Lecture 3

ME756A

Principles of Vibration Control

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Steps in Vibration Control

A *Identification and characterization of the source of vibration.*

B *Specify the level to which the vibration should be reduced.*

C *Select the method appropriate for realizing the vibration reduction level identified in step B.*

D *Prepare an analytical design based on the method chosen in step C.*

E *Realize in practice (i.e. hardware mechanization of the analytical design constructed in step D).*

Types of Deterministic Excitations

Deterministic – Fourier Series Representation

- Harmonic $x(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)$
- Periodic

$$a_0 = \frac{2}{\tau}\int_0^{\tau} x(t)\, dt$$

$$a_n = \frac{2}{\tau}\int_0^{\tau} x(t)\cos(n\omega t)\, dt, \quad b_n = \frac{2}{\tau}\int_0^{\tau} x(t)\sin(n\omega t)\, dt$$

- Non-periodic $x(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} X(\omega)e^{i\omega}\, d\omega$

(Integral Fourier Transform)

$$X(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} x(t)e^{-i\omega t}\, dt$$

Types of Stochastic Excitations

- Non-deterministic (Phenomena whose outcome at a future instant of time can not be predicted)
  - Stationary
  - Non-stationary (where the mean value and the autocorrelation function depend on time)

Mean Value: $\mu_x(t_1) = lim_{n\to\infty} \frac{1}{n} \sum_{k=1}^{n} x_k\,(t_1\,)$ ---- $\boldsymbol{lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x_k\,(t)\,dt}$

Autocorrelation Fn.: $R_x(t_1, t_1+\tau\,) = lim_{n\to\infty} \frac{1}{n} \sum_{k=1}^{n} x_k\,(t_1\,)x_k(t_1+\ \tau)$

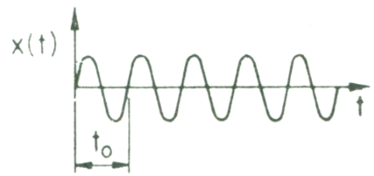
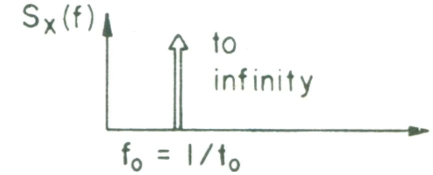
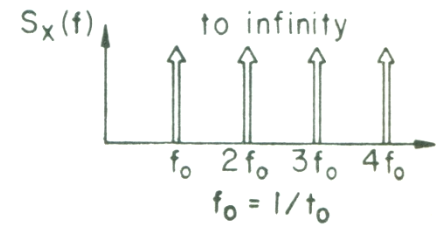
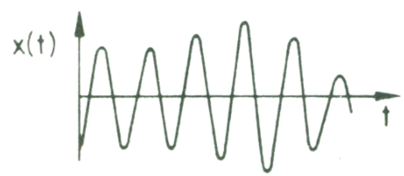
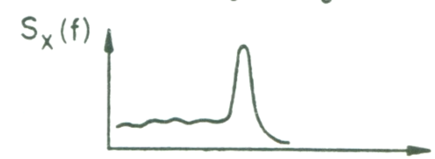
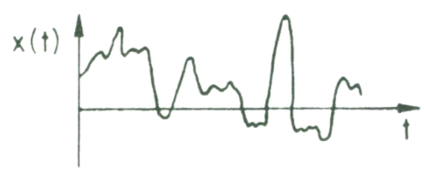
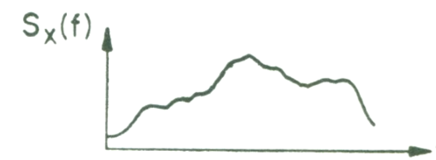
----- $\boldsymbol{lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x_k\,(t)x_k(t+\ \tau)dt}$

(temporal)

Power Spectral Density: $S_f(\omega) =\ \int_{-\infty}^{\infty} R_f(\tau)e^{-i\omega\tau}\,d\tau$

Inverse Fourier Transform: $R_f(\tau) =\ \frac{1}{2\pi}\int_{-\infty}^{\infty} S_f(\omega)e^{i\omega\tau}\,d\omega$

STEP A – Source Characterization

Nature of response, $x(t)$	Time-history signal (t, time)	Power spectral density (S_x) plot (f, frequency)
Harmonic		
Periodic		
Narrow-band random		
Broad-band random		

