진동 제어
(Vibration Control)

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Rotordynamic Consideration for Rotating Machinery

- Avoiding critical speeds, if possible
- Minimizing dynamic response at resonance, if critical speeds must be pass through
- Minimizing vibration and dynamic loads transmitted to the machine structure, throughout the operating speed range
- Avoiding rotordynamic instability
- Avoiding turbine or compressor blade tip or seal rubs, while keeping tip clearances and seals as tight as possible to increase efficiency
- Avoiding torsional vibration resonance or torsional instability of the drive train system

Ref. J.M. Vance, Rotordynamics of Turbomachinery, Wiley, 1988

Objectives of Rotordynamic Analysis, Design & Control

- Predict bending critical speeds and torsional natural frequencies
- Determine design modifications to change critical speeds
  → Resonance avoidance design & control
- Predict unbalance response amplitudes by rotor unbalance
  → Journal bearing design, damper & mounting
- Calculate balance correction masses and locations from measured vibration data → Balancing
- Predict threshold speeds for rotor instability
- Determine design modifications to suppress dynamic instability
  → Stability design & modification of bearings, seals

Rotordynamic Analysis, Design & Remedial Action

Excessive Vibration?

Contro
l

Analysis → **Design** → **Remedial action**

Installation

Prediction
- Natural frequency
- Natural mode
- Response
- Instability

Reflection
- Design change
- Resonance avoidance
- Damping
- Stabilization

Counter plan
- Vibration reduction
- Excitation sources elimination
- System characteristics → Control

Remedial Action

Configuration of Excessive Vibration

Resonance

- Natural frequency change
  → Separation margin
- Damping addition
  → Minimize Q factor

Excessive Excitation

- Exciting force reduction (balancing, alignment)
  → Minimize input force
- Damping addition
  → Minimize response
- Vibration isolation
  → Minimize transmissibility

Self-excited vibration

- Natural frequency increase due to stiffness increase
- Damping addition
  → Stabilize (maximize threshold speeds)

Types and Characteristics of Vibration

Item	Forced Vibration	Self-excited Vibration
Frequency	• Rotating speed(1X), nX or 1/nX times (*n*: integer)	• Almost constant speed which is not related rotating speed
Amplitude	• Peak amplitude at any rotating speeds	• Suddenly increase at any speeds • Not decease even then speed increases
Damping effect	• Peak amplitude can decrease • Speed of peak amplitude is not influenced	• Speed which amplitude increase rise • Amplitude after increased not change
Abnormal causes	• Amplitude varies directly as level of abnormality	• Amplitude determine without level of abnormality
Generating frequency	• 1X, nX, 1/nX or natural frequency (resonance)	• System natural frequency
Remedial action	• Separate between 1X and critical speeds • Reduce the external force • Increase the damping capacity	• Increase the stability threshold speed • Reduce the instability sources • Install the damper to increase the threshold speed
Examples	Unbalance, misalignment, nonlinear vibration (subharmonics vibration)	Oil whip, Oil whirl, Friction whip, Hydraulic whip, Steam whirl.

Methods for Vibration Control

Forced Vibration	**Self-excited Vibration**
• Change the stiffness or mass for separating between forced and natural frequencies using dynamic damper, bracer etc. (**Resonance avoidance**) • Increase the damping ratio for decreasing the Q factor (resonance amplification ratio) (**Higher damping capacity**) $Q = 1/2\varsigma$ • Decrease the excessive exciting force using balancing, alignment etc. (**Exciting source reduction**) • Minimize vibration loads transmitted to/from the machine structure using mounts (**Vibration isolation**)	• Increase stiffness for increasing the 1st natural frequency • Add the damping capability for increasing the damping ratio • As a result, equivalent damping coefficient C_c is increased $C_e = 2\varsigma\,\omega_n\,m_e = 2\varsigma\sqrt{k_e\,m_e}$ k_e, m_e : equivalent stiffness and mass of attended eigenvalue ζ : damping ratio ω_n : natural frequency • Damping coefficient means the sensitivity of vibrating system • Decrease the destabilizing force (Swirl breaker)

Stabilizing forces > Destabilizing forces

Vibration Control (진동제어, 제진)

The change of eigenvalue characteristics of machine system to change the vibration characteristics of machine itself

Types of Vibration Control

Passive

- Mass, stiffness and damping capacity are changed by using passive elements such as constant spring and damper
- Eigen property of system is changed

