Credits: 3 + 0
PG 2019
Spring 2020 Semester

Performance-based Seismic Design of Structures

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Acknowledgement

- The material for the preparation of these lectures slides are taken from different sources.
- The primary source for these lecture slides are the lectures of Prof. Dr. Pennung Warnitchai at Asian Institute of Technology (AIT), Thailand
- Some other references of this training material include the following.
  - Online Training Material from US Geological Survey (USGS)
  - Online Educational Resources from IRIS (www.iris.edu)
  - Class Notes of Prof. Dr. Worsak Kanok-Nukulchai at Asian Institute of Technology (AIT), Thailand
  - Lecture Notes of Dr. Naveed Anwar at Asian Institute of Technology (AIT), Thailand
  - Lectures of Dr. Punchet Thammarak at Asian Institute of Technology (AIT), Thailand
  - Lecture Notes of Dr. Abdul Qadir Bhatti at NUST, Pakistan

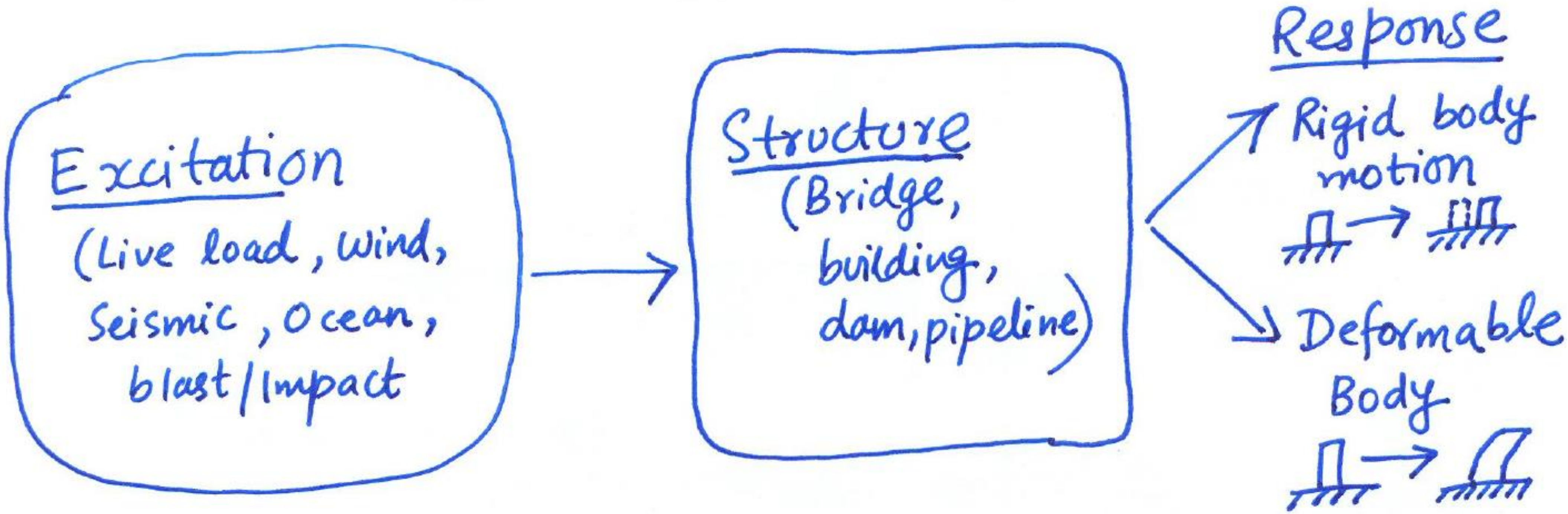
Prof. Dr. Pennung Warnitchai

- The material is taken solely for educational purposes. **All sources are duly acknowledged.**

Lecture 3: A Quick Overview of Structural Dynamics

- Dynamics of Simple Structures
- Dynamics of Discrete MDF Structures

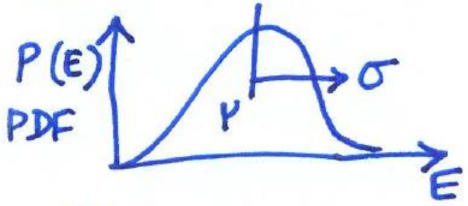
Structural Dynamics



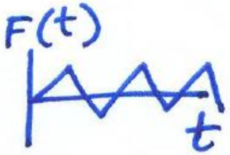
Dynamic loading

Deterministic
eg Rotating machine
or Last earthquake
(seismograph)

Probabilistic
(Random)
eg. Wind Load
or Next earthquake



Dynamic Loading
- Periodic



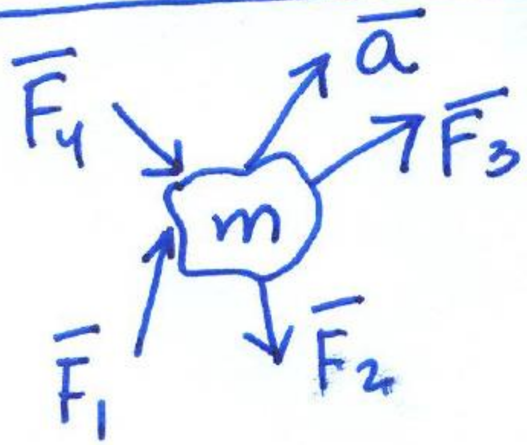
(e.g harmonic

→ Can Solve analytically

- Non-periodic
  - e.g blast

→ Often need to solve numerically

Dynamic Equilibrium (D, Alembert's Principle)



$$\sum \mathbb{F}_i = m\,\bar{a}$$

$-m\bar{a}$ = Inertial force

$$\sum \mathbb{F} = 0$$

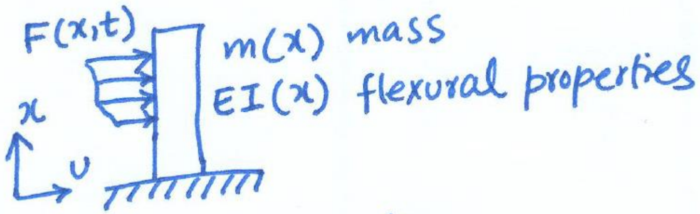
all forces including inertial force

Structural Models

(a mathematical representation of a structure)

Continuous
(Distributed Parameter)

- Realistic
- Very difficult to analyze



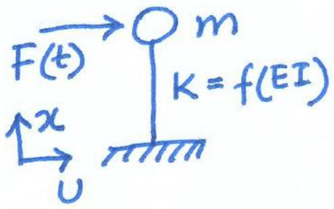
Governing equation:

$$\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 x}{\partial x^2}\right) + m(x)\cdot\frac{\partial^2 u}{\partial t^2} = F(x,t)$$

PDEs

Discrete

- Idealized
- Approximate
- Easy to analyze



Governing Equation:

