Section 14:
Fundamentals of Microgravity Vibration Isolation

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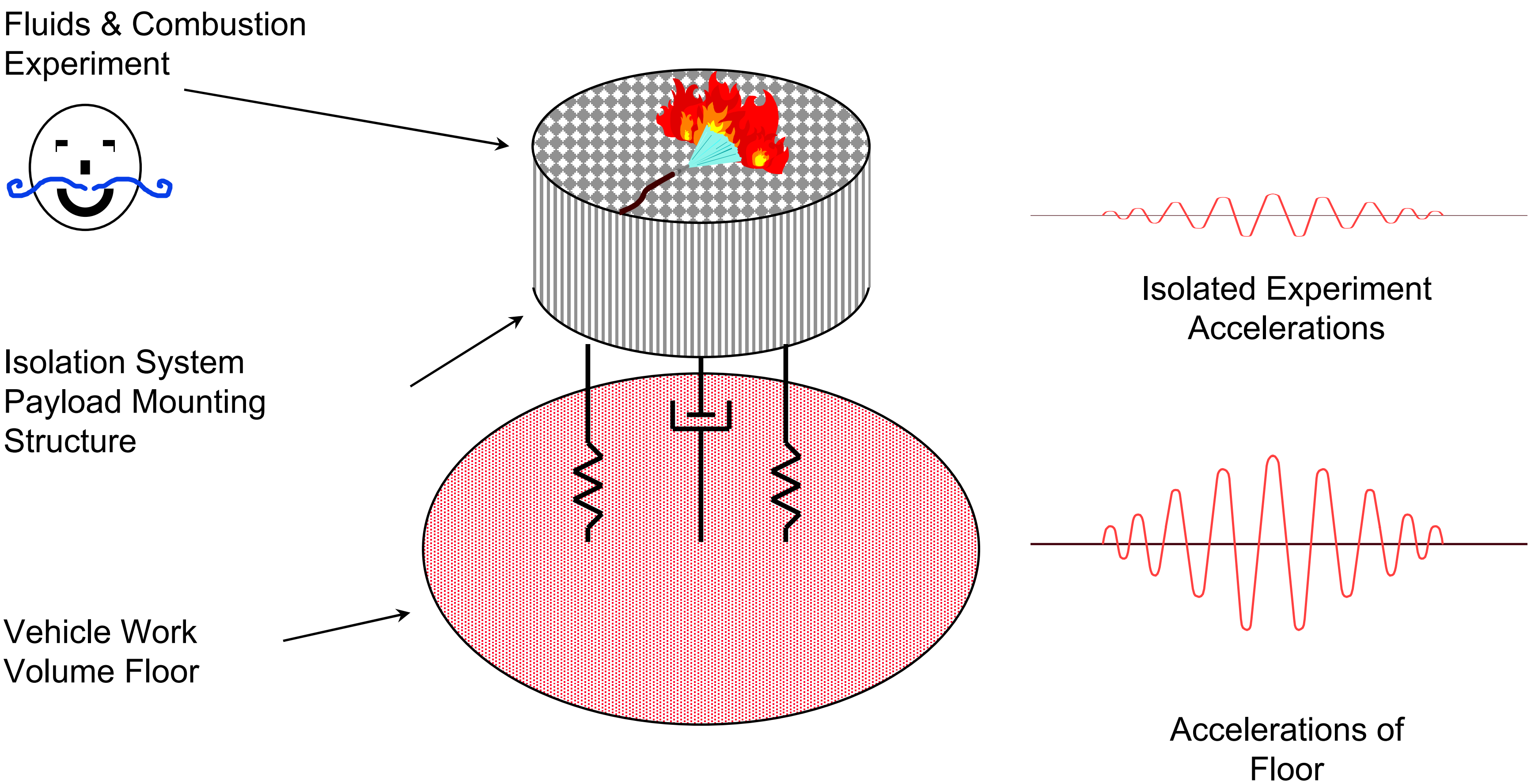
Outline:

- **Motivation**
- **Dynamics of Systems**
- **Active Control Concepts**
- **Active Control Examples**
- **Modern Control Approaches**

