Intro to Controls and the new Controls Working Group

Brett Shapiro

31 August 2016

LAAC Session

LVC Glasgow Scotland

G1601640-v2

Many other controls tutorials

- **G1600726** - Intro to Control Theory for LIGO People (3 separate lectures)
- **G1601417** - SURF lectures: Introduction to controls
- **G1600525** - Introduction to controls in LIGO
- **G1400557** - State-Space Methods for Feedback Control
- **G1400102** - Introduction to State Space Control Techniques

- This list may not be exhaustive

Outline

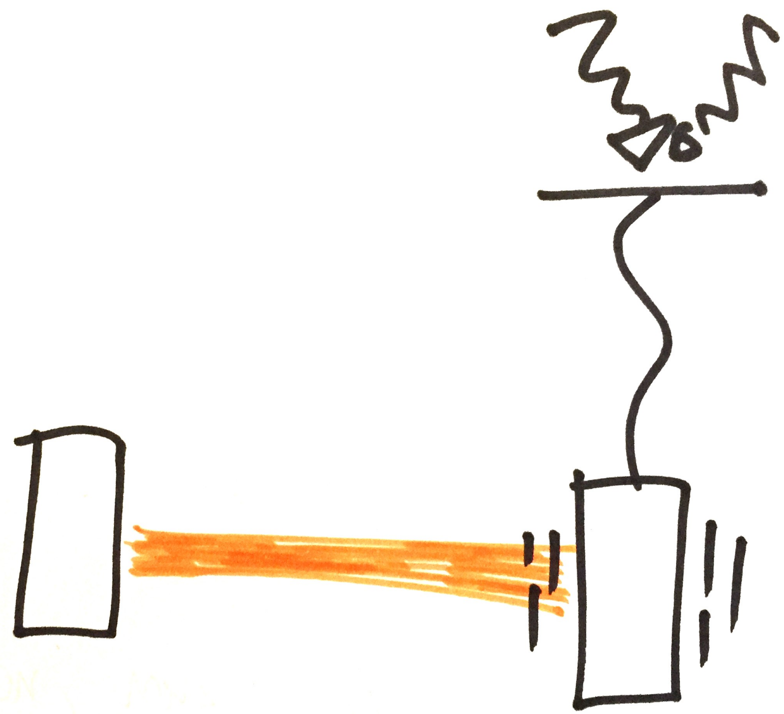
- Controls tutorial
  - Feedback control signal flow
  - Transfer function models
  - Feedback stability

- Control System Working Group (CSWG)

Why we need control

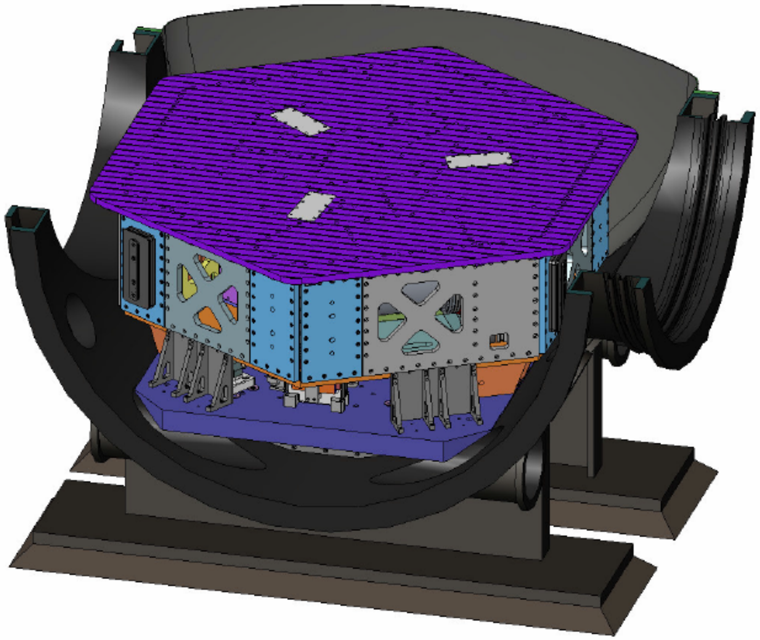
- The ground moves and disturbs our mirrors.
- We use control to keep the cavity lengths fixed and the mirrors aligned

Fabry-Perot cavity



Ref G1600525

HAM-ISI Example



CAD model of HAM-ISI in a HAM chamber

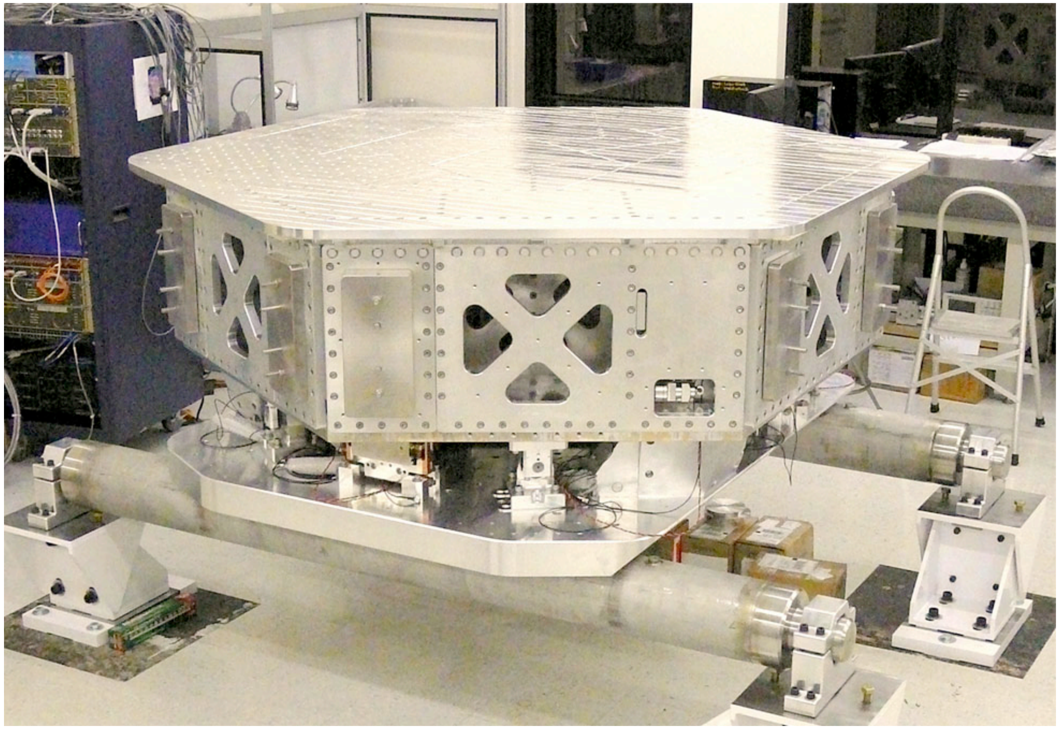
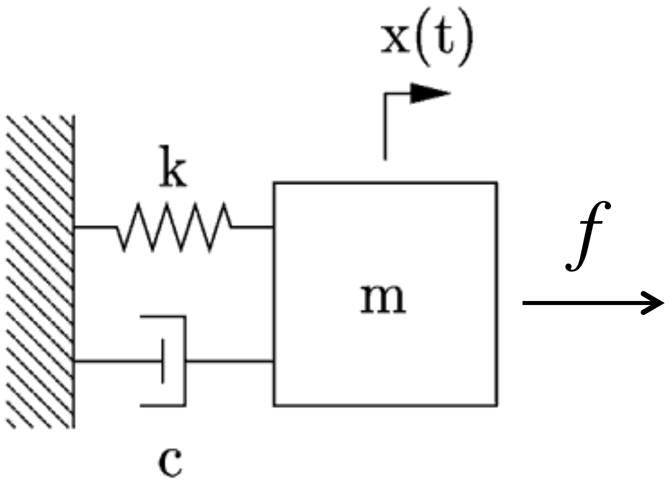


Photo of a HAM-ISI
Credit: HPD

HAM-ISI Example



Model:
single DOF mass-spring-damper system

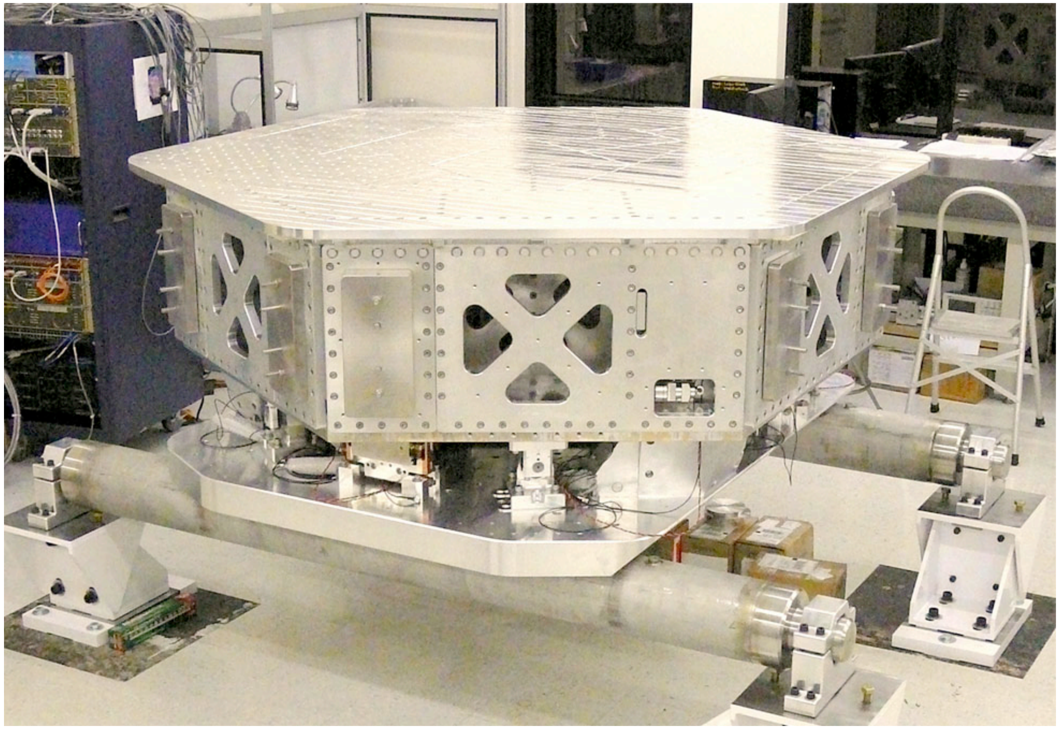


Photo of a HAM-ISI
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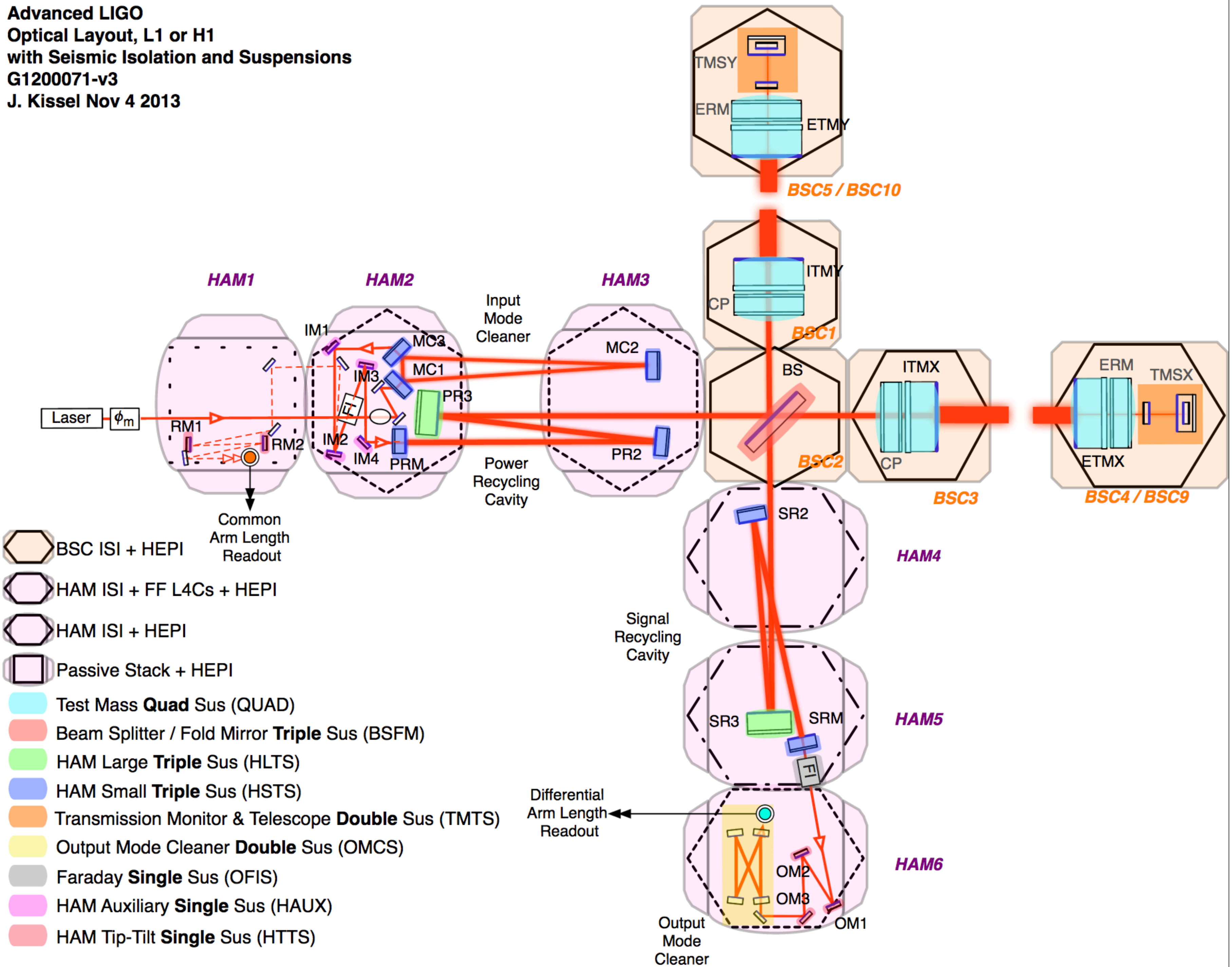
Physical parameters used in these slides: k = 250,000 N/m, m = 1900 kg, c = 870 N/(m/s)
Values adapted from G070156, slides 55 & 63: m = mu, k = kzztot, c was chosen to match measured data

Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013



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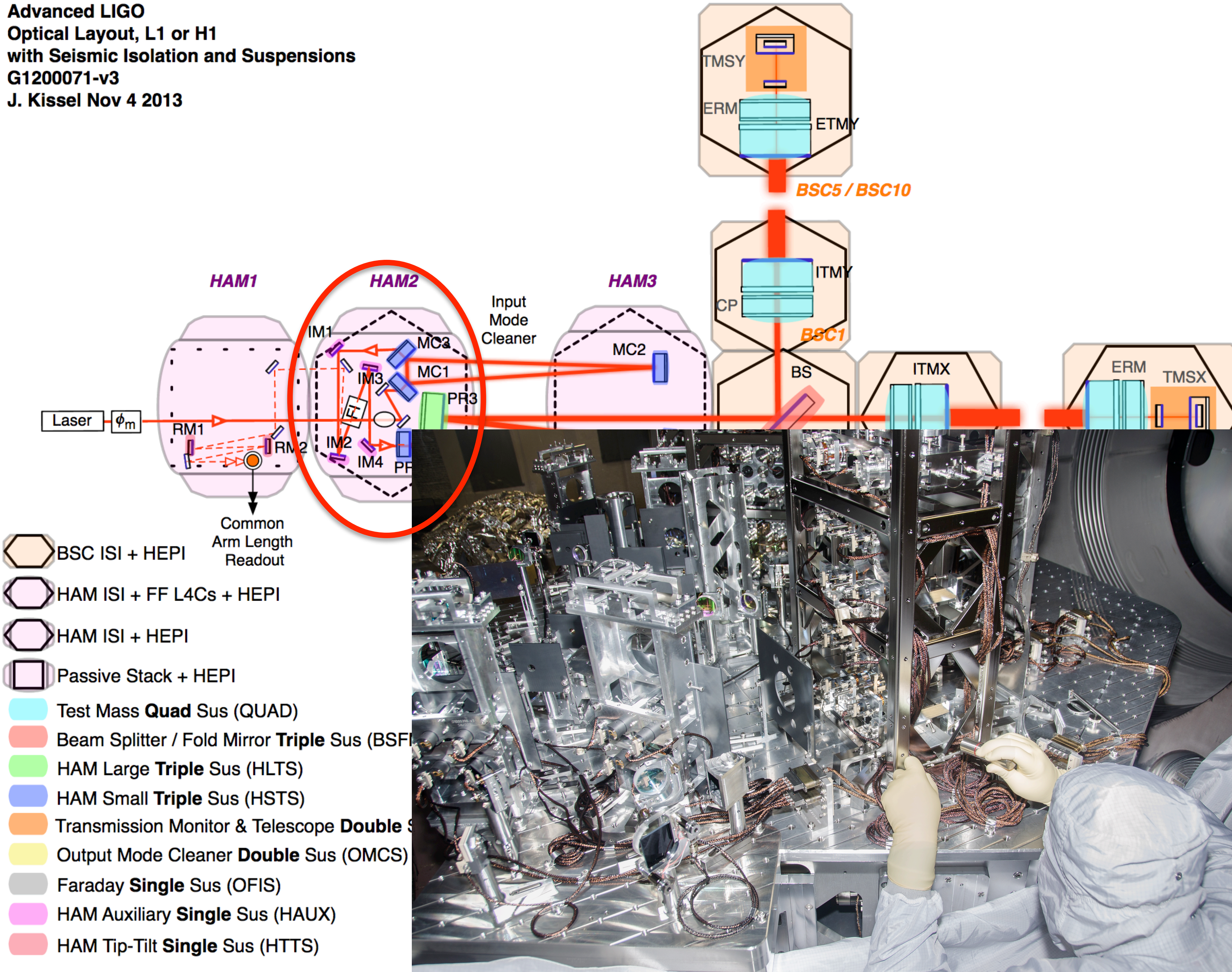
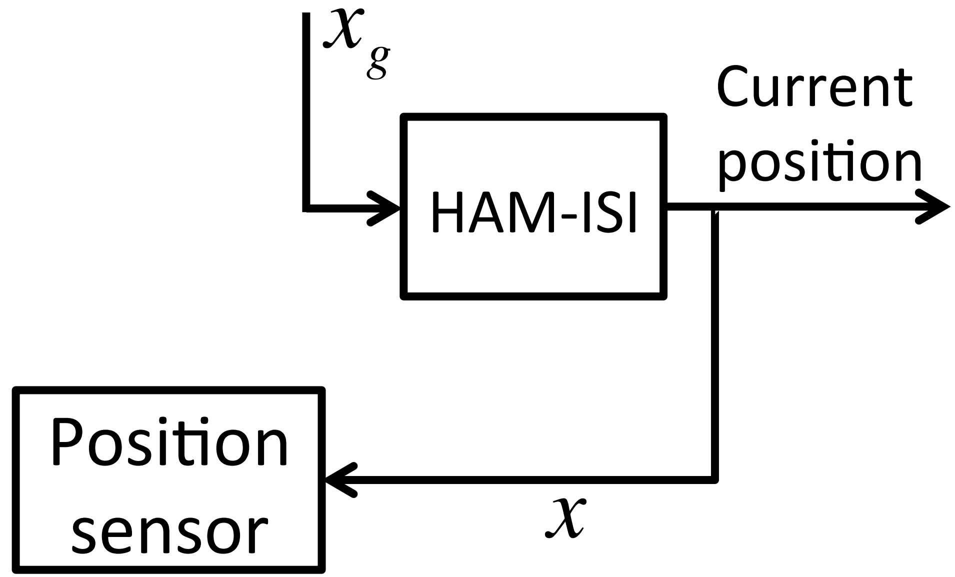
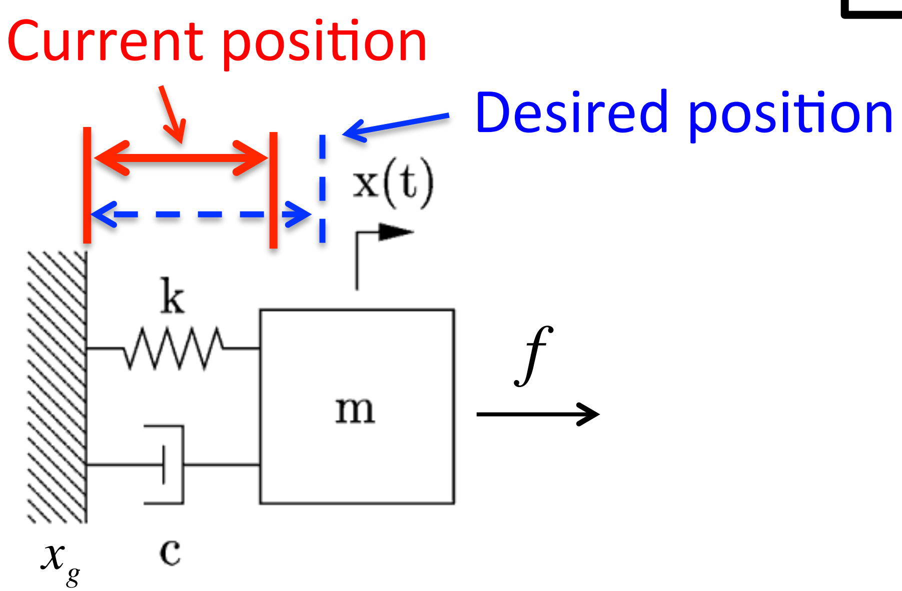


Feedback loop block diagram





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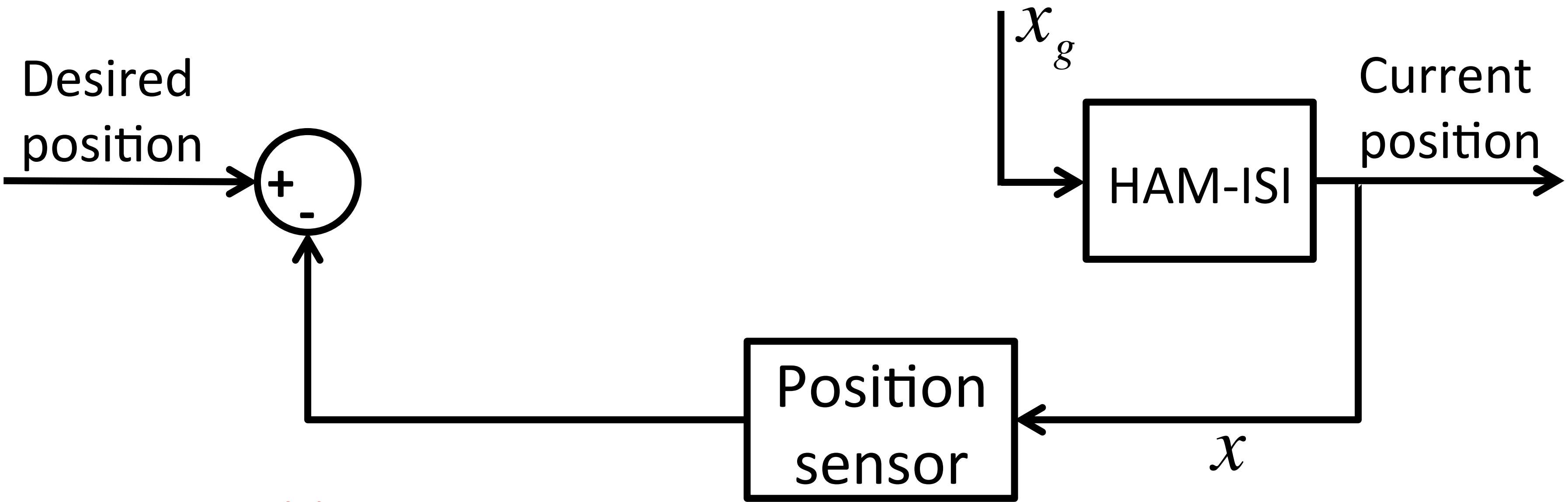

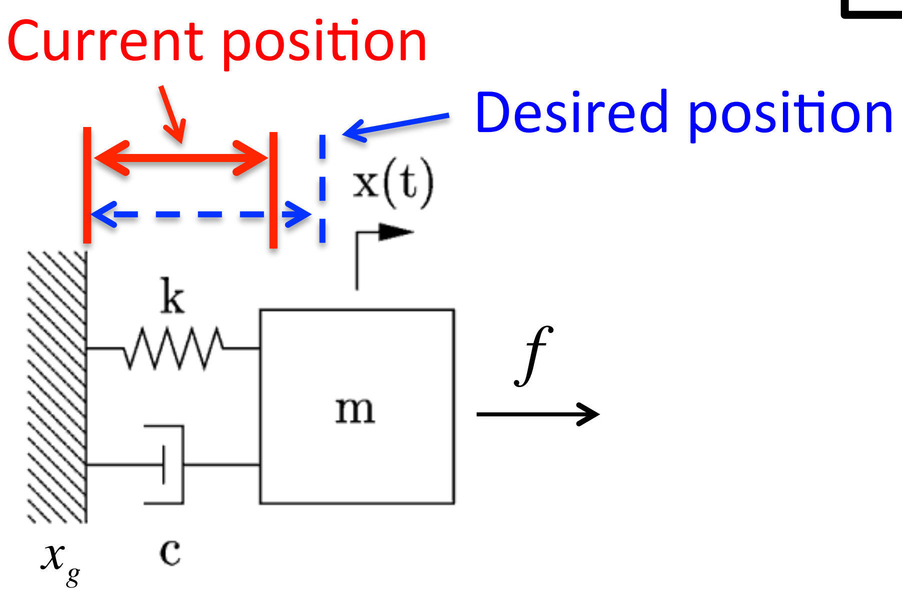

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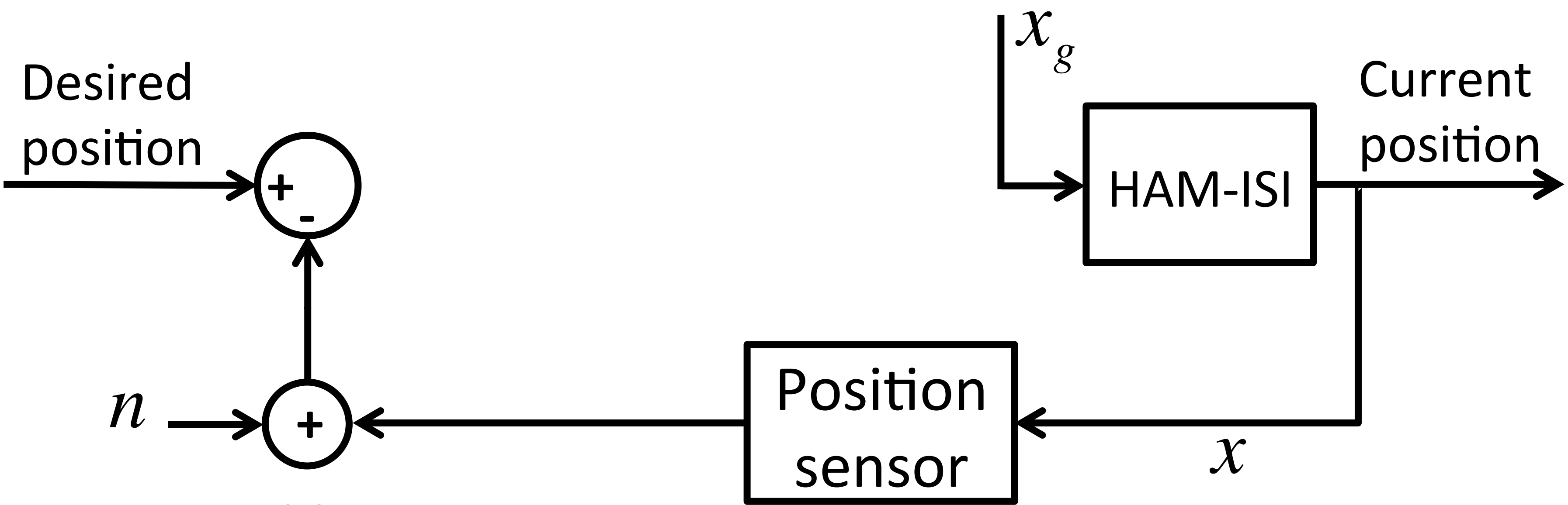