Note: Often for a linear system, the analysis of the response helps in determining the nature of the excitation. As shown here, the response can be analyzed either in time domain or in frequency domain

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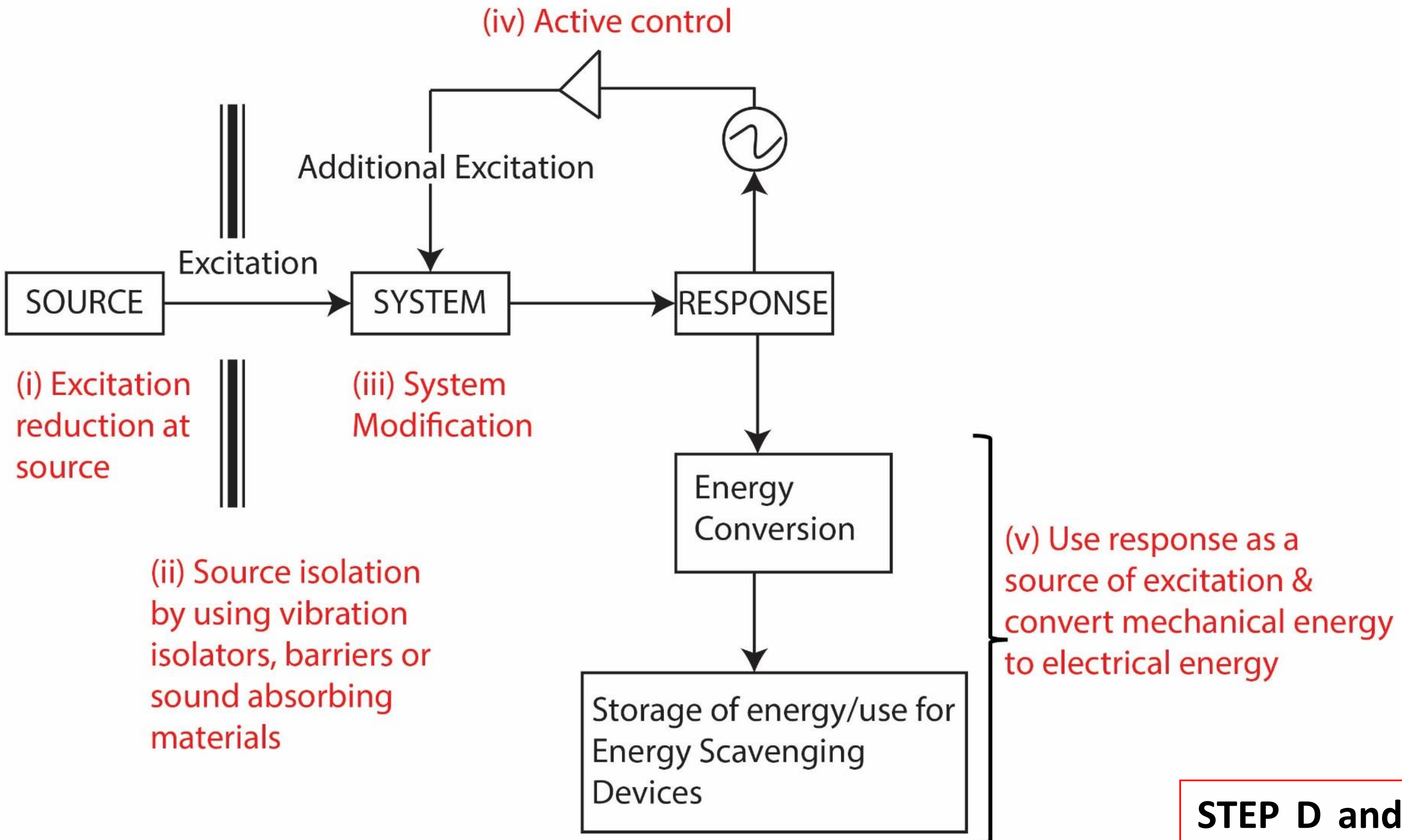
Ref.: Principles of Vibration Control, A. K. Mallik

STEP B – Identify suitable response variable and decide on the accepted level of vibration

