Modeling the instability

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Conclusion(s)

- It is an instability in the pendulum mode
- NOT in pure angular modes

Symptoms 1/2

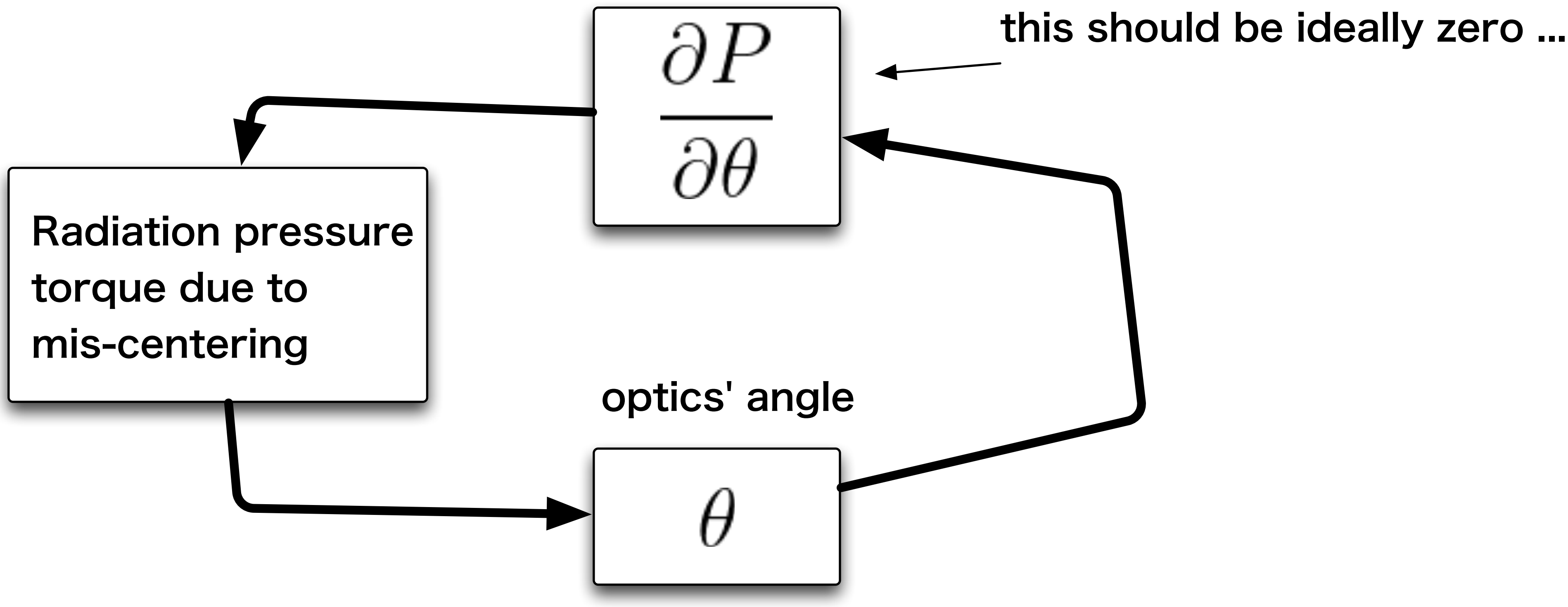
- Recently at LHO, an instability breaks lock during the power-up phase
- According to oplevs, CSOFT appears to develop an instability around 0.5 Hz in pitch
- Intracavity power for both arms are modulated at the same time and freq.
- This does not seem to be due to our servo systems.
- Engaging oplev dampings helped avoiding the instability.

Symptoms 2/2

- Ratio of oplevs' readout to cavity power is about 1%/0.1 urad [RIN/urad], almost regardless of arm power.
- Cavity power fluctuation delays by 30 -40 deg w.r.t. oplev readouts at 0.5 Hz.
- The cavity power fluctuation can flip the sign w.r.t. oplev readouts
- Oplevs are typically almost in-phase, indicating it is CSOFT

