Lecture 11

MITIGATION OF WIND-INDEUCED BUILDING VIBRATIONS

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The 21st Century Center of Excellence Program
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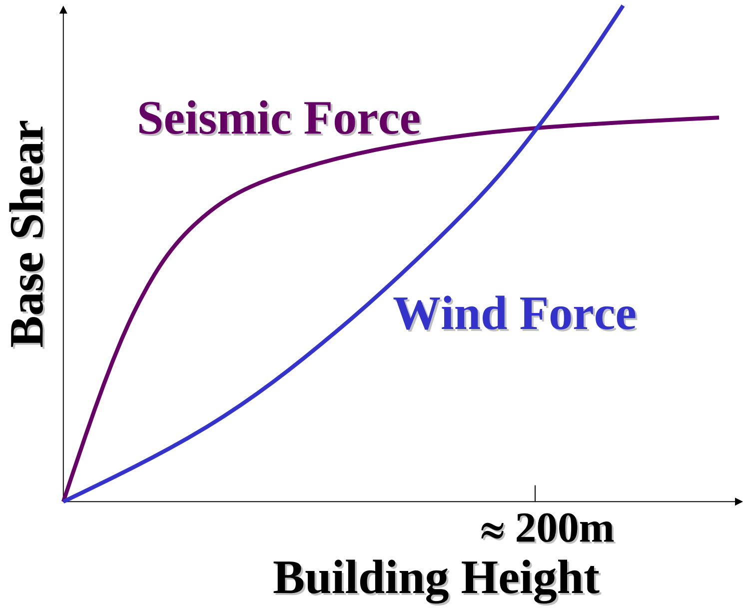
Topics

- Design criteria to be satisfied for wind-induced vibrations of buildings
- A review of various means to reduce wind-induced responses of buildings
- Some statistics on damping devices and buildings employing them in Japan
- Full-scale proof of efficiency of damping devices
- Points to note in designing damping devices and in evaluating their performance

Seismic Force & Wind Force



Seismic Force & Wind Force

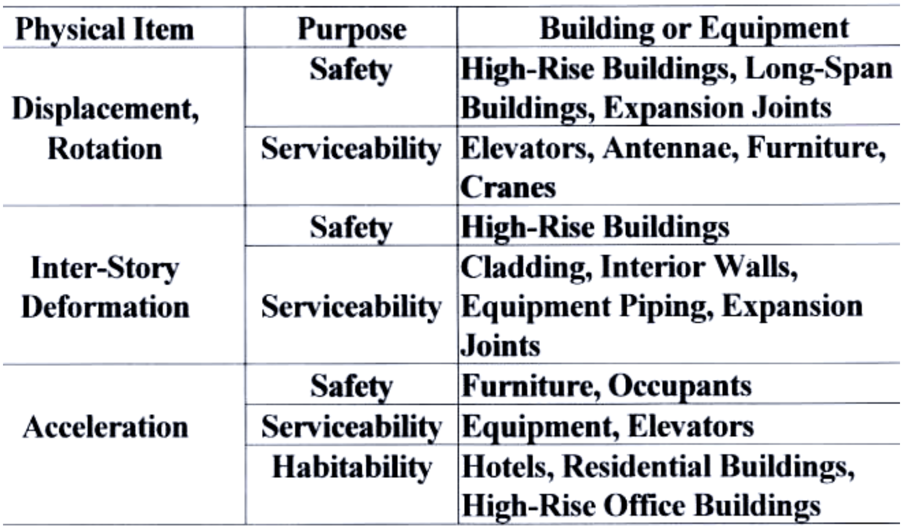
- Tall Buildings
  - Seismic Force：Inertial Force
    Light Weight & Flexible
  - Wind Force ：Surface Pressure
    Massive & Stiff
- Seismic Force＞Wind Force (H < 200m)
  - → Buildings in Japan are basically designed against seismic force.
  - → Vulnerable to Wind
  - → Auxiliary Damping Devices

Criteria for
Wind Resistant Design
in Japan

Wind Response Criteria

- **Level 0 Wind:** 1 - Year Recurrence
  Habitability Acceleration < H-1,2,3,4
- **Level 1 Wind:** 50 - Year Recurrence
  Functionality Drift Ratio < 1/200
  Stress < Allowable Stress
- **Level 2 Wind:** 500 - Year Recurrence
  Structural Safety Mostly Elastic
- **Instability :** 1000 - Year Recurrence
  Onset Wind Speed > U_{1000}

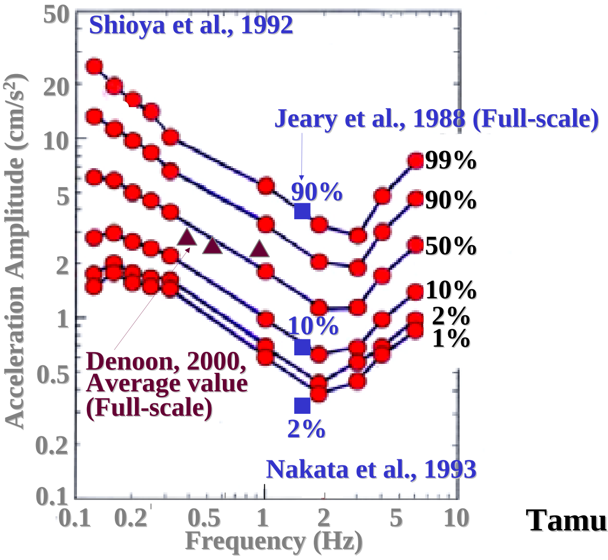
Wind-induced Vibration Problems to be Suppressed



Physical Item	Purpose	Building or Equipment
Displacement, Rotation	Safety	High-Rise Buildings, Long-Span Buildings, Expansion Joints
	Serviceability	Elevators, Antennae, Furniture, Cranes
Inter-Story Deformation	Safety	High-Rise Buildings
	Serviceability	Cladding, Interior Walls, Equipment Piping, Expansion Joints
Acceleration	Safety	Furniture, Occupants
	Serviceability	Equipment, Elevators
	Habitability	Hotels, Residential Buildings, High-Rise Office Buildings

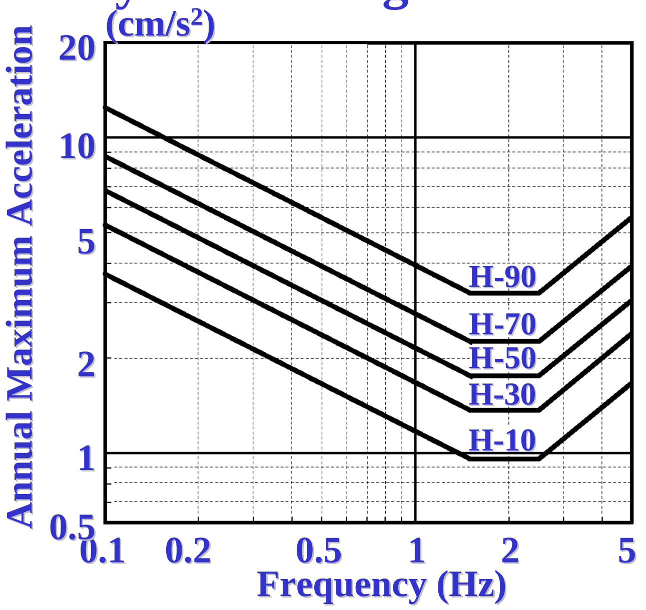
Habitability to Building Vibration

Probabilistic Human Perception Threshold

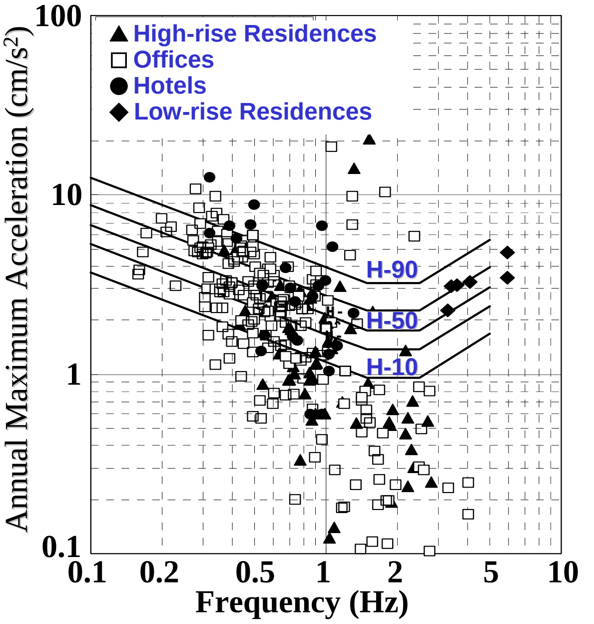


Tamura (1998)

AIJ Guidelines for the Evaluation of Habitability to Building Vibration (2004)

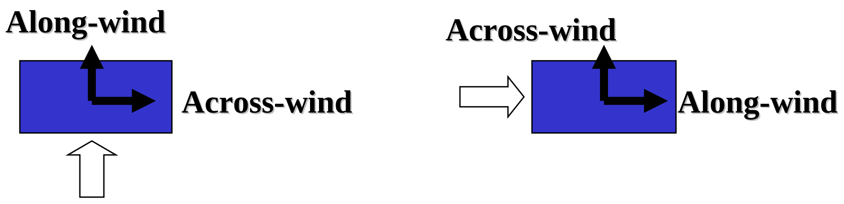


AIJ Guidelines 2004



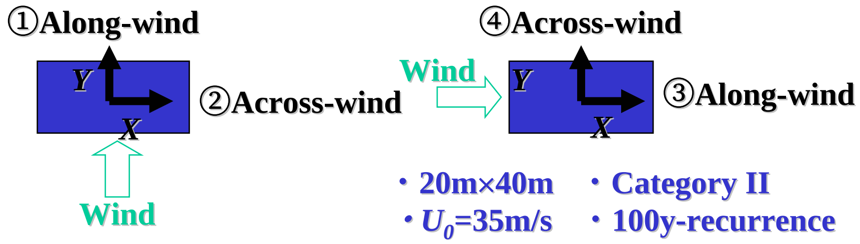
Characteristics of Wind-induced Response

Along-wind Response & Across-wind Response



- **Along-wind :**
  $$X(t) = X_m + x(t)$$
- **Across-wind: zero mean**
  $$Y(t) = y(t)$$

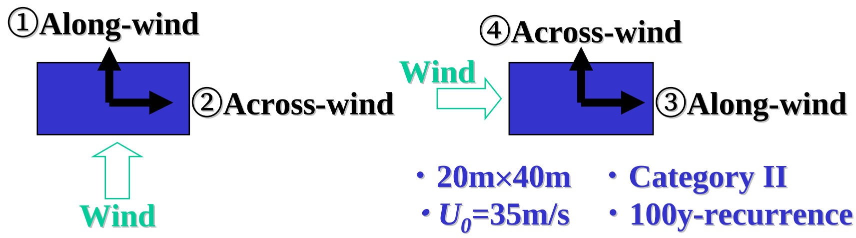
Along-wind Response & Across-wind Response



・20m×40m ・Category II
・U_0=35m/s ・100y-recurrence

- X-dir. ③Along-wind > ②Across-wind $H < 85\text{m}$
  ②Across-wind > ③Along-wind $H > 85\text{m}$
- Y-dir. ①Along-wind > ④Across-wind $H < 150\text{m}$
  ④Across-wind < ①Along-wind $H > 150\text{m}$

Along-wind Response & Across-wind Response



- 20m×40m
- U_0=35m/s
- Category II
- 100y-recurrence

- 0 < H < 150m: Max. Wind Load = ①Along-wind
- 150m < H < 250m: Max. Wind Load = ④Across-wind
- H > 300m: Max. Wind Load = ②Across-wind

Suppression of Wind-Induced Response

Suppression of Wind-Induced Response

- $M_S\ddot{Y} + C_S\dot{Y} + K_S Y$
  $= (1/2)\rho U^2 B^2 C_W(t) + F_C(t)$

M_S : Mass, C_S : Damping Factor, K_S : Stiffness,
Y : Displacement, U : Mean Wind Speed, ρ : Air-density,
$C_W(t)$: Aerodynamic Coefficient, $F_C(t)$: Control Force

