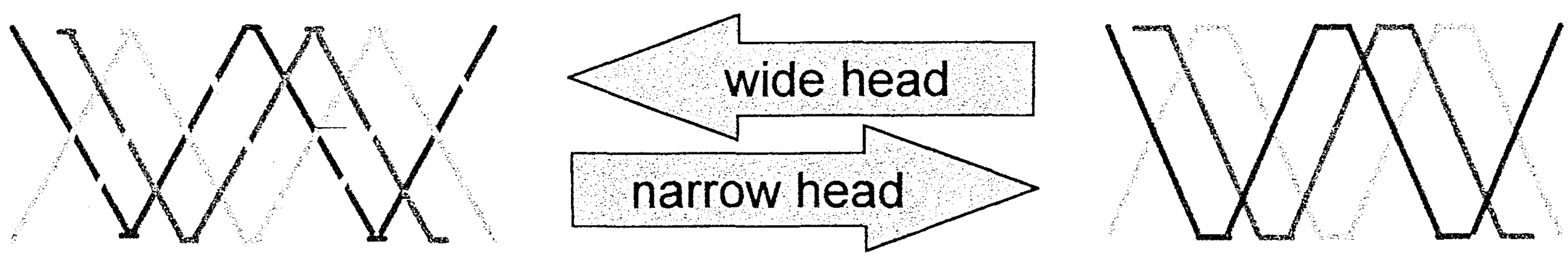
- Early HDDs used one wound inductive coil for reading and writing
- Current HDDs use two heads
  - a wide, thin-film inductive head for writing (stronger field)
  - a narrow GMR head for reading (more sensitive)
- Current technique creates some servo problems
  - skew: offset of read and write heads over the radius of the disk





