An Overview of the PES Pareto Method for Decomposing Baseline Noise Sources in Disk Drive Position Error Signals

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Motivation

- Higher track density for magnetic drives requires an understanding of limiting factors.
- Baseline noise is the least understood contributor to TMR.
- Would like to identify the strata of PES – separated out by the individual source.

Key Philosophies

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

When you have eliminated the impossible, whatever remains, *however improbable* must be the truth. — *Sherlock Holmes*

Talk Outline

- Bode's Theorem and the PES Pareto Method
- Disk Drive Example: Measurements and Decomposition
- Extensions

Pareto's Law

Wilfredo Pareto (1848-1923) was an Italian economist and political sociologist who devised the 80:20 rule - the law of the trivial many and the critical few. This rule says that, in many business activities, 80% of the potential value can be achieved from just 20% of the effort, and that one can spend the remaining 80% of effort for relatively little return.

PES Pareto Definition

Thus, we can consider a PES Pareto to be a decomposition that identifies the critical few and trivial many noise sources in PES, freeing us to work on the critical few.

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

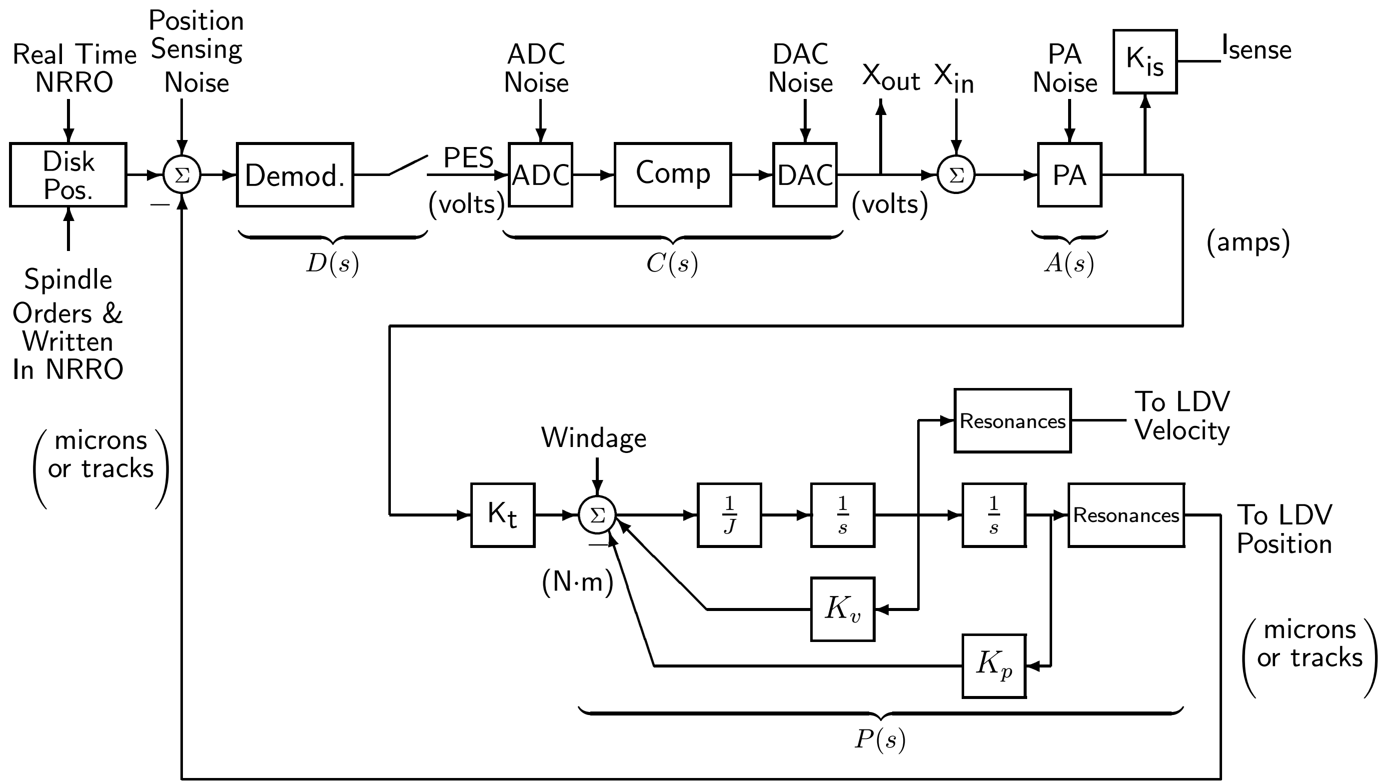
- Laser Doppler Vibrometer (Polytec LDV)
- Dynamics analyzers (low frequency spectrum analyzers) (HP 3563A, HP3567A)
- Digital Storage Oscilloscopes
- Matlab/Simulink (or similar tools)

