Chapter 3: Types of Damping

Introduction

When structures are subjected to dynamic forces such as earthquakes, they tend to vibrate. These vibrations need to be controlled or reduced to avoid structural damage or failure. One of the fundamental mechanisms that help reduce the vibratory motion in structures is **damping**. Damping is the process by which the vibrational energy of a structure is gradually dissipated over time. It acts as a resistance to motion and is vital in seismic design because it limits the amplitude of oscillations during an earthquake.

This chapter explores various **types of damping**, their modeling, and their importance in dynamic analysis and earthquake engineering. A clear understanding of damping mechanisms is crucial for civil engineers in designing resilient and safe structures.

3.1 Concept of Damping in Vibratory Systems

Damping is the mechanism by which energy is dissipated in a vibrating system. It reduces the amplitude of vibrations and brings the system back to rest after excitation. In real-world structures, damping comes from:

- Internal material friction
- Friction at joints
- Air resistance
- Energy-absorbing devices

Mathematically, damping is introduced into the equations of motion through a **damping force**, usually proportional to velocity, represented as:

$$F_d = c \cdot \dot{x}$$

Where:

- F_d = damping force
- c = damping coefficient
- $\dot{x}$ = velocity

3.2 Types of Damping

Damping can be categorized based on its nature and the physical mechanism of energy dissipation. The main types are:

3.2.1 Viscous Damping

Definition: In viscous damping, the damping force is directly proportional to the velocity of the moving mass.

$$F_d = c \cdot \dot{x}$$

Where:

- c = viscous damping coefficient (Ns/m)

Characteristics:

- Linear behavior
- Commonly used in mathematical modeling
- Idealization for many engineering problems

Examples:

- Dashpots in mechanical systems
- Fluid resistance in hydraulic dampers

Applications in Earthquake Engineering:

- Modeling energy dissipation in soil and structural components
- Used in software-based dynamic analysis

3.2.2 Coulomb (Dry Friction) Damping

Definition: This type of damping arises due to friction between two contacting surfaces. The damping force is constant in magnitude but opposite to the direction of motion.

$$F_d = \mu N$$

Where:

- μ = coefficient of friction
- N = normal reaction force

Characteristics:

- Nonlinear behavior
- Energy loss per cycle is constant regardless of amplitude
- Produces a saw-tooth shaped decay in vibration

Applications:

- Structures with sliding joints or base isolators
- Components where metal-to-metal contact occurs

3.2.3 Structural (Hysteretic) Damping

Definition: Energy dissipation occurs due to internal friction within the material. The damping is dependent on the amplitude of vibration and manifests as a hysteresis loop in the force-displacement curve.

Characteristics:

- Nonlinear and amplitude-dependent
- More realistic for materials like steel and concrete
- Energy loss is proportional to the area of the hysteresis loop

Mathematical Representation: Force-displacement loops show the energy dissipation per cycle.

Applications:

- Damping in concrete, masonry, and steel structures
- Design of energy-dissipating joints in earthquake-resistant buildings

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3.2.4 Magnetic Damping

Definition: Damping is produced using electromagnetic induction. When a conductor moves in a magnetic field, eddy currents are generated which oppose the motion, causing damping.

Characteristics:

- No mechanical contact
- Smooth and reliable operation
- Limited application in structural systems

Applications:

- Seismic instrumentation
- Tuning devices in structural health monitoring

3.2.5 Air (Pneumatic) and Fluid (Hydraulic) Damping

These damping systems use air or fluid resistance to reduce motion. Though not extensively used in large-scale structures, they are important in component-level design and devices.

Air Damping:

- Used in lightweight equipment and sensors
- Generally lower damping force

Fluid Damping:

- Viscous resistance of fluids used to reduce vibration
- Hydraulic dampers, shock absorbers

Applications:

- Tuned mass dampers in high-rise buildings
- Base-isolation systems with fluid viscous dampers

3.2.6 Radiation Damping

Definition: Occurs due to the propagation of stress waves away from the vibrating body into the surrounding medium (e.g., soil). It is important in soil-structure interaction problems.

Characteristics:

- Common in seismic soil dynamics
- Involves transfer of energy from the structure into the infinite domain

Applications:

- Foundation dynamics
- Dynamic response of underground structures

3.2.7 Composite or Equivalent Damping

In real structures, multiple damping mechanisms work simultaneously. To simplify analysis, an **equivalent damping ratio** is used, which represents all forms of damping in a single parameter.

$$\xi = \frac{c}{2\sqrt{km}}$$

Where:

- ξ = damping ratio
- c = damping coefficient
- k = stiffness
- m = mass

This damping ratio is used in **response spectrum** and **modal analysis** in earthquake engineering.

3.3 Damping Ratio and Logarithmic Decrement

3.3.1 Damping Ratio (ξ)

It is a dimensionless measure of damping in a system:

- $\xi = 0$: Undamped system
- $\xi < 1$: Underdamped
- $\xi = 1$: Critically damped
- $\xi > 1$: Overdamped

Typical values in civil engineering:

- Steel: 1–2%
- Concrete: 4–7%
- Masonry: 7–10%

3.3.2 Logarithmic Decrement (δ)

Used to estimate damping ratio from free vibration response:

$$\delta = \frac{1}{n} \ln\left(\frac{x_0}{x_n}\right)$$

Where:

- x_0 = initial amplitude
- x_n = amplitude after n cycles

Related to damping ratio as:

$$\xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}$$

3.4 Measurement and Estimation of Damping

- **Experimental Methods**:
  - Free vibration decay method
  - Forced vibration tests
  - Ambient vibration analysis
- **Numerical Estimation**:
  - Based on material properties and finite element models
- **Code Recommendations**:
  - BIS, ASCE, Eurocode provide recommended damping ratios for various materials and systems

