Energy Dissipation Systems

Dorothy Reed
Civil & Environmental Engineering

Outline

- Definitions
- Focus on semi-active systems
- Conclusions

Energy Conservation
[Uang & Bertero (1988)]

$E = E_k + E_s + E_h + E_d$

$E =$ absolute total energy input

$E_k =$ absolute kinetic energy

$E_s =$ recoverable elastic strain energy

$E_h =$ irrecoverable energy dissipated by the structural system through inelastic or other forms of action

$E_d =$ energy dissipated by supplemental damping devices

Energy Dissipation E_d aka Damping

- Passive
- Semi-active
- Active

Passive [Lowes presentation]

- Seismic Isolation
- Viscoelastic Solid Dampers
- Sometimes viscous fluid dampers included in this category

Semi-active

- “Fuzzy” category: sometimes lumped with active dampers
- Includes
  - Tuned mass dampers
  - Tuned liquid dampers
  - Variable stiffness and damping systems

Active

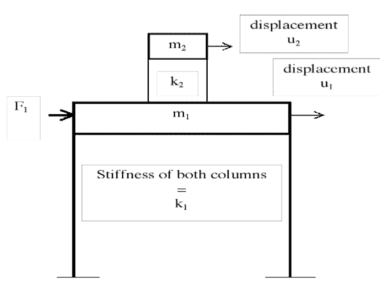
- Power added to system
- Active tuned mass dampers
- Active braced systems

Focus on Semi-active

- Observation
- Mathematical models
- Empirical analysis
- Design methodology

Observation

- Simple model
- Vibration
- Effect of sloshing



System Parameters: Ignore Damping

$$let \quad F_1 = p_0 \sin \omega t \quad so\ F = \begin{Bmatrix} p_0 \sin \omega t \\ 0 \end{Bmatrix}$$

$$M = \begin{bmatrix} m_1 & \\ & m_2 \end{bmatrix}$$

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}$$

EOM

$$m_1 \ddot{u}_1 + (k_1 + k_2) u_1 - k_2 u_2 = p_0 \sin \omega t$$

$$m_2 \ddot{u}_2 - k_2 u_1 + k_2 u_2 = 0$$

Steady-State

$$u_1 = C_1 \sin \omega t, \quad u_2 = C_2 \sin \omega t$$

$$\ddot{u}_1 = -\omega^2 C_1 \sin \omega t, \quad \ddot{u}_2 = -\omega^2 C_2 \sin \omega t$$

Substitute into EOM

$$m_1\left(-\omega^2 C_1\right)\sin \omega t + \left(k_1 + k_2\right)C_1 \sin \omega t - k_2 C_2 \sin \omega t = p_0 \sin \omega t$$

$$m_2\left(-\omega^2 C_2\right)\sin \omega t - k_1 C_1 \sin \omega t + k_2 C_2 \sin \omega t = 0$$

Solve for constants

$$-m_1\omega^2 C_1 + \left(k_1 + k_2\right)C_1 - k_2 C_2 = p_0$$

$$C_1 = \frac{p_0 - k_2 C_2}{\left(k_1 + k_2\right) - m_1\omega^2}$$

This is zero (i.e., no displacement of m_1) when $C_2 = \frac{p_0}{k_2}$.

What else? Tuning

$$-m_2\omega^2 - k_2 C_1 + k_2 C_2 = 0$$

$$C_2(-m_2\omega^2 + k_2) = k_2 C_1$$

$$C_1 = \frac{C_2\left(-m_2\omega^2 + k_2\right)}{k_2}$$

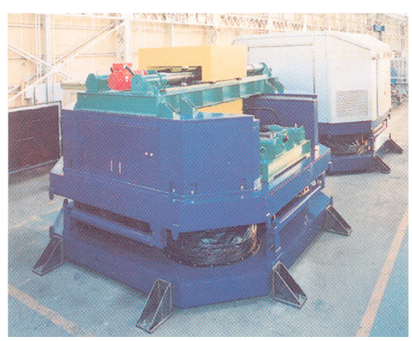
For $C_1 = 0$ but $C_2 \neq 0$, $-m_2\omega^2 + k_2 = 0$