$$m\frac{d^2u}{dt^2} + ku = F(t)$$

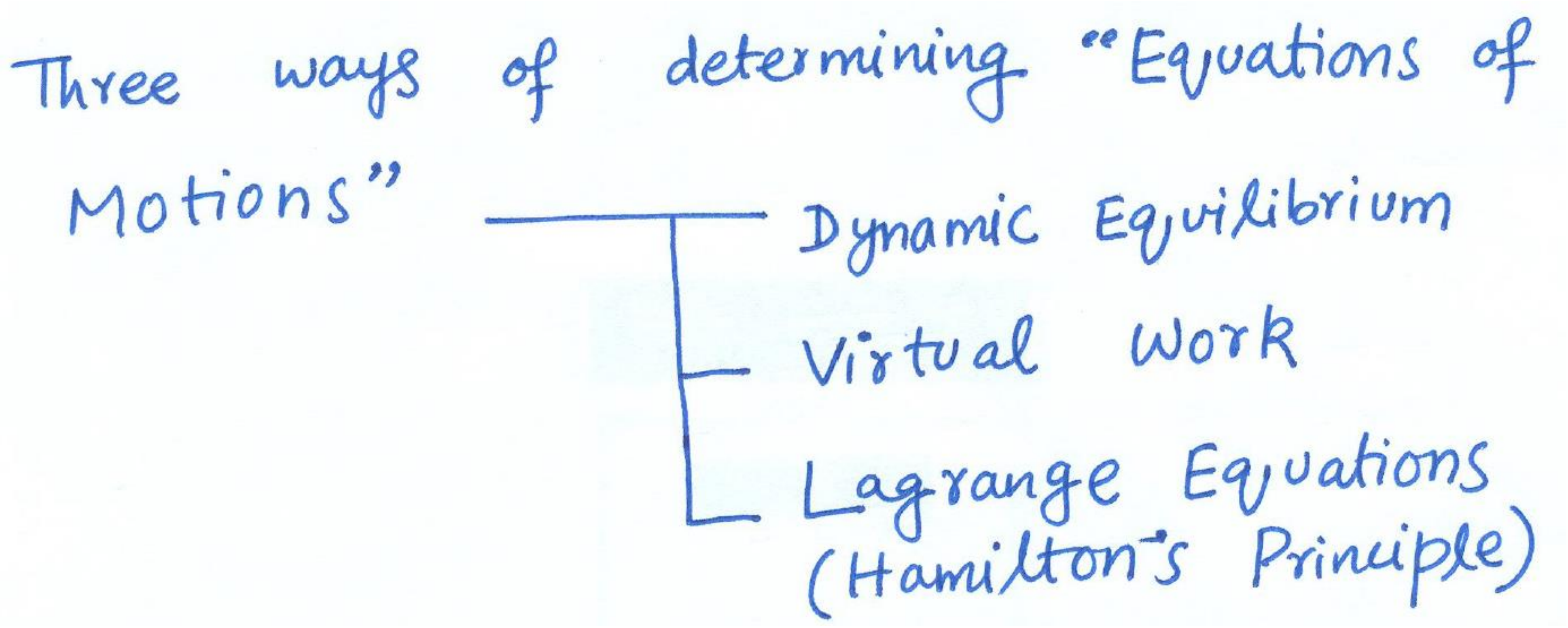
ODEs

- For "Linear Elastic" Discrete models, 

  K = Constant ($F = Ku \Rightarrow K = F/U$)
- For "non-linear" Discrete models, K is a nonlinear function (a varying slope of F–U relationship) 

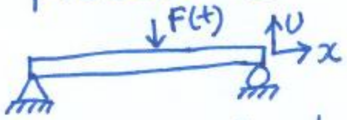
Discrete Systems
- Single-degree-of-freedom (SDF) Systems
- Multiple-degree-of-freedom (MDF) Systems

Equations of Motion



Methods of Discretization

Lumped mass procedure



Take time and and position along span as two independent

now inertial forces can only developed at these three locations.

If only vertical motion (U) is allow —— 3 DOF System

If rotation allowed —— 6 DOF

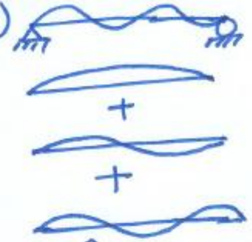
" axial affect " —— 9 DOF

If System is 3D —— 18 DOF

Generalized displacement procedure

Assumption: The deflected shape of structure = Sum of series of specified displacement patterns

so $U(x)$ =



$$U(x) = \sum_{n=1}^{\infty} b_n \sin \frac{n\pi x}{L}$$

Infact any arbitrary shape can be represented by an infinite series of assumed shapes (say $\psi_n(x)$)

so $U(x) = \sum Z_n \psi_n(x)$

Z_n — amplitude

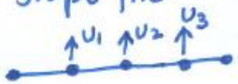
$\psi_n(x)$ — any assumed set of disp. fns compatible with boundary conditions

Finite Element Concept

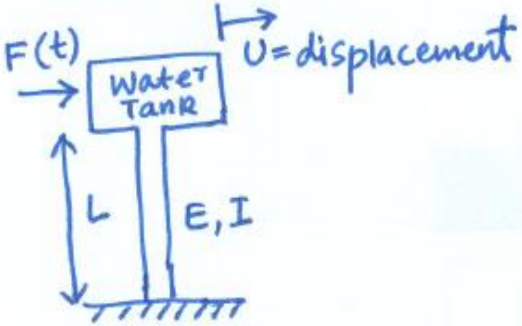
(combination of first two approaches)

↓

Z_n becomes nodal displacements and $\psi_n(x)$ becomes Interpolation fns or shape fns.



SDF Systems



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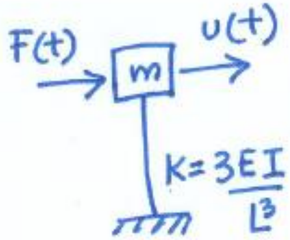

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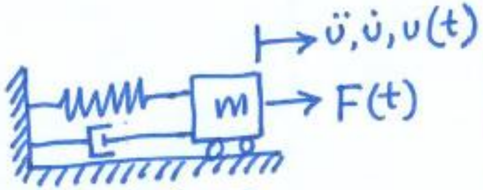

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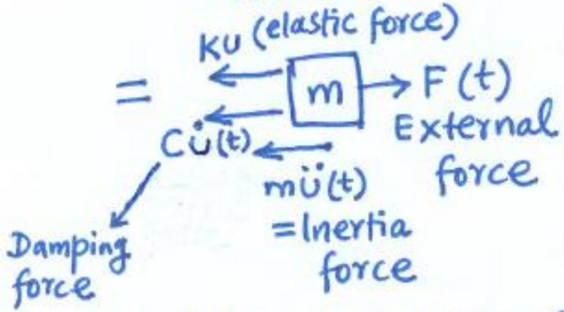
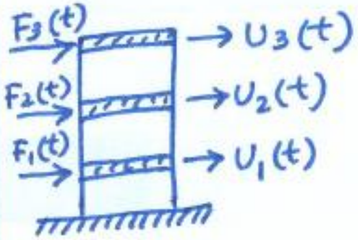


Equilibrium equation of motion

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = F(t)$$

MDF Systems



3 variables are required to describe structural dynamic motion

→ 3 DOF system

3 eq of motion (1 for each story)

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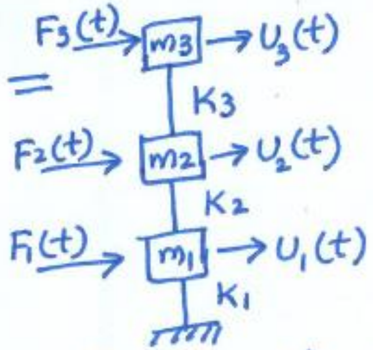


3 "Coupled" equations of motion: (without damping)

$$m_1\ddot{U}_1(t) + (K_1+K_2)U_1(t) - K_2U_2 = F_1(t)$$

$$m_2\ddot{U}_2(t) + -K_2U_1(t) + (K_2+K_3)U_2 - K_3U_3 = F_2(t)$$

$$m_3\ddot{U}_3(t) + K_3(U_3 - U_2) = F_3(t)$$

In matrix form,

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}\begin{bmatrix} \ddot{U}_1(t) \\ \ddot{U}_2(t) \\ \ddot{U}_3(t) \end{bmatrix} +$$

$$\begin{bmatrix} K_1+K_2 & -K_2 & 0 \\ -K_2 & K_2+K_3 & -K_3 \\ 0 & -K_3 & K_3 \end{bmatrix}\begin{bmatrix} U_1(t) \\ U_2(t) \\ U_3(t) \end{bmatrix} = \begin{bmatrix} F_1(t) \\ F_2(t) \\ F_3(t) \end{bmatrix}$$

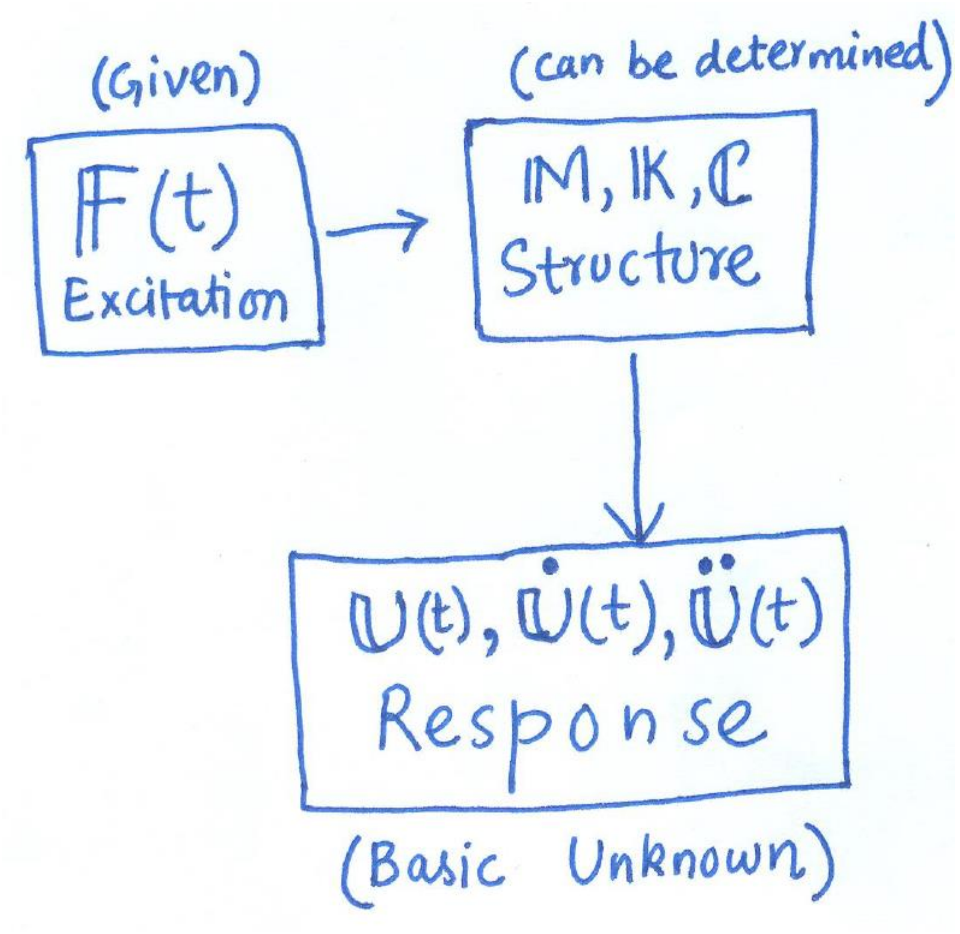
or $\mathbb{M}\ddot{\mathbb{U}}(t) + \mathbb{K}\mathbb{U}(t) = \mathbb{F}(t)$