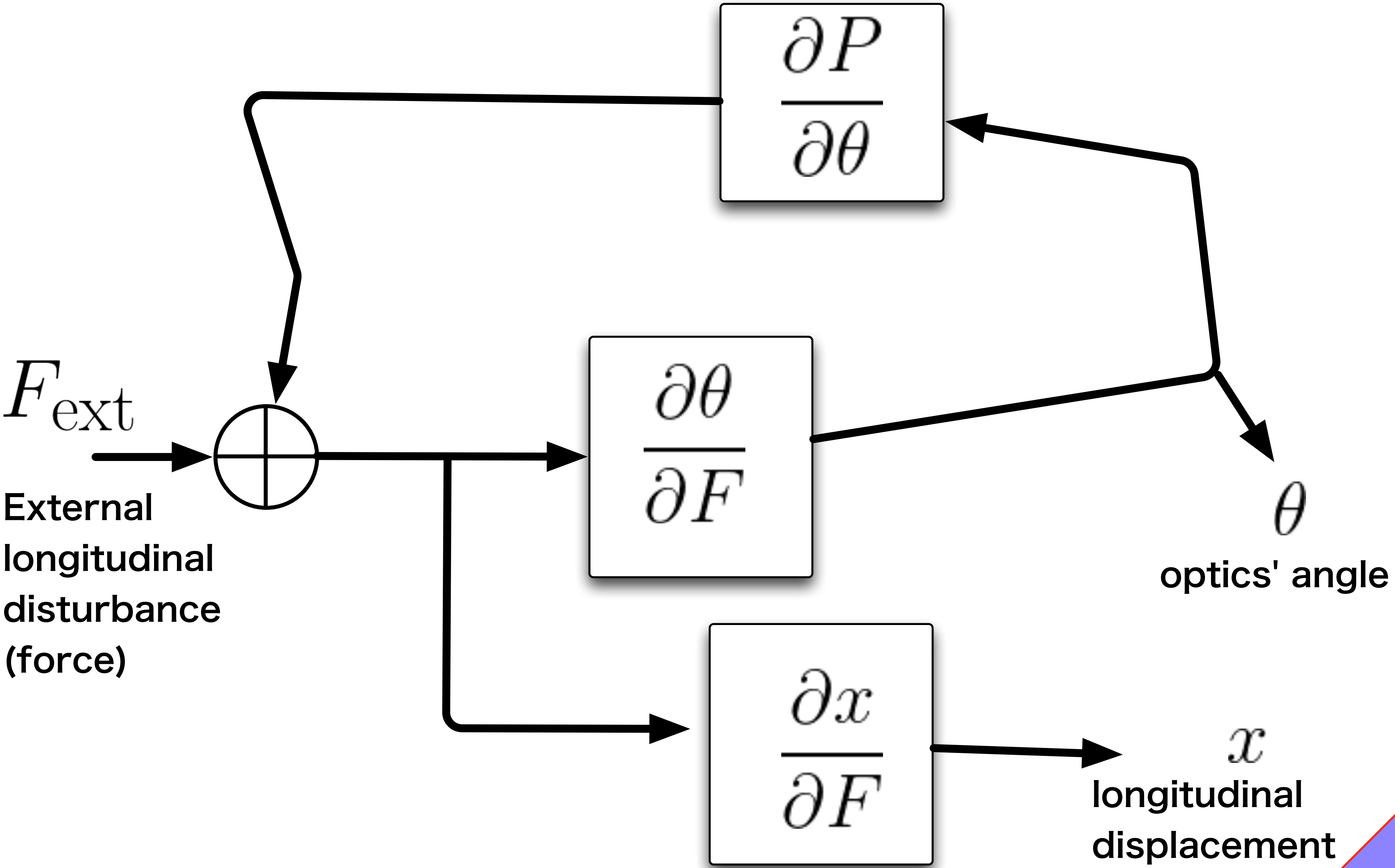
Hypothesis 1

- Radiation pressure driven torque
- Conceptually the same as optical spring



* Different from the Sigg-Sidles
(SS effect does not require power modulation)

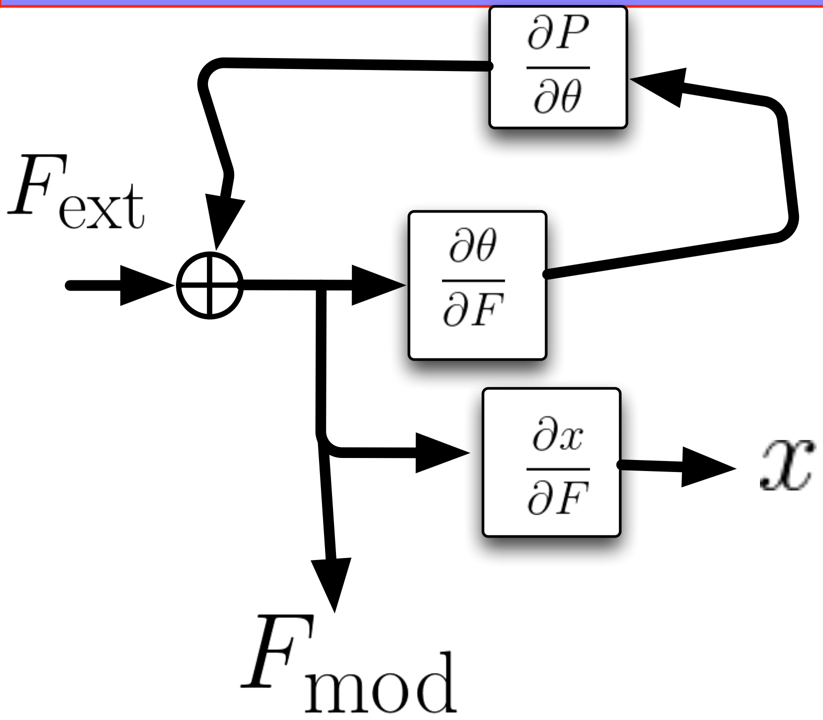
Hypothesis 2



Modeling hypothesis 1

- Hypothesis 1 was able to qualitatively reproduce the instability.
- However this hypothesis requirs large mis-centering of ~ 10 cm in common
- According to A2L measurements, mis-centering is typically below 1 cm on each optic.
- Given the measured parameters, this effect does not seem big enough. (more than a factor of 10 missing)