Types of Measurements

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

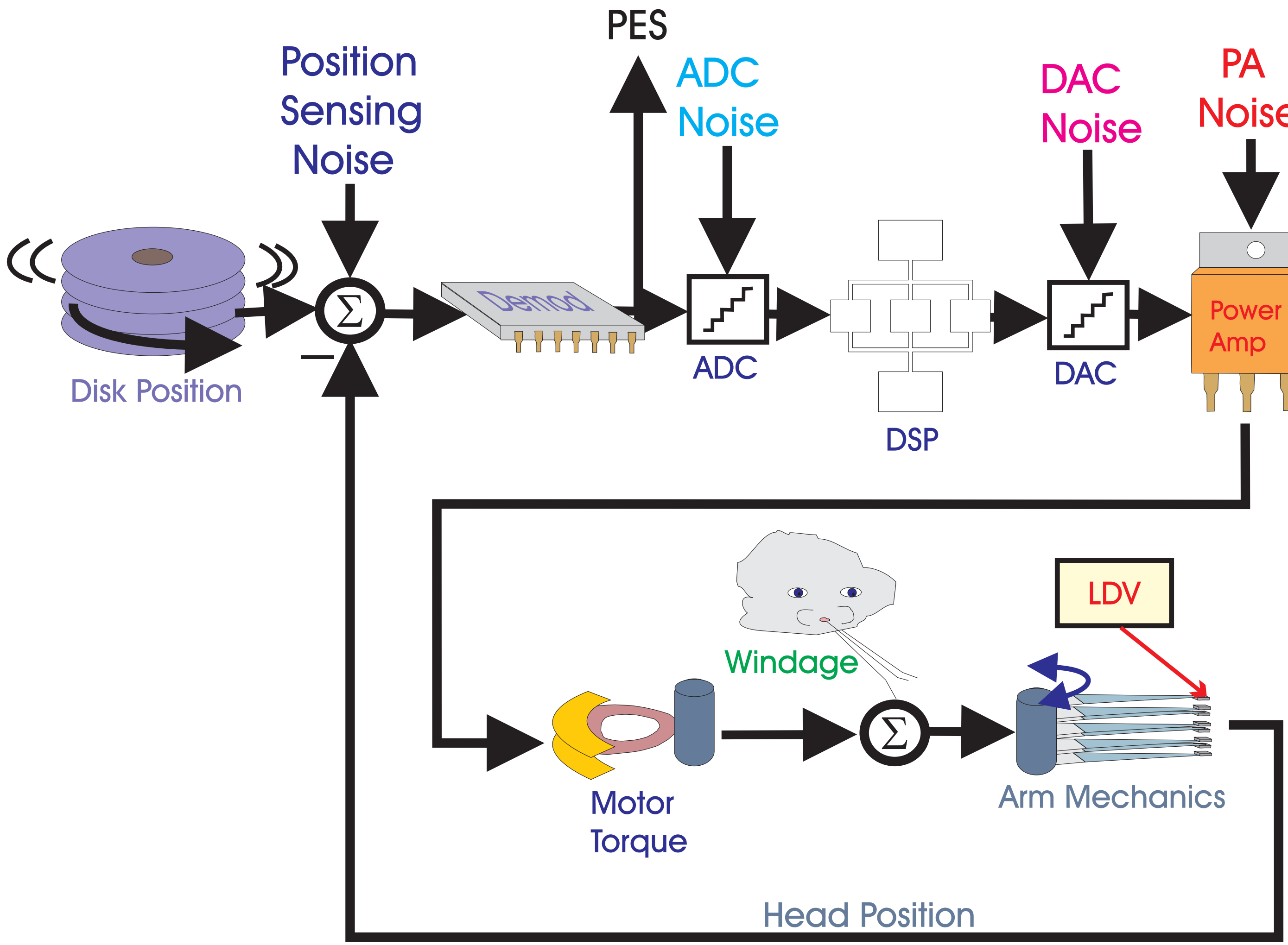
For reasons detailed in paper, choose PSDs and Power Spectra.

