Fundamental of HDD Technology (9)

Assist.Prof. Piya Kovintavewat, Ph.D.

Data Storage Technology Research Unit
Nakhon Pathom Rajabhat University

http://home.npru.ac.th/piya
Email: piya@npru.ac.th

Outline

- Read Process
  - Read Head
  - Noise and Disturbance
  - Read-Back Signal Model
  - Longitudinal and Perpendicular Pulses
- Read Channel Architecture

Read Process

- The read head converts magnetic flux to voltages.
  - Ferrite head ⇒ Good for the write process (bad for read)
  - Magneto-resistive (MR) head ⇒ Good for the read process because it is much more sensitive to changes in magnetic fields
  - Giant magneto-resistive (GMR) head ⇒ Introduced in 1997
  - Tunneling magneto-resistive (TMR) head ⇒ Recently used
- The better the heads, the higher the recording densities.
- Because of a variety of noises and disturbances in the read process, the read-back signal is distorted.

Read Process – Linear Superposition

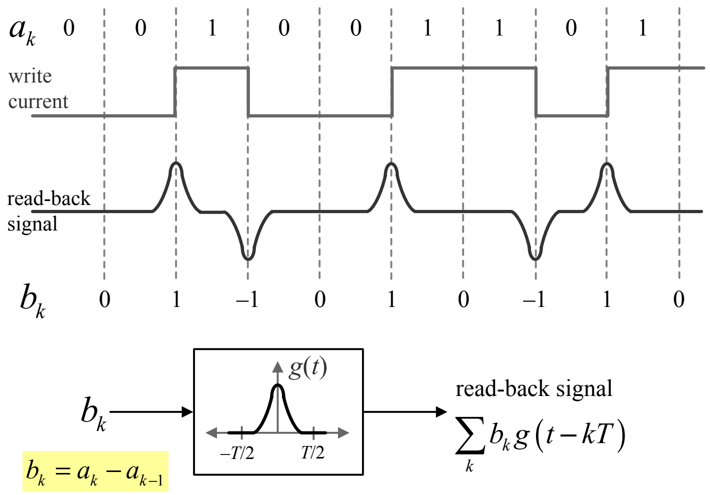
- Unlike the write process, the read process is approximately linear.
- Linear superposition:

  "*The readback voltage from a sequence of magnetic transitions is given by the sum of the single pulses corresponding to the individual magnetic transitions.*"

$$y(t) = \sum_k b_k g(t - kT)$$

b_k = transition sequence
g(t) = transition response

- Neighboring transition pulses will have opposite magnetic charge signs. Why?



Magnetic Medium Requirement

- High coercivity
  - To accommodate very sharp transition
- High remanent magnetization but small thickness
  - To provide large enough readback signal with minimum thickness space loss
- Nearly squared hysteresis loop
  - To achieve sharp transitions and satisfactory overwrite ratio
- Very smooth surface and reliable mechanical stability
  - To attain small magnetic spacing with acceptable tribological performance
- Uniform, small and magnetically isolated magnetic grains
  - To reduce medium noise in readback signals

Noises

- The higher the recording densities, the more serious the noise.
- Noises are due to uncertainties in physical phenomena and need to be treated statistically.
- Three main sources:
  - Recording medium
  - Readback head
  - Preamplifier
- Usually, a magnetic recording system is designed to be medium noise limited.

Other Disturbances

- Interferences are the reception or reproduction of signals other than those intended.
  - Deterministic
  - May be reduced to an arbitrarily small level by proper design
- Nonlinear distortion causes the linear superposition principle to fail.
  - Deterministic

Medium Noise Mechanisms

- The main source of noises in magnetic recording systems is the magnetic recording medium itself.
- Medium noises are due to the fluctuations (or uncertainties) in the medium magnetization, which can be classified into three types:
  - Transition noise
  - Particulate or granularity noise
  - Modulation noise
- As ND ↑ ⇒ Transition noise ↑

  Modulation noise ↓

  Particulate noise (independent)

Transition Noise

- Due to the magnetization fluctuation concentrated near the recorded transition centers.
- Dominant noise source in thin film disks.
- Nonstationary ⇒ this noise depends on recording patterns (i.e., data dependence)

Particulate or Granularity Noise

- Due to the random dispersion of magnetic particles or grains in magnetic medium.
- Dominant noise source in magnetic tapes, floppy disks, and particulate thin film hard disks.
- Stationary ⇒ the noise is independent of the location along the data track.

Modulation Noise

- Due to the magnetization fluctuation proportional to recorded magnetization between magnetic transitions (non-transition areas).
- Observed in both particulate and continuous thin-film disks.
- Nonstationary

Head and Electronics Noises

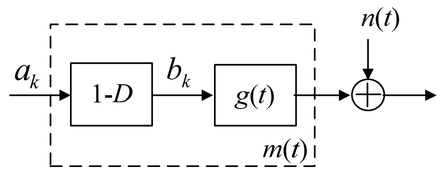
- Head noise arises from fluctuations of magnetic domain walls of the head core material (Barkhausen noise), or from the resistive dissipation in the head (Johnson noise).
- Electronics noise is caused by the random fluctuations in time of the electric carriers.
  - Mainly generated by the preamplifier (the first stage amplifier) in data-detection circuitry.
  - Shot noise and thermal noise usually dominates electronics noise in magnetic recording, which are more or less white noise.

