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U.S. DEPARTMENT OF ENERGY

Mitigating instabilities in SRF resonance control loops

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LLRF'22 Workshop

Outline

- Introduction
- Nyquist Stability Criterion
- Mechanical low-pass filters
- Performance
- Summary and Conclusions

Introduction

Simple story, once all the pieces are in place

- Plant is the superposition of many high-Q low-pass filters (Ceperley)
- Obvious controller is a "slow integrator"
- Nyquist stability criterion shows this combo naturally leads to instability
- Such instability was seen in LCLS-II cryomodules at both Fermilab and SLAC
- Slight modification to controller leads to nearly guaranteed stability

Not interested here in "Active Resonance Control" or its synonyms. Even if those techniques are used, this talk covers the setup that lets a team experiment with and commission such a tool.

Historical reading:

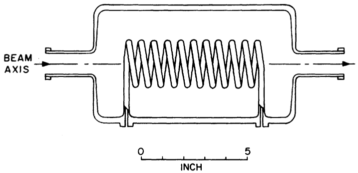
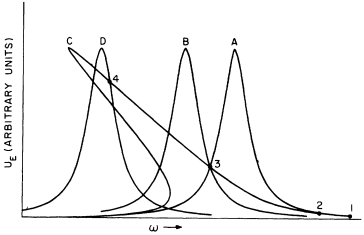


Fig. 1. Niobium helical cavity.



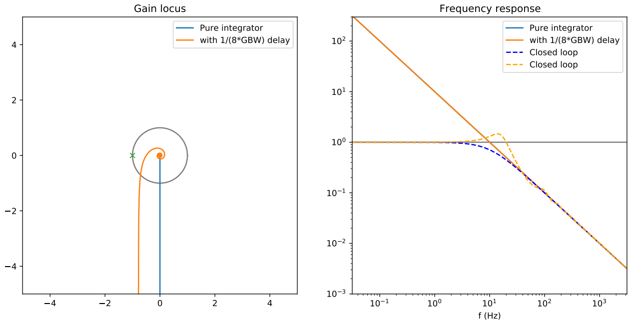
"Ponderomotive Oscillations in a Superconducting Helical Resonator," Peter H. Ceperley, 1972

"Mechanical excitation of superconducting helix resonators by external sources with slowly varying frequency," D. Schulze and A. Hornung, 1974

"Phase and Amplitude Stabilization of Superconducting Resonators," Jean Delayen, 1978

Nyquist Stability Criterion

Dates to 1930 (Strecker) and 1932 (Nyquist)
Stability is determined by looking at the number of encirclements of the point -1+0j.
Simple integrator controller is always stable; with delay it goes unstable when gain-bandwidth-product reaches 1/4T (useful behavior up to about 1/8T)
Gain and phase margin described in terms of this picture



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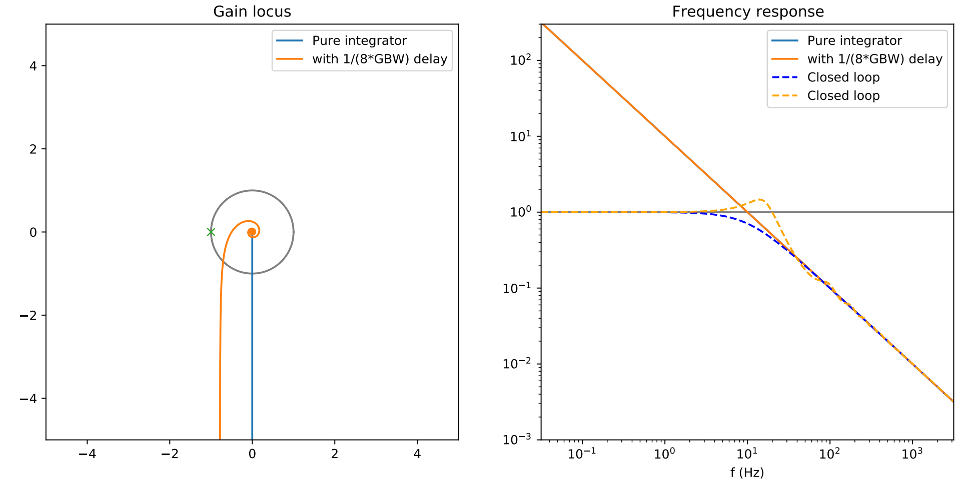