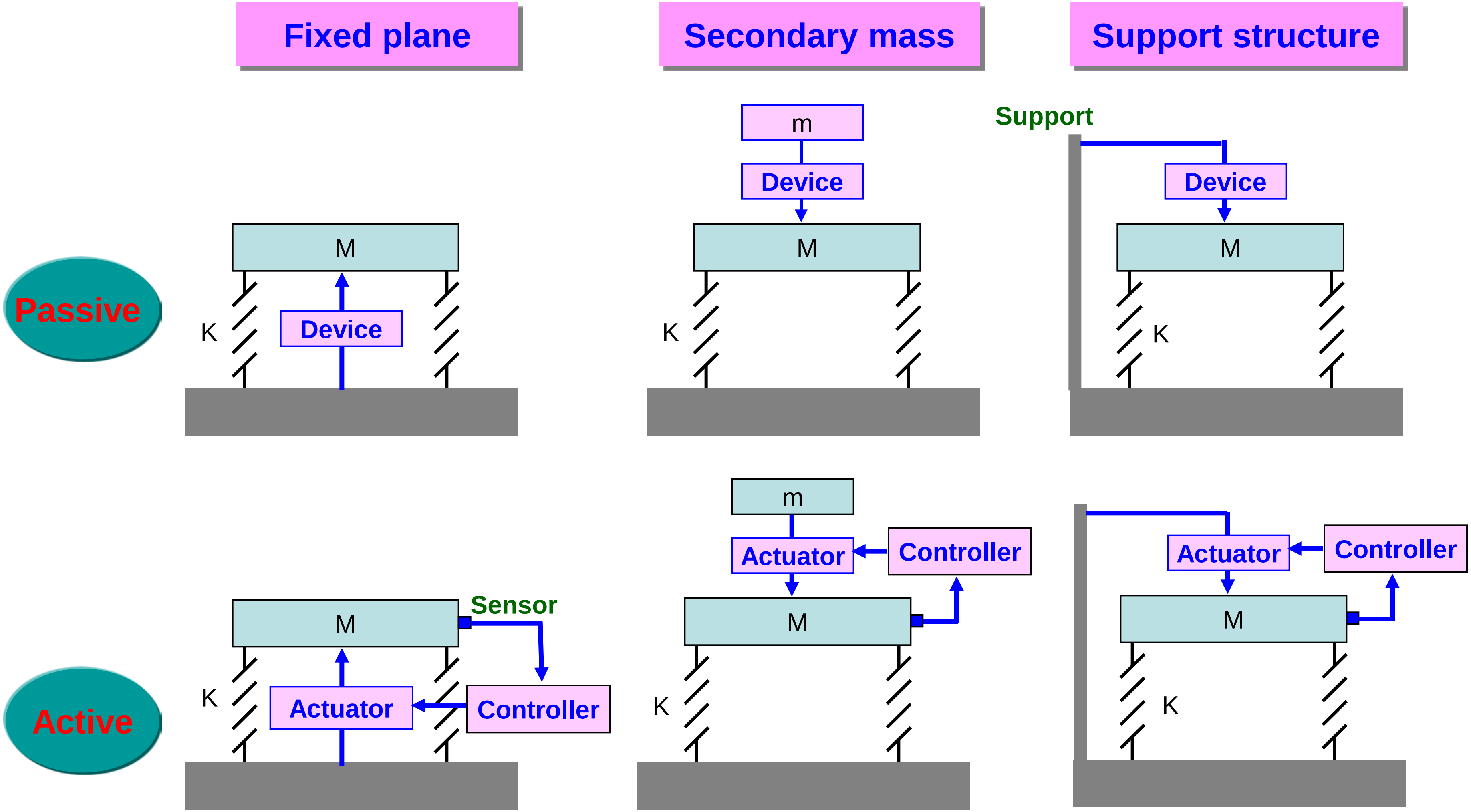
Semi-active

- Stiffness or damping can be controlled externally
- Sensor, actuator and control circuit is needed
- Not feedback the control signal

Active

- Sensor, actuator and control circuit is needed
- Feedback the control signal
- Need the large energy to control the system

