

Longitudinal Feedback Using a Low-pass Differentiator

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I.FAST Workshop 2024 on Bunch-by-Bunch Feedback Systems



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Surprise Discovery

Some
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Longitudinal Stabilization and Tune Variation

- ▶ Traditionally, longitudinal feedback controllers are designed to satisfy three requirements:
 - ▶ 90° phase shift at the synchrotron frequency;
 - ▶ DC rejection;
 - ▶ Bandpass response.
- ▶ This approach is limited in its tune acceptance range;
- ▶ Many modern light sources use harmonic cavities to lengthen the bunches for the improved lifetime;
- ▶ This leads to wide range of synchrotron frequency variation versus beam current, as well as wide spread of frequencies at nominal operating current.

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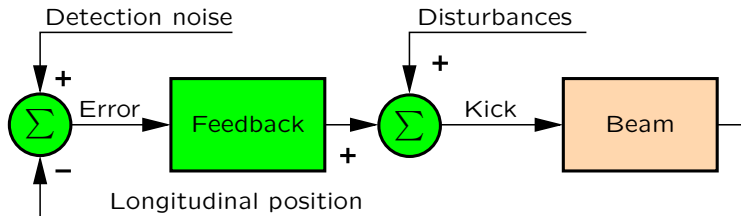
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Differentiator Feedback in the Longitudinal Plane



- ▶ Beam response $B(s) = \frac{C}{s^2 - 2\lambda s + \omega^2}$;
- ▶ C absorbs front-end and back-end gains, as well as optics parameters;
- ▶ Differentiator $F(s) = Ks$ is mathematically ideal to stabilize $B(s)$:
- ▶ Closed loop response $H_{cl}(s) = \frac{B(s)}{1 + F(s)B(s)} = \frac{C}{s^2 - (2\lambda - KC)s + \omega^2}$;
- ▶ Differentiator only affects the growth rate and provides constant damping independent of the synchrotron frequency.

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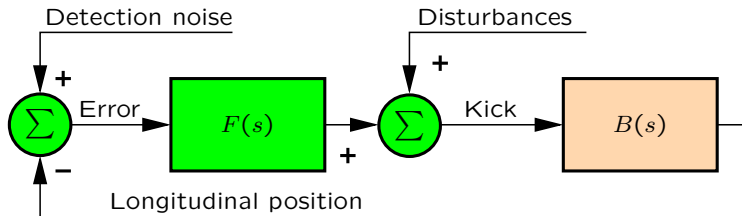
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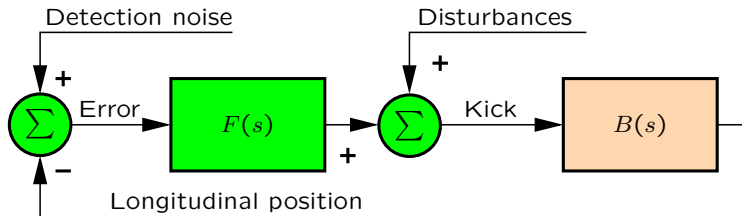
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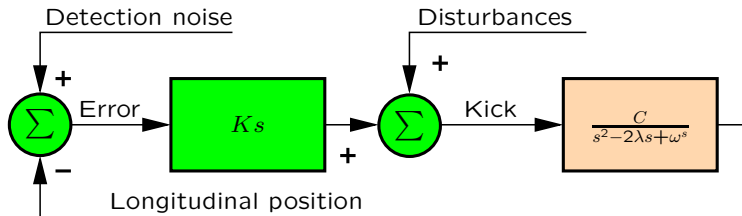
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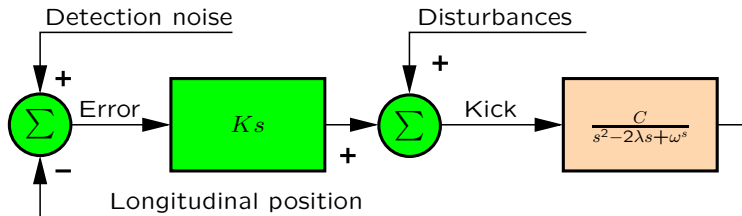
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It Could Never Work...