$$\therefore \omega = \sqrt{\frac{k_2}{m_2}} \quad for \quad C_1 = 0$$

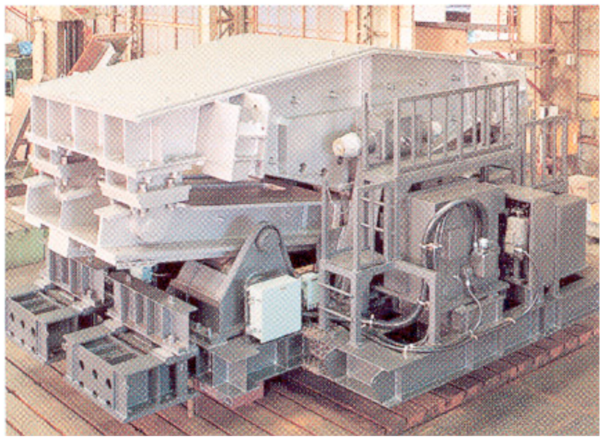
Solution Comments

$$u_2 = \frac{p_0}{k_2}\sin\sqrt{\frac{k_2}{m_2}}t \quad \mathit{for} \quad \omega = \sqrt{\frac{k_2}{m_2}}$$

DUOX: solid mass damper



TRIGON



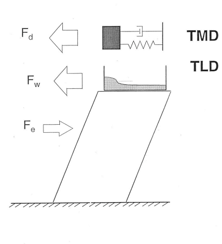
TRIGON

In practice, damping and MDOF systems complicate the process

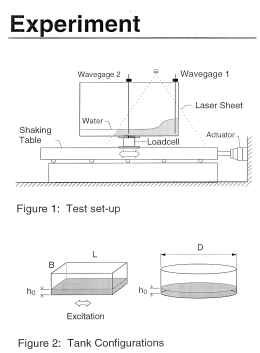
- Devise experiments to test the limits of the theory
- Use water instead of solid mass

TMD and TLD Model

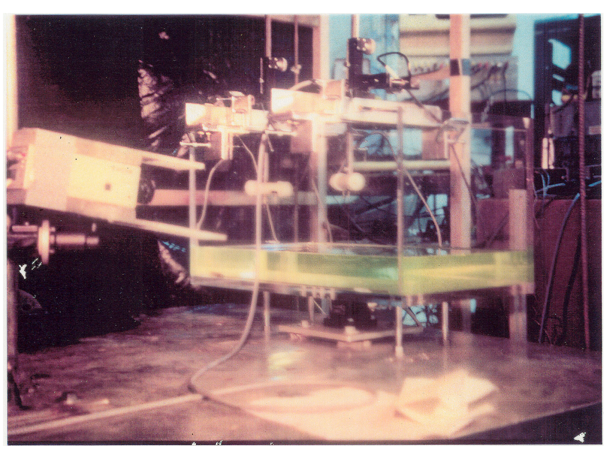
Damping Mechanism



Set-up for TLD analysis



TLD-experiment



Deep water sloshing

Linear Wave Theory: Frequency of sloshing for rectangular tank

$$f_w = \frac{1}{2\pi}\sqrt{\left(\frac{\pi g}{L}\right)\tanh\left(\frac{\pi h_0}{L}\right)}$$

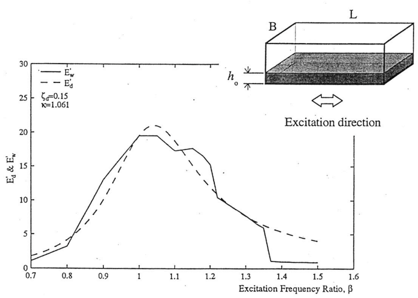
Circular Tank

$$f_w = \frac{1}{2\pi}\sqrt{\left(\frac{1.17\pi g}{D}\right)\tanh\left(\frac{1.17\pi h_0}{D}\right)}$$