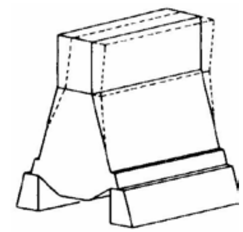
Types of Vibration Control



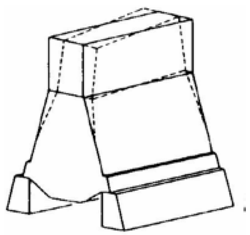
An Example of Engine Vibration Control

Vibration Mode

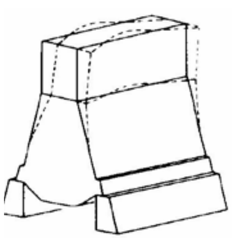
고유진동수 증가



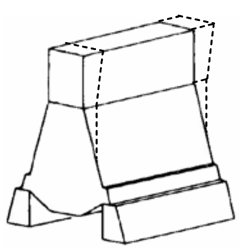
H type



X type

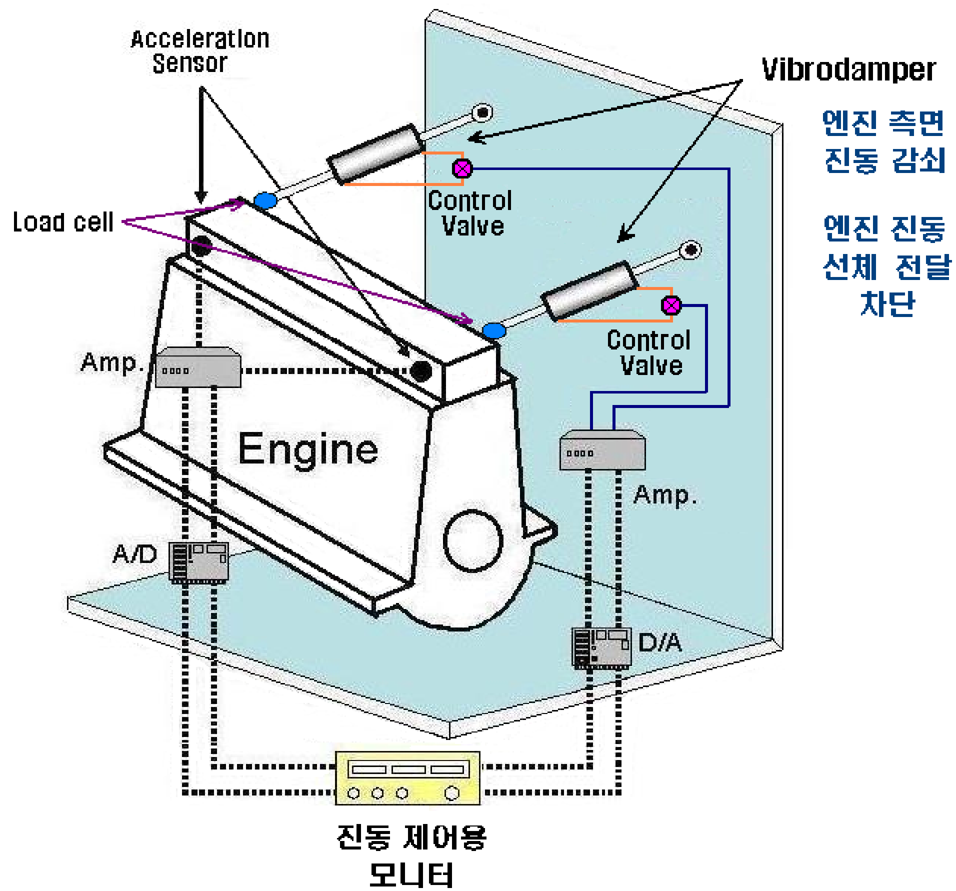


x type



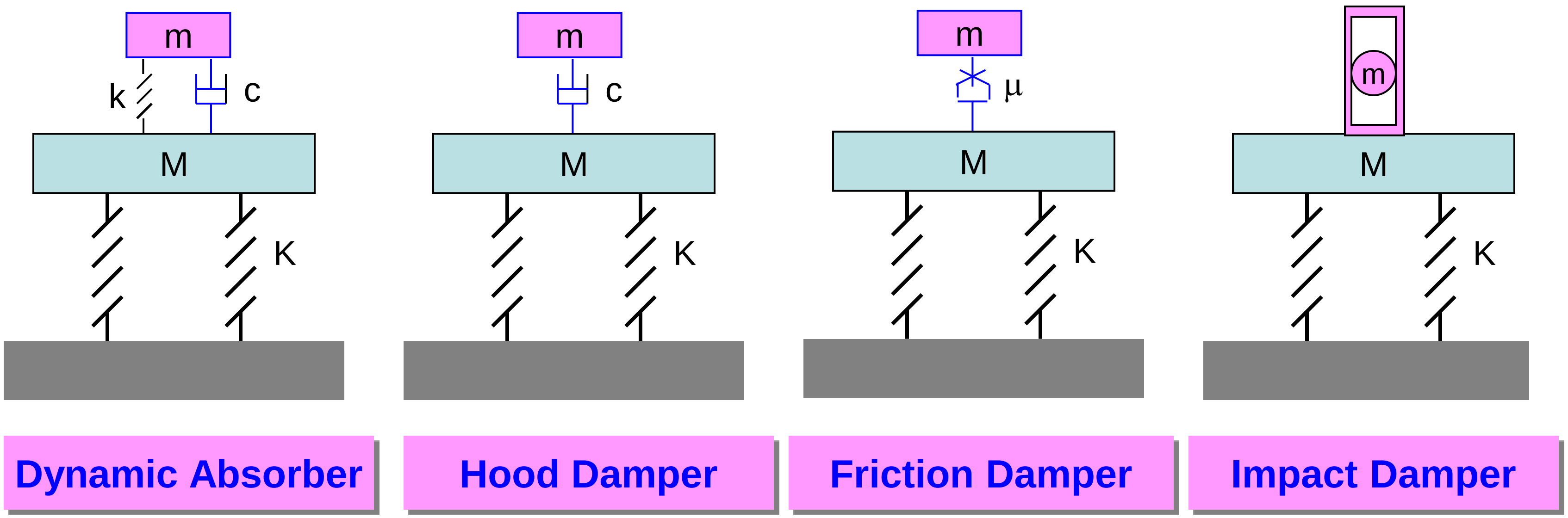
L type

Top Bracer



Passive Vibration Control with Secondary Mass

- Inertia force applied at secondary mass is used as a reaction force (vibration control force)
- Dynamic absorber is best for vibration control