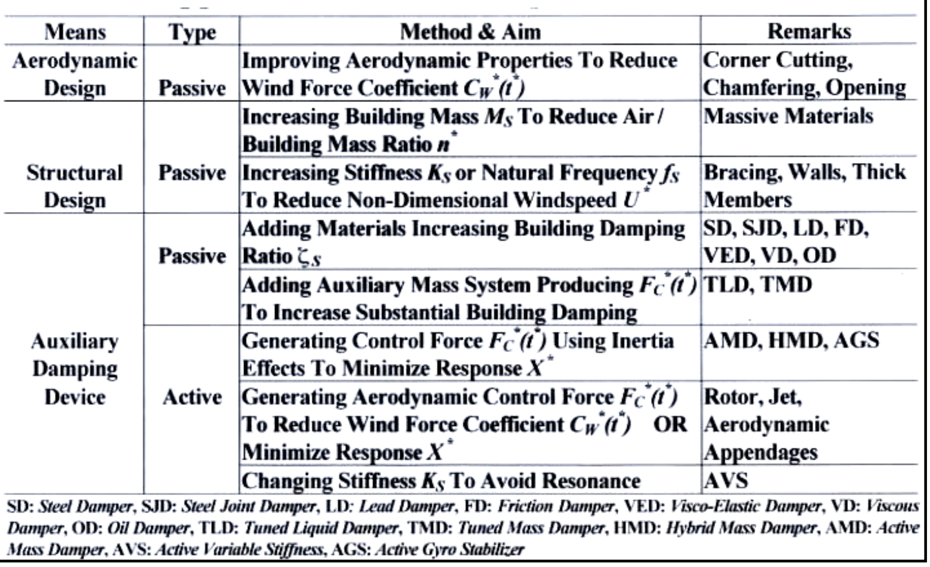
- $\ddot{Y}^* + 2\zeta_S \dot{Y}^* + Y^*$
  $= n^* U^{*2} C_W(t^*) + F_C^*(t^*)$

ζ_S : Damping Ratio, $Y^* = Y/B$: Reduced Displacement,
$U^* = U/\omega_S B$: Reduced Velocity, $n^* = \rho B^3/2M_S$: Mass Ratio,
$\omega_S = 2\pi f_S$: Building's Natural Circular Frequency,
$F_C^*(t^*)$: Non-dimensional Control Force for Unit Mass

Suppression of Wind-Induced Responses

- **Aerodynamic Means**
  - change in sectional shape
  - shear layer control
- **Structural Design**
  - increase in mass
  - increase in stiffness
- **Auxiliary Damping Devices**
  - increase in damping
  - vibration control

Various Means to Suppress Wind-induced Responses of Buildings



Means	Type	Method & Aim	Remarks
Aerodynamic Design	Passive	Improving Aerodynamic Properties To Reduce Wind Force Coefficient $C_W^*(t^*)$	Corner Cutting, Chamfering, Opening
Structural Design	Passive	Increasing Building Mass M_S To Reduce Air / Building Mass Ratio n^*	Massive Materials
		Increasing Stiffness K_S or Natural Frequency f_S To Reduce Non-Dimensional Windspeed U^*	Bracing, Walls, Thick Members
Auxiliary Damping Device	Passive	Adding Materials Increasing Building Damping Ratio ζ_S	SD, SJD, LD, FD, VED, VD, OD
		Adding Auxiliary Mass System Producing $F_C^*(t^*)$ To Increase Substantial Building Damping	TLD, TMD
	Active	Generating Control Force $F_C^*(t^*)$ Using Inertia Effects To Minimize Response X^*	AMD, HMD, AGS
		Generating Aerodynamic Control Force $F_C^*(t^*)$ To Reduce Wind Force Coefficient $C_W^*(t^*)$ OR Minimize Response X^*	Rotor, Jet, Aerodynamic Appendages
		Changing Stiffness K_S To Avoid Resonance	AVS

SD: *Steel Damper*, SJD: *Steel Joint Damper*, LD: *Lead Damper*, FD: *Friction Damper*, VED: *Visco-Elastic Damper*, VD: *Viscous Damper*, OD: *Oil Damper*, TLD: *Tuned Liquid Damper*, TMD: *Tuned Mass Damper*, HMD: *Hybrid Mass Damper*, AMD: *Active Mass Damper*, AVS: *Active Variable Stiffness*, AGS: *Active Gyro Stabilizer*

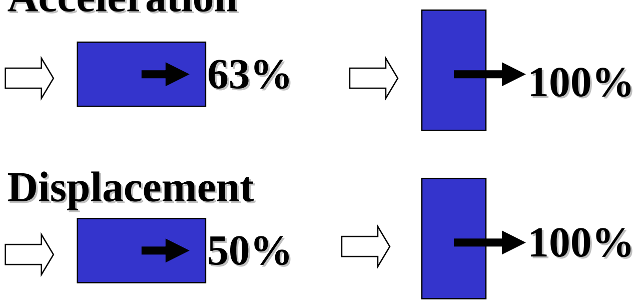
Aerodynamic Means to Suppress Wind-Induced Responses

Buildings and Tower-Like Structures

- Corner Cutting, Corner Chamfering
- Opening Holes
- Helical Strakes, Fins
- Shrouds, Splitter Plate
- Jets
- Rotors
- Vibrating Plate
- Changing Sectional Shapes
- etc.

Aerodynamic Design

- **Wind Direction (Building Orientation)**
  $B = 20\text{m}$, $D = 40\text{m}$, $H = 40\text{m}$



Max. Acceleration

63%

100%

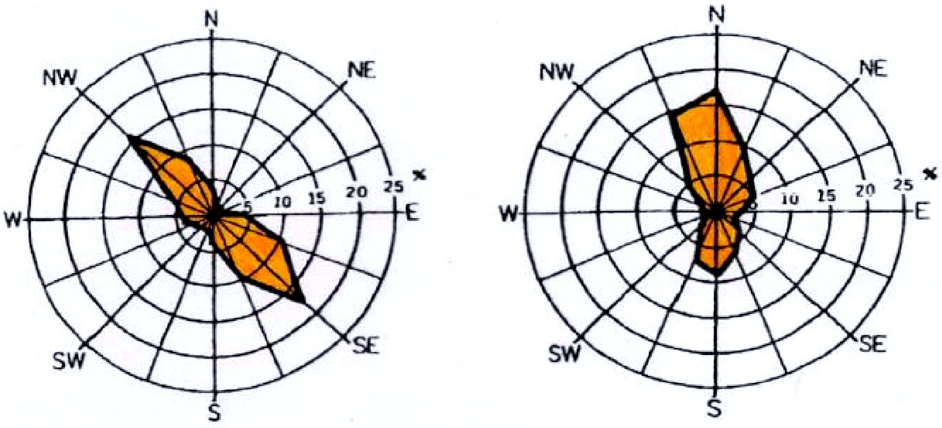
Max. Displacement

50%

100%

Aerodynamic Design

- **Wind Roses**

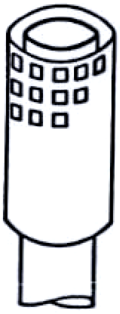


Sapporo

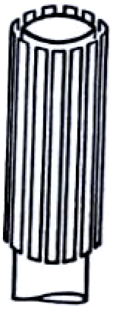
Tokyo

Aerodynamic Design

Helical Strakes



Shroud



Slats

Aerodynamic Design

Basic

Fins

Vented Fins

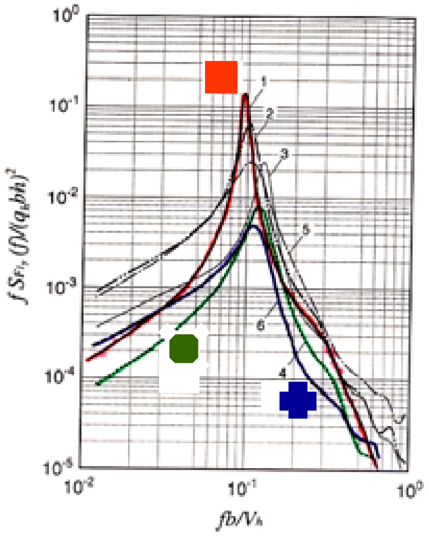
Slotted Corners

Chamfered Corners

Corner Cutting

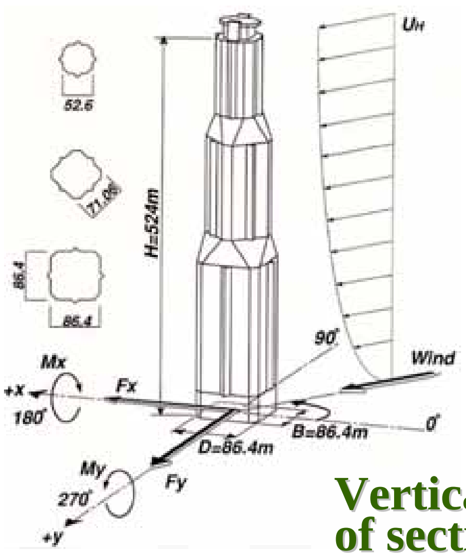
Kareem et al., 1999

Aerodynamic Design



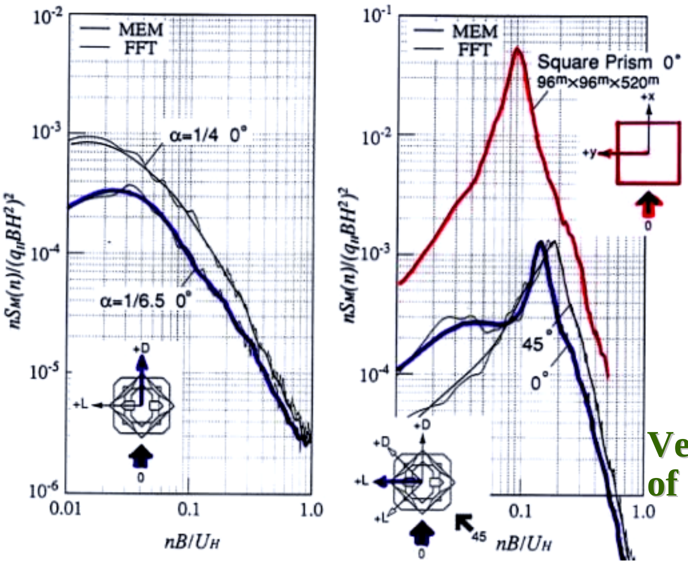
Across-wind
Force Spectra

Aerodynamic Design



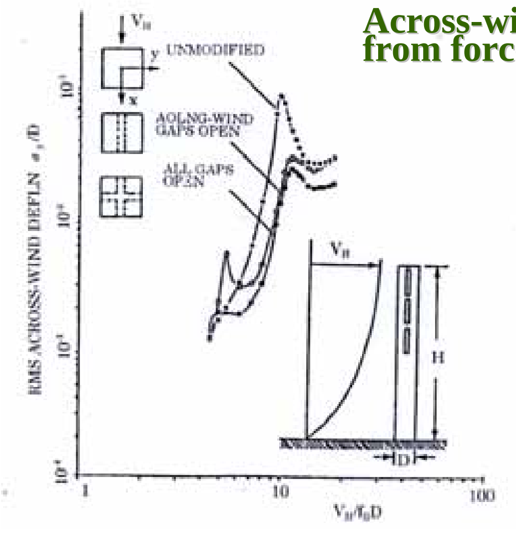
Vertical variation
of sectional shape

Aerodynamic Design



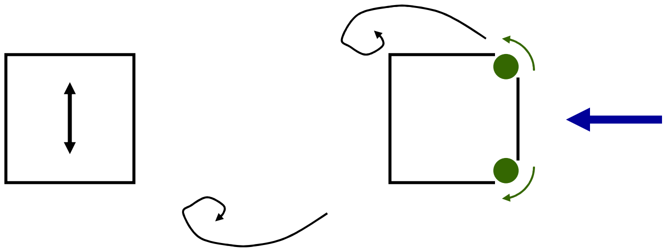
Vertical variation of sectional shape

Aerodynamic Design



Across-wind rms tip deflections from force balance tests (Isyumov)

Suppression of Wake Buffeting by Rotors



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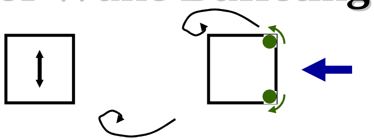

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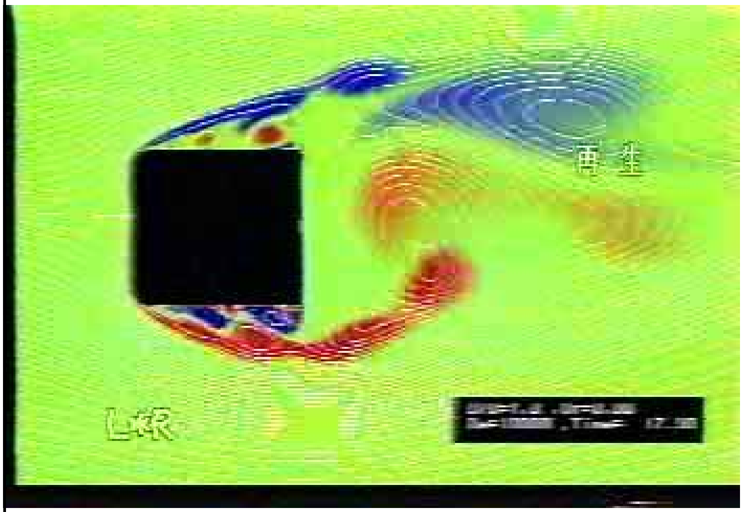
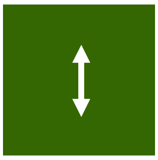
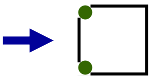




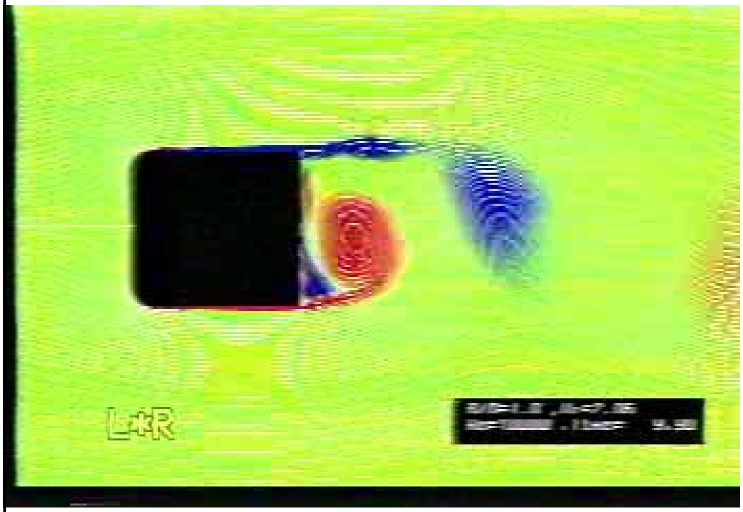
Vortex Shedding Frequency

$$f_v = \frac{SV}{D}$$

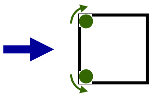


Rotors are not rotating.