Figures from IBM ARC website

  - narrow read head leads to bigger flat spots in quadrature signal

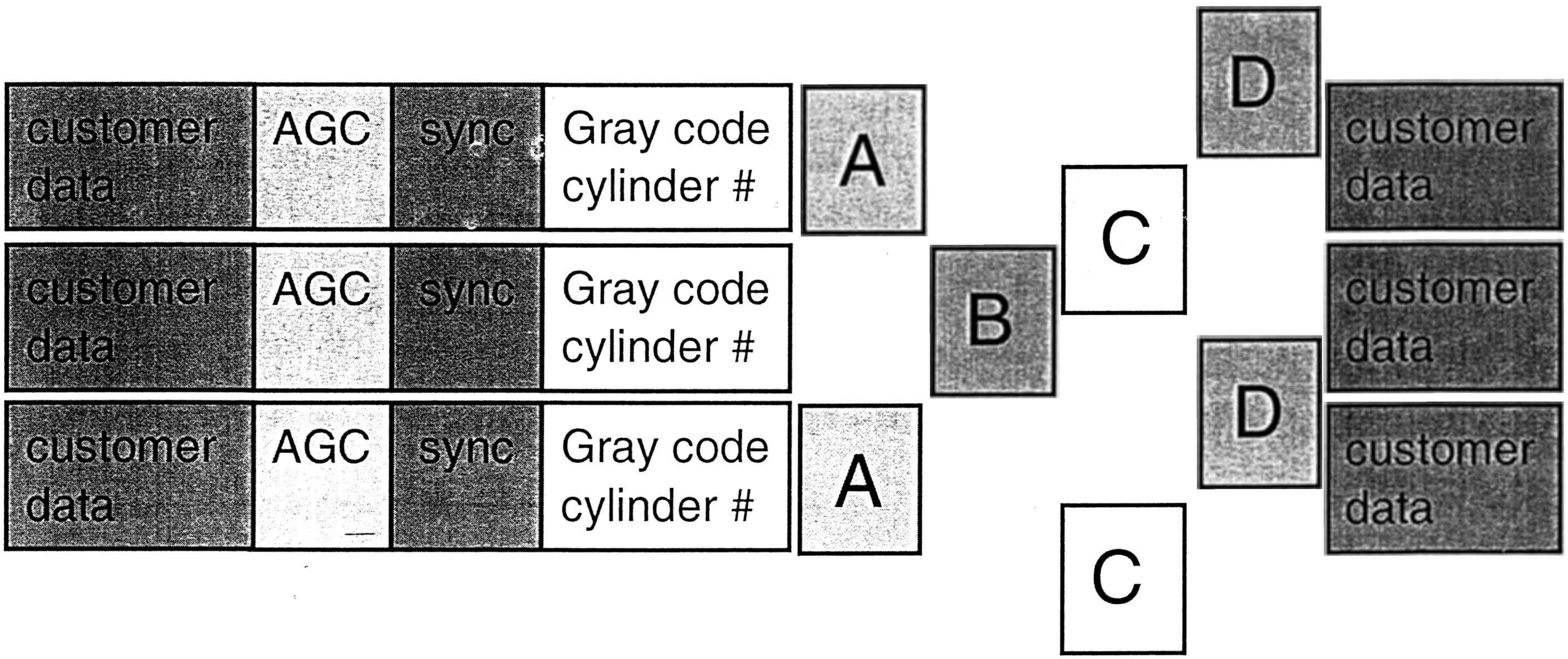


Servowriting (STW)

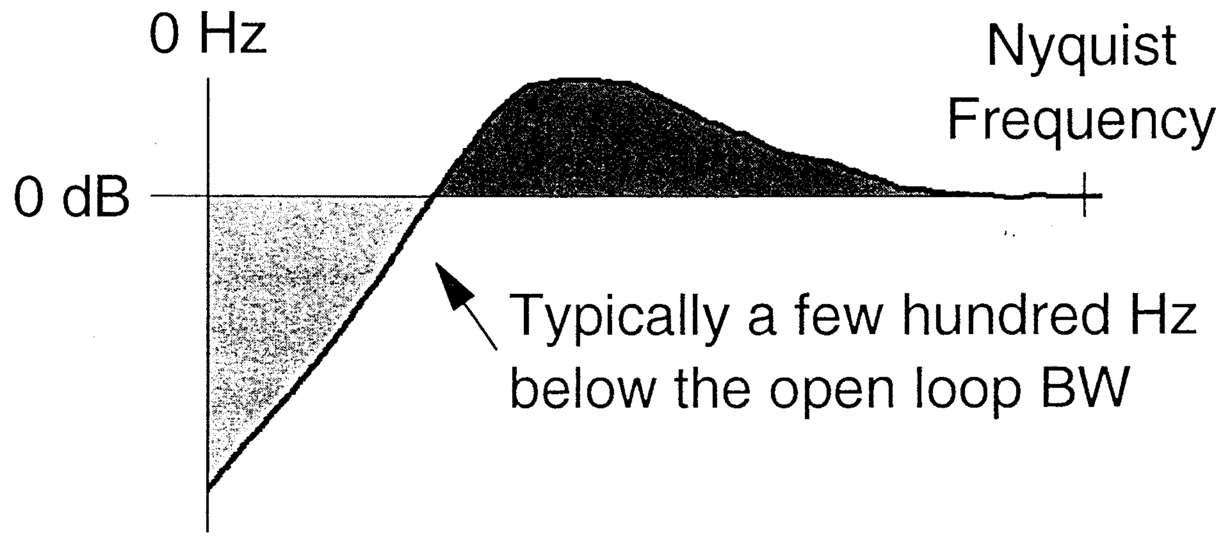
- Writes the position information on the disks during manufacturing
- Servo patterns are wider than write heads
  - write in two passes and line up magnetic transitions
  - use separate clock head with timing track for timing reference
- Traditional method is relatively expensive
  - sophisticated machines -- ***secondary servo system with a mechanical pusher and a laser positioning system***
  - time consuming
  - must be performed in a clean room due to holes in the drive enclosure for clock head and pusher pin
- Alternative technique: ***self-servowrite***
  - push actuator against crash stop
  - write the servo information for one track
  - move over 1/2 track and servo off the information that you just wrote
  - drawback -- half as much servo information as the typical track following case, errors propagate rapidly

What's in a Sector?

- AGC field helps set read channel amplitude
- Unique sync pattern provides timing reference
- Cylinder number in Gray code (which helps when trying to read cylinder number during seeks) provides track position
- ABCD bursts provide intra-track position



