Lecture 10

Damping in Buildings

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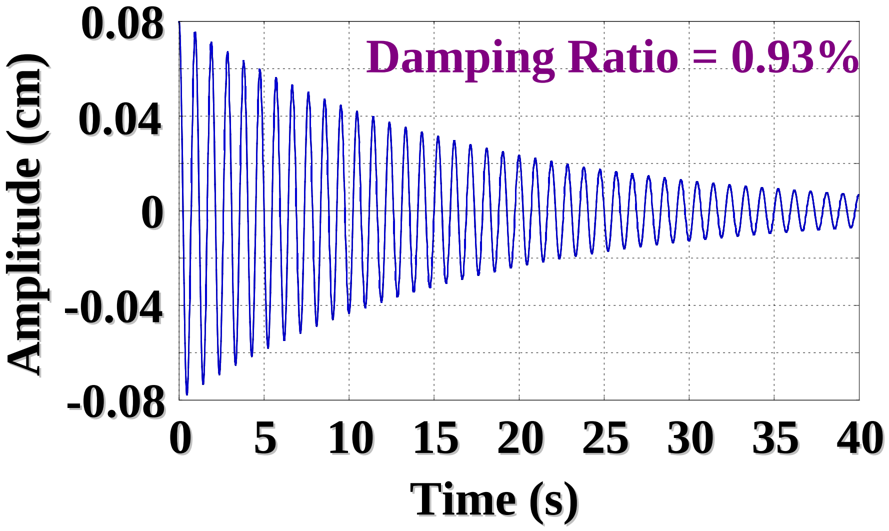
Damping

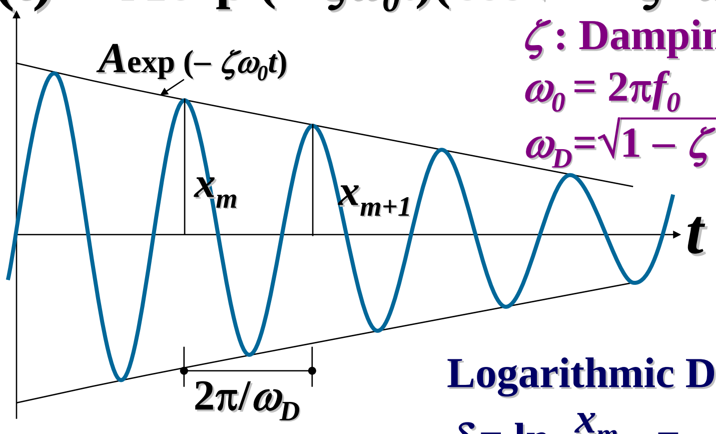
- Reduction of intensity with time or spatial propagation
  - Vibration Energy → Thermal Energy
  - Radiation to Outside
- Cease of vibration with time
- Reduction of wind-induced/earthquake-induced vibration
- Increase of onset wind speed of aerodynamic instability
- etc.

Damped Free Oscillation (Full-scale)



Damped Free Oscillation (SDOF)

$$x(t) = A\exp(-\zeta\omega_0 t)(\cos\sqrt{1-\zeta^2}\,\omega_0 t - \varphi)$$



ζ : Damping Ratio

$\omega_0 = 2\pi f_0$

$\omega_D = \sqrt{1-\zeta^2}\,\omega_0 \approx \omega_0$

Logarithmic Decrement

$$\delta = \ln\frac{x_m}{x_{m+1}} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$$

Damping in Buildings

- Estimation of damping
  - no theoretical method
  - based on full-scale data

  → significant scatter

Dispersion of Damping Data

- Structural Materials
- Soil & Foundations
- Architectural Finishing
- Joints
- Non-structural Members
- Vibration Amplitude
- Non-stationarity of Excitations
- Vibration Measuring Methods
- Damping Evaluation Techniques

etc.

Uncertainty of Response Prediction Due to Uncertainty of Damping Ratio

- Coefficient of variation of full-scale damping data

ex. Havilland (1976)   C.O.V.   70%

→ If damping ratio was estimated at ζ = 2% on average,

ζ can generally take 0.6%〜3.4% (2%±1.4%)

→ Wind-induced acceleration response

$A(\zeta = 0.6\%) / A(\zeta = 2\%) = 1.8$
$A(\zeta = 3.4\%) / A(\zeta = 2\%) = 0.8$

2.3 *times*

→ provides significant reduction of reliability of structural design

Importance of Damping

- Improvement of Reliability of Structural Design

→ Accurate Response Prediction
→ Accurate Damping Predictor
→ Reliable Damping Database

Physical Causes of Damping in Buildings

	Energy Dissipation Inside			Energy Dissipation Outside		
	Solid	Liquid	Gas	S–S	S–L	S–G
Friction	Internal Friction Damping	–		External Friction Damping	–	
Viscosity	–	Internal Viscous Damping		–	External Viscous Damping	
Radiation	–			Radiation Damping		–
Interaction	–			–	Hydro-dynamic Damping	Aero-dynamic Damping
Plasticity	Hysteretic Damping	–		–		

Internal Friction Damping

Energy dissipation due to internal friction of solid materials

- **Deformation of Materials**
  - →Relative displacement between molecules
    Slip of micro-cracks in microscopic structures such as crystals

Macroscopic: Elastic

Microscopic:

Friction damping between microscopic structures

→ Elastic hysteretic loss

Very small in metals (Energy loss ≈ 0.5%)

<< Different from energy loss due to plastic hysteresis>>

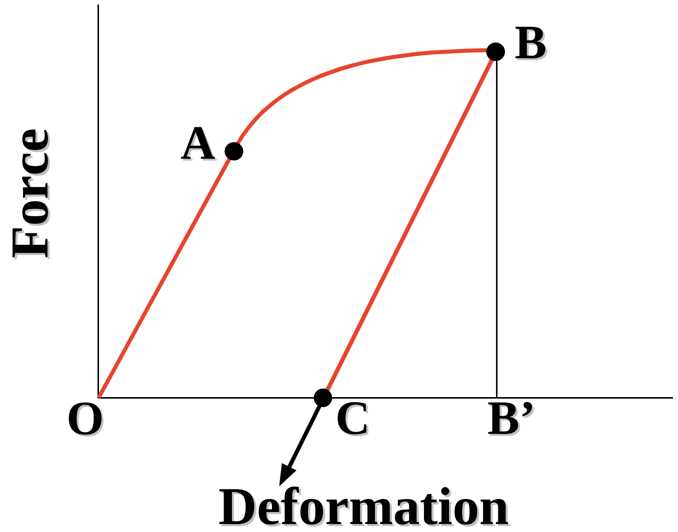
Plasticity Damping

Energy dissipation due to plasticity of solids

- Hysteresis due to Plasticity
  - → Change in microscopic structure of materials
  - → Hysteretic characteristics / Plasticity Rate

Significantly greater than the energy dissipation due to internal material friction

Force-Deformation Relation of Structural Materials



Internal Viscous Damping

Energy dissipation due to internal viscosity of liquids

- Molecular Viscosity

  Collisions of molecules

  Coefficient of Kinetic Viscosity ν

  → Conversion of kinetic energy to thermal energy

- Turbulence Viscosity

  Reynolds Stress (Virtual stress due to correlation of fluctuating velocity components of fluids)

  Coefficient of Kinetic Vortex Viscosity ν_t

  → Mixture and diffusion of kinetic energy and so on

External Friction Damping

Energy dissipation due to friction between solids

- Mainly Sliding Friction

  Coefficient of Friction

  Work done by friction force preventing relative motion between solid bodies

  → Conversion of vibration energy to thermal energy

  - Sticking of molecules due to contact
  - Damage and replacement of sticking due to relative motion
  - Digging up by projections

  ex. Friction between joints, Friction between members, finishing etc.

Radiation Damping

Energy transfer between Solid – Solid, or Solid – Liquid

- Propagation and loss of a system's energy to outside
  - Necessary work for exciting a body contacting the system
  - Penetration of wave energy through boundary

  ex.
  - Radiation damping due to soil-structure interaction
  - Damping due to wave generation for a floating body

  Reflection of ground motions from building surface: Input loss

External Viscous Damping

Energy dissipation due to viscosity of liquids or gas contacting the body

- Viscous resistance acting on a moving body in oil or water
  - Large velocity gradient near body surface
  - A function of relative velocity

  ex.
  Oil Damper, Viscous Wall Damper

Fluid-Dynamic Damping (Aerodynamic Damping)

Fluid-body interaction

- Effects of relative velocity
- Effects of additional unsteady flow induced by body motion (Feedback system)

Ex.

Along-wind Vibrations (Buffeting) due to turbulence: Positive Damping

Across-wind Vibrations (Galloping, Vortex-resonance etc.): Negative Damping

Damping and Building Vibration

Careful and precise observation of Vibration Phenomena

↓

Analytical Model with high accuracy

↓

Damping Evaluation appropriate for the model

Equivalent Model, Mathematical Formula

Treatment of Damping：Restriction in numerical analysis

Soil-Structure Dynamic Interaction
Ground Domain ／Boundary Treatment,
Internal Damping of Ground

Evaluation of higher mode damping Damping Matrix,
Value of Damping Ratio, Non-linear Range

Damping Ratio of Buildings

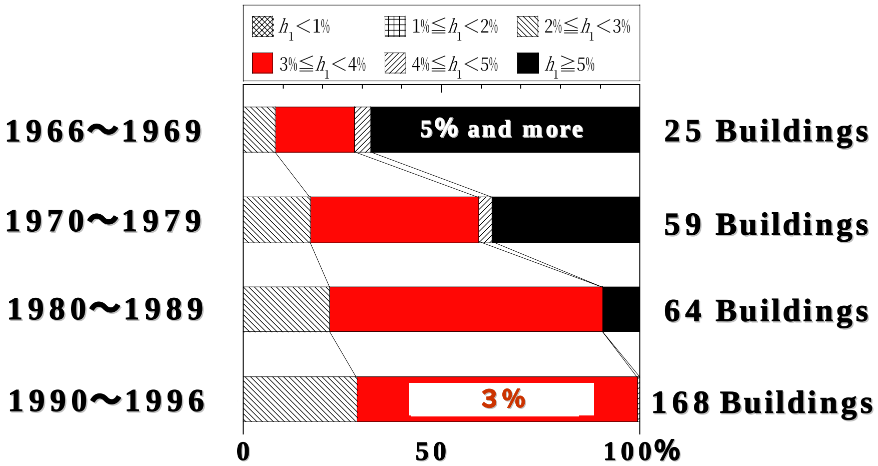
- Damping Matrix Proportional to Stiffness Matrix
- Realistic Proportional Matrix Meeting Conditions
- Actual Damping Ratio
- Design Damping Ratio Closely Following Actual Phenomena
- Variation of Natural Frequency and Damping Ratio With Amplitude / Effects of Secondary Members
- Initial Stiffness / Instantaneous Stiffness
- *Q-Δ* and Damping Characteristics in Inelastic Range During Extremely Strong Earthquake
- Damping in Above Ground Structure / Soil-Structure Interaction / Full-scale Values of Damping Ratio
- Damping for Vertical Vibrations ?

Currently Used Design Damping Values

- AS 1170.2 Part 2
- DIN1055, Teil 4
- EUROCODE 1
- ISO/CD 3010
- Swedish Code
- US Atomic Energy Commission
- Chinese Standards
- ESDU 83009
- ISO4354
- ONORM B4014

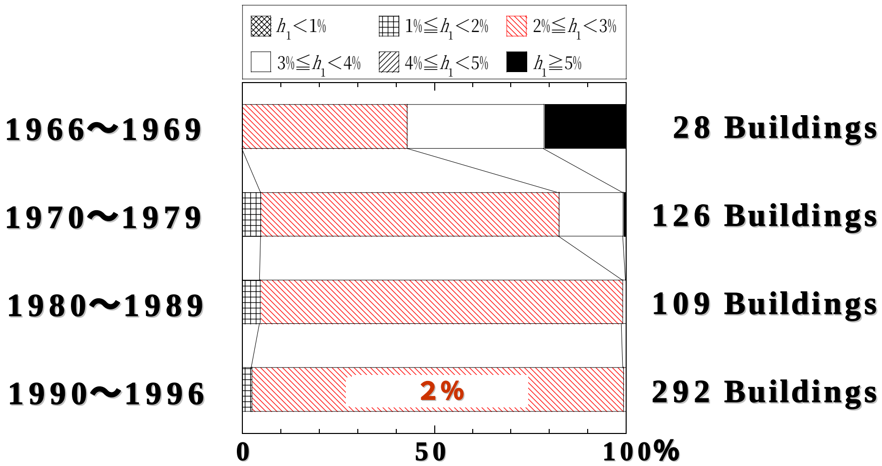
etc.