- ▶ When I started working on longitudinal bunch-by-bunch feedback as a first year graduate student I almost immediately learned that “differentiator could never work”.
- ▶ Approximate differentiator by one turn difference $u_n = z_n - z_{n-1}$
- ▶ Problems:
 - ▶ Very little gain at synchrotron frequencies — small phase advance per turn;
 - ▶ Controller gain increases linearly with frequency — output will be swamped with the amplified wideband detection and quantization noise.
- ▶ For me the matter rested there until summer 2022 (NAPAC 2022), when I learned that Ryan Lindberg of APS-U arrived at the differentiator idea;
- ▶ I set out to demonstrate why this was a bad idea and was surprised to discover that, at least in the Simulink model, it worked as well as the conventional approach;
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Test in an Accelerator

- ▶ A month later I got a call from the ALS — they had trouble reaching 500 mA operating current;
- ▶ What is ALS:
 - ▶ 1.5 GeV storage ring with normal conducting main and harmonic RF cavities;
 - ▶ Multiple unstable modes in the longitudinal plane;
 - ▶ Zero current synchrotron frequency of 8.5 kHz decreases to 5.5 kHz at full current due to the action of the harmonic cavities;
 - ▶ Mode 0 is shifted to 4 kHz by the interaction with the main RF impedance, normally stable.
- ▶ Feedback filter for the ALS is designed to damp instabilities from 5 to 9 kHz, rolls off gently below 5 kHz to avoid destabilizing mode 0.
- ▶ In September 2022, mode 0 was going unstable at the ALS and the existing feedback filter could not damp the instability;
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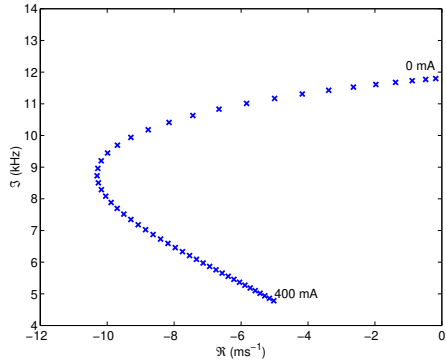
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Summary

Mode 0 vs. Beam Current



- ▶ Root locus of the modal eigenvalue versus beam current;
- ▶ Damping on the real axis, frequency on the imaginary;
- ▶ Old ALS configuration (higher RF voltage).

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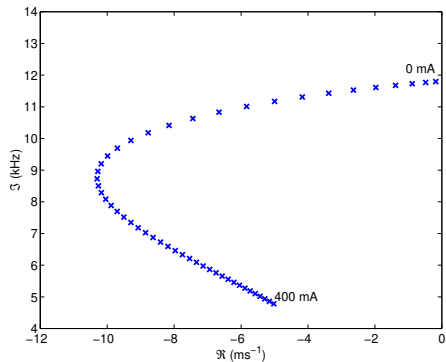
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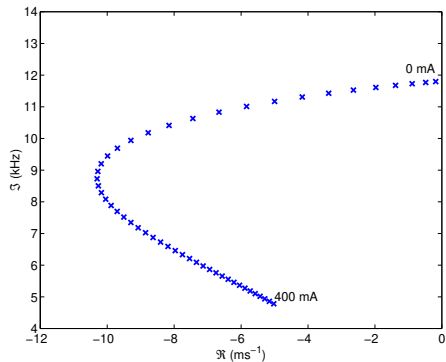
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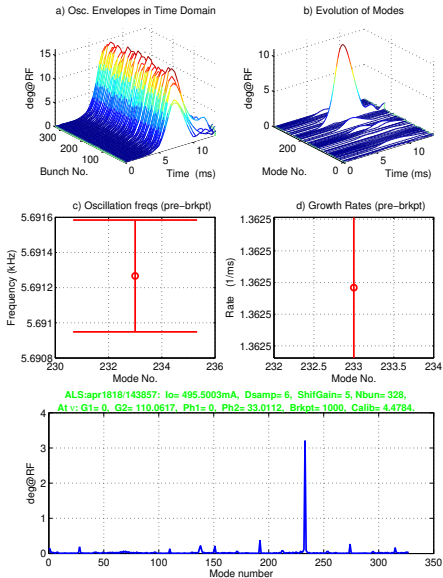
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Modal Behavior



► A grow/damp measurement from 2018;

► 12 ms growth time;

► Well-known HOMs in main RF cavities drive mode 233;

► A measurement on September 8, 2022;

► 3 ms growth time;

► Modes 0, 1, and -1 grow.