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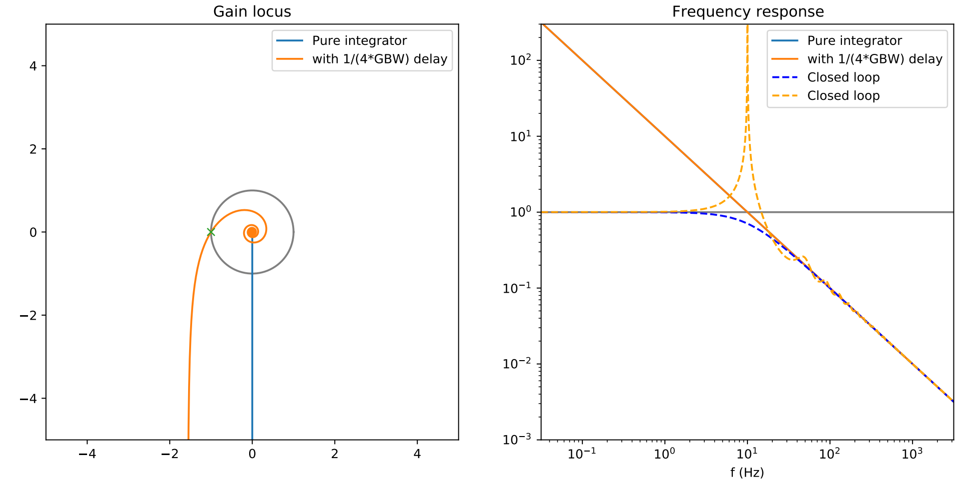

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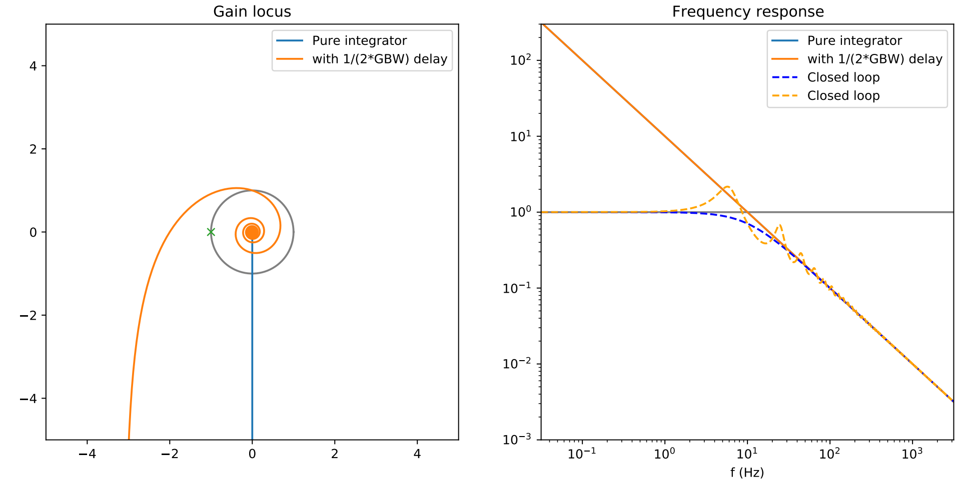


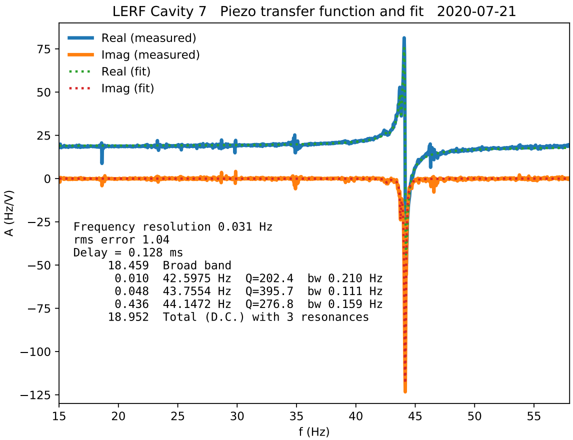
Mechanical low-pass filters

$$G(s) = \frac{\text{Detune frequency}}{\text{Piezo voltage}}$$

$$G(s) = \sum_n \frac{A_n}{1 + \frac{1}{Q_n}\left(\frac{s}{\omega_n}\right) - \left(\frac{s}{\omega_0}\right)^2}$$

where A_n, ω_n, and Q_n are experimentally determined and necessarily real.