Suppression of Wake Buffeting by Rotors



Vortex Shedding Frequency



Rotors are rotating.

$$f_v = \frac{SV}{D}$$

Structural Design

- **Increasing Stiffness K_S**
  - **- increases natural frequency f_S**
  - **- reduces non-dimensional windspeed U^***

↖ ***reduces member stresses***

- **Increasing Mass M_S**
  - **- reduces air/building mass ratio n^***
  - **- decreases natural frequency f_S**

Structural Design

- **Increase of Stiffness K_S**
  - **Reduction of Mean Displacement**

    $$Y_m \propto 1 / K_S$$
  - **Increase of Member Thickness**

    → Reduction of Stress σ
  - **Increase of Natural Frequency ω_S**

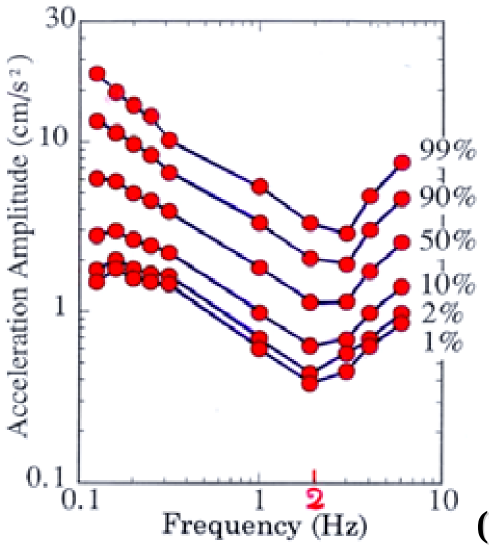
    → Reduction of Reduced Velocity $U^* = U/\omega_S B$

    → Reduction of Dynamic Displacement Y^*

    → Little Reduction of Acceleration $\ddot{Y}$?

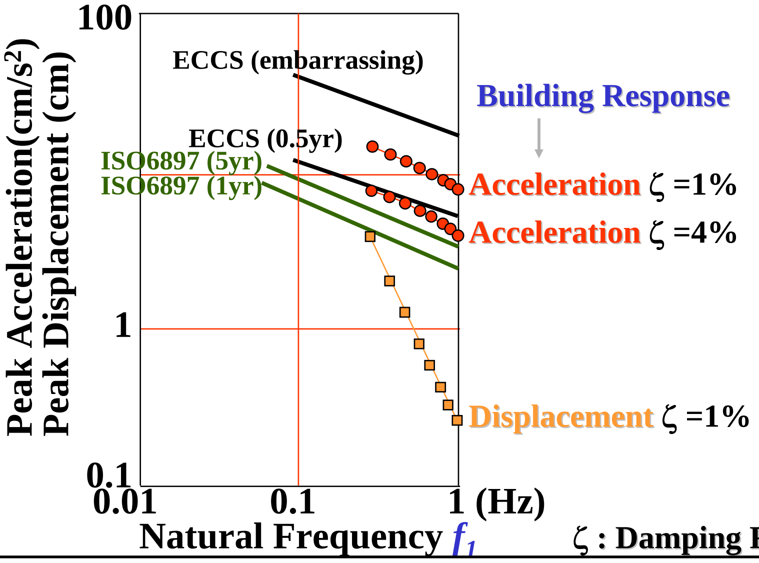
    → Almost No Improvement of Habitability !

Probabilistic Human Perception Threshold (Individual Differences)



(Tamura, 1998)

Increasing Stiffness K_S → *Increase of Natural Frequency* f_1



ζ : Damping Ratio

Structural Design

- **Increase of Mass M_S**
  - **Reduction of Mass Ratio $m^* = \rho B^3/2M_S$**
    - **→ Reduction of Dynamic Displacement Y^***
  - **Decrease in Natural Frequency ω_S**
    - **→ Increase of Reduced Velocity $U^*=U/\omega_S B$**
    - **→ Increase of Dynamic Displacement Y^***

☑**Increase of Seismic Force**

Increasing Mass M_S

- reduces air/building mass ratio n^*
- reduces natural frequency f_S
→ increases non-dimensional windspeed U^*

⇖ **occasionally increases displacement X_S**

⇖ **reduces acceleration $\ddot{X}_S$**

$\propto 1 / \sqrt{M_S}$

Increasing Mass M_S

- increases seismic inertia force
- increases sections of supporting members including foundation systems

- If M_S & K_S are both doubled, response X_S is halved.
- An auxiliary damper with a mass m_D $\quad M_S / 300$ can halve the response X_S .

Steel Buildings and Reinforced Concrete Buildings

	Steel		Reinforced Concrete
f_1	1	:	1.2
ζ_1	1	:	1.3
ρ_S	1	:	2.0
$A_{MAX,1yr}$	1	:	0.36
$X_{MAX,100yr}$	1	:	0.32

f_1 : Natural Frequency (1st mode)
ζ_1 : Damping Ratio (1st mode)
ρ_S : Building Mass per Unit Volume
$A_{MAX,1yr}$: Maximum Wind-Induced Acceleration (1yr rec.)
$X_{MAX,100yr}$: Maximum Wind-Induced Displacement (500yr rec.)

Auxiliary Damping Devices

Auxiliary Damping Devices

- **To Suppress Vibrations**

↖ **solves problems caused by vibrations**

- **To Guarantee a Certain Amount of Damping Force**

↖ **improves structural design reliability**

- ***significant uncertainty of inherent structural damping***

Uncertainty in Structural Damping

- C.O.V ≈ 70% (Havilland, 1974)

  $\zeta_S = 2\ \%$ ⇒ 0.6% ~ 3.4% (5.7 times difference)

  → 2.4 times difference of wind-induced Acceleration

- If a certain damping (e.g. $\zeta_{add} = 4\ \%$) is added artificially:

  $\zeta = \zeta_S + \zeta_{add}$ ⇒ 4.6% ~ 7.4% (1.6 times difference)

  → 1.3 times difference of wind-induced Acceleration

⇒ improves structural design reliability

Practically Used

Auxiliary Damping Systems

■Passive Damping Systems

- Hysteretic Dampers
  - Steel Dampers, Lead Dampers, Friction Dampers, Visco-Elastic Dampers
- Viscous Fluid Dampers
  - Viscous Damping Walls, Oil Dampers
- Mass Dampers
  - Tuned Mass Dampers, Tuned Liquid Dampers

■Active Control Systems

- Mass Dampers
  - Active Mass Dampers, Hybrid Mass Dampers
- Gyro Dampers
  - Active Gyro Stabilizer
- Non-Resonant Systems
  - Active Variable Stiffness

Auxiliary Damping Devices

■Tall Buildings

- **Along-wind Response (Buffeting)**

  Stationary Broad-band Random Vibration

  ・Viscous Damper ・Visco-elastic Damper
  ・Friction Damper ・Oil Damper ・TLD ・TMD

- **Across-wind Response**

  Stationary Narrow-band Random Vibration

  ・TMD ・TLD ・Visco-elastic Damper ・Viscous Damper
  ・Oil Damper ・Friction Damper

■Towers, Chimneys

- **Across-wind Response(Vortex Resonance)**

  Narrow-band Random Vibration (Quasi-harmonic Vibration)

  ・TMD ・TLD ・Oil Damper ・Impact Damper

Hysteretic Dampers

Control Force: $F_C(t) = -(C_E \dot{X}_S + K_E X_S)$

C_E **: Equivalent Damping Force Coefficient**
K_E **: Equivalent Restoring Force Coefficient**

C_E **and** K_E **depend on:**
- vibration frequency
- vibration amplitude
- temperature
- etc.

Parameters must be determined from experimental results.

Viscous Damping Walls

TV Shizuoka Media City Building

Outer Walls + Inner Wall + Hydrocarbon Polymer

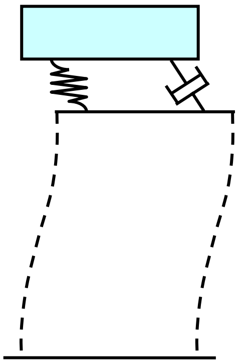
Dimensions of Walls: $H \times B$ = 290 cm × 290 cm
Gap Between Inner and Outer Walls: Δ = 6.5mm
Design Basic Viscosity: 60,000 Poise
Number of Walls Installed: 80(x-dir.) + 90(y-dir.) = 170

1st Mode Damping Ratio:
ζ = 20% (Summer 30°C)
ζ = 27% (Standard 20°C)
ζ = 35% (Winter 10°C)

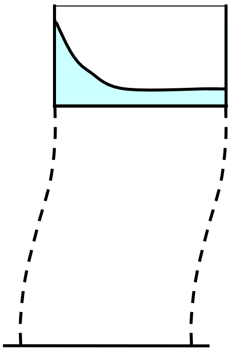
Design Formula: Voigt Model
= A Function of Basic Viscosity
Velocity Increasing Rate
Temperature & Frequency

Mass Dampers

Tuned Mass Dampers (TMD)



Tuned Liquid Dampers (TLD)



Tuned Mass Dampers

- **Control Force:**

$$F_C(t) = -m_D \ddot{X}_S$$
$$= k_D(x_D - X_S) + c_D(x_D - X_S)$$

- **Classical TMD Theory (Den Hartog):**

Optimum TMD Frequency & Damping

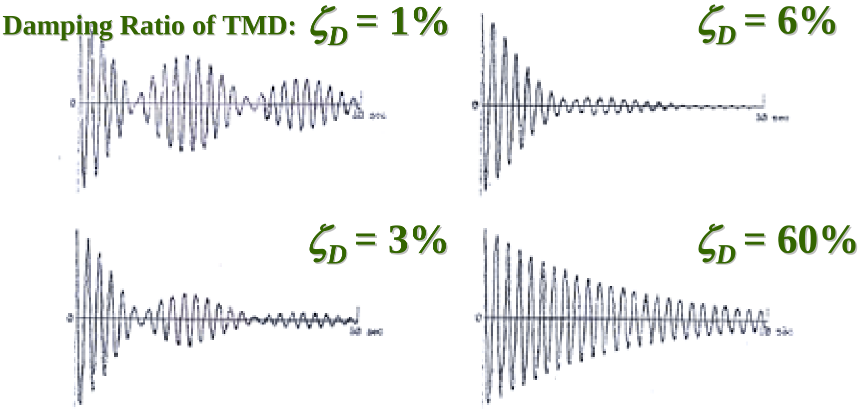
$$f_{D,opt} = \frac{f_S}{1+\mu_m}$$

$$\zeta_{D,opt} = \left\{\frac{3\mu_m}{8(1+\mu_m)^3}\right\}^{1/2}$$

μ_m **: Damper / Building Mass Ratio**

Effects of Damping Ratio of TMD

Damping Ratio of TMD:



Building Damping Ratio: $\zeta_S = 1\%$
Mass Ratio: $\mu_m = 1\%$

Optimized Tuned Mass Dampers

- Mass Ratio **Examples**

$$\mu_m = m_D / M_S \qquad = \quad 1\ \% \qquad 3\ \%$$

- Optimum Frequency and Damping

$$f_{D,opt} = \frac{f_S}{1+\mu_m} \qquad = \quad 0.99 f_S \qquad 0.97 f_S$$

$$\zeta_{D,opt} = \left\{\frac{3\mu_m}{8(1+\mu_m)^3}\right\}^{1/2} = \quad 6\ \% \qquad 10\ \%$$