Energy dissipation per cycle

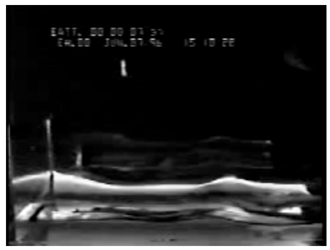
$$E_w = \oint_{T_s} F_w \, dx_s$$

Energy dissipation

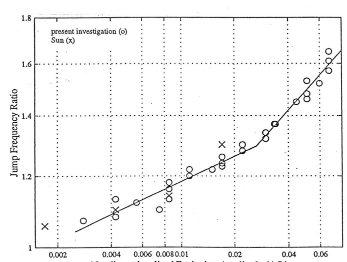


Movie Clip

Yeh, et al. experiments



Frequency investigation



Relationship between the jump frequency ratio and the nondimensional excitation amplitude based on experimental results of Sun, et al. (1991) and the present investigation.

NSD Model

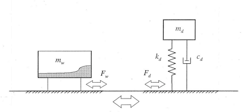
<u>Definition of the NSD Model</u>

The NSD is an equivalent TMD representation of the TLD with varying stiffness and damping.

Its stiffness and damping properties are derived from an energy dissipation matching scheme using shaking table data.

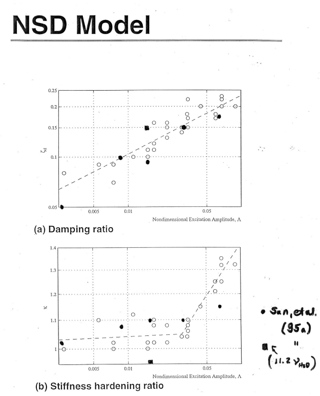
Diagram of NSD

NSD Model

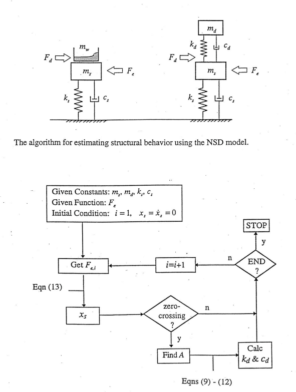


(a) TLD (b) NSD Model

Comparison

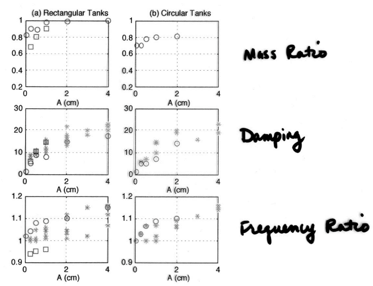


Design Algorithm

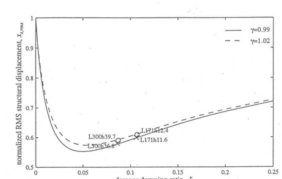


Comparison

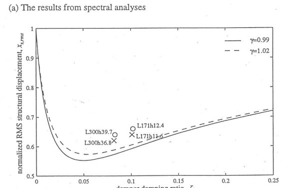
Figure 1. Comparison of the equivalent TMD models for Sun et al. (1995) (○ for water; ❑ for liquid with viscosity 11.2 times greater than that of water) with Yu (1997) (* water). Plots in column (a) are for rectangular tanks; in (b) are for circular tanks.