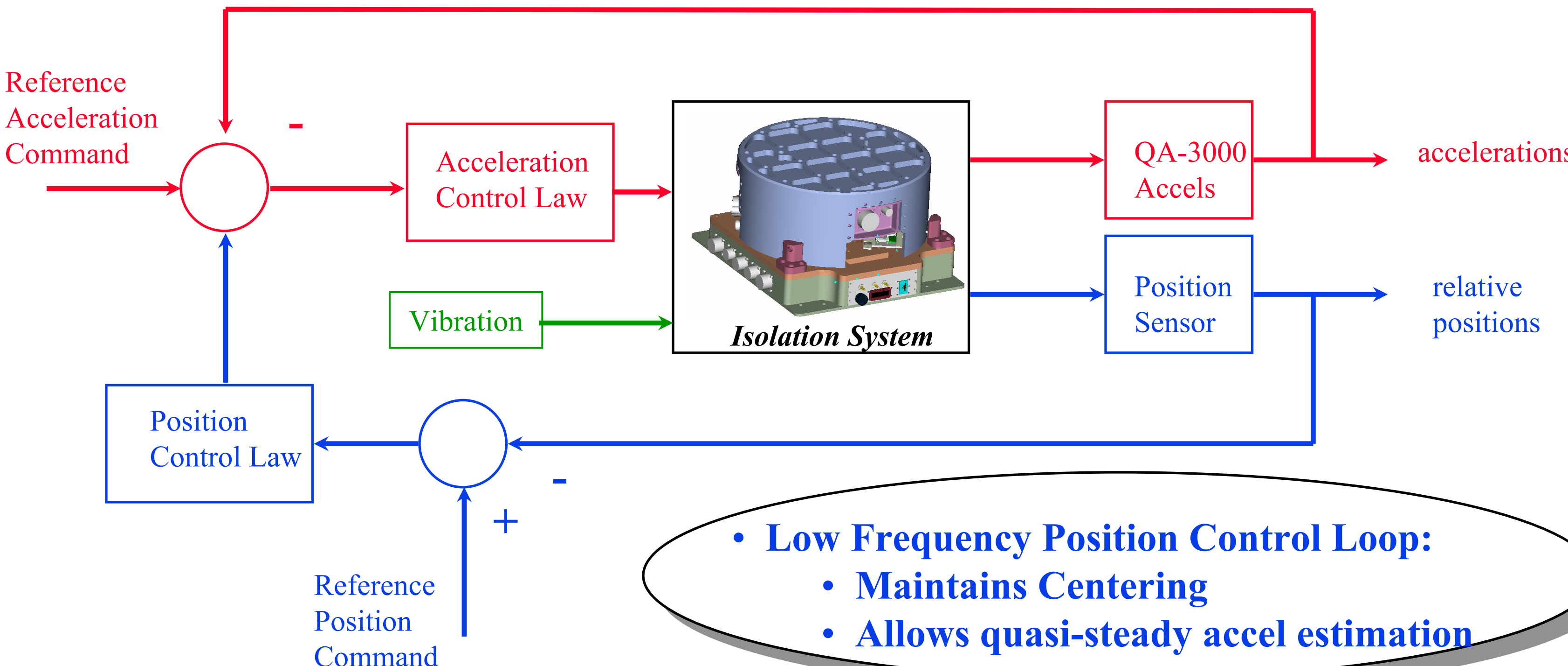
Introduction

- The ambient spacecraft acceleration levels are often higher than allowable from a science perspective.
- To reduce the acceleration levels to an acceptably quiescent level requires vibration isolation.
- Either passive or active isolation can be used depending on the needs or requirements of a specific application.

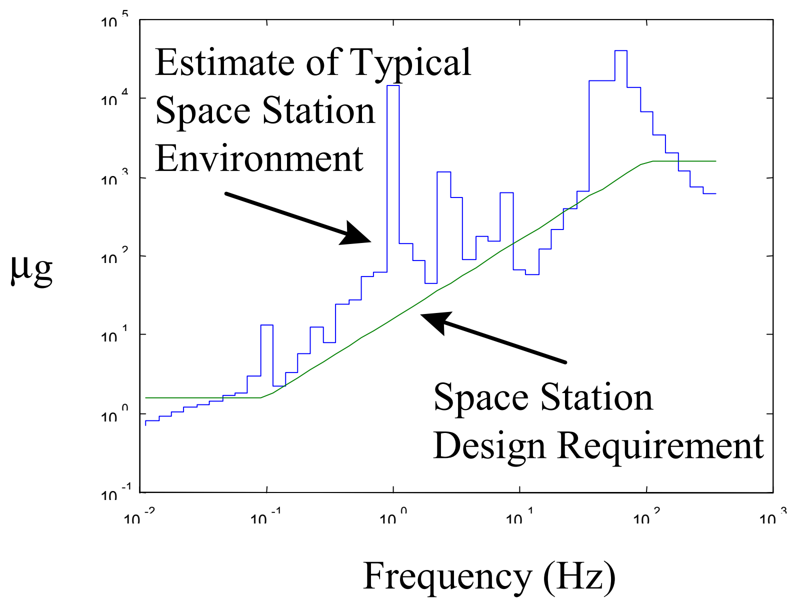
What is Vibration Isolation?