Modeling hypothesis 2



spurious feedback loop

original force

$$F_{\text{mod}} = \frac{F_{\text{ext}}}{1 + \underbrace{\frac{2}{c}\left(\frac{\partial P}{\partial \theta}\right)\left(\frac{\partial \theta}{\partial F}\right)}_{\text{open loop gain}}}$$

modified force

open loop gain

Open loop gain

- **Let's do an order estimation.**

$$\frac{\Delta P}{\Delta \theta} \sim 10^{10}\ [\mathrm{W/rad}]$$

(measured when PSL = 20 W, Parm ~ 100 kW)

$$\left.\frac{\partial \theta}{\partial F}\right|_{\sim 0.5\mathrm{Hz}} \sim 4 \times 10^{-2}\ [\mathrm{rad/N}]$$

(from quad model)

- **Open loop gain should be**

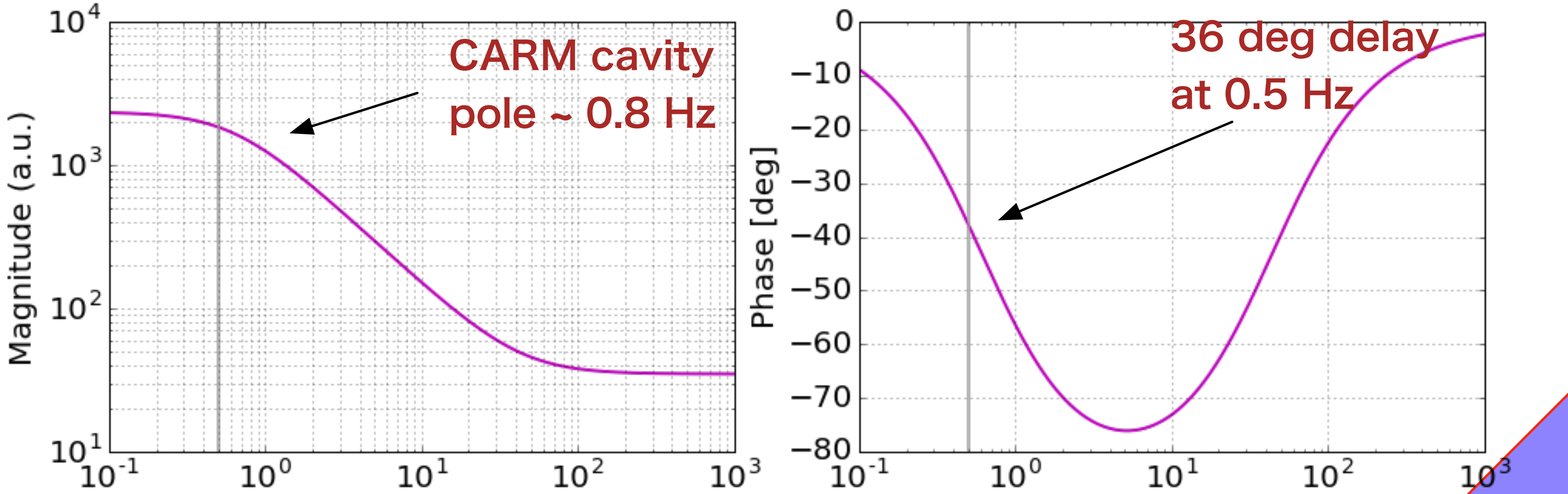
$$\left.\frac{2}{c}\left(\frac{\partial P}{\partial \theta}\right)\left(\frac{\partial \theta}{\partial F}\right)\right|_{0.5\mathrm{Hz}} \sim 3$$

worrisome!

dP/d (theta)

- We assume angle-dependent loss (clipping, misalignment, point defect, ...) in power-recycling cavity,
- DC value is calibrated to measured dP/d (theta).