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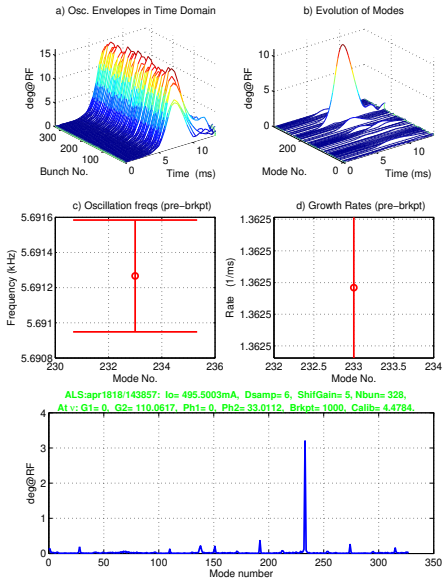
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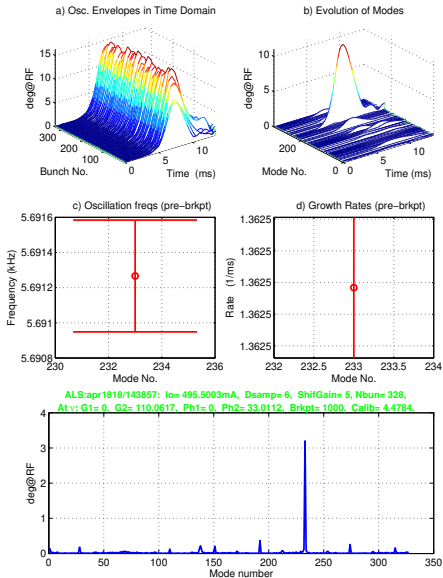
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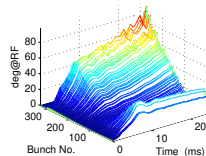
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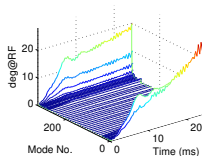
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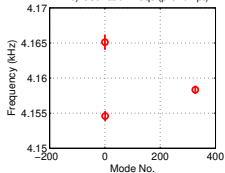
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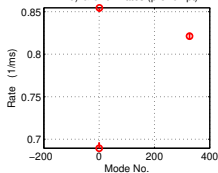
b) Evolution of Modes



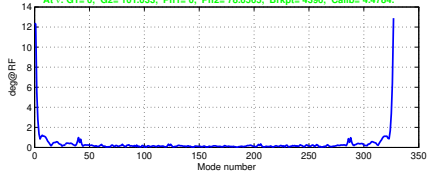
c) Oscillation freqs (pre-brkpt)



d) Growth Rates (pre-brkpt)



ALS:sep0822/095711: Io= 496.8892mA, Dsamp= 1, ShifGain= 6, Nbnun= 328,
At v: G1= 0, G2= 101.033, Ph1= 0, Ph2= 78.6565, Brkpt= 4396, Calib= 4.4784.



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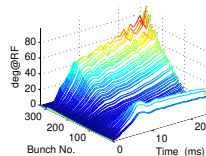
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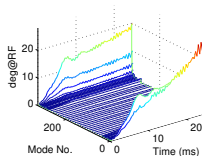
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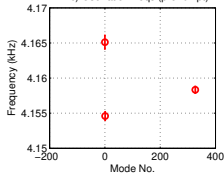
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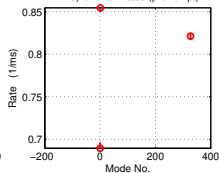
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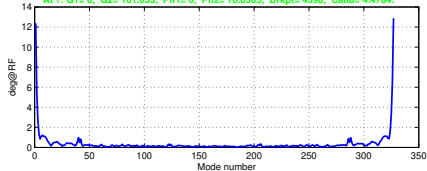
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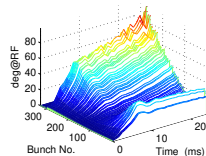
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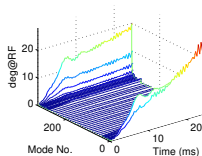
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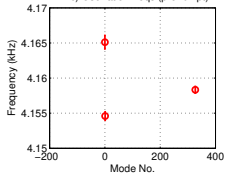
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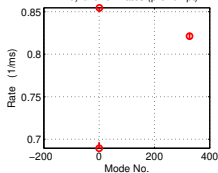
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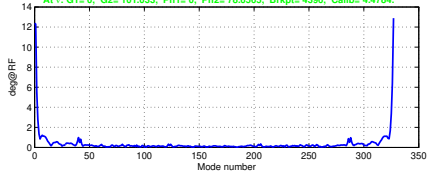
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- ▶ Well-known HOMs in main RF cavities drive mode 233;
- ▶ A measurement on September 8, 2022;
- ▶ 3 ms growth time;
- ▶ Modes 0, 1, and -1 grow.