Passive Vibration Control : Damper

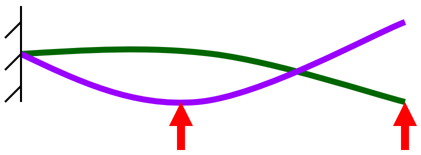
- To maximize the damping effect, the damper is installed at place which is large the relative velocity (relative displacement) of particular eigenmode
- Damping ratio of damper can be calculated by modal analysis

$$\varsigma = \frac{\Phi^2 c}{2\omega_n m_e} \qquad \sqrt{k^2 + c^2\omega_n^2} << k_e$$

Φ : relative displacement mode(velocity mode)

k_e : equivalent stiffness at damper position

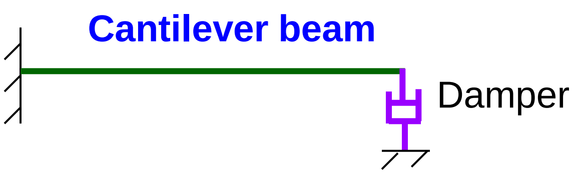
k : stiffness of damper



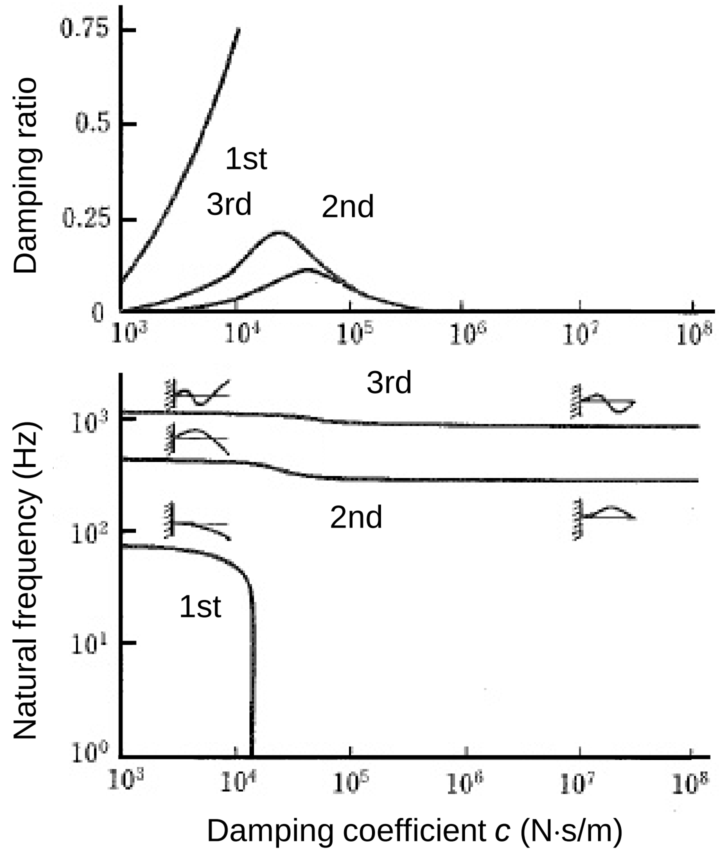
Damper	Principle	Loss factor	Remarks
Fluid, oil	Squeeze effect, shear loss	50 ~ 100%	Best damping capability
Air	Squeeze effect, compression, expansion	~ 100%	
Rubber	Inner friction	10 ~ 50%	Convenient
Magnetic	Eddy current loss	Very low	Non-contacting
Powder	Friction in particles	A few %	
Plastic	Plastic hysteresis	-	For force vibration

Passive Vibration Control : Damper

- If the damping coefficient increases, the 1st mode becomes over-damping. But 2nd and 3rd modes have a peak value and are approaches to zero value.
- If the damping effect → large, the relative displacement mode Φ → small (The motion of beam is constrained by the damper) $\therefore \zeta \rightarrow$ small
- That means there is an optimum value



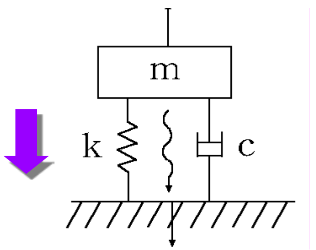
Length : 1 m
Mass : 61.26 kg



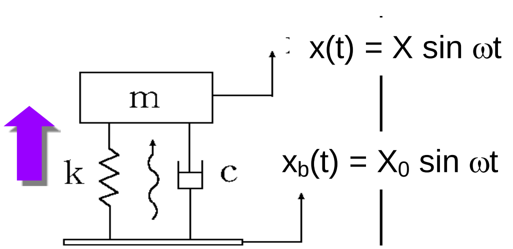
Passive Vibration Control : Foundation

- Two types of transmission : From machine to base and reverse
- Frequency ratio λ = force frequency/ natural frequency ($\omega_n = \sqrt{m/k}$)
- $\lambda < \sqrt{2}$: Amplification, $\lambda > \sqrt{2}$: Vibration isolation