- Additional Damping Ratio

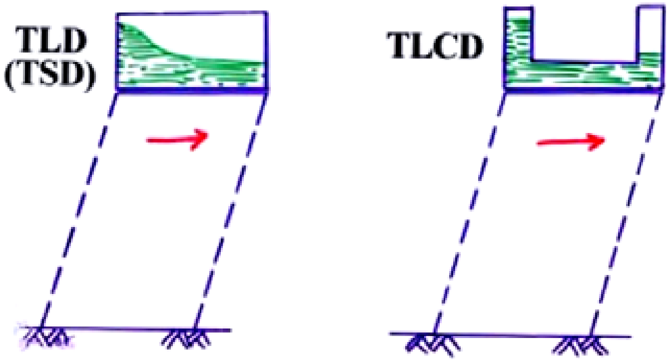
$$\zeta_{S,add} = \left\{\frac{\mu_m}{4(2+\mu_m)}\right\}^{1/2} = \quad 3.5\ \% \qquad 6\ \%$$

Tuned Mass Dampers

- **Maximum Stroke** $\delta_{MAX} = x_D - X_S \big|_{MAX}$
  - Available Space
  - Design of Mass Support System
    - → Upper Limit of Efficient Vibration Level
- **Friction Between Auxiliary Mass and Supporting System**
  - Design of Mass Supporting System
    - → Lower Limit of Efficient Vibration Level

Tuned Liquid Dampers

Sloshing Dampers **Liquid Column Dampers**



Tuned Liquid Dampers

- **TMD Model:**
  - **Effective Mass:** m_D
  - **Effective Damping:** c_D
    - **of water is generally less than optimum value**
  - **→ Floating Particles, Nets, Projections, etc.**
- **Amplitude Dependence**
- **Depth of Liquid**
- **Shape of Containers**

Tuned Liquid Dampers

- absorb building vibration energy as kinetic energy of liquid motion
- dissipate energy through:
  - shear of liquid
  - friction between liquid and container walls, nets, etc.
  - collision of floating particles
  - etc.

TLD Frequency

- Circular Container

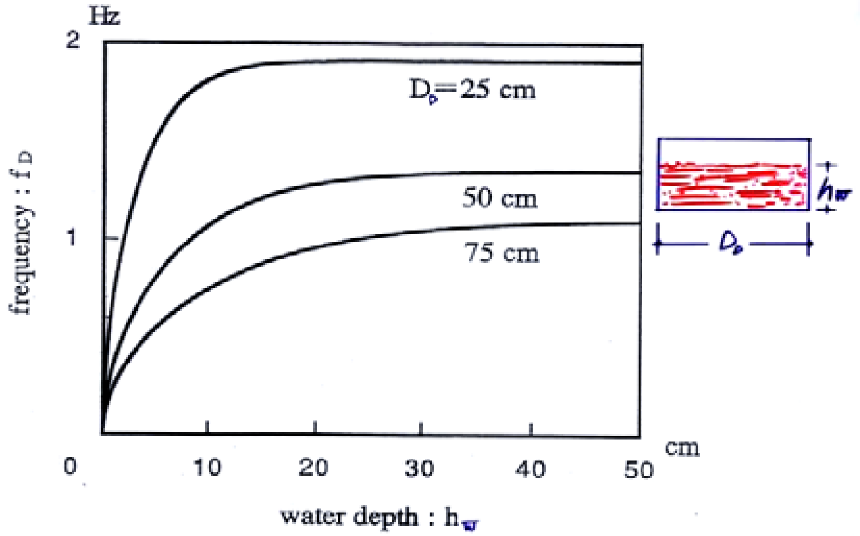
$$f_D = \frac{1}{2\pi}[\frac{3.67g}{D_D}\tanh(\frac{3.67h_W}{D_D})]^{1/2}$$

- Rectangular Container

$$f_D = \frac{g}{4\pi D_D}\tanh(\frac{\pi h_W}{D_D})]^{1/2}$$

h_W : Water Depth
D_D : Container Diameter or Length
g : Gravity Acceleration

Fundamental Natural Frequency of Sloshing Motion of Water Inside a Circular Cylindrical Vessel



Advantages in TLDs

- Low Initial and Running Cost
- Low Maintenance
- Efficient from Small Amplitude Level to Large Amplitude Level
- Ease of Application to Existing Buildings

etc.

———————————————

TLCVA (Kwok et al.)
Active TLCD (Kareem)

Active Control Systems

- Active Mass Damper
- Hybrid Mass Damper
- Active Gyro Damper
- Active Variable Stiffness System
- Electro-rheological Fluid Damper
- Magneto-rheological Fluid Damper
- etc.

Active Control Systems

Equation of Building Motion

$$M_S \ddot{X}_S + C_S \dot{X}_S + K_S X_S = F_W(t) + F_C(t)$$

Feed-Forward Active Control

Control Force $F_C(t) = -F_W(t)$ **Wind Force**

- requires accurate prediction of $F_W(t)$

ex. Active Variable Stiffness (AVS)

Feed-Back Active Control

$$F_C(t) = F_{CA}(X_S{:}t)$$

Feed-Back Active Control

- State Equation :

$$\{\dot{X}_S(t)\} = [A]\{X_S(t)\} + [B]\{F_C(t)\} + [D]\{F_W(t)\}$$

$\{X_S(t)\}$: State Vector, $\{F_W(t)\}$: Wind Force

- Control Force : $\{F_C(t)\} = [G]\{X_m(t)\}$

$[G]$: Feed-Back Gain Matrix

$\{X_m(t)\}^{T} \overset{ex.}{=} \{X_S, \dot{X}_S, x_D, \dot{x}_D\}$: Monitored State Vector

- Evaluation Function to be Minimized

(LQ Control): Riccati Equation

$$J = \int_0^{t_f} \left[\{X_m(t)\}^{T}[Q]\{X_m(t)\} + \{F_C(t)\}^{T}[R]\{F_C(t)\}\right] dt$$

$[Q]$ and $[R]$: Weighting Matrix

☐ Spillover   Collocation

HMD Operation

- No Vibration

  $X_S < A_L$ Waiting Mode

- Small Amplitude Range

  $A_L \leqq X_S < A_M$ Active Mode

- Large Amplitude Range

  $A_M \leqq X_S < A_G$ Passive Mode

- Extremely Large Amplitude Range

  $A_G \leqq X_S$ Shut Down (Locked)

Kansai International Airport Tower Employing HMD (H=86m)

HMD installed in Kansai International Airport Tower

(5×10^3kg×2)

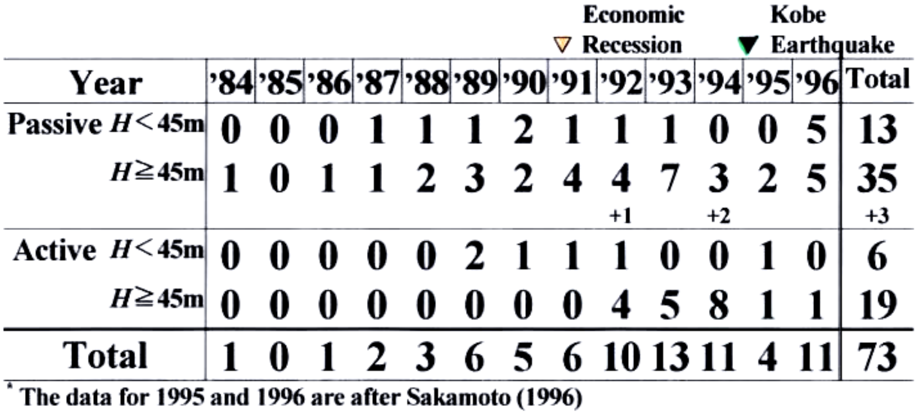
Active Gyro Damper

(by courtesy of Taisei Corporation)

Statistics on Buildings Employing Damping Devices in Japan (as of 1997)

Buildings Employing Auxiliary Damping Devices in Japan

☐Yearly Variation of Number of Buildings



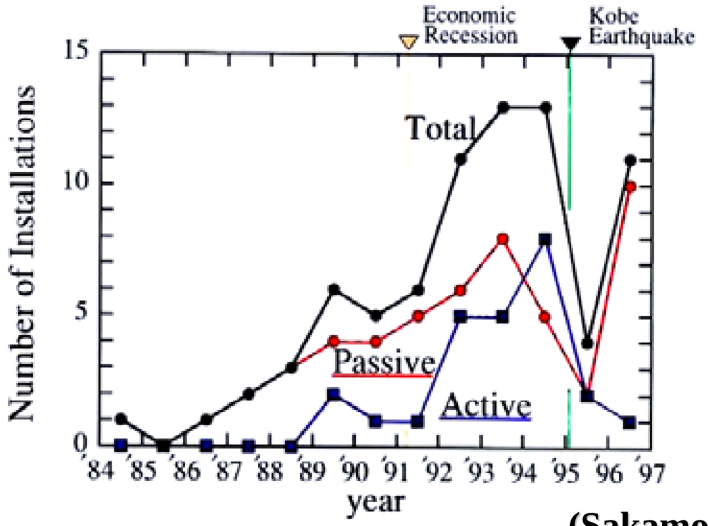
Economic ▽ Recession

Kobe ▼ Earthquake

Year		’84	’85	’86	’87	’88	’89	’90	’91	’92	’93	’94	’95	’96	Total
Passive	$H<45$m	0	0	0	1	1	1	2	1	1	1	0	0	5	13
	$H\geqq 45$m	1	0	1	1	2	3	2	4	4	7	3	2	5	35
										+1		+2			+3
Active	$H<45$m	0	0	0	0	0	2	1	1	1	0	0	1	0	6
	$H\geqq 45$m	0	0	0	0	0	0	0	0	4	5	8	1	1	19
Total		1	0	1	2	3	6	5	6	10	13	11	4	11	73

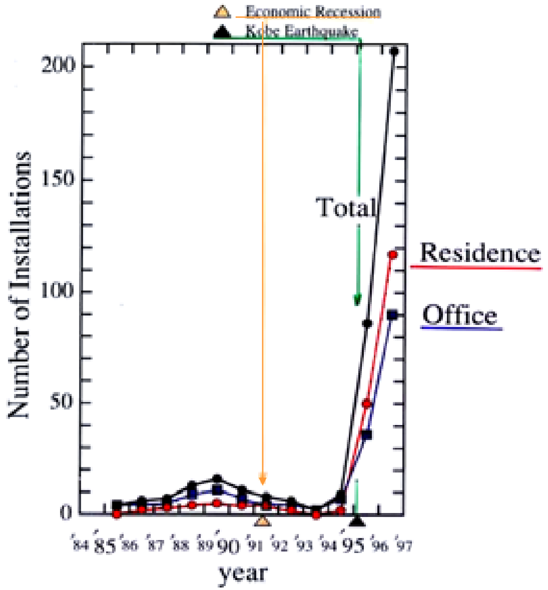
* The data for 1995 and 1996 are after Sakamoto (1996)

Number of Buildings Employing Auxiliary Damping Devices in Japan



(Sakamoto, 1996)

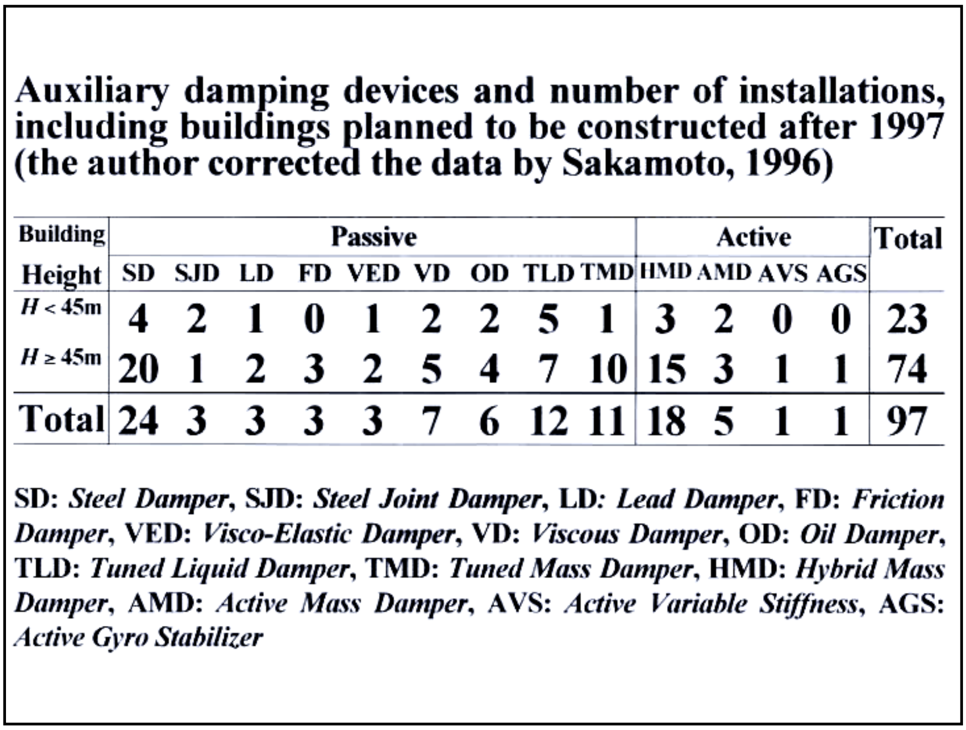
Number of Base-isolated Buildings Which Structural Design was Approved by The Building Center of Japan