Motivation

Concept

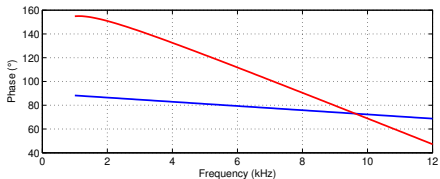
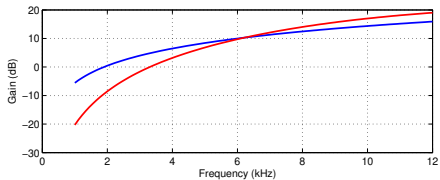
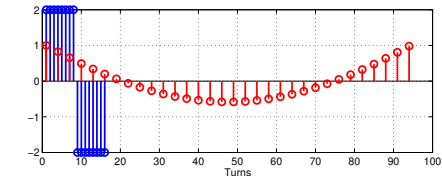
Surprise Discovery

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Summary

ALS Filter Comparison



- ▶ Comparison of the normal ALS filter and a 16-tap low-pass differentiator;
- ▶ Similar gains in the working range;
- ▶ Much steeper slope for the normal filter (32 taps, downsampling of 3);
- ▶ Log scale plot over a wider frequency range.

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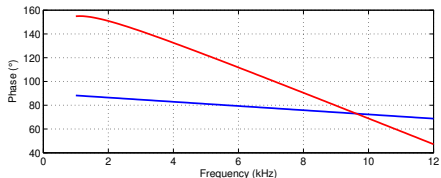
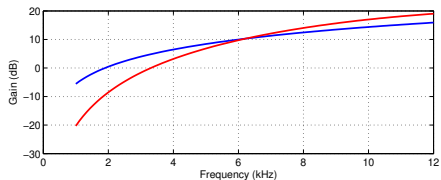
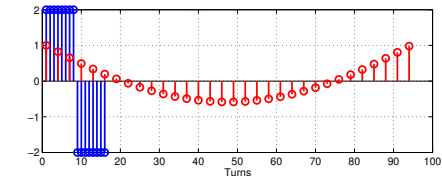
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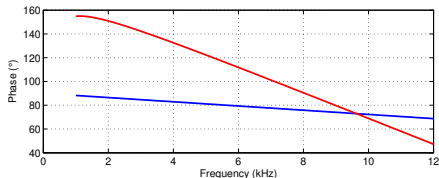
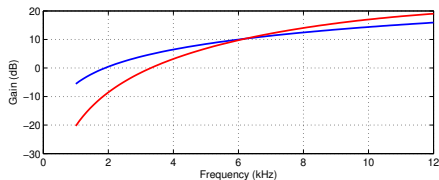
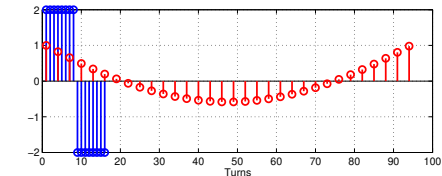
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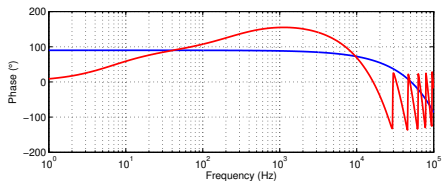
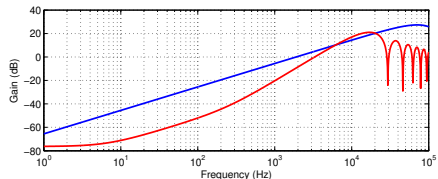
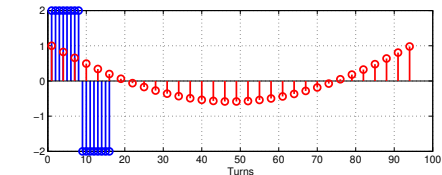
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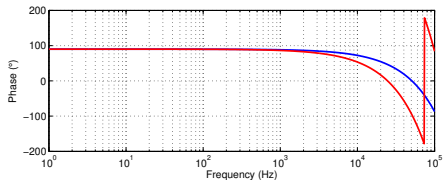
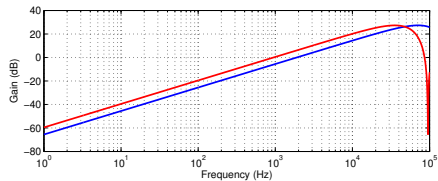
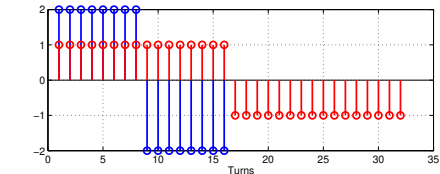
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Summary