Noises, Distortions, and Interference in Magnetic Recording

Noises	**Medium noises**	Transition noise Particulate noise Modulation noise
	Head noises	Johnson noise Barkhausen noise
	Electronics noises	Shot noise Johnson noise Flicker noise
Distortions	**Write distortions**	Nonlinear transition shift Hard transition shift
	Read distortions	Partial erasure AMR head nonlinearity GMR head nonlinearity
Interferences	**On-track**	Linear transition shift Residual old information
	Off-track	Side read, track edge effect Head position misregistration

- Thermal noise $\Rightarrow$ from the read head and pre-amp
- Background noise $\Rightarrow$ from the media
  - Due to the slight misalignment of magnetic grain axes
- Offtrack noise:
  - From the "erase band" region (similar to background noise), or
  - Due to transitions on an adjacent track
- Transition noise $\Rightarrow$ mainly from thin-film media
  - Uncertainties in the position of a transition
  - Deviations in the shape of a transition
  - Changes in the length of a transition
- Most noise sources are statistically independent of the signal, except the transition noise, which only occurs when the signal contains transitions.

Model for Generating a Read-Back Signal



Read-back signal

$$p(t) = \underbrace{\sum_k \{a_k - a_{k-1}\} g(t-kT)}_{= \sum_k a_k m(t-kT)} + n(t)$$

where $a_k \in \{\pm 1\}$ = data bit

D = delay operator

$b_k = a_k - a_{k-1} \in \{0, \pm 2\}$ = transition bit

$g(t)$ = transition response

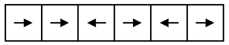
$m(t) = g(t) - g(t-T)$ = dibit response (or symbol response)

T = bit period

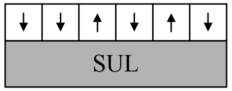
$n(t)$ = additive white Gaussian noise (AWGN)

Longitudinal vs. Perpendicular

- Orientation:



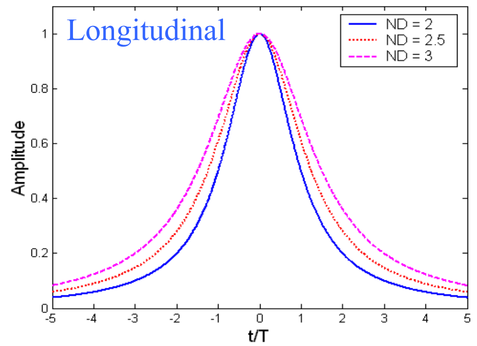
Longitudinal recording

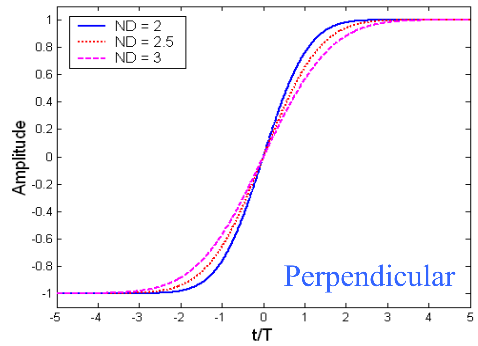


Perpendicular recording

- Design issues:
  - Magnetic medium
  - Read/write head
  - Signal Processing
    - Target ⇒ PR or GPR
    - Dominant error sequence ⇒ longitudinal {-, +, -}
      perpendicular {-, +}

Transition Response: g(t)



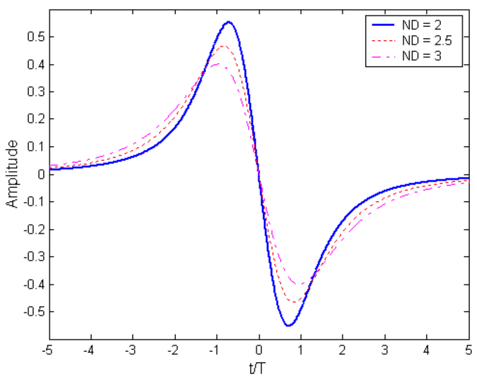


$$g_L(t)=\frac{1}{1+(2t/PW_{50})^2}$$

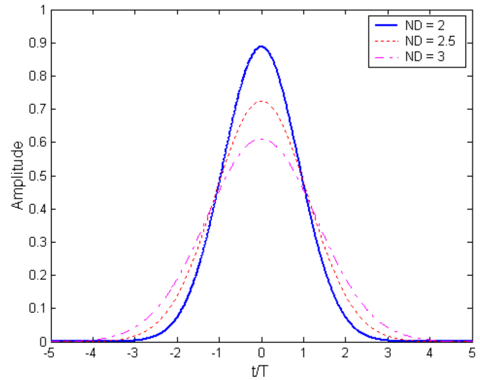
$$g_P(t)=\mathrm{erf}\left(\frac{2t\sqrt{\ln 2}}{PW_{50}}\right)$$

- ND = PW_{50}/T is a normalized recording density.
- PW_{50} is the width of $g_L(t)$ or $g'_P(t)$ at half of its peak value.