Sources	Total equivalent acceleration, m/s^2
Hand tools	**Guideline 5 m/s^2**
Impact drill	10 - 110
Rock drill	5 - 13
Rail saw	3 - 6
Steel plate cutter	4 - 20
Chain saw	2 - 5
Grinder	1 - 3
Bench grinder	15
Bolt and nut wrench	5 - 15
Concrete vibrators	5 - 20
Vehicles	**Guideline 1.15 m/s^2**
Excavator	1 - 5
Caterpillar with push plate	1 - 3
Motor sledge	2 - 5
Terrain vehicle	3 - 5

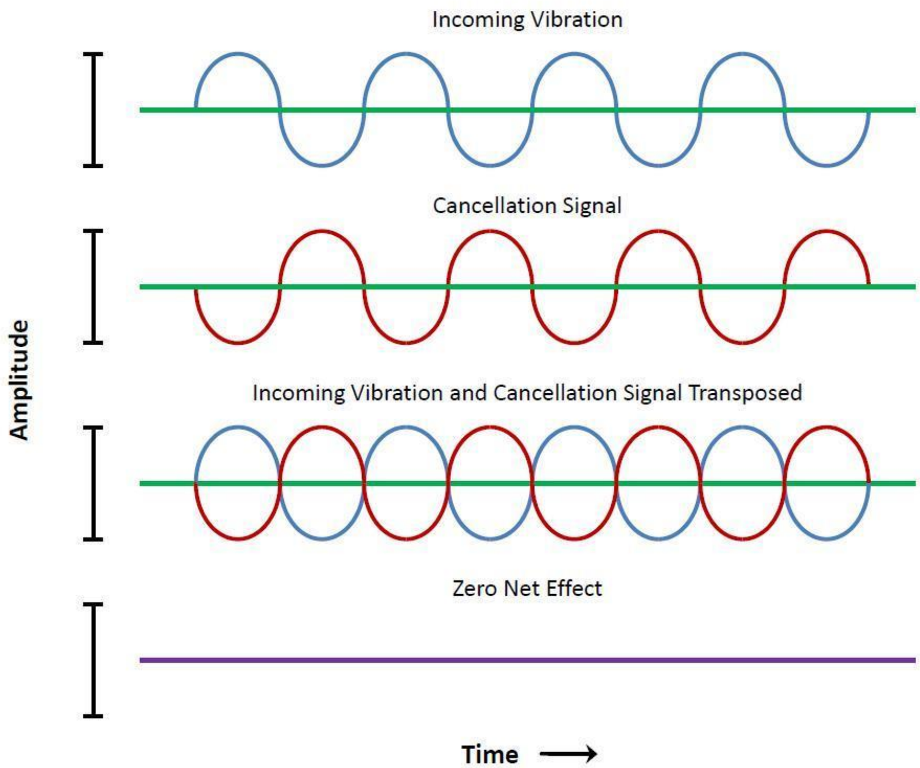
STEP C: Choice of a Method of Vibration Control

To control vibration effectively one can choose any of the five methods as discussed earlier or a combination of these methods.



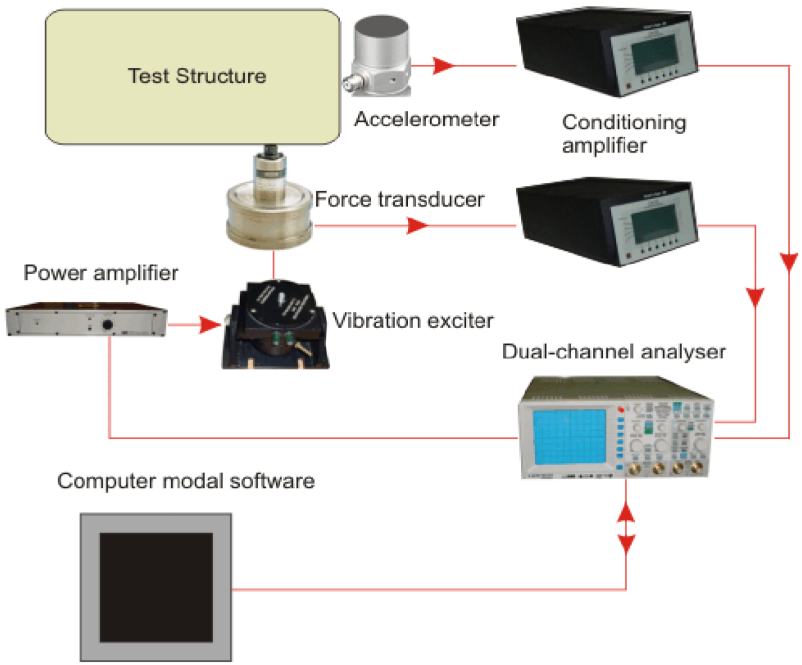
STEP D and E will be discussed in later weeks