Including damping,

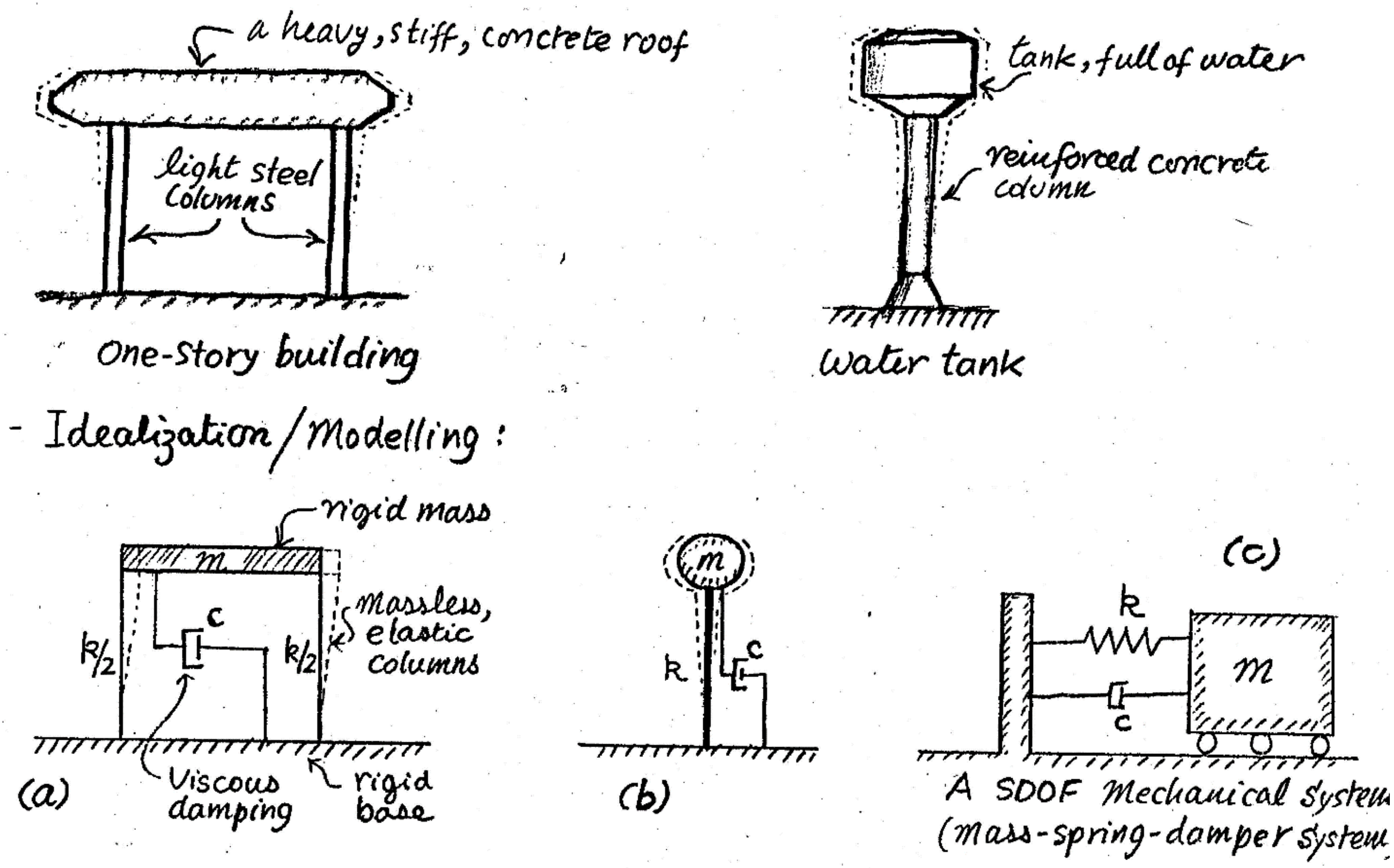
$$\mathbb{M}\ddot{\mathbb{U}}(t) + \mathbb{C}\dot{\mathbb{U}}(t) + \mathbb{K}\mathbb{U}(t) = \mathbb{F}(t)$$

The coupling terms in these equations represent the interaction b/w dynamic equilibriums at different stories.

The Basic Problem of Structural Dynamics



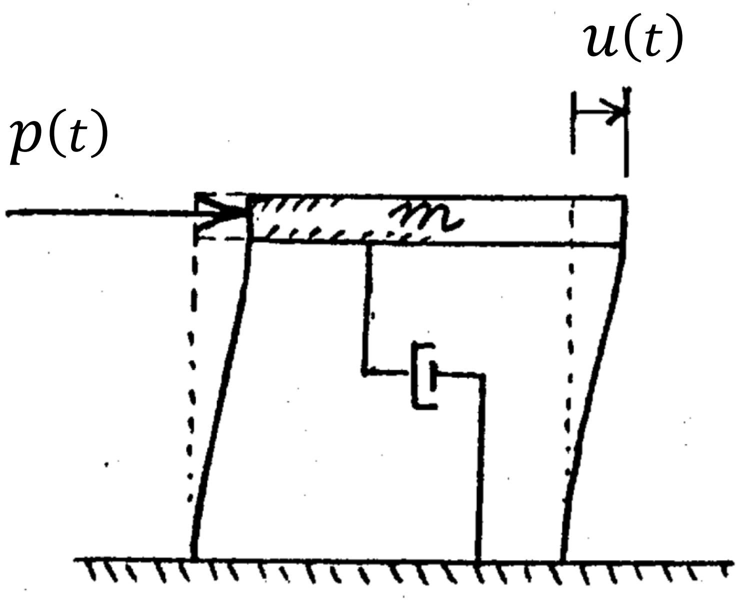
Simple Structures: Structures that can be idealized as concentrated mas “m” supported by a massless structure with stiffness “k” in lateral direction

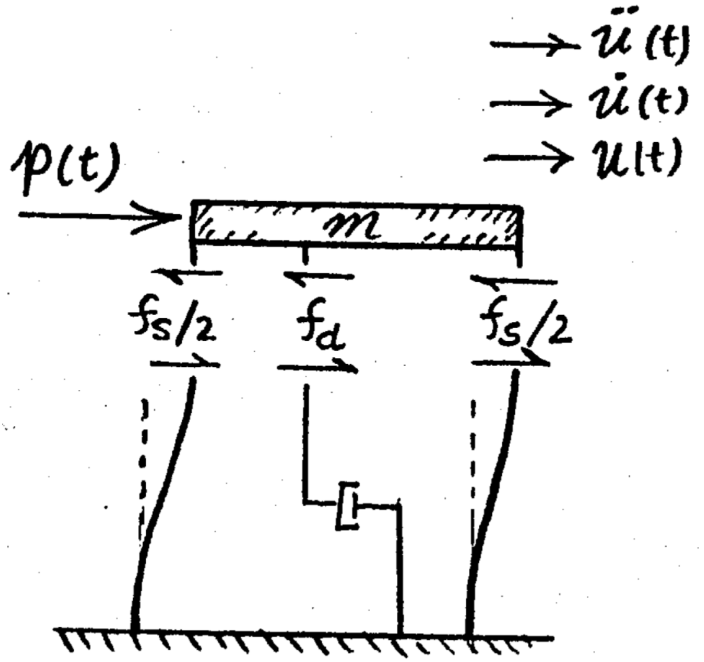


The viscous damping element is added here to model **the energy dissipation** in the structural system which is caused by various mechanisms, such as thermal effect of repeated elastic straining of material , friction at steel connections, opening and closing of micro cracks in concrete, friction between the structure itself and nonstructural elements, energy radiation by waves form the foundation, etc.