Our Trusty System Map

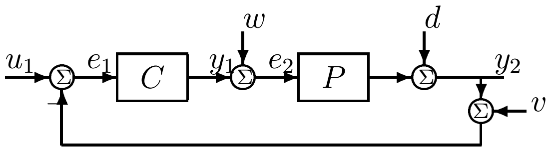


- This block diagram is our map around the servo-mechanical system.
- It helps us locate where the noises are relative to the places where we measure them.
- It helps us understand how each noise will affect PES.

Executive Summary Block Diagram



Sensitivity Functions



- Closed-Loop Transfer Function:

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

- Closed-Loop Sensitivity Function:

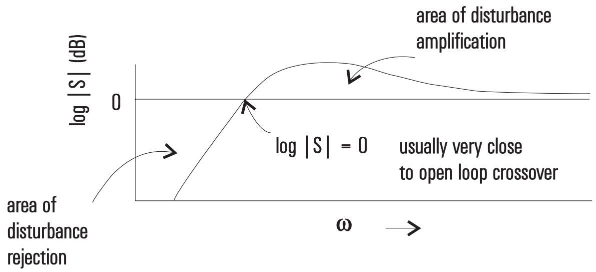
$$S = \frac{1}{1+PC} = \frac{e_1}{u_1} = \frac{y_2}{d} = -\frac{e_1}{d}.$$

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

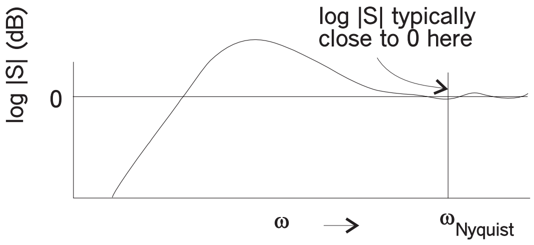
- Bode's Integral Theorem (Frequency Domain):
  - $\int_0^\infty \log|S(\omega)|d\omega = c_1.$
  - In other words:

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

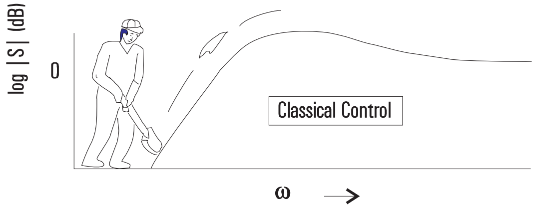
  - Stein visualized this as shoveling dirt.



Sensitivity function



Sensitivity function in discrete time.

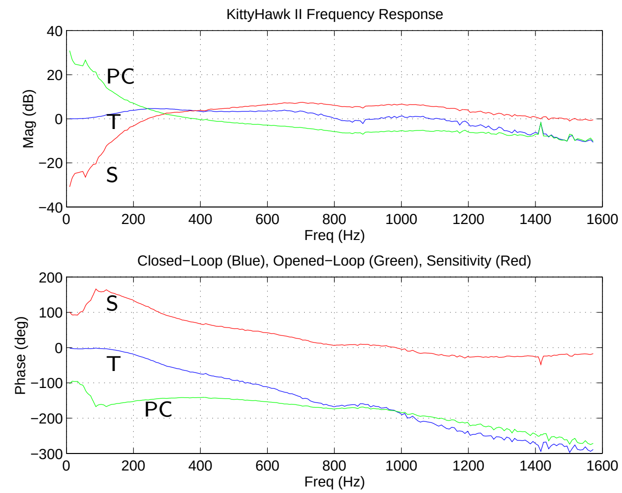


Stein's depiction of classical control.

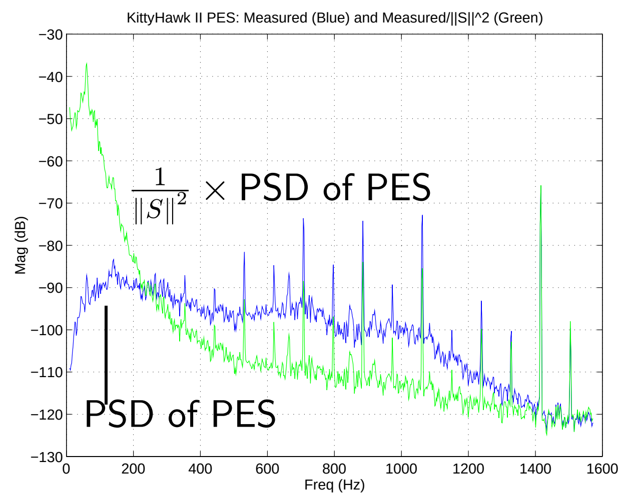
Using Bode's Theorem in PES PSD Measurements

- Understanding Bode's Theorem tells us that we must look at PES as an input to the system.
- Method is straightforward:
  - 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 measurable noise sources.