Design Damping Ratio Used in Japan



Fundamental damping ratio h_1 of tall buildings which structural design was inspected by BCJ (RC-Buildings)

Design Damping Ratio Used in Japan



Fundamental damping ratio h_1 of tall buildings which structural design was inspected by BCJ (Steel Buildings)

Currently Used Damping Values
(Steel Buildings)

Country	Actions/Stress Levels	Joints/Structures	Damping ratios ζ_1 (%)
Australia (AS1170.2)	Serviceability		0.5 – 1.0
	Ultimate & Permissible	Frame Bolted	5
		Frame Welded	2
Austria	(ÖNORM B4014)		
China	(GB50191-93)	Steel (TV) Tower	2
France		Standard Bolt	0.8
		High Resistance Bolt	0.5
		Welded	0.3
	Earthquake	Bolt	4
		Welded	2
Germany	Wind (DIN 1055)		
Italy	Wind (EUROCODE 1)		
	Earthquake		5
Japan	Habitability		1
	Earthquake		2
Singapore			1
Sweden	(Swedish Code of Practice)		0.9
United Kingdom	Wind (ESDU)		
USA (Penzien, US Atomic Energy Commission)			

Currently Used Damping Values
(RC Buildings)

Country	Actions/Stress Levels	Structures	Damping ratios ζ_1 (%)
Australia (AS1170.2)	Serviceability	RC or Prestressed C	0.5 – 1.0
	Ultimate & Permissible	RC or Prestressed C	5
Austria	(ÖNORM B4014)		
China	(GB50191-93)	RC Structures	5
		RC (TV) Towers	5
		Prestressed RC Tower	3
France		Standard	1.6
		Reinforced	0.65
	Earthquake	Standard	3 - 4
		Reinforced	2
Germany	Wind (DIN 1055)		
Italy	Wind (EUROCODE 1)		
	Earthquake		5
Japan	Habitability		1
	Earthquake		3
Singapore			2
Sweden	(Swedish Code of Practice)		1.4
United Kingdom	Wind (ESDU)		
USA	(US Atomic Energy Commission)		

DIN 1055

Teil 4, The German Pre-Standard

Wind **(Actual Wind Load Code)**

Structures	Conditions	Damping ratios ζ_1 (%)
- Steel	Bolted Welded	0.5 – 0.8 0.3
- Reinforced C	Without cracks With cracks	0.6 1.6
- Prestressed C		0.6

ESDU

Damping of Structures – Part 1
Tall Buildings, 83009, 1983

Wind

- 1st mode damping ratio ζ_1 (%)

$$\zeta_1 = \zeta_s + \zeta_a$$

ζ_s : Structural damping ratio

$$\zeta_s = 100(\zeta_{s0} + \zeta' \frac{x_H}{H}) \leq \frac{60}{H} + 1.3 \quad (\%)$$

$\zeta_{s0} = f_1 / 100$ (Most Probable), $f_1/250$ (Lower Limit)

$\zeta' = 10^{\sqrt{D}/2}$ (Most Probable), $10^{\sqrt{D}/2.5}$ (Lower Limit)

ζ_a : Aerodynamic damping ratio

x_H : Tip displacement (m), H : Building height (m)

f_1 : 1st mode natural frequency (Hz)

EUROCODE

Wind Actions, ENV-1991, 1994

Wind

- 1st mode damping ratio ζ_1 (%)

$$\zeta_1 = \zeta_s + \zeta_a + \zeta_d$$

ζ_s : Structural damping ratio

$$\zeta_s = a\, f_1 + b \geq \zeta_{min}$$

$f_1 = 46 / H$ (1st mode natural frequency)

$a =$ 0.72 (Steel), 0.72(RC)

$b =$ 0 (Steel), 0.8 (RC)

$\zeta_{min} = 0.8$ (Steel), 1.6 (RC)

ζ_a : Aerodynamic damping ratio

ζ_d : Damping ratio due to vibration control devices

ÖNORM B4014

Teil 1, Code for Austria

Wind (Actual Wind Load Code for Austria)

- 1st mode damping ratio ζ_1 (%)

$$\zeta_1 = \zeta_m + \zeta_c + \zeta_f$$

ζ_m : Structural damping ratio due to materials (%)

0.08 (Steel)
0.72 (RC with cracks), 0.4 (RC without cracks, PSRC)

ζ_c : Structural damping ratio due to constructions (%)

0.32 (Steel tall buildings),
0.32 (RC tall buildings, Panel systems)
0.64 (RC tall buildings, Frame systems)

ζ_f : Structural damping ratio due to foundations (%)

0.08 (Support with hinges)
0.24 (Support with sliding bearings)
0.16 (Fixed support of frame structures)
etc.

US Atomic Energy Commission
"Regulatory Guide"

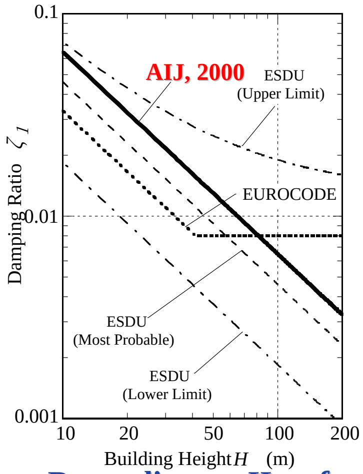
Structures	Damping Ratio (%)	
	OBE or ½ SSE	SSE
Welded Steel	2	4
Bolted Steel	4	7
Prestressed C	2	5
Reinforced C	4	7

OBE : Operating Basis Earthquake
SSE : Safe Shutdown Earthquake

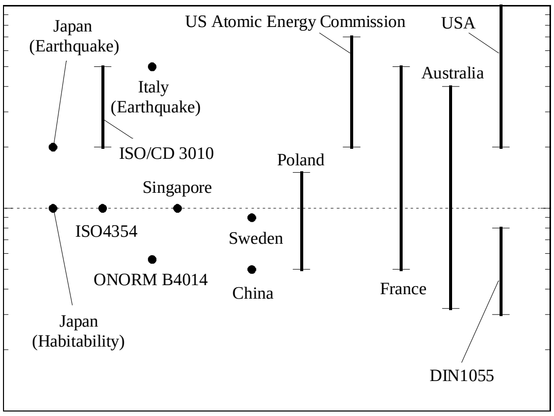
ISO

- **ISO4354** (Wind Actions on Structures, 1997)
  1st mode damping ratio
  ζ_1 = 1.0 % (Steel Buildings)
  ζ_1 = 1.5 % (RC Buildings)
- **ISO/CD3010** (Seismic Actions on Structures, 1999)
  1st mode damping ratio
  ζ_1 = 2 - 5 %

Design Damping Ratios Currently Used in Various Countries (Steel Buildings)

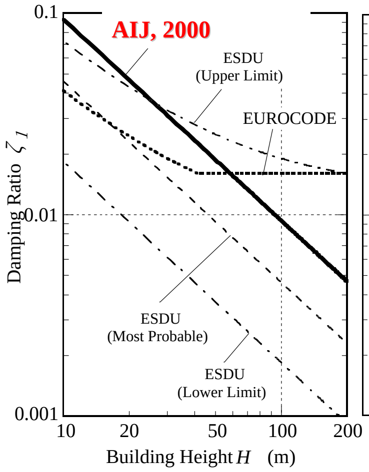


Depending on H or f_1

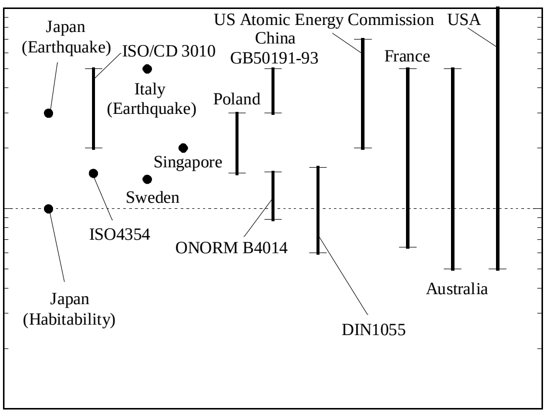


For All Buildings: Depending on Connection Types, Stress Levels, Foundation Types, etc.

Design Damping Ratios Currently Used in Various Countries (RC Buildings)



Depending on H or f_1



For All Buildings: Depending on Concrete Materials, Stress levels, Foundation Types, etc.

Damping Data & Predictors

- Penzen, J. (1972), U.C. Berkley
- Haviland, R. (1976), MIT
- Cook, N.J. (1985) 'The designer's guide to wind loading of building structures'
- Davenport, A.G. & Hill-Carrol, p. (1986), ASCE
- Jeary, A.P. (1986), *JEESD*
- Lagomarsino, S. (1993), *JWEIA*
- Ellis, B.R. (1998)
- *etc.*

Desirable Damping Database

- Enough Data
- Enough Building Types
- High-Quality & Accurate
- Information in Detail
  - Building & Soil
  - Measuring Conditions
  - Evaluation Techniques
  - Amplitudes
  - Stationarity

Japanese Damping Database

Research Committee on Damping Data
organized by
Architectural Institute of Japan
(1993-2000)

Sources of Damping Data

- **Original data from Members of the Research Committee**
- **Research Committee Report on Evaluation of Damping of Buildings, Building Center of Japan, 1993**
- **Summary Papers presented at the *Annual Meeting of Architectural Institute of Japan* (AIJ) 1970 -**
- ***Journal of Structural and Construction Engineering* (Transactions of AIJ), 1970 -**
- **Proc. *Annual Meeting of Kanto Branch of Architectural Institute of Japan*, 1970 -**
- **Proceedings of *Annual Meeting of Kinki Branch of Architectural Institute of Japan*, 1970-**
- **Proc. *National Symposium on Wind Engineering*, 1970 -**
- **Proc. *National Symposium on Earthquake Engineering*, 1970 -**
- **Proc. *International Conference on Earthquake Engineering*, 1974 -**
- **Vibration Tests of Buildings, *Architectural Institute of Japan*, 1978**
- **Technical Reports published by *Research Institute of Construction Companies*, 1974 -**

Accuracy and Quality of Damping Data

Questionnaire Studies to Designers and Owners

- Confirmation of Values
  - Dynamic Properties in Literature
- Collection of Necessary Data
  - Building Information
  - Measurement Methods
  - Evaluation Techniques
  - Amplitudes
- Exclusion of Unreliable Data
- Approval for World-Wide Distribution

↸ *Many original non-published data and additional information were collected.*

Japanese Damping Database

(Damping in buildings, AIJ, 2000)

Number of Buildings and Structures			
285			
Steel Buildings (Steel)	Steel Encased Reinforced Concrete Buildings (SRC)	Reinforced Concrete Buildings (RC)	Tower-Like Non-Building Structures
137	43	25	80
$H_{Ave.}$= 101m	$H_{Ave.}$= 60m		$H_{Ave.}$= 124m
15.5m ～ 282.3m	11.6m～167.4m	10.8m～129.8m	9.1m～226.0m
Office : 99 Hotel : 25 Others : 13	Apartment : 35 Office : 20 School : 4 Others : 9		Chimney : 26 Lattice : 24 Tower : 23 Others : 6

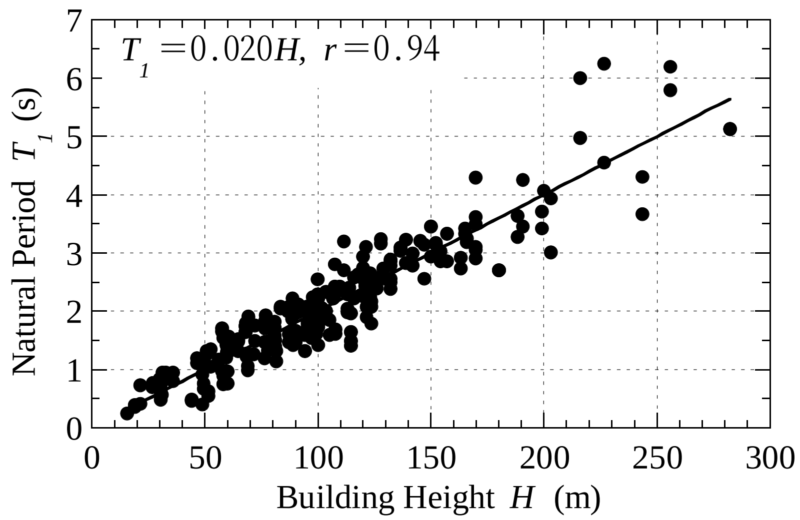
Japanese Damping Database (JDD)

(Damping in buildings, AIJ, 2000)

Contained Information		
Building Information	Location Time of Completion Building Usage Shape Height Dimensions Number of Stories	Structural Type Cladding Type Foundation Type Embedment Depth Length of Foundation Piles Soil Conditions Reference
Dynamic Properties	Damping Ratio (up to the 6th mode) Natural Frequency (up to the 6th mode) Time of Measurement	Excitation Type Experimental & Measurement Method Evaluation Technique Amplitude etc.