These simple structures are sometimes called “**Single degree of freedom structures**” (SDOF structures) because the displaced positions of overall structural body relative to their original position can be defined by one independent displacement [for example, the lateral displacement of the original mass in the case (a)].

Equation of Motion Considering dynamic forces that are acting on the vibrating mass "m":





$$f_s(t) = k\, u(t) \qquad (1)$$

$$f_d(t) = c\, \dot{u}(t) \qquad (2)$$

$p(t)$: external force

$f_s(t)$: elastic restoring force

$f_d(t)$: damping force

where k is the lateral stiffness of the structures

c is the viscous damping coefficient

Using Newton's second law of motion, we obtain:

$$p(t) - f_s(t) - f_d(t) = m\,\ddot{u}(t) \qquad \text{—— (3)}$$

or

$$\boxed{m\,\ddot{u} + c\,\dot{u} + k\,u = p(t)} \qquad \text{———— (4)}$$

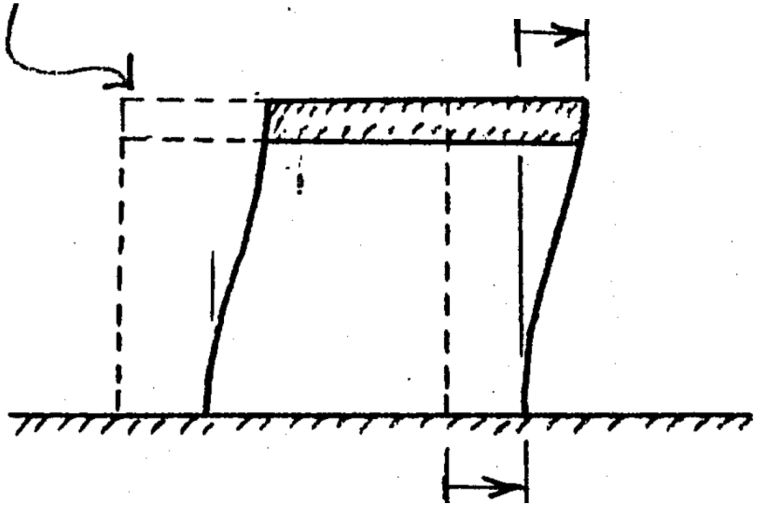
This equation is the equation of motion governing the deformation $u(t)$ of the idealized structure.

Earthquake Excitation

(The displacement of structure relative to the ground)
Structural deformation

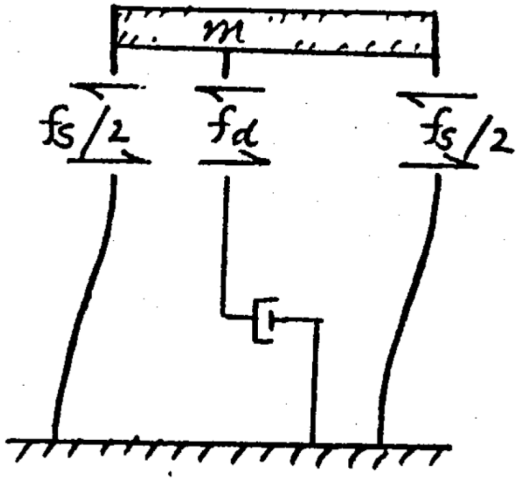
Initial configuration

$u(t)$



$u_g(t)$

ground displacement



Using the Newton's second law of motion, we obtain:

$$0 - f_s(t) - f_d(t) = m\,\ddot{u}_t(t) \qquad (5)$$

In which

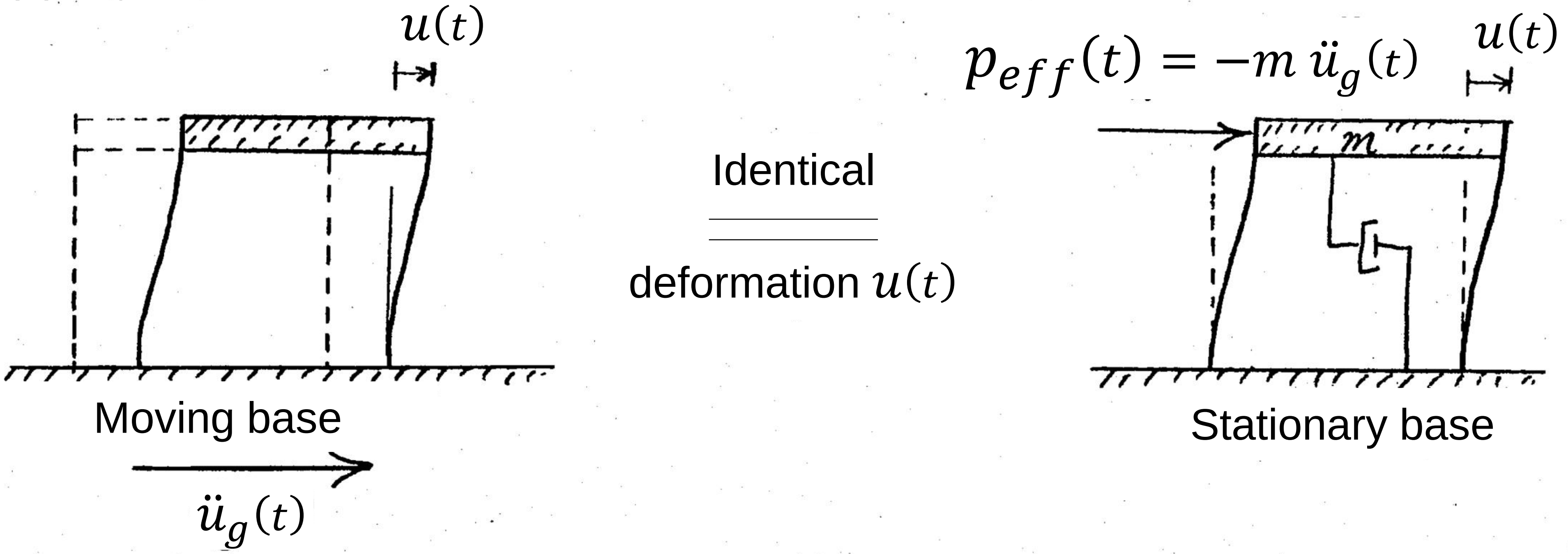
$u_t(t)$: the total (or absolute) displacement of the mass "m"

$$\left.\begin{aligned} &u_t(t) = u_g(t) + u(t) \\ &f_s(t) = k\,u(t) \\ \text{and}\quad &f_d(t) = c\,\dot{u}(t) \end{aligned}\right\} \qquad (6\ \text{a,b,c})$$

Substituting Eqs. (6) in Eq. (5) gives :

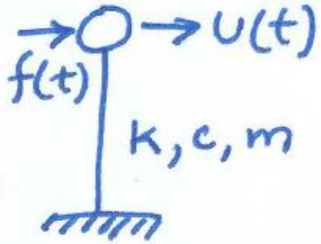
$$m\,\ddot{u} + c\,\dot{u} + k\,u = -m\,\ddot{u}_g(t) \qquad (7)$$