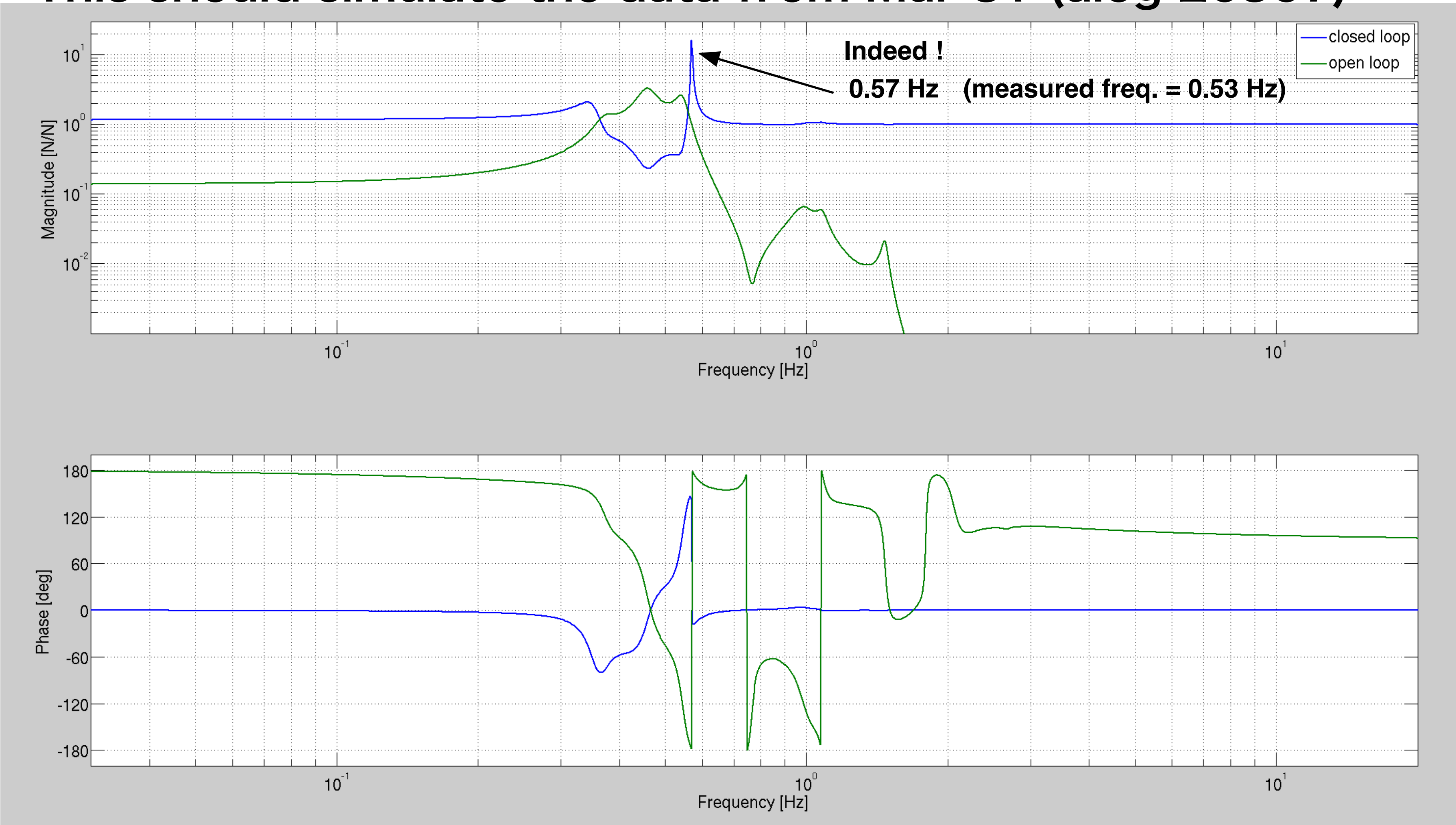
Calculated TF from loss (AM) in PRC -> arm power