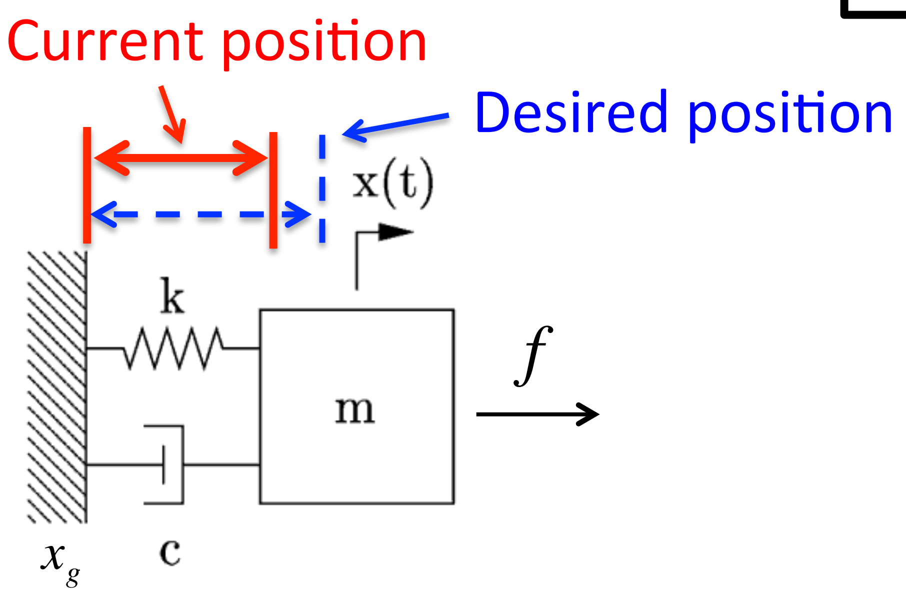

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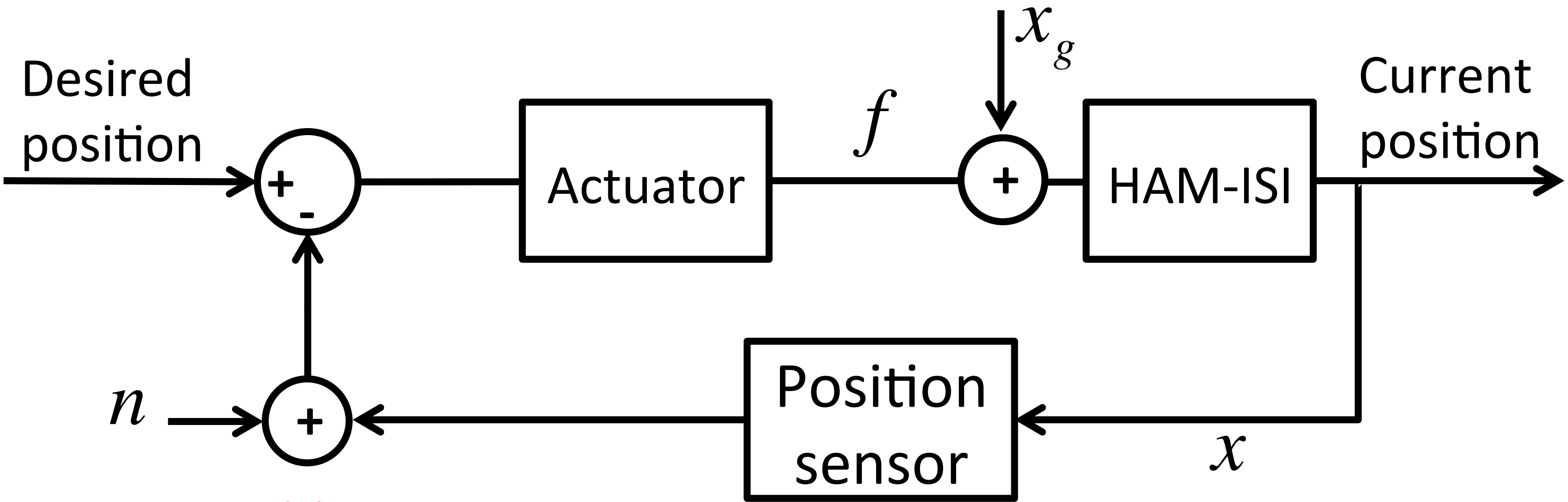

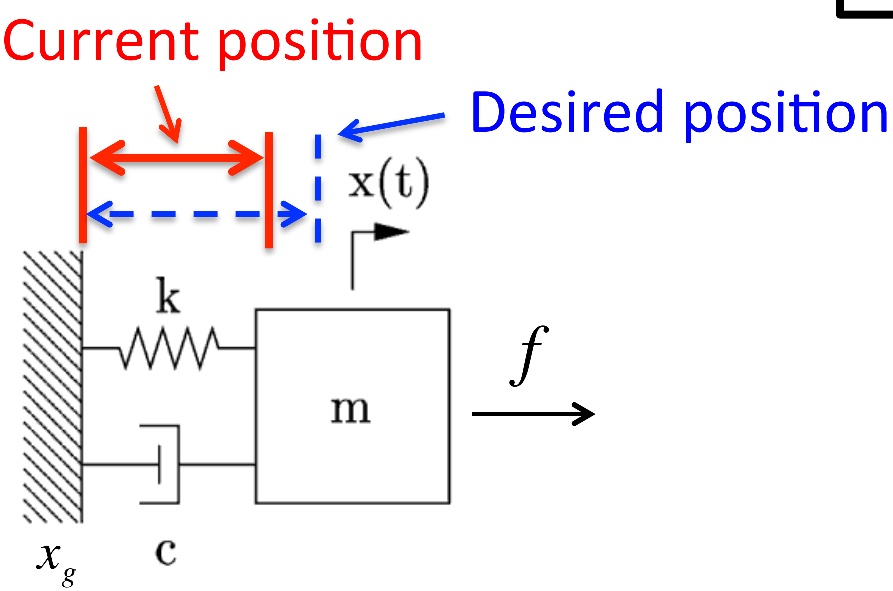

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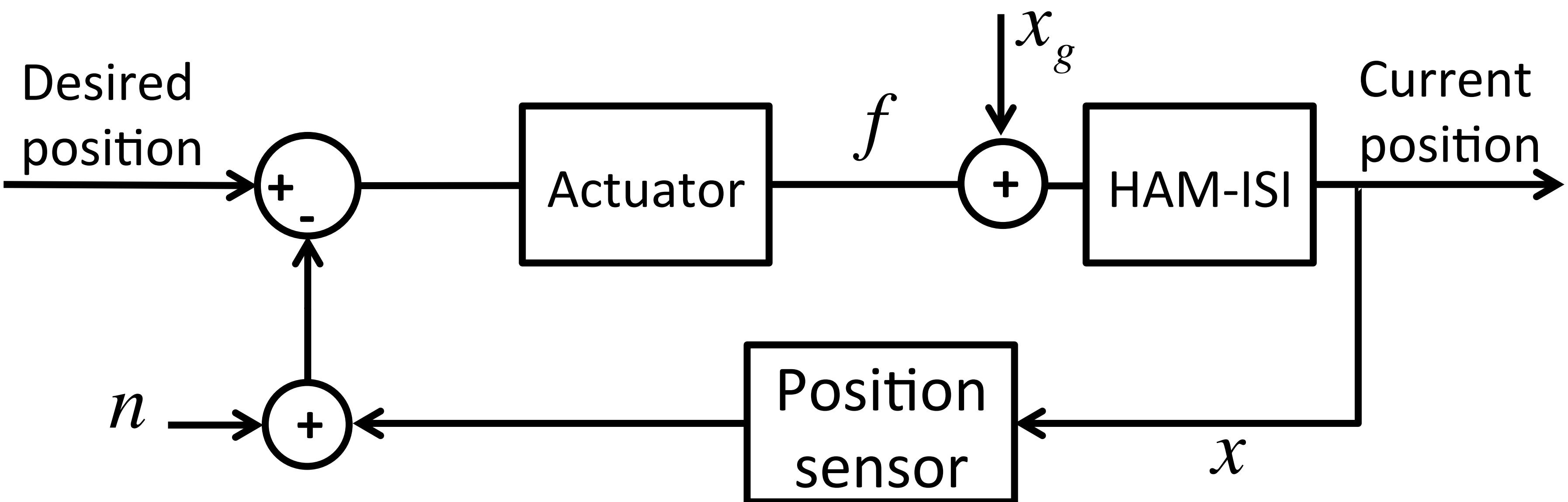
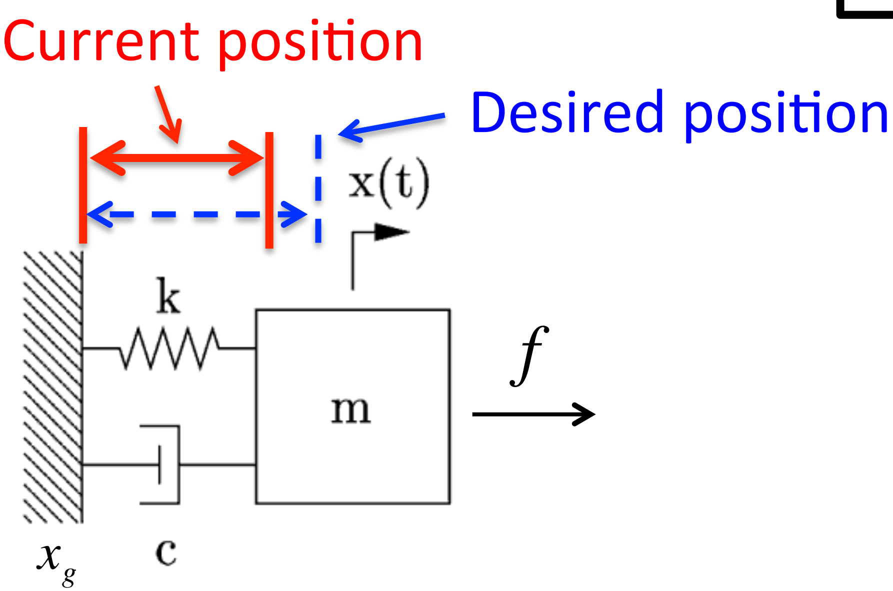
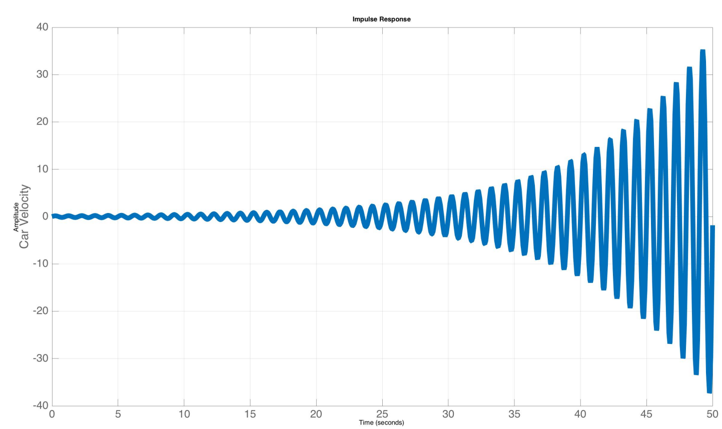




In general unstable!



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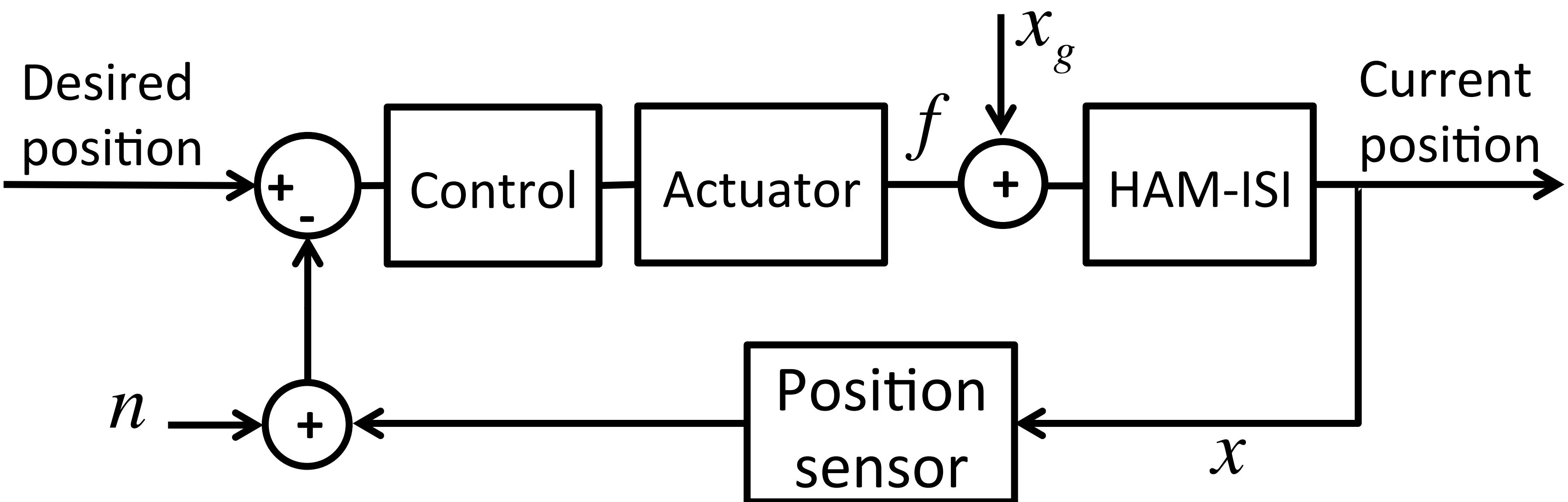
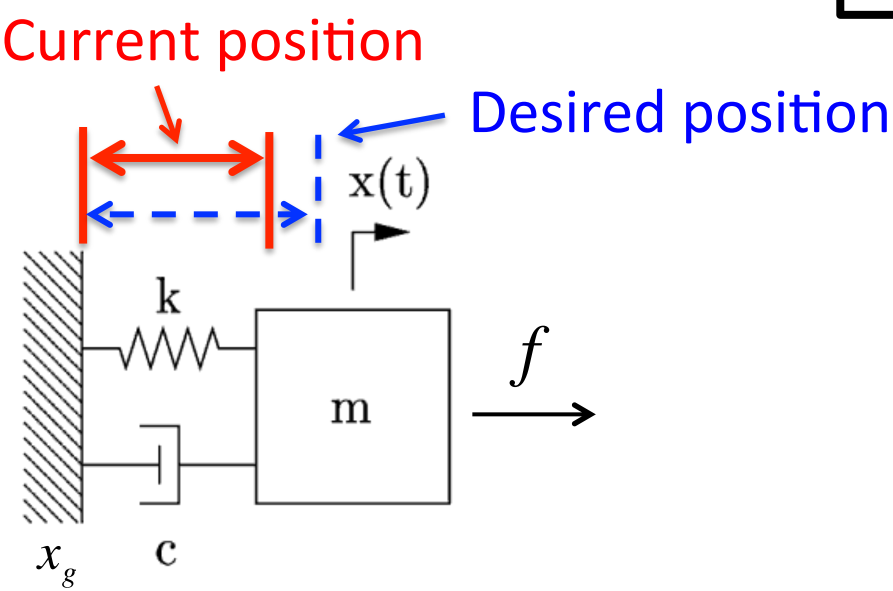


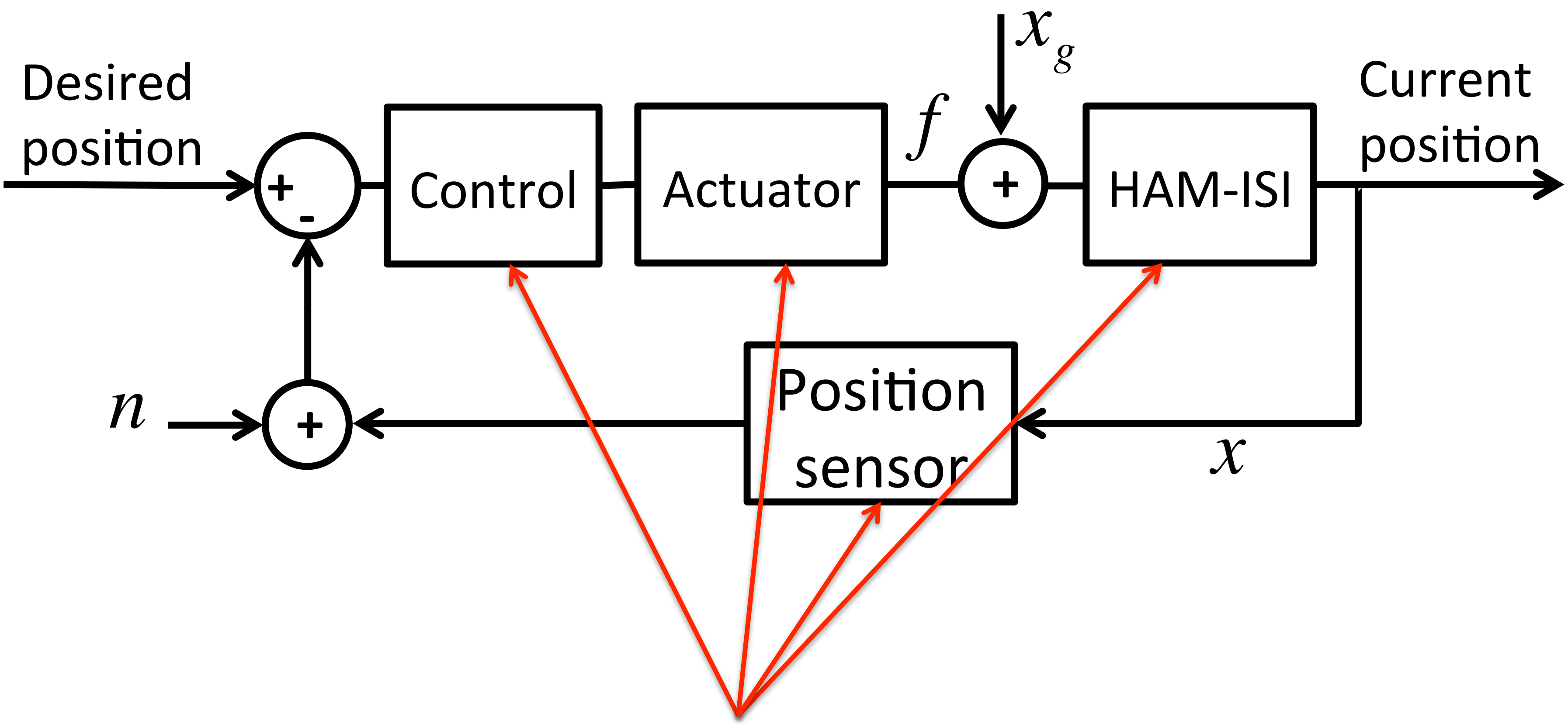


- Stabilize with the addition of a control filter
- Also gives you parameters to tune the response

Transfer functions

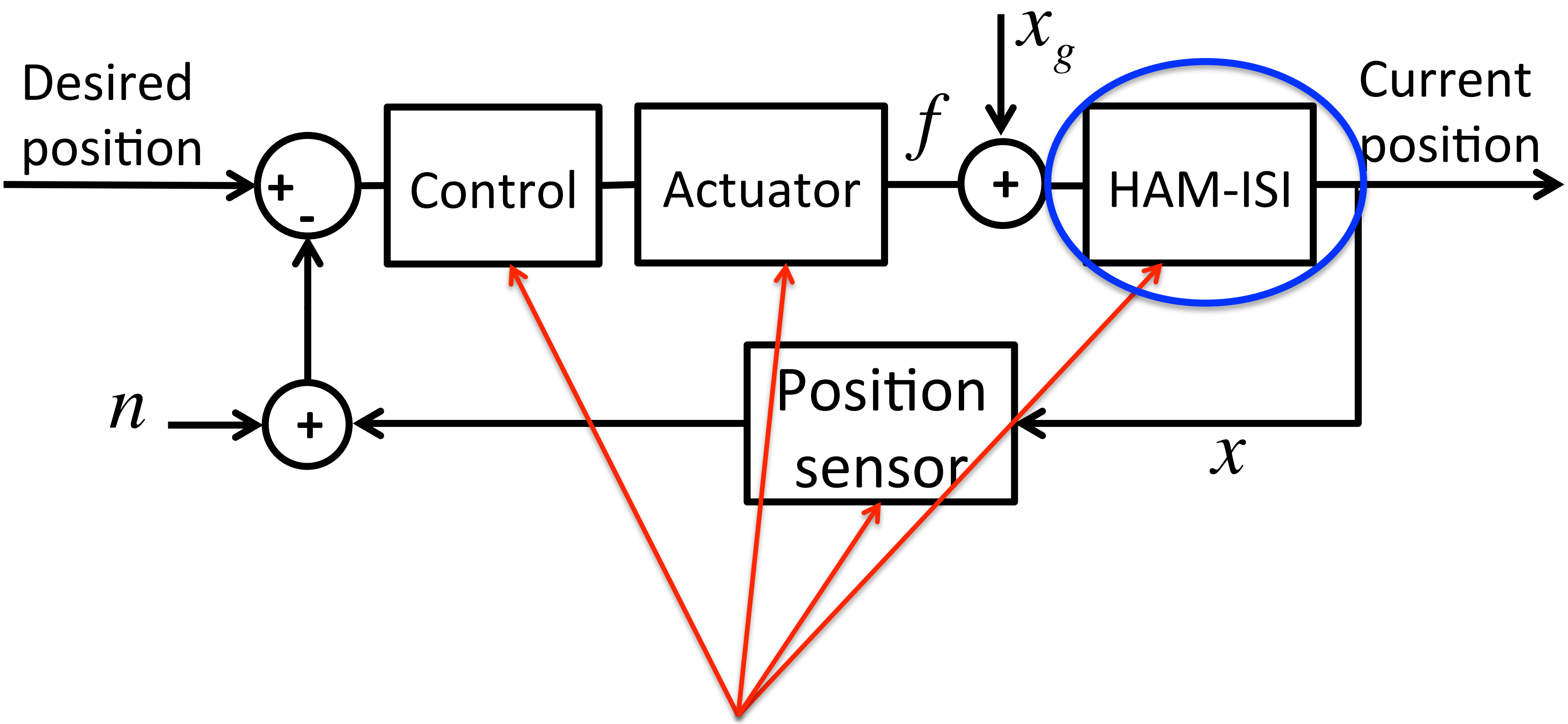
Used for modeling each block in the loop

Feedback loop block diagram



Each block has a model associated with it.
-typically represented a as **transfer function**

