

The PES Pareto Method: Uncovering the Strata of Position Error Signals in Disk Drives

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Sooner or later, you must pay for every good deed. — *Eli Wallach in the “The Magnificent Seven”*

Talk Outline

- Bode's Theorem and the PES Pareto Method (Danny)
- Noise Source Measurements and ANOVA (Terril)
- Noise Decomposition Results and Extrapolations (Danny)

Components of Hard Disk PES

- External Shock and Vibration
 - more a function of environment
 - Been there. Done that. See 1996 IFAC.
- Synchronous or Repeatable Excitations
 - synchronous with spindle orders
 - handled with feedforward adaptive cancellers
- Non-synchronous or Non-repeatable Excitations
 - sharp spectral peaks due to spindle bearing cage orders and structural resonances
 - handled with damped substrates, fluid bearing spindles
- Broadband or Baseline Noise
 - what remains when all of the narrow band components have been removed
- First three categories have reasonable engineering solutions. \Rightarrow Study the fourth.

Available Tools

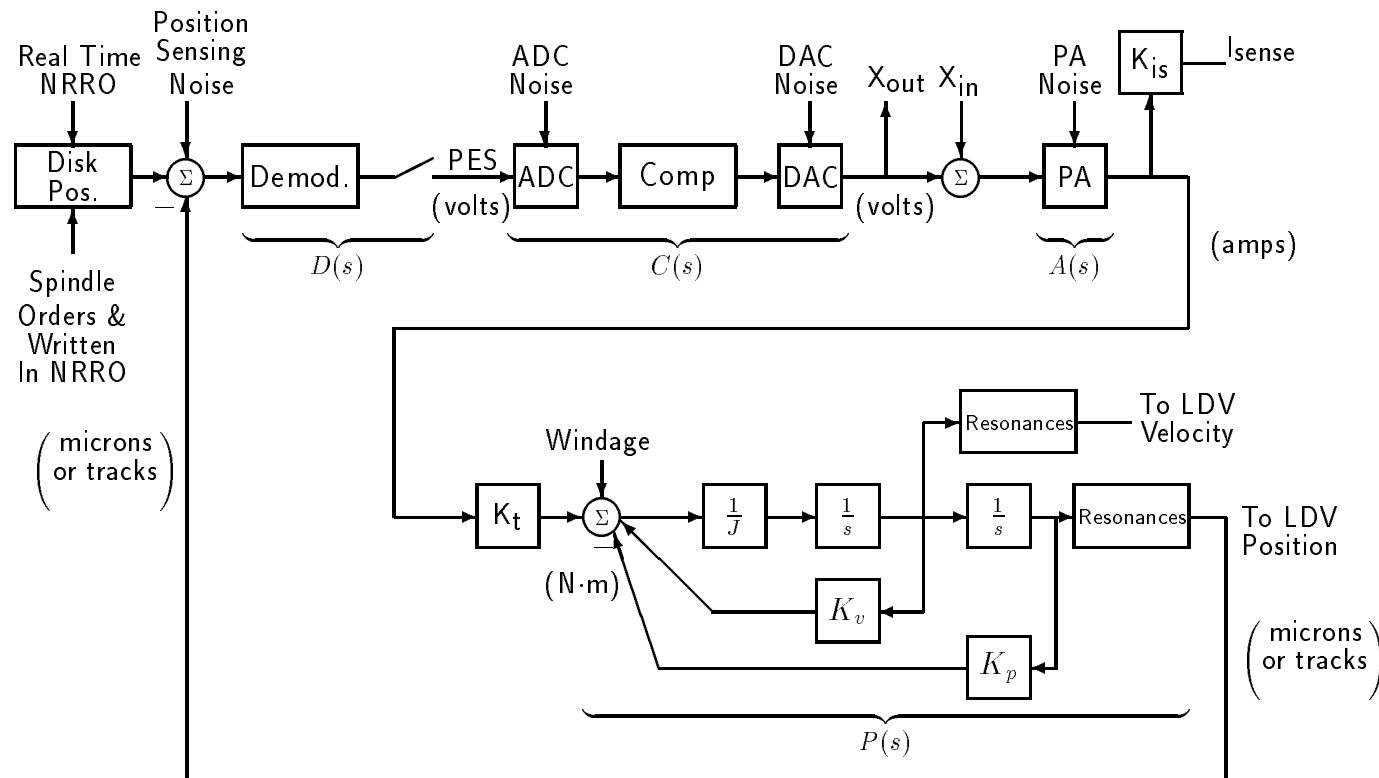
- Laser Doppler Vibrometer (Polytec LDV)
- Dynamics analyzers (low frequency spectrum analyzers) (HP 3563A, HP3567A)
- Digital Storage Oscilloscopes
- Matlab/Simulink (or similar tools)