Simple Low-pass Differentiators



- ▶ Since the original “emergency intervention” we have updated the ALS differentiator from 16 to 32 taps;
- ▶ Factor of 2 in the shorter filter’s coefficients reflects higher shift gain;
- ▶ 6 dB gain difference in the linear range;
- ▶ As expected, a longer filter has faster phase roll due to higher group delay;
- ▶ Identical peak gains.

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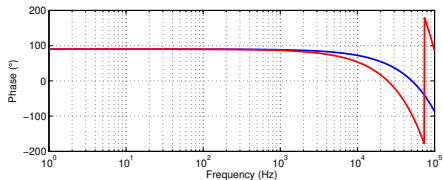
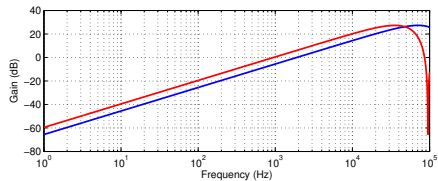
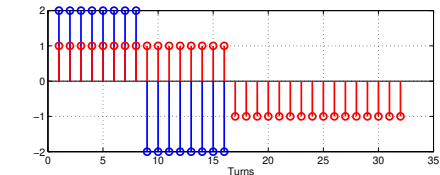
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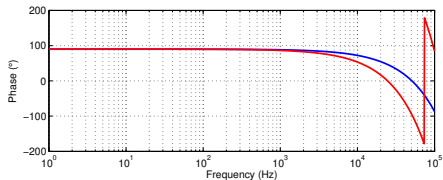
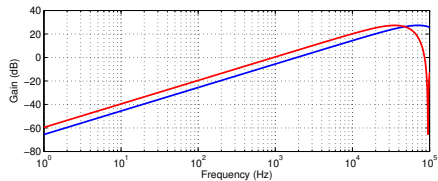
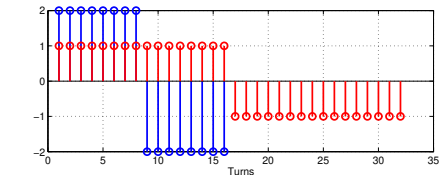
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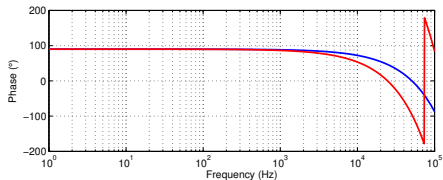
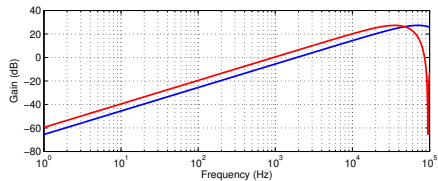
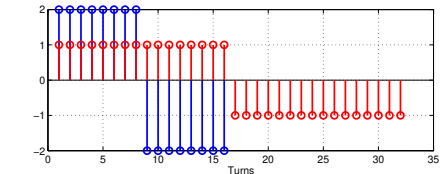
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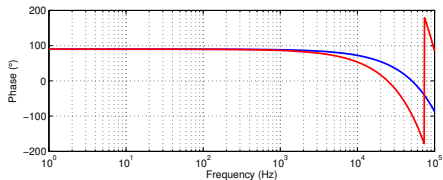
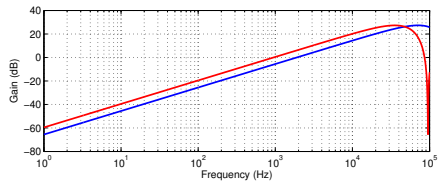
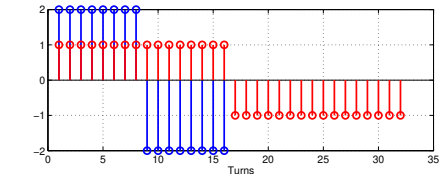
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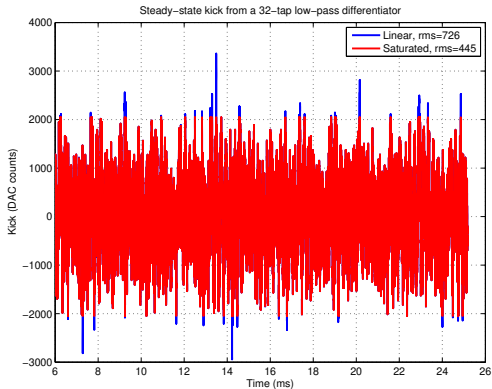
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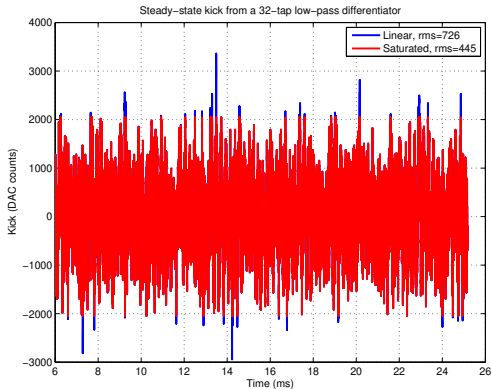
Summary