Modification of force

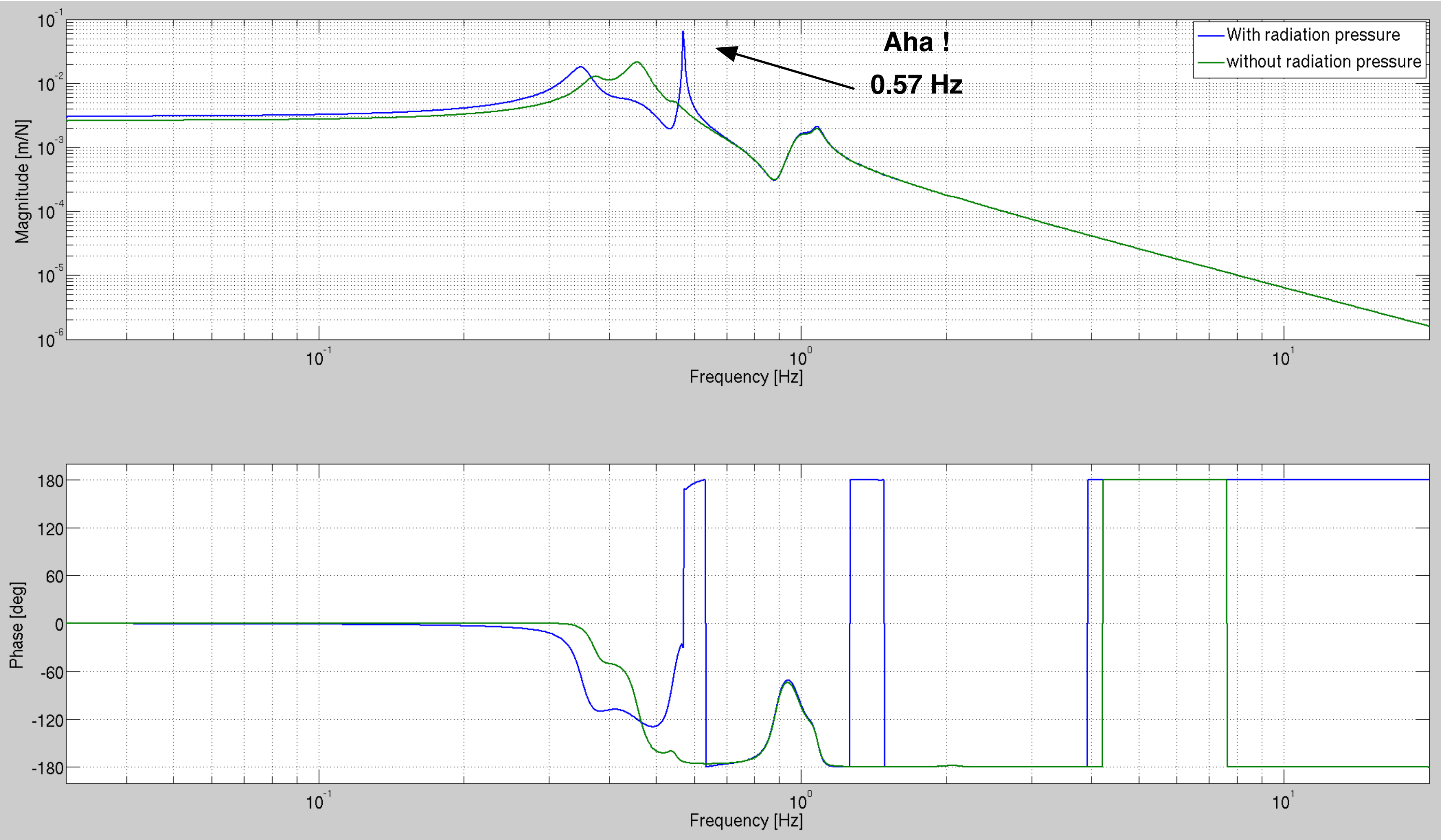
- dP/d(theta) = 1 kW/ 0.1 urad with pole@ 0.8 Hz, No DARM offset, no Sigg-Sidles for simplicity

This should simulate the data from Mar 31 (alog 26367)



Longitudinal TF

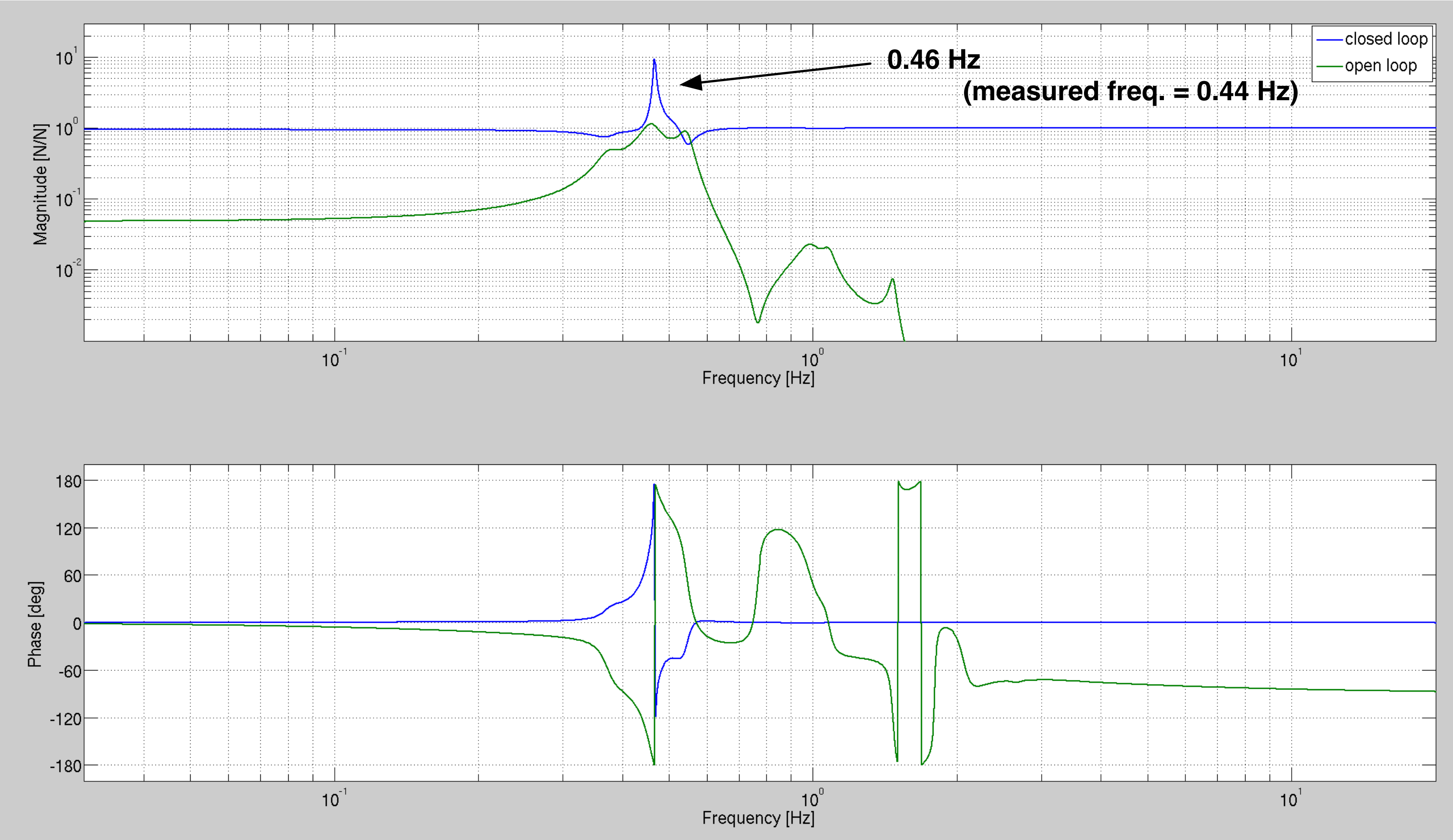
- As a result, overall longitudinal TF obtains a (unstable) peak