Dibit Response: m(t) = g(t) – g(t-T)

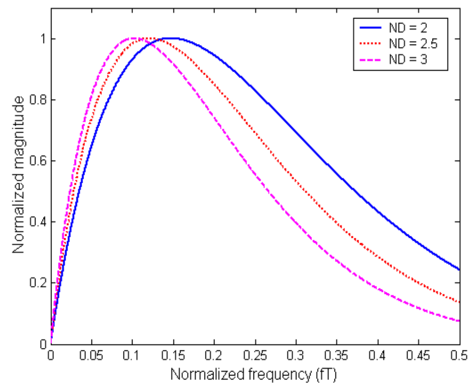


Longitudinal

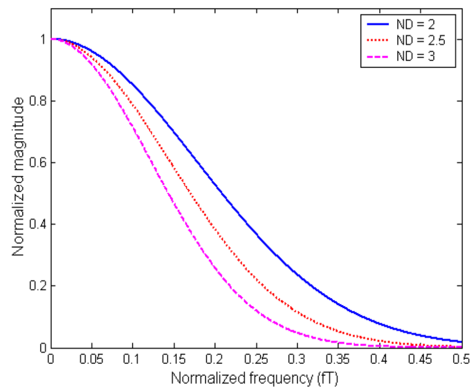


Perpendicular

Frequency Response (of Dibit Response)



Longitudinal

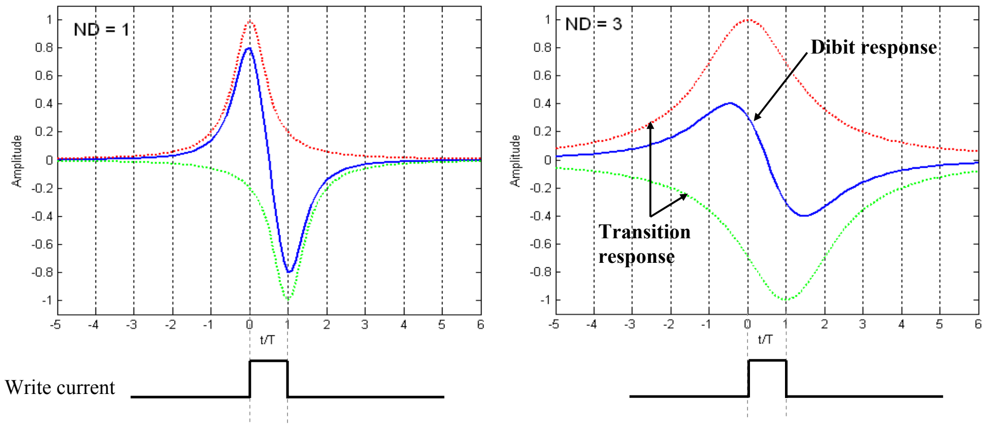


Perpendicular

$$M_L(f)=\exp\{-\pi|f|PW_{50}\}\cdot(1-e^{-j2\pi fT})$$

$$M_P(f)=\frac{1}{j\pi f}\cdot\exp\left\{-\frac{\pi^2 f^2 PW_{50}^2}{\ln 16}\right\}\cdot(1-e^{-j2\pi fT})$$

Linear Combination of Two Adjacent Transitions



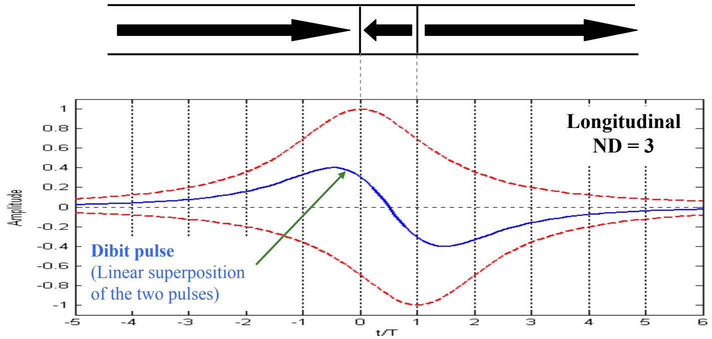
Observe ⇒ ND increases ⇒ signal amplitude is reduced, and peak is shifted.

- This results in a symbol response or a dibit response.