Feedback loop block diagram



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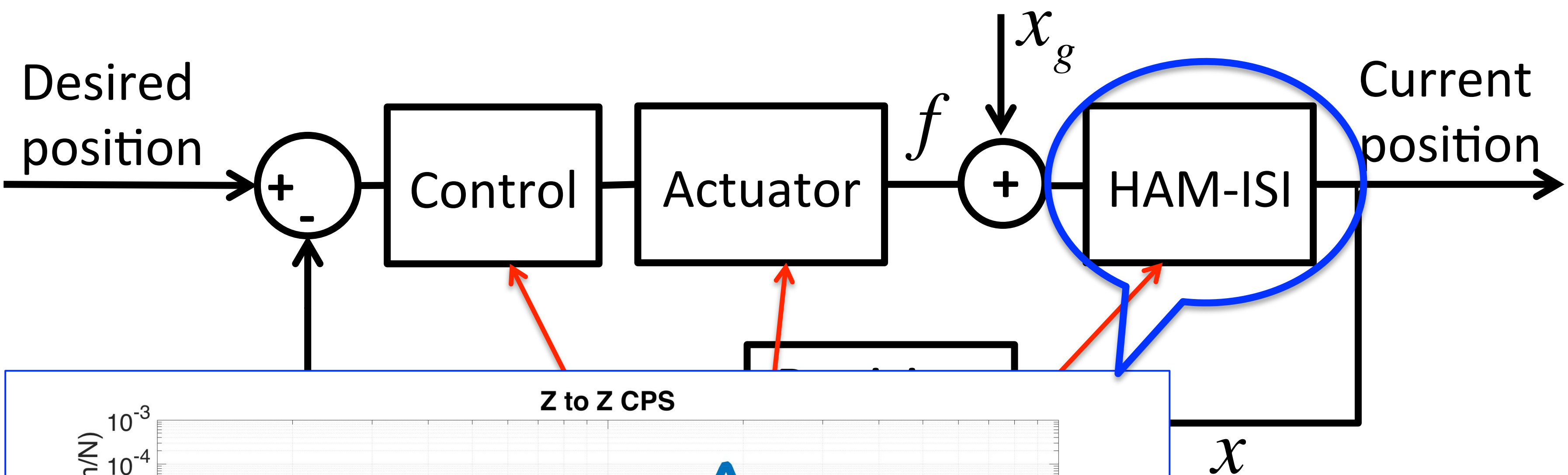
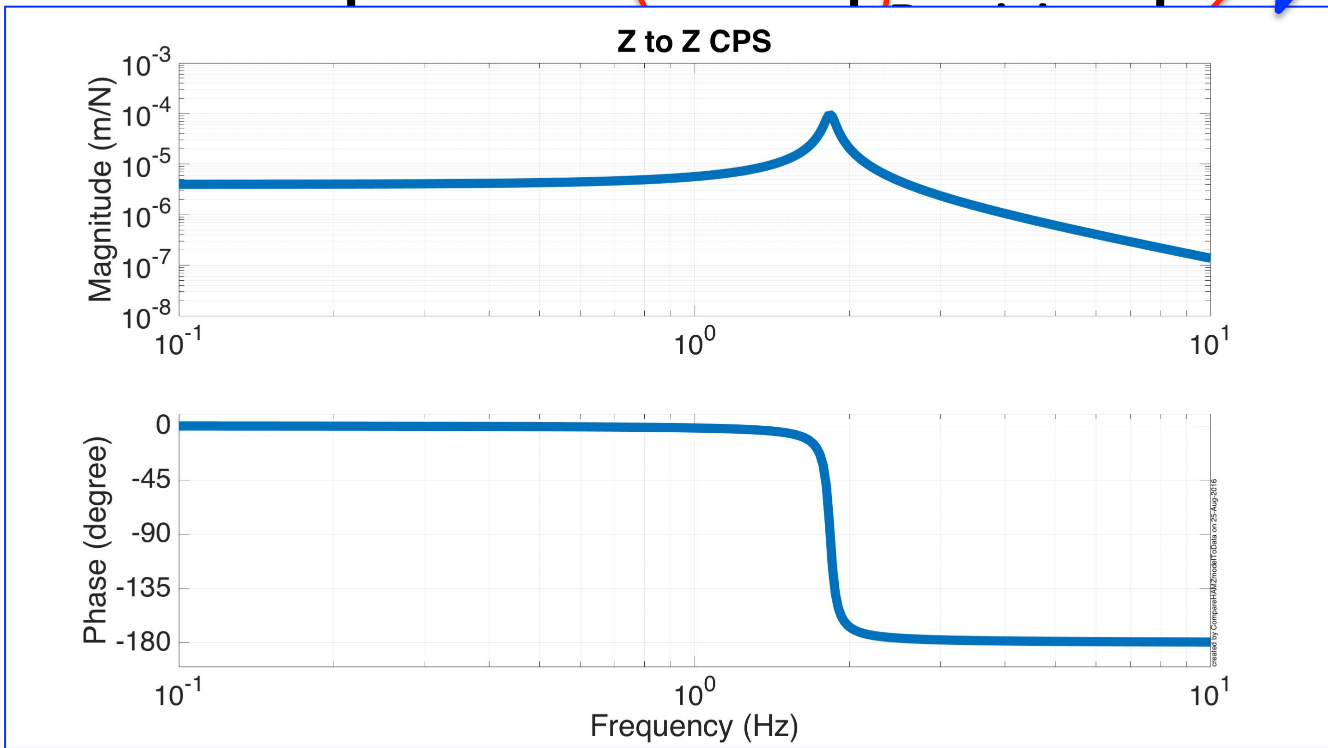
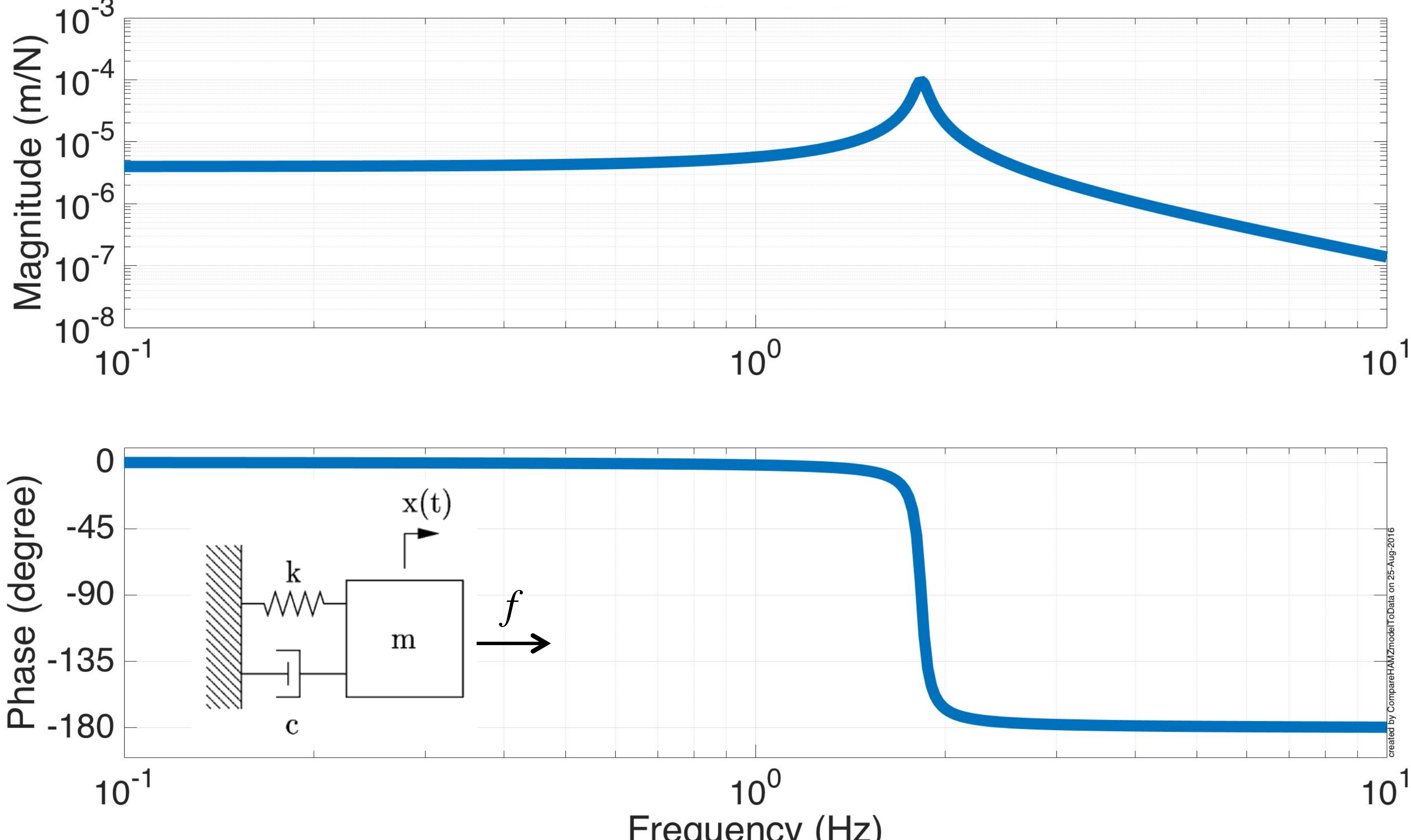




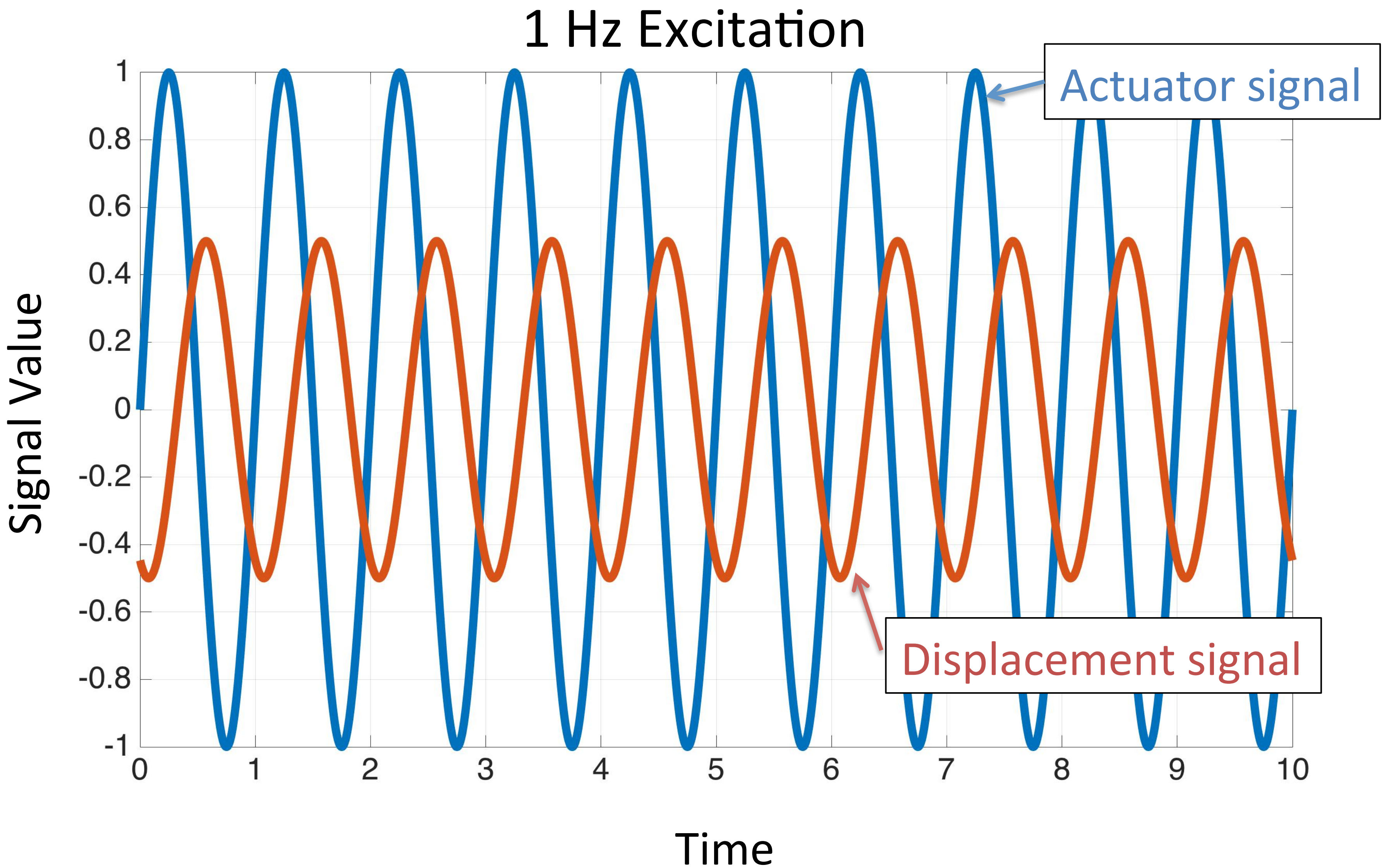
on

System models: Transfer Functions

Bode plot of the *x/f* transfer function



TF input/output relationship



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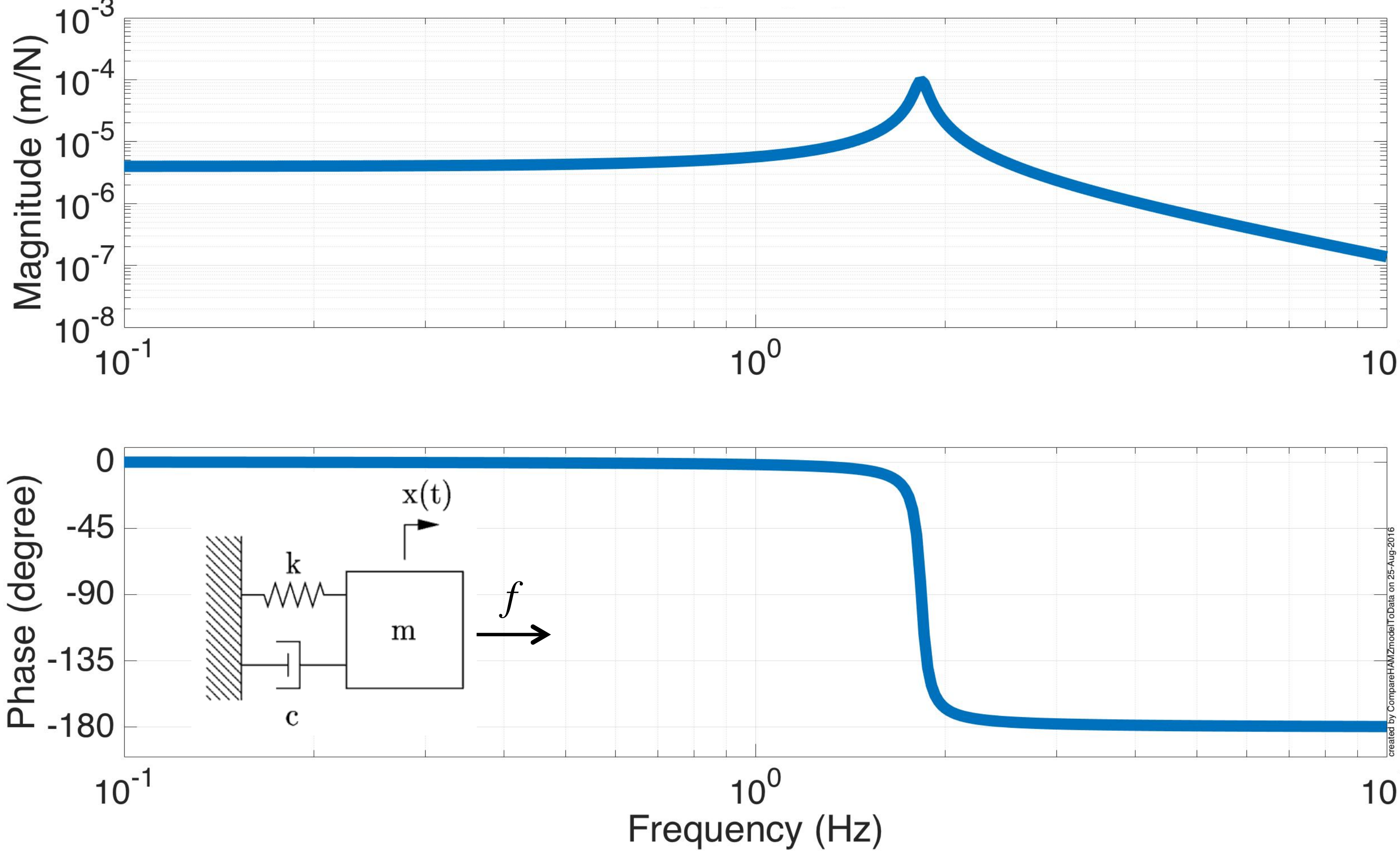

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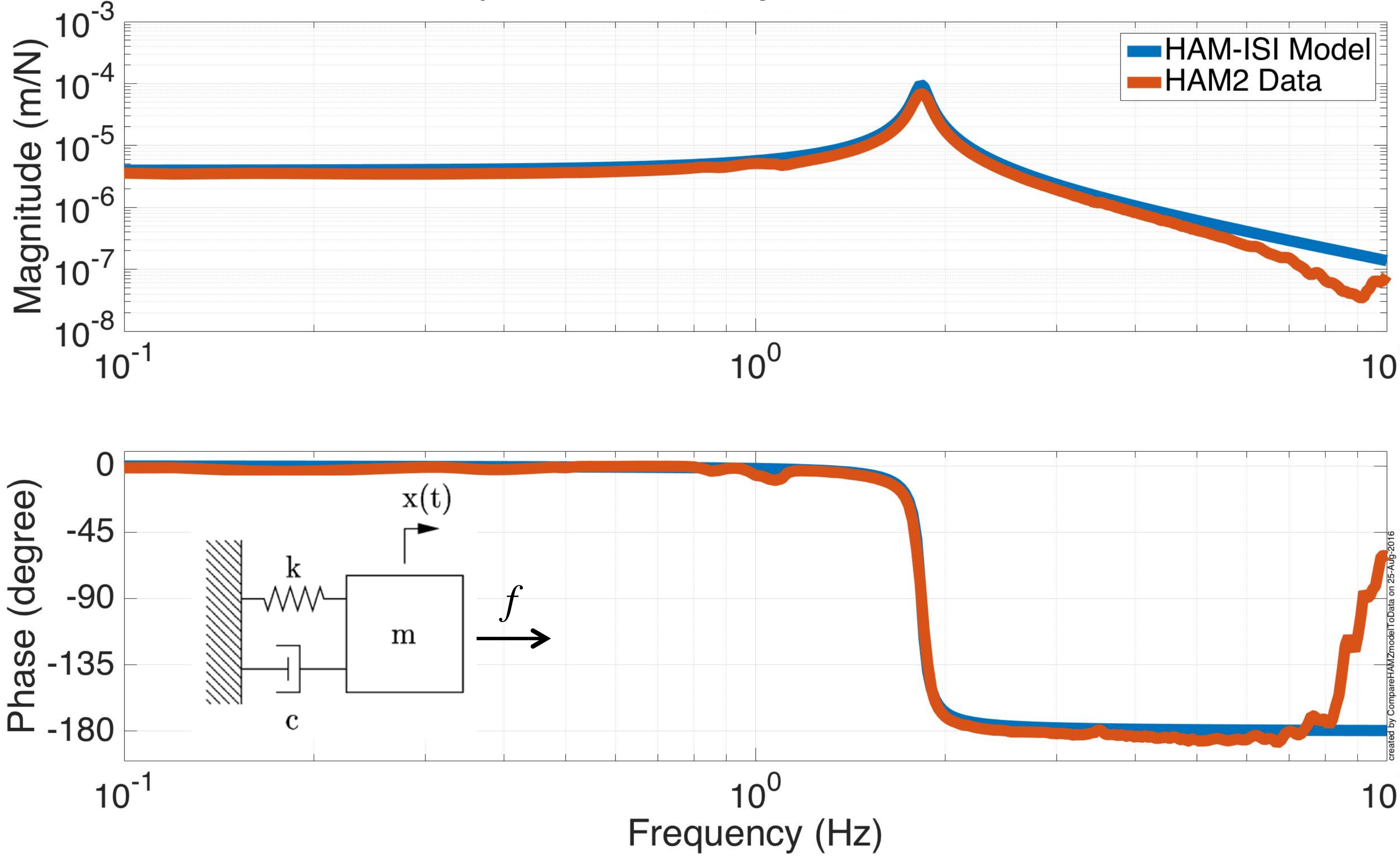

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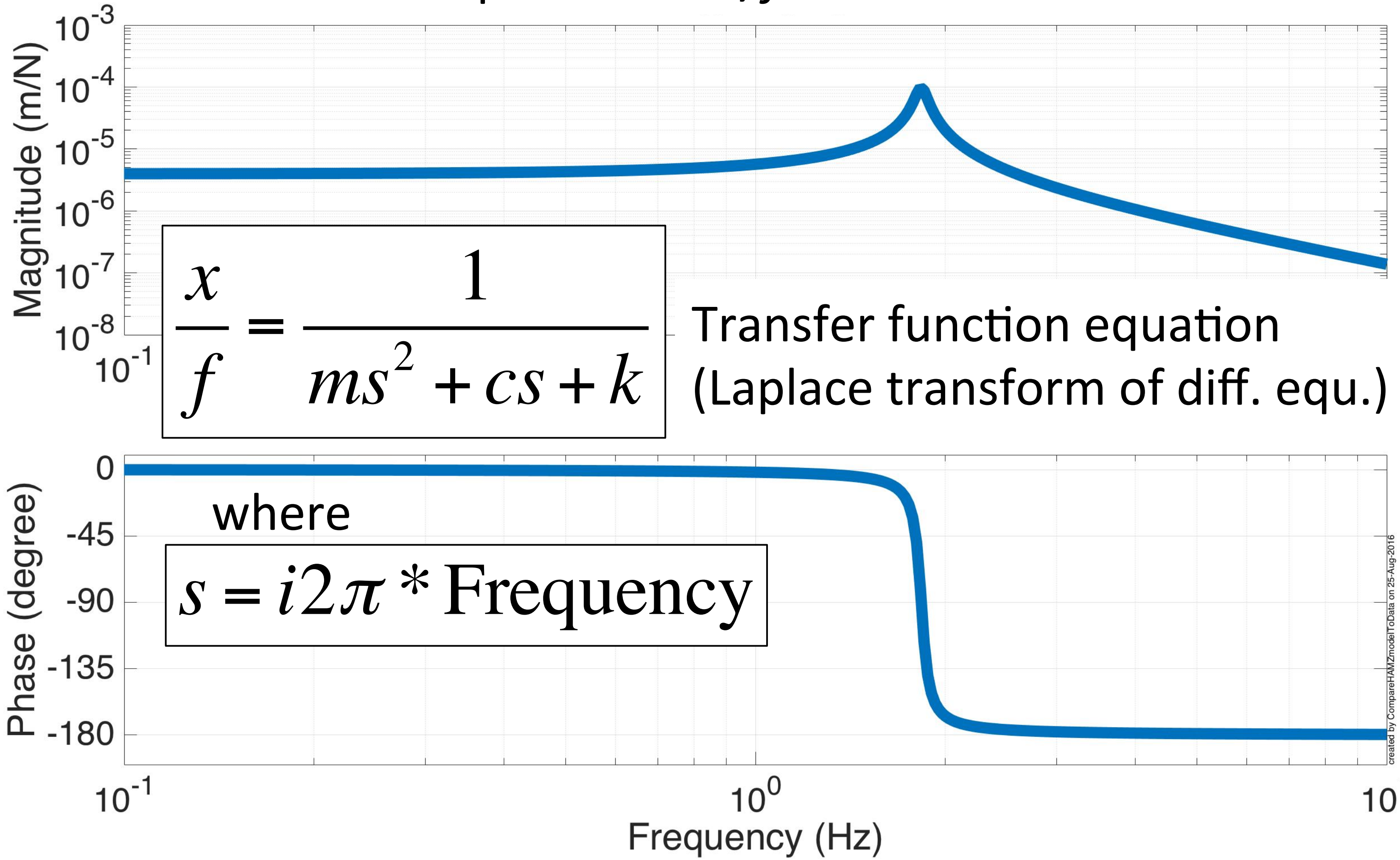


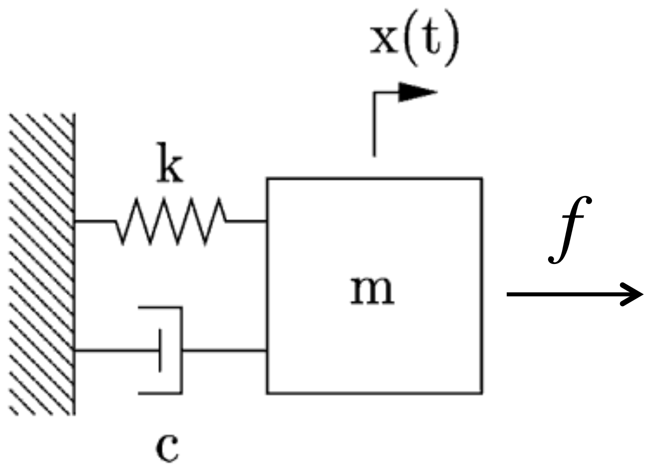
$$\frac{x}{f} = \frac{1}{ms^2 + cs + k}$$

Transfer function equation
(Laplace transform of diff. equ.)

where

$$s = i2\pi * \text{Frequency}$$

What determines the TF?



Time Domain

Differential equation

$$m\ddot{x} + c\dot{x} + kx = f$$

Laplace Transform

Replace all time derivatives with ***s***

Frequency Domain

Transfer function

$$\frac{x}{f} = \frac{1}{ms^2 + cs + k}$$

What determines the TF?

Transfer function

$$\frac{x}{f} = \frac{1}{ms^2 + cs + k}$$

$$ms^2 + cs + k = 0$$

Roots of polynomial –> poles

$$\text{poles} = \sigma \pm i\omega$$

What determines the TF?

Transfer function

$$\frac{x}{f} = \frac{1}{ms^2 + cs + k}$$

$$ms^2 + cs + k = 0$$

Roots of polynomial –> poles

$$\text{poles} = \sigma \pm i\omega$$

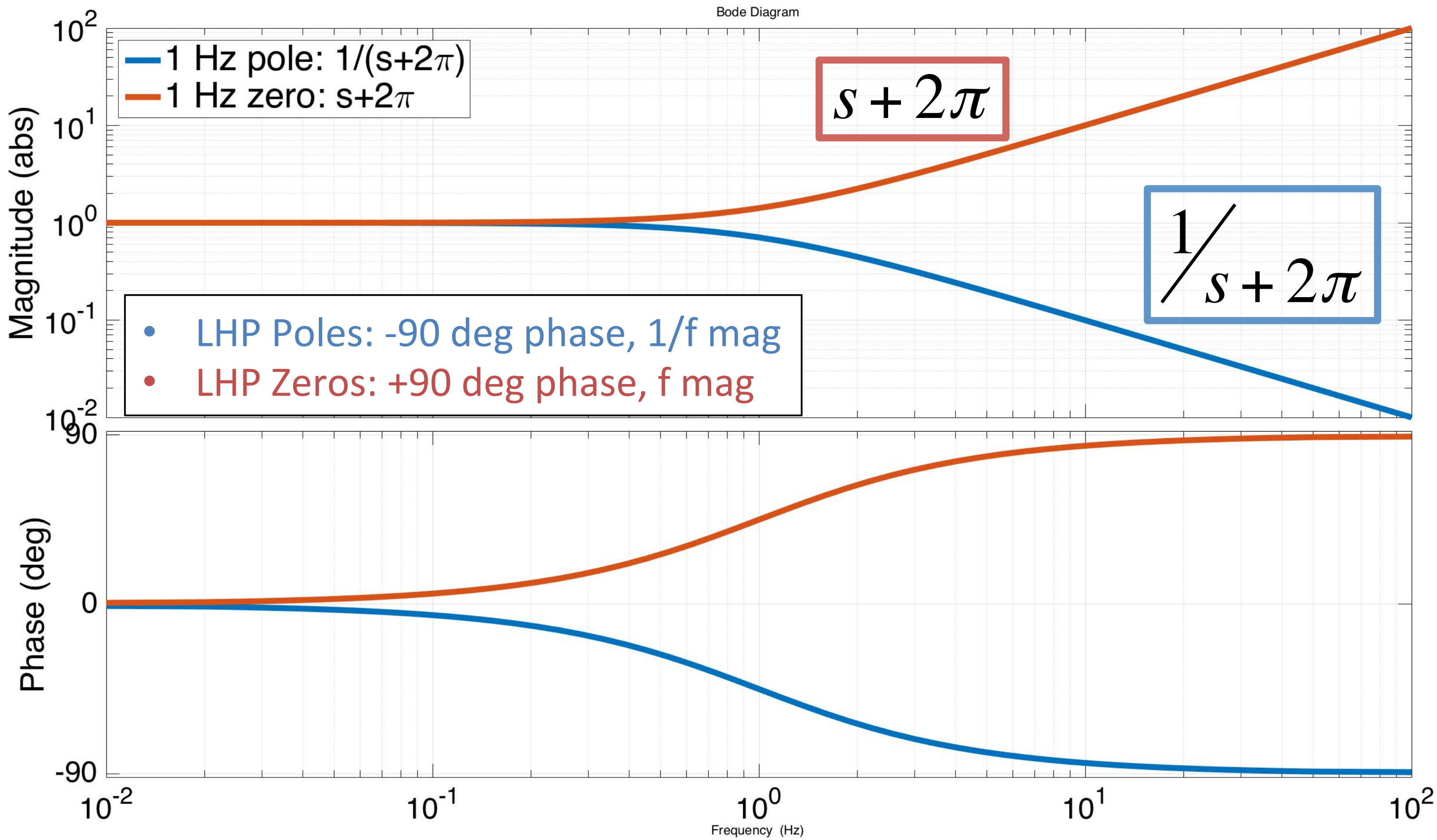
The poles are the system time constants

$$x[t] = A_1 e^{(\sigma + i\omega)t} + A_2 e^{(\sigma - i\omega)t} + x_f$$

Solution to the differential equation

Control design: poles and zeros

Recall: $s = i2\pi f$ to generate the bode plot



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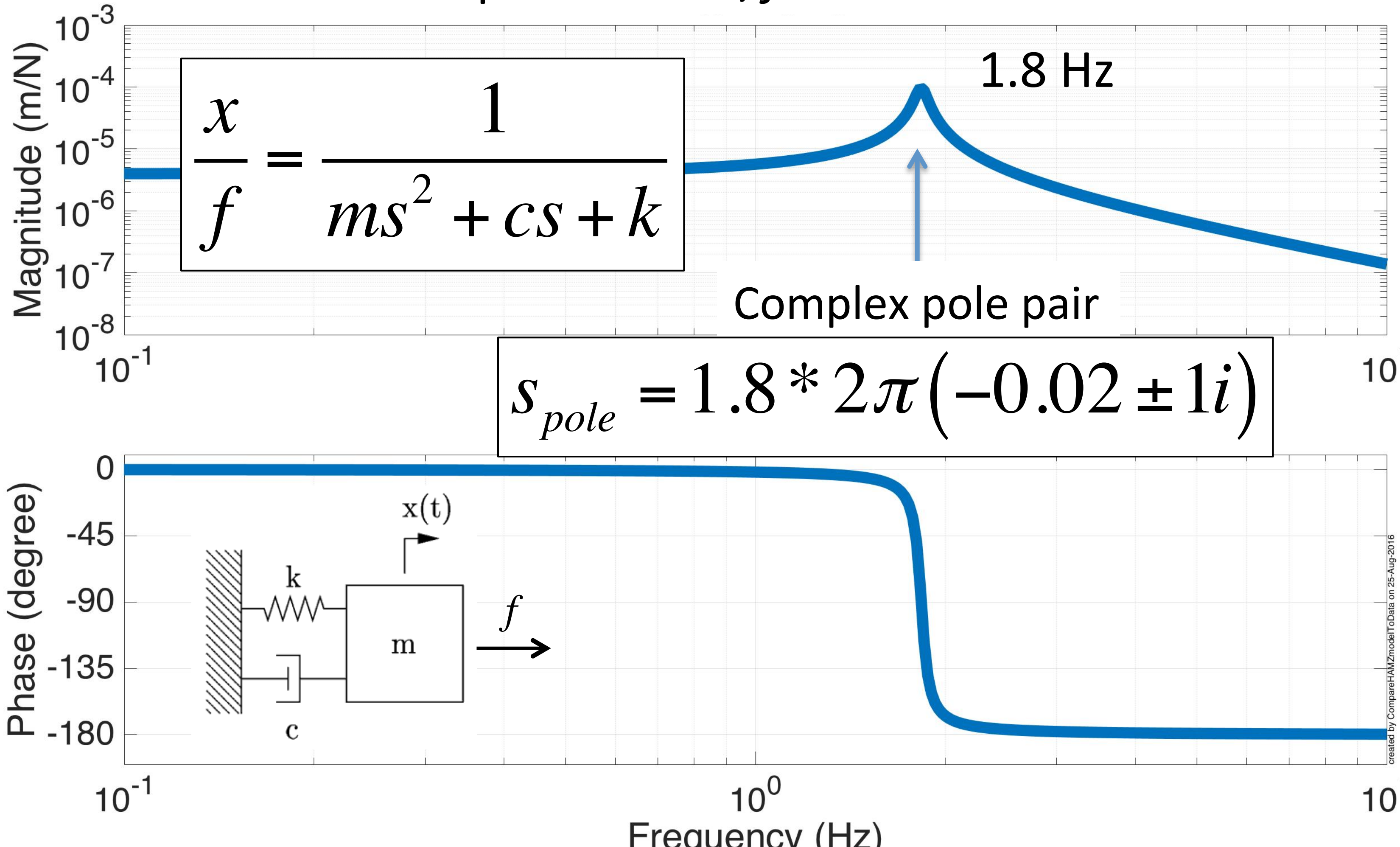