Error Rejection Frequency Response

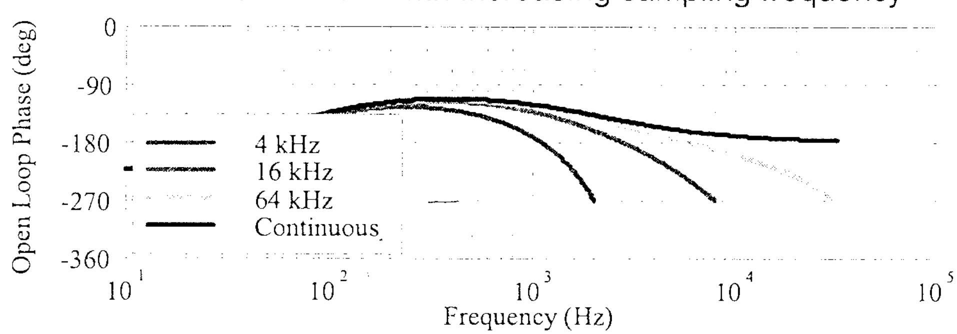


- Bode Integral Theorem implies that below the Nyquist frequency, the area above 0 dB must equal the area below 0 dB
- In other words, the red and green areas must be equal and there is always some region where disturbances are amplified
- The error rejection function is completely determined by the open loop transfer function -- it is often difficult to satisfy requirements on both

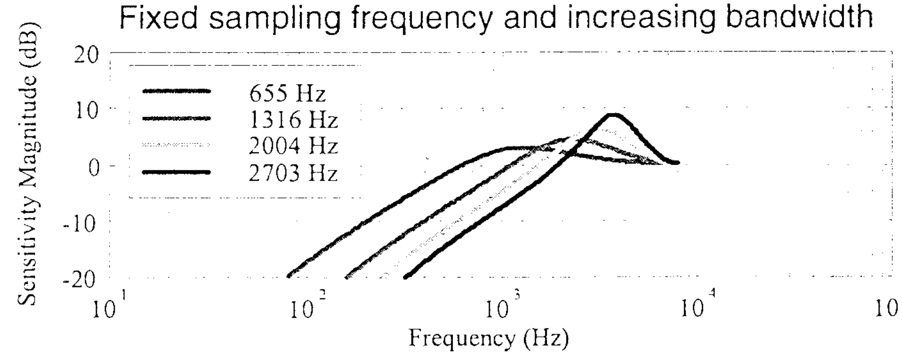
Sampling Frequency Tradeoffs

- Set the bandwidth *as high as possible* for better disturbance rejection and faster response times
  - the sampling frequency limits the bandwidth due to the Sampling Theorem and loss of phase margin
  - the amplitude and frequency of the sensitivity function *(a.k.a.* the error rejection function) peak requires careful design to avoid amplifying significant disturbances
- Set the Nyquist frequency above the many important resonances
- Additional position sensors are too expensive or inaccurate
- Dedicated servo platters use too much space and don't measure the correct head (arm modes and thermal shift can cause significant position differences between heads)

Fixed bandwidth with increasing sampling frequency



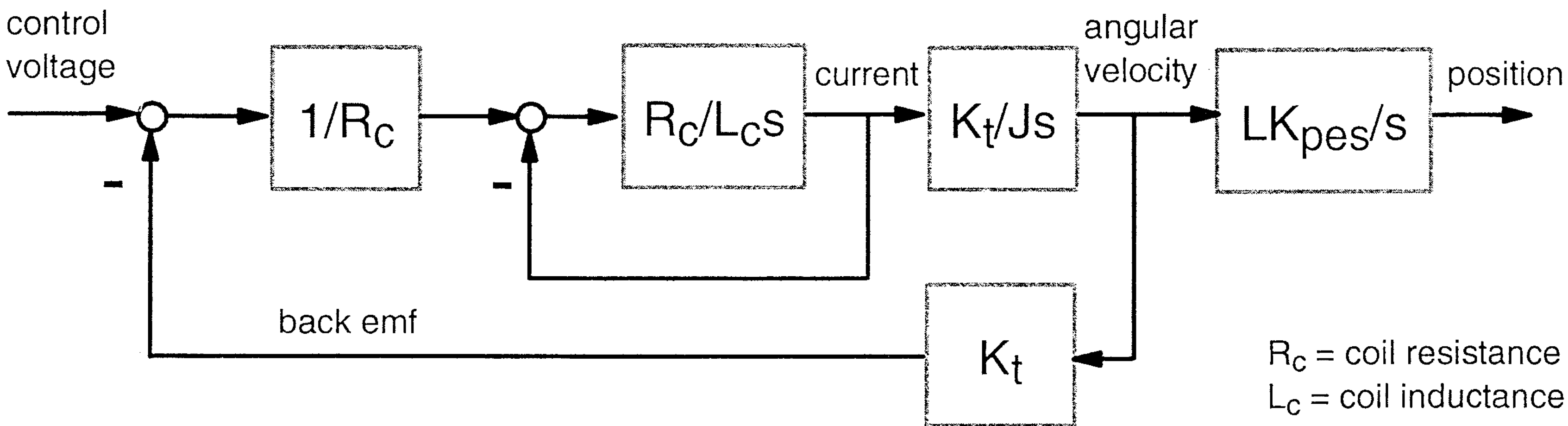
Fixed sampling frequency and increasing bandwidth