Another example 1/2

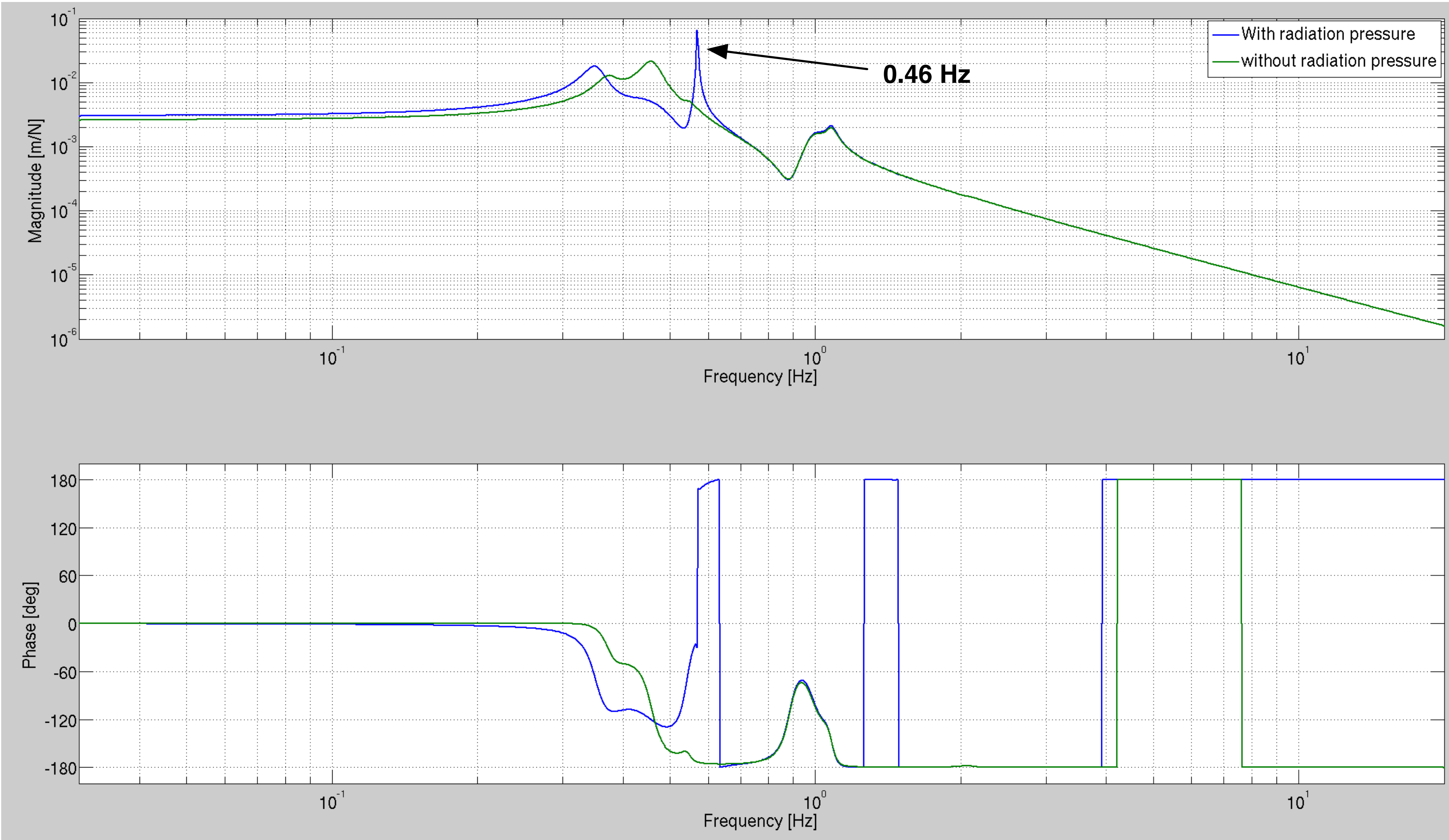
- dP/d(theta) = -350 W/ 0.1 urad with pole@ 0.8 Hz, No DARM offset, no Sigg-Sidles for simplicity