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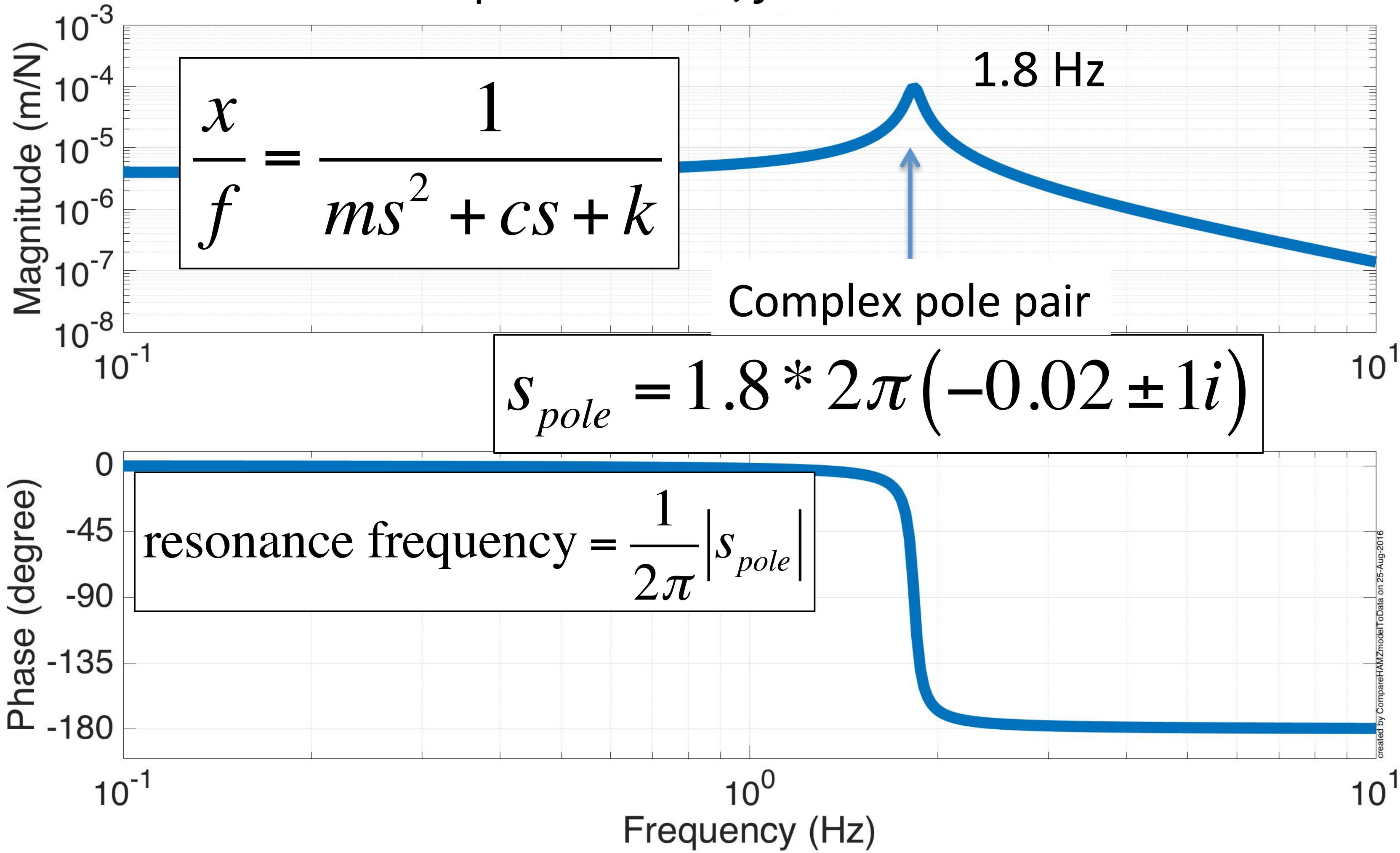


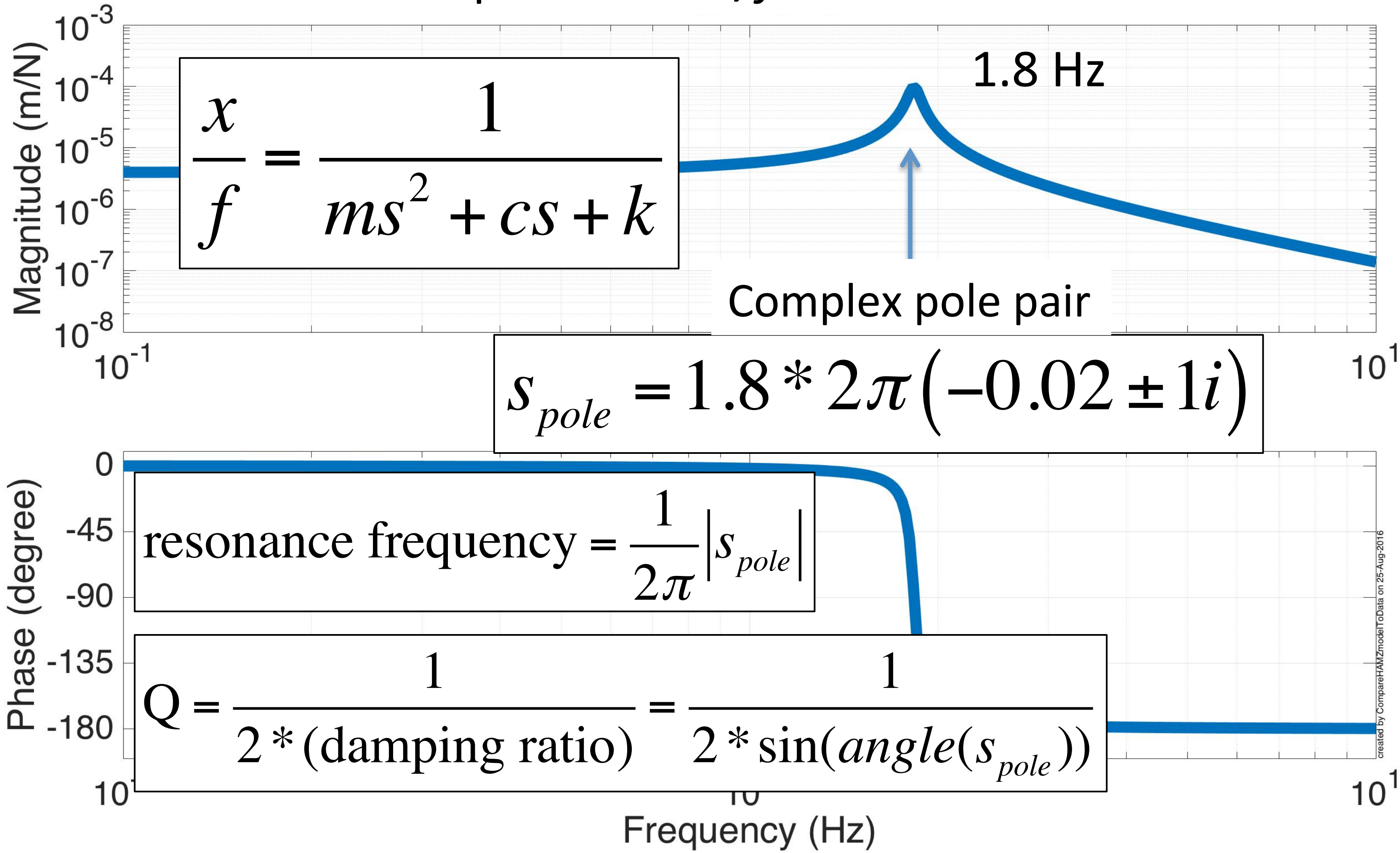
$$\frac{x}{f} = \frac{1}{ms^2 + cs + k}$$

$$s_{pole} = 1.8 * 2\pi\left(-0.02 \pm 1i\right)$$

$$\text{resonance frequency} = \frac{1}{2\pi}\left|s_{pole}\right|$$

System models: Transfer Functions

Bode plot of the *x/f* transfer function



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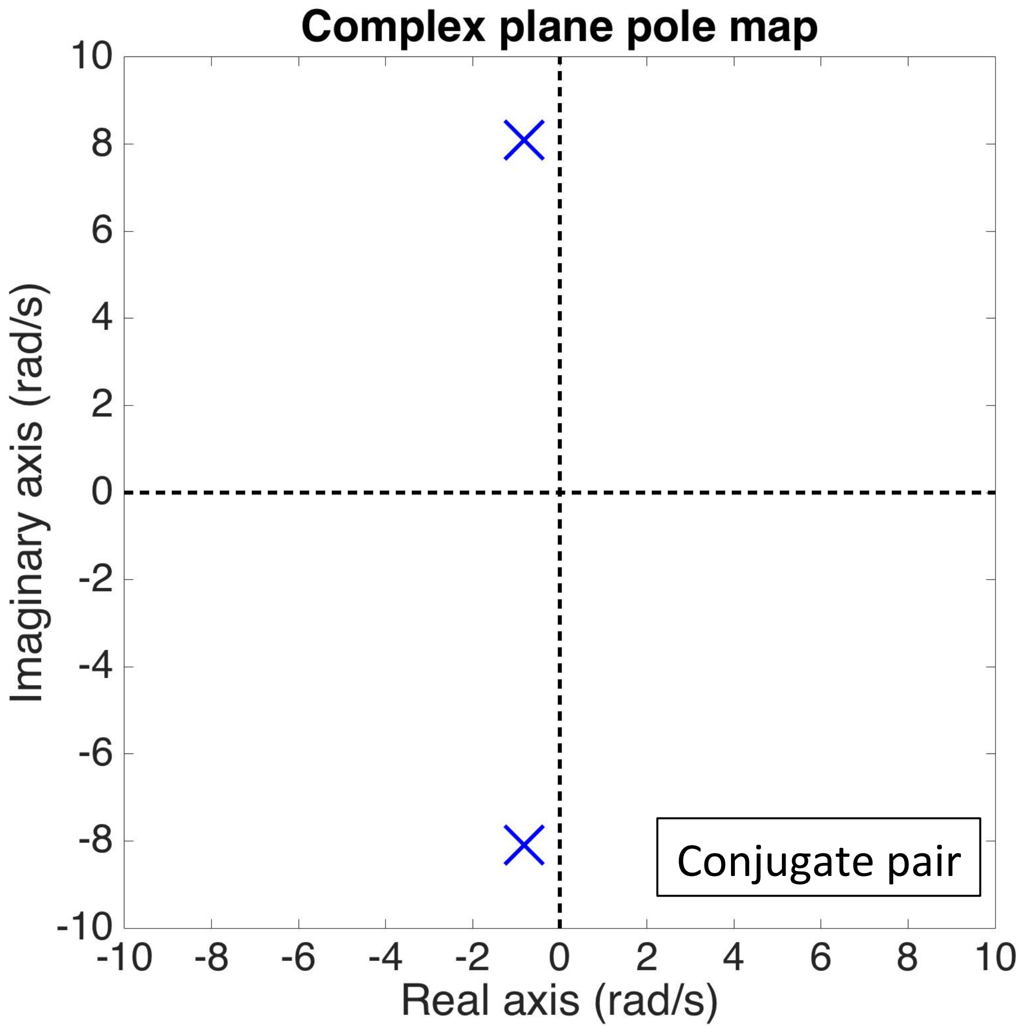
$$Q = \frac{1}{2 * (\text{damping ratio})} = \frac{1}{2 * \sin(angle(s_{pole}))}$$

Poles in the complex plane

$$s_{pole} = -0.814 \pm 8.10i$$



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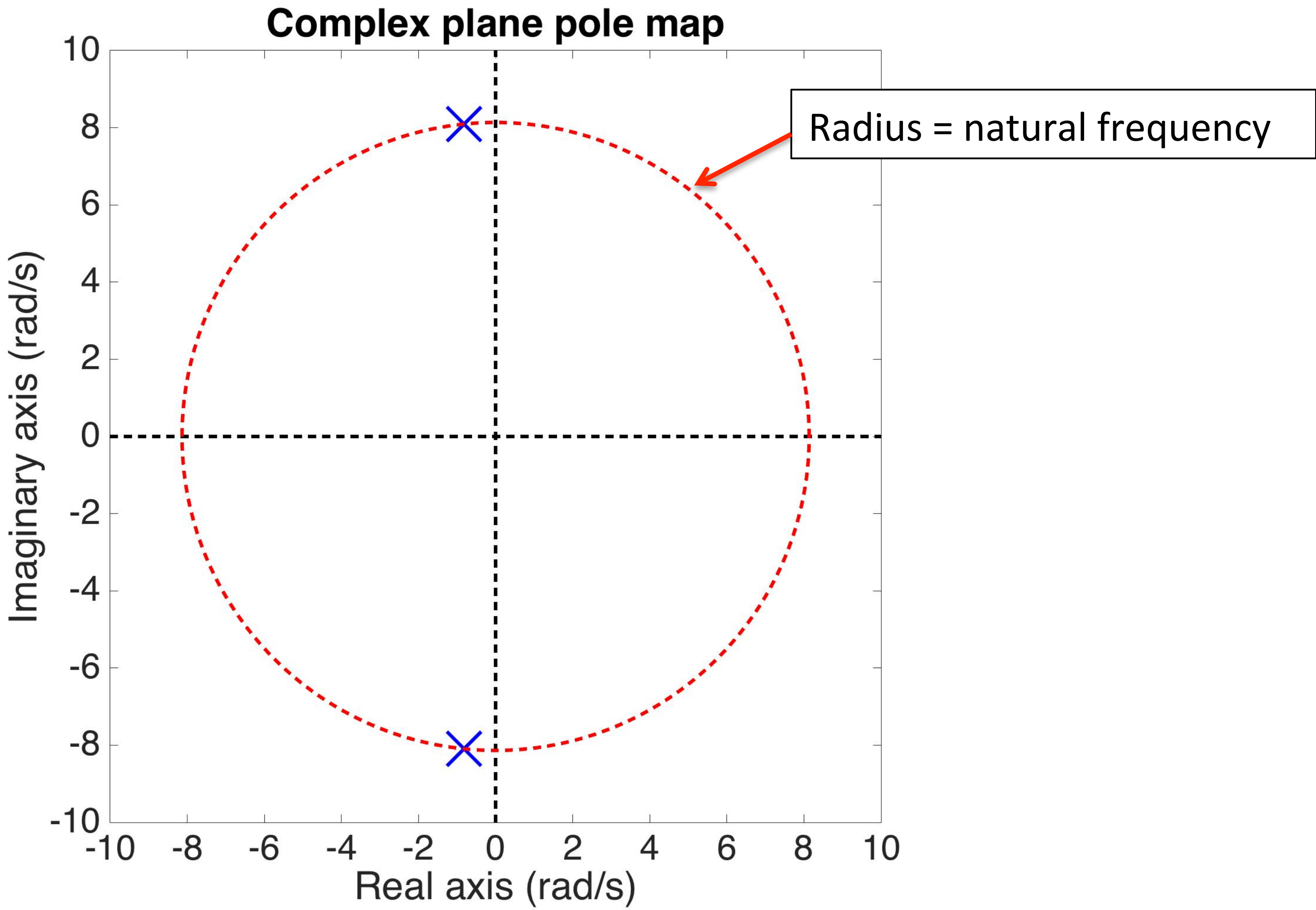

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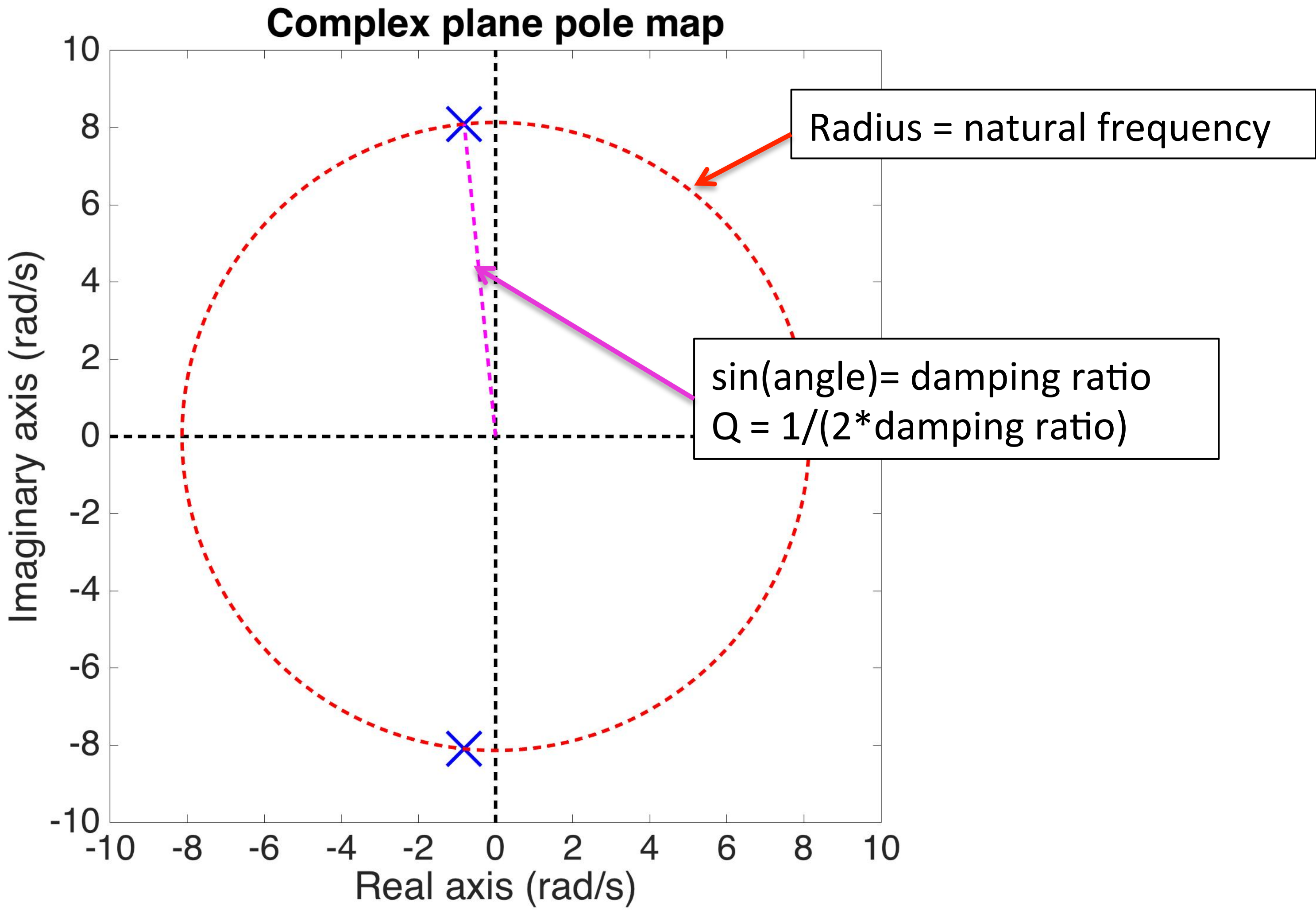

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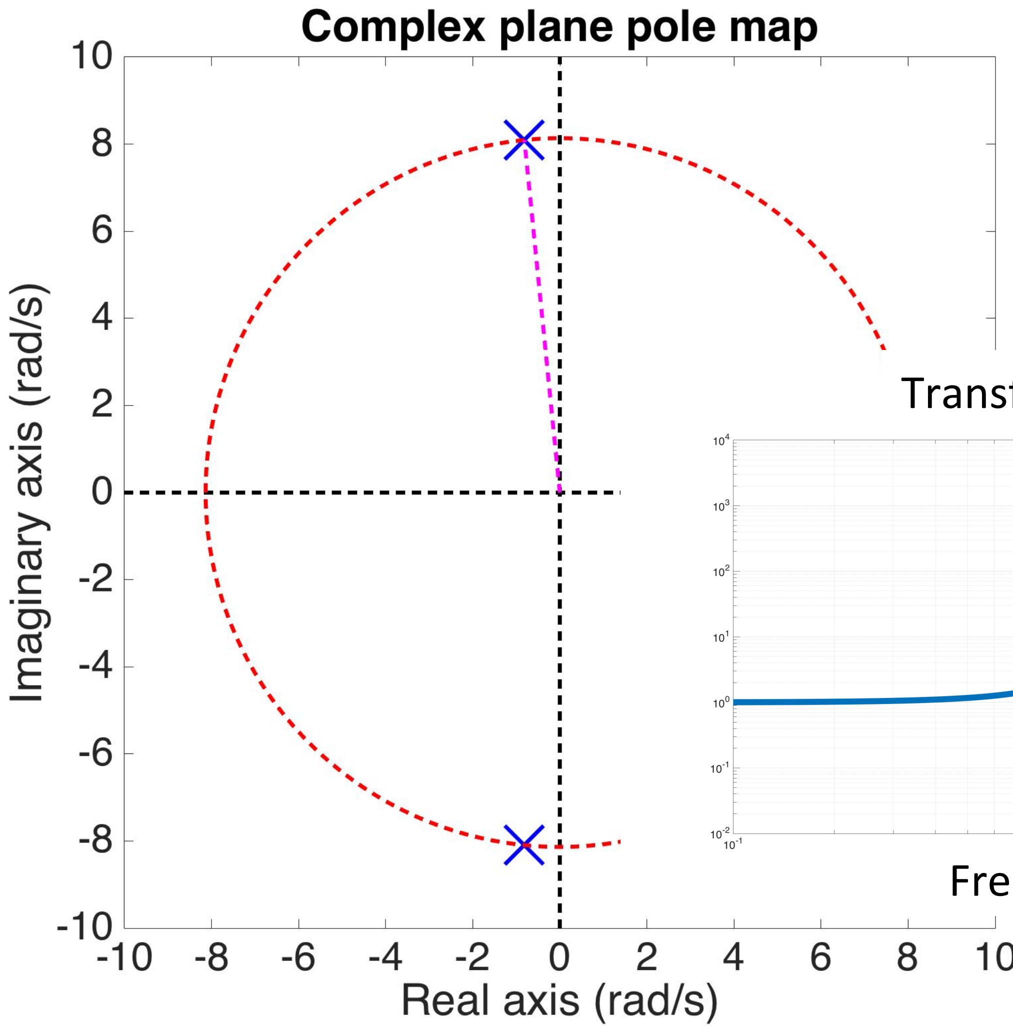