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3.5 Role of Damping in Earthquake Engineering

Damping plays a pivotal role in:

- Reducing seismic response of structures
- Preventing resonance during ground shaking
- Enhancing the performance of base isolators and dampers
- Increasing safety and serviceability of buildings and infrastructure

Common damping devices used in seismic design:

- Tuned Mass Dampers (TMD)
- Viscous Fluid Dampers
- Friction Dampers
- Yielding Metallic Dampers

3.6 Damping in Building Codes and Standards

Earthquake design codes specify damping ratios and reduction factors. For example:

- **IS 1893** (India): Assumes 5% damping for general buildings
- **ASCE 7**: Provides damping modification factors
- **Eurocode 8**: Includes damping correction factors in spectral analysis

Codes allow adjustment of spectral accelerations based on actual damping values, encouraging use of energy-dissipating devices in design.

3.7 Damping Modification Factors (DMF)

When designing structures for seismic resistance, design codes allow adjustments in the response spectra based on actual or assumed damping levels. These adjustments are implemented using **Damping Modification Factors (DMF)**, which correct the spectral accelerations to account for damping values other than the standard 5%.

3.7.1 Concept and Definition

The DMF is a multiplier applied to reduce (or increase) the spectral response when damping is higher (or lower) than the reference value.

Let:

- $S_{5\%}$ be the spectral acceleration for 5% damping
- η be the damping modification factor
- S_{ξ} be the spectral acceleration for a different damping ξ

Then,

$$S_{\xi} = \eta(\xi) \cdot S_{5\%}$$

3.7.2 Empirical Formulas

Different codes use different expressions. For example, Eurocode 8 suggests:

$$\eta(\xi)=\sqrt{\frac{10}{5+\xi}}$$

Where ξ is the damping percentage.

This shows that increasing damping leads to a lower spectral demand, which directly affects the base shear, inter-story drifts, and design forces.

3.7.3 Code-Based Recommendations

Damping Ratio (%)	η (Eurocode 8)	Reduction in Spectral Demand (%)
2	1.29	-29% Increase
5 (Standard)	1.00	Reference
10	0.77	23% Reduction
20	0.58	42% Reduction
30	0.50	50% Reduction

This has significant implications for structures with base isolators or damping devices, which can legally and practically reduce design forces.

3.8 Energy Dissipation Devices in Structures

Modern seismic design incorporates **passive, active, and semi-active damping systems** to absorb seismic energy and reduce the demand on primary structural elements.

3.8.1 Passive Energy Dissipaters

These work without external power input and include:

- **Viscous Fluid Dampers**: Cylinders filled with viscous fluid; dissipate energy via flow resistance.
- **Friction Dampers**: Dissipate energy via sliding friction between surfaces.
- **Metallic Yield Dampers**: Elements that yield under seismic loads to dissipate energy through plastic deformation.

- **Tuned Mass Dampers (TMDs)**: A mass-spring-damper system tuned to the structure's natural frequency to counteract oscillations.

3.8.2 Active and Semi-Active Dampers

- **Active Control Systems**: Use sensors and actuators to apply counter-forces in real time.
- **Semi-Active Dampers**: Adjust stiffness or damping properties during motion (e.g., Magnetorheological and Electro-Rheological dampers).

These are generally used in high-performance or mission-critical buildings and require continuous power and control logic.

3.9 Influence of Damping on Structural Response Parameters

Damping influences several critical structural parameters during seismic loading:

3.9.1 Natural Frequency and Resonance Avoidance

Although damping does not significantly shift the natural frequency, it limits amplification when the excitation frequency nears resonance.

3.9.2 Displacement and Drift

Higher damping reduces:

- Peak displacements
- Inter-story drifts
- Nonstructural damage

This is particularly beneficial in tall or flexible structures.

3.9.3 Base Shear and Force Distribution

Damping directly affects base shear:

$$V = C_s \cdot W$$

Where C_s is the seismic coefficient, influenced by damping via spectral acceleration values.

Lower spectral values from higher damping mean reduced force demands on structural members.

3.10 Experimental Evaluation of Damping in Structures

Laboratory and field tests are used to evaluate damping characteristics of materials and structures:

3.10.1 Shake Table Tests

Used to replicate ground motion and measure real-time structural response including damping properties.

3.10.2 Ambient Vibration Testing

- Non-intrusive method
- Uses environmental inputs (wind, traffic) to estimate modal properties and damping

3.10.3 Free and Forced Vibration Tests

- Measure decay of vibration after impulse or sinusoidal loading
- Used in component testing or model validations

Data from these experiments help calibrate finite element models and refine damping assumptions used in dynamic analysis.

3.11 Damping Considerations in Seismic Retrofitting

For **seismic rehabilitation or retrofitting**, damping enhancement is a major strategy. The addition of dampers or alteration of material properties helps:

- Improve energy dissipation
- Reduce seismic demand on weak components
- Increase overall resilience of old structures

Common Techniques:

- Installing viscous or friction dampers in braced frames
- Adding base isolation to separate the structure from ground motion
- Incorporating energy dissipating connections in beam-column joints

3.12 Limitations and Challenges in Damping Modeling

While damping models help simulate real-world structural response, they come with limitations:

- **Oversimplification**: Viscous damping models assume proportional damping, which may not hold true for all materials.
- **Amplitude Dependence**: Structural damping is often nonlinear and varies with amplitude.
- **Material Degradation**: Damping properties can change with repeated seismic events or aging.
- **Coupled Effects**: In soil-structure interaction, radiation damping is hard to isolate from material damping.

Engineers must use caution while assigning damping parameters in simulations, especially for performance-based designs.