Position Information Using Sector Servo

- Position information is encoded on each surface, interspersed with customer data at regular intervals
- Sampling frequency is the product of the spindle rotation speed and the number of sectors per rev
- *Sampling frequencies kept as low as possible!*
  - Faster spindle rotation requires more power and increases disturbance amplitudes
  - Increasing the number of sectors per revolution means less room for customer data
  - Acceptable loss of disk space for servo information typically about 10%

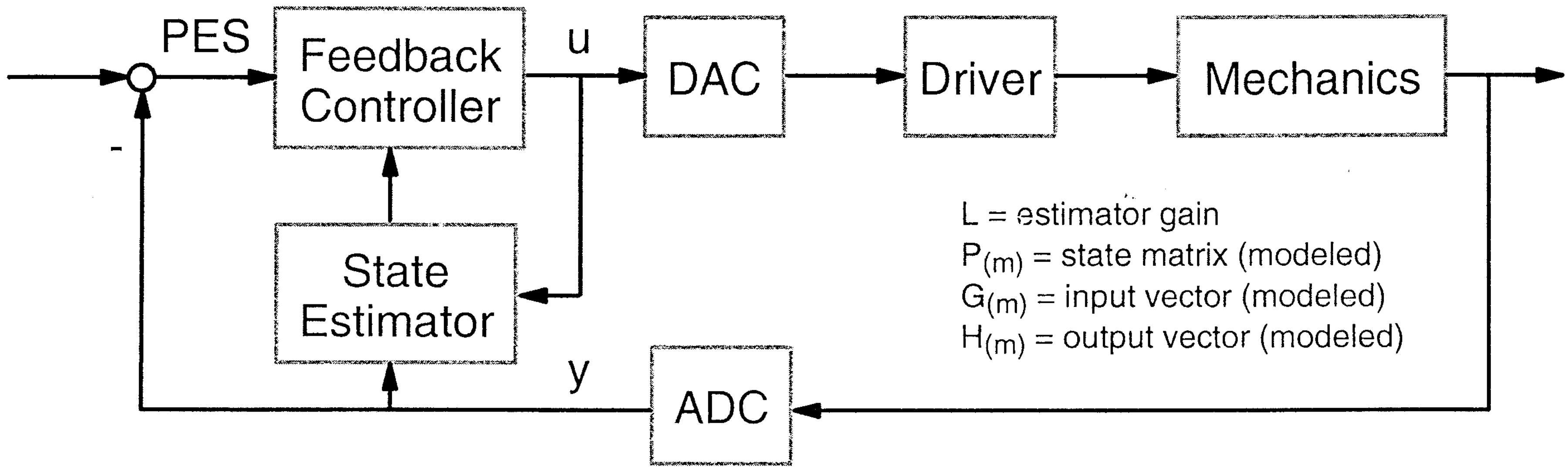
Driver/VCM Block Diagram



R_c = coil resistance
L_c = coil inductance
K_t = torque constant
J = inertia
L = arm length
K_{pes} = gain

- Higher frequency dynamics not shown
- Back emf significant for seeking
- Double integrator model typically used for track following