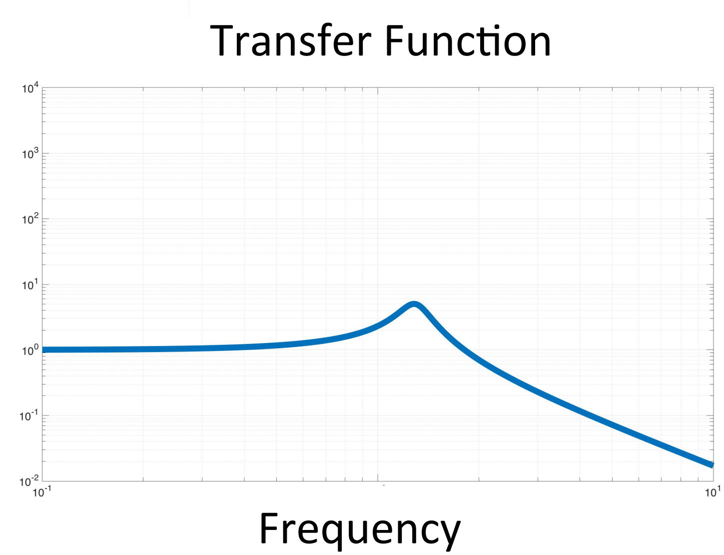

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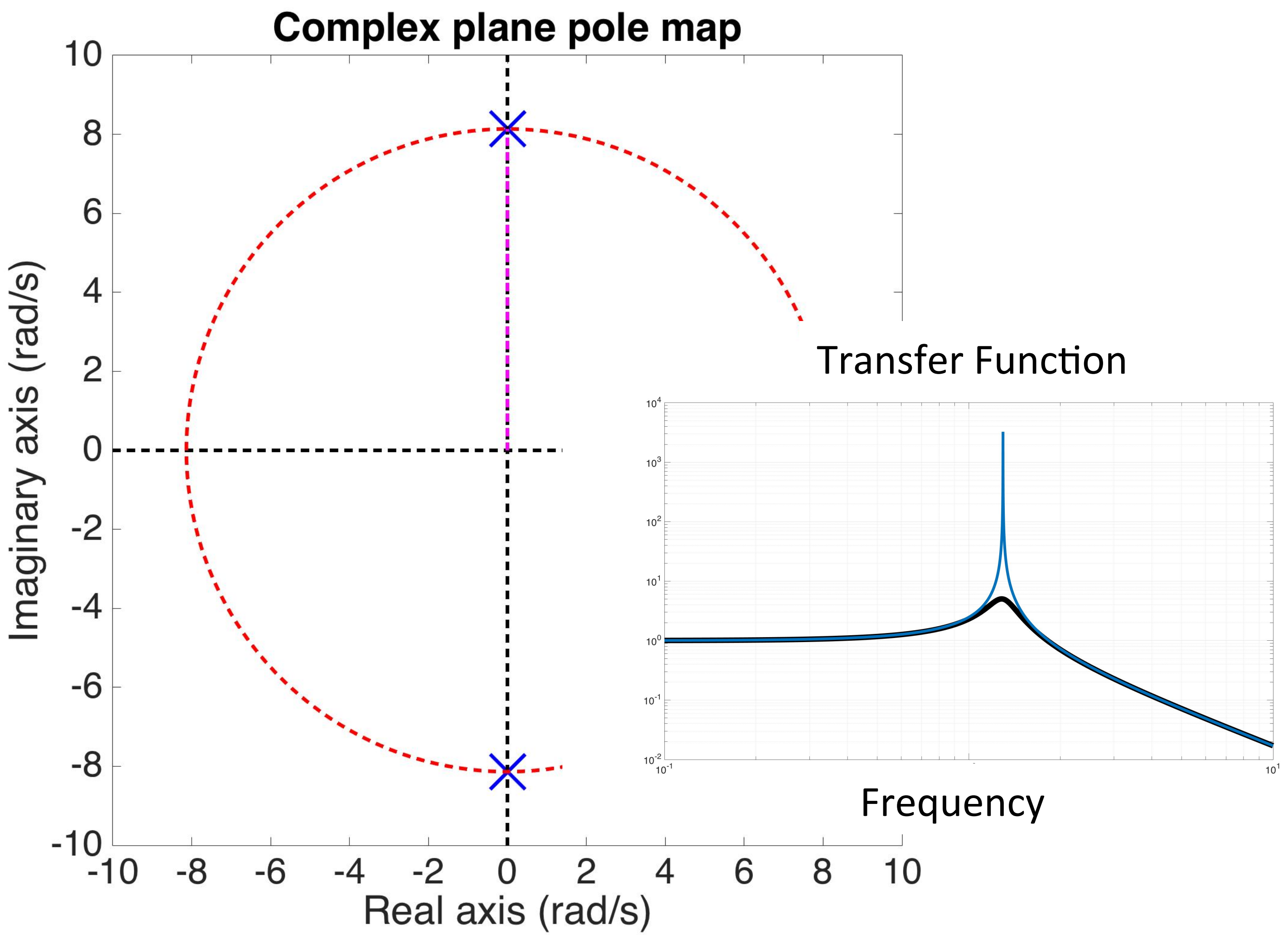
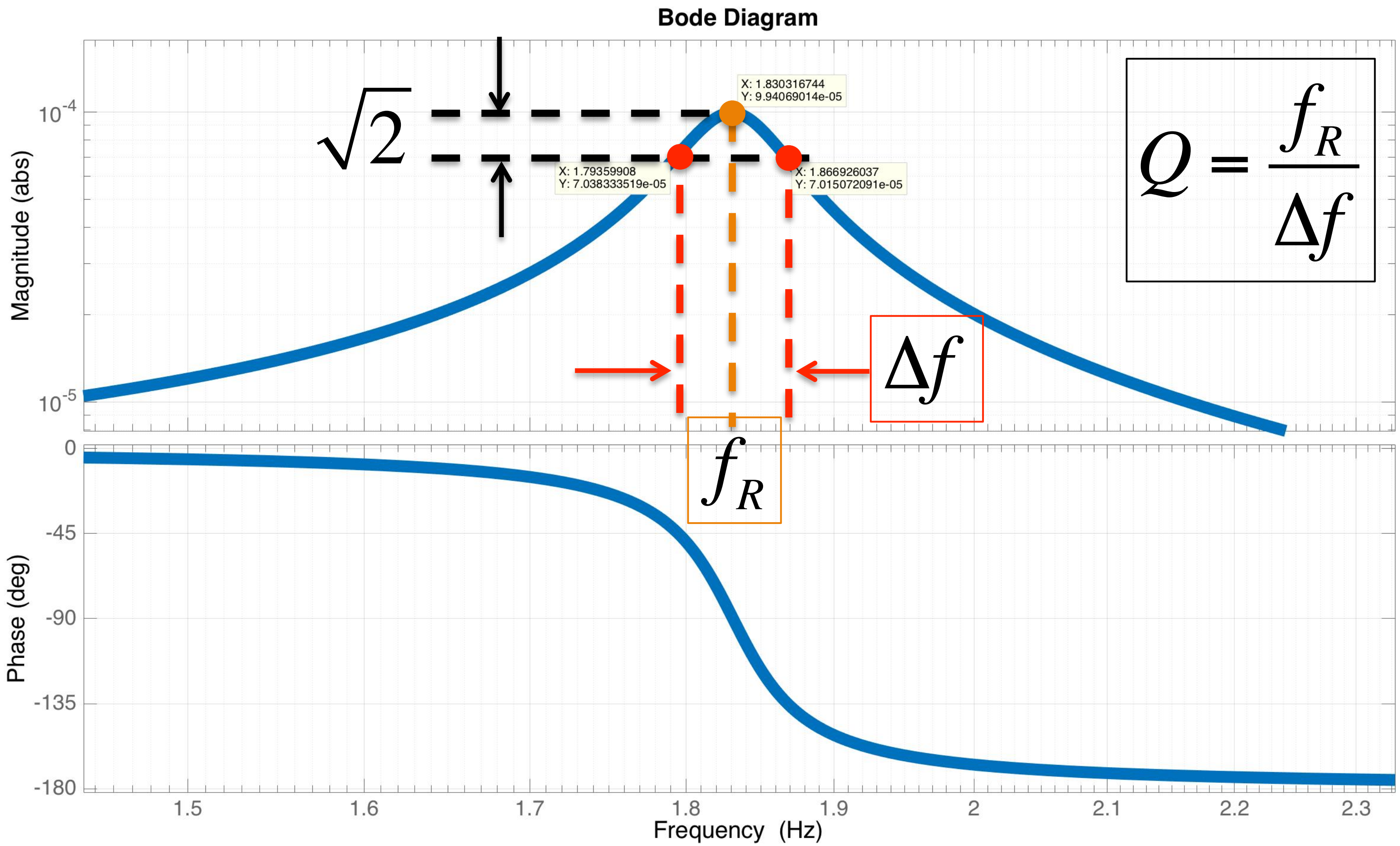


Resonance Quality (Q) factor



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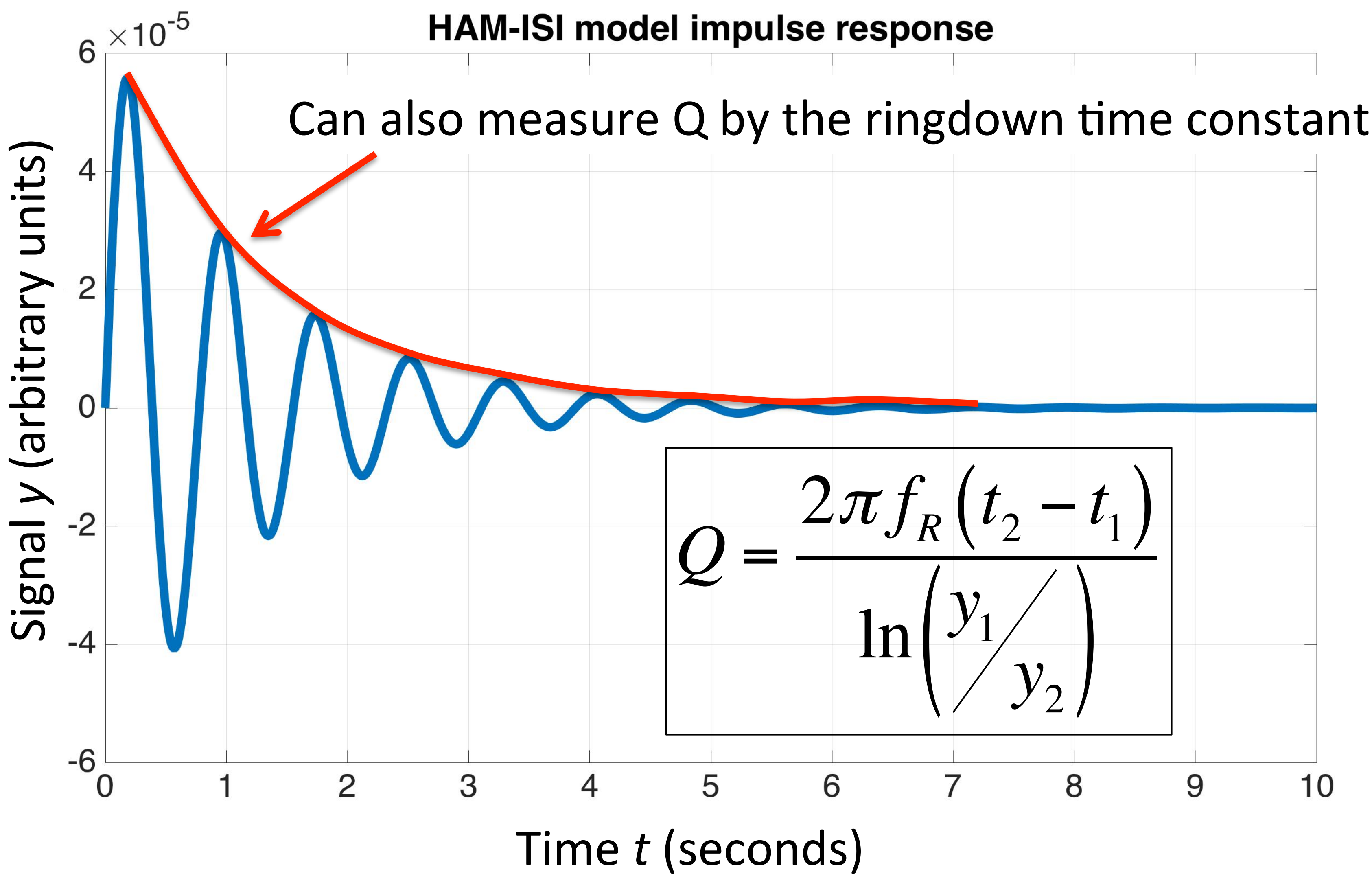
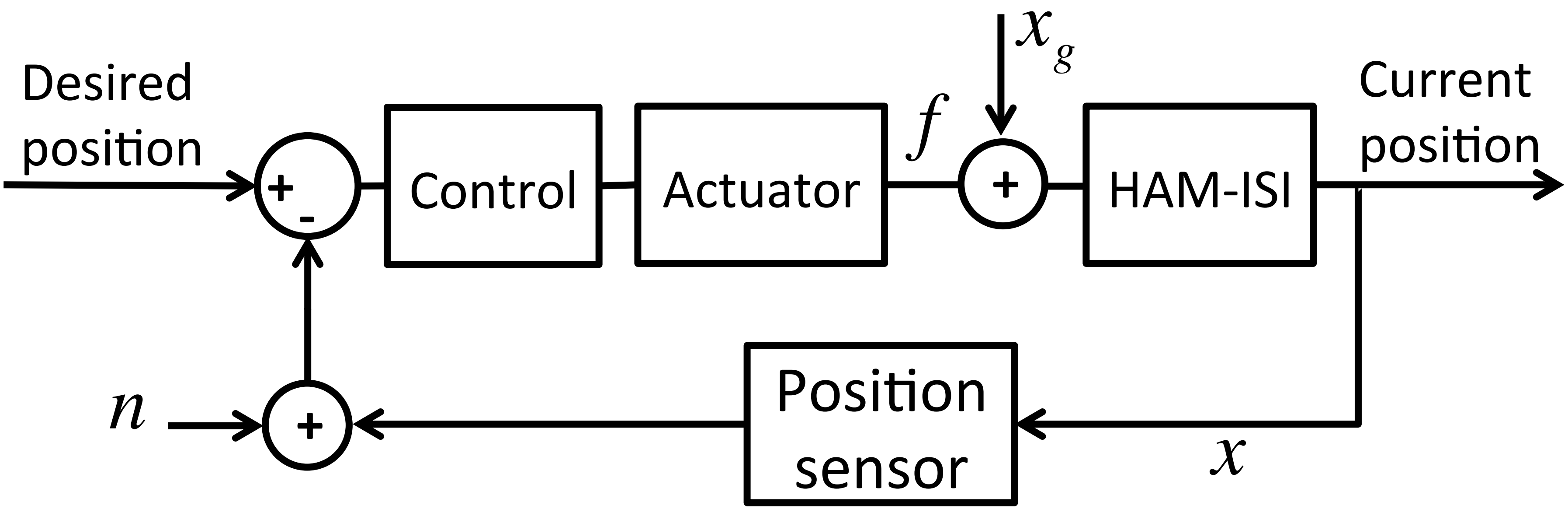


$$Q = \frac{2\pi f_R (t_2 - t_1)}{\ln\left(y_1 / y_2 \right)}$$

Feedback Stability

Feedback loop block diagram



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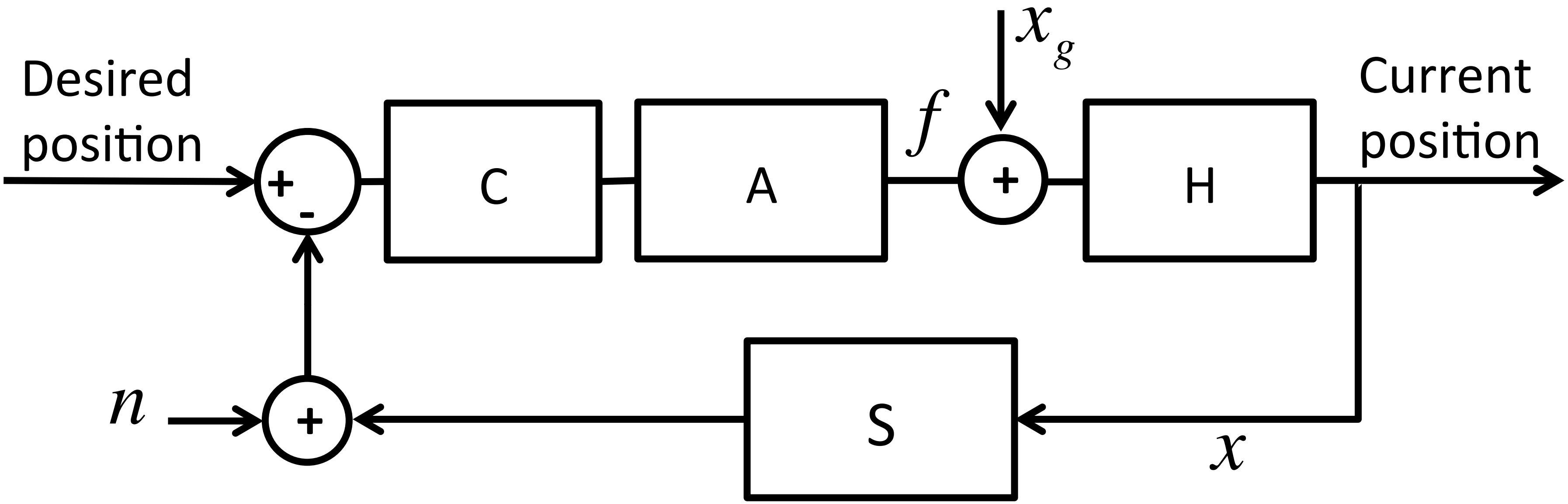

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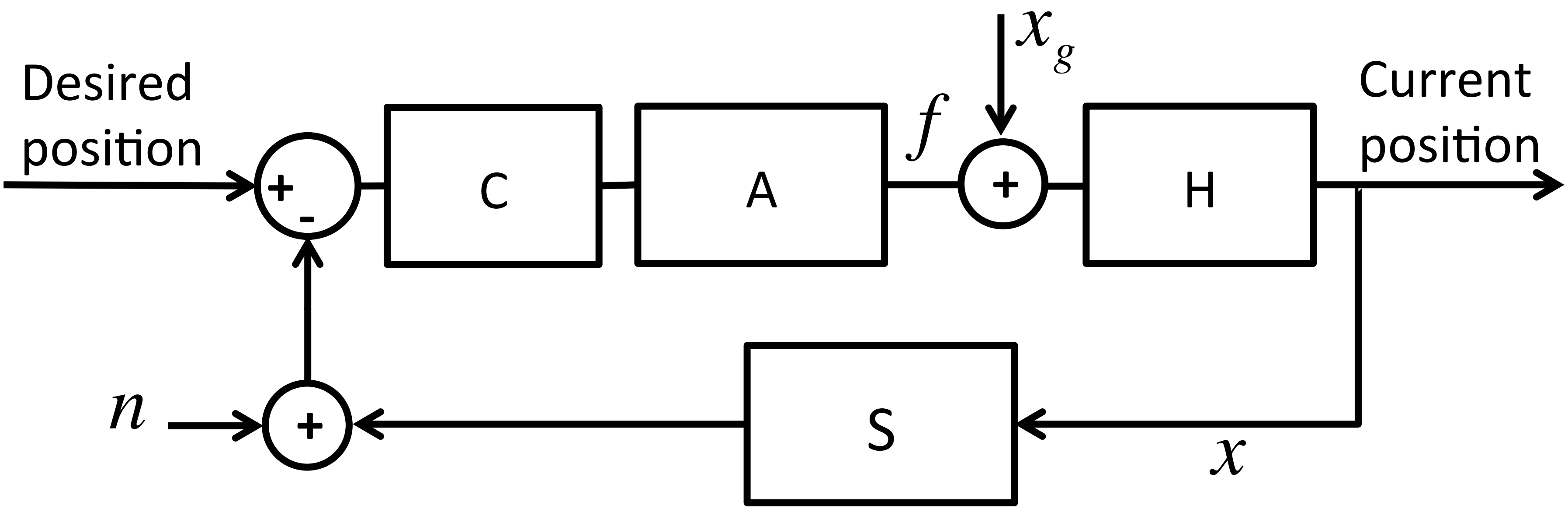
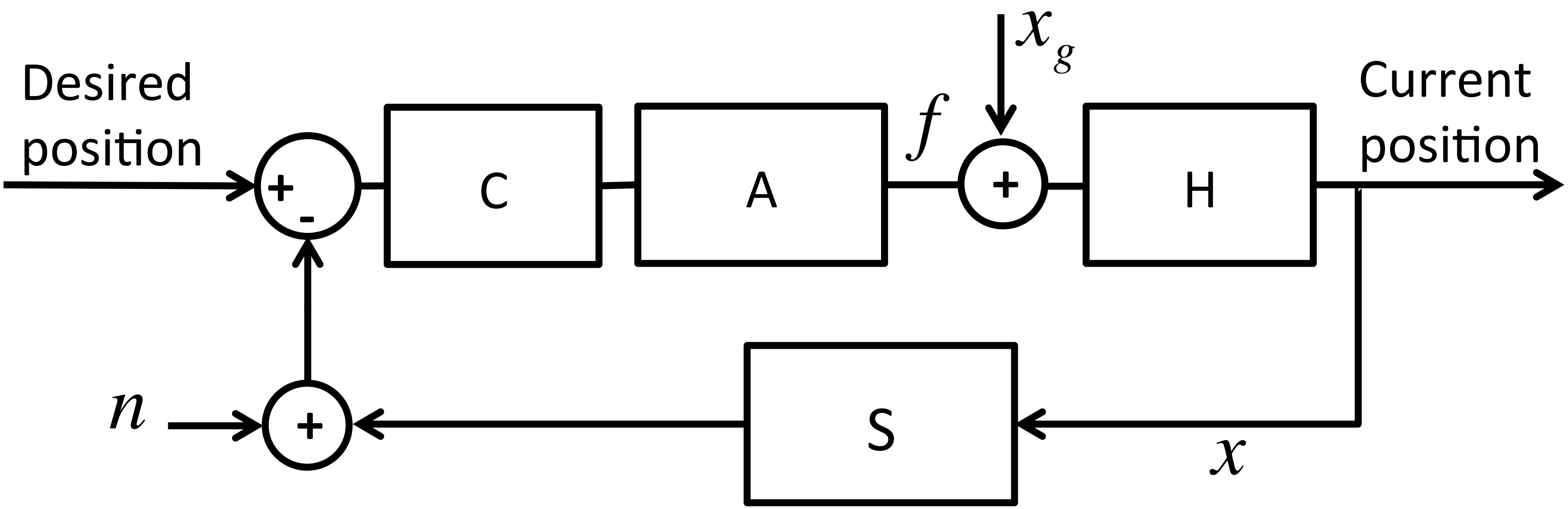


$$x = \frac{H}{1 + CAHS} x_g$$

Seismic noise transmission

Feedback loop block diagram



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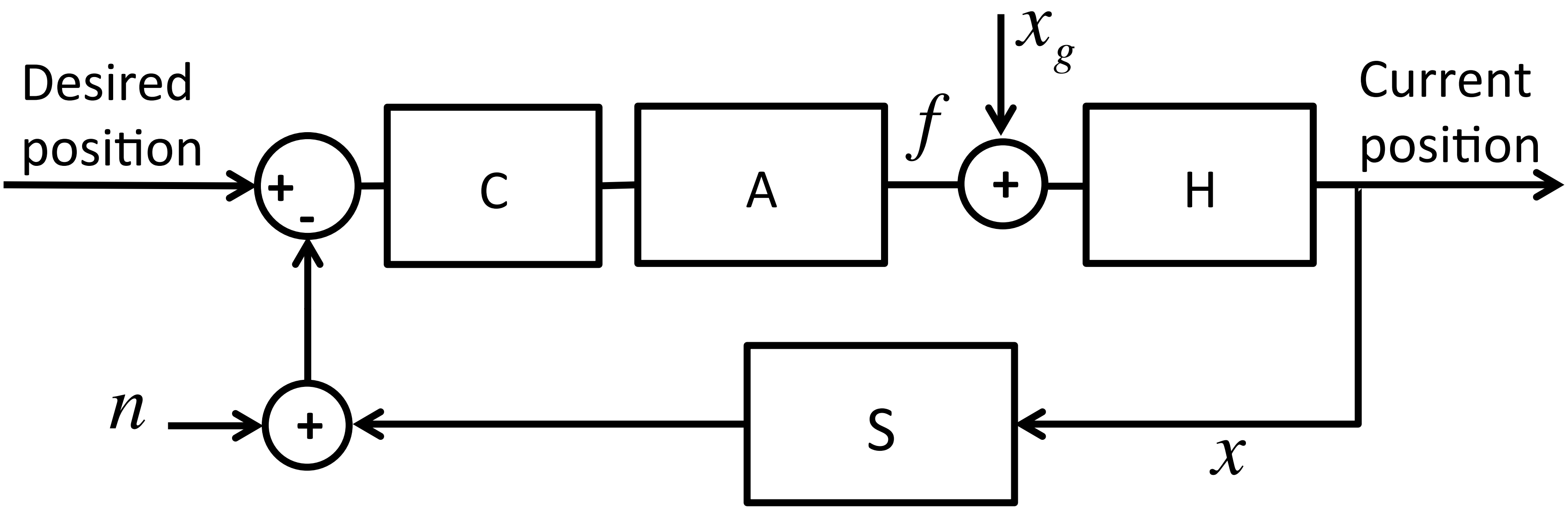
Loop gain transfer function

