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

Daniel Abramovitch
E-mail: danny@hpl.hp.com

Terril Hurst
E-mail: terril@hpl.hp.com

Dick Henze
E-mail: Dick_Henze@hpl.hp.com

Storage Technologies Department
Hewlett-Packard Laboratories
1501 Page Mill Road, M/S 2U-10
Palo Alto, CA 94304

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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 Decompostiion 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. $\Longrightarrow$ Study the fourth.

Available Tools

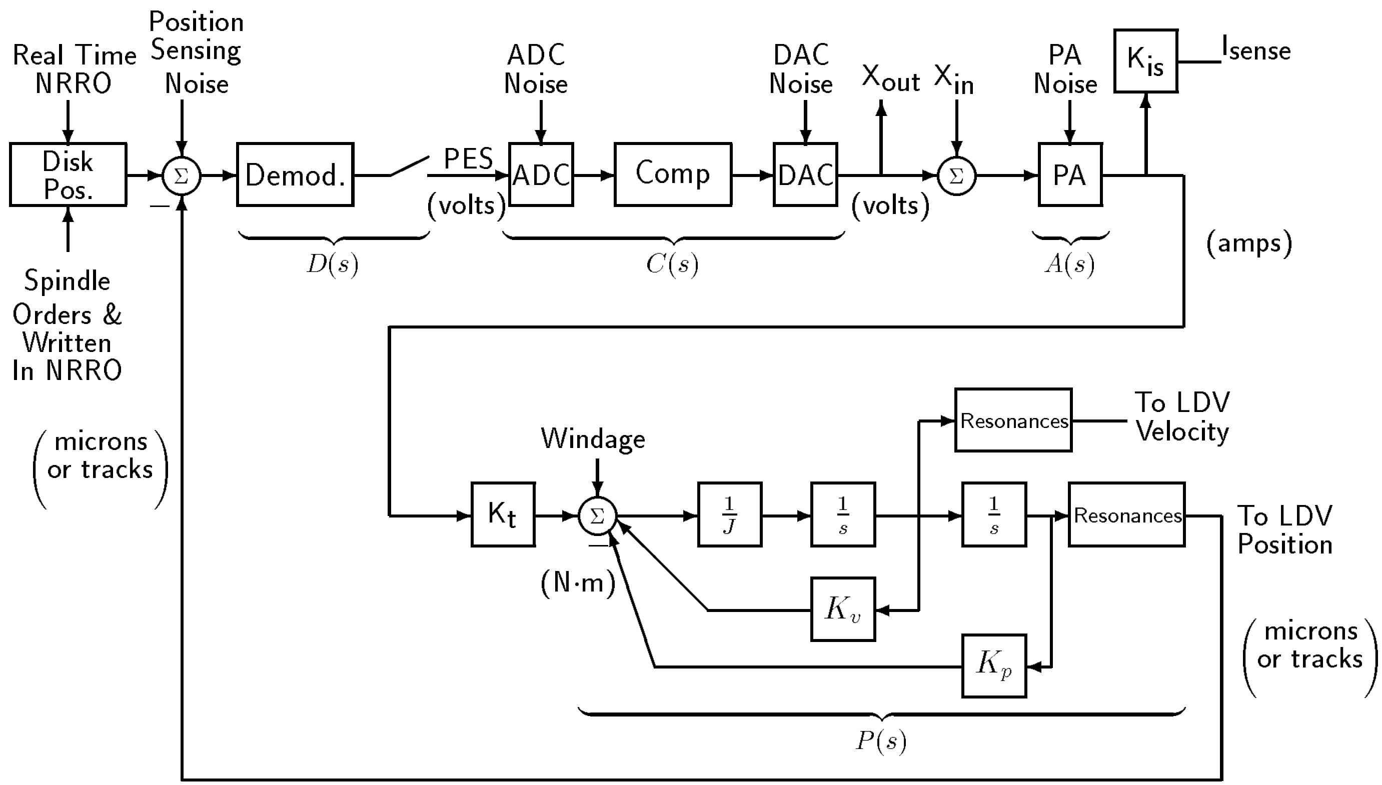
- Laser Doppler Vibrometer (Polytec LDV)
- Dynamics analyzers (low frequency spectrum analyzers) (HP 3563A, HP3567A)
- Digital Storage Oscilloscopes
- Matlab/Simulink (or similar tools)