Installation of Damping Devices Before and After Kobe Earthquake

☐ Before Kobe Earthquake
- by designers and researchers
- for high-rise buildings
- to improve habitability

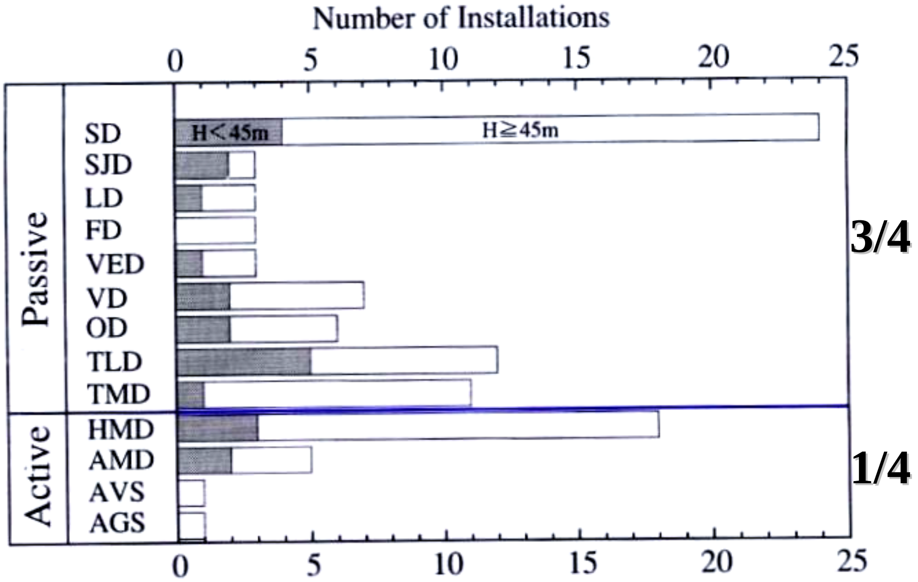
☐ After Kobe Earthquake
- by building owners
- also for middle-height buildings
- demanding safer buildings



Auxiliary damping devices and number of installations, including buildings planned to be constructed after 1997 (the author corrected the data by Sakamoto, 1996)

Building Height	Passive									Active				Total
	SD	SJD	LD	FD	VED	VD	OD	TLD	TMD	HMD	AMD	AVS	AGS	
$H < 45\text{m}$	4	2	1	0	1	2	2	5	1	3	2	0	0	23
$H \geq 45\text{m}$	20	1	2	3	2	5	4	7	10	15	3	1	1	74
Total	24	3	3	3	3	7	6	12	11	18	5	1	1	97

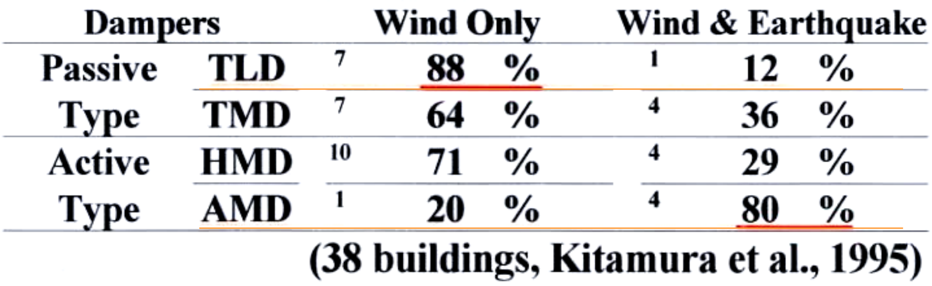
SD: *Steel Damper*, SJD: *Steel Joint Damper*, LD: *Lead Damper*, FD: *Friction Damper*, VED: *Visco-Elastic Damper*, VD: *Viscous Damper*, OD: *Oil Damper*, TLD: *Tuned Liquid Damper*, TMD: *Tuned Mass Damper*, HMD: *Hybrid Mass Damper*, AMD: *Active Mass Damper*, AVS: *Active Variable Stiffness*, AGS: *Active Gyro Stabilizer*



Auxiliary damping devices and number of installations, including buildings planned to be constructed after 1997

(The author corrected the data in Sakamoto,1996)

Target Excitations on Design Stage



Dampers			Wind Only		Wind & Earthquake
Passive	TLD	7	88 %	1	12 %
Type	TMD	7	64 %	4	36 %
Active	HMD	10	71 %	4	29 %
Type	AMD	1	20 %	4	80 %

(38 buildings, Kitamura et al., 1995)

Active Mass Dampers

-- are designed only for

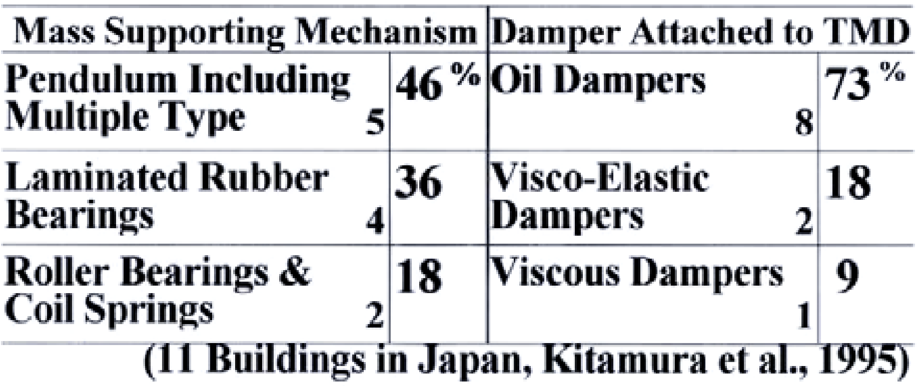
- strong wind
- middle class earthquakes

☐Application to

- extremely strong wind
- extremely strong earthquakes

are still on the research stage

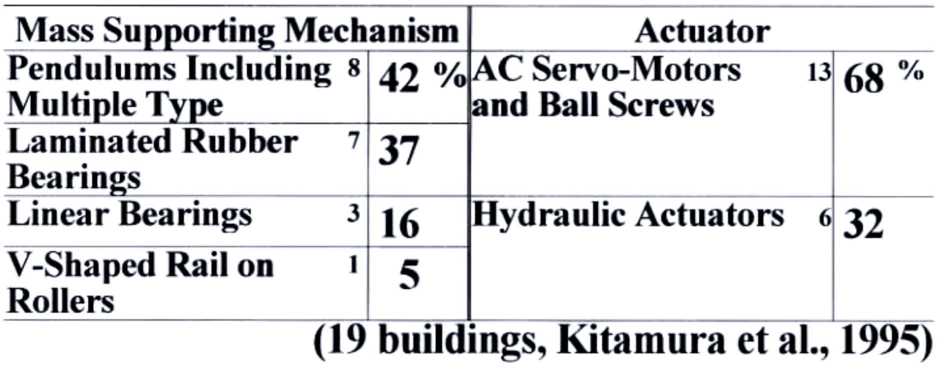
Mass Supporting Mechanisms and Dampers for TMD



Mass Supporting Mechanism		Damper Attached to TMD	
Pendulum Including Multiple Type 5	46 %	Oil Dampers 8	73 %
Laminated Rubber Bearings 4	36	Visco-Elastic Dampers 2	18
Roller Bearings & Coil Springs 2	18	Viscous Dampers 1	9

(11 Buildings in Japan, Kitamura et al., 1995)

Mass Supporting mechanisms and Actuators for AMDs and HMDs



Mass Supporting Mechanism		Actuator	
Pendulums Including Multiple Type 8	42 %	AC Servo-Motors and Ball Screws 13	68 %
Laminated Rubber Bearings 7	37		
Linear Bearings 3	16	Hydraulic Actuators 6	32
V-Shaped Rail on Rollers 1	5		

(19 buildings, Kitamura et al., 1995)

Mass Ratio and Maximum Stroke

Most Important Design Parameters:

Mass Ratio $\mu_m = m_D/M_S$
Maximum Stroke $\delta_{MAX} = x_D - X_S \mid_{MAX}$

of Mass Effective Dampers:

Tuned Mass Damper (TMD)
Tuned Liquid Damper (T L D)
Hybrid Mass Damper (HMD)
Active Mass Damper (AMD)
etc.

Mass Damper Systems

- **Accumulated Kinetic Energy:**

$$E_D \propto \mu_m \delta_{MAX}$$

$\mu_m = m_D / M_S$: Mass Ratio
$\delta_{MAX} = x_D - X_S \mid_{MAX}$: Maximum Stroke

↓**represents vibration reduction ability**

Mass Ratio and Stroke of Actual Dampers in Japan

- Tuned Mass Damper
- Active Mass Damper
- Hybrid Mass Damper

Accumulated Kinematic Energy of TMD

- Accumulated Kinematic Energy: E_D

$$E_D \propto \frac{m_D}{M} \times \delta_D$$

Mass Ratio

Mass Ratio

- TMD only for Wind

$$\frac{m_D}{M} \times \delta_D < 0.2\text{cm}$$

- TMD for Wind & Earthquake

$$\frac{m_D}{M} \times \delta_D > 0.5\text{cm}$$

Accumulated Kinematic Energy of AMD

- **Accumulated Kinematic Energy: E_D**

$$E_D \propto \frac{m_D}{M} \times \delta_D$$

Mass Ratio

Mass Ratio

■**AMD**

$$\frac{m_D}{M} \times \delta_D < 0.5\text{cm}$$

$$\approx \frac{1}{2} \text{ of TMD}$$

Maximum Control Force

Designed for Wind Force Only

$$F_{C,\,MAX} \leqq 0.10\, m_D g$$

Designed for Wind and Seismic Forces

$$F_{C,\,MAX} \quad 0.15 \sim 0.25 m_D g$$

Numerical Example of Maximum Stroke and Control Force

- **Analytical Model: 10DOF System**
- **Building: $B \times D$ = 50m×50m, H = 200m**
- **Across-Wind Excitation: Wind Tunnel Data**
- **AMD and HMD:**

  Mass Ratio $\mu_m = m_D / M_S$ = 1%
- **Windspeed: U_{10} = 20m/s (1-yr rec.)**
- **Criteria: H-2 (AIJ Guidelines) Residences**

  H-3 (AIJ Guidelines) Offices

Efficiency of TMD, HMD and AMD for Suppressing Wind-Induced Responses

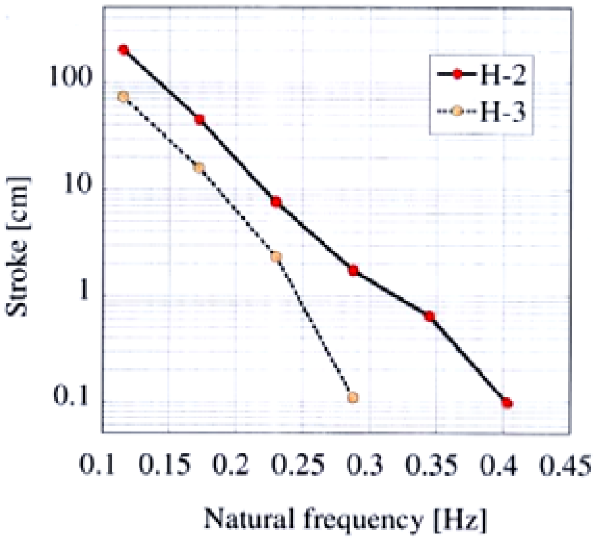
- **LQG Design**

  Minimize:

$$J = \int \{ q_T \, x_T(t)^2 + q_S \, x_S(t)^2 + q_D \, f_D(t)^2 \} dt$$

q_T, q_S, q_D : **Weighting Constants**
$x_T(t)$: **Tip Displacement**
$x_S(t)$: **Damper Stroke**
$f_D(t)$: **Control Force**
q_T / q_D : **varied**
q_S / q_D : **constant**

Variation of Maximum Stroke of AMD to Satisfy AIJ Guidelines *H-2* and *H-3* with Natural Frequency of a 200m High Building



Full-Scale Proof

Efficiency of Damping Devices for Suppressing Wind-Induced Responses

Full-Scale Proof of Efficiency of TLD

Nagasaki Airport Tower	(1987)
Yokohama Marine Tower	(1987)
Shin-Yokohama Prince Hotel	(1992)
Tokyo International Airport Tower	(1993)

- **The TLD reduced the acceleration responses during strong winds down to 1/2 - 1/3 of the response without the TLD when the water mass ratio to the total mass of structures was around 0.3% - 0.6%.**

Efficiency of Dampers During Strong Winds

- Full-Scale Measurements of Wind-Induced Responses of Buildings with/without Dampers
- Tuned Liquid Dampers
- Hybrid Mass Dampers

etc.