Eq. (7) says that



Dynamics of Simple Structures

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = f(t)$$



Lets define $\xi = \dfrac{c}{2\sqrt{mk}}$ = Critical damping ratio

circular natural frequency = ω

$$\omega = 2\pi f$$

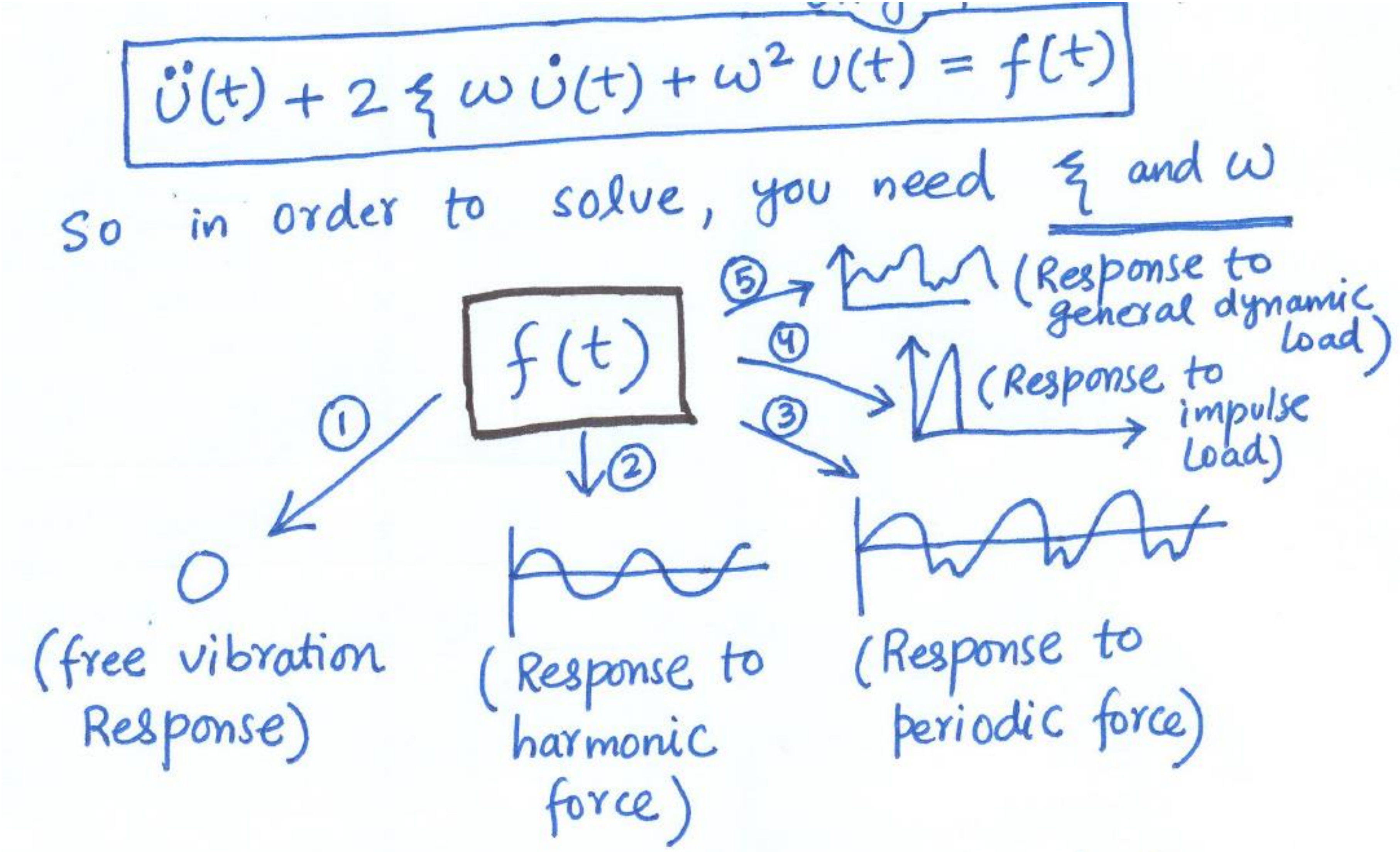
$$f = \frac{1}{T}$$

$$T = 2\pi\sqrt{\frac{m}{k}}$$

so $\omega = \sqrt{k/m}$ → natural frequency of SDF system is only function of m, k

$$\ddot{u}(t) + 2\xi\omega\dot{u}(t) + \omega^2 u(t) = f(t)$$

Dynamics of Simple Structures



Undamped Free Vibration

Suppose that the structure has no damping (an ideal case) and its motion is initiated by distributing the system from its static equilibrium position such that $u(0)$ and $\dot{u}(0)$ are non-zero.

($u(0)$ and $\dot{u}(0)$ describe the conditions of the structure at the time zero; they are called “initial conditions”)

It can be shown that

$$u(t) = u(0)\, cos\ \omega_n t + \frac{\dot{u}(0)}{\omega_n}\ sin\omega_n t \qquad (8)$$

where

$$\omega_n = \sqrt{\frac{k}{m}} \qquad (rad/\text{sec}) \qquad (9)$$

In terms of mathematics $u(t)$ of Eq. 8 is the solution of the second order differential equation:

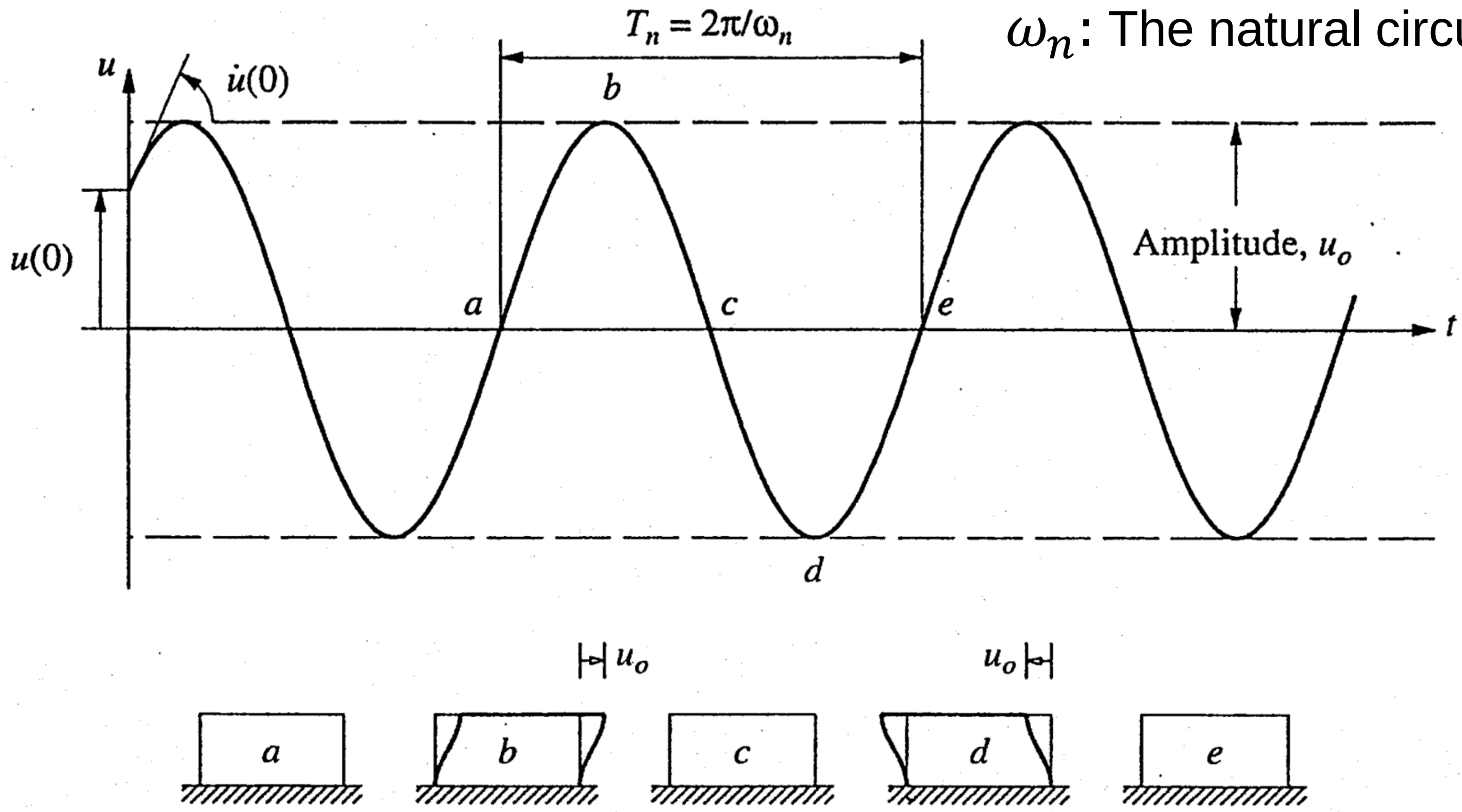
$$m\,\ddot{u} \;+\; k\,u \;=\; 0 \qquad (10)$$

and the solution is also satisfying the prescribing initial conditions $u(0)$ and $\dot{u}(0)$.

This can be easily checked by substituting the expression of $u(t)$ in Eq. (8) to the L.H.S of Eq. (10). You will see that all terms are cancelled out and the final result is equal to the R.H.S of Eq. (10) – “0”).

T_n: The natural period of vibration (sec)

ω_n: The natural circular frequency (rad/sec)



$$u_0 = \sqrt{u(0)^2 + \left(\frac{\dot{u}(0)}{\omega_n}\right)^2}$$

Free vibration of a system without damping

The natural vibration properties ω_n, T_n and f_n depend only on the mass and stiffness of the structure.