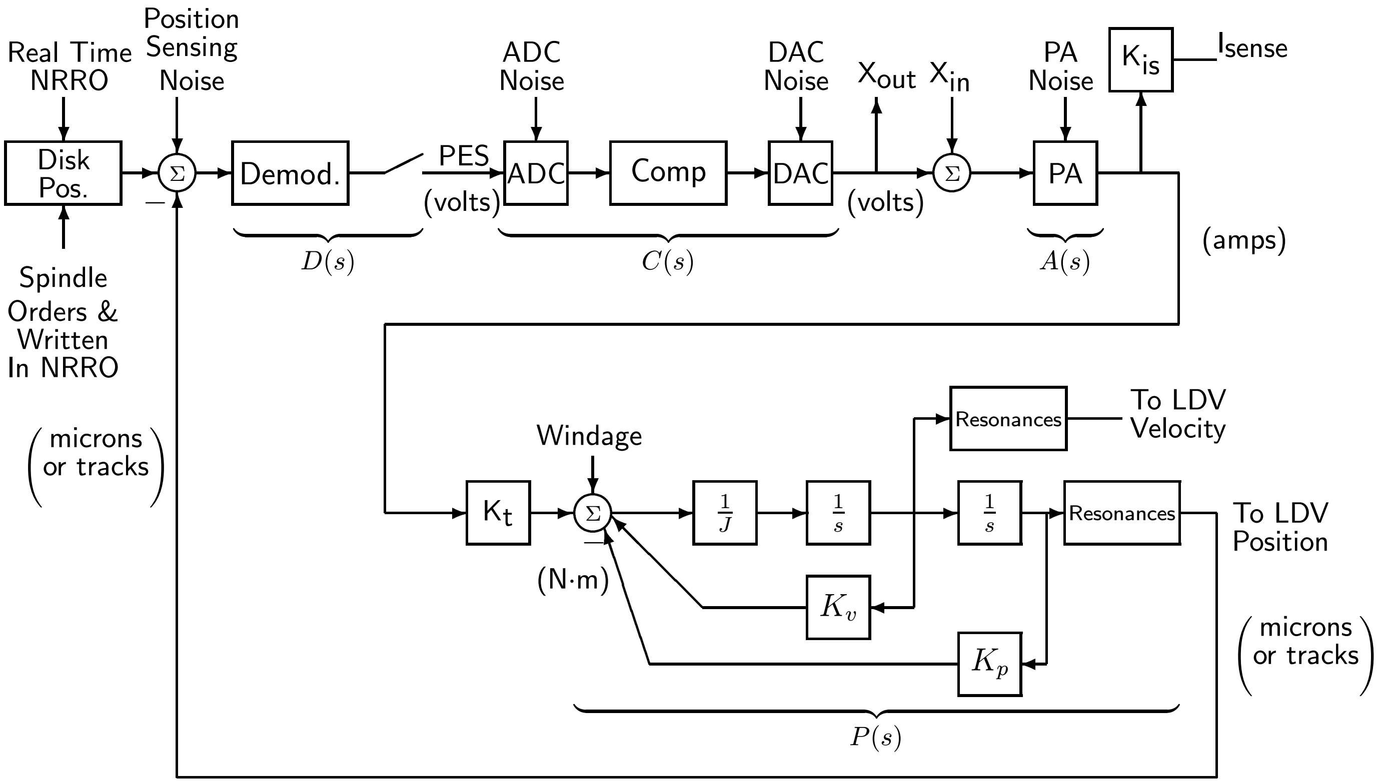


Frequency response of a KittyHawk II.