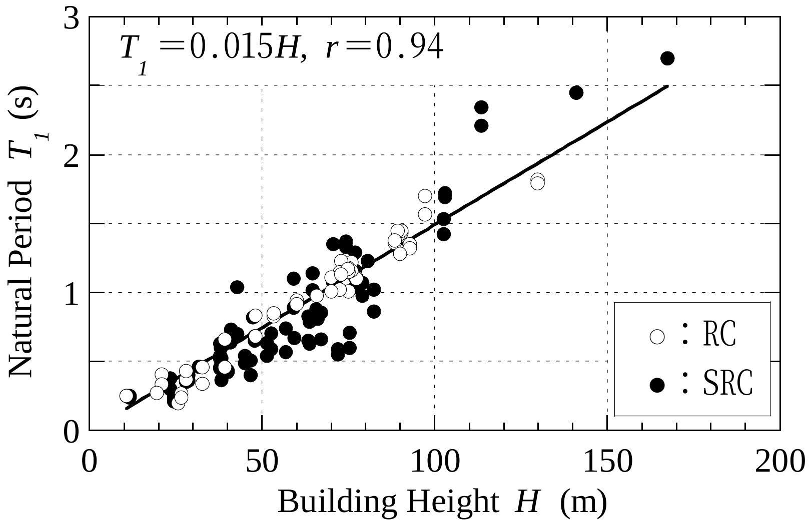
Fundamental Natural Period (JDD) (Steel Buildings)

(Damping in buildings, AIJ, 2000)



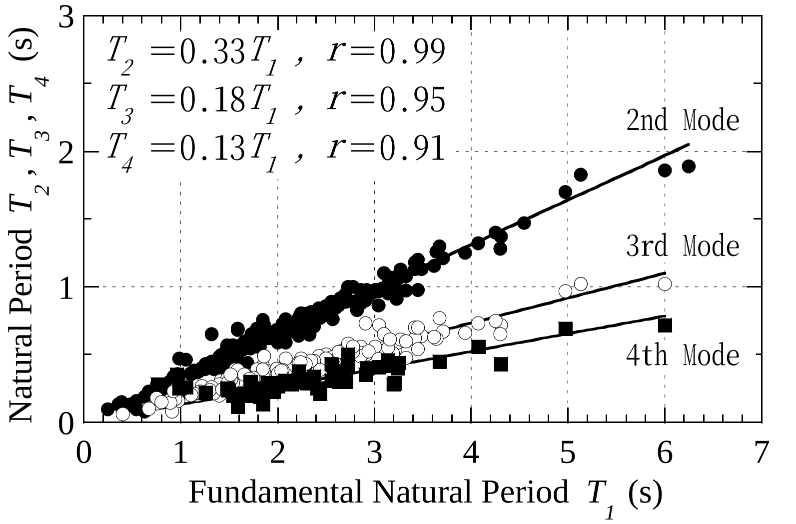
Fundamental Natural Period (JDD)
(RC/SRC Buildings)

(Damping in buildings, AIJ, 2000)



Higher Translational Mode (JDD)
Natural Periods (Steel Buildings)

(Damping in buildings, AIJ, 2000)

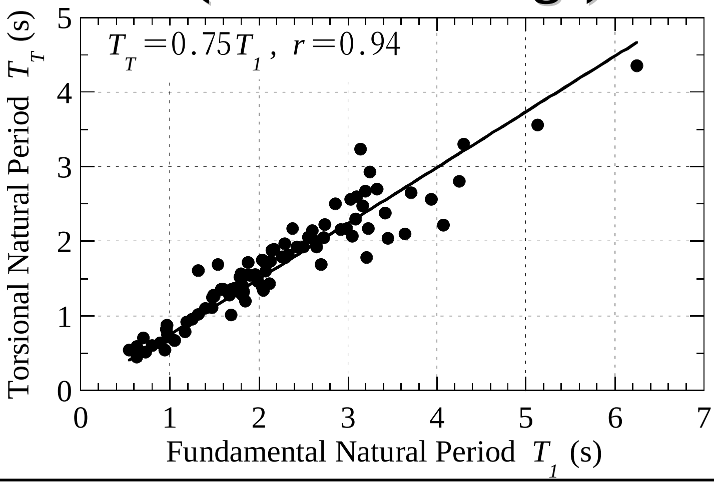


Torsional Mode Natural Periods

(JDD)

(Damping in buildings, AIJ, 2000)

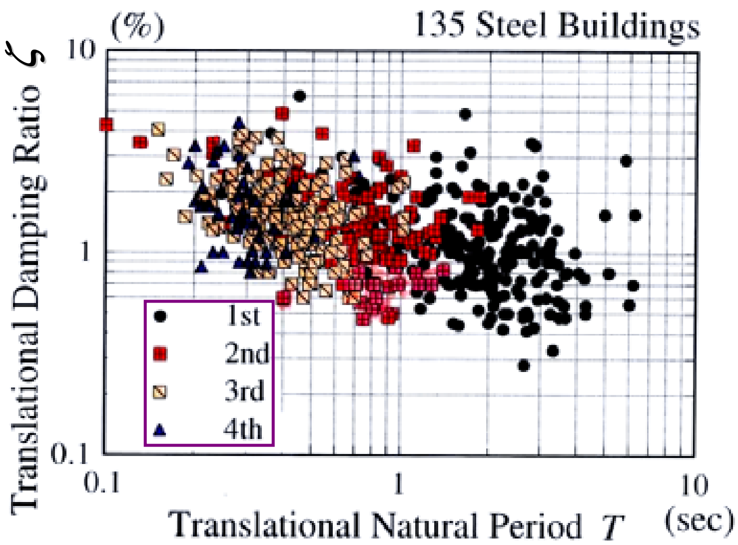
(Steel Buildings)



Damping Ratios & Natural Periods

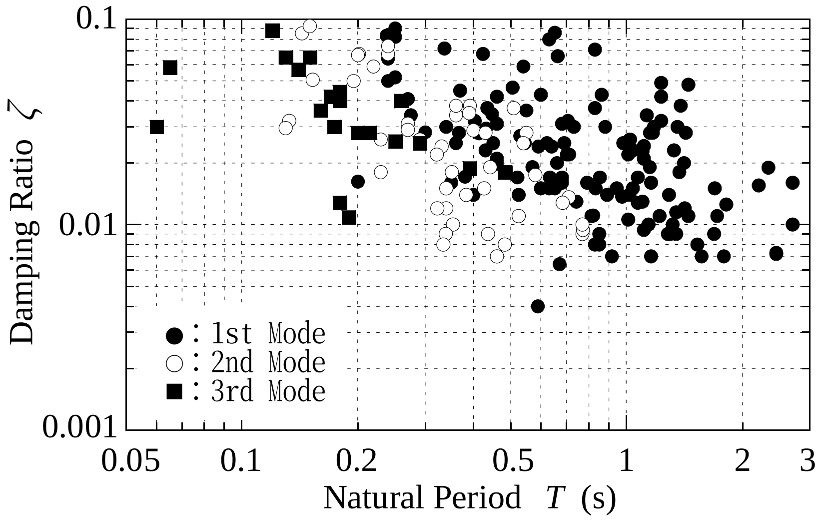
(Steel Buildings)

(Damping in buildings, AIJ, 2000)



Damping Ratios & Natural Periods
(RC/SRC Buildings)

(Damping in buildings, AIJ, 2000)



Damping Predictors

- **Jeary (1986) :**

  $$\zeta_1 = 0.01 f_1 + 10^{\sqrt{D}/2}(x_H/H)$$

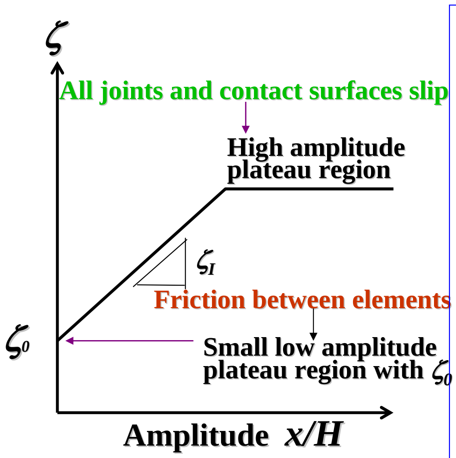
- **Lagomarsino (1993) :**

  $$\zeta_1 = \alpha / f_1 + \beta f_1 + \gamma (x_H/H)$$

D : Building Dimension along Vibration Direction

x_H/H : Tip Drift Ratio

Jeary's Damping Predictor



$$\zeta_1 = \zeta_0 + \zeta_I \cdot x/H$$

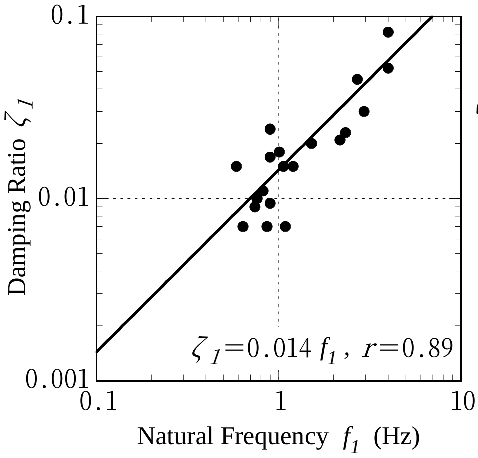
$$\zeta_0 = f_1/100$$

$$\zeta_I = 10^{\sqrt{D}/2}$$

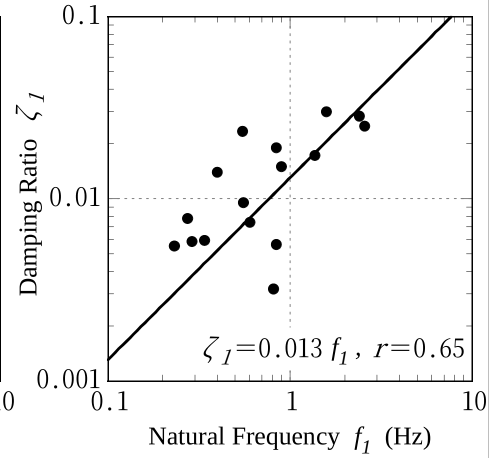
f_1 : Lowest Natural Frequency (Hz)

D : Width of Building Base in Vibration Direction (m)

Fundamental Damping Ratios for Very Low-Amplitude Data



RC Buildings



Steel Buildings

Very Low-Amplitude Data

- **Frequency Dependent Term**

RC buildings :

$\zeta_1 = 0.0143\, f_1$ (r = 0.89)

SRC buildings :

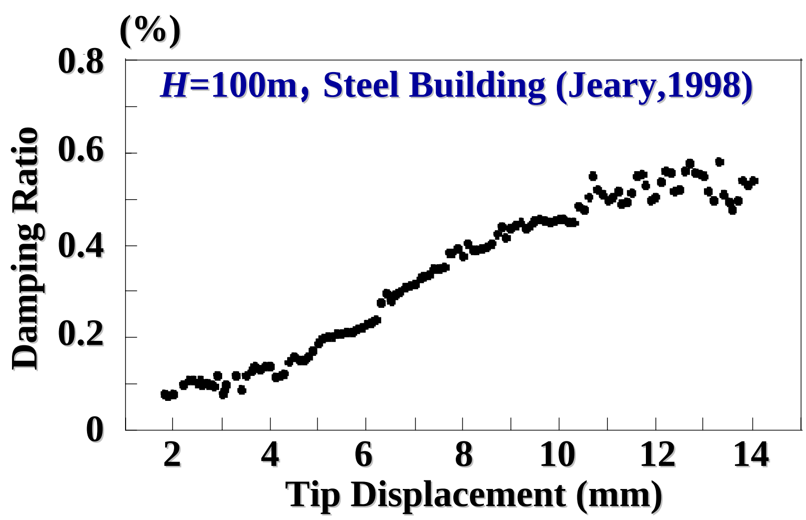
$\zeta_1 = 0.0231\, f_1$ (r = 0.32)

Steel buildings :

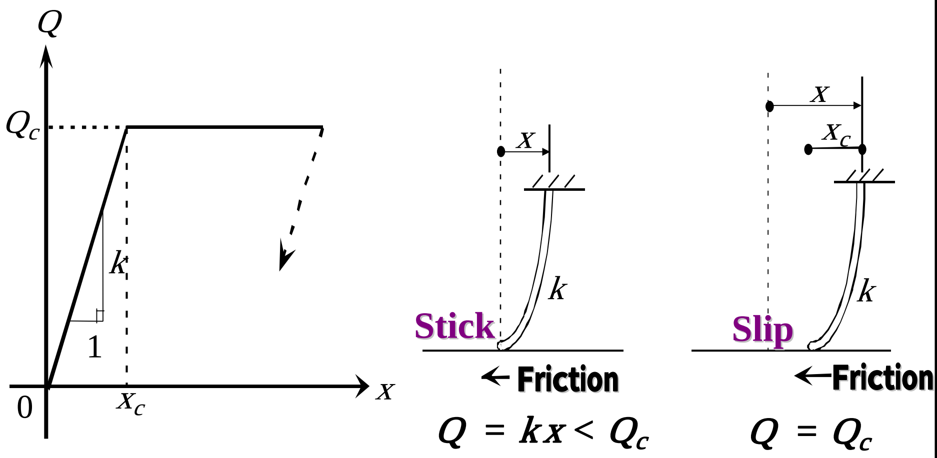
$\zeta_1 = 0.013\, f_1$ (r = 0.65)

f_1: Fundamental Natural Frequency (Hz)

Variation of Damping Ratio with Amplitude



Stick-slip Model for Damping in Buildings



Stick-slip Model for Damping in Buildings

Increase of amplitude

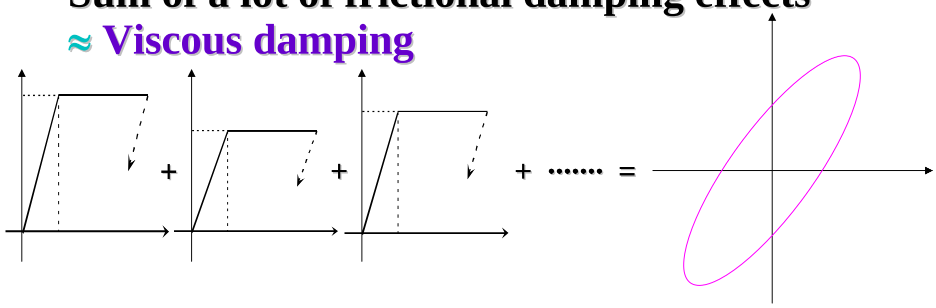
→ Increase of number of slipping joints

→ **Increase of friction damping**

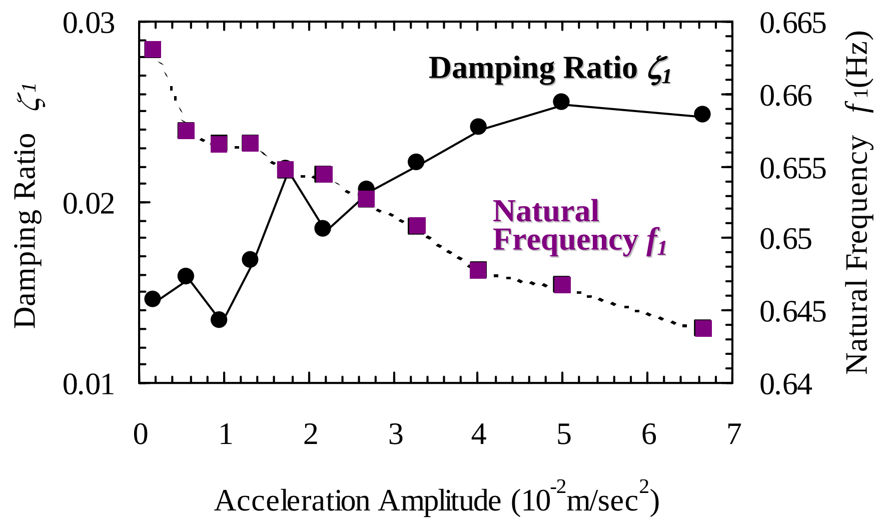
& **Decrease of stiffness**

Sum of a lot of frictional damping effects

≈ **Viscous damping**



An Observatory Building (H=99m)