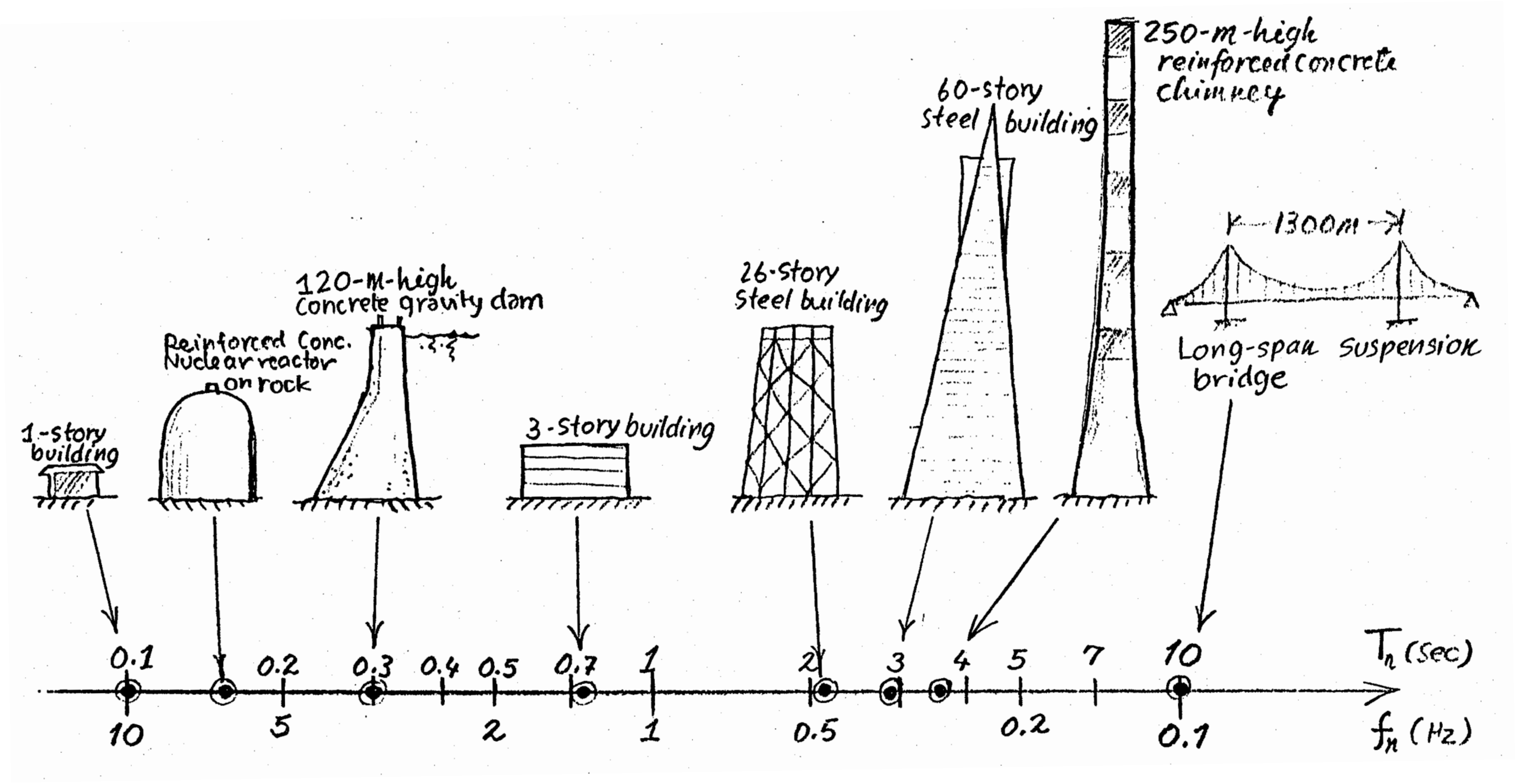
The natural (cyclic) frequency

$$f_n = \frac{1}{\mathrm{T}_n} = \frac{\omega_n}{2\pi} \qquad {}^{cycle}/_{sec}\ (Hz)$$

The natural vibration properties ω_n, T_n and f_n depend only on the mass and stiffness of the structure.

Therefore, these properties are **the natural properties of the structure.**

The natural frequency and period of various structures vary over a wide range:



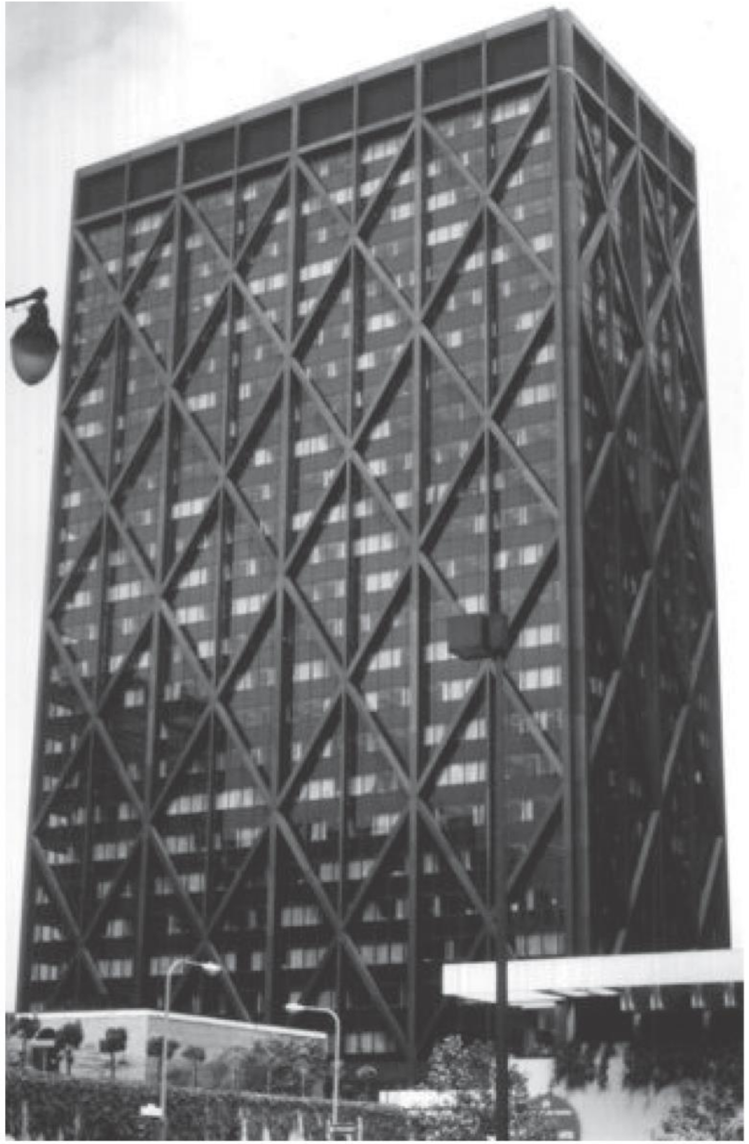


Figure 2.1.2a Alcoa Building, San Francisco, California. The fundamental natural vibration periods of this 26-story steel building are 1.67 sec for north–south (longitudinal) vibration, 2.21 sec for east–west (transverse) vibration, and 1.12 sec for torsional vibration about a vertical axis. These vibration properties were determined by forced vibration tests. (Courtesy of International Structural Slides.)

Figure 2.1.2b Transamerica Building, San Francisco, California. The fundamental natural vibration periods of this 49-story steel building, tapered in elevation, are 2.90 sec for north–south vibration and also for east–west vibration. These vibration properties were determined by forced vibration tests. (Courtesy of International Structural Slides.)

Figure 2.1.2c Medical Center Building, Richmond, California. The fundamental natural vibration periods of this three-story steel frame building are 0.63 sec for vibration in the long direction, 0.74 sec in the short direction, and 0.46 sec for torsional vibration about a vertical axis. These vibration properties were determined from motions of the building recorded during the 1989 Loma Prieta earthquake. (Courtesy of California Strong Motion Instrumentation Program.)

Figure 2.1.2d Pine Flat Dam on the Kings River, near Fresno, California. The fundamental natural vibration period of this 400-ft-high concrete gravity dam was measured by forced vibration tests to be 0.288 sec and 0.306 sec with the reservoir depth at 310 ft and 345 ft, respectively.