HDD Servo Block Diagram

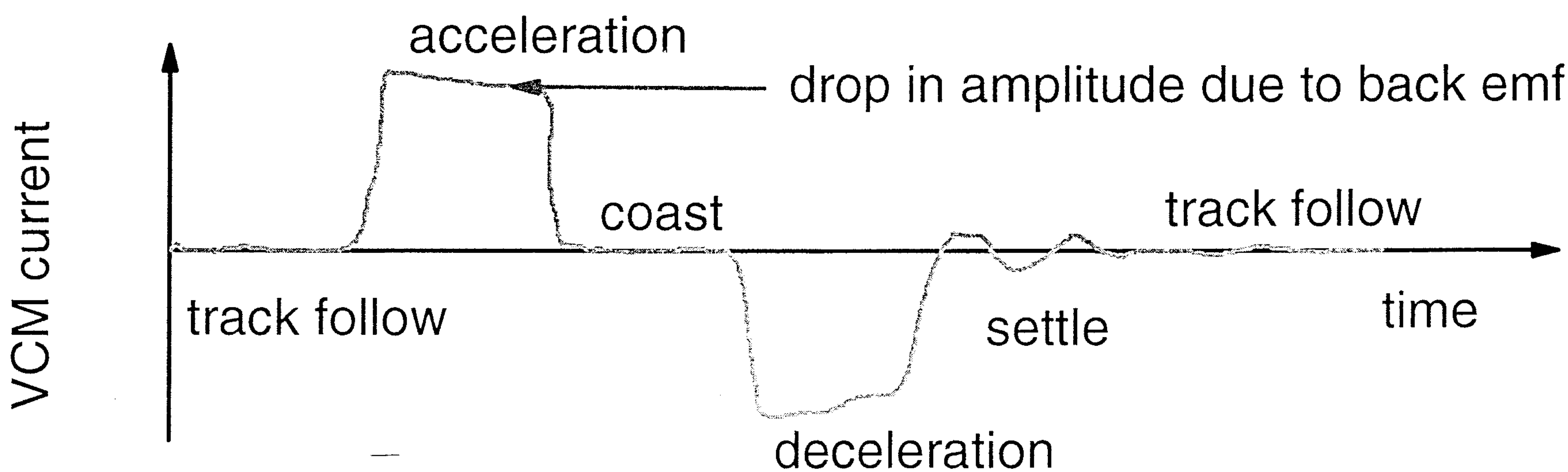


Estimator equations

- current estimator states: $x_c(k) = x_p(k) + L*[y(k) - H_m*x_p(k)]$
- predicted estimator states: $x_p(k) = P_m*x_c(k-1) + G_m*u(k-1)$
- actual states: $x(k+1) = P*x(k) + G*u(k)$
- output: $y(k) = H*x(k)$

More on Seeking

- Velocity tracking used for seeking
- Limits on velocity for crash stop and reading position information
- VCM driver saturated on acceleration
- Back emf effects can be significant



HDD Servo: Track Seeking Steps

1. MOVE to the desired track

2. SETTLE to within the required position
   - ***read commands*** can use relaxed settling criteria
     - error correction codes can tell if the data was read correctly
     - no chance for permanent damage to data
   - ***write commands*** require full settle
     - writing off track can corrupt data on adjacent tracks

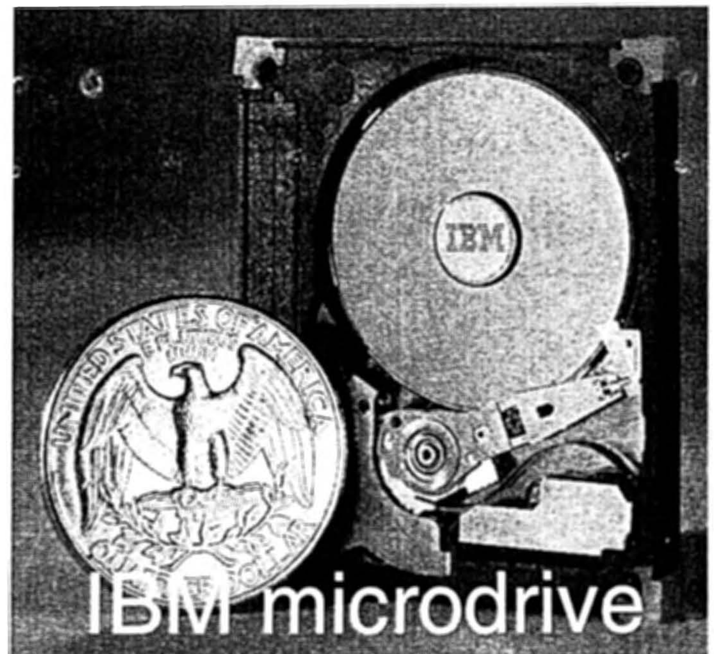
3. wait for the data block to come under the head (LATENCY)
   - increased spindle RPM can decrease latency but increase disk vibration, power consumption, etc.
   - intelligent queuing of commands can improve performance

HDD Servo: Mode Switching Control

- Mode 1: Track following
  - often a lead-lag controller with state observer
  - states useful for error checking as well as control
  - disturbance rejection: shocks for mobile, vibration for RAIDs
- Mode 2: Track seeking
  - modified bang-bang control is often used
  - design track seeking trajectory to avoid exciting higher frequency resonances
  - time gained in move may be lost in extremely long settling