Amplitude Dependence of Damping Ratio

(Damping in buildings, AIJ, 2000)

- **Steel Buildings**

$$\zeta_1 = A + B\frac{x_H}{H}$$

Tall Office Buildings :

B = 400, Upper Limit $x_H / H = 2\times10^{-5}$

$\Delta\zeta_1 (x_H / H)$ = 0.8%

Tall Towers :

B = 3000, Upper Limit $x_H / H = 5\times10^{-6}$

$\Delta\zeta_1 (x_H / H)$ = 1.5%

Proposed Damping Predictor in AIJ 2000

Natural Frequency Dependent Term
←Height Dependent
←Soil-Structure-Interaction

- **RC buildings :**

$$\zeta_1 = 0.0143\, f_1 + 470(x_H / H) - 0.0018$$

$x_H / H < 2\times10^{-5}$, 30m < H < 100m

Large in Low-rise Buildings

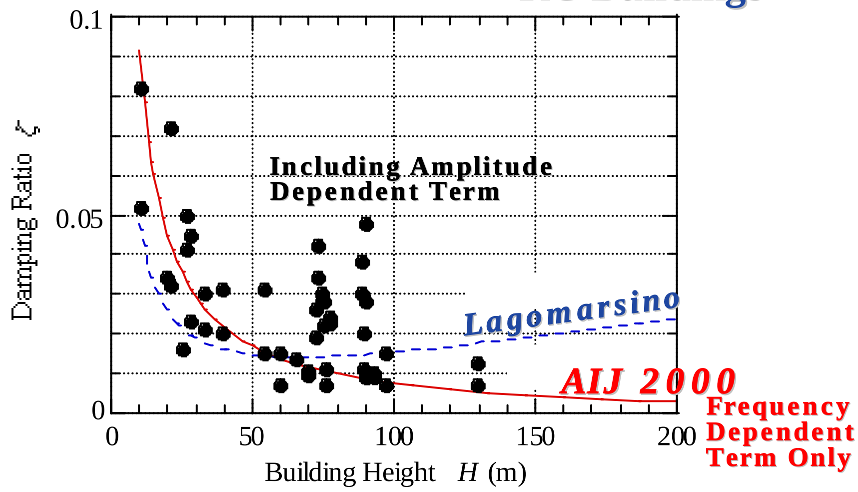
- **Steel buildings :**

$$\zeta_1 = 0.013\, f_1 + 400(x_H / H) + 0.0029$$

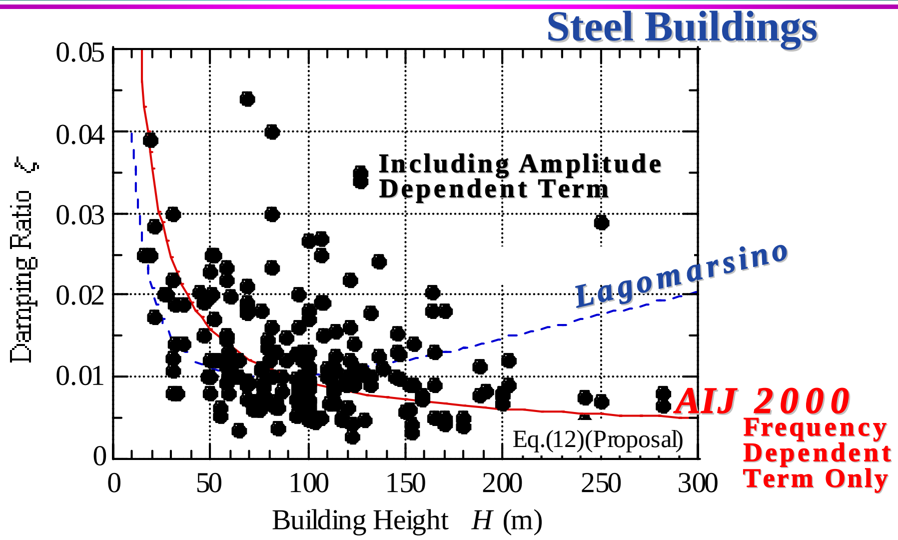
$x_H / H < 2\times10^{-5}$, 30m < H < 200m

Comparison of Full-Scale Damping Ratios and Proposed Predictors

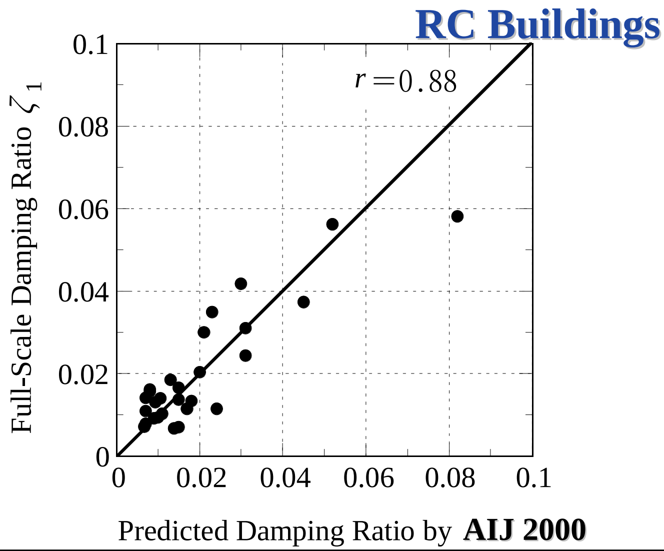
RC Buildings



Comparisons of Full-Scale Damping Ratios and Proposed Predictors



Full-Scale Known Amplitude Damping Ratios vs Proposed Predictor in AIJ 2000



Damping Ratio for Structural Design (AIJ, 2000)

(JDD)

- **Damping Ratio for Habitability**
  - Human Comfort
  - Vibration Perception Threshold
  - *H-3 Level* (AIJ Guidelines, 1991)
- **Damping Ratio for Structural Safety**
  - Elastic Region

Fundamental Natural Periods T_1 (sec)

(Damping in buildings, AIJ, 2000)

- RC/SRC Buildings :

  $T_1 = 0.015\,H \quad (f_1 = 67/H)$
- Steel Buildings :

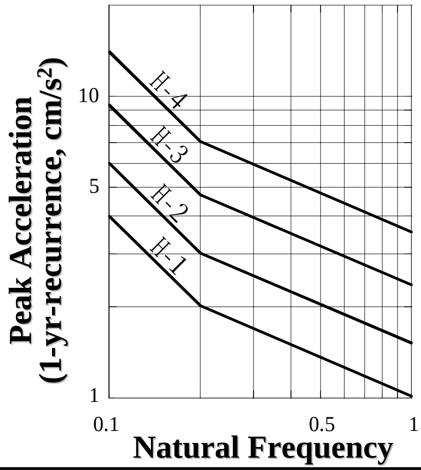
  $T_1 = 0.020\,H \quad (f_1 = 50/H)$
- Ellis (1980) S/SRC/RC buildings:

  $T_1 = 0.022\,H \quad (f_1 = 46/H)$

H : Building Height (m)

Performance Evaluation of Habitability to Building Vibration

Guidelines for the evaluation of habitability to building vibration (AIJ, 1991)



Performance Evaluation of Habitability to Building Vibration

- **1-year-recurrence Peak Acceleration**

$$A = 2.3\, f_1^{\,-0.431}$$

Level H-3 **: Guidelines for the evaluation of habitability to building vibration (AIJ, 1991)**

- **Foundamental natural Frequency**

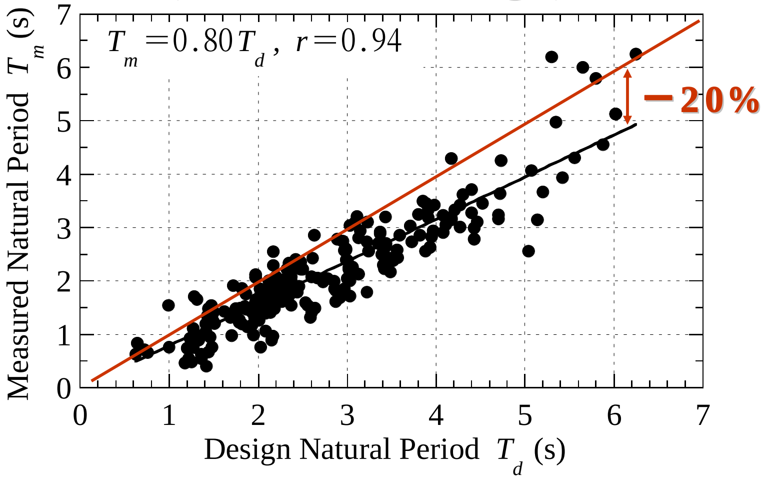
$$f_1 = 1 / 0.015H \text{ (RC Buildings)}$$

$$f_1 = 1 / 0.020H \text{ (Steel Buildings)}$$

Full-scale Fundamental Natural Periods & Their Design Values

(Damping in buildings, AIJ, 2000)

(Steel Buildings)



Full-scale Natural Period T_m (JDD) and Design Natural Period T_d

- $T_m = 0.80\ T_d$

Steel Buildings : ***Satake et al. (1997)***
RC Buildings : ***Shioya et al. (1993)***

Contributions of Secondary Members to Stiffness

Design Damping Ratio for Structural Safety

(JDD)

Tip Drift Ratio $x_H / H = 2\times10^{-5}$

- **RC Buildings**

$$f_1 = 1 / 0.018H$$

- **Steel Buildings**

$$f_1 = 1 / 0.024H$$

AIJ 2000 (RC Buildings)

(JDD)

(Damping in buildings, AIJ, 2000)

Height H (m)	Habitability: Natural Frequency f_1 (Hz)	Habitability: Damping Ratio ζ_1 (%) Rec.	Habitability: Damping Ratio ζ_1 (%) Standard	Safety: Natural Frequency f_1 (Hz)	Safety: Damping Ratio ζ_1 (%) Rec.	Safety: Damping Ratio ζ_1 (%) Standard
30	2.2	2.5	3	1.9	3	3.5
40	1.7	1.5	2	1.4	2	2.5
50	1.3	1.2	1.5	1.1	2	2.5
60	1.1	1.2	1.5	0.93	1.5	2
70	0.95	0.8	1	0.79	1.5	2
80	0.83	0.8	1	0.69	1.2	1.5
90	0.74	0.8	1	0.62	1.2	1.5
100	0.67	0.8	1	0.56	1.2	1.5

- "Rec." : "Recommended" values.
- $f_1 = 1/0.015H$ (Habitability), $f_1 = 1/0.018H$ (Safety)
- Safety : Elastic Range

(JDD)

AIJ 2000 (Steel Buildings)

(Damping in buildings, AIJ, 2000)

Height H (m)	Habitability: Natural Frequency f_1 (Hz)	Habitability: Damping Ratio ζ_1 (%) Rec.	Habitability: Damping Ratio ζ_1 (%) Standard	Safety: Natural Frequency f_1 (Hz)	Safety: Damping Ratio ζ_1 (%) Rec.	Safety: Damping Ratio ζ_1 (%) Standard
30	1.7	1.8	2.5	1.4	2	3
40	1.3	1.5	2	1.0	1.8	2.5
50	1.0	1	1.5	0.83	1.5	2
60	0.83	1	1.5	0.69	1.5	2
70	0.71	0.7	1	0.60	1.5	2
80	0.63	0.7	1	0.52	1	1.5
90	0.56	0.7	1	0.46	1	1.5
100	0.50	0.7	1	0.42	1	1.5
150	0.33	0.7	1	0.28	1	1.5
200	0.25	0.7	1	0.21	1	1.5

- "Rec." : "Recommended" values.
- $f_1 = 1/0.020H$ (Habitability), $f_1 = 1/0.024H$ (Safety)
- Safety : Elastic Range

(JDD)

Effects of Building Use

(Damping in buildings, AIJ, 2000)

Steel Buildings

- **Office Buildings**

  ζ_{AVE} = 1.15 % (H_{AVE} = 112.6m)