Types of Measurements

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

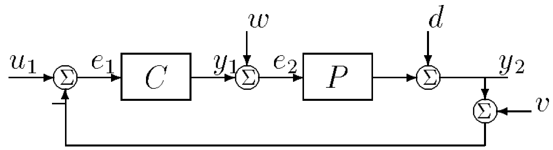
For reasons detailed in paper, choose PSDs and Power Spectra.

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



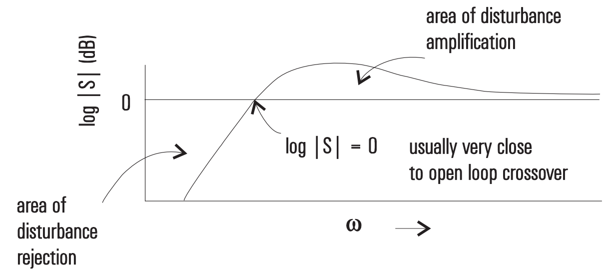
- Closed-Loop Transfer Function:

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

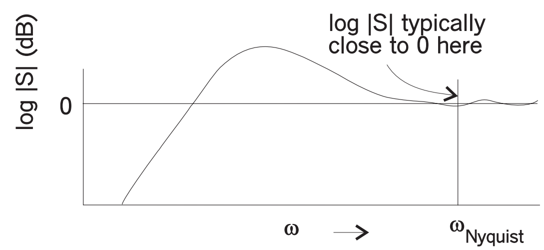
- Closed-Loop Sensitivity Function:

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

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



Sensitivity function



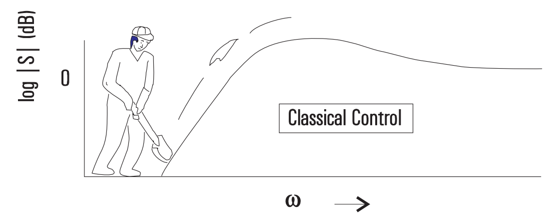
Sensitivity function in discrete time.

Three Statements of the Same Thing

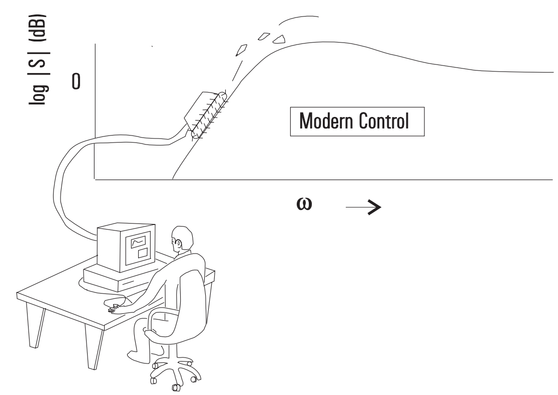
- "Sooner or later, you must pay for every good deed."
  (Eli Wallach in the *The Magnificent Seven*)
  (Time Domain)
- "No good deed ever goes unpunished."
  (The 285th Ferengi Rule of Aquisition)
  (Time Domain)
- Bode's Integral Theorem (Frequency Domain):
  - $\int_0^\infty \log|S(\omega)|d\omega = c_1$.
  - In other words:

    the area of disturbance rejection = the area of disturbance amplification.

  - Stein visualized this as shoveling dirt.



Stein's depiction of classical control.



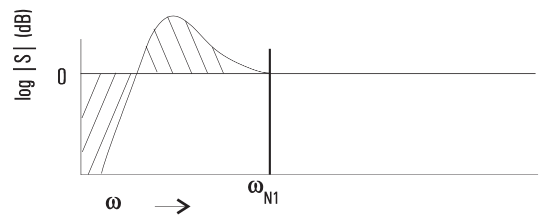
Stein's depiction of modern control.