Additional damping investigation

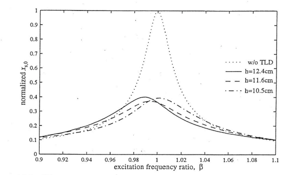


(a) The results from spectral analyses

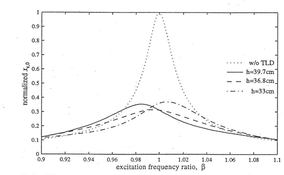


(b) The results from time history analyses

Comparison

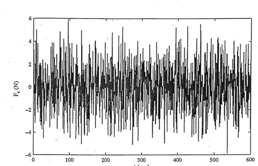


(a) $L = 171$cm

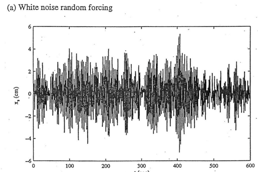


(b) $L = 300$cm

Simulation

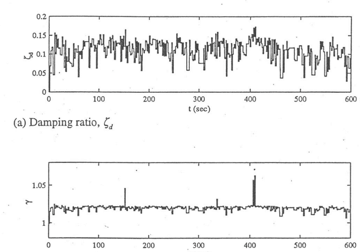


(a) White noise random forcing



(b) Structural displacement induced by the random forcing

Simulation



(a) Damping ratio, ζ_d

(b) Tuning ratio, γ

Design Equation

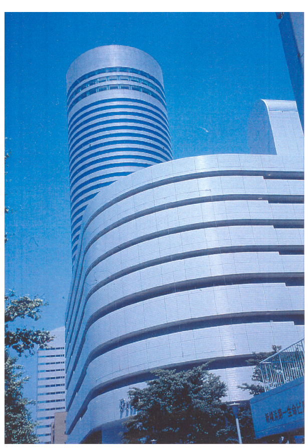
$$h_0 = \frac{L}{\pi}\tanh^{-1}\left(\frac{4\pi L f_s^{2}}{g\beta^{2}}\right)$$

where $\beta = 1.038\left(\frac{x_s}{L}\right)^{0.0034}$ *for* $\frac{x_s}{L} \leq 0.03$ weak wave breaking

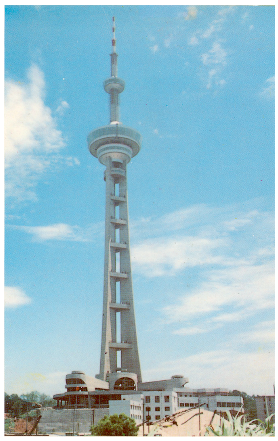
$\beta = 1.59\left(\frac{x_s}{L}\right)^{0.125}$ *for* $\frac{x_s}{L} > 0.03$ strong wave breaking

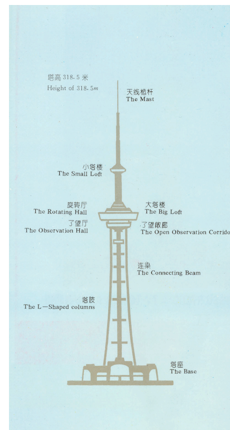
Shimizu TLD

Rooftop of Yokohama Hotel

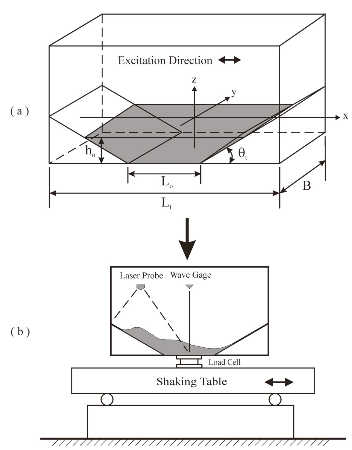


Nanjing Tower [PRC]





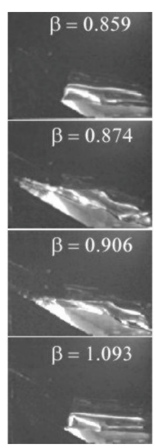
Sloped Bottom (Gardarsson, Olsen)



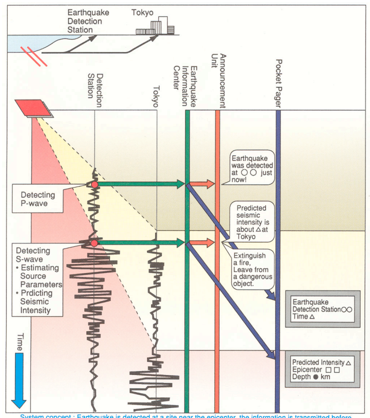
Sloped Tank Notes

- Angle of slope modifies water sloshing behavior
- No simple water frequency equation exists so empirical investigation of sloshing required
- Stiffness degrading system vs stiffness hardening

Tank behavior: □=f_e/f_w



Active Control Scheme



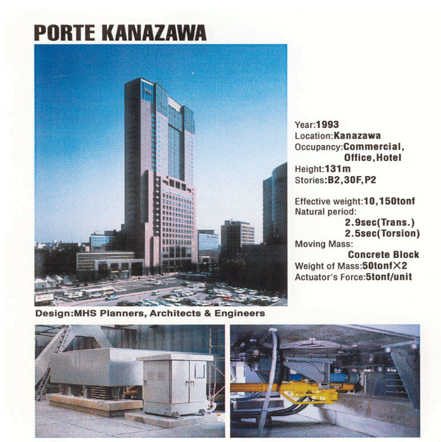
System concept : Earthquake is detected at a site near the epicenter, the information is transmitted before coming of strong motion at Tokyo, and the earthquake damage is reduced.