Cold cryomodules have most dissipation mechanisms "frozen out", so the mechanical Q of these low-pass filters can be very high.



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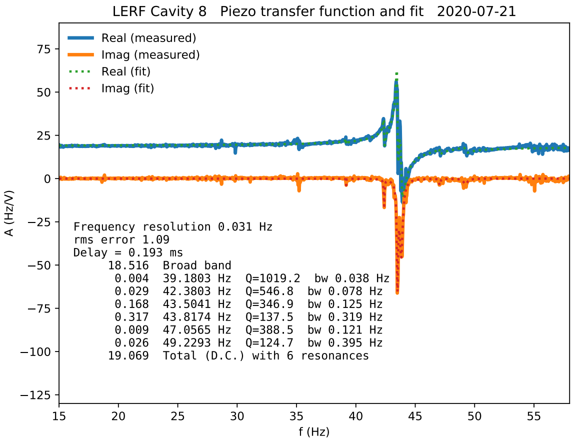

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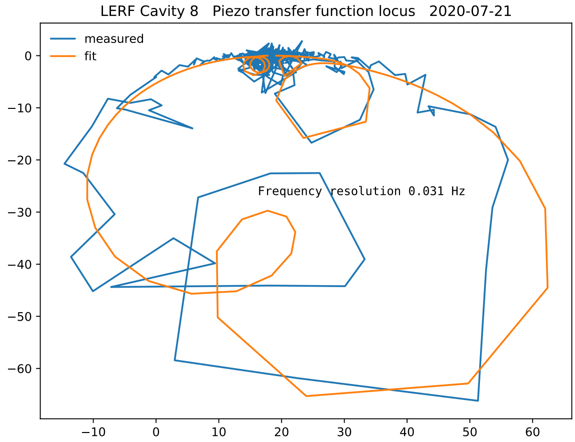
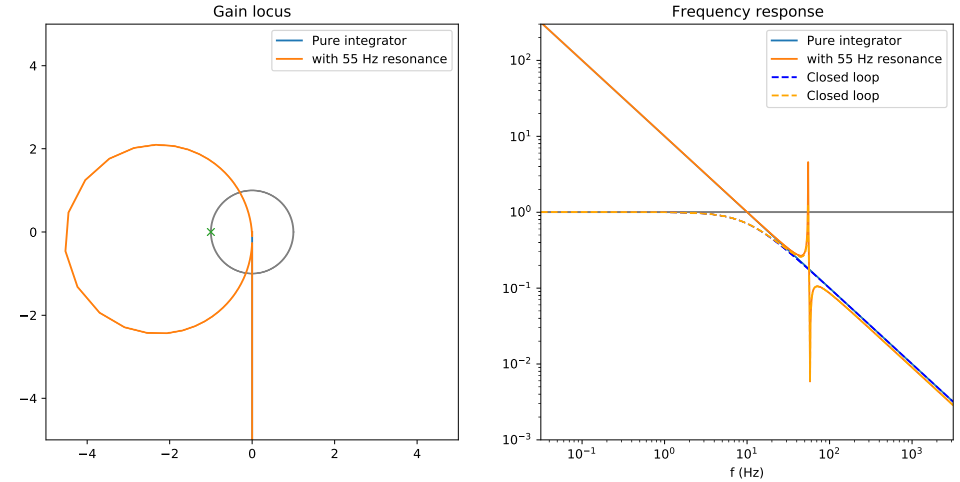