Types of Measurements

- PSDs and Power Spectra
- Linear Spectra
- Time Domain Measurements

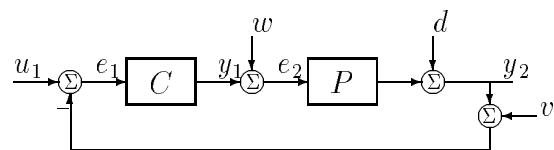
For reasons detailed in paper, choose PSDs and Power Spectra.

Our Trusty System Map



- This block diagram is our map around the servo-mechanical system.
- It helps us locate where the noises are relative to the places where we measure them.
- It helps us understand how each noise will affect PES.

Sensitivity Functions



- Closed-Loop Transfer Function:

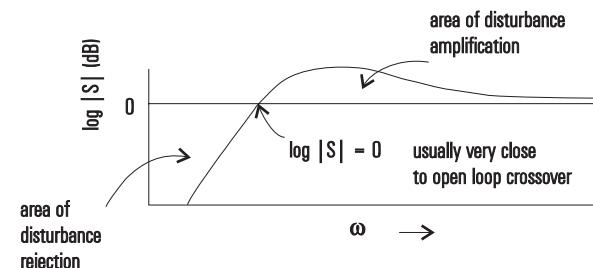
$$T = \frac{PC}{1 + PC} = \frac{y_2}{u_1}.$$

- Closed-Loop Sensitivity Function:

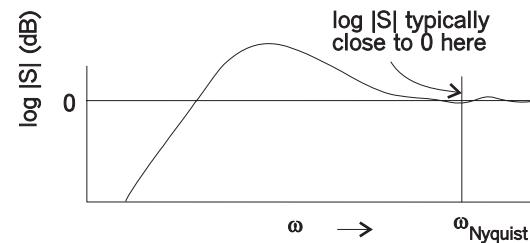
$$S = \frac{1}{1 + PC} = \frac{e_1}{u_1} = \frac{y_2}{d} = -\frac{e_1}{d}.$$

-

$$S + T = \frac{1}{1 + PC} + \frac{PC}{1 + PC} \equiv 1$$



Sensitivity function



Sensitivity function in discrete time.

Three Statements of the Same Thing

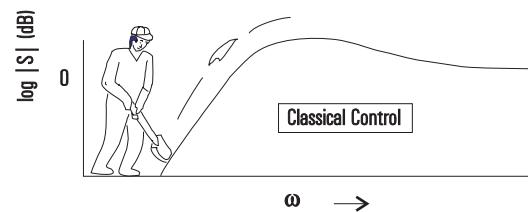
- “Sooner or later, you must pay for every good deed.”
(Eli Wallach in the *The Magnificent Seven*)
(Time Domain)
- “No good deed ever goes unpunished.”
(The 285th Ferengi Rule of Acquisition)
(Time Domain)
- Bode’s Integral Theorem (Frequency Domain):

$$- \int_0^\infty \log |S(\omega)| d\omega = c_1.$$

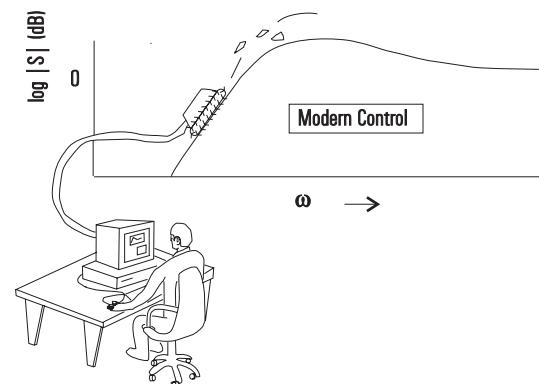
– In other words:

$$\frac{\text{the area of disturbance}}{\text{rejection}} = \frac{\text{the area of disturbance}}{\text{amplification.}}$$

– Stein visualized this as shoveling dirt.