Bode's Integral Theorem for Discrete Time

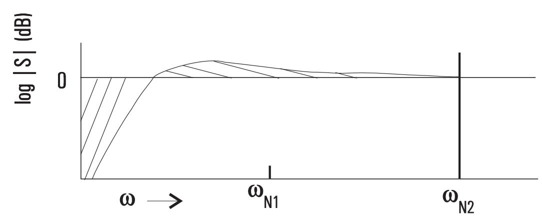
- $\frac{1}{\pi}\int_0^\pi \ln\left|S(e^{j\phi})\right| d\phi = c_2$
- Once again:

$$\begin{array}{c}\text{the area of}\\ \text{disturbance}\\ \text{rejection}\end{array} = \begin{array}{c}\text{the area of}\\ \text{disturbance}\\ \text{amplification.}\end{array}$$

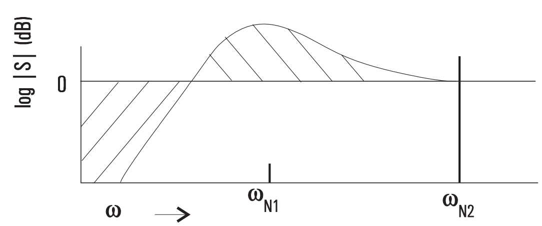
- The Nyquist Frequency is a retaining wall for our dirt.
- Higher sample rate $\Longrightarrow$
  - more bandwidth and/or
  - more filtering



Sensitivity function at nominal sample rate.



Doubling the sample rate (more filtering)

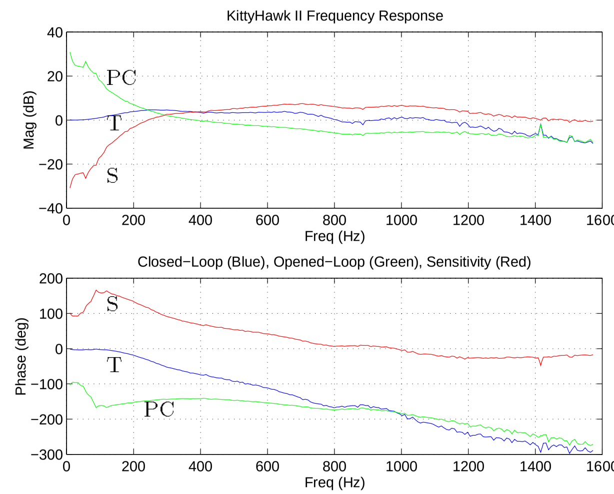


Doubling the sample rate (more bandwidth)

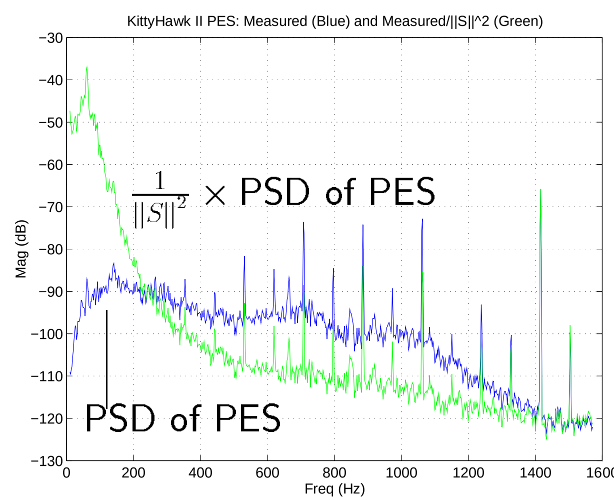
Using Bode's Theorem in PES PSD Measurements

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

$\Longrightarrow$ We can do this for all of our measureable noise sources.