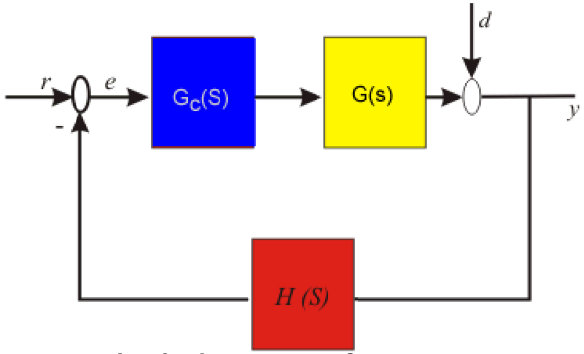
Active Vibration Control



Active Vibration Control

- Active application of force in an equal and opposite manner to the forces imposed by external vibration.
- With this application, a precision industrial process can be maintained on a platform essentially vibration-free.
- It involves design of suitable vibration sensors, processing of sensory data and then feeding back necessary signal to the actuators for vibration control.





Block diagram of AVC system

r – reference signal
e – error signal
s - variable in the frequency domain
H – Transfer function of the sensor
G – Transfer function of the vibrating system
d - disturbance
G_c - Transfer function of the controller
y – output/response of the system

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Applications
of
Active Vibration Control

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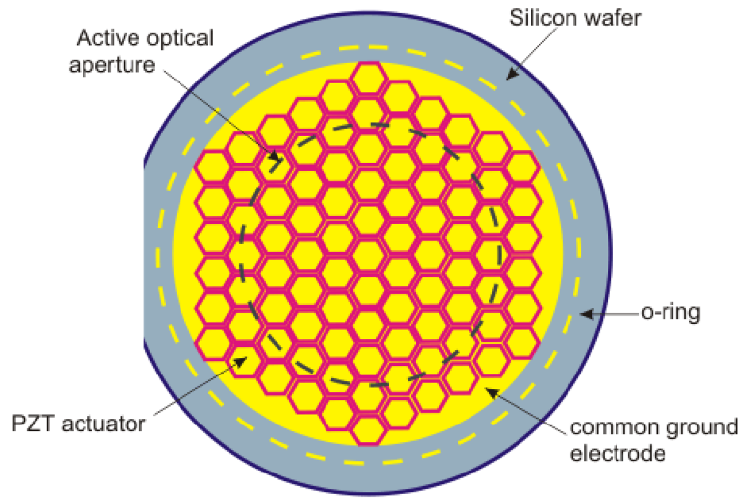
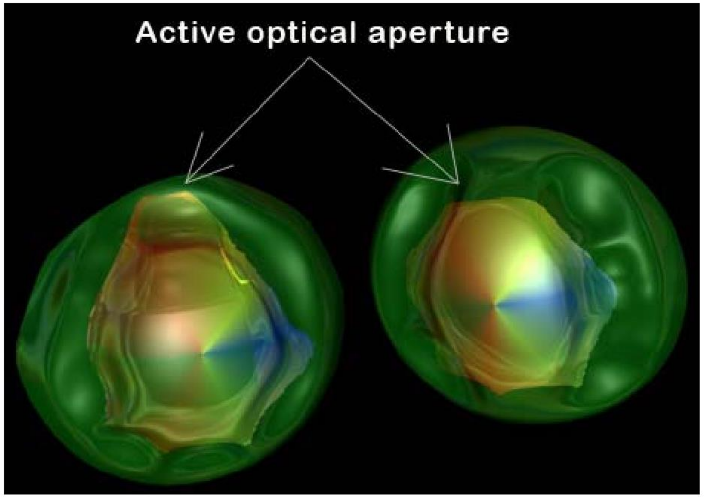
Application 1: Vibration and shape control of flexible systems like *Optical mirror*