Seismic noise transmission

Feedback loop block diagram

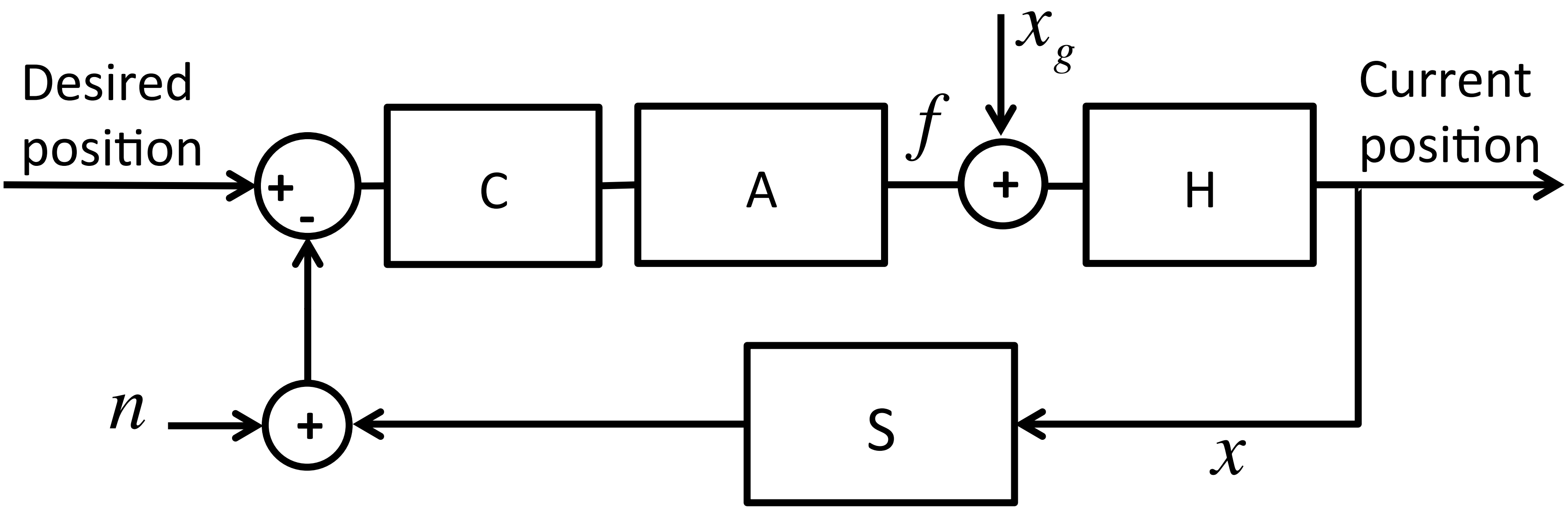


$$x = \frac{H}{1 + CAHS} x_g$$

Loop gain transfer function
CAHS = -1= bad

Seismic noise transmission

Feedback loop block diagram



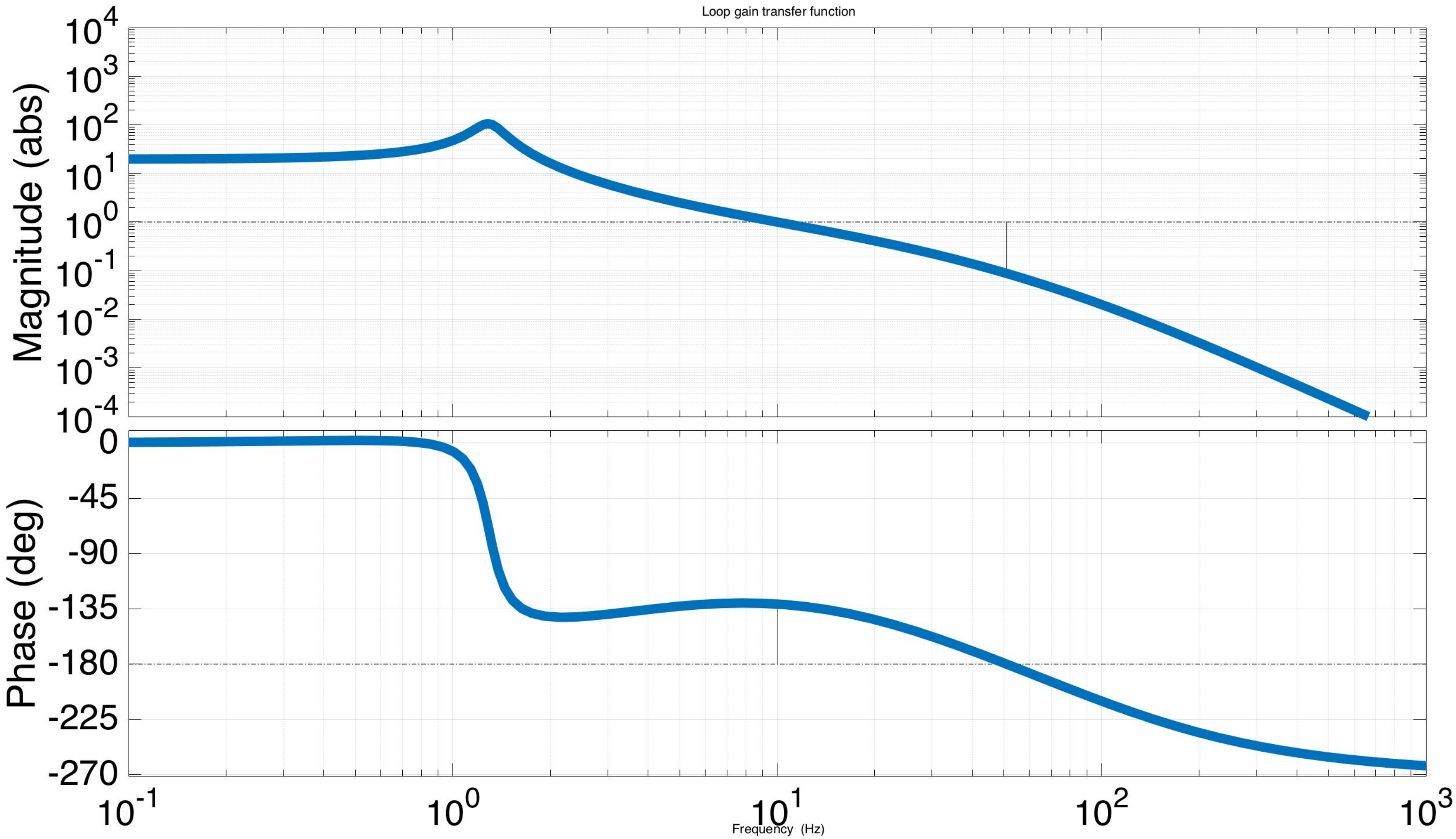
$$x = \frac{H}{1+CAHS} x_g$$

Seismic noise transmission

$$x = \frac{-CAH}{1+CAHS} n$$

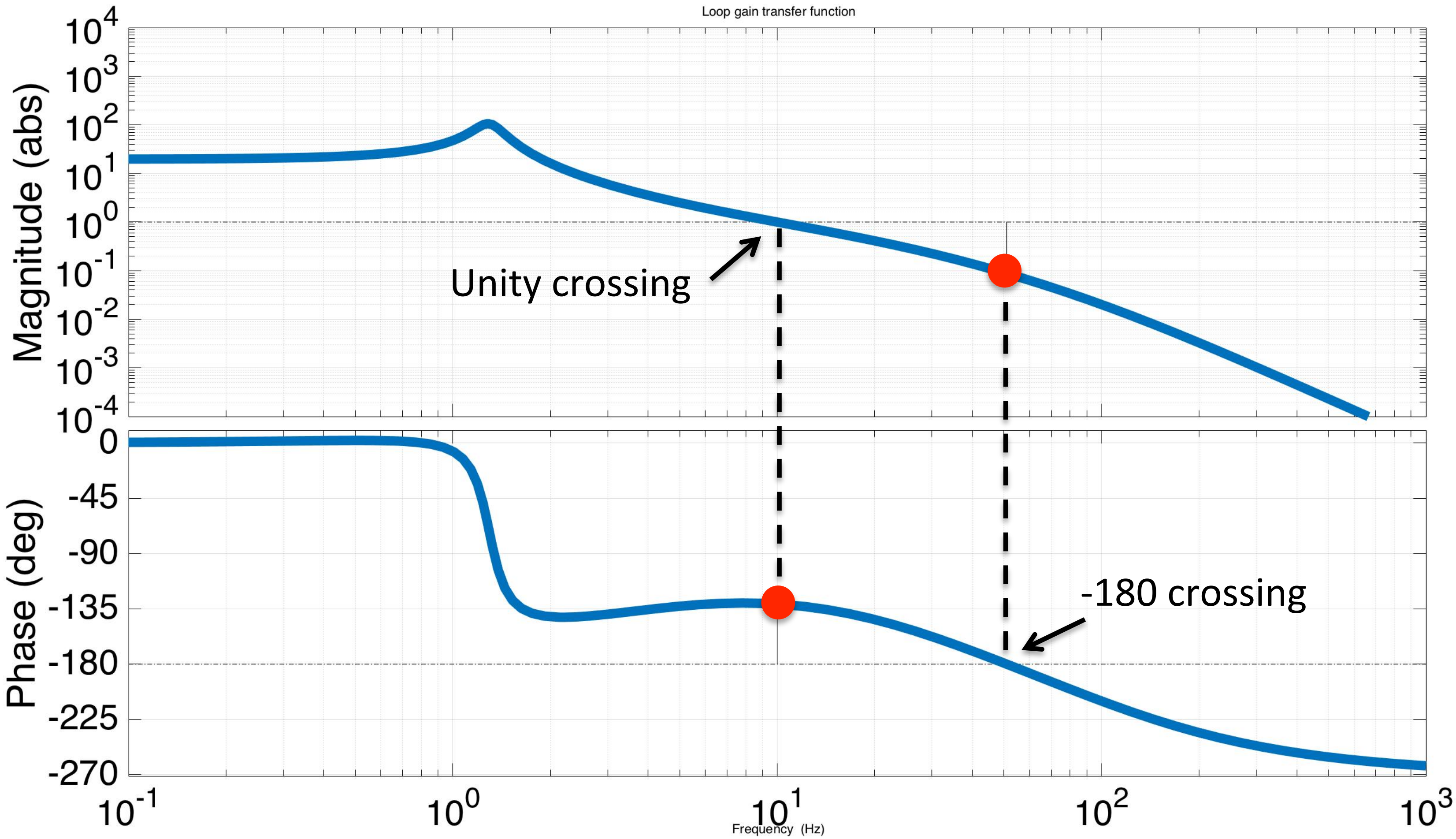
Sensor noise transmission

Ex. Loop Gain TF: *CAHS*



Matlab for control filter: `C = zpk(-2*pi*3.33,-2*pi*[30;100],1.4e+10)`

Ex. Loop Gain TF: *CAHS*



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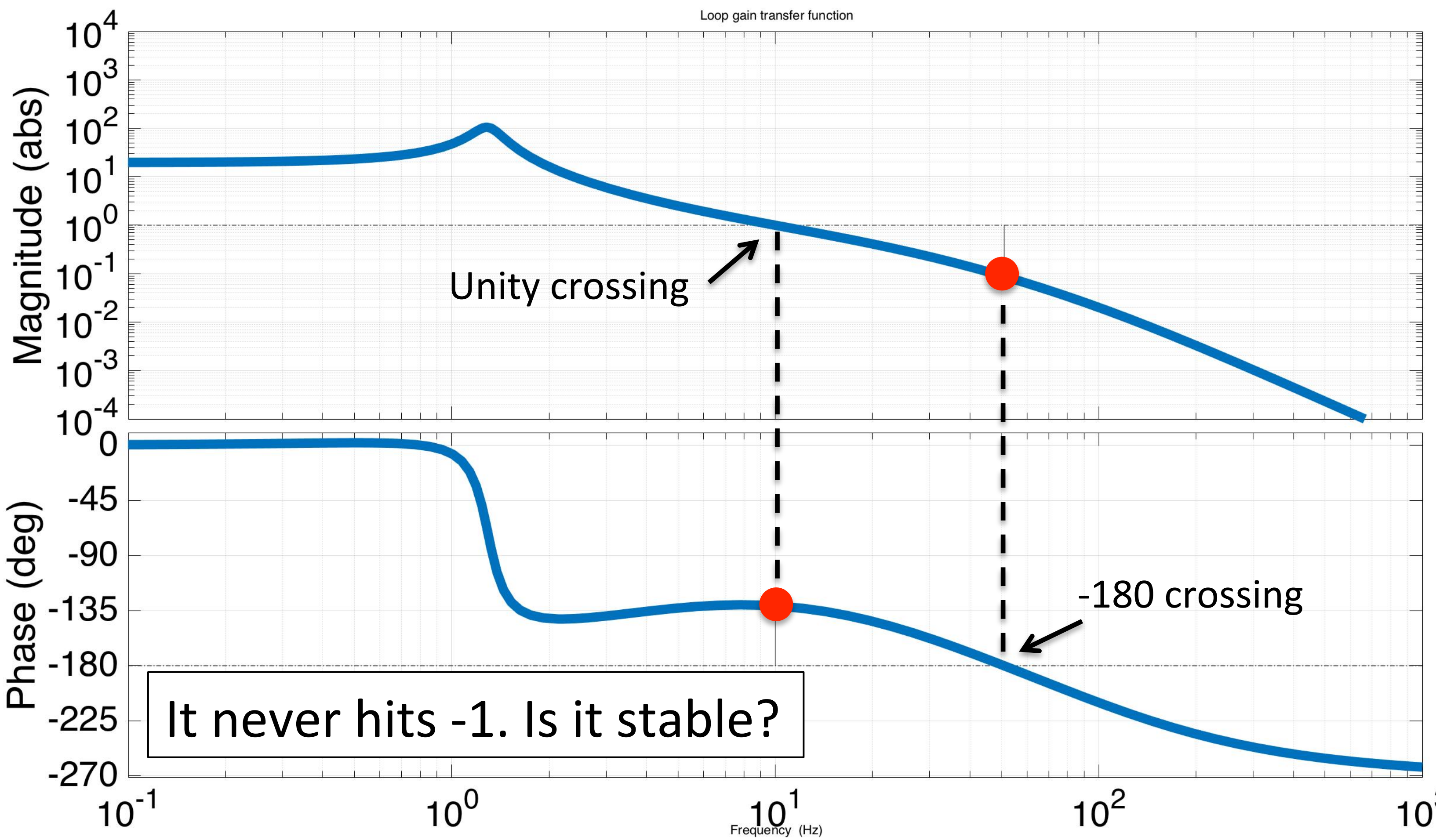

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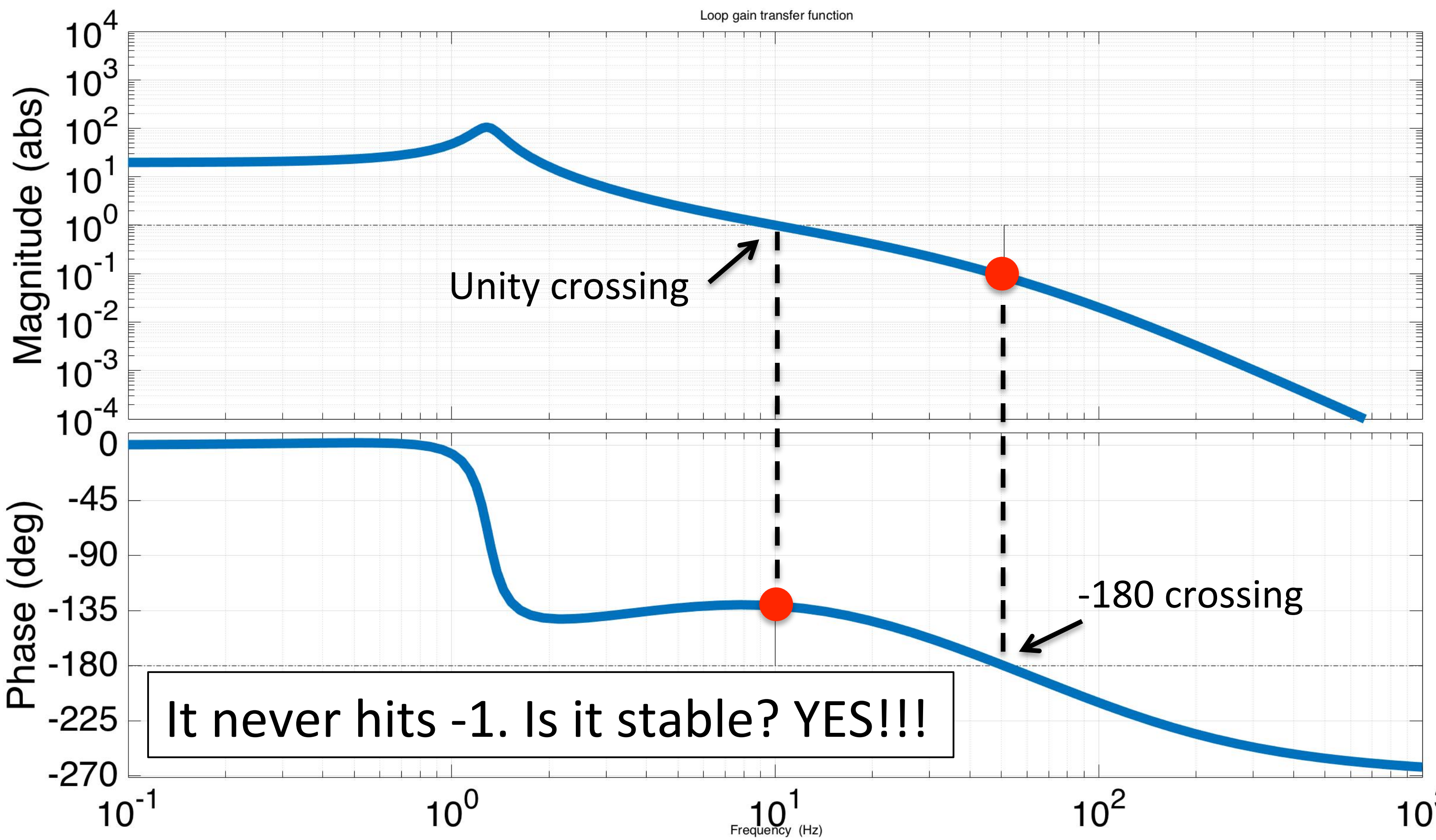

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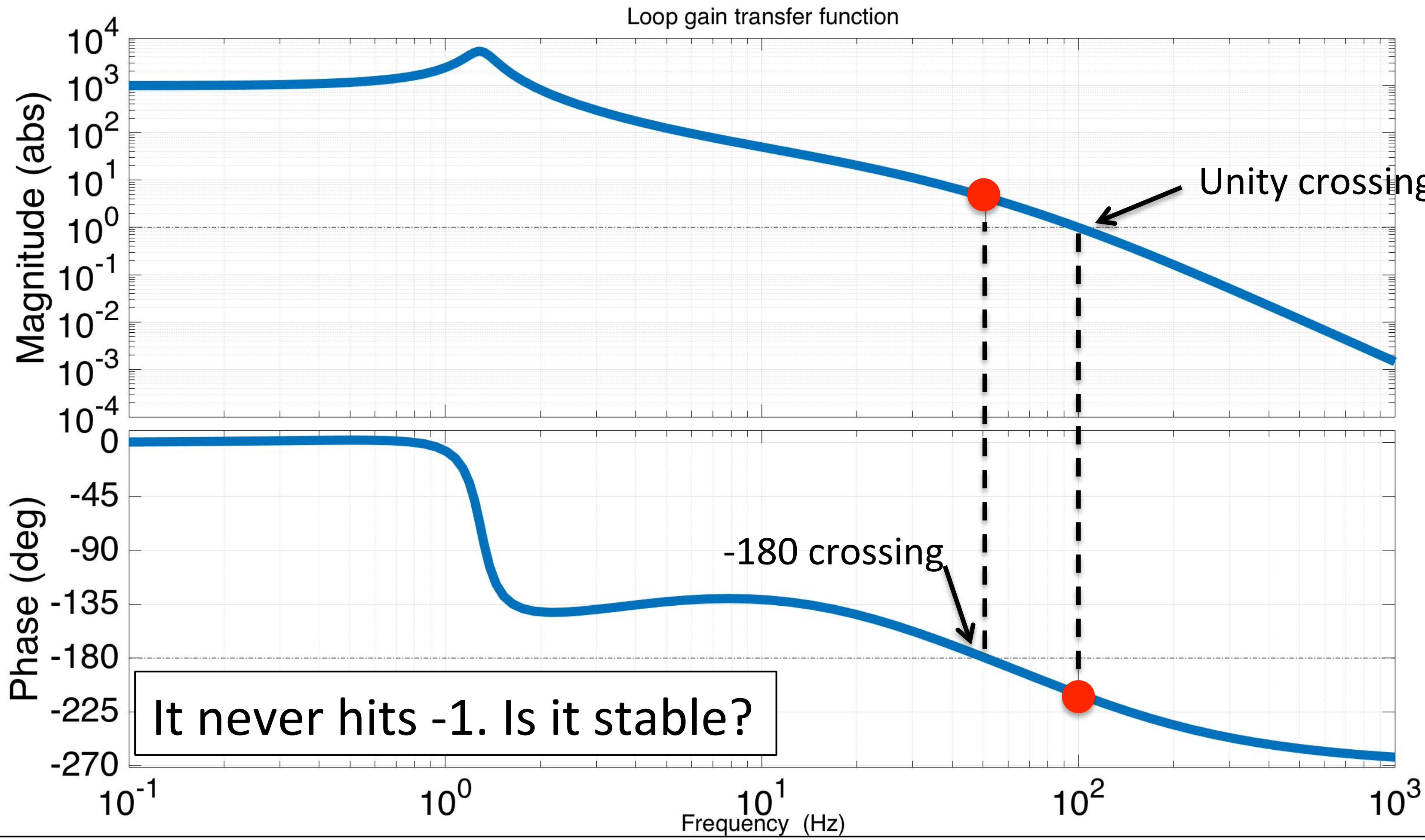
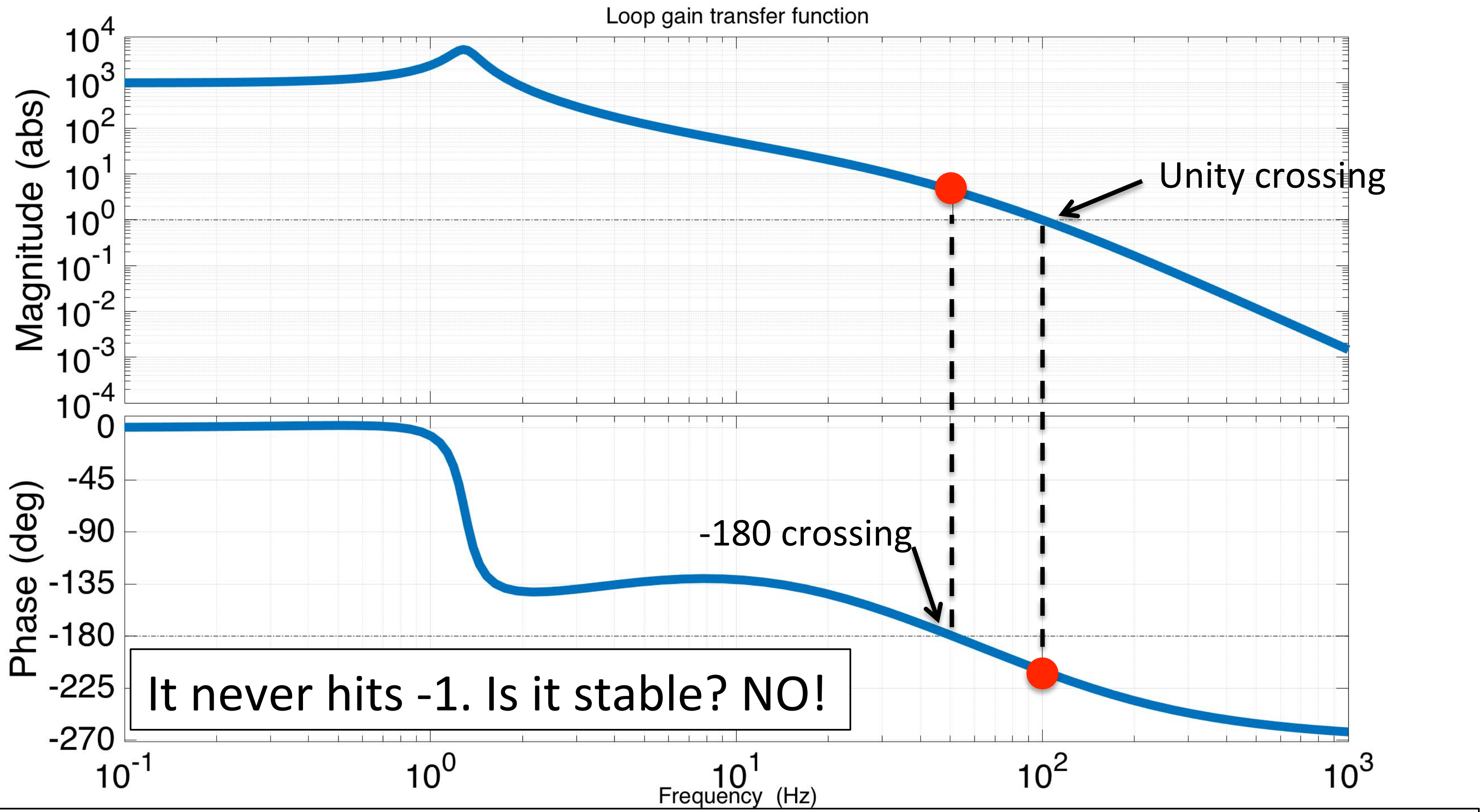
Ex. Loop Gain TF: 50**CAHS*



Matlab for control filter: `C = zpk(-2*pi*3.33,-2*pi*[30;100],7.0e+11)`

Ex. Loop Gain TF: 50*CAHS



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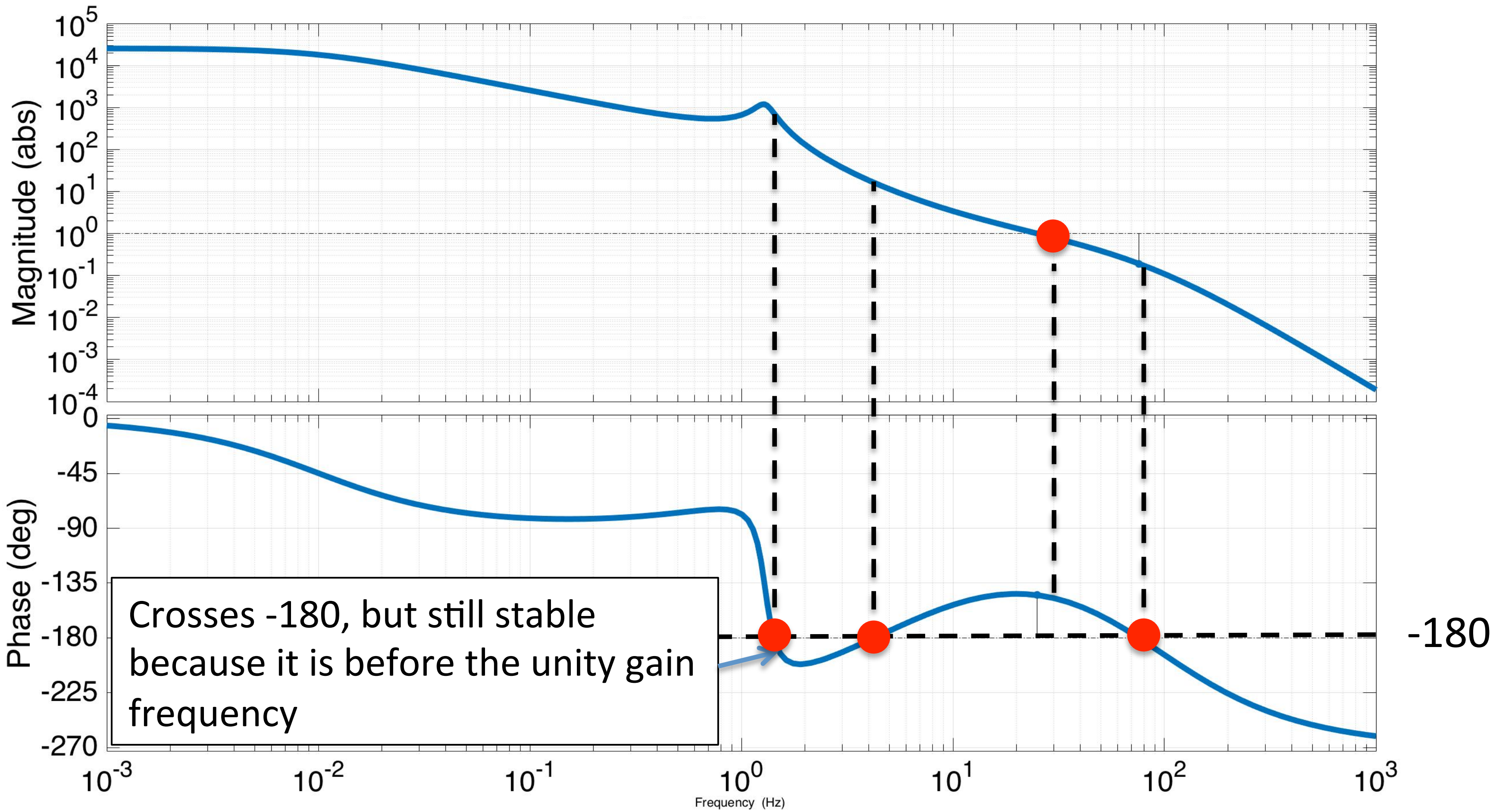
Another Loop Gain Example

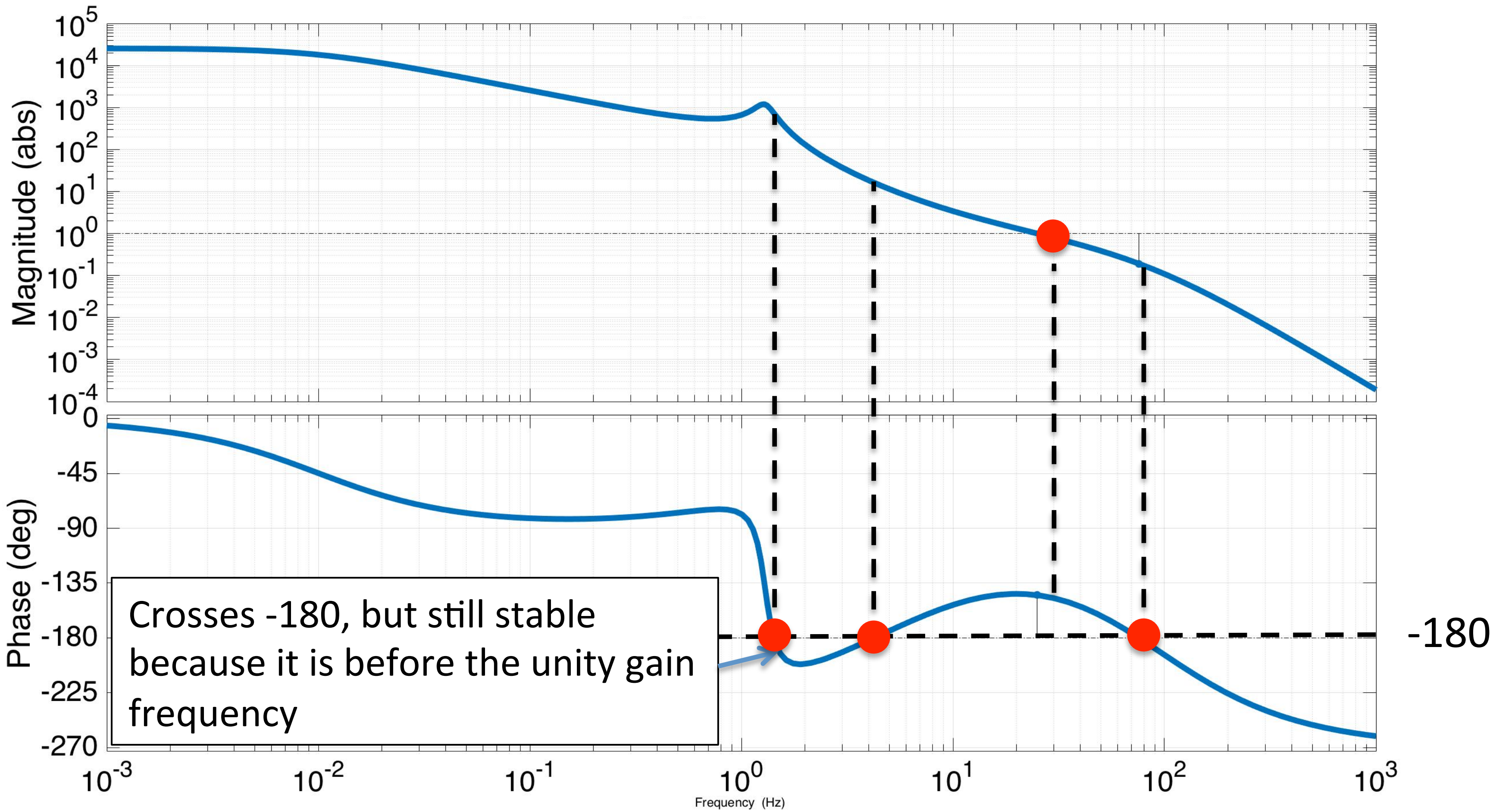
Multiple 180^o crossings. Stable?