Effects of ISI

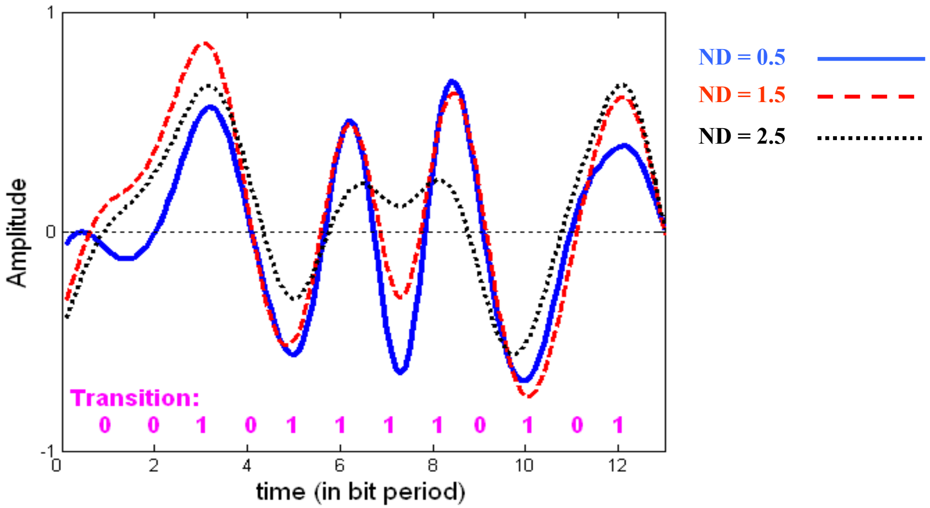
Media

Read-back signal



- Reduce pulse amplitude
- Move peaks apart
- Is #1 source of error in peak detection (the higher the ND, the more severe the ISI).

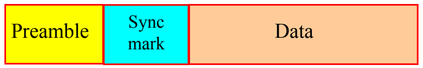
Example of Read-Back Signals (@ SNR = 20 dB)



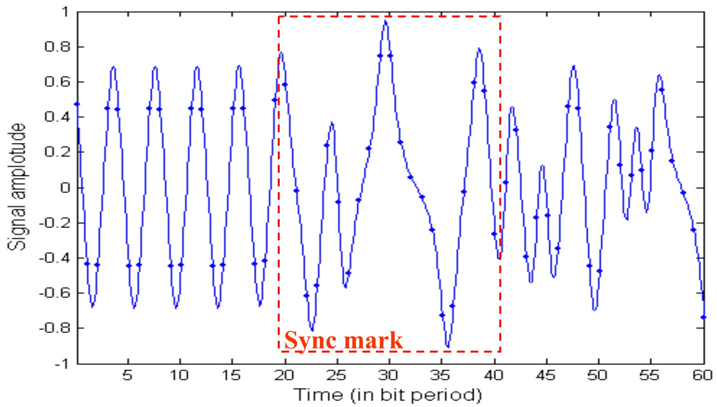
Ways to Handle ISI

- Prevent it by
  - Precompensation
  - Pulse slimming (read-channel equalization)
  - RLL codes
- Encounter and attack it by
  - Partial response maximum-likelihood (PRML) technique

Example of Read-Back Signals (no noise)



Preamble is constant frequency
Sync mark is a fixed pattern
Data bits are normally random



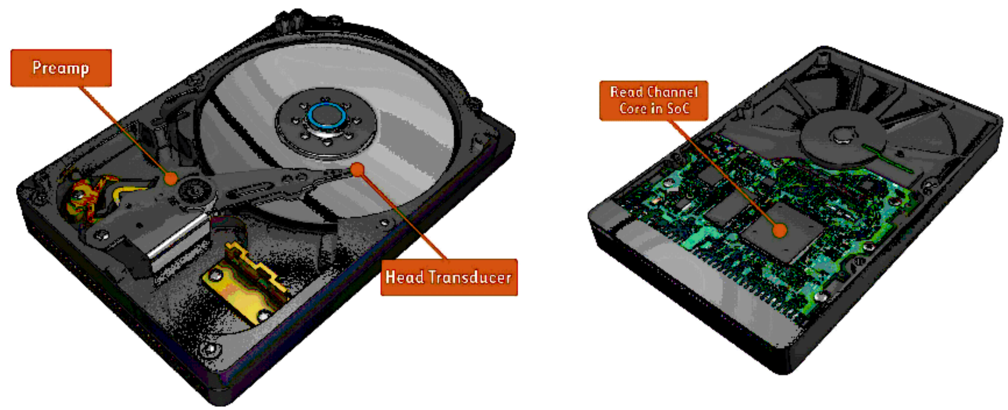
Read Channel Architecture

- Pre-Amp
- Variable Gain Control
- Thermal Asperity
- Amplitude Asymmetry
- Continuous-Time Filter
- Analog-to-Digital Converter
- Timing Recovery
- Equalizer
- Symbol Detector

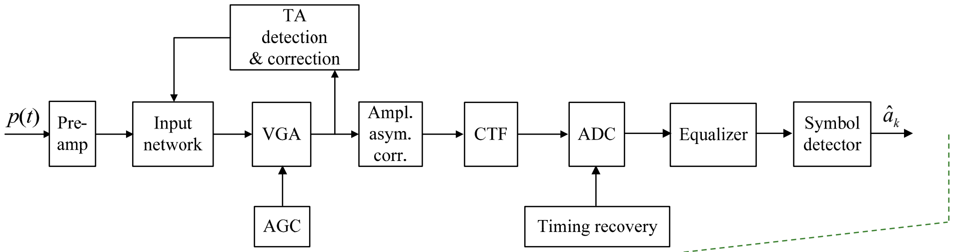
Read Channel

- The read-channel integrated circuit (IC) is an electronic heart of HDDs.
- Over the years, read-channel designers have delivered dramatic improvement in SNR, enabling accurate, reliable recovery of user data from noisy analog signal.
- Hard disk designers have taken advantage of SNR improvements to make data tracks on a storage disk smaller and pack those tracks tighter.
- Today's areal density $\Rightarrow$ > 150 GB/platter (3.5")

