Day 2 — Mechanical

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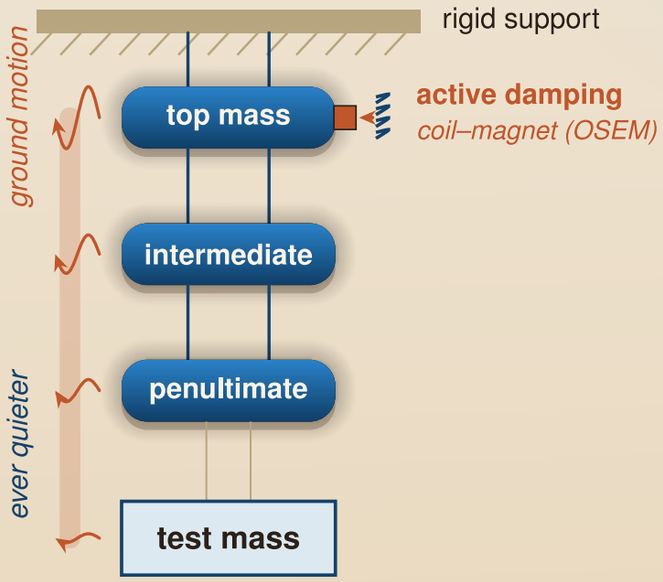
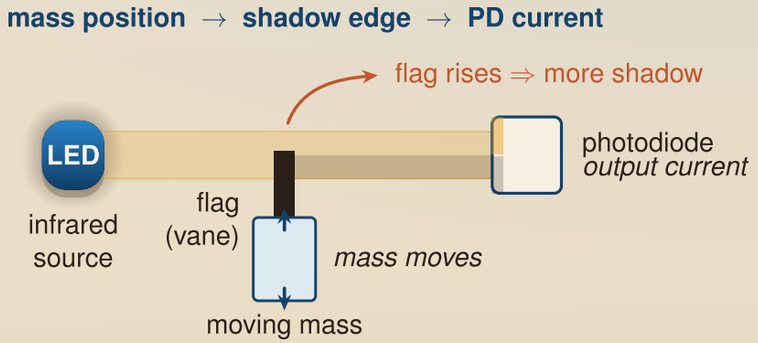
The first loop on real hardware: damp a suspension, then budget the closed loop.