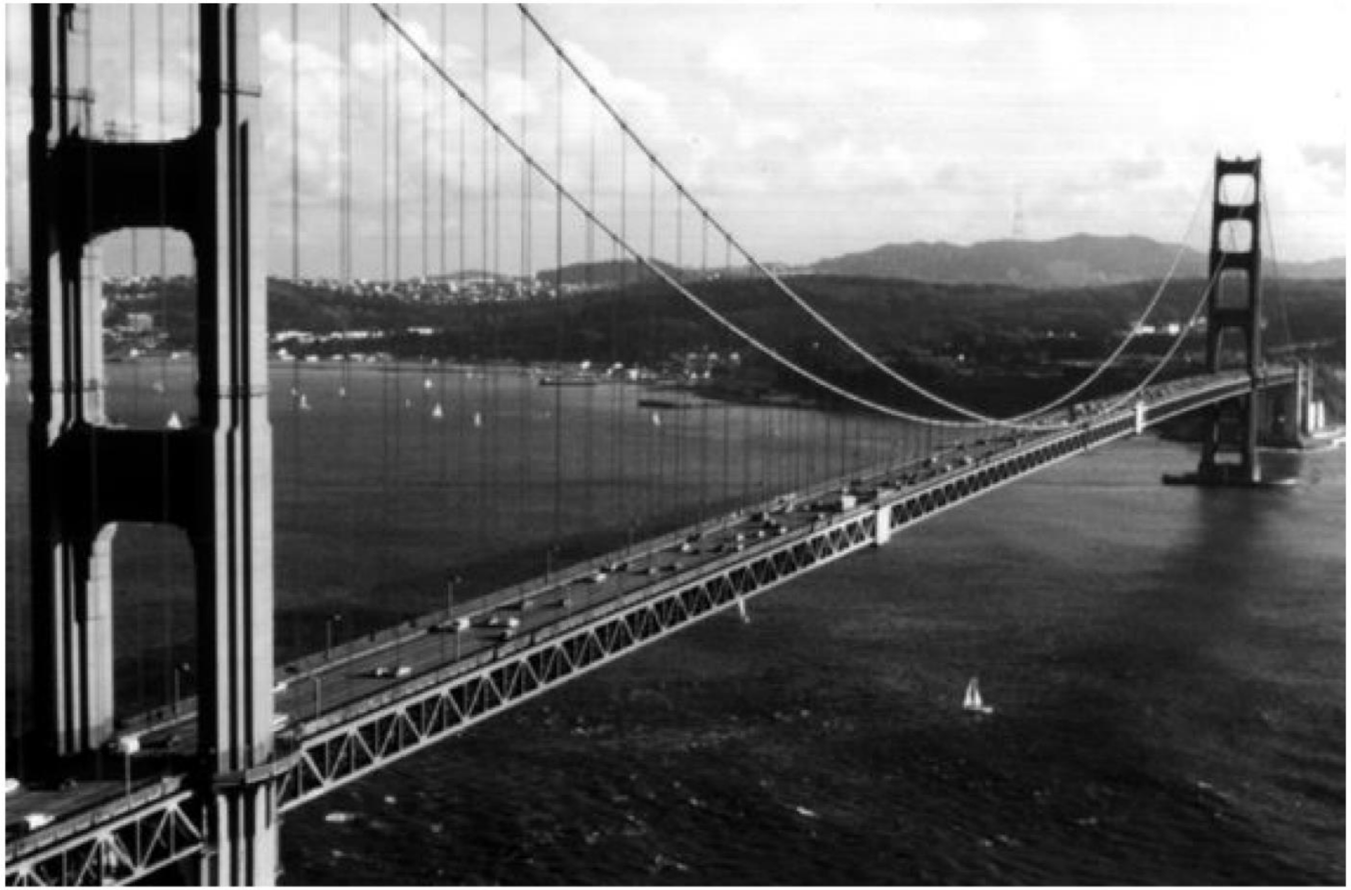


Figure 2.1.2e Golden Gate Bridge, San Francisco, California. The fundamental natural vibration periods of this suspension bridge with the main span of 4200 ft are 18.2 sec for transverse vibration, 10.9 sec for vertical vibration, 3.81 sec for longitudinal vibration, and 4.43 sec for torsional vibration. These vibration properties were determined from recorded motions of the bridge under ambient (wind, traffic, etc.) conditions. (Courtesy of International Structural Slides.)

Dynamics of Structures, Theory and Applications to Earthquake Engineering (Anil K. Chopra)

Figure 2.1.2f Reinforced-concrete chimney, located in Aramon, France. The fundamental natural vibration period of this 250-m-high chimney is 3.57 sec; it was determined from records of wind-induced vibration.

Damped Free Vibration

In this case, damping is present in the structure – a more realistic case

Equation of Motion:

$$m\ddot{u} + c\dot{u} + ku = 0 \qquad (11)$$

or

$$\ddot{u} + 2\xi\omega_n\dot{u} + \omega_n^2 u = 0 \qquad (12)$$

where $\xi = \dfrac{c}{2m\omega_n} = \dfrac{c}{c_r}$ The damping ratio (of critical damping) (13)

c_r is the critical damping coefficient

$$c_r = 2\sqrt{km} = 2m\omega_n$$

*most structures have the value of ξ less than 0.2

Initial Conditions:

Suppose that the values of $u(0)$ and $\dot{u}(0)$ have been given.

Solution:

The solution of Eq. (12) and its associated initial conditions for $\xi < 1$ is given by:

$$u(t) = e^{-\xi \omega_n t}(\, A\, cos\, \omega_D t + B\, sin\, \omega_D t) \qquad (14)$$

where

$$\left. \begin{aligned} A &= u(0), \\ B &= \frac{\dot{u}(0) + \xi \omega_n u(0)}{\omega_D}, \end{aligned} \right\} \qquad (15a,b)$$

and

$$\omega_D = \omega_n \sqrt{1 - \xi^2} \qquad (16)$$

Using equation (16), it can be shown that $\omega_D \approx \omega_n$ for most structures, which have "ξ" less than 0.2.

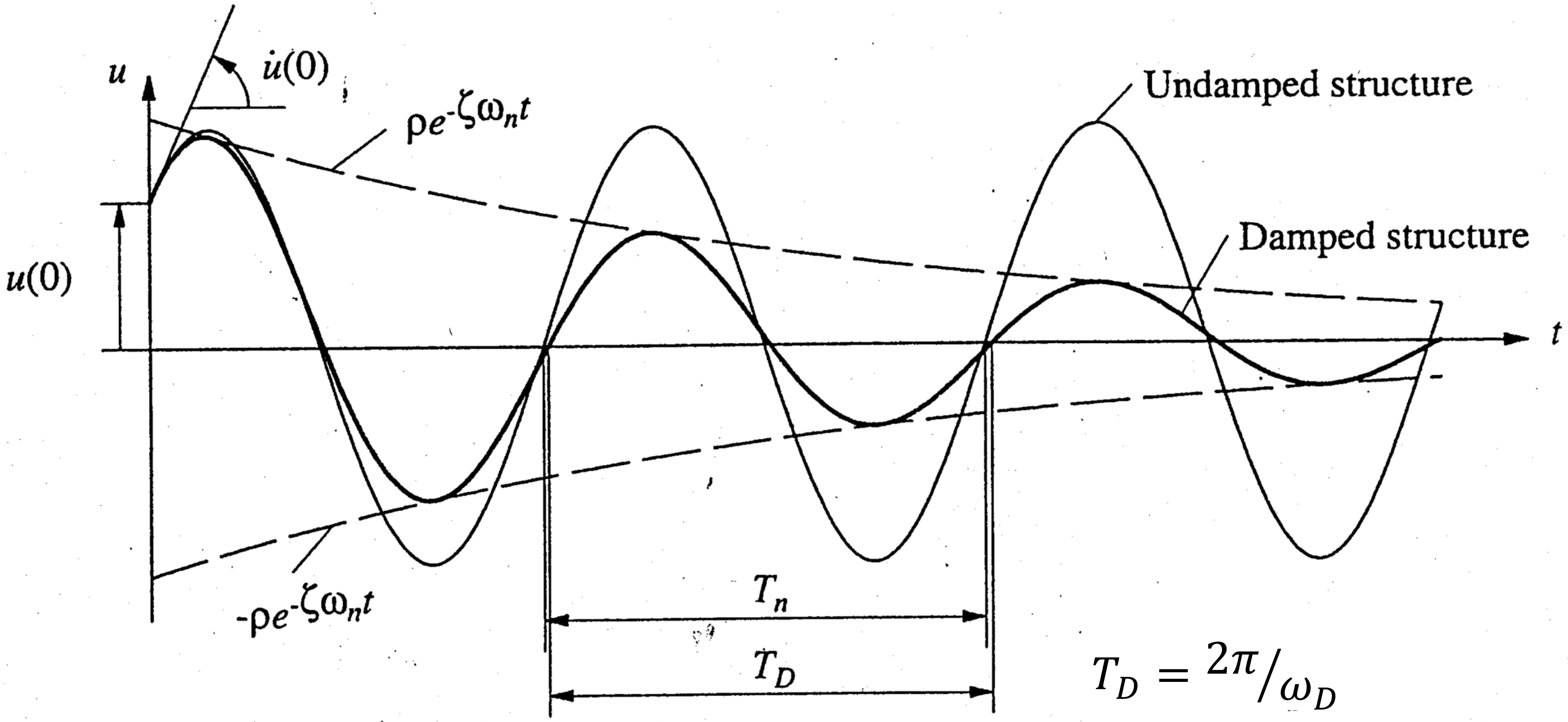
Equation (14) can be presented in another form:

$$u(t) = e^{-\xi \omega_n t} \rho \, cos(\omega_D t - \theta) \qquad \text{———— (17)}$$