Buildings Employing TLDs

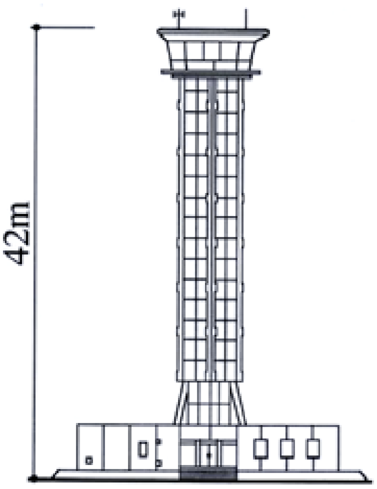
Buildings	H	M_S	f_S (Hz)		ζ_S (%)		$D_D \times h_D$	n	N	h_W	f_D	m_D	μ_{m1}**
	(m)	(10^6kg)	x	y	x	y	(m)×(m)			(m)	(Hz)	(10^3kg)	(%)
NAT	42	0.17	1.07	1.07	0.9	0.9	0.38×0.50	7	25	0.048	1.02	0.95	1.5
YMT	101	0.54	0.55		0.6		0.49×0.50	10	39	0.021	0.54	1.54	0.98
SYPH	149	26.4	0.31	0.32	1.0	1.0	2.00×2.01	9	30	0.120	0.31	101.7	0.97
TIAT*	78	3.24	0.77	0.98	0.84	1.24	0.60×0.13	1	1404	0.053	0.74	22.7	3.5

h_D : height of a vessel, n : number of layers for each vessel,
N : number of vessels installed

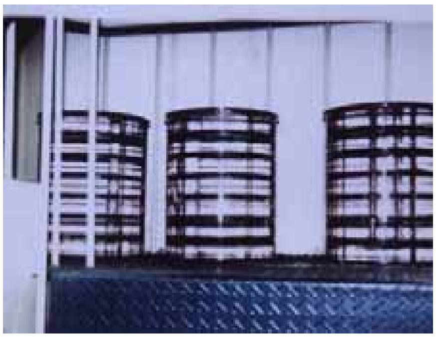
* The damper is designed for the x - direction only. Floating particles (7.5% of m_D) are used.

** Damper / building mass ratio μ_{m1} is the ratio of the total water mass m_D to the fundamental generalized mass M_{S1} where the first mode is defined as unity at the top.

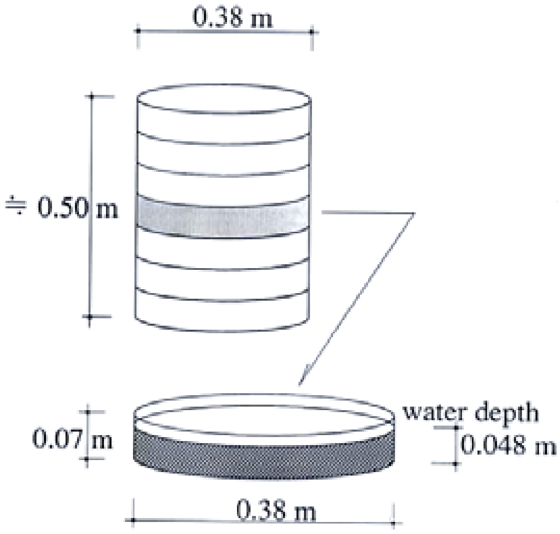
Nagasaki Airport Tower Employing TLDs (March 1987)



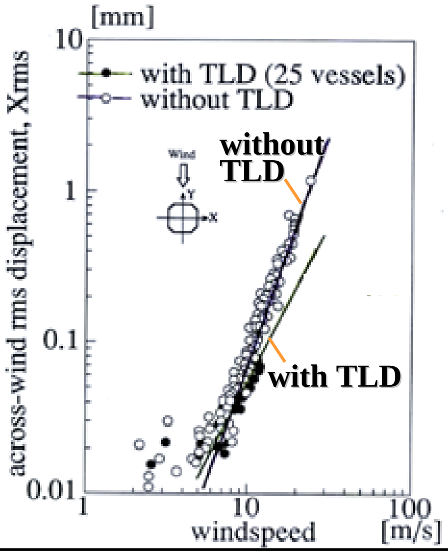
TLD Vessels Installed in Nagasaki Airport Tower



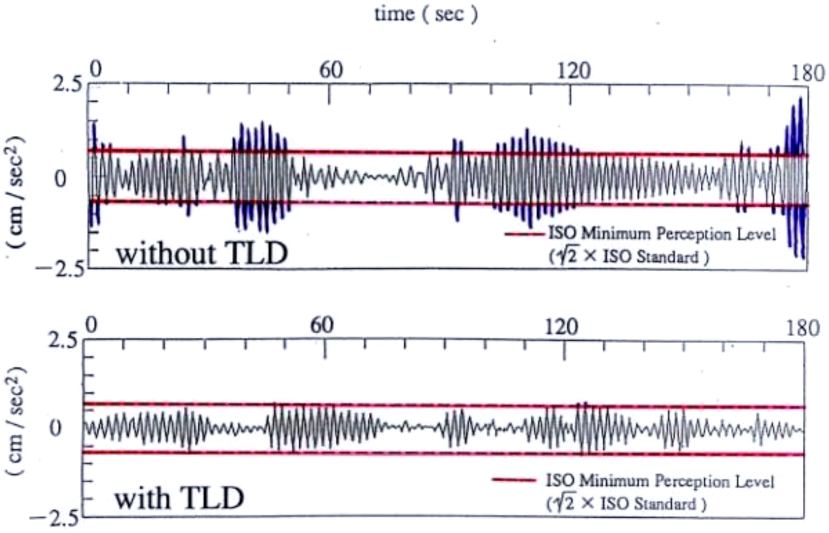
TLD Vessel for Nagasaki Airport Tower



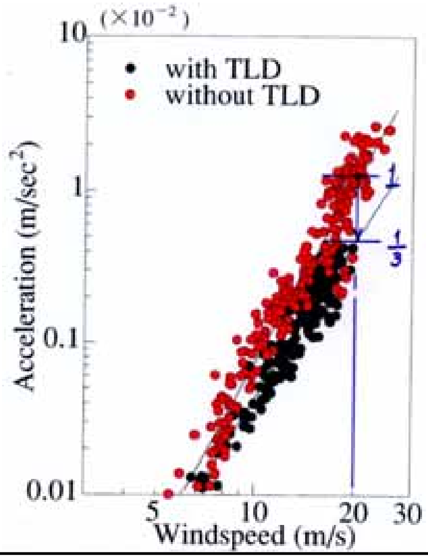
Across-wind Responses of Nagasaki Airport Tower With/Without TLDs



Across-wind Accelerations of Yokohama Marine Tower With/Without TLDs



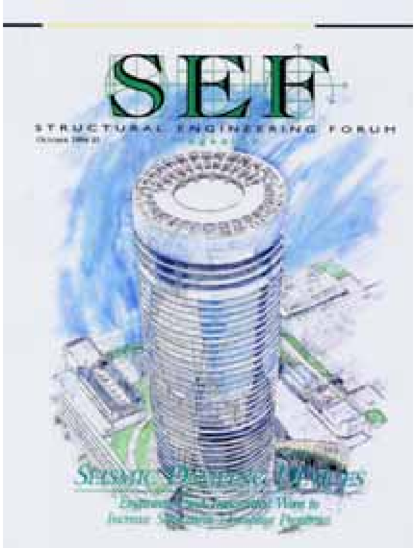
Across-wind r.m.s. Accelerations of Yokohama Marine Tower With/Without TLDs



Shin-Yokohama Prince Hotel Employing TLDs (March 1992)

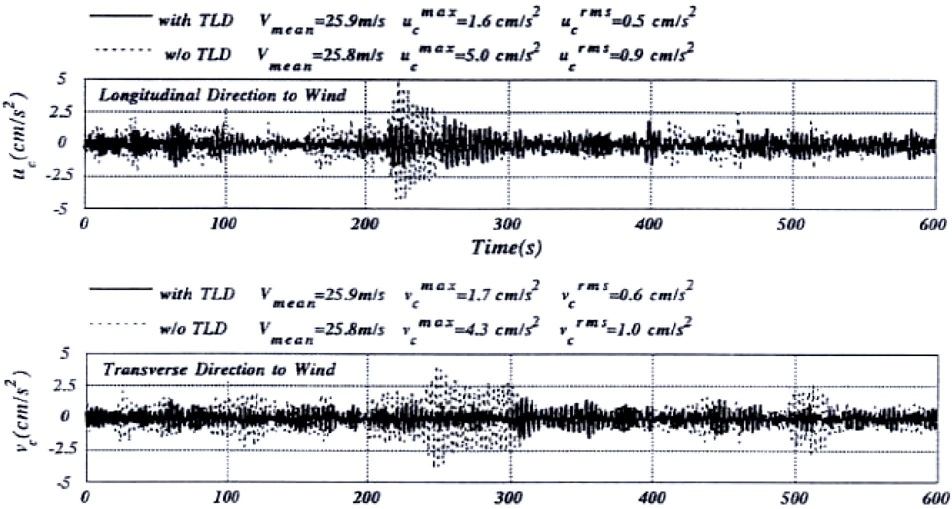
H = 149m

Shin-Yokohama Prince Hotel Employing TLDs (March 1992)



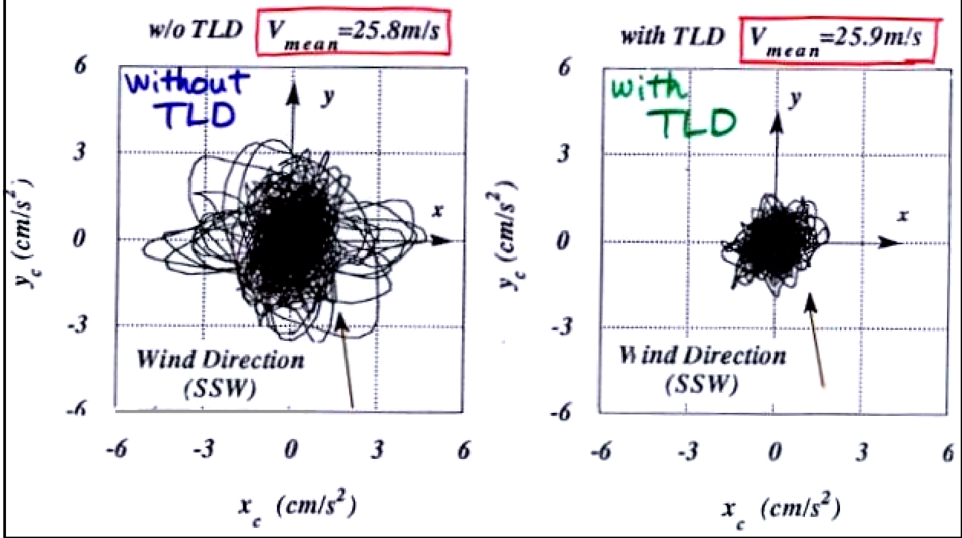
***H* = 149m**

Wind-induced Accelerations of Shin-Yokohama Prince Hotel



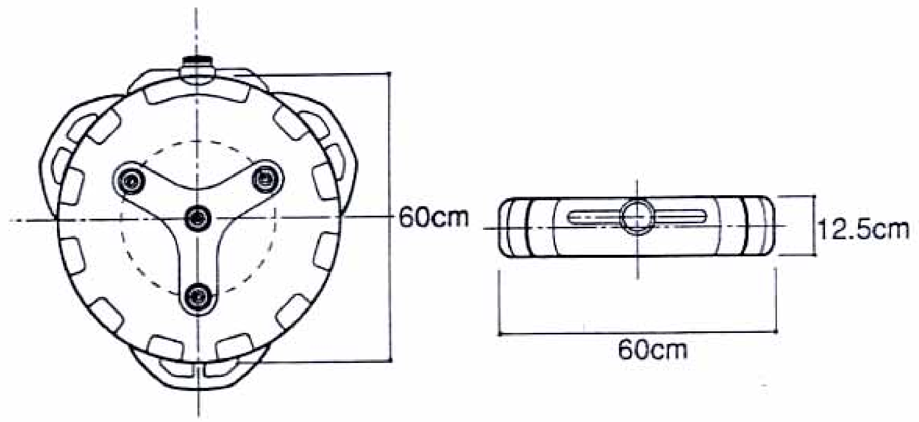
(Wakahara et al., 1993)

Trajectories of Wind-induced Accelerations of Shin-Yokohama Prince Hotel



TLD Vessels Installed in Tokyo International Airport Tower

TLD Vessel Installed in Tokyo International Airport Tower

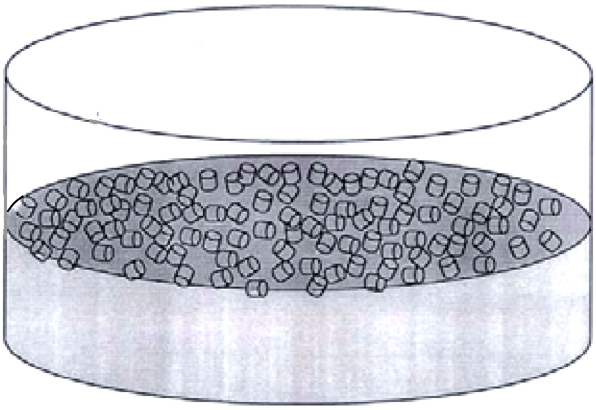


TLD Vessel Installed in Tokyo International Airport Tower

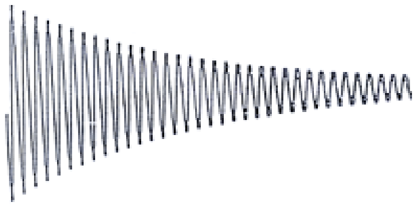
$D \times H$ (cm × cm)	N	f_D (Hz)	M_W (kg)	m_F (kg)	m_D (kg)	$\mu = \frac{m_D}{M_1}$ (%)
60 × 12.5	1404	0.74	14.9	1.2	2.27×10^4	3.2 (x-dir.) 2.0 (y-dir.)