Combination easily unstable



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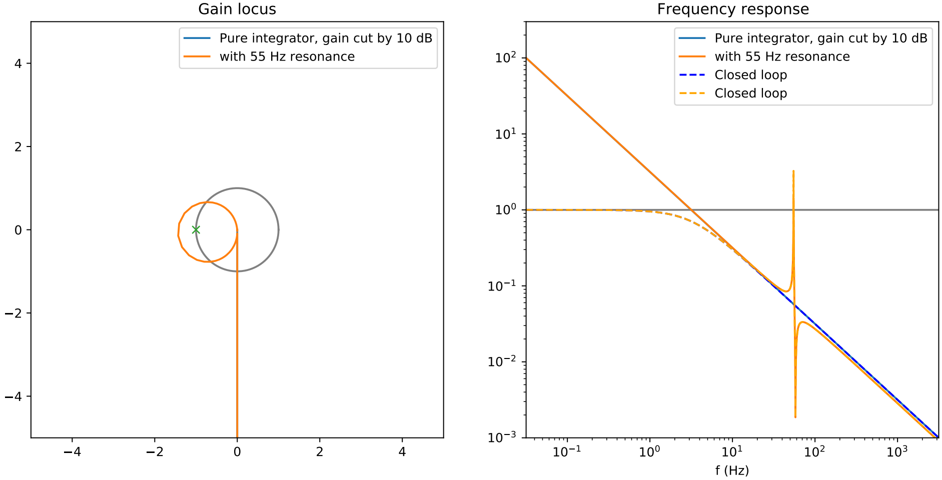

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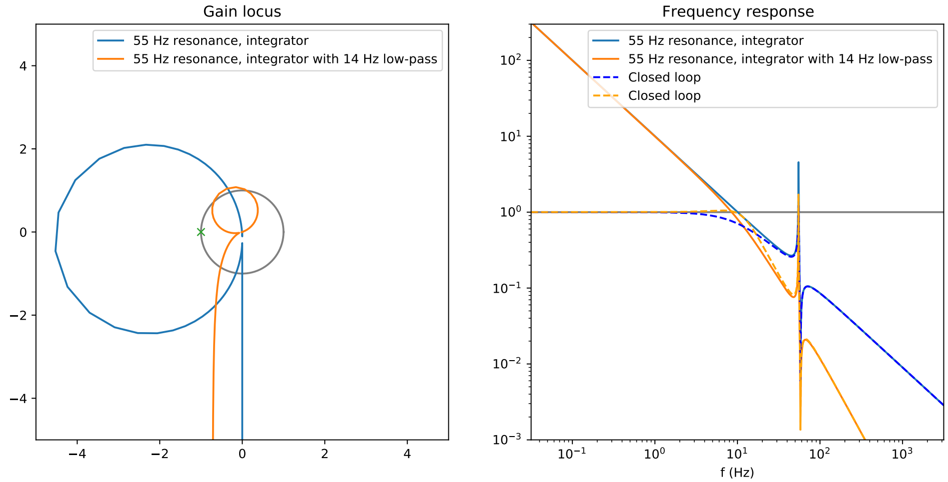

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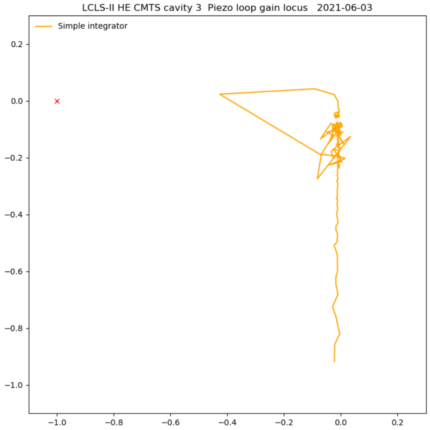

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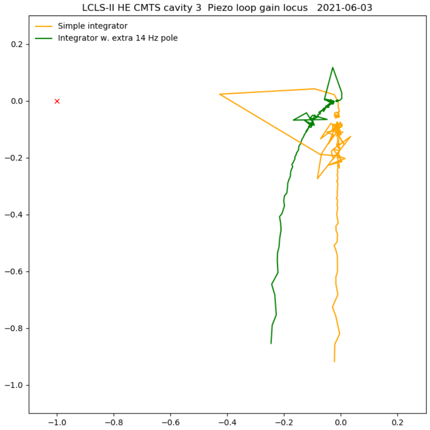

Conclusions

Math works!

High-Q mechanical modes + simple integrator feedback = likely tuning instability

Adding a low-pass element to control loop fixes* this

Issue discovered and fix demonstrated during tests at partner lab

250+ LCLS-II cavities at SLAC run like this without problem

Danke Schön!

* Not guaranteed