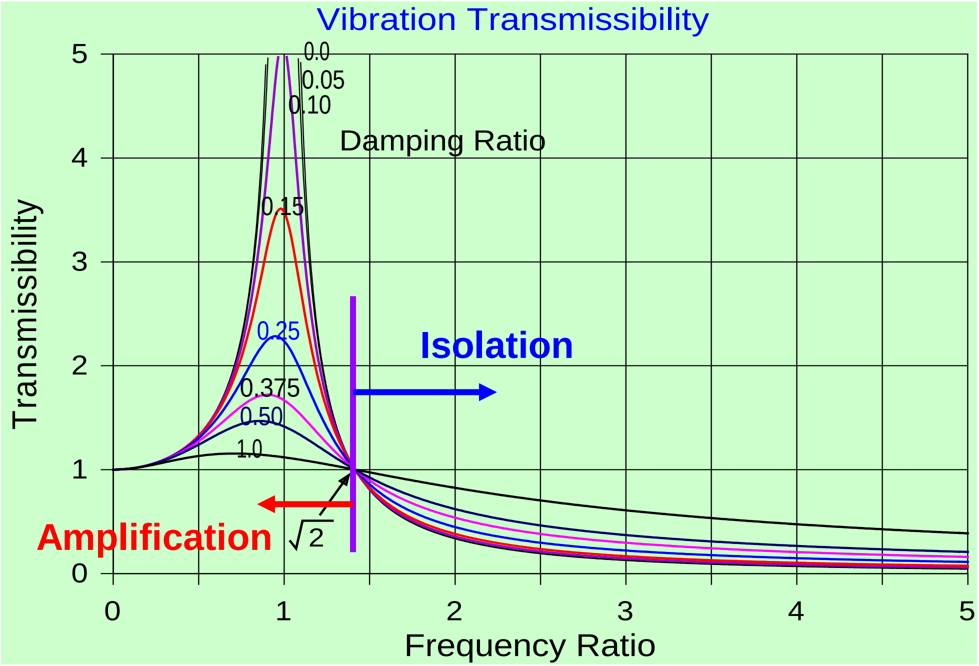
Rubber mount
Air mount



Machine forced force

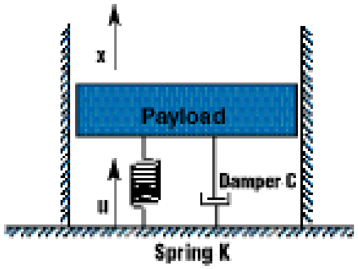


Base forced displacement



Passive Vibration Control : Mass Damper

- Dynamic damper or dynamic absorber
- Primary system (1DOF) + secondary system(1DOF) = 2 DOF
- Separate natural frequency from resonance region
- Natural frequency : In-phase mode → decrease, out-of-phase mode → increase
- Vibration energy supplied to primary system is dissipated at secondary system
- **Optimum Tuning Condition :** $\frac{\sqrt{k/m}}{\sqrt{K/M}} = \frac{1}{\mu+1}$
- **Optimum damping ratio :** $\varsigma_{opt} = \frac{\sqrt{3\mu}}{\sqrt{8(1+\mu)^3}}$
- **Maximum amplitude ratio :** $Q = \frac{x}{x_{st}} = \sqrt{1+\frac{2}{\mu}}$