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

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



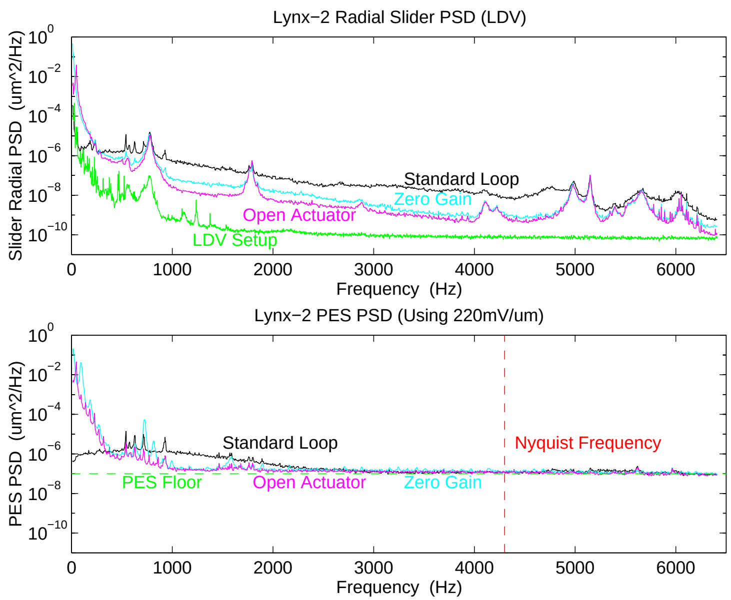
- Isolate measurement of noise source ("common mode reject")
- Filter backwards for source PSD
- Filter forwards for effect on PES PSD
- Compare and add to cumulative

Hard Disk Drive Example

Isolation Measurements

- Different Loop Conditions
  - Standard Loop
  - Low/Zero Gain
  - Open Actuator
  - LDV Setup
- Artificial masking of quantizer bits (DSP)
  - ADC
  - DAC
- Noise sources isolated
  - Power Amp
  - Windage
  - ADC
  - DAC

LDV vs. PES for Various Loop Conditions



First PSN estimate from noise floor:

$$\sqrt{1.2 \times 10^{-7} \mu m^2/Hz \times 6400 Hz} \quad = \quad 0.028 \mu m$$

$\Rightarrow \; 3\sigma_{PSN} \; = \; 1.34\%$ of track pitch.

Measuring Position Sensing Noise (PSN)

PSN

- Enters system directly via reference summing junction (difficult to isolate).
- Seek an independent estimate of PSN besides low–gain measurement.
- Want to compare independent estimate with what is left when other noises are eliminated.

ANOVA

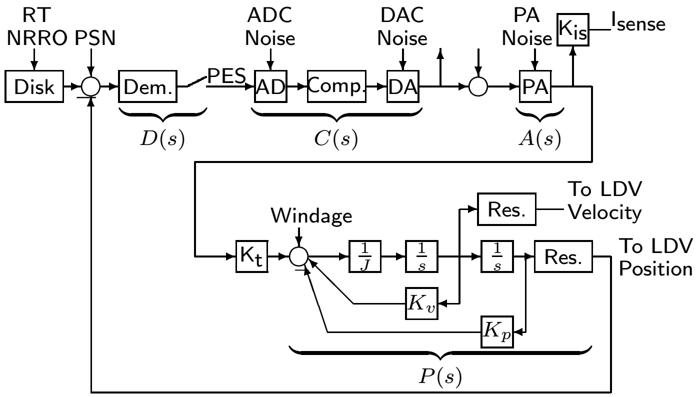
- Standard Statistical Two–Way Analysis of Variance
- Under certain assumptions it can isolate noise in servo dibits from movement of the head and disk.
- Yields an independent estimate of PSN variance.