- **Hotels and Residential Buildings**

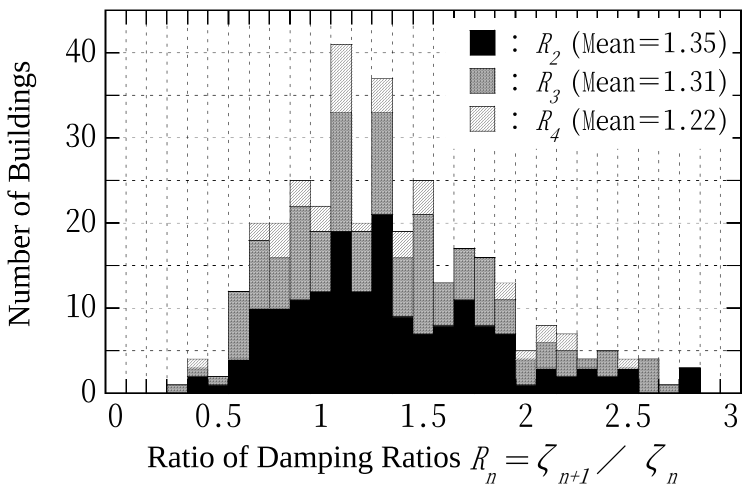
  ζ_{AVE} = 1.45 % (H_{AVE} = 100.4m)

25% Increase due to interior walls

Ratio of Higher Mode Damping to Next Lower Mode Damping

(Damping in buildings, AIJ, 2000)

Steel Buildings



Higher Mode Damping Ratio

(Damping in buildings, AIJ, 2000)

(AIJ2000)

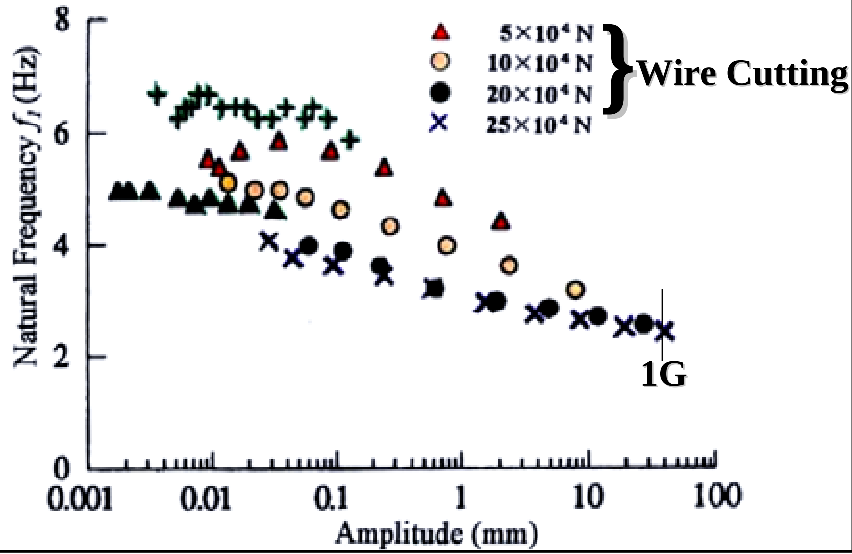
- **RC Buildings**

  $$\zeta_{n+1} = 1.4\ \zeta_n\ , \quad (n=1,2)$$

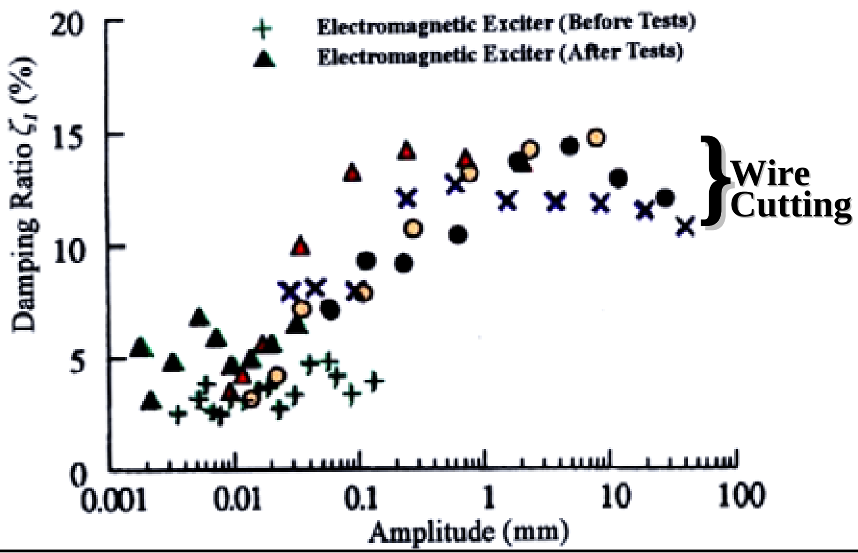
- **Steel Buildings**

  $$\zeta_{n+1} = 1.3\ \zeta_n\ , \quad (n=1,2)$$

Large Amplitude Tests
(A Steel Model House)



Large Amplitude Tests
(A Steel Model House)



Damping Ratio for Ultimate Limit State

- Damage to Secondary Members
- Development of Micro Cracks

↙Larger Damping Values

Almost No Quantitative Evidence

■Effects of Hysteretic Response of Frames

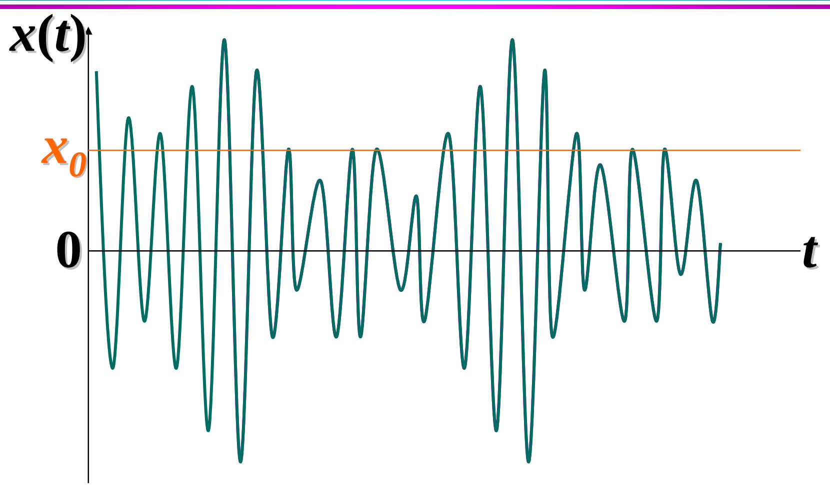
Evaluation of Damping Ratio from Randomly Excited Motion

Output Information

- ■ Spectral Methods
  - Hal-Power Method
  - Auto-Correlation Method
- → Stationarity is strictly required.
- ■ Random Decrement Technique
- → Stationarity is not necessarily required.
- → Appropriate for amplitude dependent phenomena
- → Each mode should be clearly separated.
- ■ Frequency Domain Decomposition
- → Each mode does not have to be well separated.

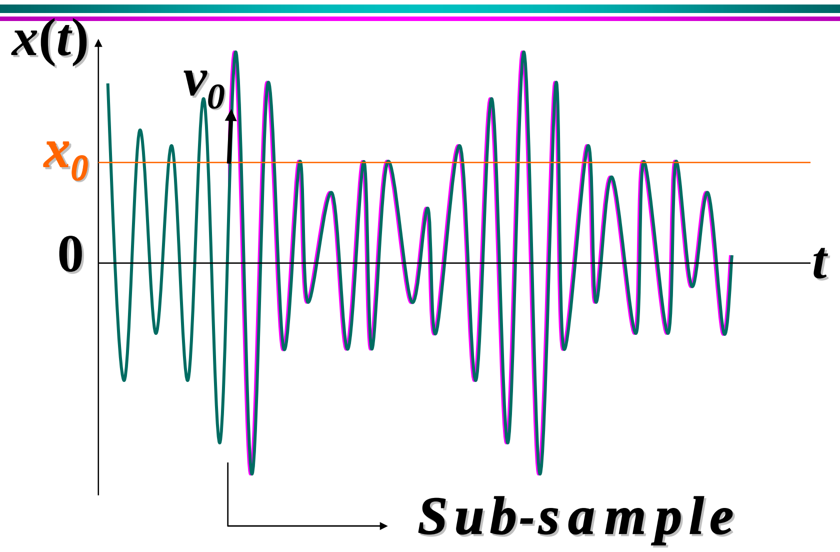
35-03

Random Decrement Technique
Estimation by SDOF Fitting



35-04

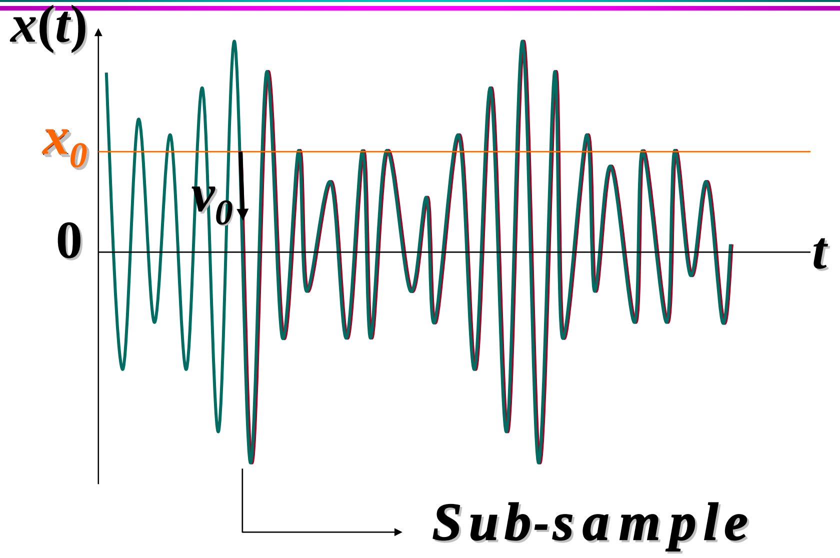
Random Decrement Technique
Estimation by SDOF Fitting



35-05

Random Decrement Technique

Estimation by SDOF Fitting



35-06

Random Decrement Technique

Estimation by SDOF Fitting

General Solution of SDOF

$M\ddot{x} + C\dot{x} + Kx = f(t)$ ← zero-mean random excitation

$x(t) = D(t) + R(t)$

$D(t)$: Damped Free Component Depending on Initial Condition (x_0, v_0)

$R(t)$: Randomly Excited Component

$$= \int_0^t f(\tau)h(t-\tau)d\tau$$

→ Superimposition of Sub-samples (Ensemble Averaging)

35-07

Random Decrement Technique

Estimation by SDOF Fitting

Superimposition of Sub-samples (Ensemble Averaging)

= Random Decrement Signature

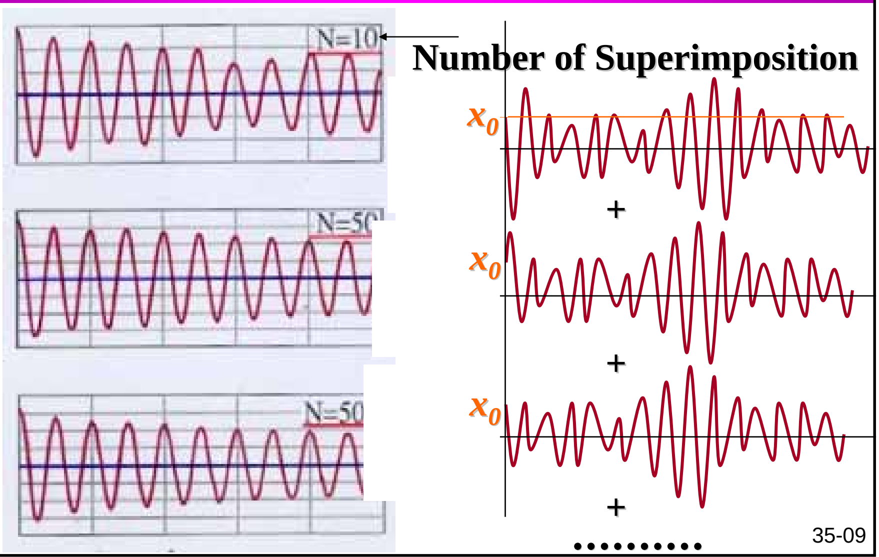
∝ Auto-correlation Function

≈ Damped Free Component with Initial Amplitude x_0

$$\propto \exp(-\zeta\omega_0\tau)\left(\cos\sqrt{1-\zeta^2}\,\omega_0\tau + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin\sqrt{1-\zeta^2}\,\omega_0\tau\right)$$

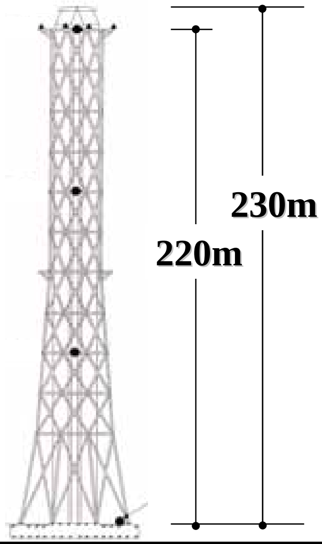
35-08

Random Decrement Signature



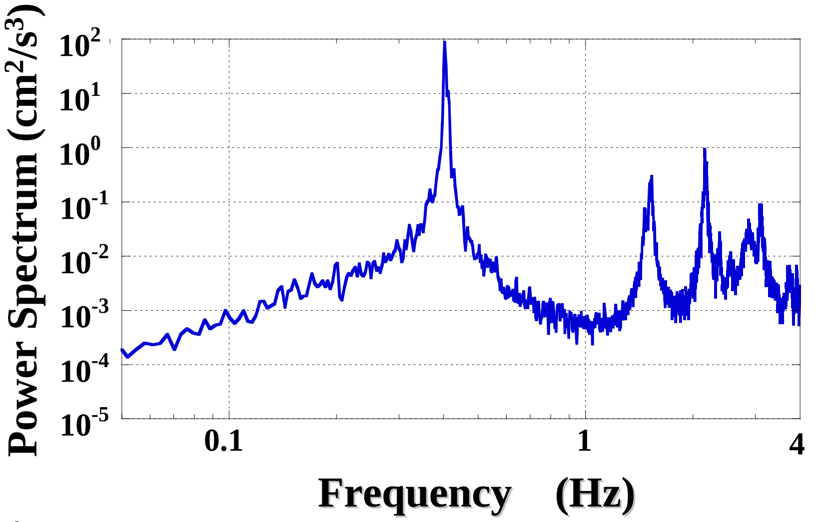
35-09

Damping Estimation of Chimney with Closely Located Natural Frequencies by Random Decrement Technique