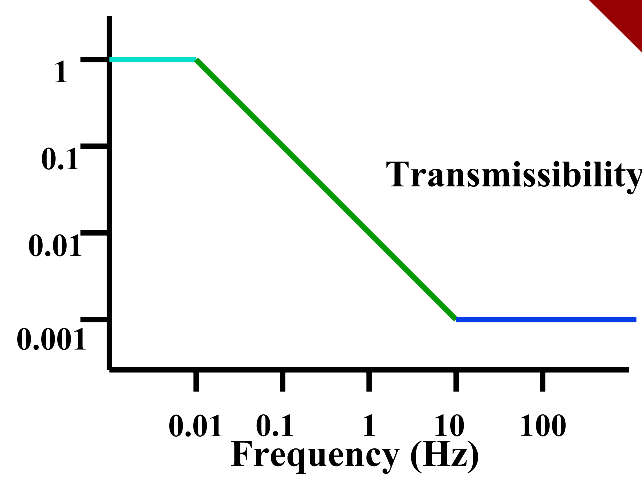
- **High Frequency Acceleration Control Loop:**
  - **Cancels Inertial Motion of the Platform**
  - **Allows "Good Vibrations"**



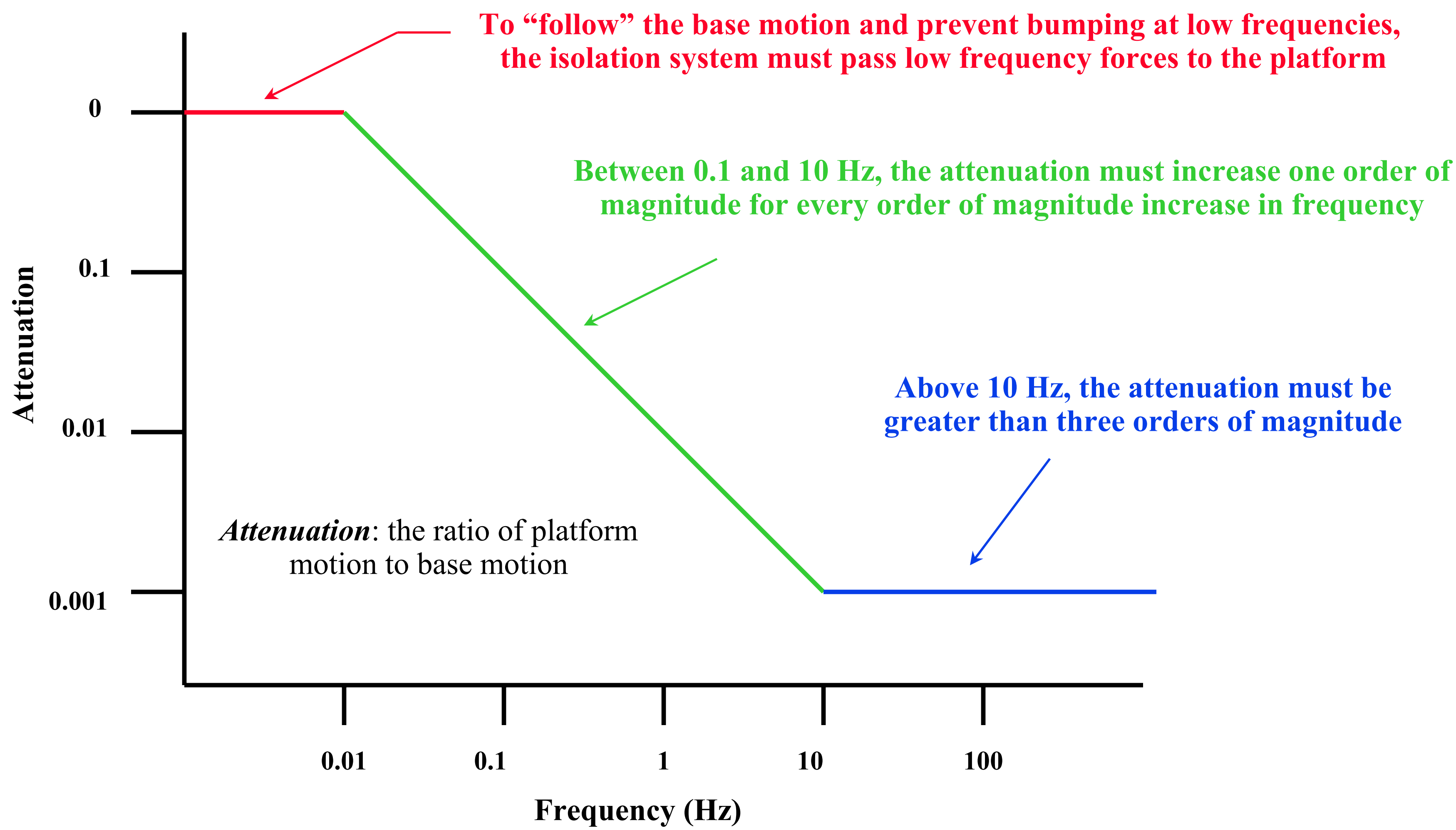
- **Low Frequency Position Control Loop:**
  - **Maintains Centering**
  - **Allows quasi-steady accel estimation**