Kick Signals



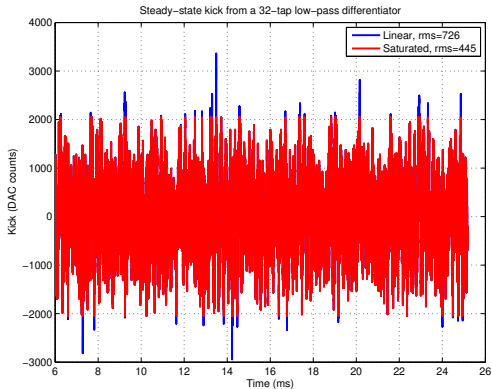
- ▶ Standard worry — differentiator will saturate the output with amplified noise, leaving no power for feedback correction;
- ▶ Steady-state kick at 500 mA with a 32-tap low-pass differentiator;
- ▶ Consistently hits full scale, reflected in the difference in the RMS kick;
- ▶ When longitudinal motion develops, power is directed exactly where it's needed.

Kick Signals



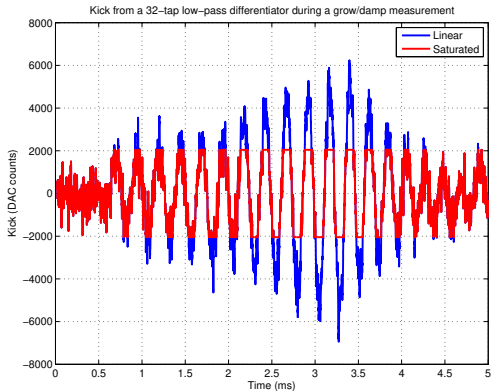
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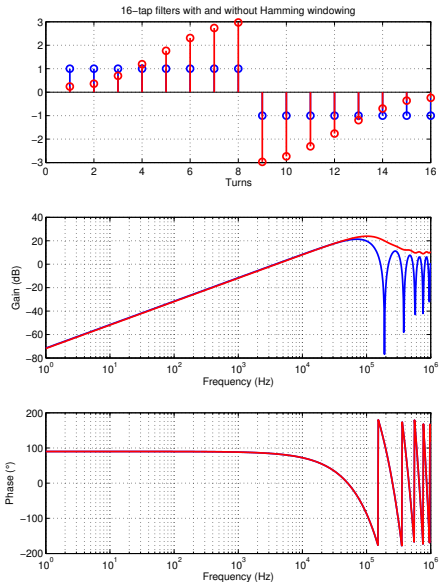
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Low-pass Differentiator Optimization