This should simulate the data from Mar 30 (alog 26367)



Another example 2/2

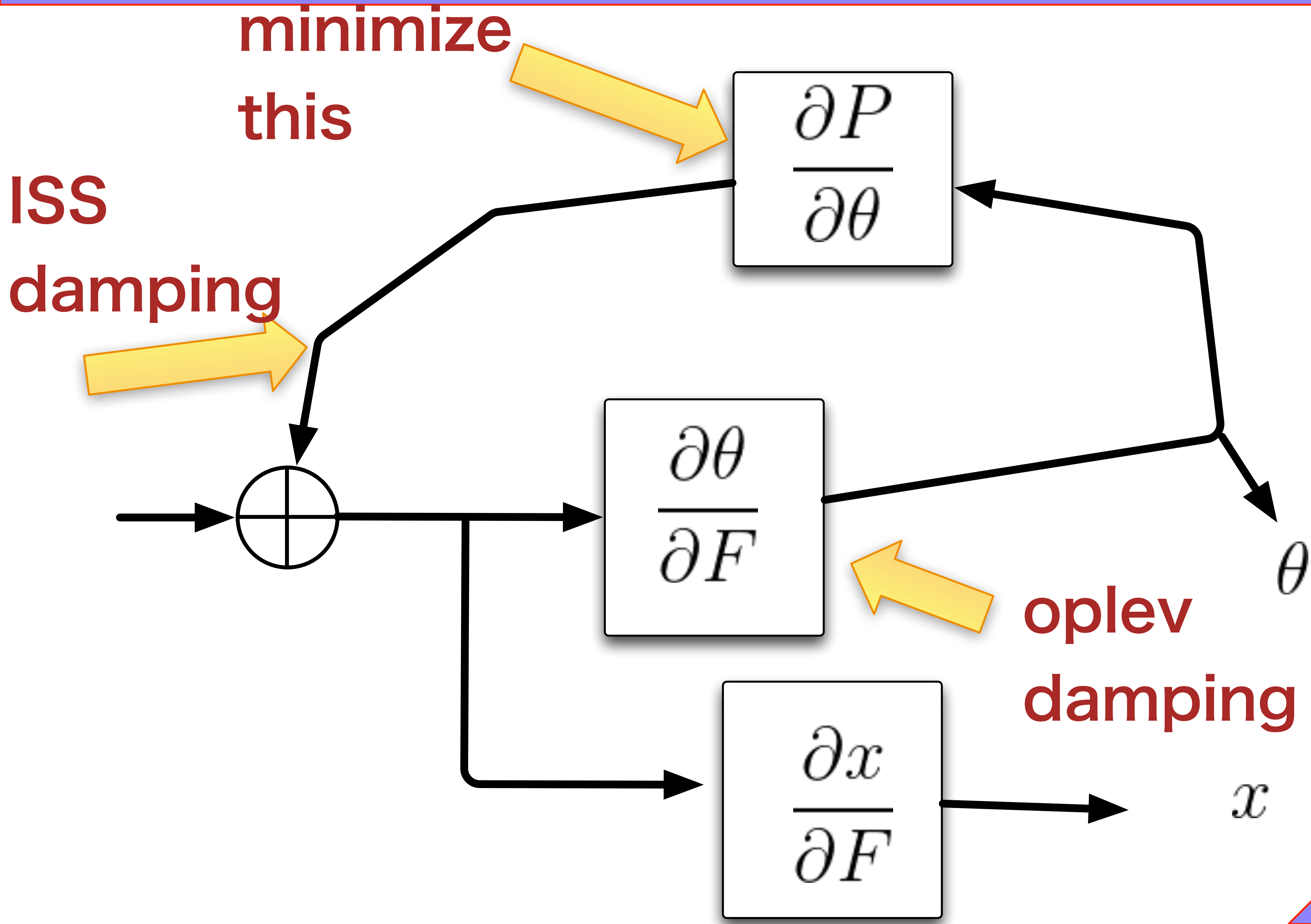
Longitudinal TF



Mysteries almost solved

- Why during power-up ?
  => because dP/d(theta) is prop. to arm power
- Why only in CSOFT ?
  => because of oscillating CARM -> F2P
- Why did oplev damping help ?
  => because oplev reduces F2P coupling
- Why does instability freq. change ?
  => depending on the sign of dP/d(theta)
  one can change the instability freq. point.
- Why does dP/d(theta) exist ?
  => we do not know.