Matlab for control filter: `C = zpk(-2*pi*[2,25/3],-2*pi*[0.01,25*3,100],9.1e10)`

Another Loop Gain Example

Multiple 180^o crossings. Stable? Yes!



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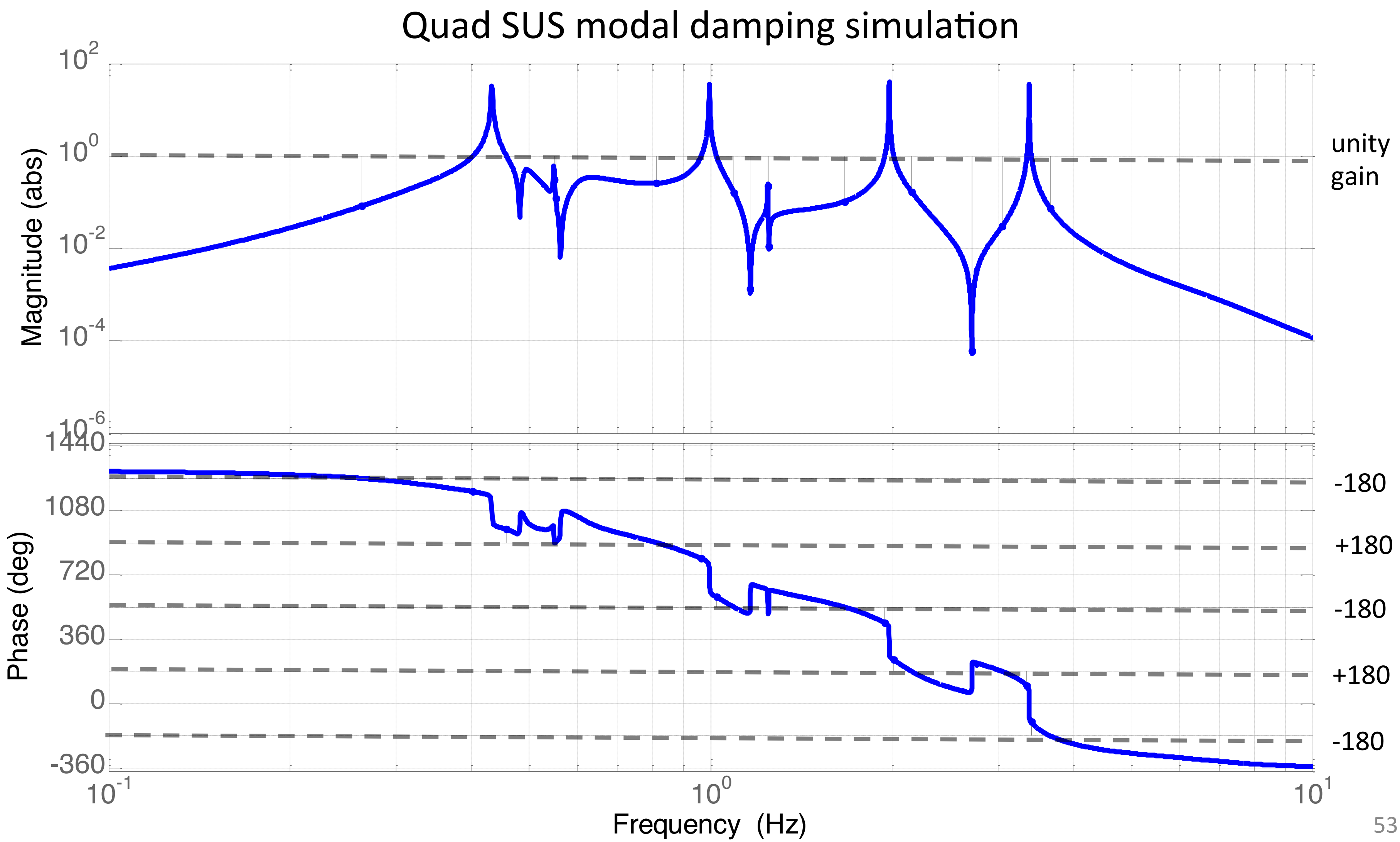
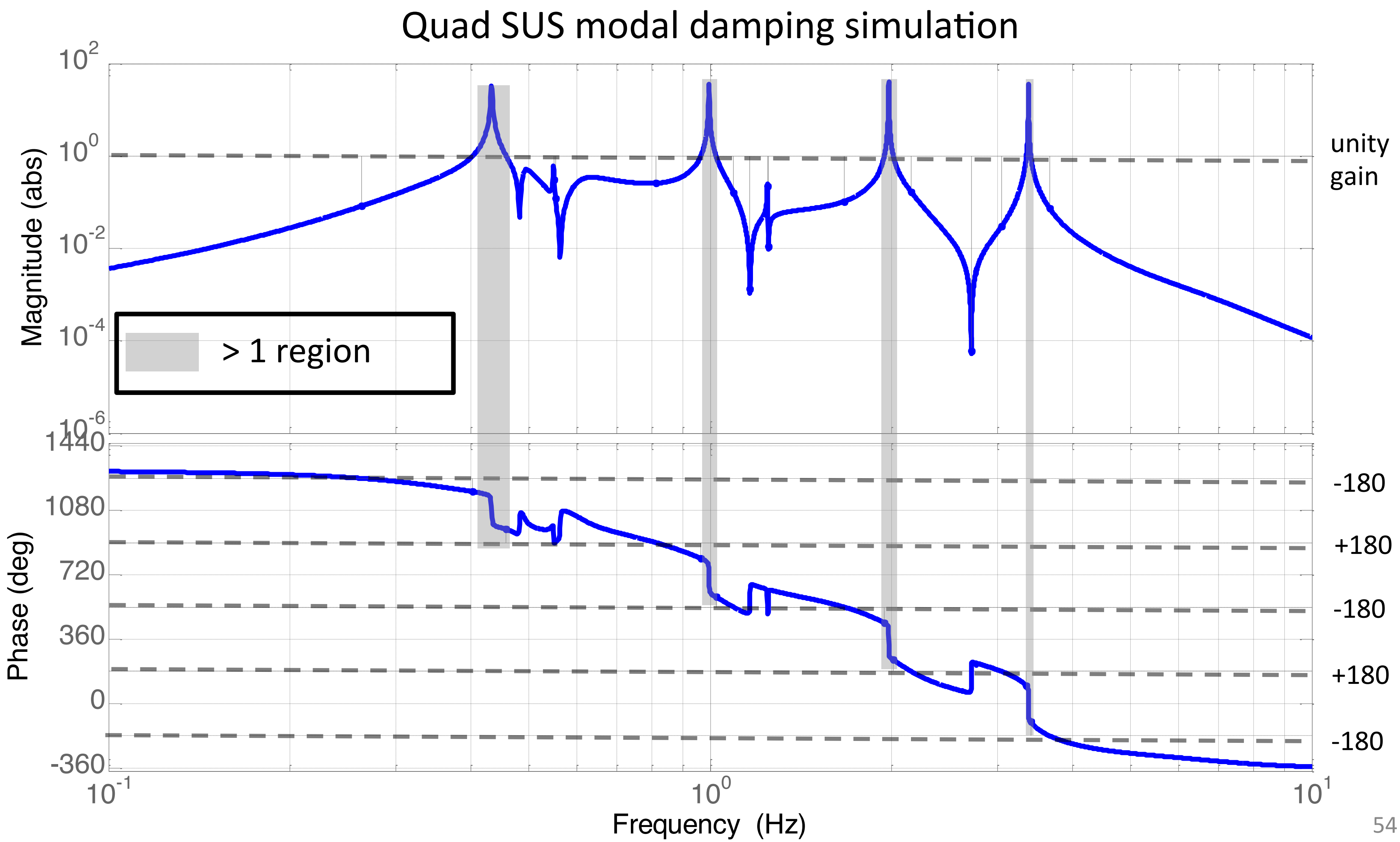
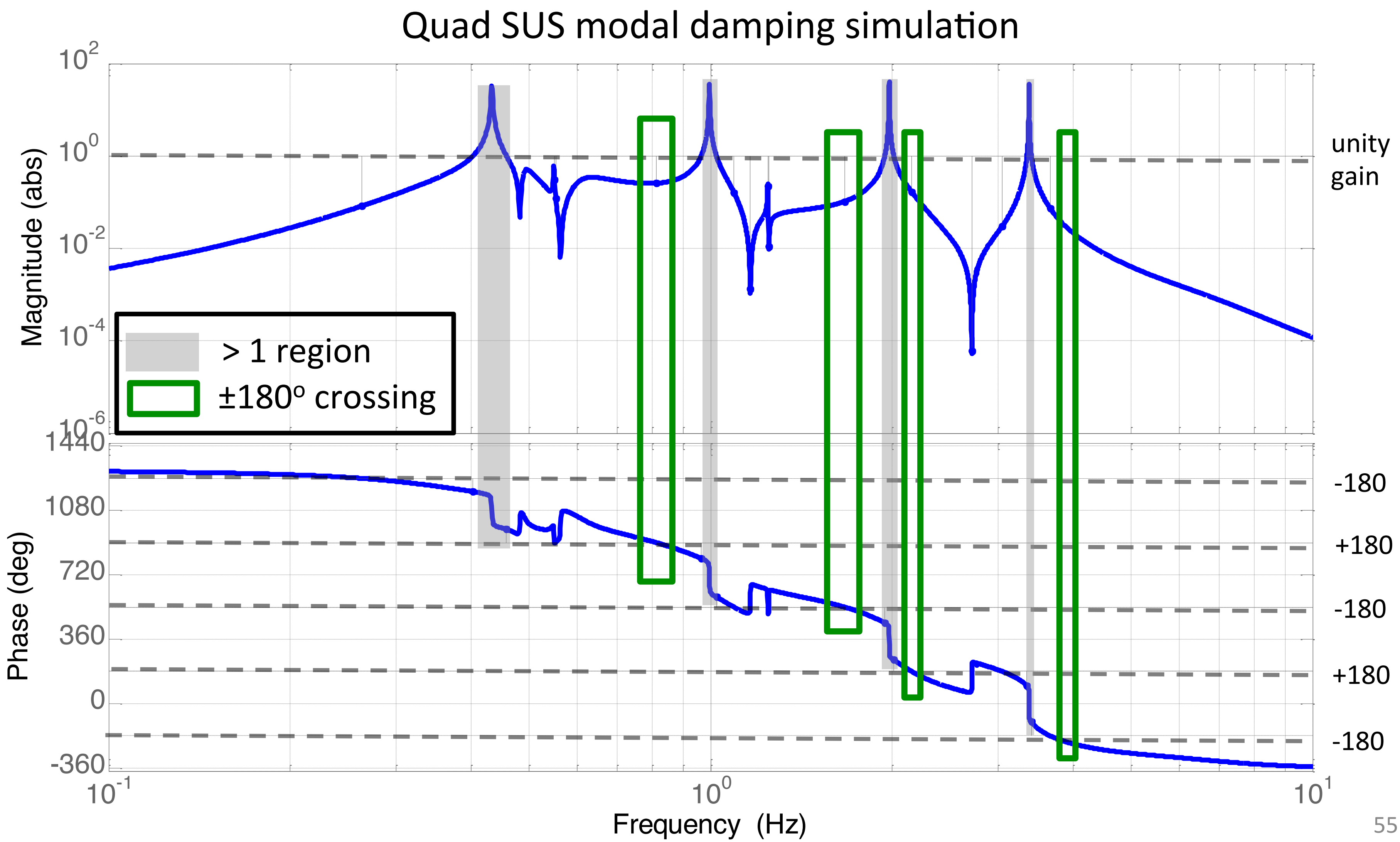
This is Stable!?

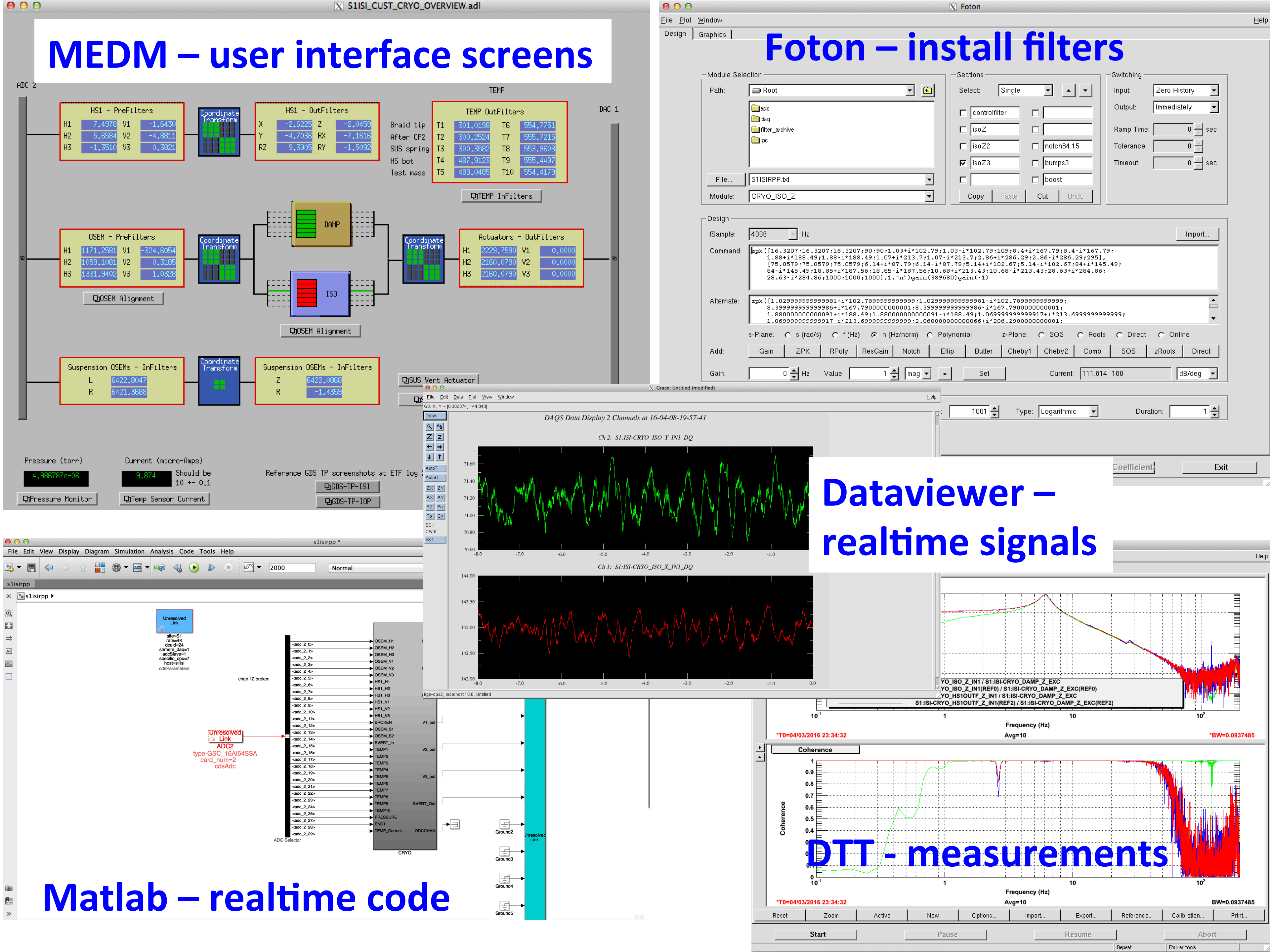


This is Stable!?



This is Stable!?





MEDM – user interface screens
Foton – install filters
Dataviewer – realtime signals
DTT - measurements
Matlab – realtime code
S1ISI_CUST_CRYO_OVERVIEW.adl
Foton
DAQS Data Display 2 Channels at 16-04-08-19-57-41
Coherence

Controls text books

- Digital Control of Dynamic Systems, 3rd Ed. Franklin, Powell, and Workman.
  - Main focus is on the control of digitally sampled systems, but also has a good review of continuous control, system identification, optimal control, and nonlinear systems.
- Modern Control Engineering, 5th Ed. Ogata
  - Standard introductory text to control

Control System Working Group (CSWG)

See G1601671

Control System Working Group (CSWG)

- Formally organized at the March 2016 LVC
- Group charter at M1600033
- Chair: Dennis Coyne.
- Deputy co-chairs: Brett Shapiro, Robert Ward.

CSWG Role

The CSWG is unique among working groups

- Feedback control is used by many of the other instrument science working groups.
- It's relevance is demonstrated through application to the other working groups.

CSWG Role

- Support of other groups
  - training references: G1600726, G1601640, G1601417, G1600525, G1400557, G1400102
  - support of particular problem areas
  - review the applicability of new controls techniques
- Research into advanced techniques
  - Machine learning
  - Feedback optimization (automated design)
  - etc

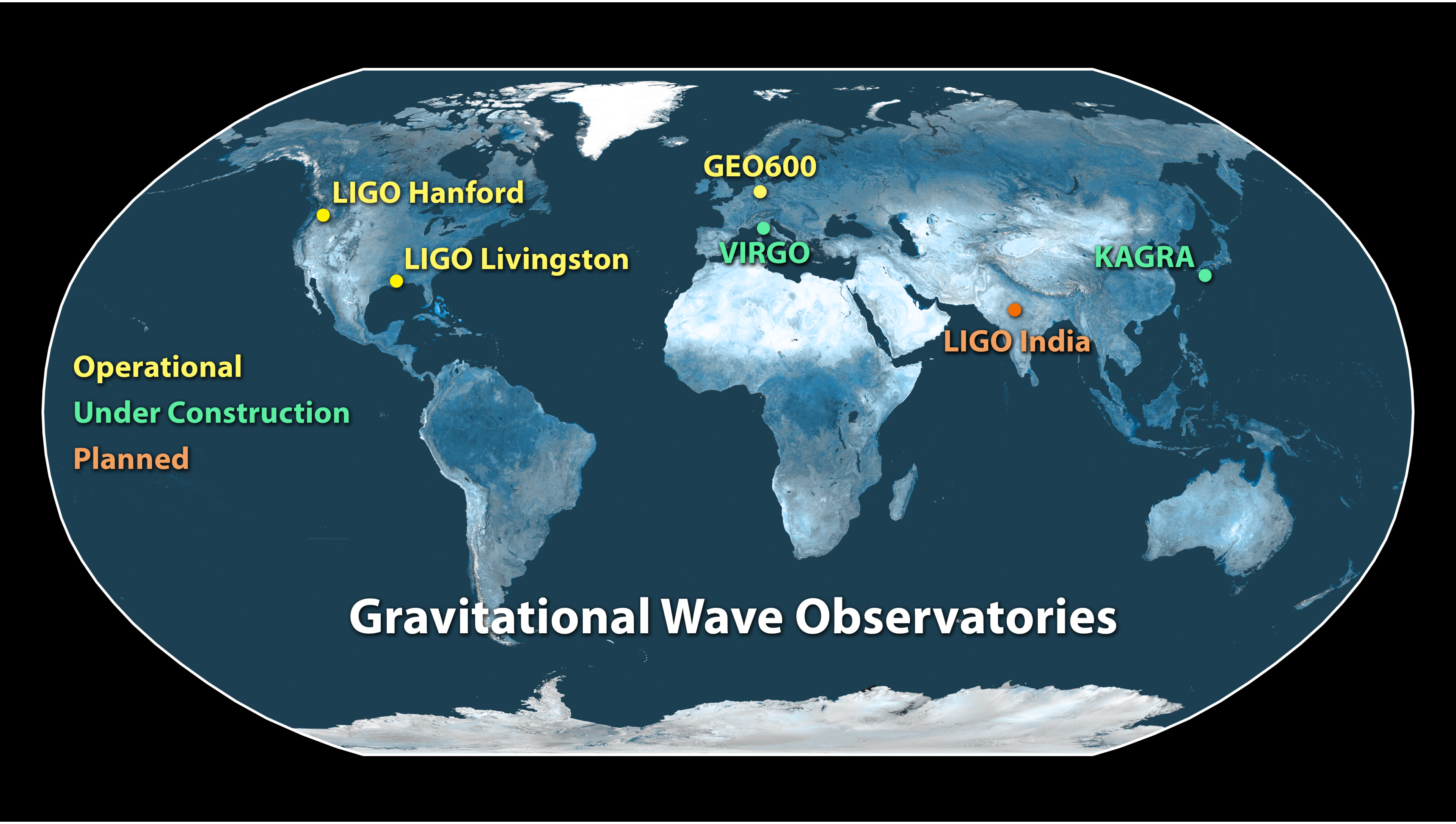
5 current focus areas identified

- 5 problem/focus areas identified to support CSWG's role
- Get involved in these focus areas!
  1) IFO lock maintenance with machine learning
  2) Test mass length-to-angle decoupling
  3) Feedback optimization
  4) Transfer function fitting algorithms
  5) IFO earthquake robustness

Additional Focus Areas?

- The CSWG is not restricted to these 5 areas
- Please suggest any other areas the CSWG should prioritize

A Global Working Group



Reference LIGO-G1600275

Meetings

Bi-monthly Teamspeak meetings

- US-western hemisphere: 1st Fri of the month, 9am US-PT (6pm CET, 9:30pm IST)

- US-eastern hemisphere: 3rd US Thu of the month, 4pm US-PT (Fri 9am AET, 8am JST, 4:30am IST)

CSWG Wiki

Jump | Search

CSWG

Hello Brett Shapiro?

– Create personal sidebar

Toolbox

- Create New Topic
- Index
- Search
- Changes
- Notifications
- RSS Feed
- Statistics
- Preferences

Webs

- AIC
- ALIGOSystemsAcceptance
- AuthProject
- Bursts
  - BayesWave
  - EMFollow
  - GRBExternal
  - GWNU
  - LIB
- CSWG
  - L2A_Decoupling
- CW
- Calibration
- ComputerSecurity
- DAC
- DASWG
- DetChar
  - ALIGOpapers
  - BilinearCouplingVeto

You are here: LIGOWiki > CSWG Web > WebHome (19 Aug 2016, BrettShapiro)

Edit | Attach

Welcome to the CSWG web

- ↓ Overview
- ↓ How to Join
- ↓ Meetings and Notebook
- ↓ White Paper
- ↓ Focus Areas
- ↓ List of Models and Measurements
- ↓ CSWG Web Utilities

Overview

The Control System Work Group (CSWG) covers fundamental and applied research in control systems as it relates to GW interferometers, including:

- system identification
- modeling
- synthesis,
- analysis,
- optimization
- performance assessment,
- hardware and software implementation

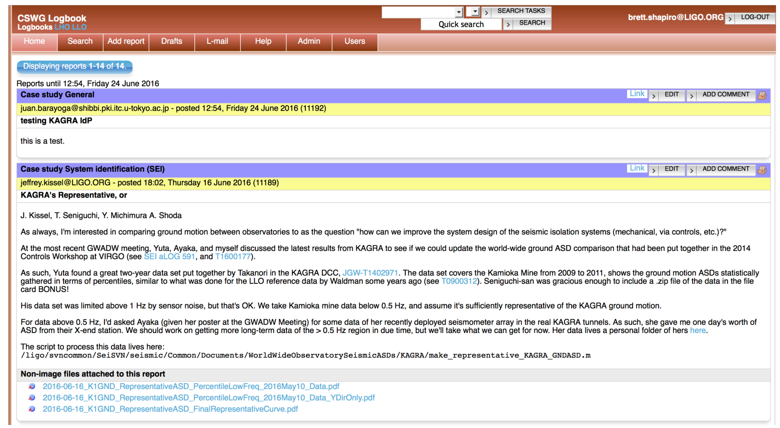
The role of the CSWG is unique within the LSC's instrument science working groups. The use of control systems is pervasive within, and enabling to, the work of many of the other instrument science working groups. In addition to supporting its own fundamental research in cutting-edge control system techniques, the CSWG should support and enable the research of other LSC WGs. The relevance and import of the CSWG's work is demonstrated through application to the other instrument science subsystems. Consequently there is an abiding need for significant collaboration between the CSWG and the other instrument science WGs. To foster this tight connection, the CSWG will also develop and maintain control system documentation relevant to the GW community:

- training references - see intro to controls tutorial at G1600726
- canonical examples

https://wiki.ligo.org/viewauth/CSWG/WebHome

CSWG tools

- alog



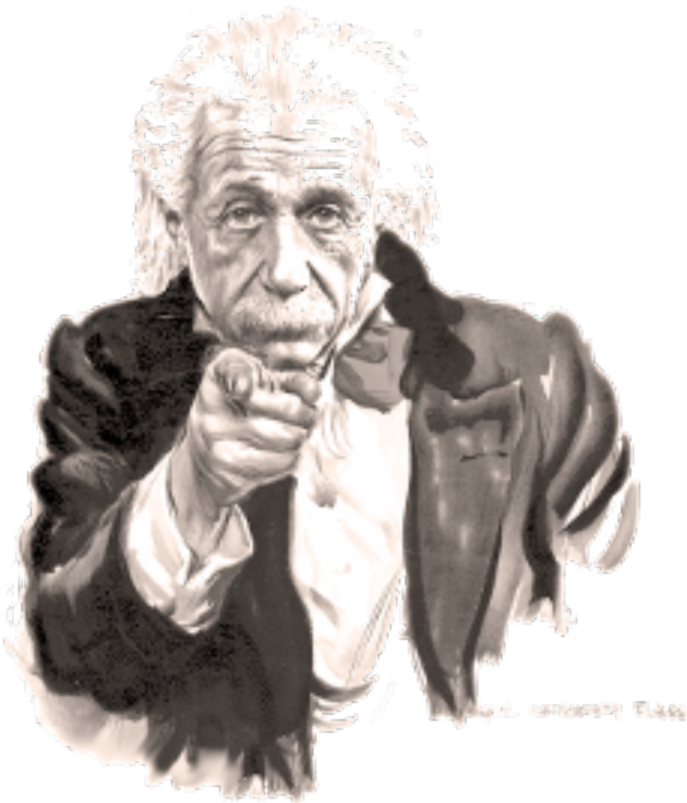
https://alog.ligo-la.caltech.edu/CSWG/

- Mailing list: cswg@sympa.ligo.org

  Sign up at https://grouper.ligo.org/mailinglists/cswg

- Teamspeak channel: CSWG

We Need You!