New HDD Markets

- A/V (set-top boxes or personal video recorders)
  - rapid access to random sectors and high transfer rates for "simultaneous" read and write -- moderate performance by disk drive standards
  - low acoustics, heat, and cost -- okay to sacrifice performance
  - unique error handling -- missed video frames are okay, missed programming instructions aren't
- Handheld (microdrive)
  - Compact Flash Type II
  - low power
  - high shock resistance
  - single disk, two heads, 1 GB
  - digital cameras, digital audio, handheld and sub-notebook computers



HDD Trends' Impact on the Servo

- Shrinking tracks require better tracking control at the same or reduced cost
  - bits are currently very wide in the track direction
  - projections are for faster increases in tracks per inch (TPI)
    - in the past, TPI increased at 25%, BPI at 25%
    - in the future, TPI may increase at 35%, BPI at 15%
    - thermal stability issues dictate move to bits that are more nearly square (4:1 aspect ratio from today's 16:1)
    - data rate issues may limit bit per inch (BPI)
- At the same time, performance (time to access tracks) is also expected to improve

Traditional HDD Markets

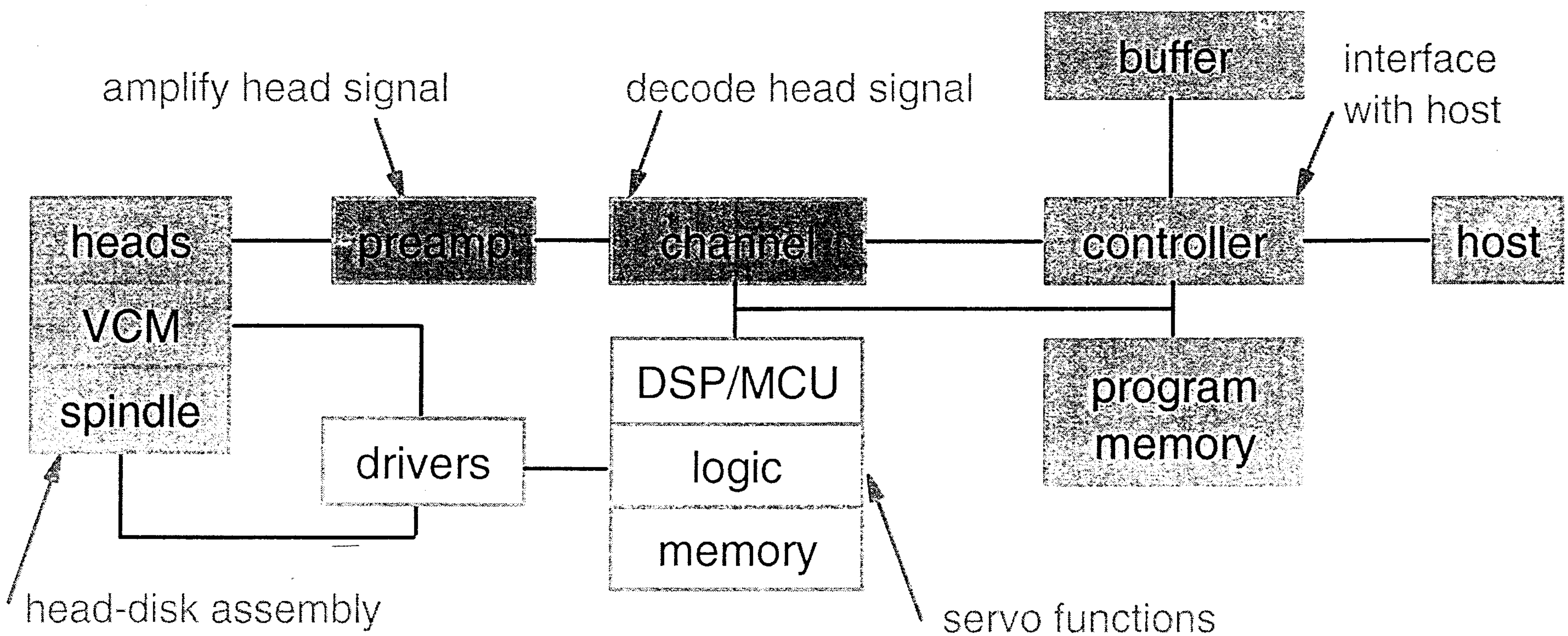
- Server - 3.5 inch form factor
  - high performance
  - higher spindle speeds ⇨ shrinking disks
  - more sophisticated mechanics and electronics
- Desktop - 3.5 inch form factor
  - moderate performance and capacity
  - largest volumes, lowest profit margins
- Mobile - 2.5 inch form factor
  - high areal density
  - low power ⇨ lower RPM and performance