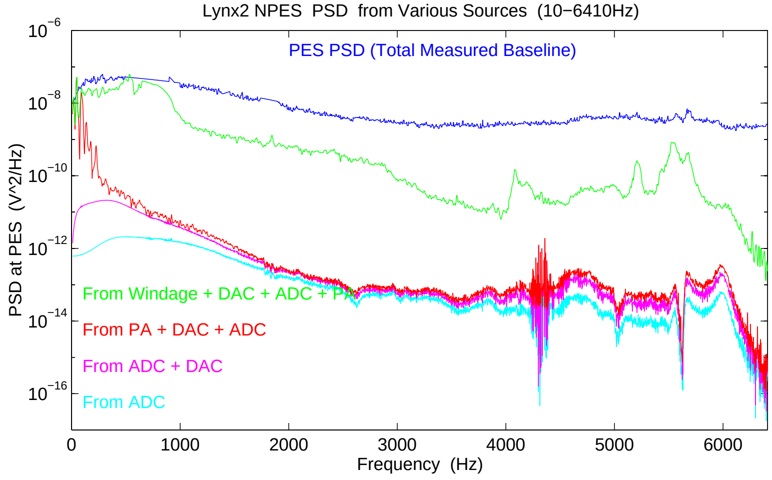
ANOVA Estimate of σ_S

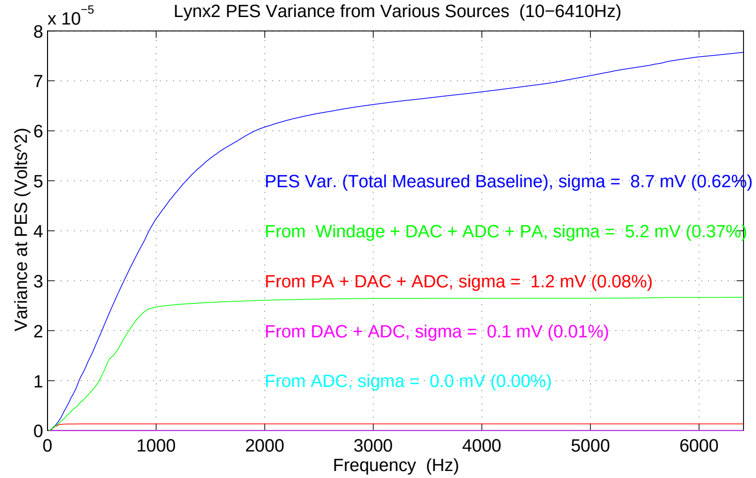
σ_S matches PES Pareto "What's Left" Value:

$0.029\ \mu m$!

Cumulative Noise Sources at PES

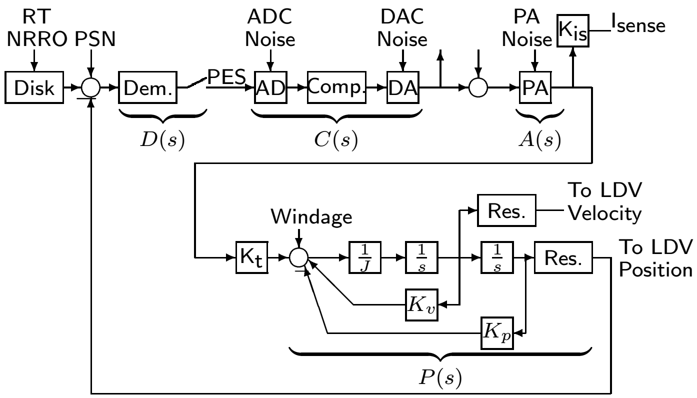






- Feed all the noise sources to PES with appropriate unit conversions.
- Stack them up.

Unaccounted PES Noise as an Input

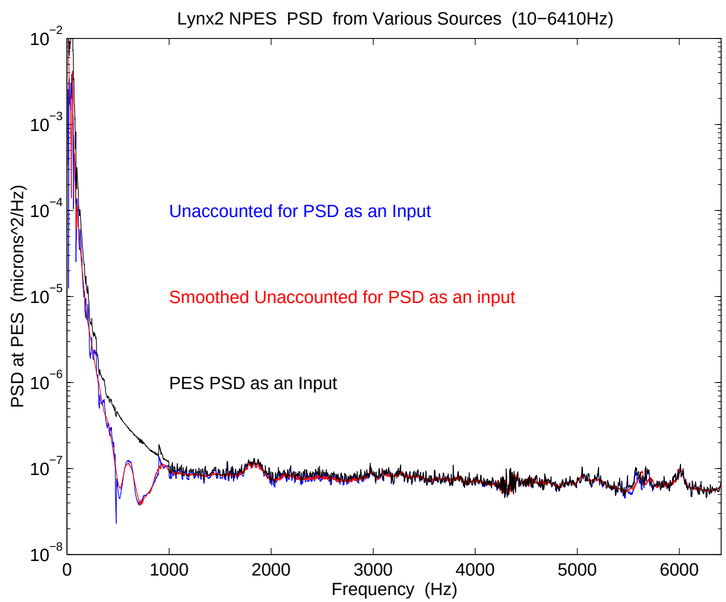


- Position Sensing Noise (PSN) enters right in front of PES.
- Filter PES PSD and unaccounted for PSD by