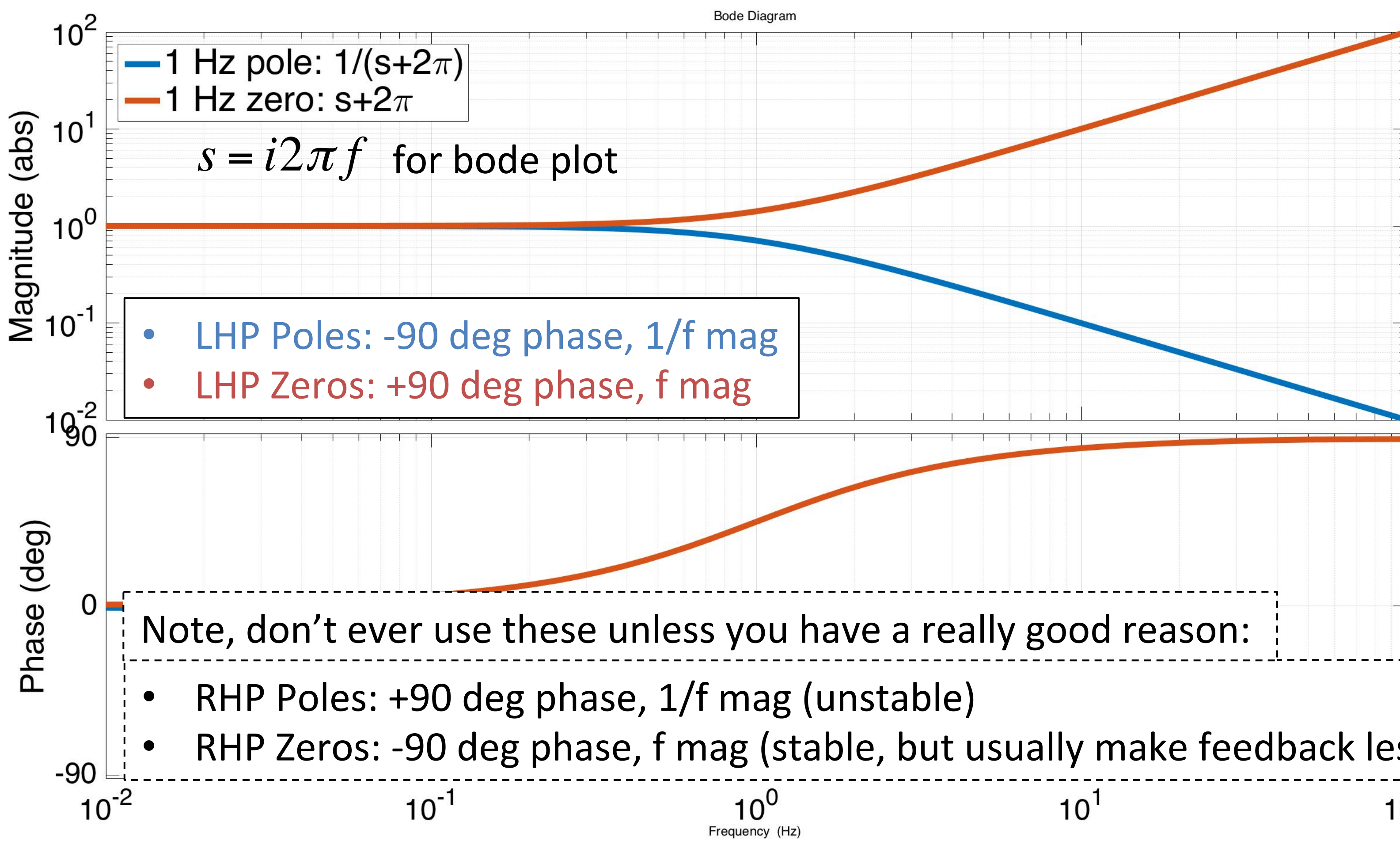
Credit: http://einsteinpostdocs.info/

- Many areas where work is needed
- Get involved!
- Students encouraged to take a controls course
- GW interferometers don't work without controls!

Extra Slides

Control design: poles and zeros

Recall: $s = i2\pi f$ to generate the bode plot



$s = i2\pi f$ for bode plot

- LHP Poles: -90 deg phase, 1/f mag
- LHP Zeros: +90 deg phase, f mag

Note, don't ever use these unless you have a really good reason:

- RHP Poles: +90 deg phase, 1/f mag (unstable)
- RHP Zeros: -90 deg phase, f mag (stable, but usually make feedback less stable)

5 current focus areas identified

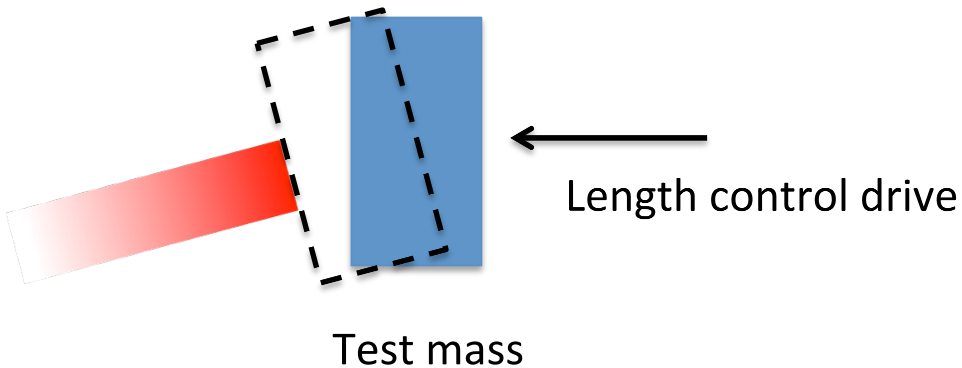
1) Machine Learning for lock maintenance
   - Leader - Rob Ward
   - Use an algorithm to 'learn' the best way to maintain lock
   - See example of acquiring a Bose-Einstein condensate

P. B. Wigley, et al. Fast machine-learning online optimization of ultra-cold-atom experiments. *Scientific Reports*, 2016; 6: 25890

5 current focus areas identified

2) Length to angle decoupling

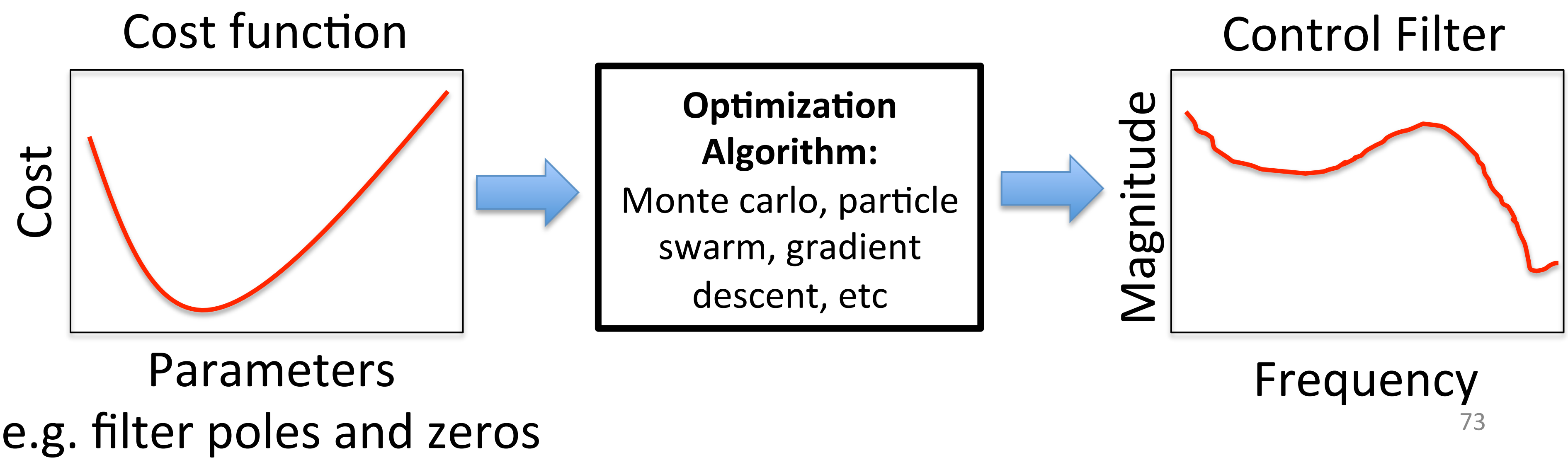
- Leader – TBD
- Separate the problems of controlling cavity length and alignment. Alignment control is currently suboptimal and contributing noise to the IFO.



5 current focus areas identified

3) FB optimization (esp. applied to angular controls)

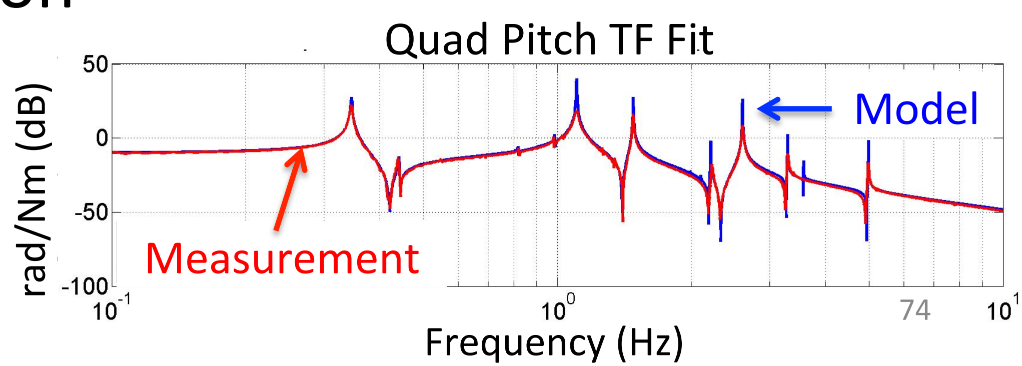
- Leader – TBD
- Collaboration with UC Berkeley and Google



5 current focus areas identified

4) Transfer function fitting algorithms

- Leader – TBD
- Motivation: G1601173 - Hopes and Dreams: One TF Fitting Program to Rule Them All
- Various tools exist: vectfit, n4sid, etc. How to best apply them? Do we need something new?
- Part of a more general topic of experiment design and system identification

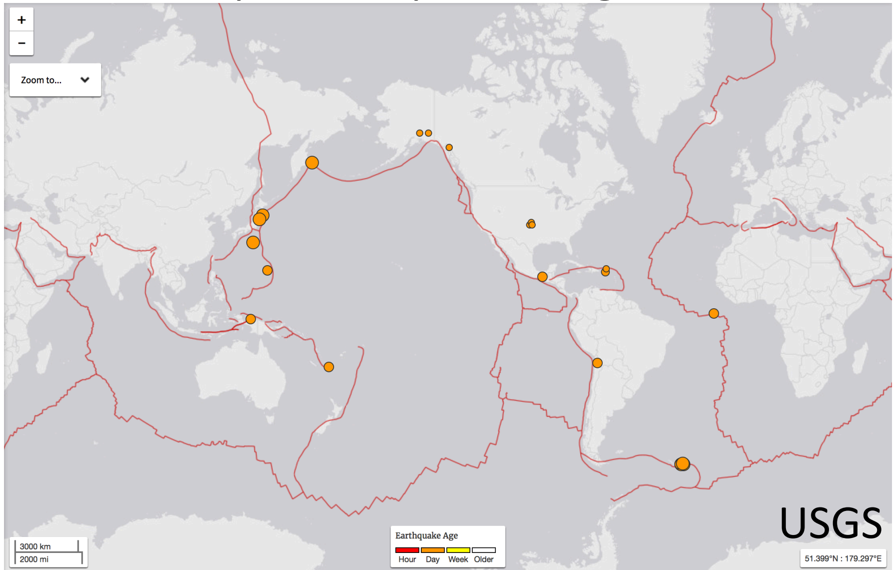


5 current focus areas identified

5) IFO robust configuration for earthquakes

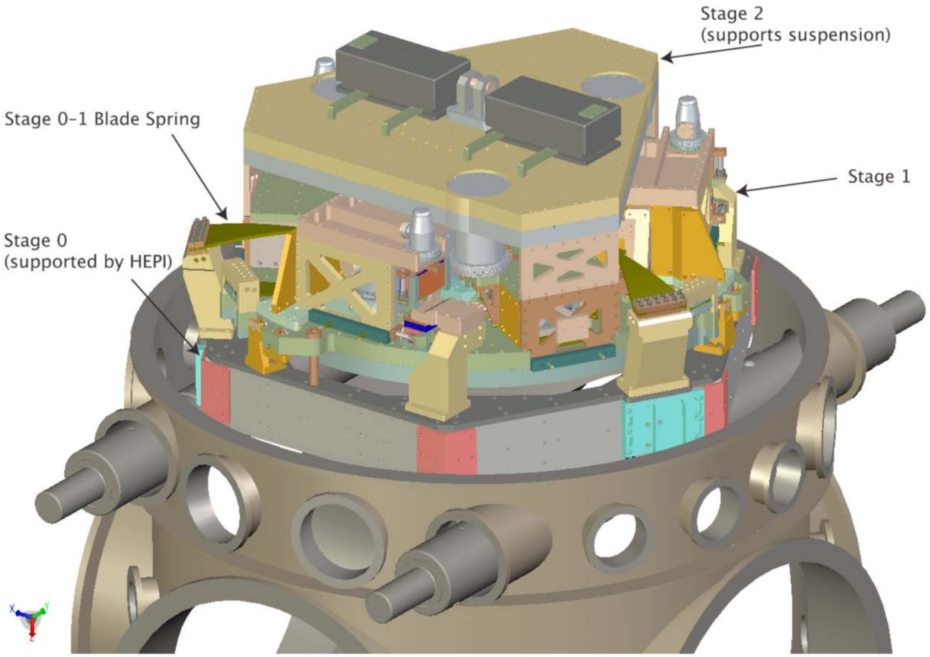
- Leader – Sebastien Biscans
- We already receive early warnings. How best to configure the IFO to not loose lock?

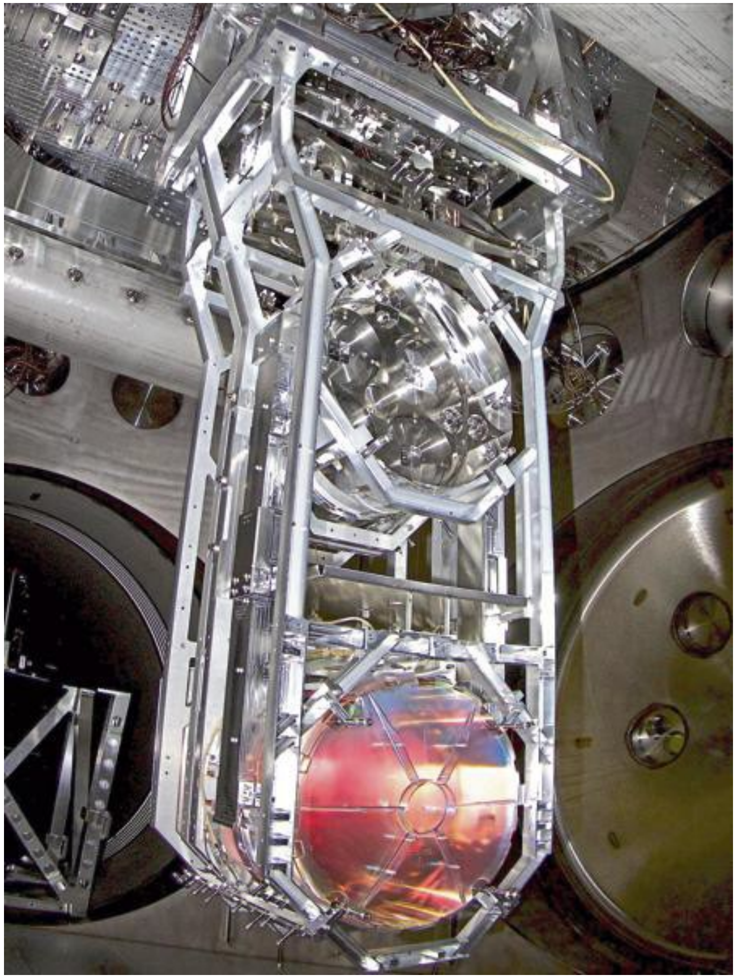
Earthquake map – 22 August 2016



Control Loops Everywhere

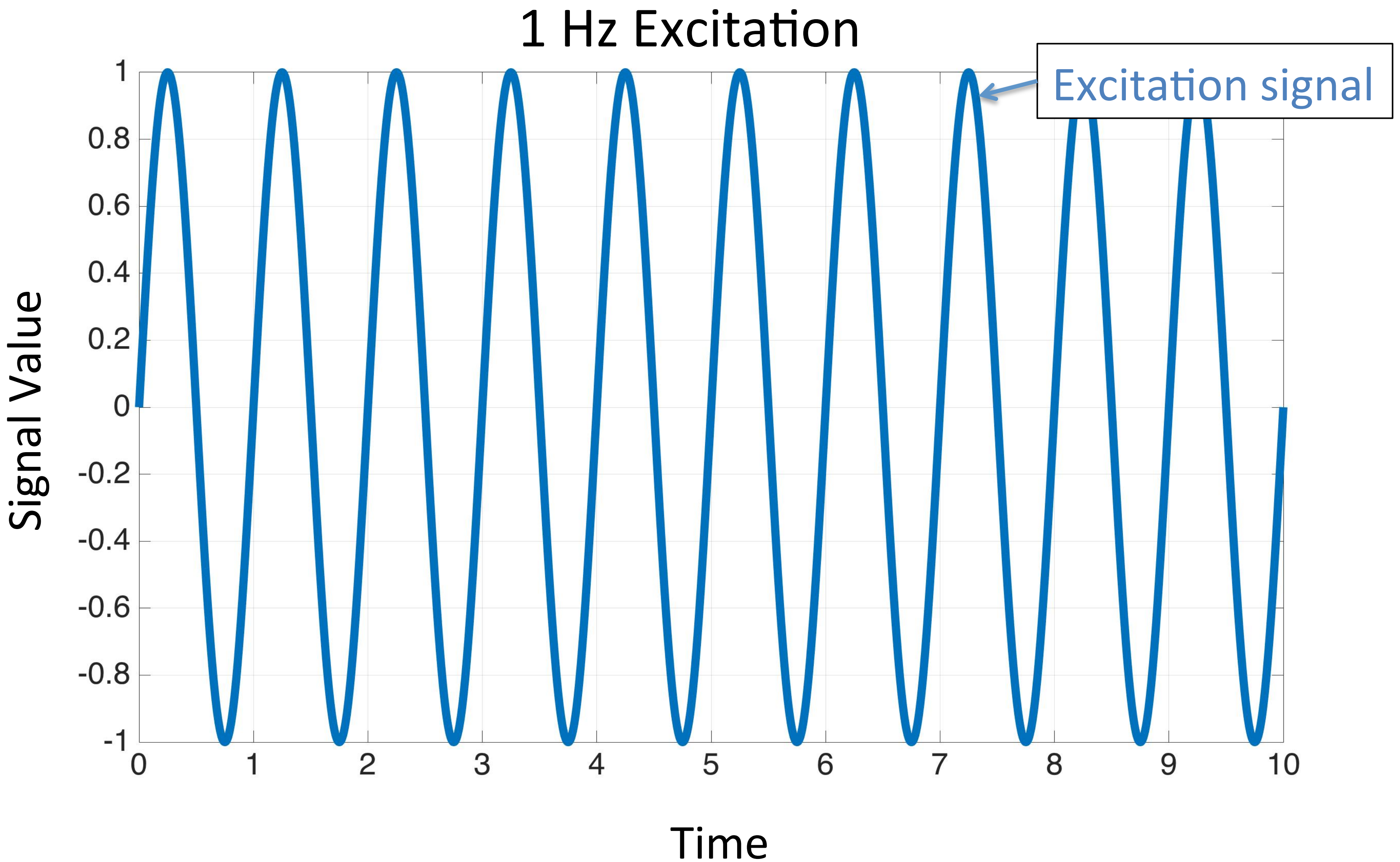
- Cavity lengths
- Angular motion of all mirrors
- Motion of the input beam
- Laser power and frequency
- Multi-degree of freedom control of the seismic isolation systems (ISIs) and suspensions





Adapted from G160525

What TFs mean?



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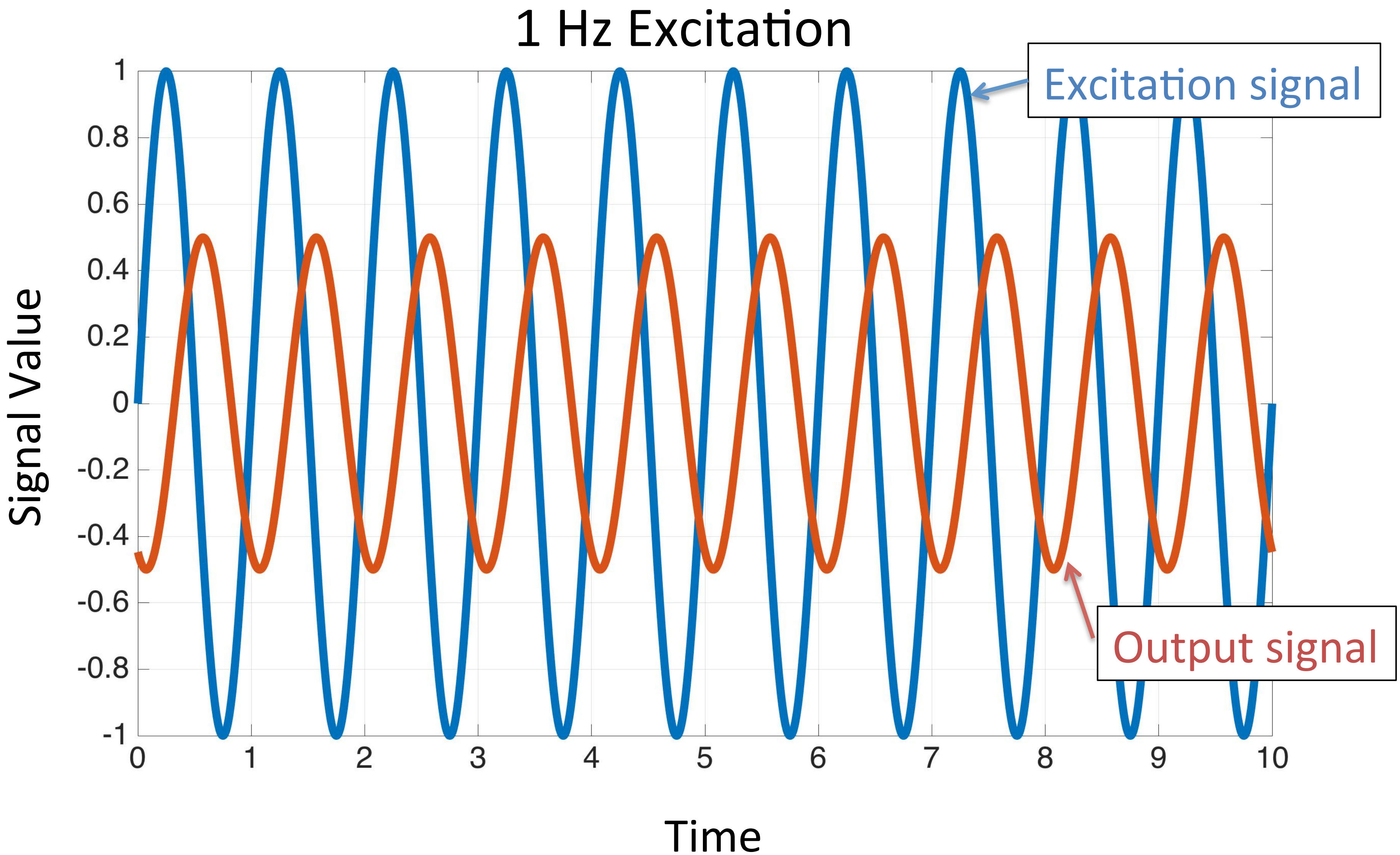

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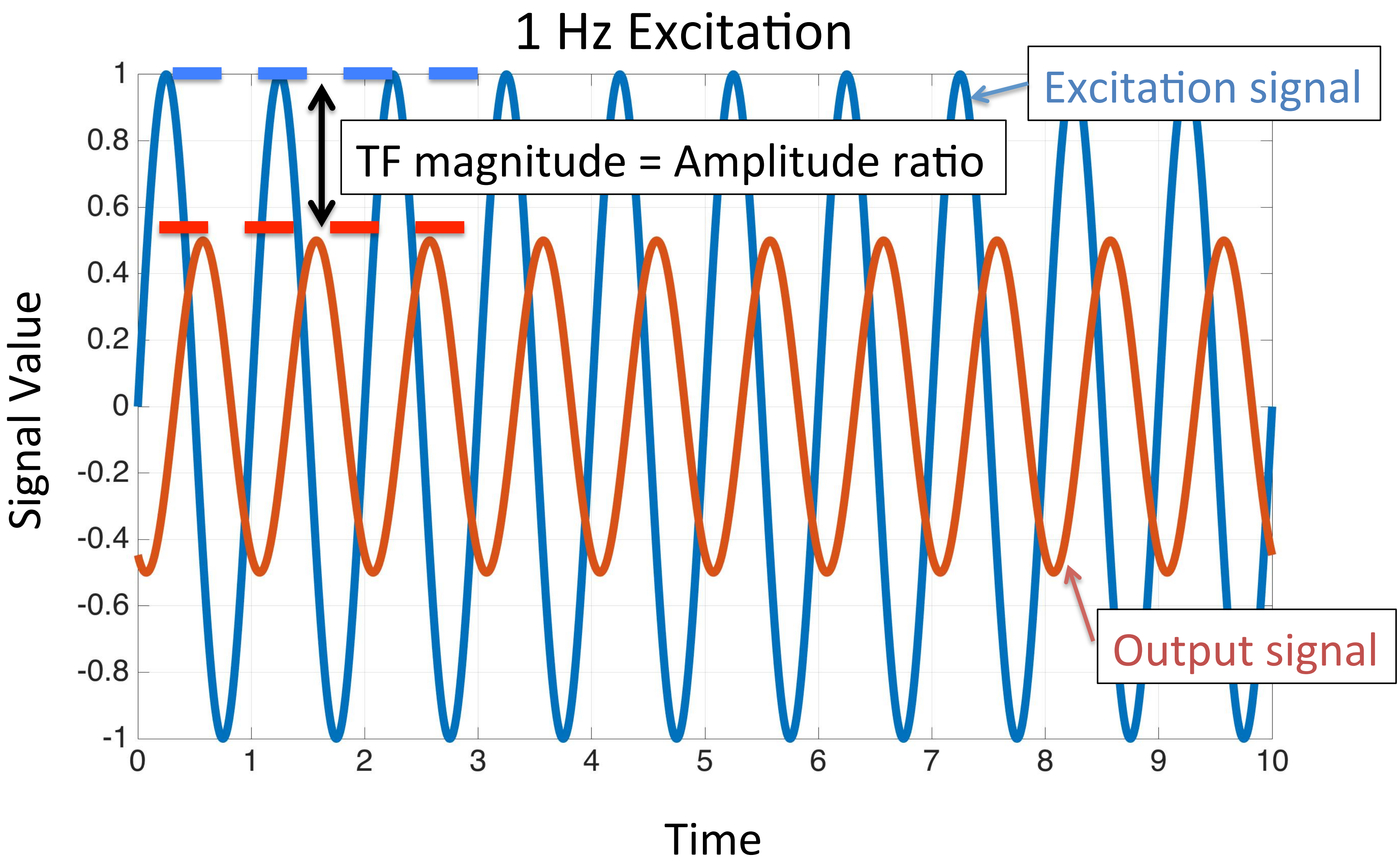

What TFs mean?