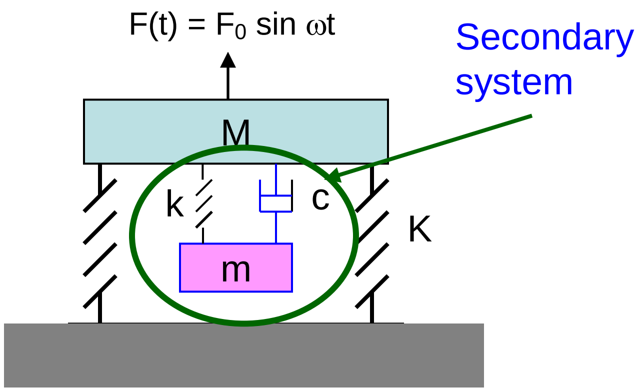
Parameters

$x_{st} = F/K,$

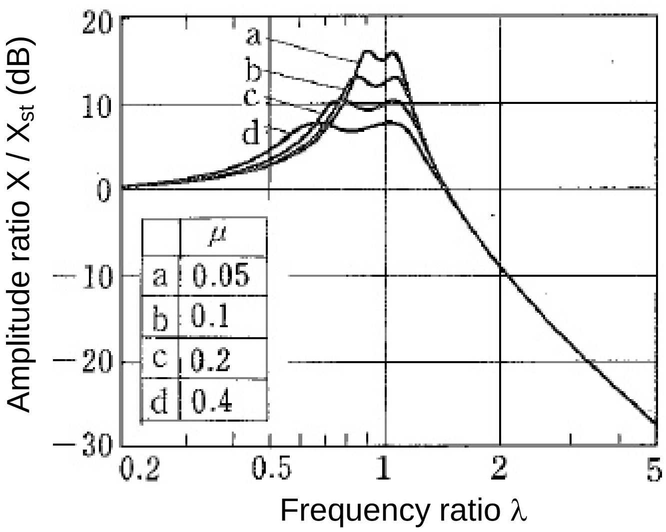
$\lambda = \omega/\sqrt{K/M}$

$\mu = m/M,$

$\varsigma = c/(2m\sqrt{K/M})$

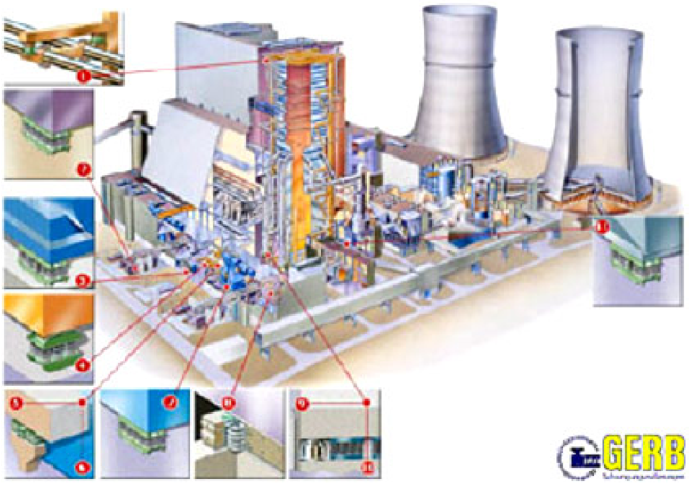


Mass damper model

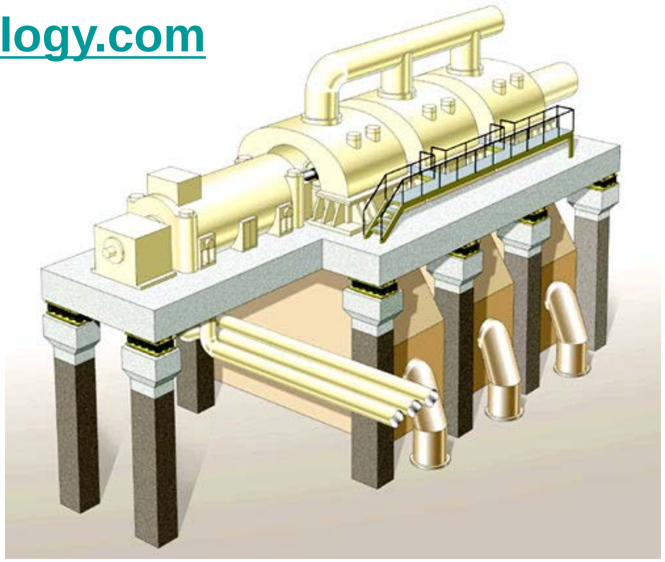


Applications

www.power-technology.com



Vibration control in power plants



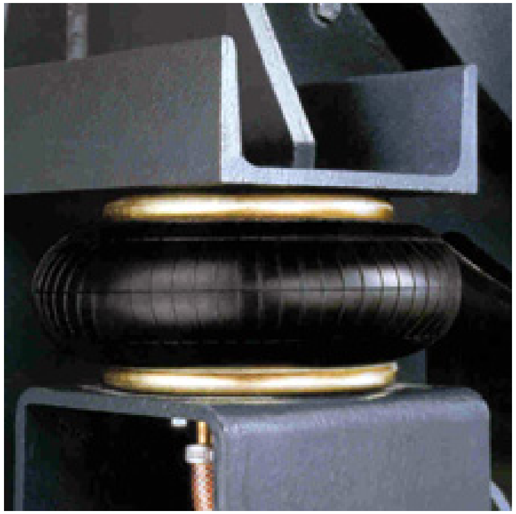
Spring supported turbine table

Vibration isolation of a fan

Pipework damper

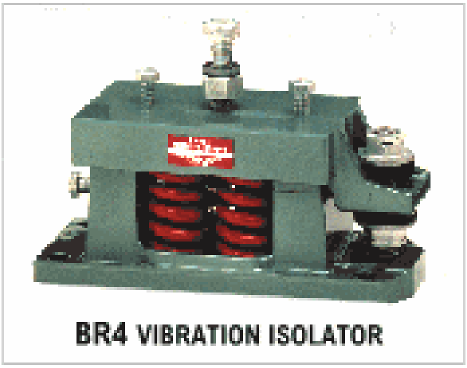
Applications

Vibration isolation mount



Air spring system for vibration isolation

Vibration isolation mount



♣ Self-study & Presentation

- Basic Theory & Industrial Applications
- Presentation material using Power Point File
- Written by English
- 3 times for 50 minute, 3 persons per week