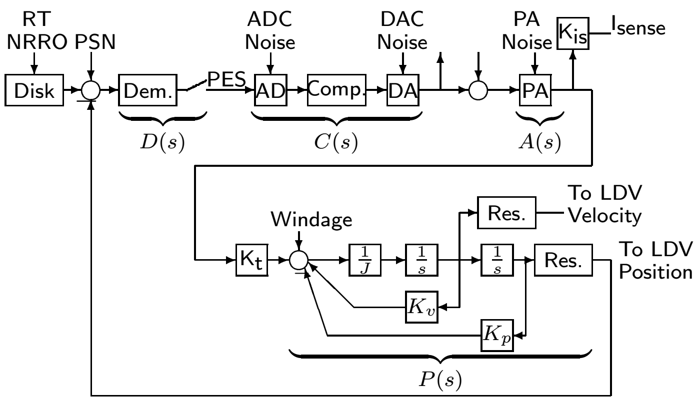
$$\left\| \frac{1}{D(s)S_{cl}(s)} \right\|^2$$

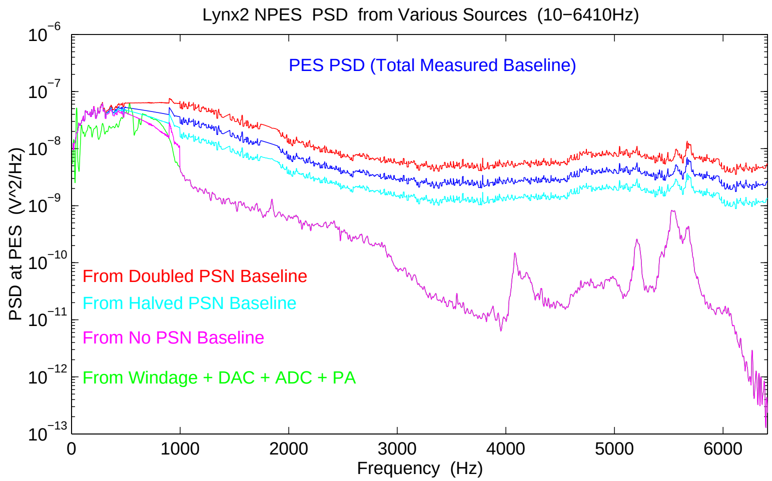
to get possible input PSN PSD.

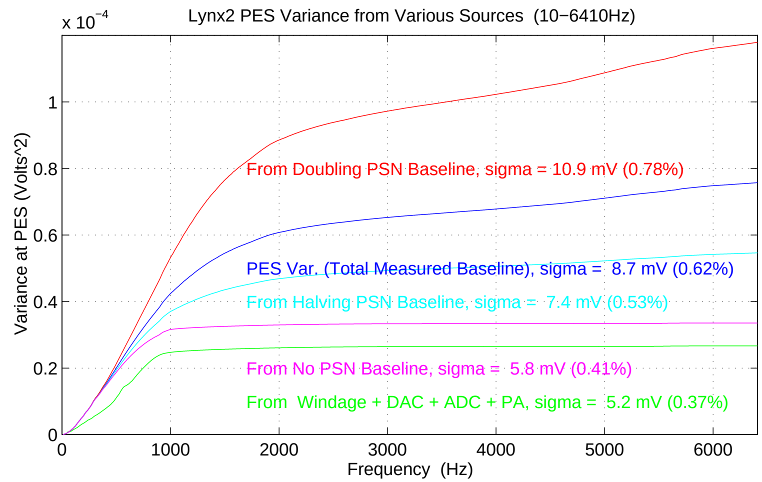
- *Qualitatively* and *quantitatively* matches what ANOVA says we should get.