Number of vessels
Sloshing frequency
Water mass in a vessel
Mass of floating particles in a vessel
Total mass of TLDs (water + floating particles)
Mass ratio of TLDs to 1st generalized mass of tower

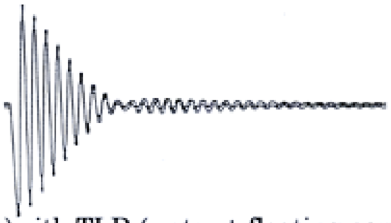
Floating Particles



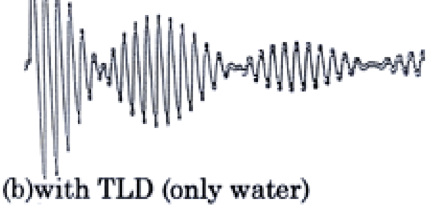
Efficiency of Floating Particles



(a)without TLD



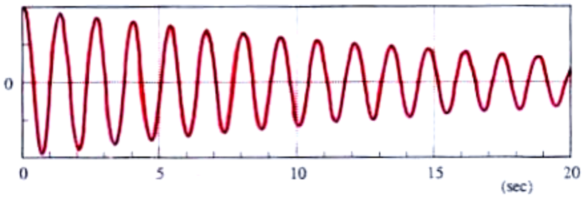
(c)with TLD (water + floating particles)



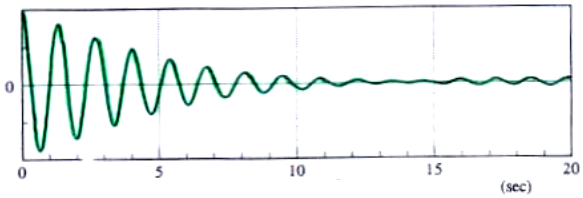
(b)with TLD (only water)

Damped-free oscillations of building model with/without TLD

Damped free components extracted by Random Decrement Technique from wind-induced accelerations (Tokyo International Airport Tower)

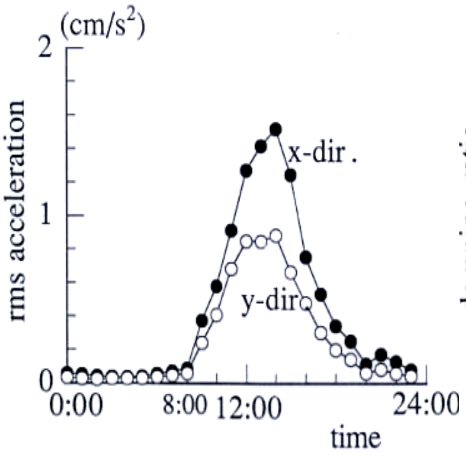


Without TLDs : ζ **= 1.2 %**

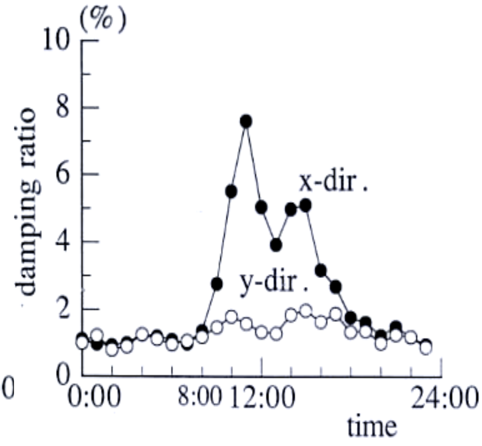


With TLDs : ζ **= 7.6 %**

Temporal variations of wind-induced responses and damping ratios during a typhoon (Tokyo International Airport Tower)

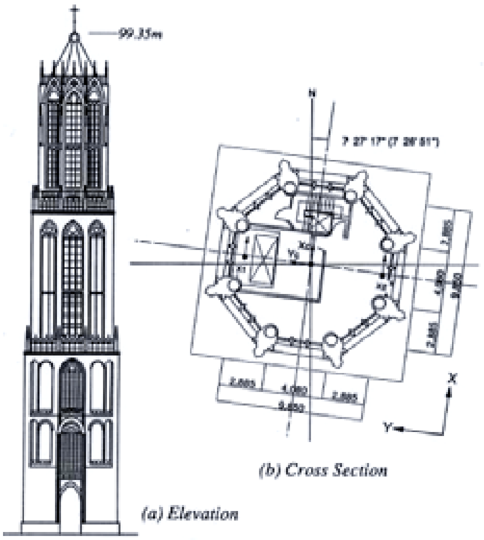


Acceleration Responses



Damping (RD technique)

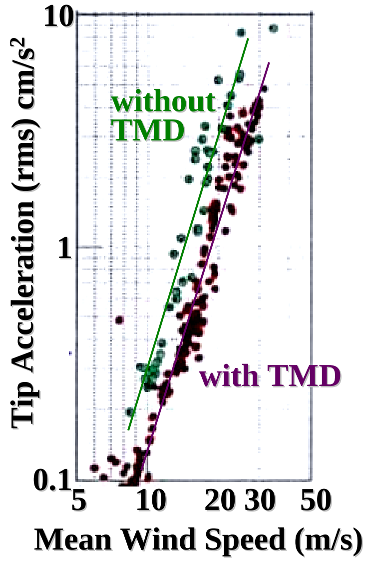
Nagasaki Huis Ten Bosch Domtoren Employing TMD (1992)



(b) Cross Section

(a) Elevation

Wind-induced Responses of Nagasaki Huis Ten Bosch Domtoren With/Without TMD



Building Employing AMD

- Kyobashi Seiwa Building (1989)

H = 32.8m, M_S=340×10^{3}kg

Mass:

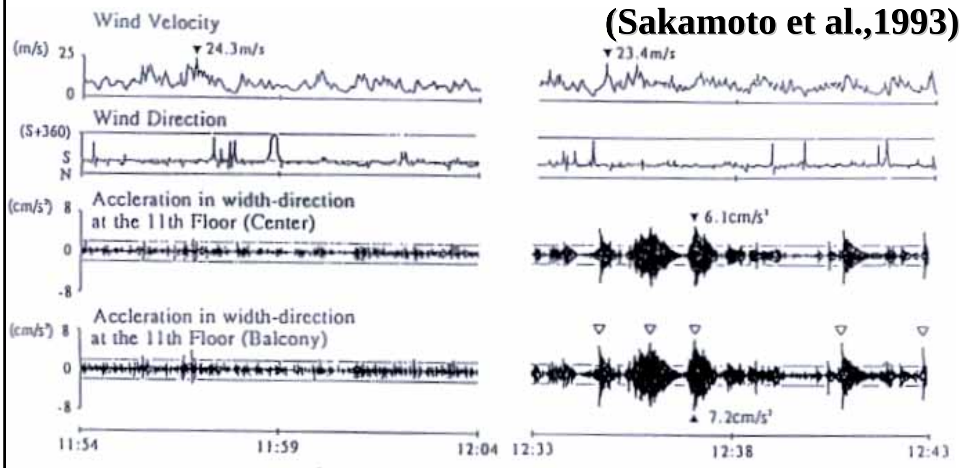
m_D = 4×10^3 kg, F_C = 10 kN
(For Translational Component)
m_D = 1×10^3 kg, F_C = 2.5 kN
(For Torsional Component)

Maximum Stroke: δ_{MAX} = ±25cm
Actuator: Hydraulic Actuator
Electric Power: 22kW Pump
1.5kW Pump and Accumulator
(Ceaseless Engagement)

Relative velocity

Wind-induced Responses of Kyobashi Seiwa Building With/Without AMD Operation

(Sakamoto et al.,1993)



Control **Without Control**

Building Employing HMD

Osaka ORC Symbol Tower (1992)

H = 200m, M_S=56,680×10^3kg

Damper Mass: $m_D = (100 \times 10^3\ \mathrm{kg}) \times 2$

TMD(longitudinal x-dir.)

Maximum Stroke: $\delta_{MAX} = \pm 50$cm

HMD(transverse y-dir.)

Maximum Stroke: $\delta_{MAX} = \pm 100$cm

Maximum Control Force: F_C = 70 kN

Electric Power: AC Servo Motor 55kW

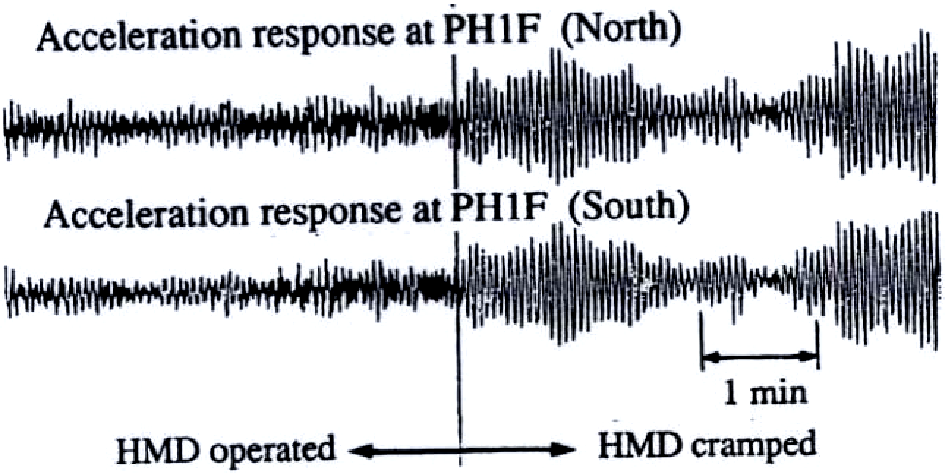
HMD Operation Mode

0→→→→→→→→→ Amplitude →→→→→→→ Large

Waiting Mode⇔Active Mode⇔Passive Mode⇔Anchored (Air Brake)

Osaka ORC Symbol Tower Building (H=200m) Employing HMD and TMD [Maebayashi, 1993]

Wind-induced Responses With/Without HMD Operation(Osaka ORC Symbol Tower Building)

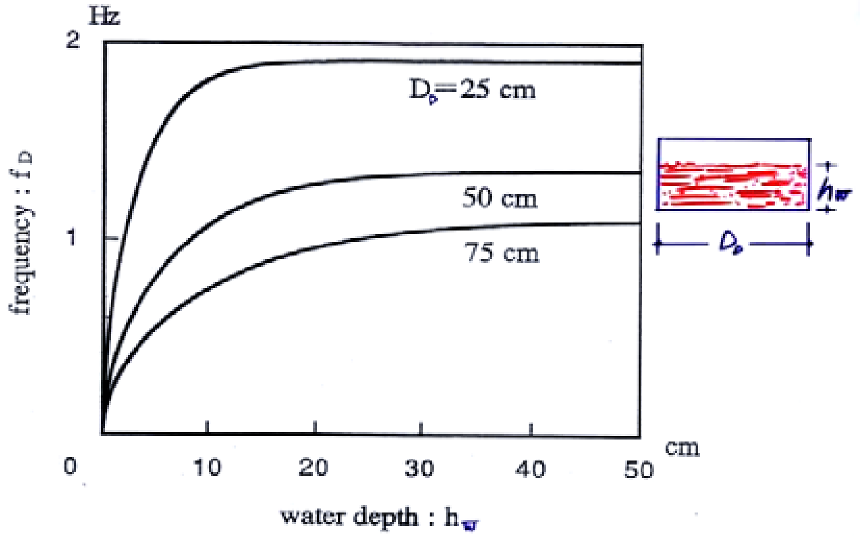


[Maebayashi, 1993]

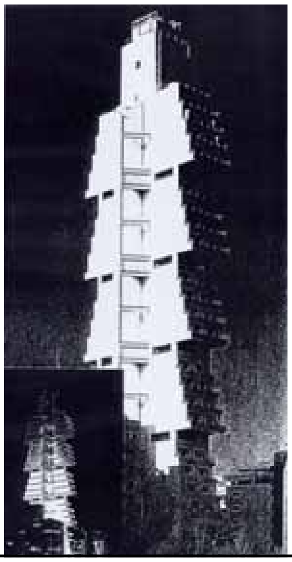
Devices to Adjust Frequency etc.