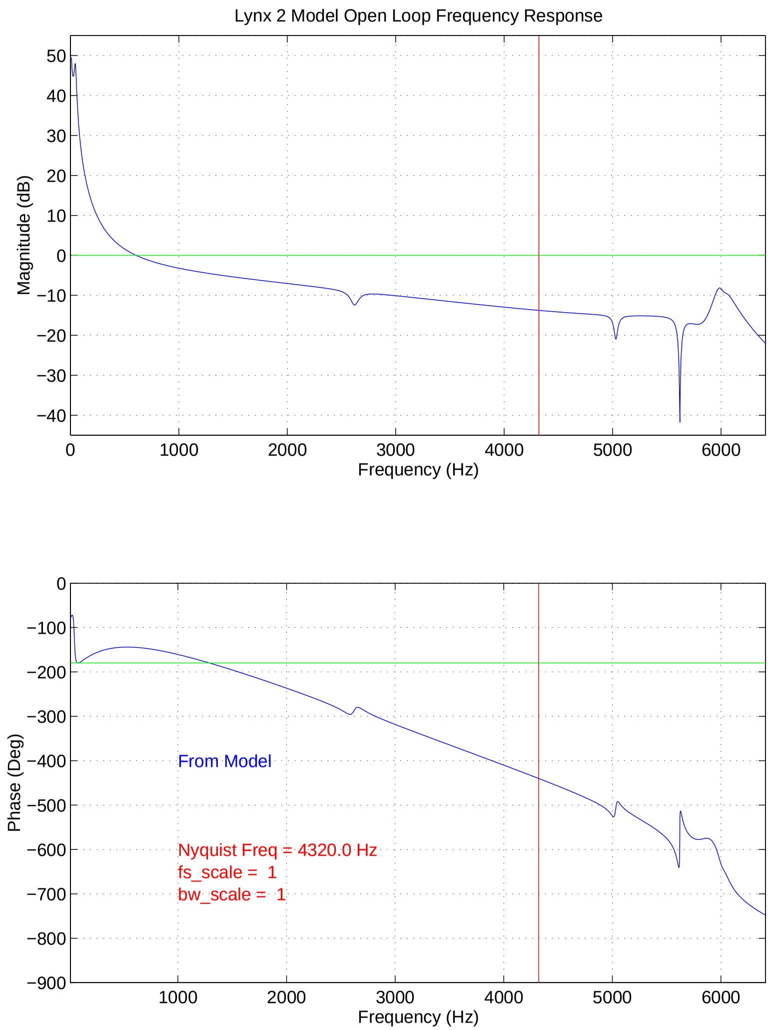


Frequency response of a KittyHawk II.

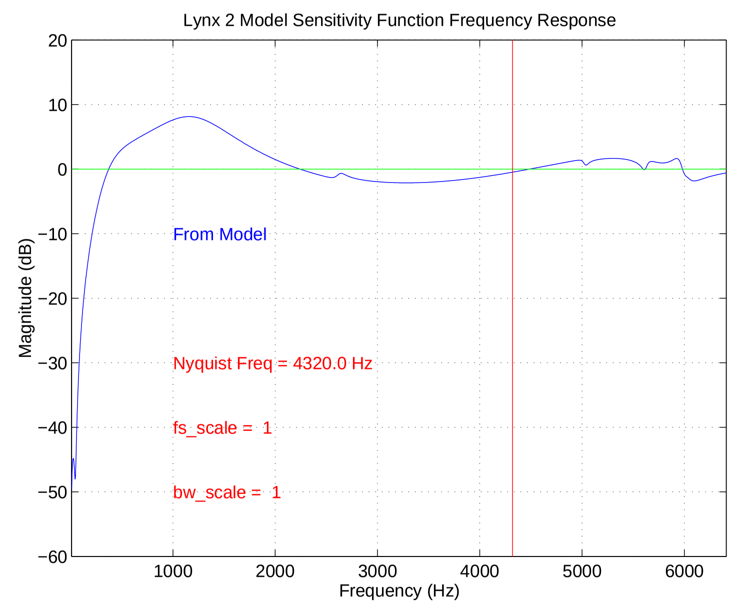


PSD of PES, and PSD of PES filtered by $\frac{1}{\|S\|^2}$.