Possible mitigations



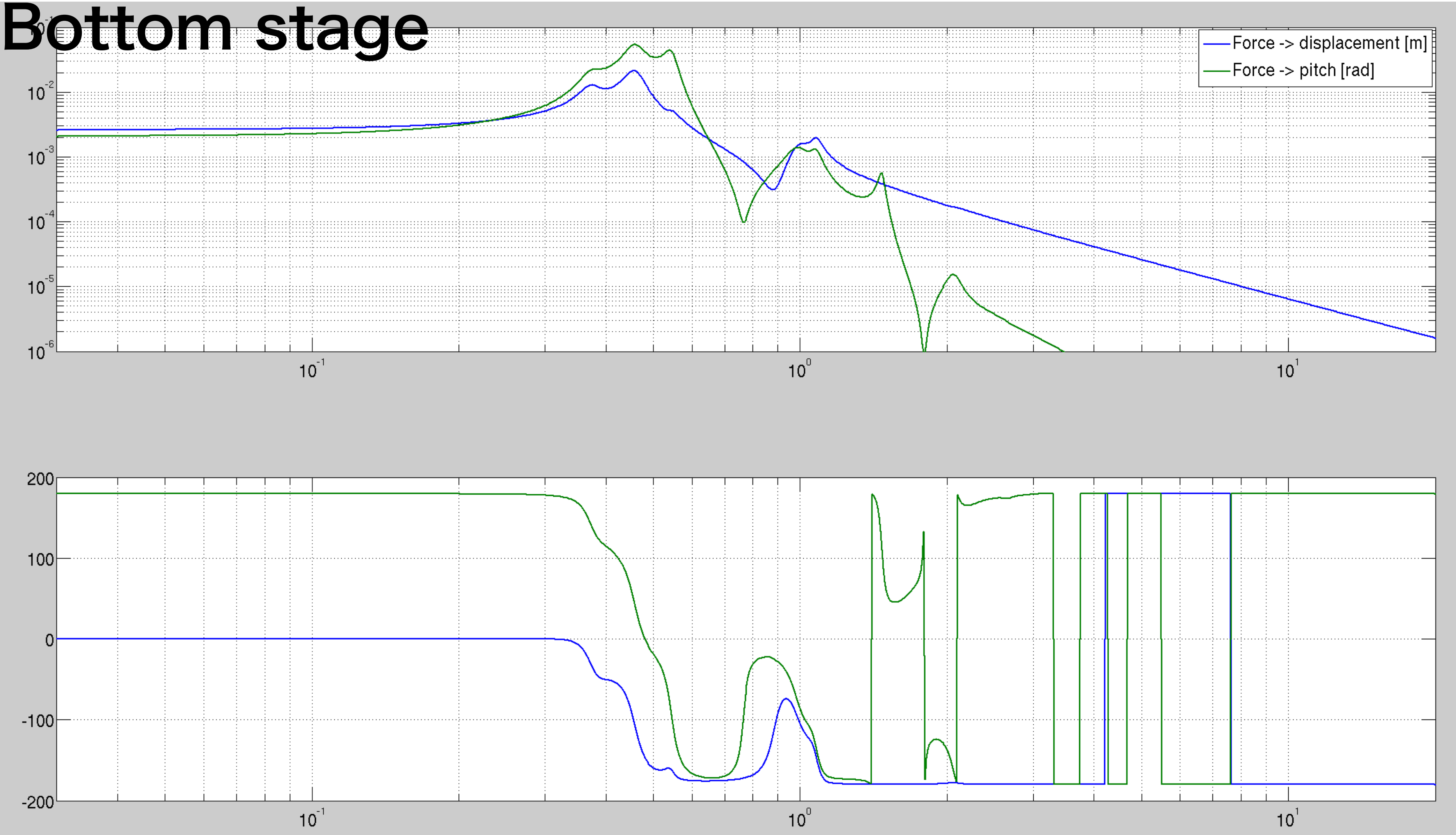
Summary

- The pendulum mode becomes unstable
- LHO has a spurious dP/d(theta) coupling of ~1e10 [W/rad] when PSL=20W.
- Pendulum mode is driven by radiation pressure which is amplified by a spurious feedback loop by a combination of F2P and dP/d(theta).
- More damping loops (ISS and oplevs) and experimentally minimizing dP/d(theta) should help.

Appendix 1

■ **Quad model without radiation pressure.**

Bottom stage



Appendix 2

F(ITMX) -> P(SOFT) with various arm power