Active Mass Damper [AMD]

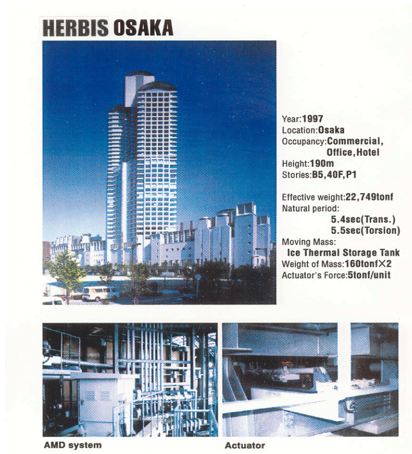
AMD


APPLAUSE TOWER
Year:1992
Location:Osaka
Occupancy:Commercial, Office,Hotel
Height:161m
Stories:B3,34F
Effective weight:13,943tonf
Natural period:
4.8sec(trans.)
4.7sec(Longi.)
Moving Mass:Heliport
Weight of Mass:480tonf
Actuator's Force:
5tonf×2/direction
Actuator & Rubber Bearing
Controll Panel

AMD


PORTE KANAZAWA
Year:1993
Location:Kanazawa
Occupancy:Commercial, Office,Hotel
Height:131m
Stories:B2,30F,P2
Effective weight:10,150tonf
Natural period:
2.9sec(Trans.)
2.5sec(Torsion)
Moving Mass:
Concrete Block
Weight of Mass:50tonf×2
Actuator's Force:5tonf/unit
Design:MHS Planners, Architects & Engineers
AMD system
Actuator

AMD

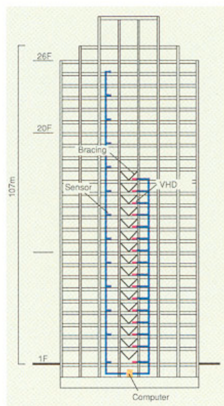


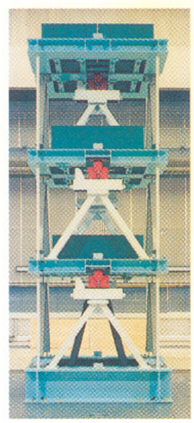
HERBIS OSAKA
Year:1997
Location:Osaka
Occupancy:Commercial, Office,Hotel
Height:190m
Stories:B5,40F,P1
Effective weight:22,749tonf
Natural period:
5.4sec(Trans.)
5.5sec(Torsion)
Moving Mass:
Ice Thermal Storage Tank
Weight of Mass:160tonf×2
Actuator's Force:5tonf/unit
AMD system
Actuator

AVS

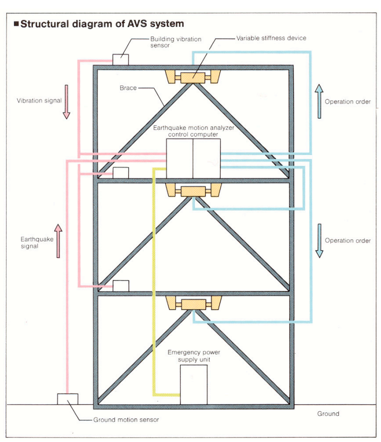
鹿島技研21号館
KaTRI No.21 Building

AVS


26F
20F
Bracing
Sensor
VHD
107m
1F
Computer



AVS


■Structural diagram of AVS system
Building vibration sensor
Variable stiffness device
Brace
Vibration signal
Operation order
Earthquake motion analyzer control computer
Earthquake signal
Operation order
Emergency power supply unit
Ground motion sensor
Ground

Conclusions

- Passive systems best for earthquakes
- Hybrid passive coupled with semi-active or active devices gaining in popularity
- Semi-active TMD, TLD most popular outside of US, especially for wind loadings
- AMD systems have promise but require reliable power sources