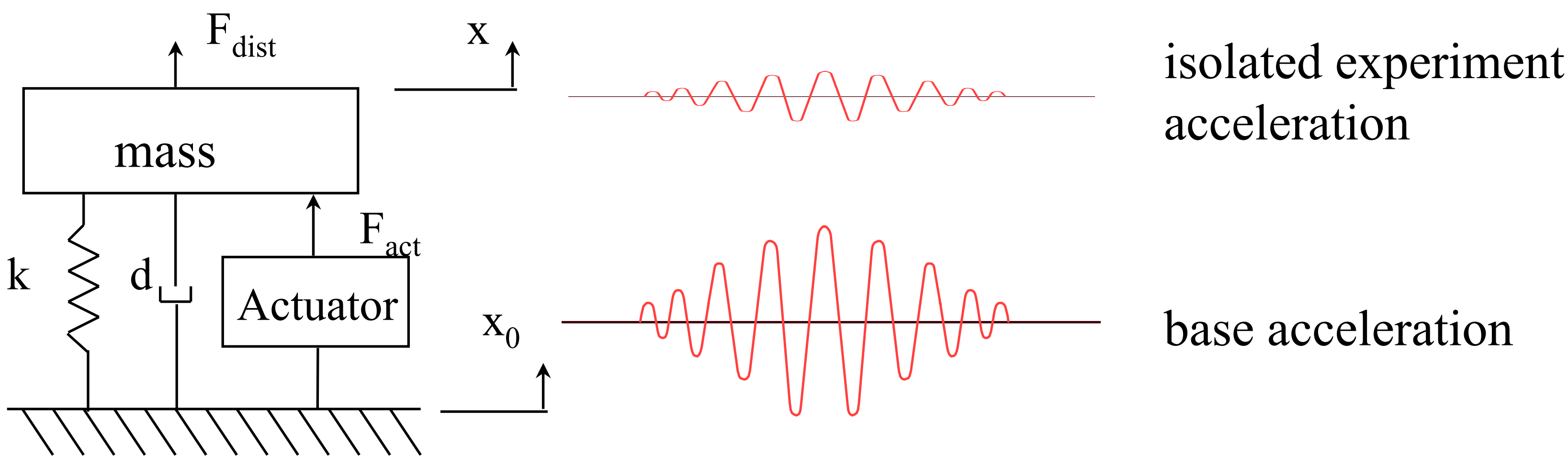
The acceleration environment is expected to significantly exceed acceptable levels



Attenuation Requirement



Single Degree Of Freedom (DOF) Example: Spring-Mass-Damper

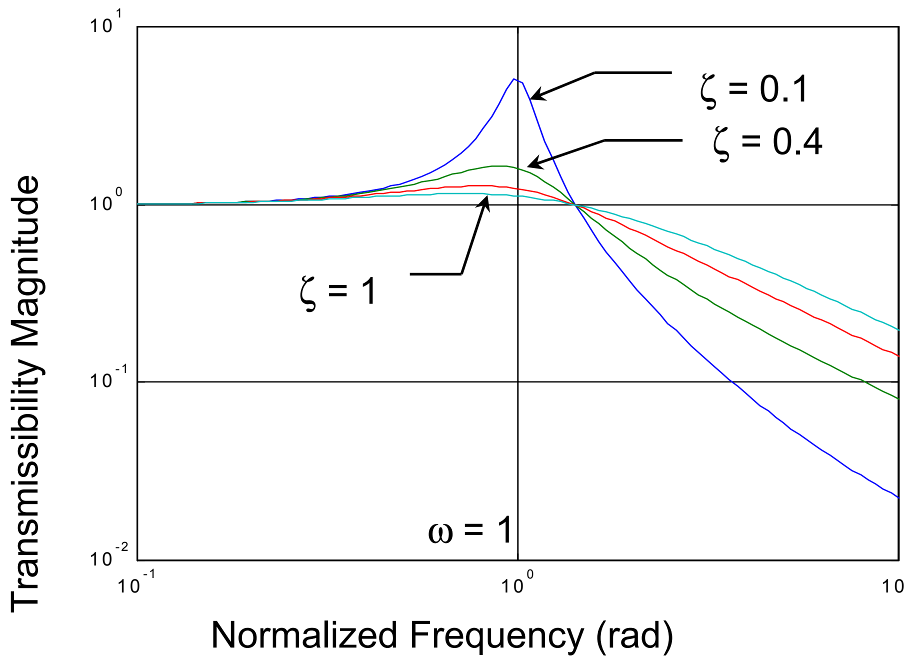


Equation of motion: $m\ddot{x} + d(\dot{x} - \dot{x}_0) + k(x - x_0) = F_{dist} + F_{act}$