The plant to damp



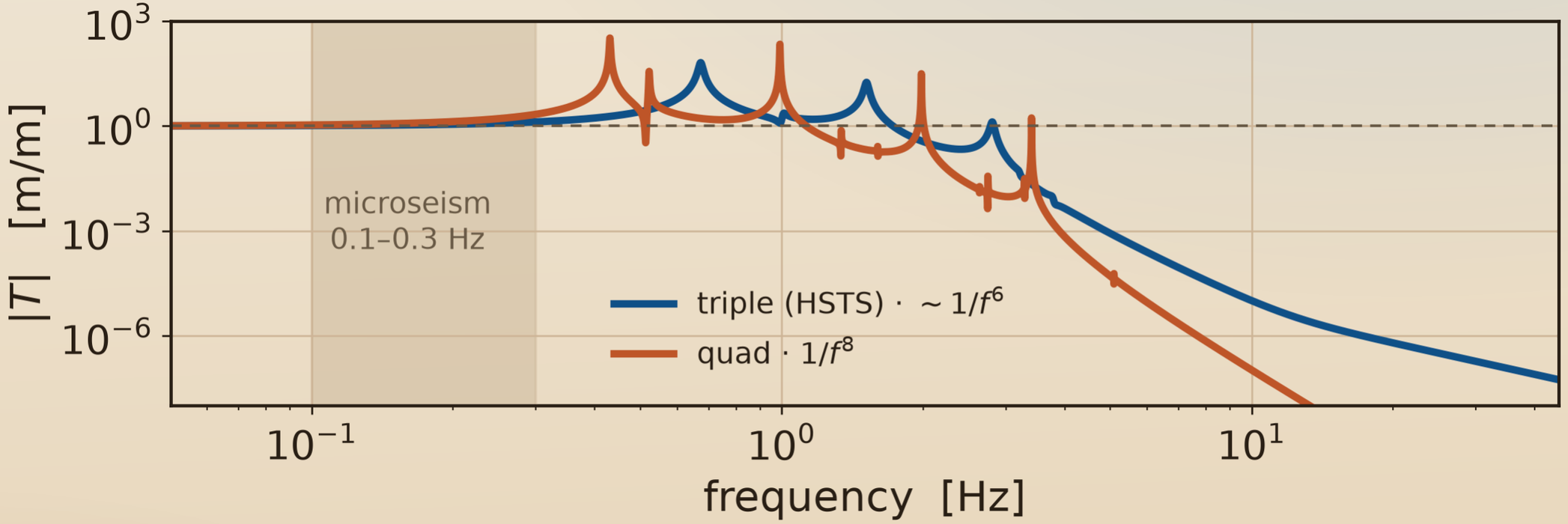
plant · multi-stage pendulum



sensor · OSEM shadow

A high-Q pendulum, sensed by an OSEM at the top mass. Motion gets quieter down the chain; damping wraps a loop around the top and knocks the peak down.

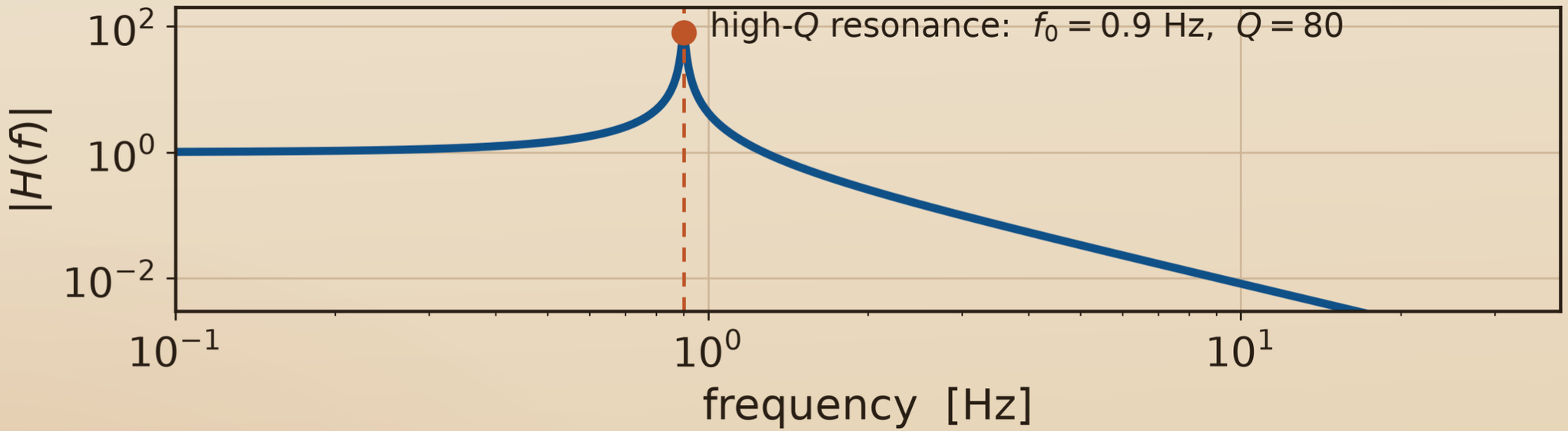
What the chain does to the ground



Transmissibility (m/m): the ground rides through at $|T| = 1$ below the modes, **amplifies** on resonance (×65 triple, ×330 quad), then rolls off two poles per stage. Real `ctlib` models — lowest mode 0.67 Hz (triple) / 0.43 Hz (quad); at 10 Hz the triple gives 10^{-5}, the quad 10^{-7}.