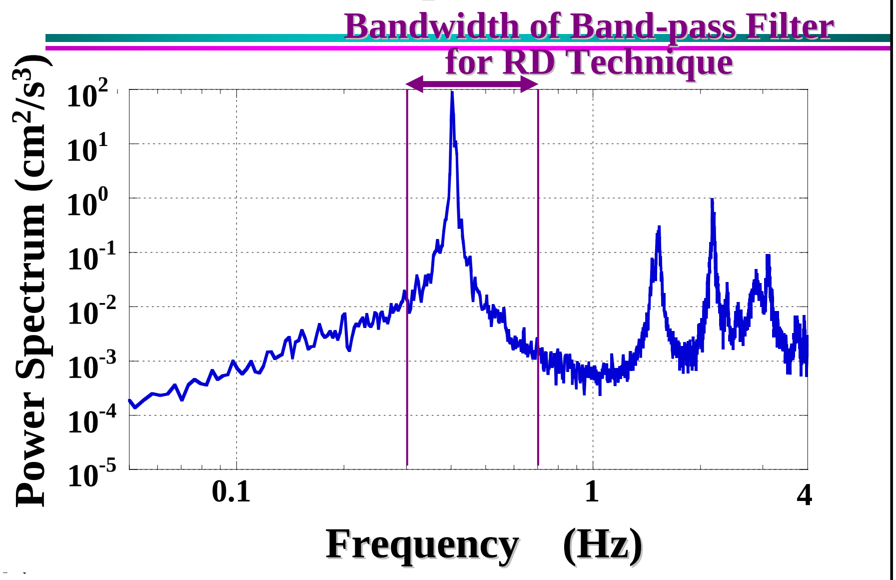


35-10

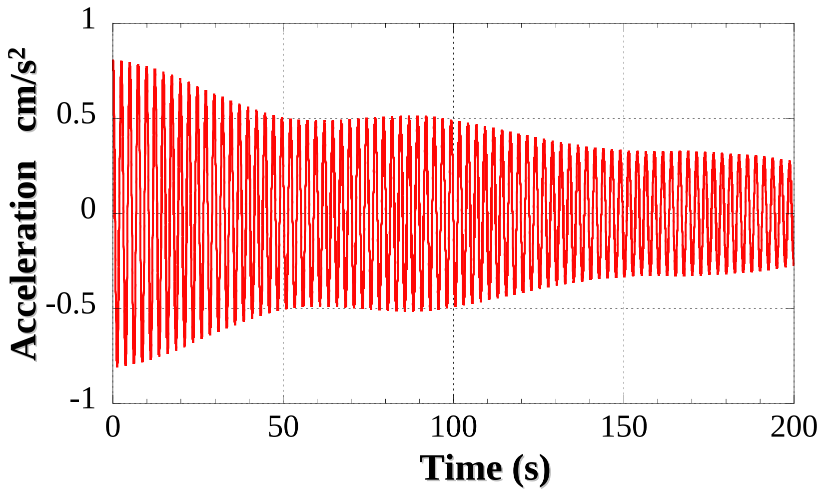
Power Spectral Density of Ambient Acceleration Response (NS comp. at 220m)



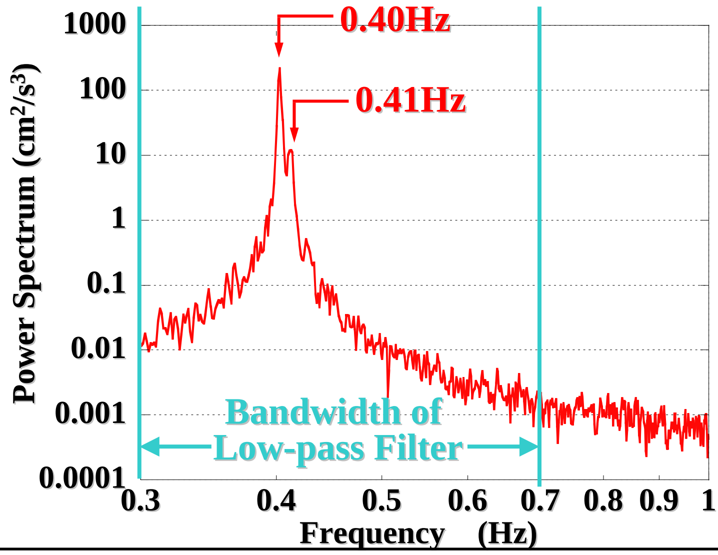
Power Spectral Density of Ambient Acceleration Response (NS comp. at 220m)



Random Decrement Signature



Power Spectral Density of Ambient Acceleration Response (NS comp. at 220m)



35-11

Least Square Approximation of MDOF Random Decrement Signature

$$x_1 = \frac{x_{01}}{\sqrt{1-\zeta_1^2}} e^{-\zeta_1 \omega_1 t} \cos\left(\sqrt{1-\zeta_1^2}\,\omega_1 t - \phi_1\right)$$

$+$

$$x_2 = \frac{x_{02}}{\sqrt{1-\zeta_2^2}} e^{-\zeta_2 \omega_2 t} \cos\left(\sqrt{1-\zeta_2^2}\,\omega_2 t - \phi_2\right)$$

$+$

$\cdots\cdots\cdot$

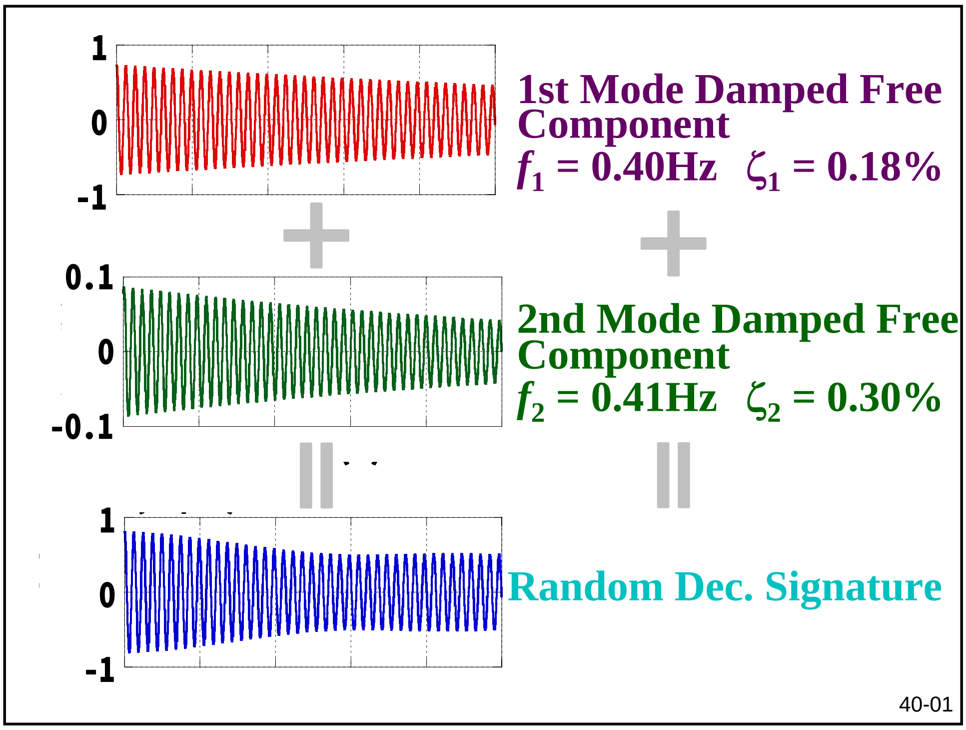
$+$

$$x_N = \frac{x_{0N}}{\sqrt{1-\zeta_N^2}} e^{-\zeta_N \omega_N t} \cos\left(\sqrt{1-\zeta_N^2}\,\omega_N t - \phi_N\right)$$

Mean Value Error

$$x = x_1 + x_2 + \cdots\cdots + x_N + m$$

35

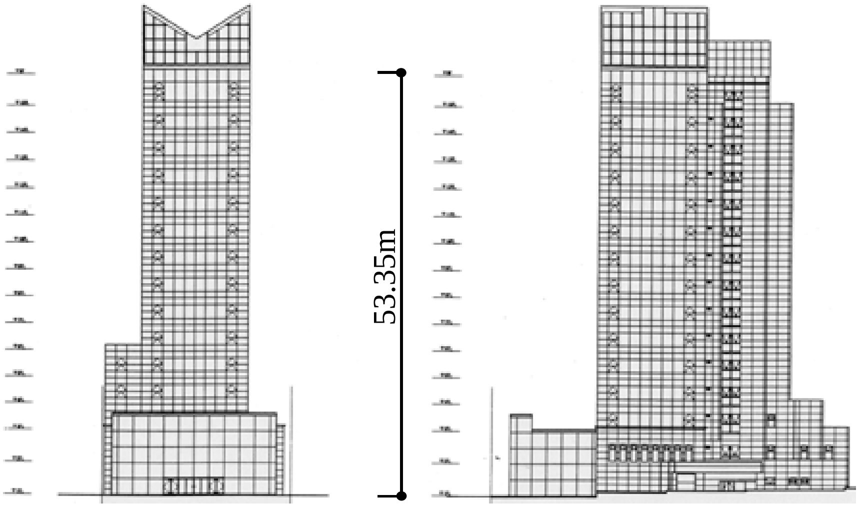


Estimated Dynamic Characteristics of a 230m-high Chimney by 2DOF RD technique and FDD

Mode #	Natural Frequency (Hz)		Damping Ratio (%)	
	RD	FDD	RD	FDD
1	0.40	0.40	0.18	0.24
2	0.41	0.41	0.30	0.39
3	1.47	1.47	0.83	0.30
4	1.53	1.52	0.85	0.91
5	2.17	2.17	0.55	0.65
6	2.38	2.38	0.42	0.39
7	–	2.87	–	–
8	–	3.10	–	0.77

40-02

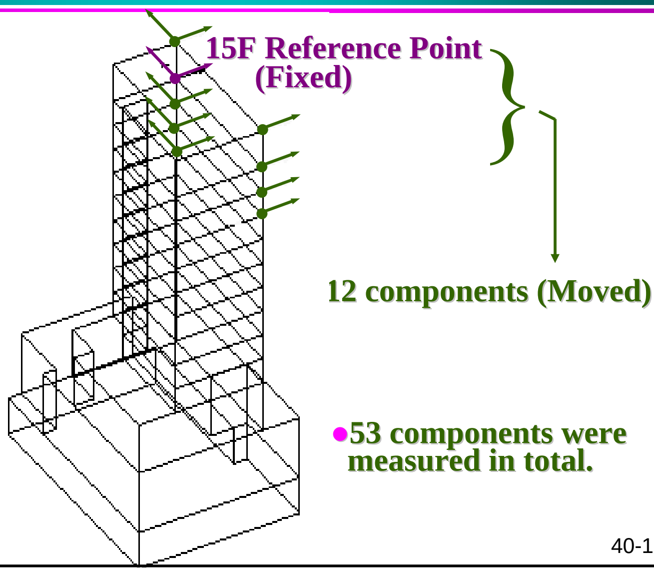
Full-scale Measurement of Dynamic Properties of a 15-story CFT Building



SE Elevation | SW Elevation

40-04

Ambient Vibration Measurement of Completed Building



- 53 components were measured in total.