The dynamic response of the mass to a base acceleration is a function of the system mass, stiffness, and damping.

System Dynamics: Transmissibility

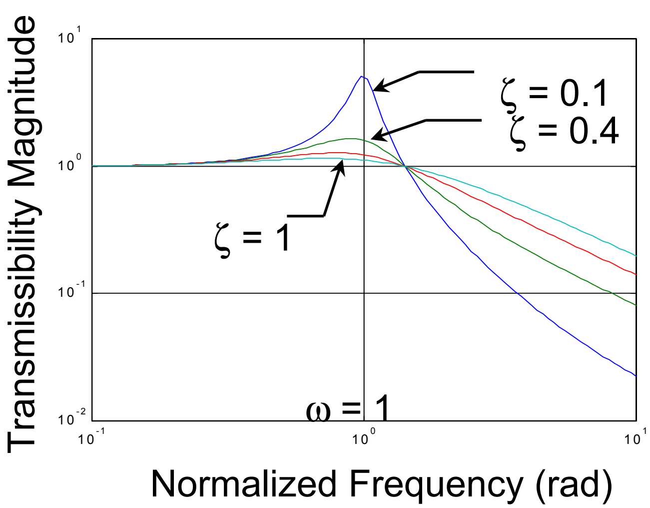
Transmissibility is the magnitude of the transfer function relating the acceleration (or position) of the mass to the base acceleration (or position). The transmissibility specifies the attenuation of base motion as a function of frequency.



Passive Vibration Isolation

- Select spring stiffness, mass, and damping for attenuation
- Reduce break frequency by minimizing spring stiffness

  Typically not desirable to increase isolated mass
- Select damping to trade between damped resonance and rate of attenuation



Transmissibility: $$\frac{x}{x_0} = \frac{2\varsigma\omega s + \omega^2}{s^2 + 2\varsigma\omega s + \omega^2}$$

Natural Frequency: $$\omega = \sqrt{\frac{k}{m}}$$

Damping Ratio: $$\varsigma = \frac{d}{2\sqrt{km}}$$

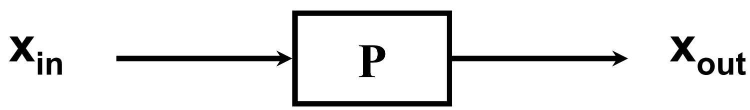
Active Vibration Isolation

- Reduce the inertial motion of payload by sensing motion and applying forces to counter measured motion
- Active control can effectively change the system mass, stiffness, and damping ***as a function of frequency***
- Whereas passive isolation only attenuates forces in passive elements, active control attenuates measured motion
  - Only active control can mitigate payload response to payload-induced vibrations
- Requires power, sensors, actuators, control electronics (analog and digital)

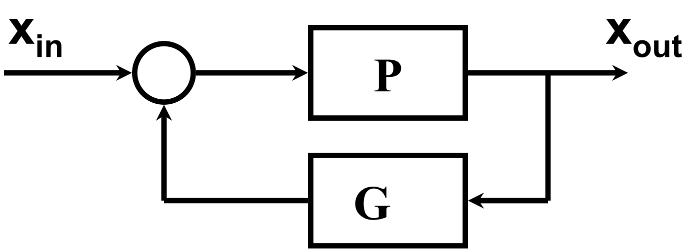
Active Control Illustration

Consider the transfer function from base position to mass displacement:

$$P = \frac{ds + k}{ms^2 + ds + k}$$



Now measure the displacement and "feed it back" with gains (K_a, K_v, K_p) and a control law given by $G = - K_a s^2 - K_v s - K_p$