♣ 진동 제어이론 (Vibration Control Theory)

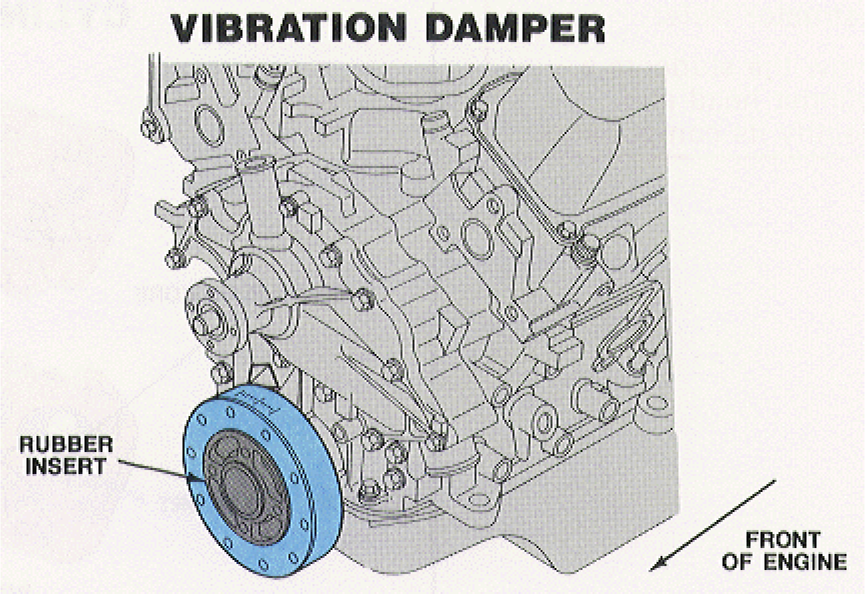
Vibration with Control, Measurement, and Stability
Daniel J. Inman

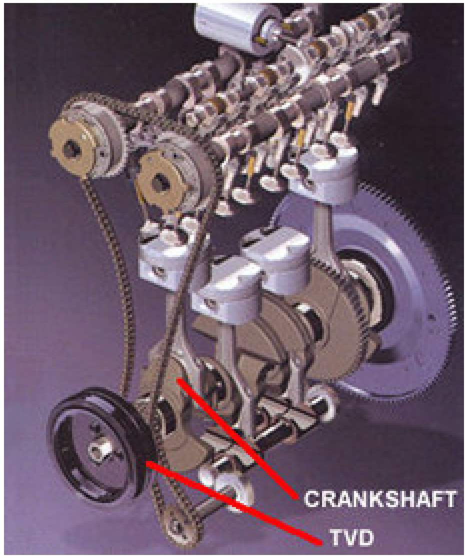
Chapter 7 by Mr. Widodo

♣ 진동 마운트 (Vibration Mount)

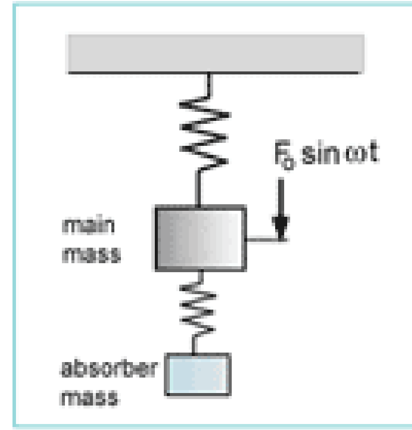
www.vibrationmount.com & other materials

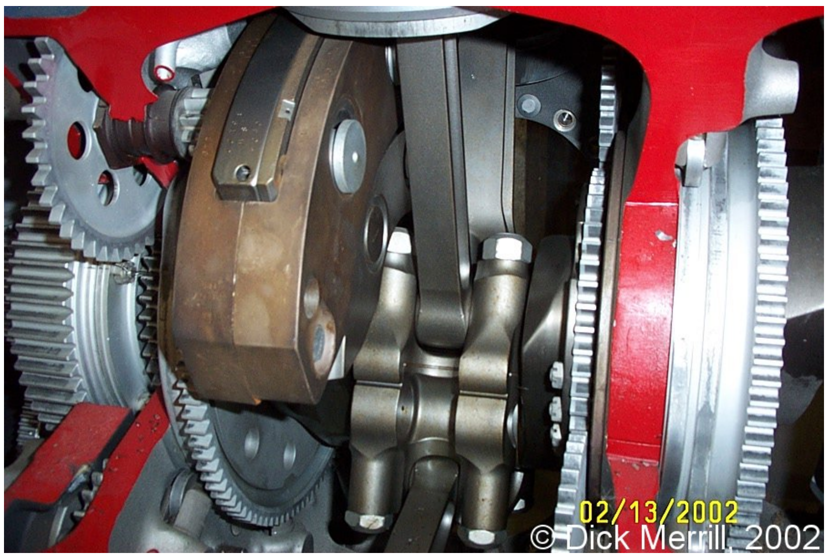
♣ 진동 감쇠기 (Vibration Damper)