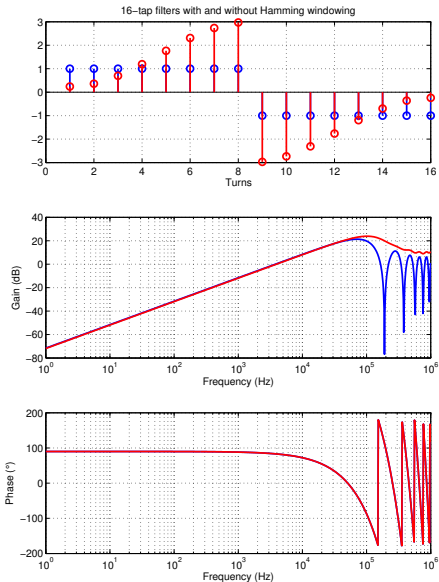
- ▶ Boxcar low-pass differentiator is an obvious choice, but is there something better?
- ▶ Multiplied by a Hamming window;
- ▶ Worse than the boxcar — more high-frequency gain;
- ▶ Smooth noise-robust differentiator — same problem;
- ▶ Optimization needed to maximize the ratio of in-band gain to the average high-frequency gain;
- ▶ Possibly the optimization will tell us that the boxcar is optimal...

Concept

Some Observations

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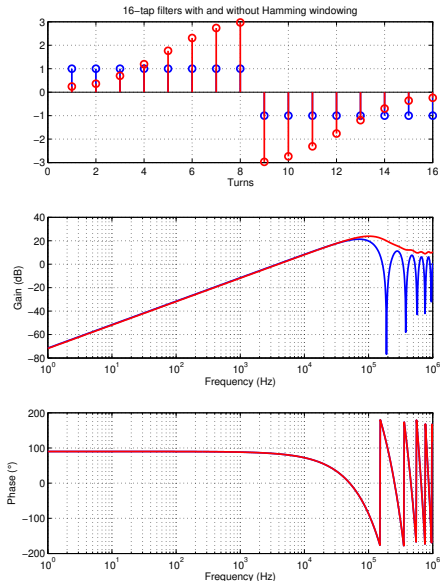
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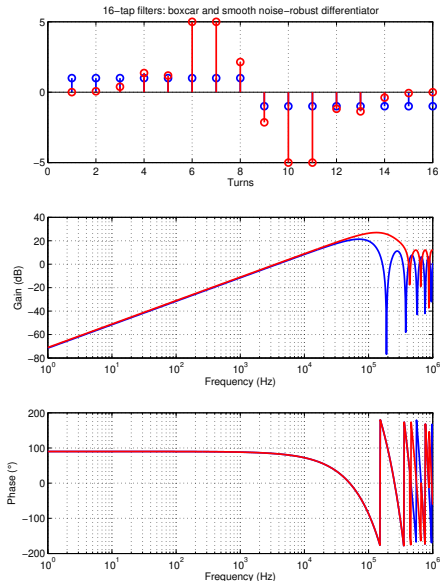
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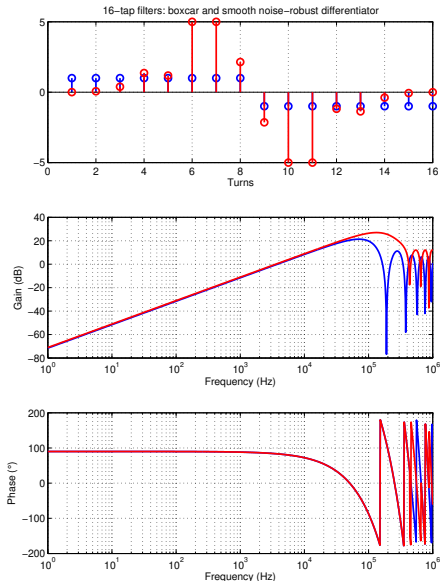
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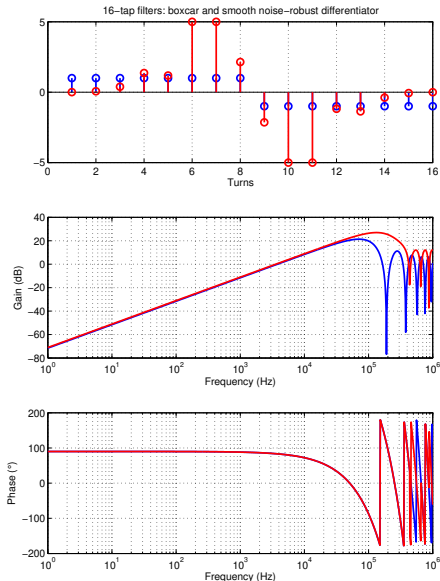
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- ▶ Low-pass differentiator has been deployed in the longitudinal plane at the ALS since September 2022;
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