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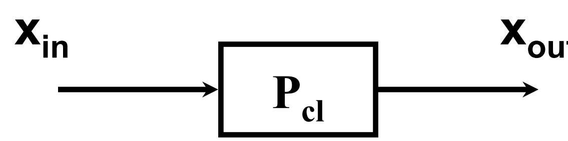
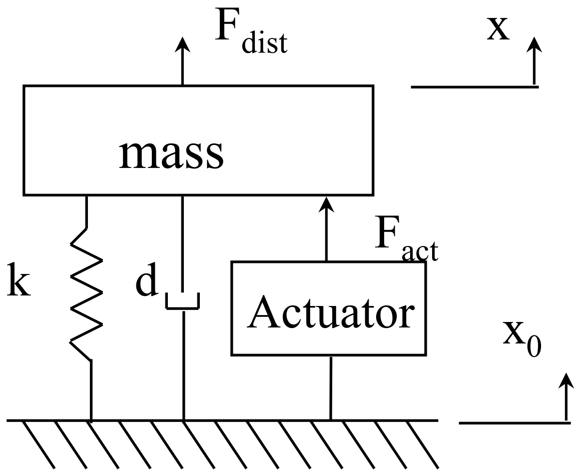


The closed loop transfer function becomes:

$$P_{cl} = \frac{ds + k}{\underbrace{(m+K_a)}_{\tilde{m}}s^2 + \underbrace{(d+K_v)}_{\tilde{d}}s + \underbrace{(k + K_p)}_{\tilde{k}}}$$

Active Isolation Example



Recall the Spring-Mass-Damper Example

Equation of motion:

$$m\ddot{x} + d(\dot{x} - \dot{x}_0) + k(x - x_0) = F_{dist} + F_{act}$$

Consider the control law: $F_{act} = -K_a \ddot{x} - K_v(\dot{x} - \dot{x}_0) - K_p(x - x_0)$

The resulting closed loop transmissibility is:

$$\frac{x}{x_0} = \frac{2\varsigma_{cl}\omega_{cl}s + \omega_{cl}^2}{s^2 + 2\varsigma_{cl}\omega_{cl}s + \omega_{cl}^2}$$

and the closed loop natural frequency and damping become:

$$\omega_{cl} = \sqrt{\frac{k + K_p}{m + K_a}} \qquad \varsigma_{cl} = \frac{(d + K_v)}{2\sqrt{(k + K_p)(m + K_a)}}$$

	Passive Isolation	**Active Isolation**
Transmissibility:	$\frac{x}{x_0} = \frac{2\varsigma\omega s + \omega^2}{s^2 + 2\varsigma\omega s + \omega^2}$	$\frac{x}{x_0} = \frac{2\varsigma_{cl}\omega_{cl}s + \omega_{cl}^2}{s^2 + 2\varsigma_{cl}\omega_{cl}s + \omega_{cl}^2}$
Natural Frequency:	$\omega = \sqrt{\frac{k}{m}}$	$\omega_{cl} = \sqrt{\frac{k + K_p}{m + K_a}}$
Damping Ratio:	$\varsigma = \frac{d}{2\sqrt{km}}$	$\varsigma_{cl} = \frac{(d + K_v)}{2\sqrt{(k + K_p)(m + K_a)}}$

Active Control Concepts

However, it isn't as easy as it seems --

• Real systems aren't simple one degree of freedom lumped masses with discrete springs and dampers.

• Control system design is a function of system properties which typically aren't well known.

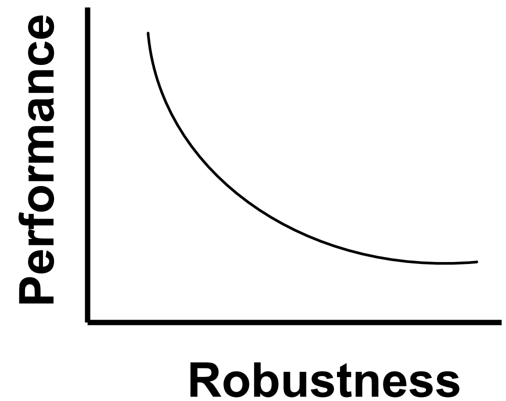
The two key control design issues are ***performance*** and ***robustness***.

•***Performance***: how well is isolation achieved?

•***Robustness***: how well are uncertainties tolerated by the control system?