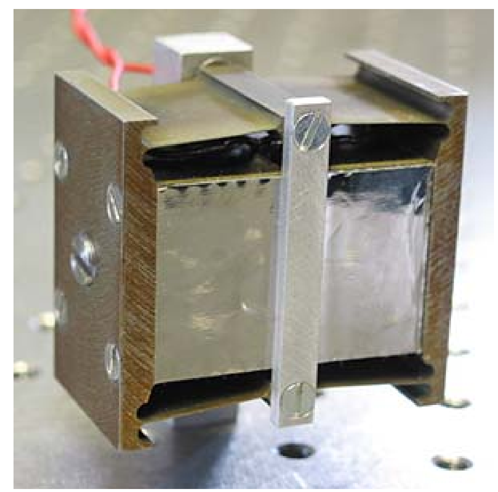




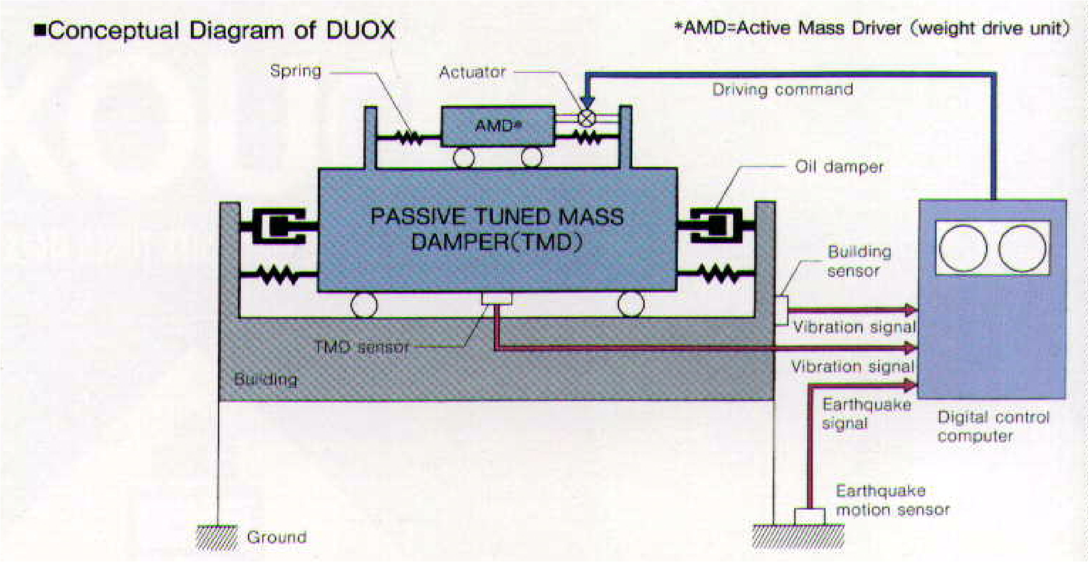
♣ 동 흡진기 (Dynamic Absorber)

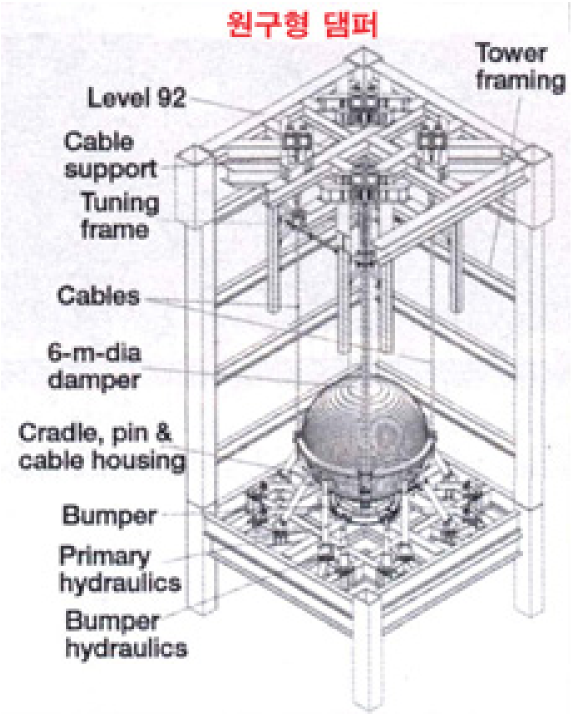


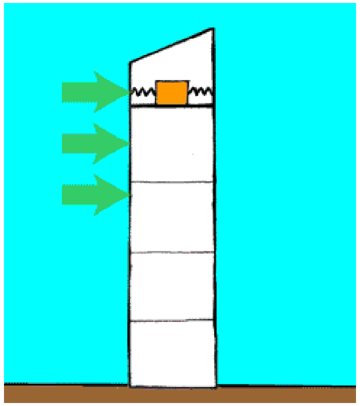




♣ 동조 질량 감쇠기 (Tuned Mass Damper)







Assignment & Presentation

♣ 평형잡기(Balancing)

♣ 정렬(Alignment)