Stein’s depiction of classical control.



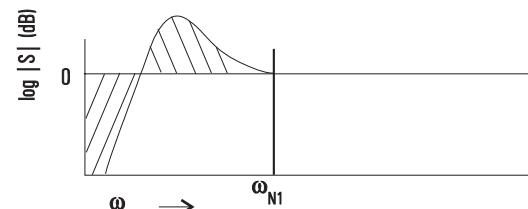
Stein’s depiction of modern control.

Bode's Integral Theorem for Discrete Time

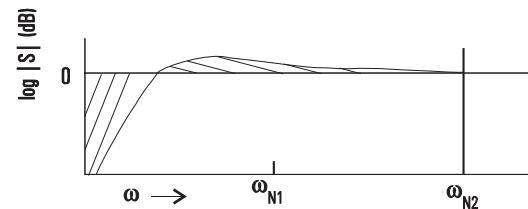
- $\frac{1}{\pi} \int_0^\pi \ln |S(e^{j\phi})| d\phi = c_2$
- Once again:

$$\text{the area of disturbance} = \text{the area of disturbance rejection} = \text{the area of disturbance amplification.}$$

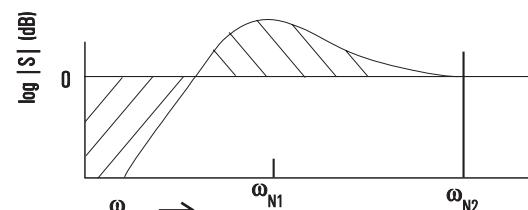
- The Nyquist Frequency is a retaining wall for our dirt.
- Higher sample rate \Rightarrow
 - more bandwidth and/or
 - more filtering



Sensitivity function at nominal sample rate.



Doubling the sample rate (more filtering)

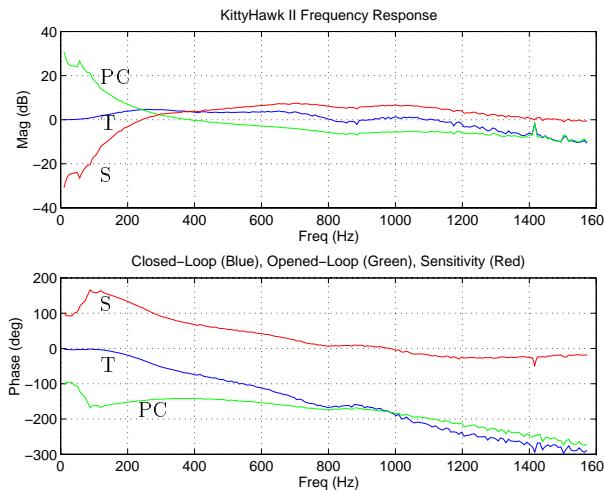


Doubling the sample rate (more bandwidth)

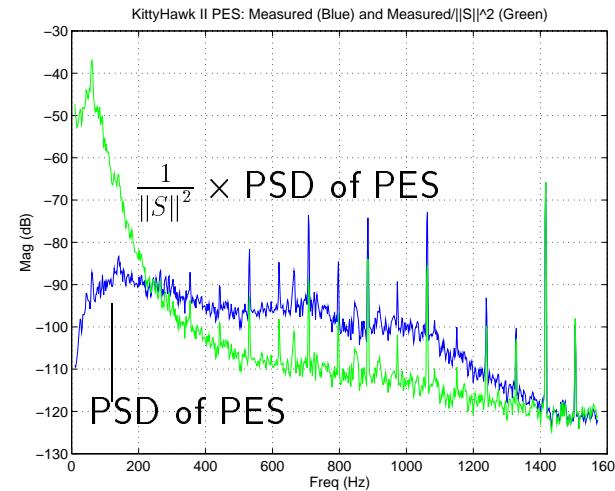
Using Bode's Theorem in PES PSD Measurements

- Measure $T = \frac{PC}{1 + PC}$
- Derive $S = \frac{1}{1 + PC}$
- Filter PES PSD by $\frac{1}{\|S\|^2} = \|1 + PC\|^2$
- We get PES Input PSD, with effects of the loop removed.
- Low gain PES PSD essentially matches “opened-loop.”