Why it rings: the high-Q resonance

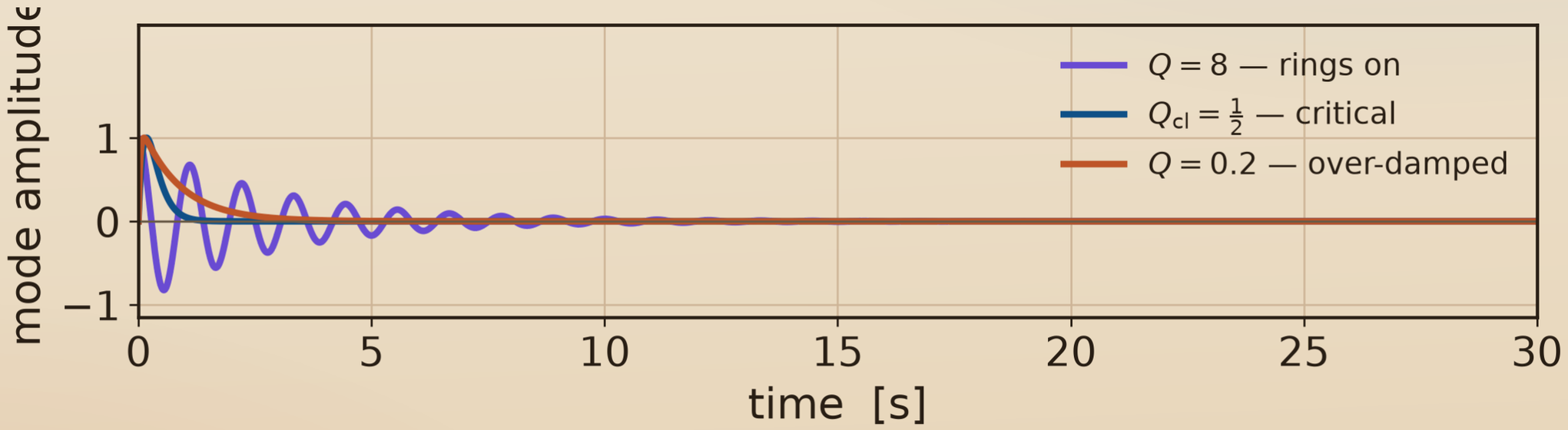
$$H(s) = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q}\, s + \omega_0^2}$$



Illustrative Q, so the peak fits. Real pendulum: $Q \sim 10^8$ — it rings for **a year**.

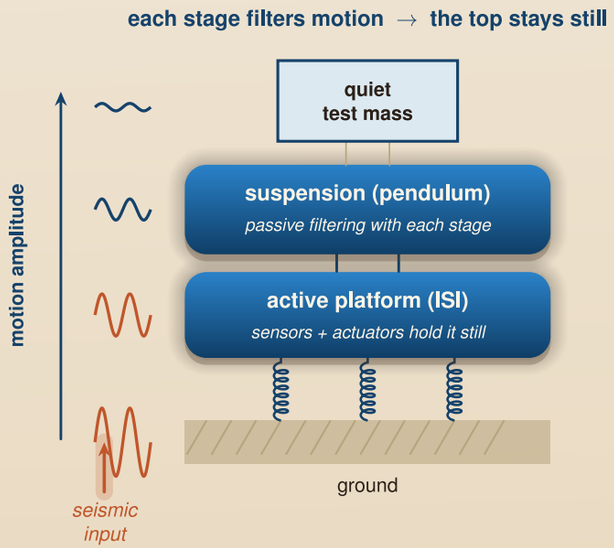
Damp it: the critical boundary

$$s_{\pm} = -\frac{\omega_0}{2Q} \pm j\,\omega_0\sqrt{1 - \frac{1}{4Q^2}} \qquad \Rightarrow \qquad Q_{\mathrm{cl}} = \tfrac{1}{2} \text{ is where the ring stops.}$$



More velocity gain pulls the poles left until they meet at $Q_{\mathrm{cl}} = \frac{1}{2}$. Illustrative $Q = 8$, so the ringdown fits in 30 s. A real pendulum ($Q \sim 10^8$) rings for **years** — hence damping.