  > 80 GB/platter (2.5")



Read Channel Architecture



Notation:

TA = Thermal Asperity

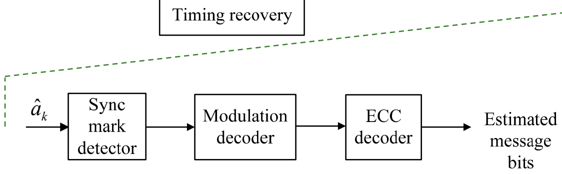
VGA = Variable Gain Amplifier

AGC = Automatic Gain Control

Ampl. asym. corr. = Amplitude Asymmetry Correction

CTF = Continuous-Time Filter (or a low-pass filter)

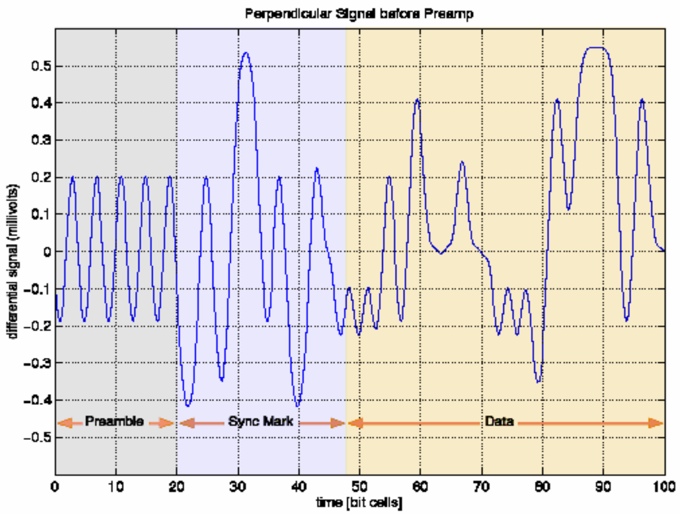
ADC = Analog-to-Digital Converter



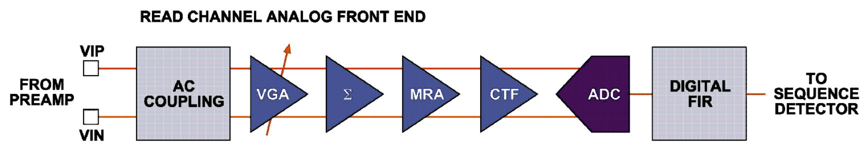
Pre-Amp

- The head signal is very small.
  - As small as 300 microvolts peak-to-peak
- Pre-amp:
  - To amplify the head signal to significantly higher amplitude to meet the tens of millivolts required to preserve the SNR level capability of the head signal and maximize the read-channel's capabilities once it arrives at the channel.

Ideal perpendicular magnetic signal output from the head transducer before the preamp

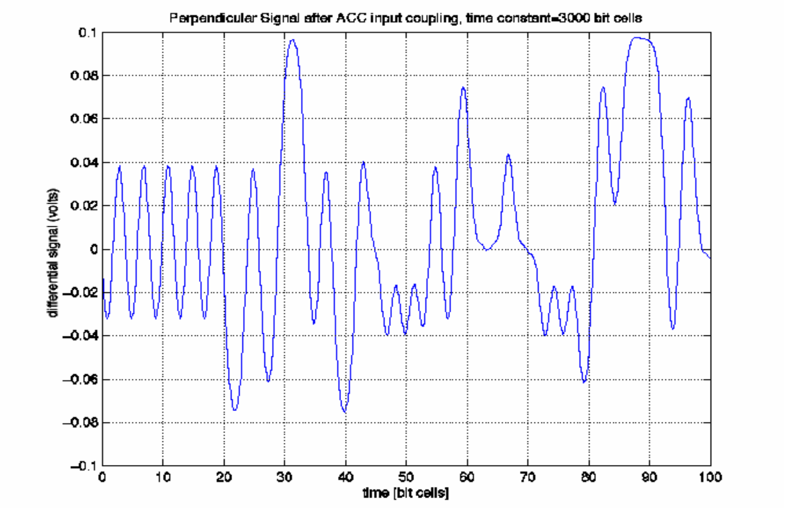


AC Coupling



- The first stage of the analog front end of the channel core consists of a stage to remove DC offset in the signal.
- This is accomplished through AC coupling and DC baseline correction.

Perpendicular signal after AC coupling still showing some DC offset of positive versus negative peaks in the preamble.