⇒ We can do this for all of our measurable noise sources.

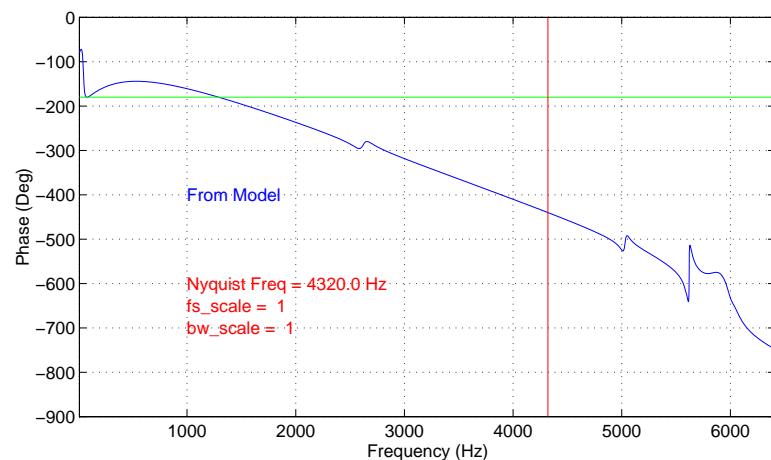
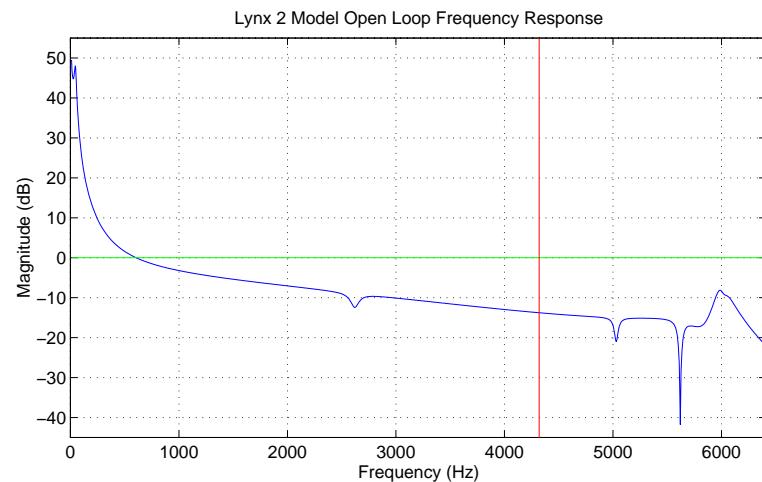


Frequency response of a KittyHawk II.

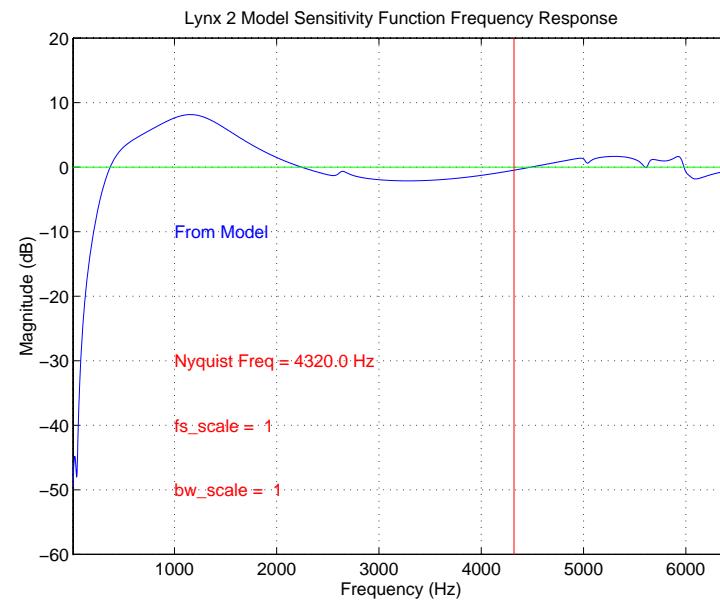


PSD of PES, and PSD of PES filtered by $\frac{1}{\|S\|^2}$.