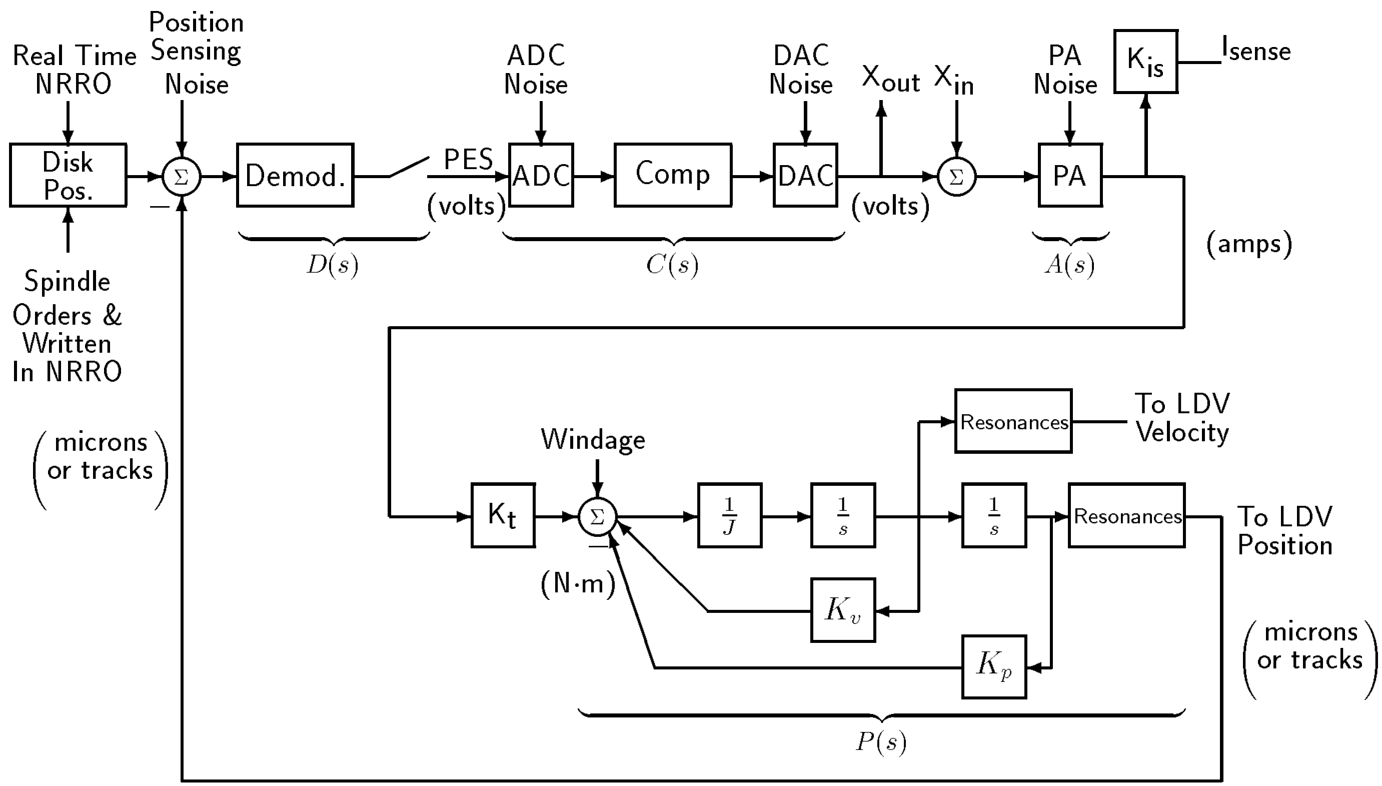
Lynx II Sensitivity Functions



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

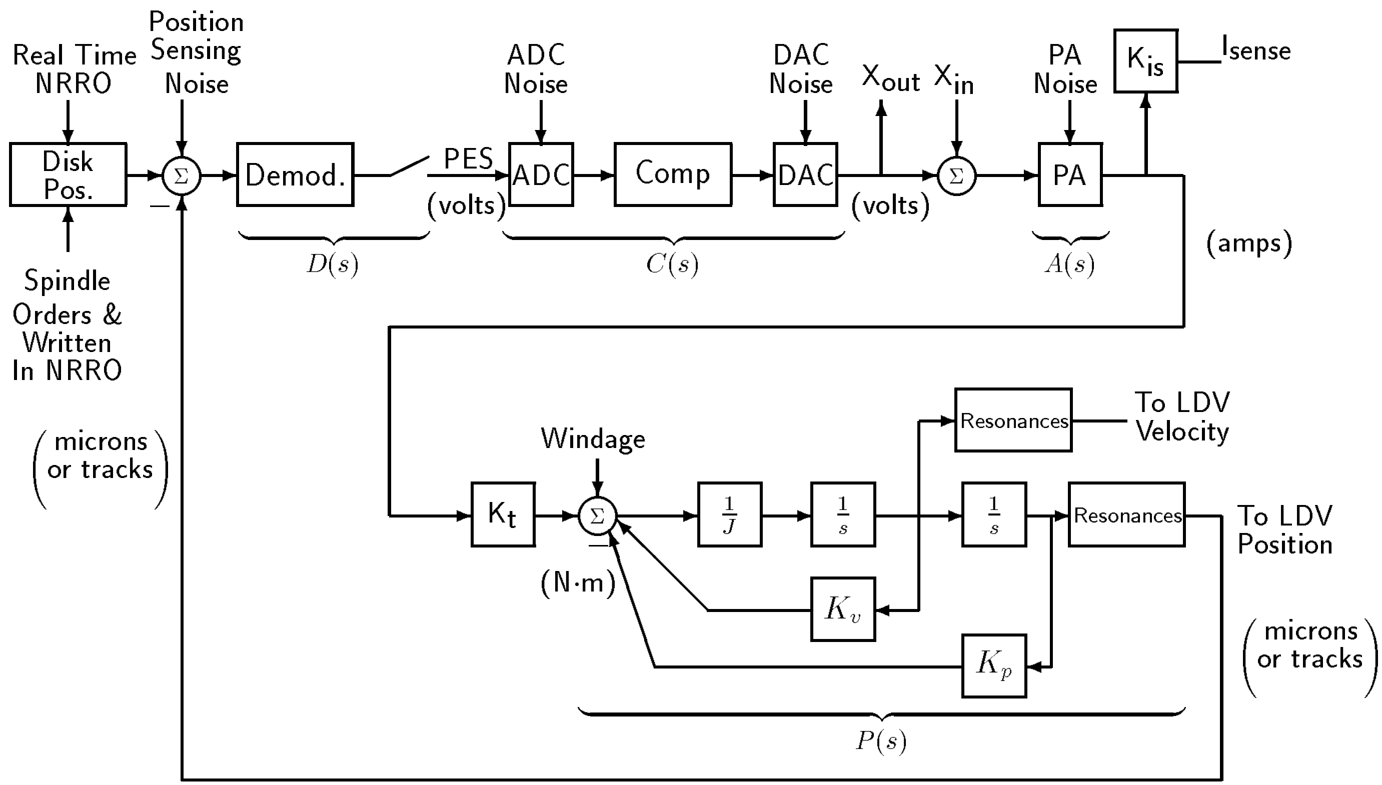


The PES Pareto Method: A Common Theme for Each Noise Source



- 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



- $P(s) = \left(\frac{LDV}{I_{sense}}\right)_{\text{3-wire meas}} \times \frac{1}{K_t} = \left(\frac{LDV}{X_{in}}\right)_{\text{opened CL-meas}} \times \frac{1}{K_t A(s)}$
- $A(s)$: from DMD model
- $C(s) = \left(\frac{X_{out}}{PES}\right)_{\text{meas}}$
- $D(s) = \frac{\left(\frac{NPES}{I_{sense}}\right)_{\text{meas}}}{\left(\frac{LDV}{I_{sense}}\right)_{\text{meas}}}$