40-10

Frequency Domain Decomposition (FDD)

Spectral Density Matrix of Measured Responses

$G_{yy}(j\omega)$

Singular Value Decomposition

$G_{yy}(j\omega_k) = U_k S_k V_k^H$

- Singular Value ($\omega_k \approx \omega_i$) becomes large

$\rightarrow$ has a peak equivalent to SDOF-PSD function

- Left Singular Vector u_r associated with a peak

  $\approx$ Mode Shape

Natural Frequencies, Damping Ratios, Mode Shapes

40-11

FDD : Basic Formulations

- PSD: Input/Output relation

$$G_{yy}(j\omega) = H(j\omega)^* G_{xx}(j\omega) H(j\omega)^T$$

- PSD: Modal Decomposition

$$G_{yy}(j\omega) = \sum_{r=1}^{N} \frac{d_r \phi_r \phi_r^H}{j\omega - \lambda_r} + \frac{d_r \phi_r \phi_r^H}{j\omega - \lambda_r^*}$$

- PSD: Singular Value Decomposition

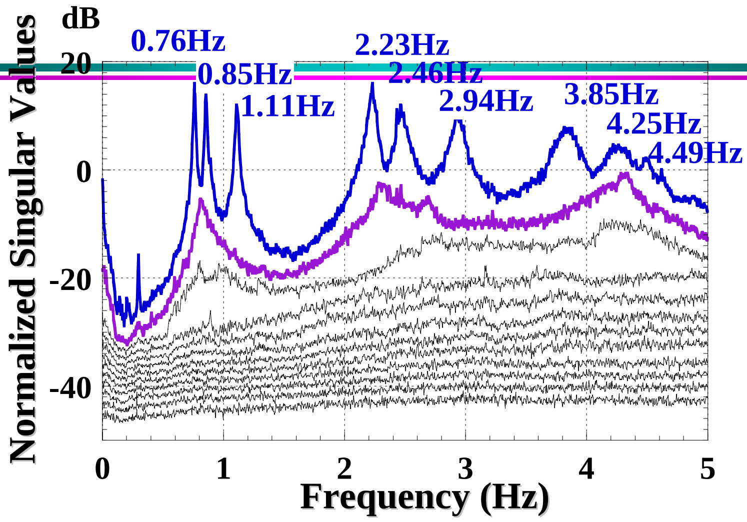
$$G_{yy}(j\omega_k) = U_k S_k V_k^H$$

- Mode Shape Estimation

$$\hat{\phi}_r = u_r$$

40-12

Singular Value Plots

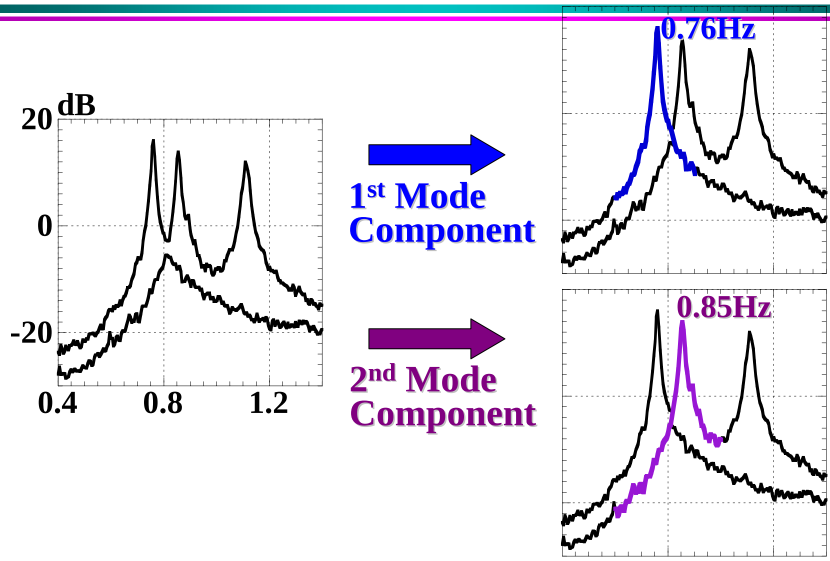


- Peak-Picking
- Average of Normalized S.V. of PSD Matrices of All Data Sets
- Analytical Software: ARTeMIS

40-13

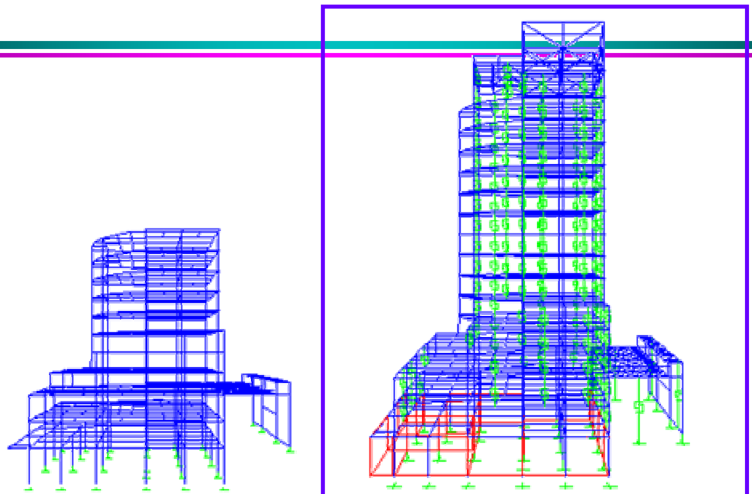
Identification of Closely Located Peaks

- SV Plot : Single Mode Selection -



40

FEM Analytical Models



11-story Model   15-story Model

45-01

Natural Frequencies of 15-Story CFT Building

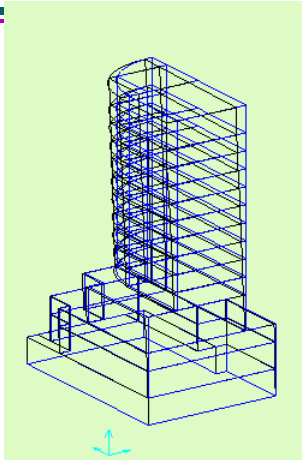
Field Data (→ AMB)

Mode	FEM (Hz)	AMB (Hz)	Error (%)
1	0.76	0.76	0
2	0.87	0.86	2.22
3	1.15	1.11	3.51
4	2.14	2.23	-3.99
5	2.53	2.47	2.59
6	3.02	2.94	2.82
7	3.85	3.85	0
8	4.26	4.26	0
9	4.67	4.47	4.29

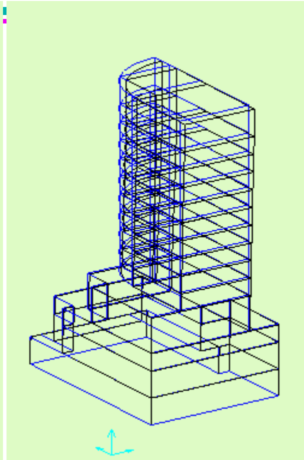
Adjusted by Additional Stiffness (→ Mode 1 FEM 0.76)

45-02

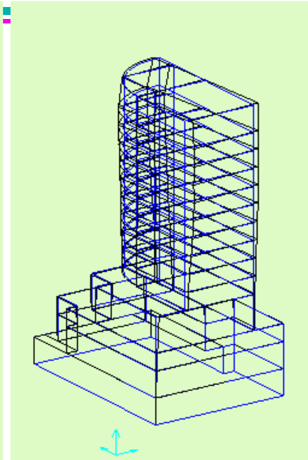
FDD IDENTIFIED MODE SHAPES (1-3)



$f_1 = 0.760$ Hz



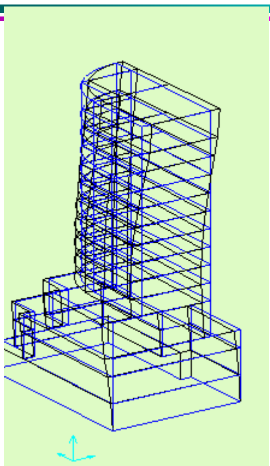
$f_2 = 0.854$ Hz



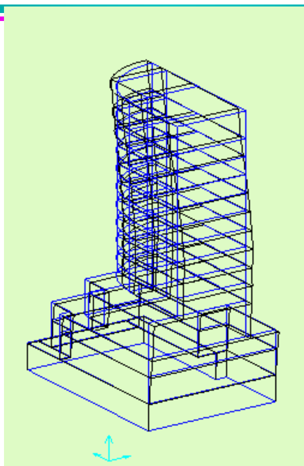
$f_3 = 1.111$ Hz

45-03

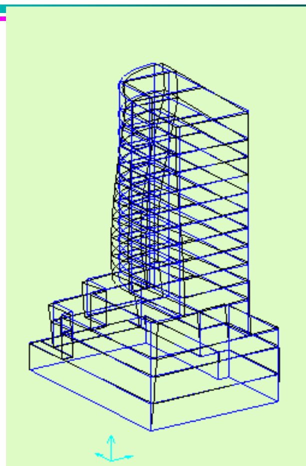
FDD IDENTIFIED MODE SHAPES (4-6)



$f_4 = 2.230$ Hz



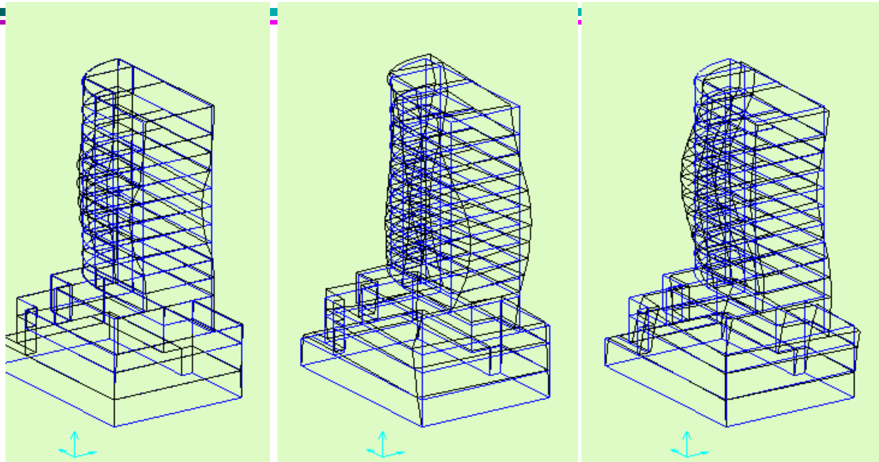
$f_5 = 2.468$ Hz



$f_6 = 2.939$ Hz

45-04

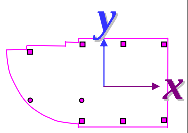
FDD IDENTIFIED MODE SHAPES (7-9)