Variable Gain Amplifier (VGA)

- To provide gain determined by the automatic gain control (AGC).
- To control the signal level for optimum performance in the analog-to-digital converter (ADC) block.
- **Note:**
  - Too much gain can cause the ADC sample values to rail at maximum or minimum ADC levels.
  - Too little gain can cause quantization noise to dominate SNR and adversely affect bit-error rate performance.

Automatic Gain Control (AGC)

- In practice, the read-back signal levels may vary widely.
- The AGC is used to make the signal levels behind the VGA are more or less constant.
  - AGC is typically an analog circuit.
- Category:
  - Non-data-aided AGC
  - Data-aided AGC

Summing Junction Σ

- Add in any additional DC correction necessary beyond the DC attenuation provided in the AC coupling stage.
- Keep the signal centered on the baseline which will become mid scale for the ADC converter
  - So that the sequence detector trellises will work optimally
- So correction reduces the preamble offset, thus producing a more centered signal.

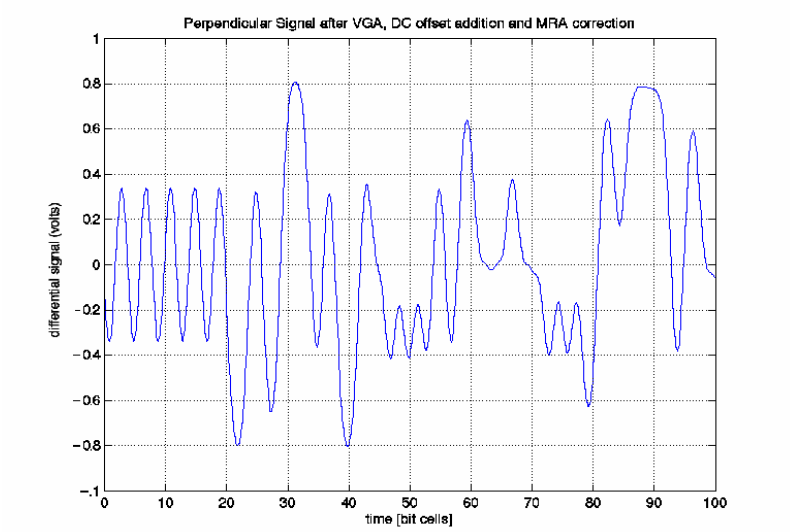
Amplitude Asymmetry

- The use of the MR read head can result in positive-negative peak "asymmetry" in the data signal at the output of the read head [Tsang *et al*, 1990].
  - The magnitude of the response due to a positive magnetic transition differs from that of a negative magnetic transition.
  - In the absence of asymmetry, the read-back signal can be viewed as the linear combination of transmitted pulses.
- Positive-negative peak asymmetry is an approximation for nonlinear behavior that occurs when a biased MR head slightly saturates in one direction.
- This asymmetry causes many errors in data detection process.

Amplitude Asymmetry Correction

- Reconstruct linearity that may have been lost in the head transducer stage during the conversion of the magnetic signal on the disk to an electrical signal at the output of the head
- The biasing of the head signal is adjusted to keep the signal in the linear range of the head sensitivity curve.
- Use signal offset to determine the amount of squared signal to add back to restore the positive and negative symmetry of the signal

Perpendicular signal after DC offset and MRA correction

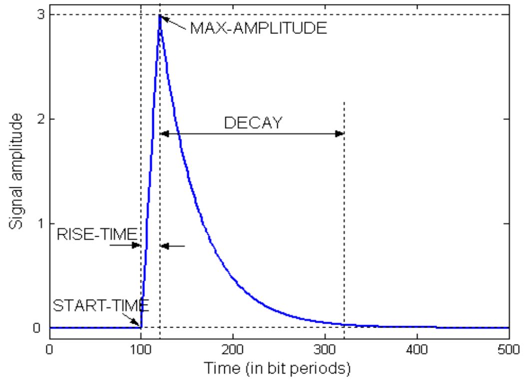


Thermal Asperity (TA)

- When an asperity (or a surface roughness) comes into contact with the slider, both the surface of the slider and the tip of the asperity are heated, which results in an extra voltage transient known as thermal asperity (TA).
- TA causes a major problem in magnetic recording systems.
  - Loss of synchronization
  - Off-track perturbation
- Without TA detection and correction algorithms [Erden and Kurtas, 2004], the system performance can be unacceptable, depending on how severe the TA effect is.