HDD Trends

- Areal density increasing at 60% to 100% per year
- Price per megabyte decreasing about 50% per year
- In general, capacity is now outstripping demand -- end-user capacity demand increasing about 45% per year
- Areal density improvement has become a cost issue
  - disks and heads are costly
  - higher areal density allows fewer heads and disks to be used for the same capacity point
  - result is lower cost per megabyte

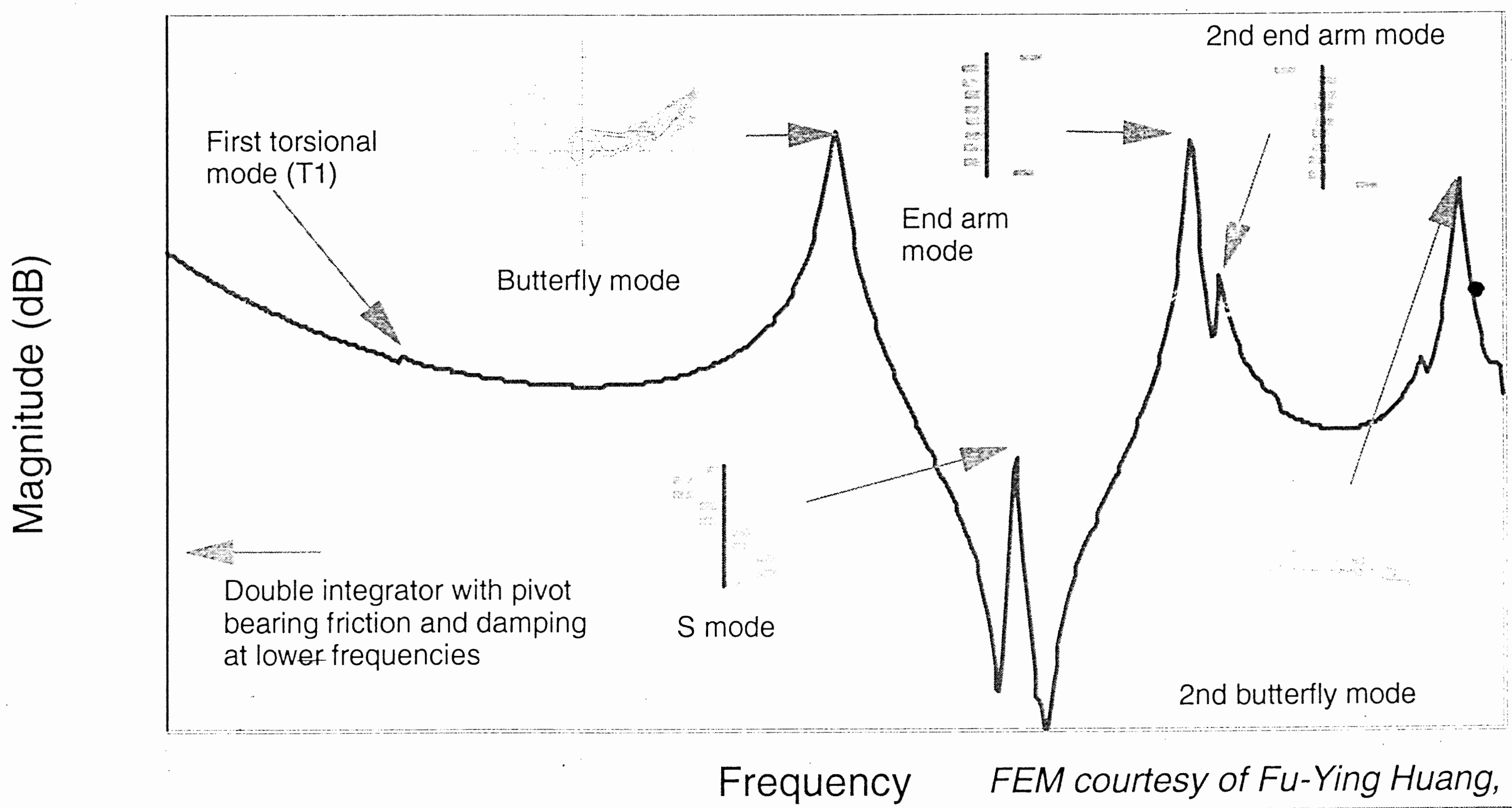
What's in a drive? Electronics

- To lower cost and decrease size, the industry is moving towards integration of many of these functions into fewer chips