- **Period Adjustable TLD**
  ex. Hotel Cosima (112m)
- **Period Adjustable Pendulum HMD**
  ex. Hikarigaoka MKD8 (100m)
- **V-Shaped HMD**
  ex. Shinjuku Park Tower (226.5m)
- **Multi-Pendulum AMD**
  ex. Yokohama Landmark Tower (296m)
- **Variable Stiffness AVS**
  ex. KaTRI No.21 Building (12m)

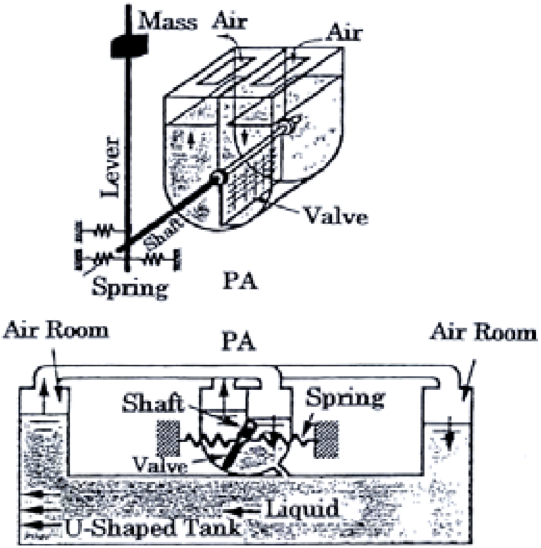
Fundamental Natural Frequency of Sloshing Motion of Water Inside a Circular Cylindrical Vessel



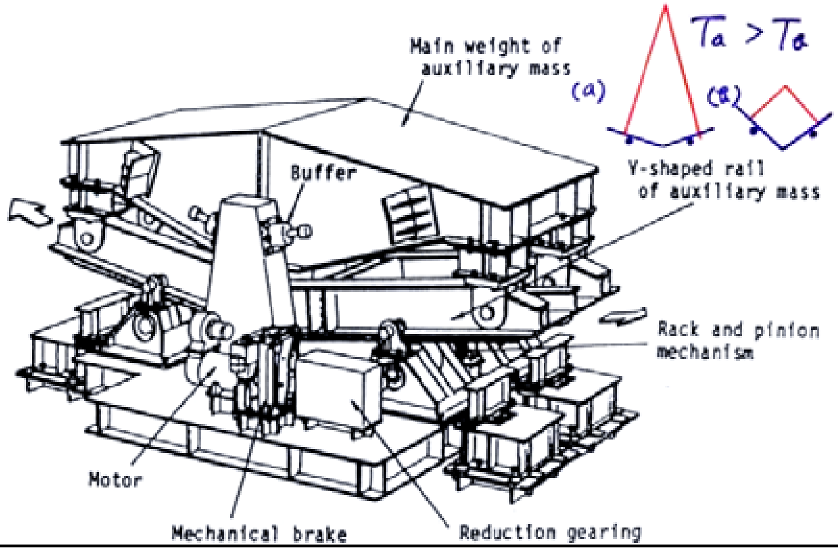
Hotel Cosima employing a TLCD with a frequency adjustable system [Teramura, 1995]



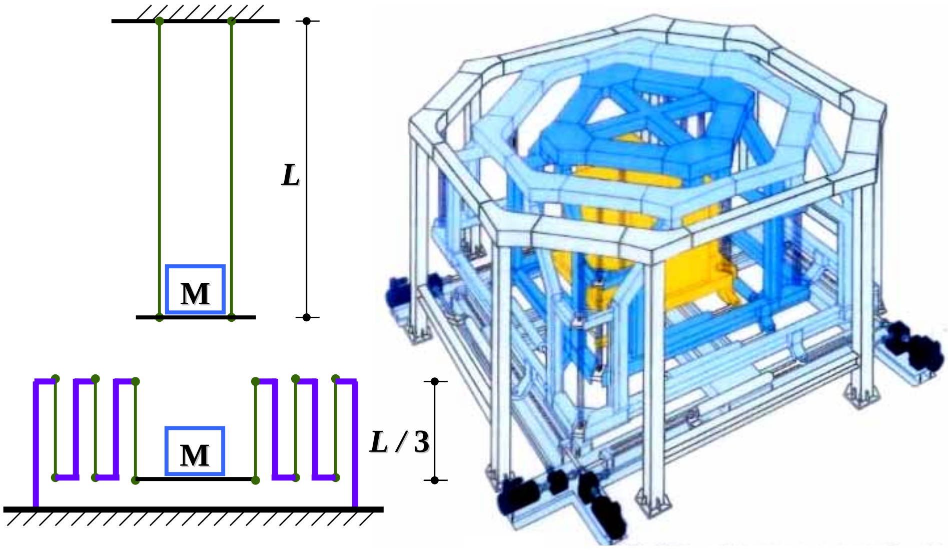
Frequency Adjustable TLCD Installed in Hotel Cosima [Teramura, 1995]



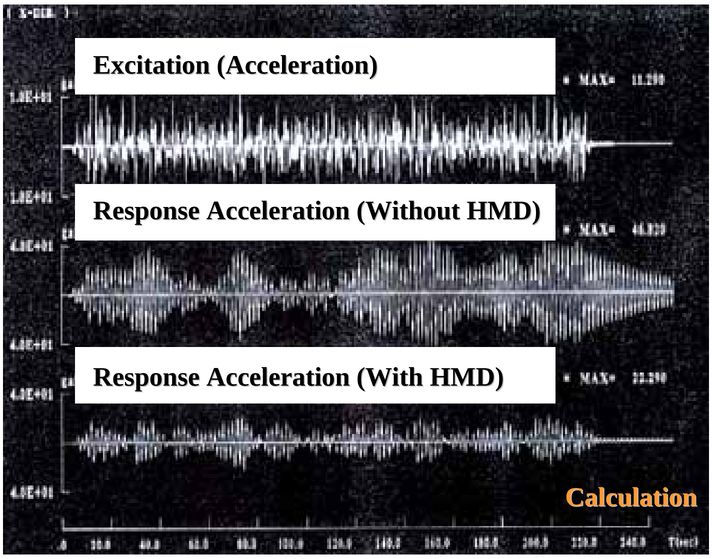
V-shaped HMD installed in Shinjuku Park Tower Building [Tanida et al., 1993]



Multiple-pendulum HMD (170×10^3kg) installed in Yokohama Landmark Tower [Yamazaki et al., 1993]



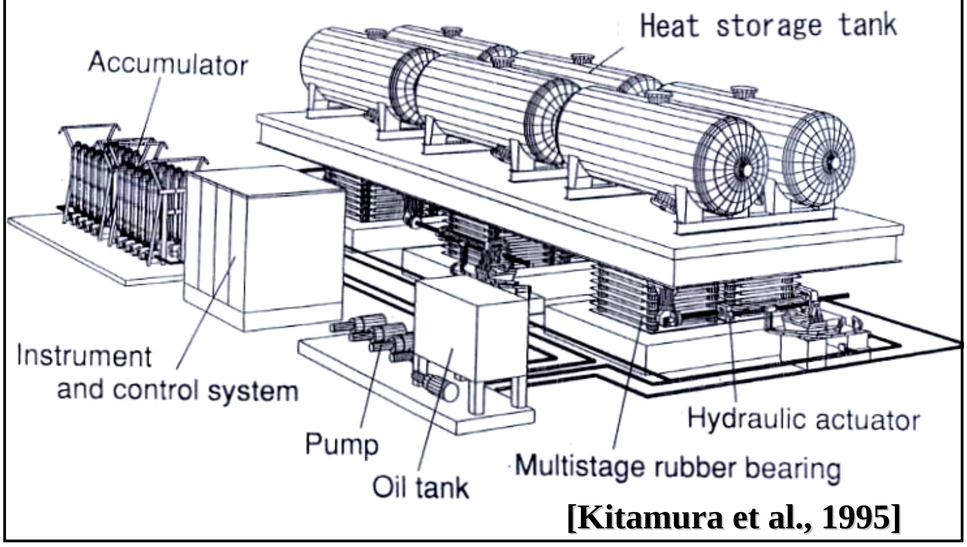
Effects of HMD installed in Yokohama Landmark Tower [Yamazaki et al., 1993]



Utilization of Existing Mass

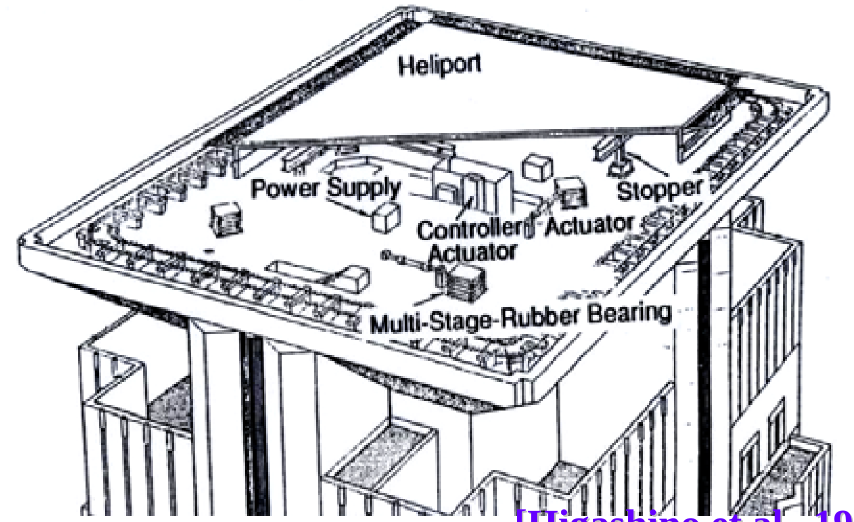
- **Heat Storage Tanks**
  L.T.C. Bank of Japan: 200 × 10^3 kg AMD × *x*-, *y*-dirs.
- **Ice Thermal Storage Tanks**
  Sendagaya INTES: 36 × 10^3 kg × 2 AMD
  Crystal Tower: *x*-dir. 90 × 10^3 kg × 4 TMD
  ***y*-dir. 90 × 10^3 kg × 2**
- **Water Supply Tanks**
  Hotel Cosima: 49 × 10^3 kg TLD
- **Heliport Decks**
  Hankyu Chayamachi Building:
  480 × 10^3 kg AMD

AMD utilizing 200×10^3kg (×2 dirs.) heat storage tanks as the mass, LTC Bank of Japan



[Kitamura et al., 1995]

AMD utilizing a 480×10³kg heliport deck as a mass, Hankyu Chayamachi Building



[Higashino et al., 1993]

Anti-seismic Shaft in the Marunouchi Building (Inada et al., 2002)

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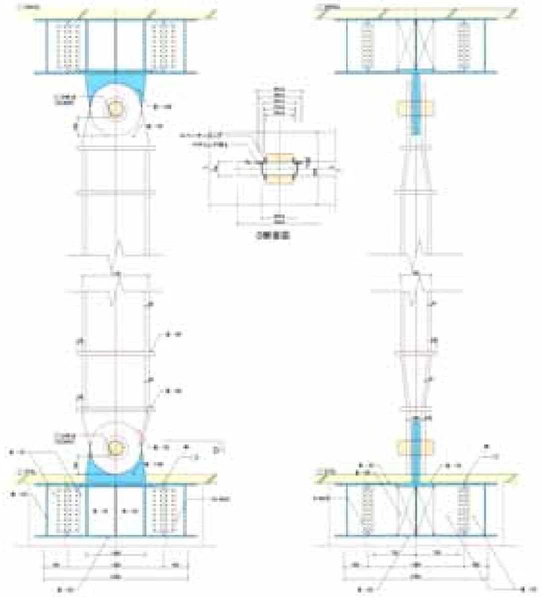

Anti-seismic Shaft in the Marunouchi Building