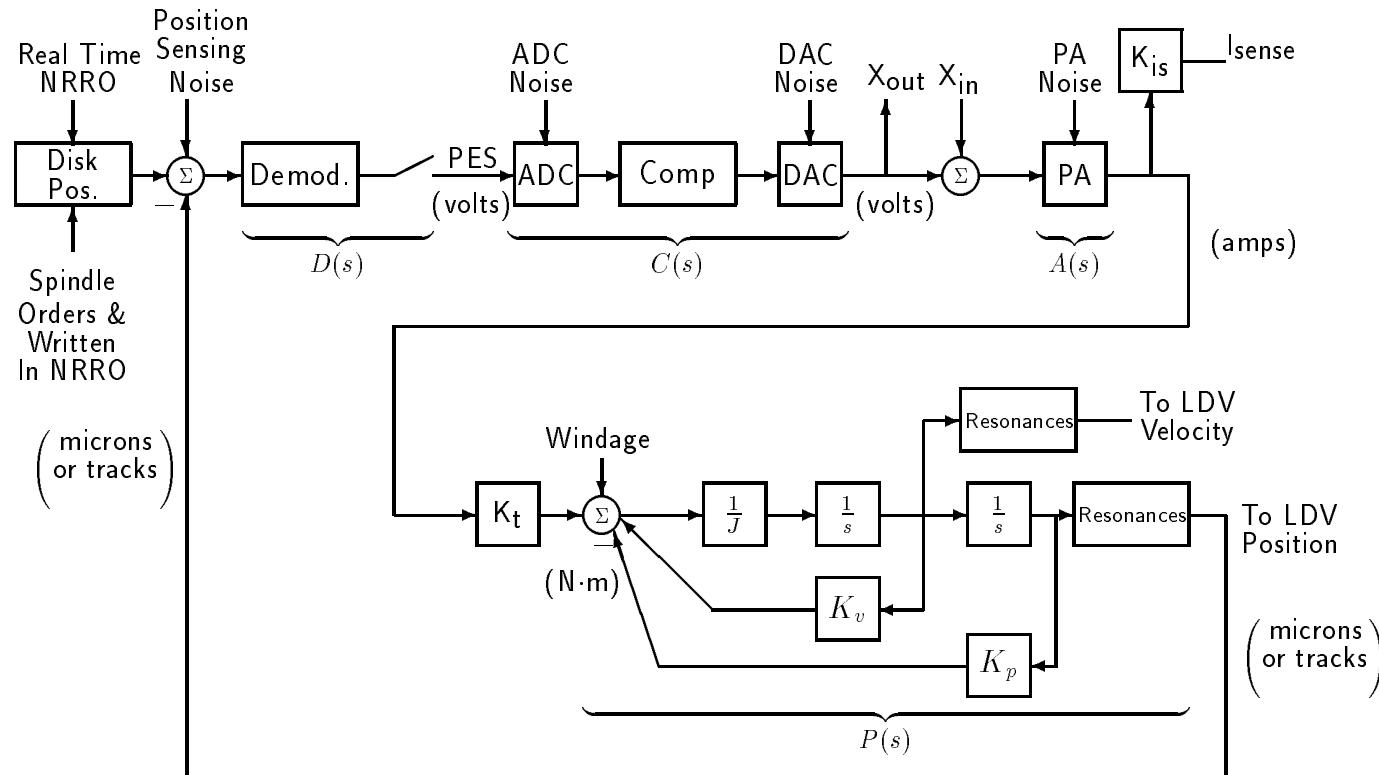
Lynx II Sensitivity Functions



- Standard Lynx 2 servo loop.
 - Standard sample rate (8640 Hz)
 - Standard bandwidth (≈ 500 Hz OL crossover)