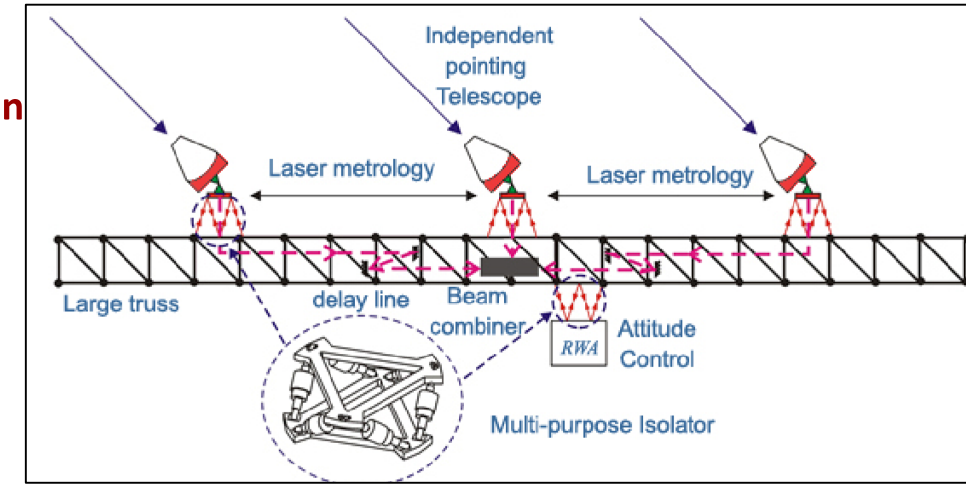
- This type of mirrors are ideally suitable for light weight ultra-large space telescopes. A set of such flexible mirror segments could be assembled to form the actual mirror. The surface quality is < 30nm.
- Stroke requirements for such adjustments is <2μm. Usually PZT actuators are bonded behind deformable silicon mirror membranes for this purpose.
- An electric field applied perpendicular to the piezoelectric layer plane will induce lateral contraction and thereby cause large out of plane deformation of the membrane.



Application 2: A future Interferometric Mission

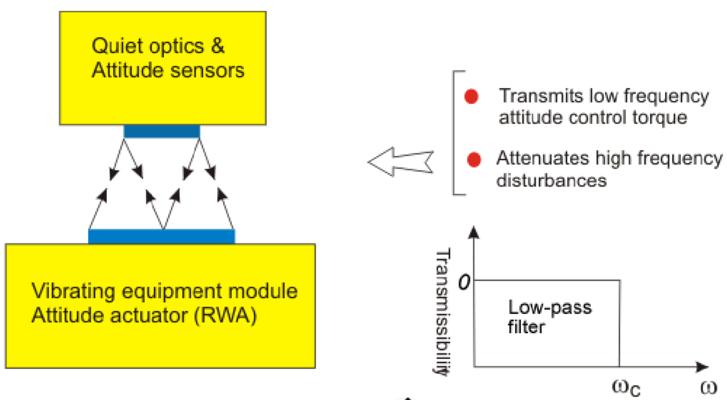
Aim: To use a number of smaller telescopes as an interferometer to achieve a resolution which could only be achieved with a much larger monolithic telescope.

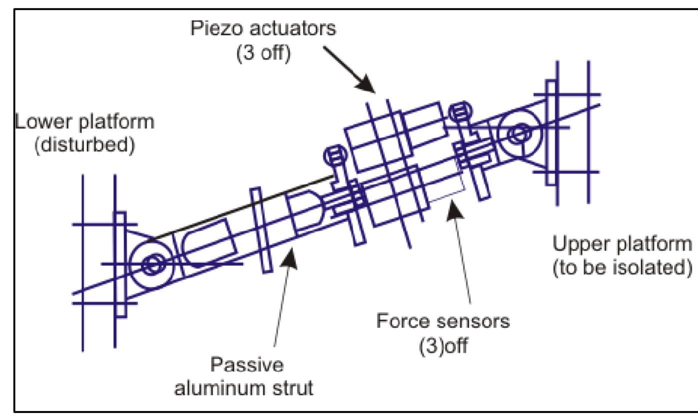
Error in the optical path length: **nanometer**
Pointing error of individual telescope: **nanoradian**



For a 6 DOF active Isolator

- Piezo - actuators offer transmission of low frequency torque and suppression of high frequency vibration isolation.
- Alternate to piezo -actuators are Terfenol - D rod, voice-coil etc.