Key Control Issues

Robustness and **Performance** of a closed loop system are ***always*** in opposition



- Robustness to uncertainties:
  - umbilical properties
  - structural flexibility
  - mass and inertia variations
  - sensor & actuator dynamics
- Performance:
  - base motion attenuation
  - payload disturbances
  - forced excitation

Control Challenges

- Robustness to uncertainties:
  - umbilical properties
  - structural flexibility
  - mass and inertia variations
  - sensor & actuator dynamics

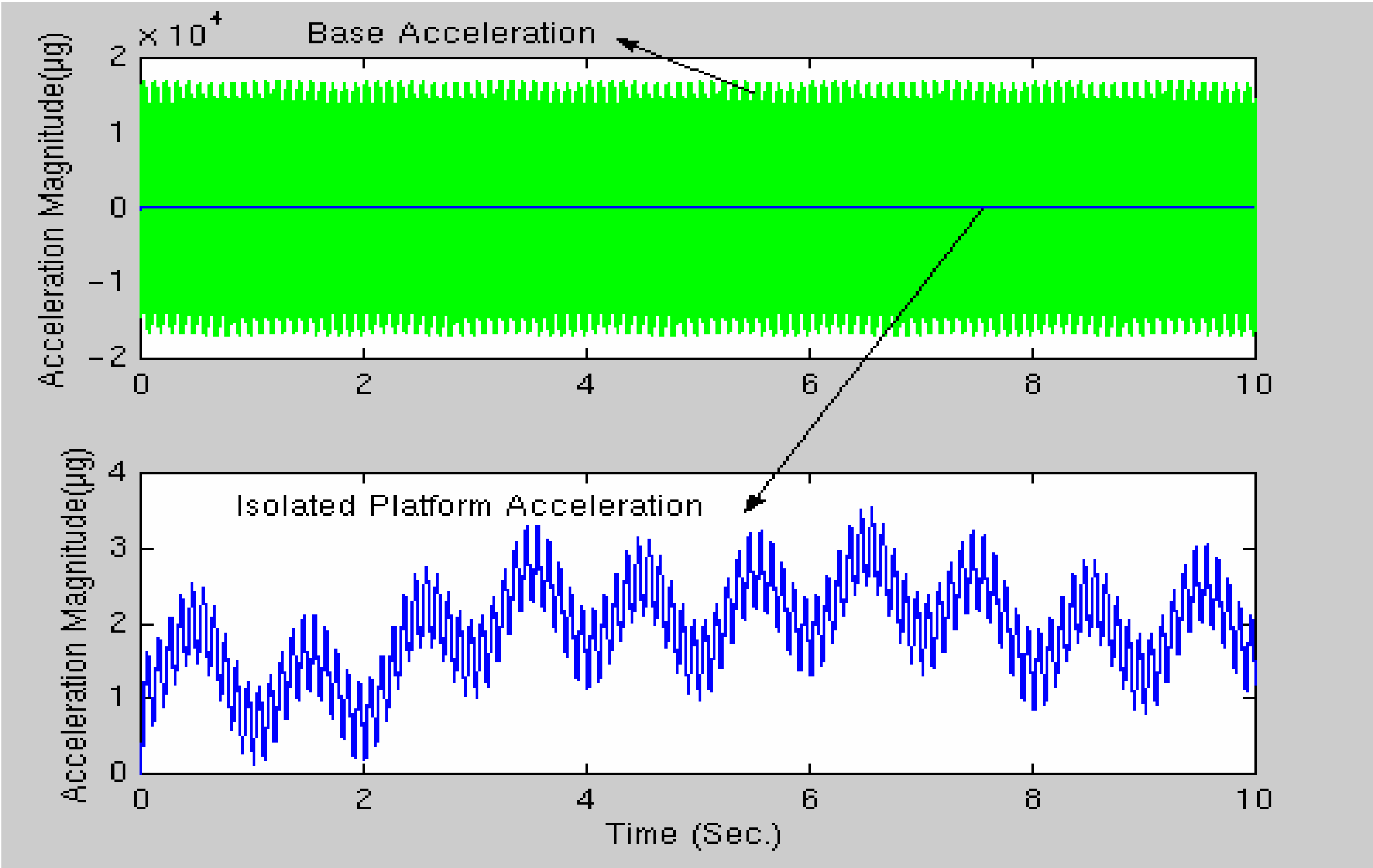
Low Gain &/or Low Bandwidth

- Performance:
  - base motion attenuation
  - payload disturbances
  - forced excitation