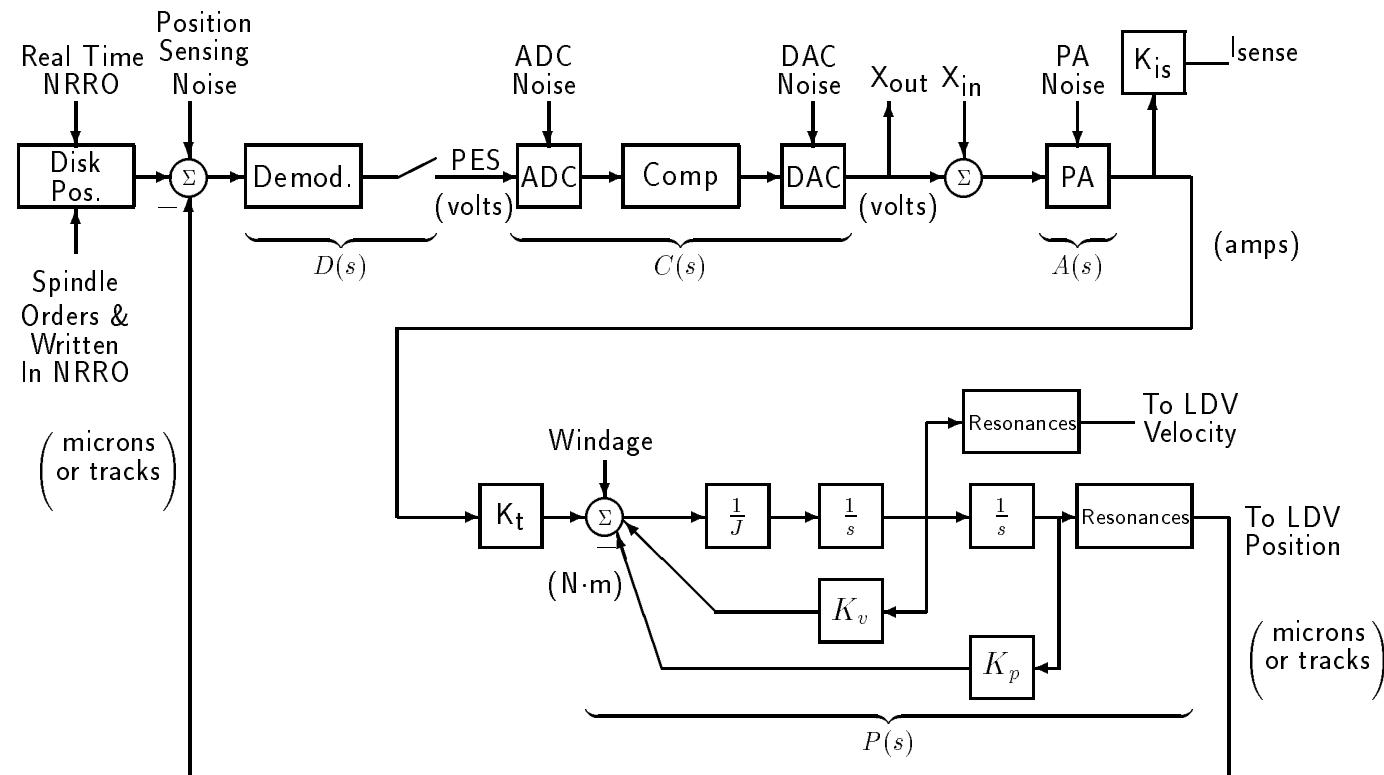


The PES Pareto Method: A Common Theme for Each Noise Source



- Isolate measurement of noise source ("common mode reject")
- Filter backwards for source PSD
- Filter forwards for effect on PES PSD
- Compare and add to cumulative

Filters from Frequency Response Function Measurements



$$\bullet P(s) = \left(\frac{LDV}{I_{sense}}\right)_{\text{meas}} \times \frac{1}{K_t} = \left(\frac{LDV}{X_{in}}\right)_{\text{open CL-meas}} \times \frac{1}{K_t A(s)}$$

- $A(s)$: from DMD model

$$\bullet C(s) = \left(\frac{X_{out}}{PES}\right)_{\text{meas}}$$

$$\bullet D(s) = \frac{\left(\frac{NPES}{I_{sense}}\right)_{\text{meas}}}{\left(\frac{LDV}{I_{sense}}\right)_{\text{meas}}}$$