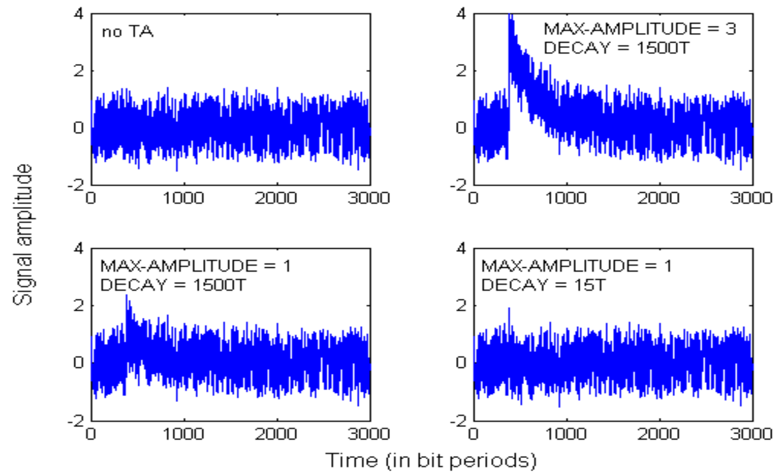
Modeling the TA Signal

- The widely used TA model* [Stupp *et al*, 1999] is specified by four parameters:
  - ❑ START TIME
  - ❑ RISE TIME
  - ❑ MAX AMPLITUDE
  - ❑ DECAY CONSTANT

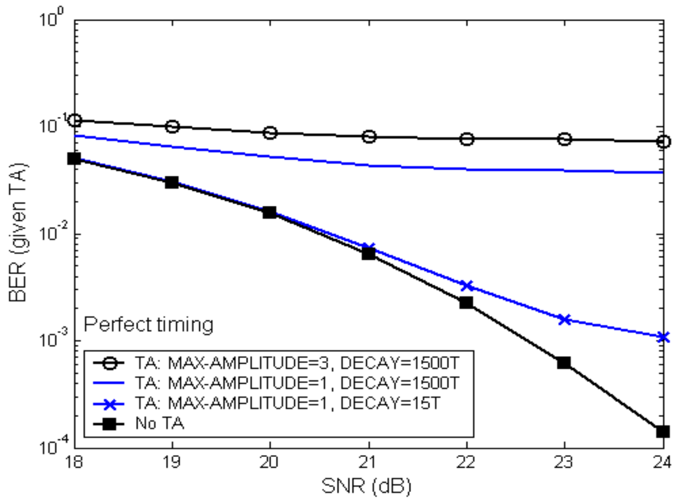


* Because it fits captured spin stand data and drive data very well.

Read-Back Signals with TA



Example: System Performance with TA



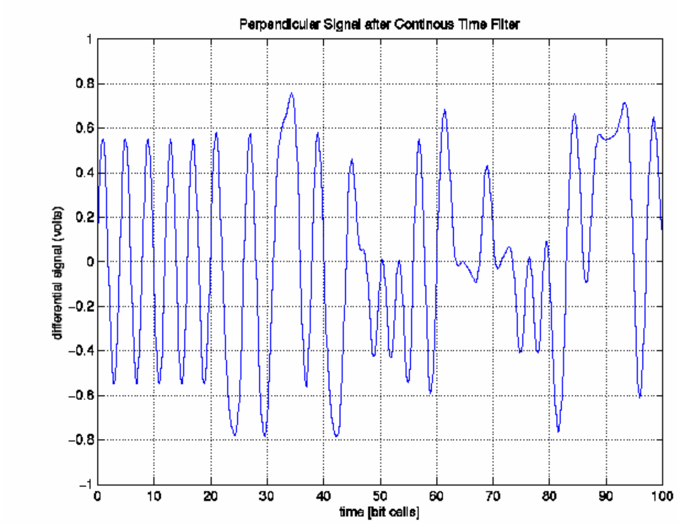
Continuous-Time Filter (CTF)

- CTF $\Rightarrow$ 7th-order equi-ripple lowpass filter
- To provide mid-band peaking to help with achieving the target signal response.
- To keep the signal energy below the Nyquist rate to minimize any aliases that may occur when the analog signal is converted to a sampled representation
- To eliminate the out-of-band noise.

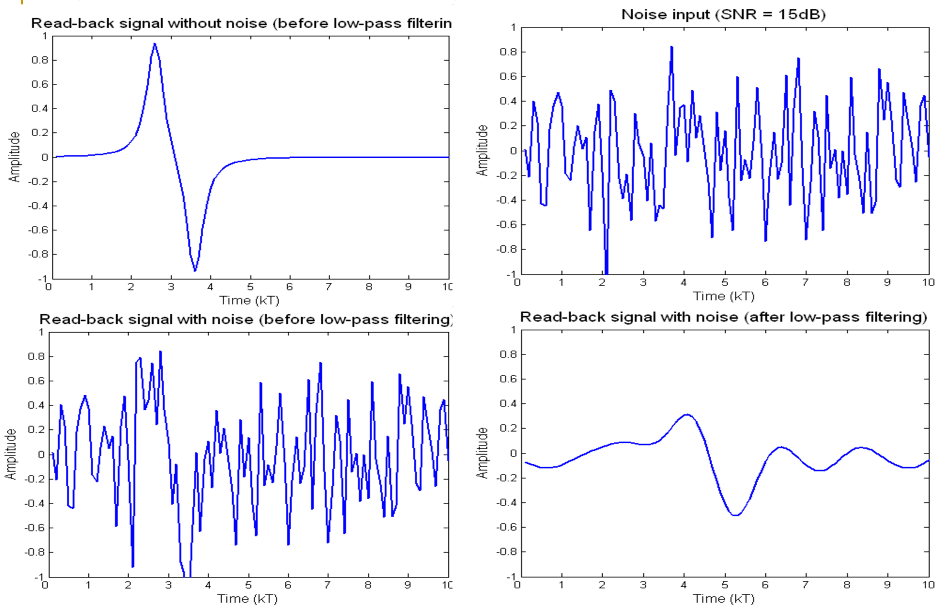
Booster in CTF

- Closely spaced multiple transitions result in high frequency energy in the signal, which is attenuated by the lowpass nature of the read process [Uehara and Gray, 1994].
- Boosting high frequency energy in the signal is useful in shaping the signal to meet the digital target signal characteristics.