Day 2 · afternoon



Morning: seismic → HAM-ISI → suspension → linear-systems math.

“Damp the HSTS, budget the loop”

An HSTS rings with high-Q resonances. We model it as a linear mechanical system — a SISO loop now, and a MIMO loop later. Design the damping loops to knock the Q's down, keep it stable — then compute the closed-loop noise budget.

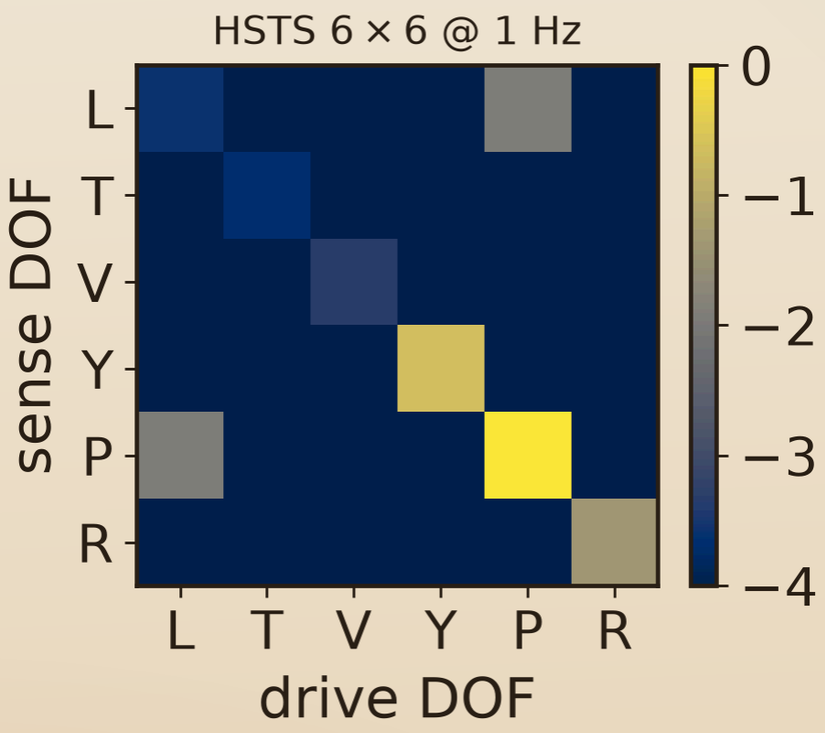
More gain kills the resonance on S but re-injects sensor noise on T. Find *just enough* damping — not maximum.

`Deliverable · before/after ringdowns + S/T budget & chosen gain`

NAME THE MOVE

Damping is a loop; its noise is $T \cdot n_{\text{sensor}}$; commission at the gain where the budget is lowest.

MIMO later — the 6-DOF suspension



"A SISO loop now, a MIMO loop later" — here is later. Each mass moves in **six** DOF: **L, T, V, Y, P, R**. They couple (the off-diagonal above is real), so the honest path is:

SISO dampers first — one loop per DOF. Then, where the cross-terms bite, the **Day-1 decoupler** $\mathbf{D} = \widehat{\mathbf{M}}^{-1}$, tested for robustness to a mis-measured sensing matrix.

`Stretch · the QUAD — 4 stages, same 6-DOF structure, the` $1/f^8$ `chain`

NAME THE MOVE

The suspension is one 6×6 plant; damp the diagonal, decouple the rest — the coupled loop from Day 1, on real hardware.