Expanded view of the legs of a 6 DOF Isolator

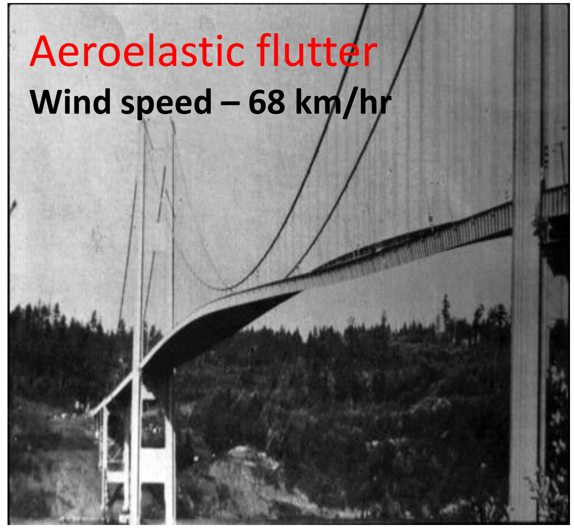
Ref.: Vibration Control of Active Structures, **A Premount**

Resonance: Detuning and Decoupling

Detuning

- We know that **excitation** or operating **close to natural frequency** would create **resonance** and consequently **large amplitude** of **vibration** of the system.
- Hence, it is always desirable to keep the **natural frequency** of the system away from the **excitation frequency**.
- The technique of change of system parameters like mass and stiffness to avoid resonance is known as Detuning.

Tacoma narrows suspension bridge, USA



Collapsed: November 7, 1940

Solid sides not allowing wind to pass through the bridge's deck

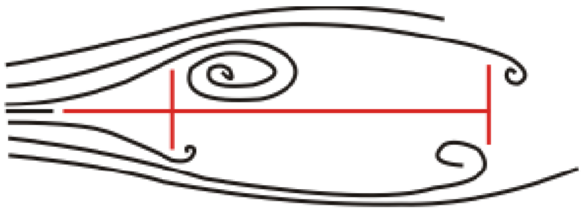
Re-opened: October 14, 1950

A parallel bridge also opened on July 15, 2007

Image: Wikipedia

Tacoma narrows suspension bridge

- The original open section was replaced by a closed-box section.
- In the modified design, the side trusses were lowered and tied at the bottom end by a horizontal truss.
- The new design is torsionally much stiffer than the original design.
- As a result, the fundamental torsional natural frequency exceeds the excitation frequencies generated even by a very high wind speed.
- In this way, the bridge was detuned from the excitation frequencies.



(a) Original Design

(b) Modified Design

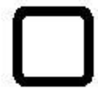
Section type	Flat	H-Sections (Typical)	I-Sections (Typical)	Hollow sections (Typical)
Section properties				
A Area	1	1	1	1
I_y (Vertical loading)	1	0,35	1	0,2
I_z (Horizontal loading)	0,2	3,5	1	3,5
J (Twisting)	1	1	1	100

Figure 1 Types of cross-section used as beams showing relative values of section properties

http://fgg-web.fgg.uni-lj.si/~/pmoze/esdep/master/wg07/l0910.htm

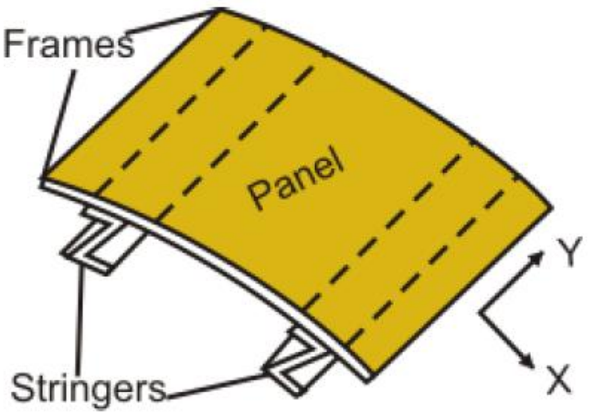
Decoupling

- In an assembly process, an attempt should be made such that the natural frequencies of the various components and the assembly itself are detuned from one another.
- The technique of decreasing the number of coupled resonators in a system is known as **decoupling**.
- A complex system like control board of automobiles consists of many subsystems. It is always attempted that the subsystems are integrated mechanically in such a way that the whole system behaves as a single united system with a natural frequency beyond excitation frequency level.
- The methods of detuning and decoupling we have suggested are more suitable for a system subjected to broad- band excitation.

When using any such method, it should be ensured that the new natural frequencies are not more harmful than the original ones.