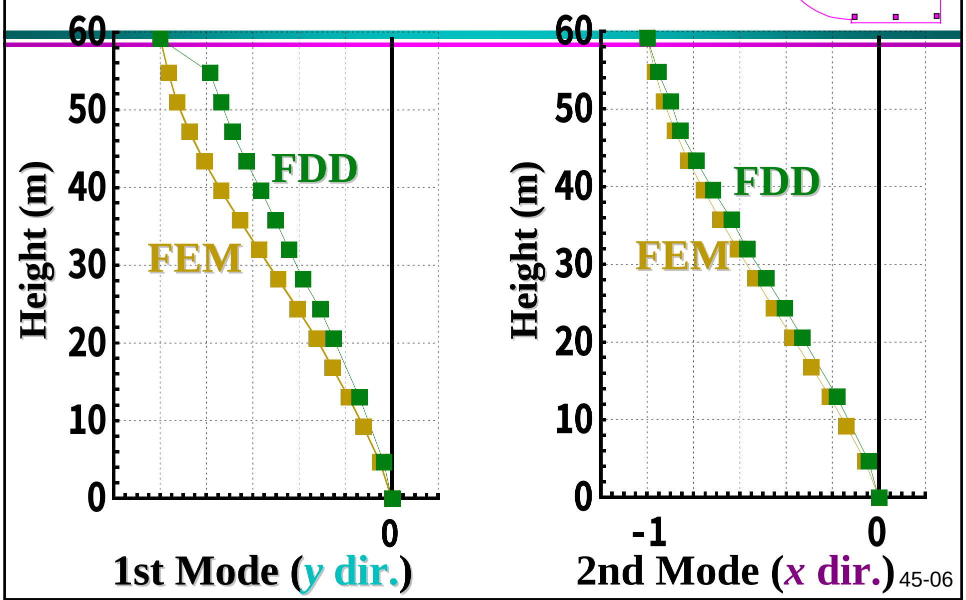


f_7= 3.849 Hz f_8= 4.255 Hz f_9= 4.493 Hz

45-05

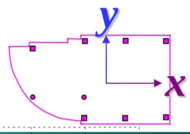
Mode Shapes by FDD & FEM

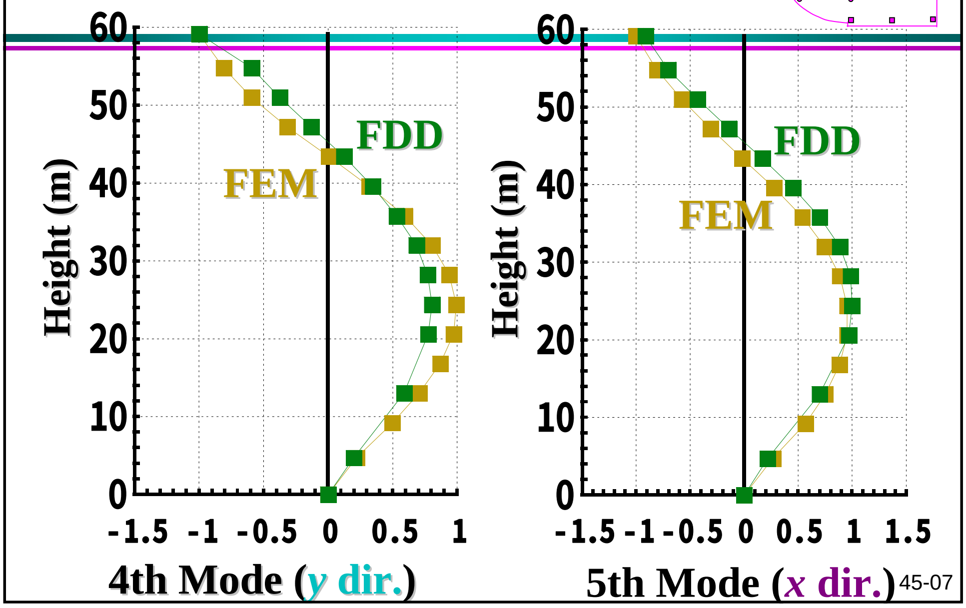




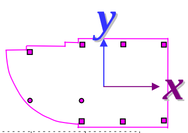
45-06

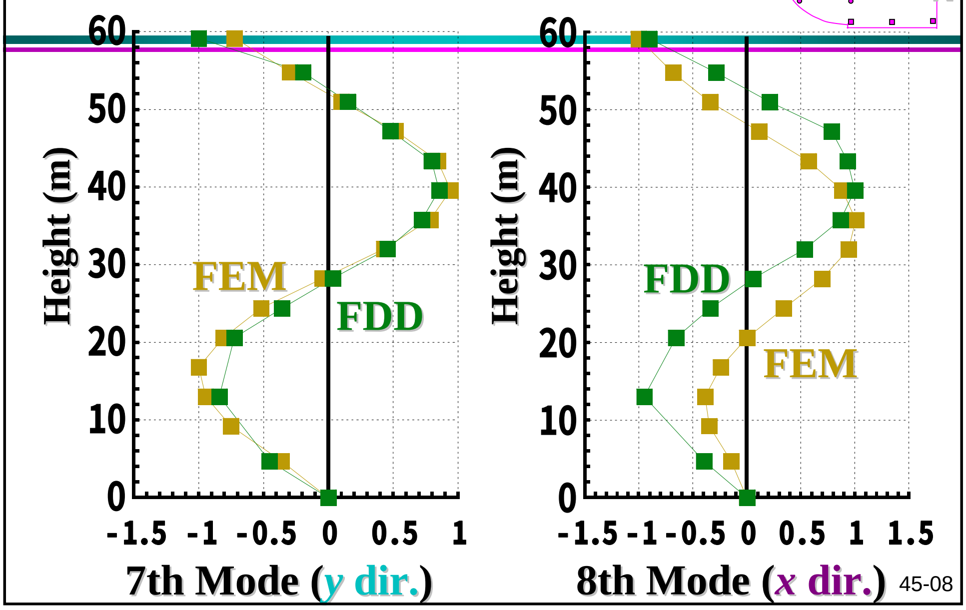
Mode Shapes by FDD & FEM





Mode Shapes by FDD & FEM

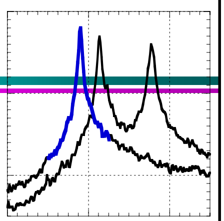




Basic Idea & Procedure of Damping Estimation

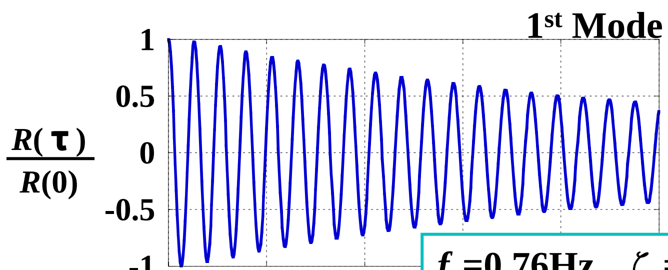
- Select SDOF approximation of the “PSD Bell” based on using MAC
- Calculate SDOF correlation function via Inverse FFT of the selected “PSD Bell”
- Estimate damping ration by Logarithmic Decrement Technique

Damping Estimation



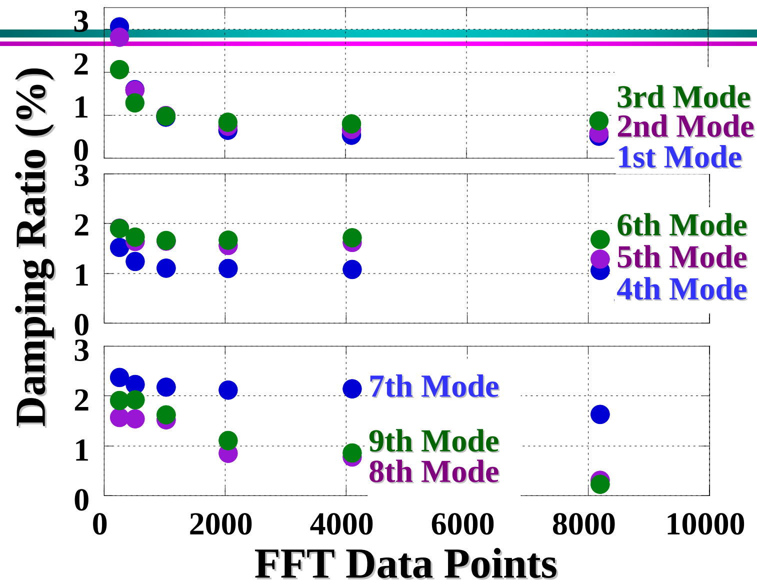
Inverse Fourier Transform of Identified Mode Component (SDOF-PSD)

Auto-Correlation Function: $R(\tau)$



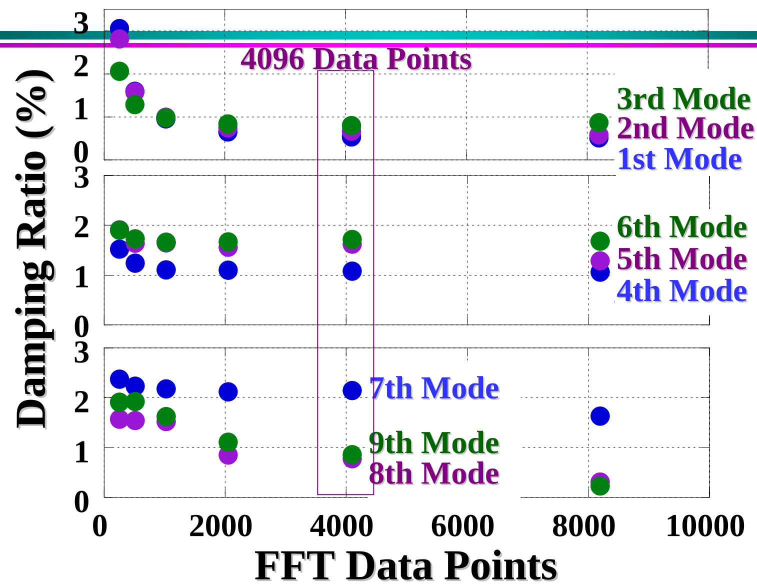
f_1=0.76Hz, ζ_1=0.54%

Variation of Estimated Damping Ratios by FDD with FFT Data Points (Frequency Resolution)



45-11

Variation of Estimated Damping Ratios by FDD with FFT Data Points (Frequency Resolution)



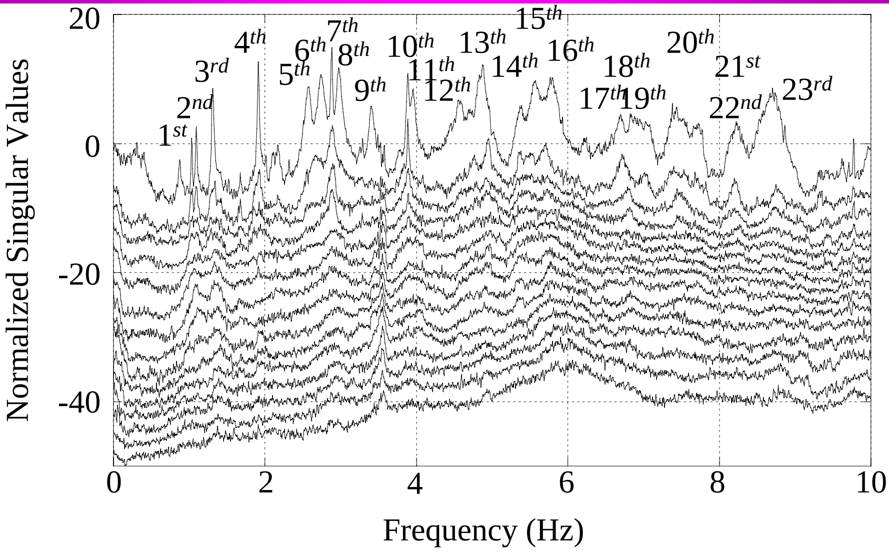
45-12

Estimated Damping Ratios and FFT Data Points

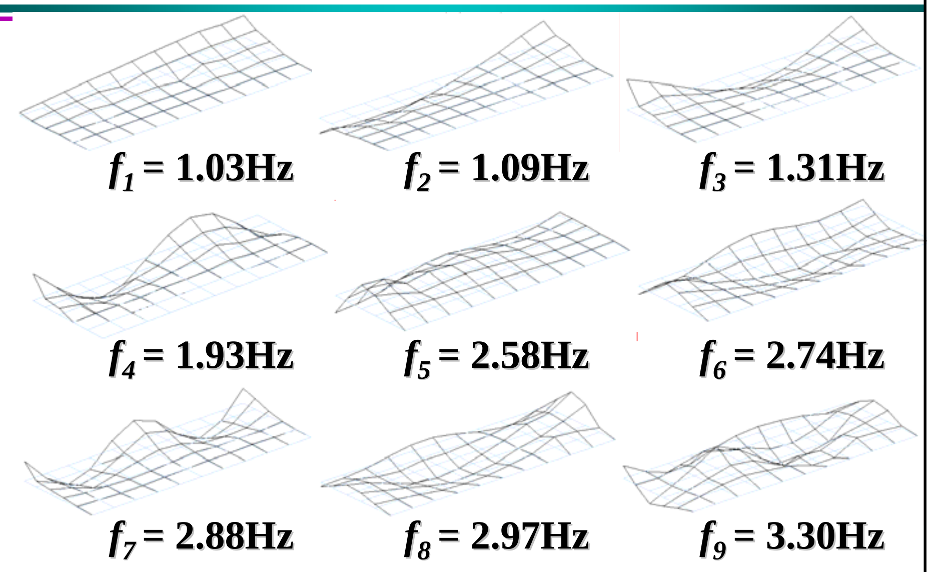
Data Points	256	512	1024	2048	4096	8192
1st	3.05	1.60	0.95	0.65	0.54	0.51
2nd	2.81	1.58	0.99	0.74	0.67	0.58
3rd	2.06	1.29	0.98	0.84	0.80	0.87
4th	1.52	1.24	1.11	1.10	1.08	1.06
5th	1.91	1.64	1.65	1.56	1.62	1.29
6th	1.90	1.73	1.66	1.67	1.72	1.68
7th	2.37	2.23	2.18	2.15	2.11	1.63
8th	1.57	1.60	1.38	0.85	0.78	n/a
9th	1.91	1.92	1.62	1.25	0.86	n/a

45

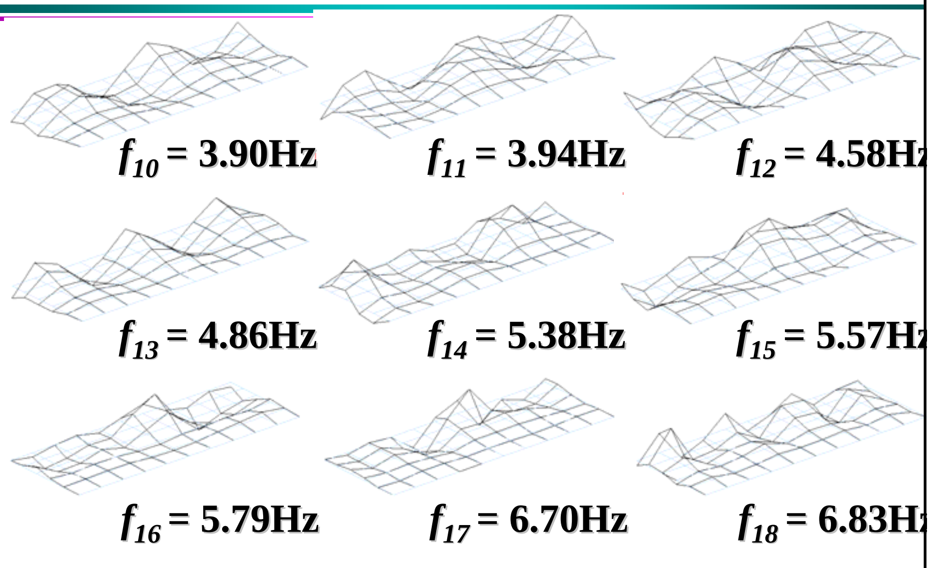
Singular Values of PSD Matrix of Ambient Vibrations



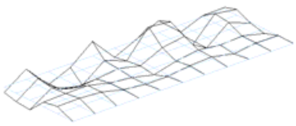
Mode Shapes Obtained by SVD of PSD Matrix



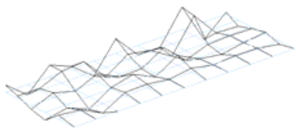
Mode Shapes Obtained by SVD of PSD Matrix



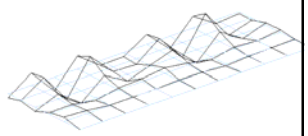
Mode Shapes Obtained by SVD of PSD Matrix



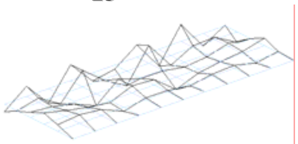
f_{19} = 7.00Hz



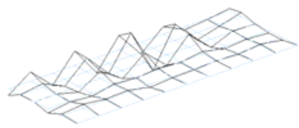
f_{20} = 7.42Hz



f_{21} = 7.71Hz



f_{22} = 8.23Hz



f_{23} = 8.70Hz

Damping Ratios Obtained by SVD of PSD Matrix

Mode	ζ (%)	Mode	ζ (%)	Mode	ζ (%)
1	0.69	9	0.91	17	0.73
2	0.59	10	1.44	18	0.75
3	0.56	11	0.66	19	0.50
4	0.21	12	0.98	20	0.51
5	2.17	13	1.01	21	1.04
6	1.38	14	0.83	22	0.72
7	1.47	15	0.85	23	0.50
8	0.27	16	0.61	-	-