Measurements for the PES Pareto Method of Identifying Contributors to Disk Drive Servo System Errors in Disk Drives

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Outline

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- Primary Tools/Capabilities Used
- Measurement Results
  - Frequency Response Functions
  - Power Spectra
  - Position Sensing Noise (ANOVA)
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System Model and Measurement Goals

- Obtain Frequency Response Functions (10-6410Hz; 2-Hz resolution)
- Obtain Power Spectral Density Responses (same bandwidth/resolution as FRF’s)
Primary Tools/Capabilities

- Lynx-2 disk drive and exerciser
  - Set loop parameters
  - Measure and compare key signals
- Polytec Laser Doppler Vibrometer (LDV)
- HP3567A 5-channel Digital Signal Analyzer
- HP54720D Digital Storage Oscilloscope
- The Network (including Web)
- Matlab
Closed Loop Transfer Function: Xout/Xin

Lynx II Closed Loop Frequency Response (xo_xi6k)

Freq (Hz)  Mag (dB)
0   1000   2000   3000   4000   5000   6000   7000
-50  -40  -30  -20  -10  0  10

Freq (Hz)  Phase (deg)
0   1000   2000   3000   4000   5000   6000   7000
-800  -600  -400  -200  0
Compensator Transfer Function: Xout/NPES

Lynx II Compensator Frequency Response (xo_np6k)

- Mag (dB)
- Phase (deg)

Freq (Hz)

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Mechanics Transfer Function: LDV/Torque–In

Lynx II (LDV Position)/(Torque In) Frequency Response (hd_is6k)

- Frequency (Hz)
- Magnitude (dB)
- Phase (deg)
- Units of microns/Nm

Freq (Hz)

In Units of microns/Nm

Freq (Hz)
Procedure:

- Mask off DAC LSB’s (alter DSP firmware);
- Send result to VCMDAC;
- Losing even 1 bit results in noticeable difference in PSD.
Procedure:

- Read ADC value and Mask off LSB's;
- Measure PSD of altered ADC value;
- Losing 2-3 bits results in minimal effect.
Power Amplifier Noise: $I_{\text{sense}}$ vs. Current Probe

- $I_{\text{sense}}$ was verified using current probe on actuator leads.
- Zero value at DAC isolates power amplifier.
- Disconnect actuator wires to isolate actuator.
LDV vs. PES for Various Loop Conditions

Lynx–2 Radial Slider PSD (LDV)

Lynx–2 PES PSD (Using 220mV/um)

- First PSN estimate: \( \sqrt{1.2 \times 10^{-4} \mu m^2/Hz \times 6400Hz} = 0.028 \mu m \Rightarrow 3\sigma_{PSN} = 1.34\% \) of track pitch.
Slider/Arm Movement vs. Spindle RPM

Lynx2 (LDV) Windage Response Vs. RPM

PSD (um^2/Hz)

Frequency (Hz)

9600 RPM
7200 RPM
5400 RPM
3600 RPM
LDV Setup
Measuring Position Sensing Noise (PSN)

- Enters system directly via reference summing junction (difficult to isolate).
- Seek an independent estimate of PSN besides low-gain measurement.
- Can then compare “forward-path” estimate with “what’s left” value.
Lynx-2 Servo Signal and Frame Format

Lynx-2 Servo Signal, On-Track and 20% Off-Track

- Question: How much of signal is from PSN vs. actual off-track?
Statistical Two-Way Analysis of Variance (ANOVA)

- Required Assumptions
  - Assume constant position during each of \( k \) servo bursts, each of length \( n \) servo bits.
  - Variations within each \( n \)-burst are uncorrelated.
  - Instrumentation measurement error is negligible.

- Model each servo bit, \( Y_{ij} \), as a sum of displacement, \( \Delta_i \), and measurement, \( E_{ij} \), errors, each normally distributed about zero mean: \( Y_{ij} = \mu + \Delta_i + E_{ij} \); \( i = 1, 2, \ldots k \), \( j = 1, 2, \ldots n \)

- Variances are given by Expected Values: \( E(SSD) = \sigma^2 + n\sigma^2_{\Delta} \); \( E(SSE) = \sigma^2 \); \( SSD = n \sum_{i=1}^{k} (\bar{Y}_i - \bar{Y})^2 \); \( SSE = \sum_{i=1}^{k} \sum_{j=1}^{n} (Y_{ij} - \bar{Y}_i)^2 \).

- Variance of (sectored) PES Measurement Error (based on \( Y \mid A \) - \( Y \mid B \)): \( \sigma^2_m = \frac{\sigma^2_{\Delta}}{n} + \frac{\sigma^2_n}{n} \).

- \( \sigma_m \) is an estimate of PSN.
ANOVA Comparison: Integrate vs. Peak-Detect; Kittyhawk, Lynx-3, and Lynx-2

<table>
<thead>
<tr>
<th>Disk Drive and Track Pitch (μm)</th>
<th>Peak-Detect</th>
<th>Integrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A/B Variance (μm²)</td>
<td>Sample σ (μm)</td>
</tr>
<tr>
<td>Kittyhawk (9.41)</td>
<td>0.086 / 0.046</td>
<td>5</td>
</tr>
<tr>
<td>Lynx-3 (4.43)</td>
<td>0.043 / 0.042</td>
<td>9</td>
</tr>
<tr>
<td>Lynx-2 (6.35)</td>
<td>0.070 / 0.076</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- PES Sample Uncertainty, Kittyhawk and Lynx-3: $\sigma_m^2 = \frac{\sigma_A^2}{n} + \frac{\sigma_B^2}{n}$.

- Computing Lynx-2 (continuous servo) Sample Uncertainty:
  - Digitize PES waveform;
  - Matlab Peak–detect (or Integrate) and ANOVA $\Rightarrow \sigma_{bit}$;
  - Generate Gaussian noise time sequence $X(t)$:
    $t = [0 : 200E - 9 : 12E - 3]' ; X(t) = \sigma_{bit} \times \text{randn(size}(t)\text{)}$;
  - Low-pass filter $X(t)$ by model of Lynx-2 demodulation filter:
    $G(s) = \frac{10^{10}}{8.61 \times 10^{-7}s^3 + 3.95 \times 10^{-1}s^2 + 1.49 \times 10^8s + 10^{10}} ; Y(t) = \text{lsim}(G(s), X(t), t)$;
  - Resultant $\sigma_S$ of $Y(t)$ is estimate of Lynx-2 Position Sensing Noise (PSN).

- And the result is:
$\sigma_S$ matches PES Pareto “What’s Left” Value: 0.029 $\mu m$!
Measurement Summary

- In–drive characterization of Lynx–2 FRF’s and PSD’s was accomplished.
- ANOVA was adapted and used for Lynx–2 (continuous–servo vs. embedded).
- Measurements and PES Pareto estimates were cross-checked, e.g.:
  - LDV vs. PES at zero gain
  - PSN from ANOVA vs. “What’s Left” from PES Pareto.
- Key work remains for more precise characterization and improvement:
  - CMU/DSSC work on optimal position signal generation (Sacks/Mathur/Messner).
  - NSIC: PSN and Windage thrusts.