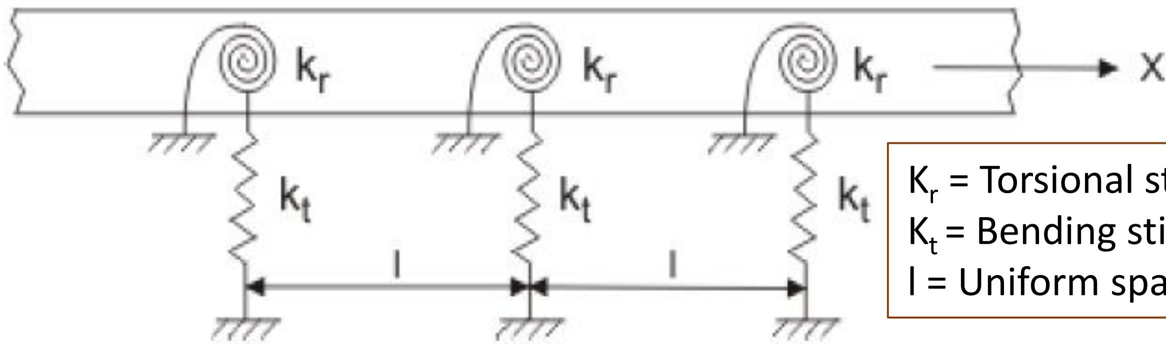
Application of the Concept in Aircraft Structure

- In a continuous system subjected to broad-band excitation, the **natural frequencies should be separated** as widely as possible so that not too many modes participate in the response.
- Jet noise often generates broad band excitation of modern aircraft fuselage.
- To **reduce** the effect of **vibration**, the fuselage structure is **stiffened** by using **stringers** in between the shell panels.



Shell panel with stringers

- As the **stringers are identical** and **equally spaced** and the excitation is predominant along the X-direction neglecting the curvature of the panel, the structure can be **modelled** as a **periodically supported beam.**



K_r = Torsional stiffness of stringers
K_t = Bending stiffness of stringers
l = Uniform spacing between the stringers

Periodically supported beam

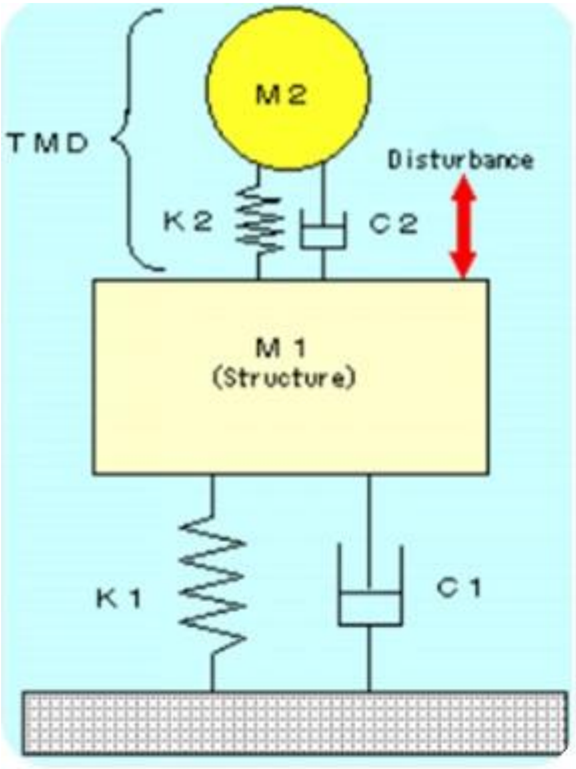
- The stringer cross-section should be such that it has a **low torsional stiffness** and a **high bending stiffness**.

- Thus, cross-section such as **Z-section** and top-hat section is preferred.