Perpendicular signal after CTF low pass filter

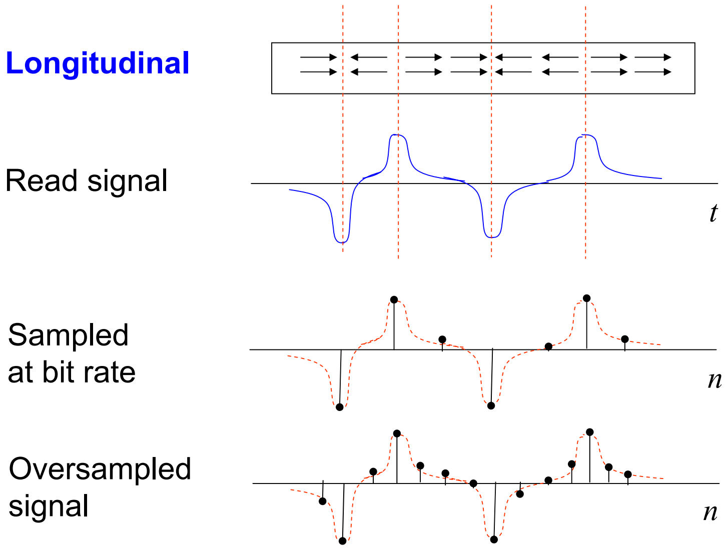


Signal Response @ Long, ND = 0.5, SNR = 15 dB

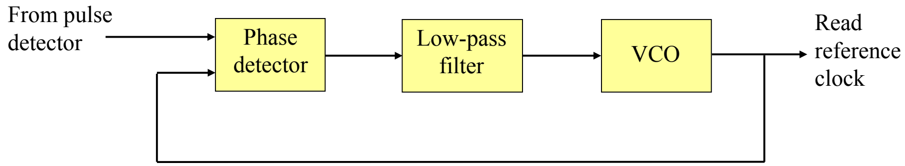


Analog-to-Digital Converter (ADC)

- Used to convert an analog signal to a digital samples, quantized in time and amplitude.
- Controlled by a timing recovery block.
- Currently, a 6-bit ADC is employed in HDD.
  - More bits $\Rightarrow$ low quantization noise, high complexity, expensive
  - Less bits $\Rightarrow$ high quantization noise, low complexity, cheap
- Sampling rate:
  - Symbol-rate sampling
  - Oversampling
    - Give more samples per one clock period $\Rightarrow$ more information for timing recovery
    - Expensive for implementation

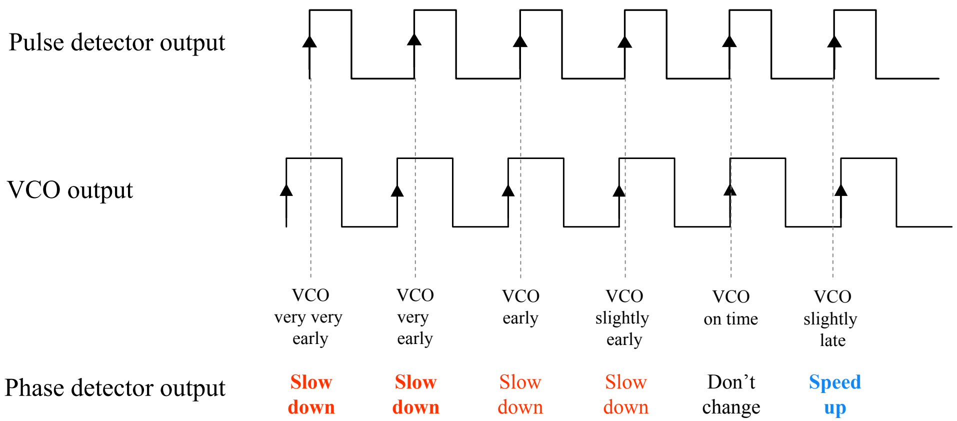


Phase Locked-Loop (PLL)



- Phase detector: Compare the input pulse with the clock pulse
  - If the clock is later than the input ⇒ speed up the VCO
  - If the clock is earlier than the input ⇒ slow down the VCO
- Low-pass filter: Average the signal from the phase detector to reduce the effect of noise.
- Voltage-controlled oscillator (VCO): Generate a clock with the frequency determined by the voltage of the input.

Example: PLL Operation



Sampled signal after ADC, analog to digital converter