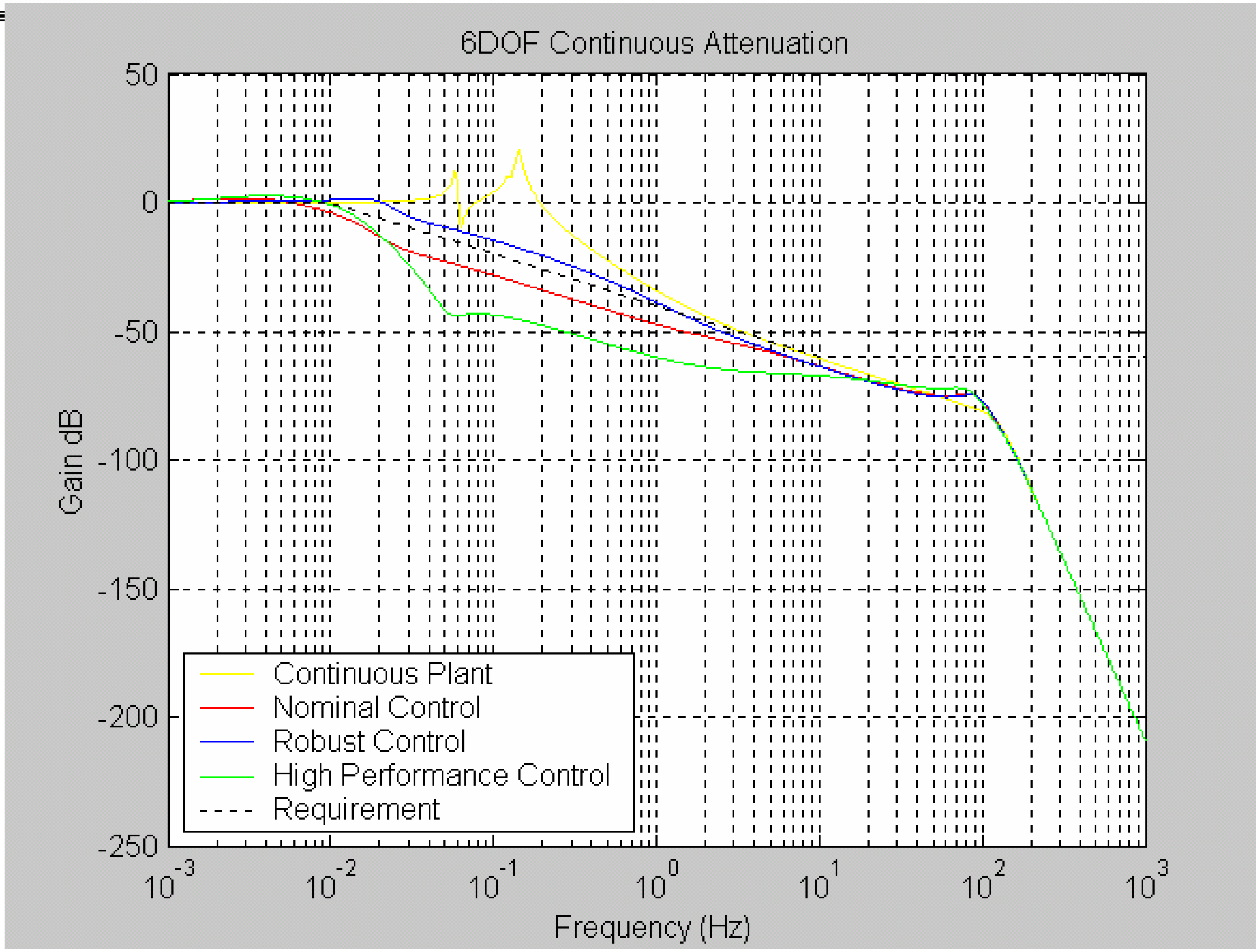
High Gain

High Bandwidth

g-LIMIT 6DOF, Acceleration Time Response (X-axis)



Base acceleration = 1.6 sin(0.01 hz*t)+16 sin(0.1 hz*t)+160 sin(1 hz*t)+1600 sin(10 hz*t)+16000 sin(100 hz*t)


6DOF Continuous Attenuation
Gain dB
Frequency (Hz)
50
0
-50
-100
-150
-200
-250
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
Continuous Plant
Nominal Control
Robust Control
High Performance Control
Requirement

Microgravity Vibration Isolation Systems may require more advanced control technology

- **Multivariable coupling between sensor-actuator pairs**
- **Complex and uncertain structural dynamics**
- **Considerable variation in payload properties**
- **Control / structure interaction**

Classical Control:

- Well developed / mature theory

Modern Control:

- Multivariable, linear, uncertain dynamic systems
- Distinct set of analysis and design tools

Intelligent Adaptive Control:

- Autonomous adaptation
- Minimal sustaining engineering
- Robust performance

Further Reading:

1. Grodsinsky C. and Whorton, M., "Survey of Active Vibration Isolation Systems for Microgravity Applications," *Journal of Spacecraft and Rockets*, Vol. 37, No. 5, Sept. – Oct. 2000.
2. Knospe, C. R., Hampton, R. D., and Allaire, P. E., "Control Issues of Microgravity Vibration Isolation," *Acta Astronautica*, Vol. 25, No. 11, 1991, pp. 687-697.
3. Kuo, Benjamin C., Automatic Control Systems, Prentice-Hall, 1987
4. Thomson, William T., Theory of Vibration With Applications, Prentice-Hall, 1988.