Tuned Mass Damper

General Principle

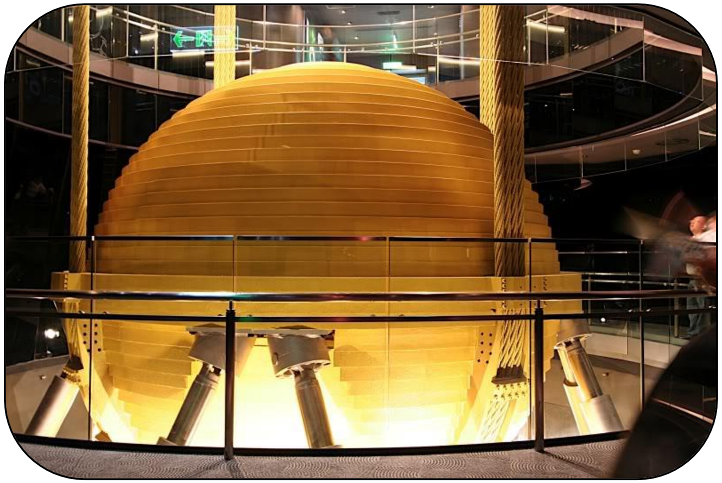
- The damper consists of a mass M_2, of a spring K_2 and of a damping C_2
- The value of M_2 and K_2 are chosen so that the moving part of the damper system can be tuned properly to the structure frequency.



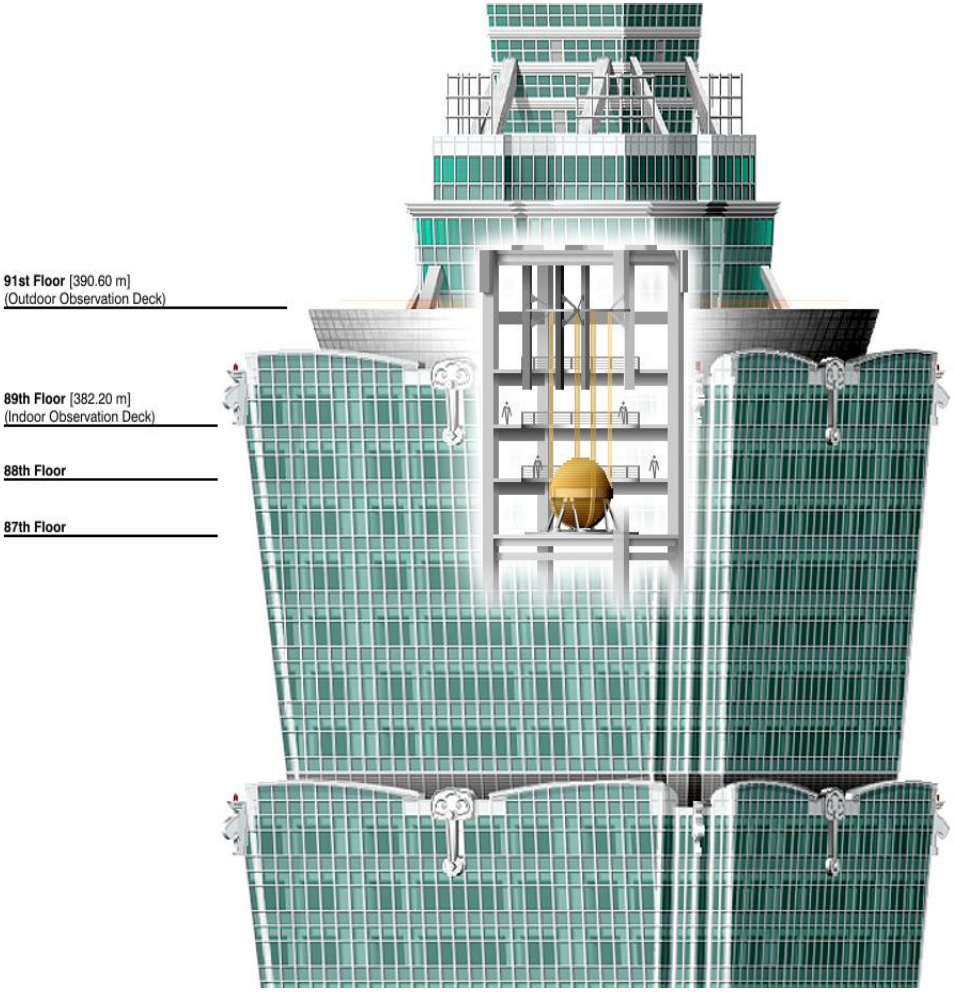
Mathematical part will be discussed later in detail

Application

- Tall and slender free-standing structures (Skyscrapers, bridges, chimneys, etc.)



Largest Tuned Massed Damper (TMD) in the world - 730 tons and 5.5 m diameter



Taipei 101 skyscraper, Taiwan

Image: Wikipedia

In the **next lecture**, we will learn about:

✓ Various Damping models

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