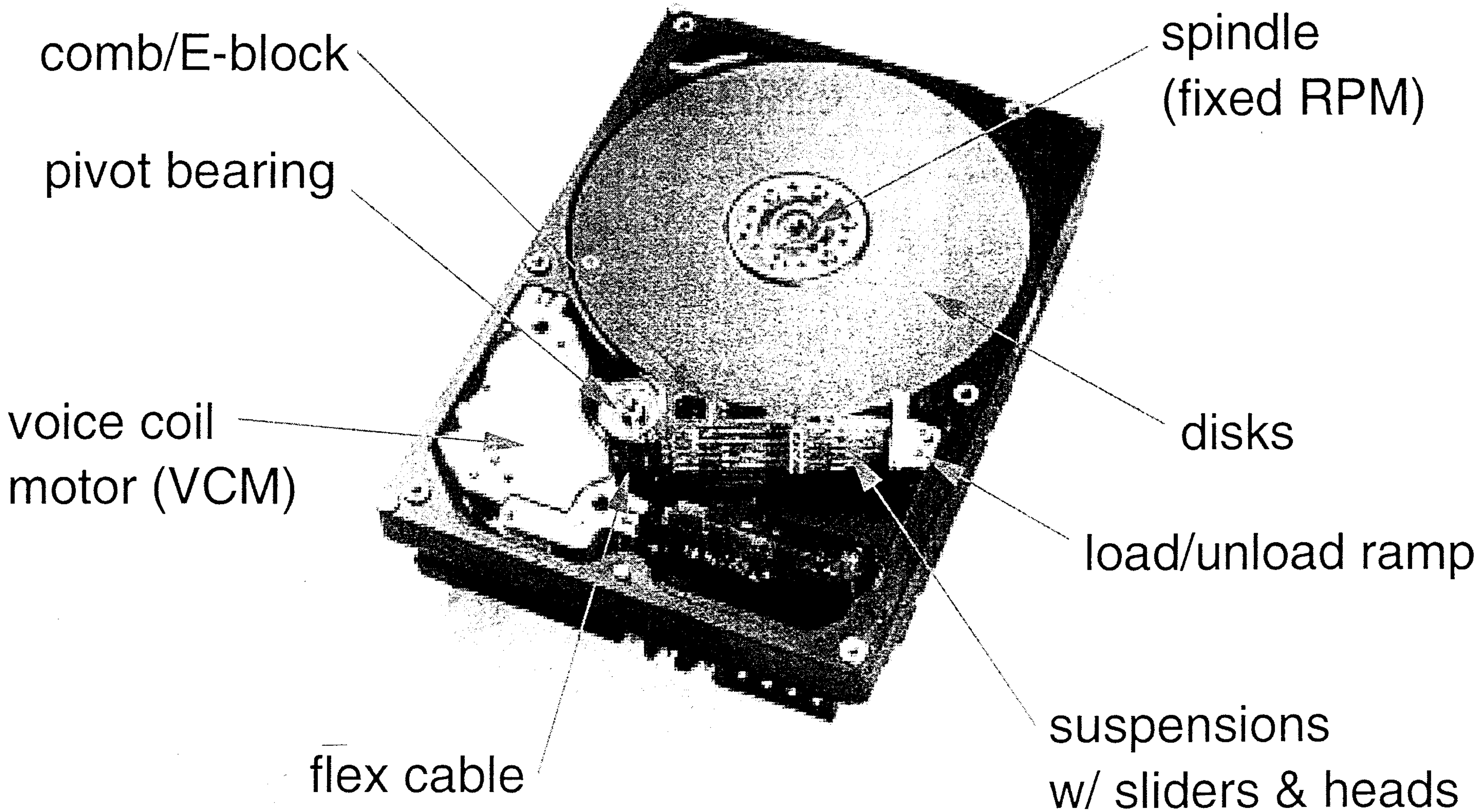
VCM to Head Position Frequency Response

- Butterfly mode is typically the first mode to limit the bandwidth -- compensate with phase stable design, notch filter, or active damping
- Arm modes may also be notched
- T1 is small in this freq resp, but is easily excited by airflow within the drive



FEM courtesy of Fu-Ying Huang, IBM ARC

What's in a drive? Mechanics



Outline

- Hard disk drive (HDD) basics
  - mechanics and electronics
  - market trends and segments
- Servo system overview
  - typical control algorithms
  - position error signal (PES) generation
  - performance issues
- Advanced servomechanical topics
  - active damping
  - dual actuation
  - other control algorithms