Extrapolation: Changing Baseline PSN

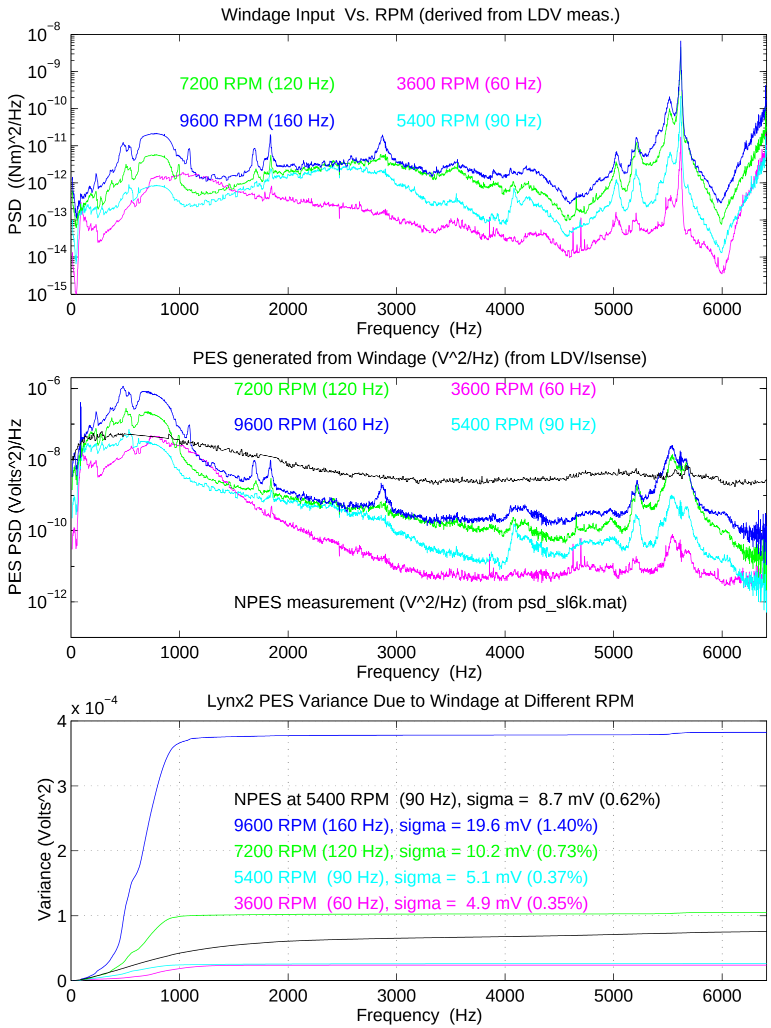




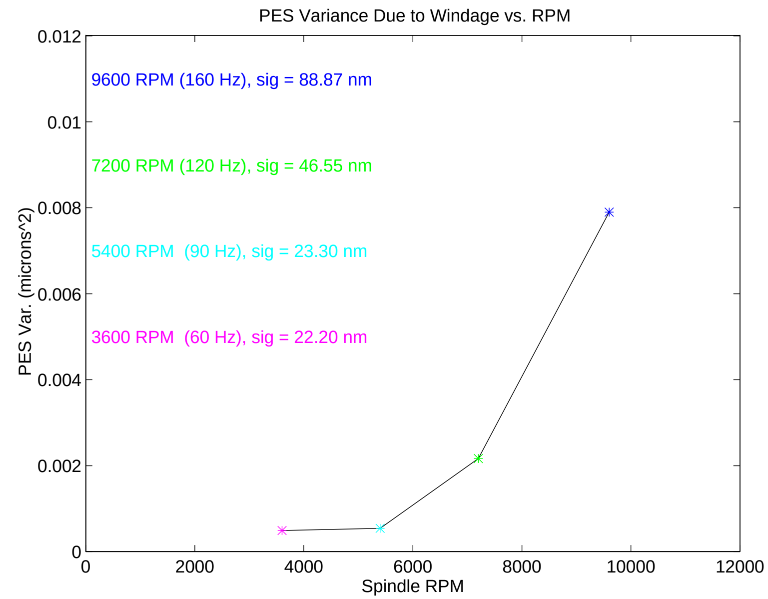


- Standard Lynx 2 servo loop.
  - Standard sample rate (8640 Hz)
  - Standard bandwidth ($\approx$ 500 Hz OL crossover)
- Change value of baseline PSN.
- Add to other PES PSD sources, for new PES PSD.

Extrapolation: Windage Versus RPM



- Change spindle RPM: 3600, 5400, 7200, 9600.
- Change in PES PSD is not linear.



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Conclusions

- There are two major baseline noise sources:
  - Windage
  - Position Sensing Noise (PSN)
- Step on one and you amplify the other (Bode's Integral Theorem).
- Windage gets significantly worse at higher RPM.
- To drive down PES baseline noise:

$\Longrightarrow$ We need to reduce windage input noise.

$\Longrightarrow$ We need a better position sensing method to dramatically reduce PSN.