where

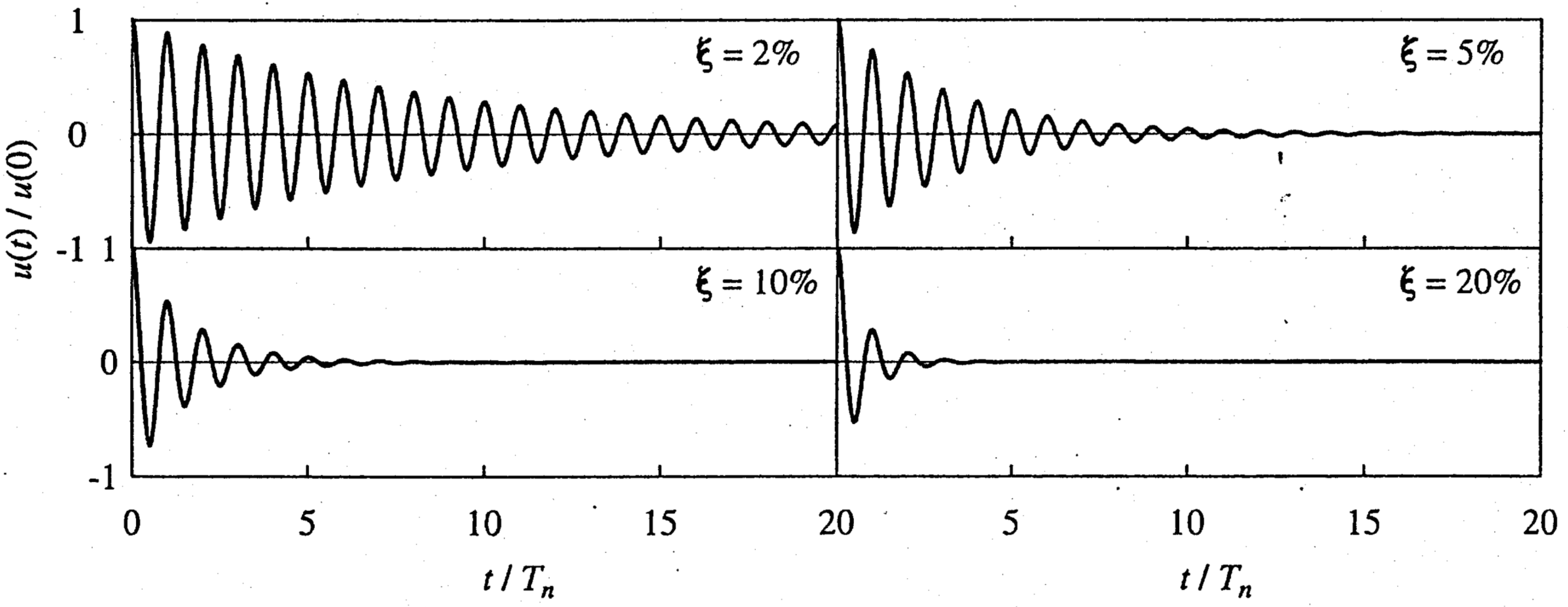
$$\left.\begin{aligned} \rho &= \sqrt{A^2 + B^2} \\ \theta &= tan^{-1}(B/A) \end{aligned}\right\} \qquad \text{———— (18a,b)}$$

Effect of Damping on Free Vibration



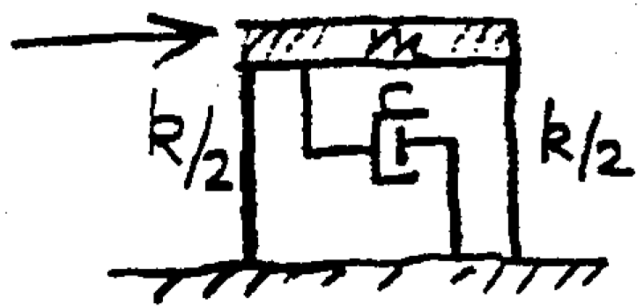
$$T_D = {}^{2\pi}/_{\omega_D}$$

Free Vibration of Systems with Four Levels of Damping: $\xi = 0.02, 0.05, 0.1, 0.2$



Response to Harmonic Excitation

$$p(t) = p_0 \, sin\omega t$$



Equation of motion: $$m\,\ddot{u} + c\,\dot{u} + k\,u = p_0 \, sin\omega t \qquad (19)$$

Initial conditions: $u(0)$ and $\dot{u}(0)$

The solution of Eq. (19) and its associated (given) initial conditions is:

$$u(t) = e^{-\xi \omega_n t} \rho \cos(\omega_D t - \theta) + \frac{p_0}{k} R_d \sin(\omega t - \phi) \qquad (20)$$

where $\frac{p_0}{k}$ is the maximum value of the static response of the harmonic force $p_0\ sin\omega t$; the value is denoted by "U_{st}"

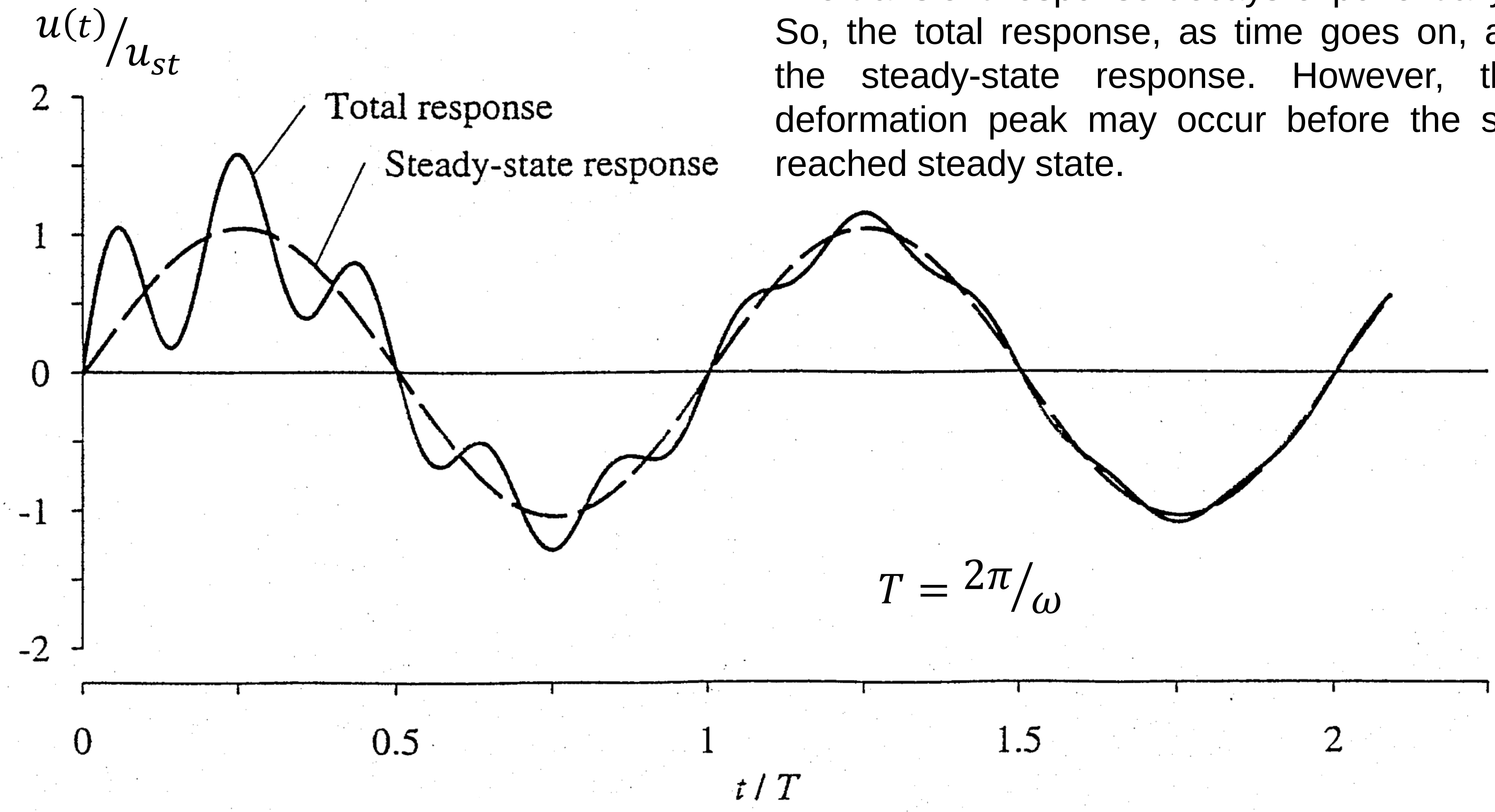
R_d is the dynamic response factor,

$$R_d = \frac{1}{\sqrt{\{1 - (\frac{\omega}{\omega_n})^2\}^2 + \{2\ \xi \frac{\omega}{\omega_n}\}^2}} \qquad (21)$$

$$\phi = tan^{-1}\left\{\frac{2\,\xi\,\frac{\omega}{\omega_n}}{1-(\frac{\omega}{\omega_n})^2}\right\} \qquad (22)$$

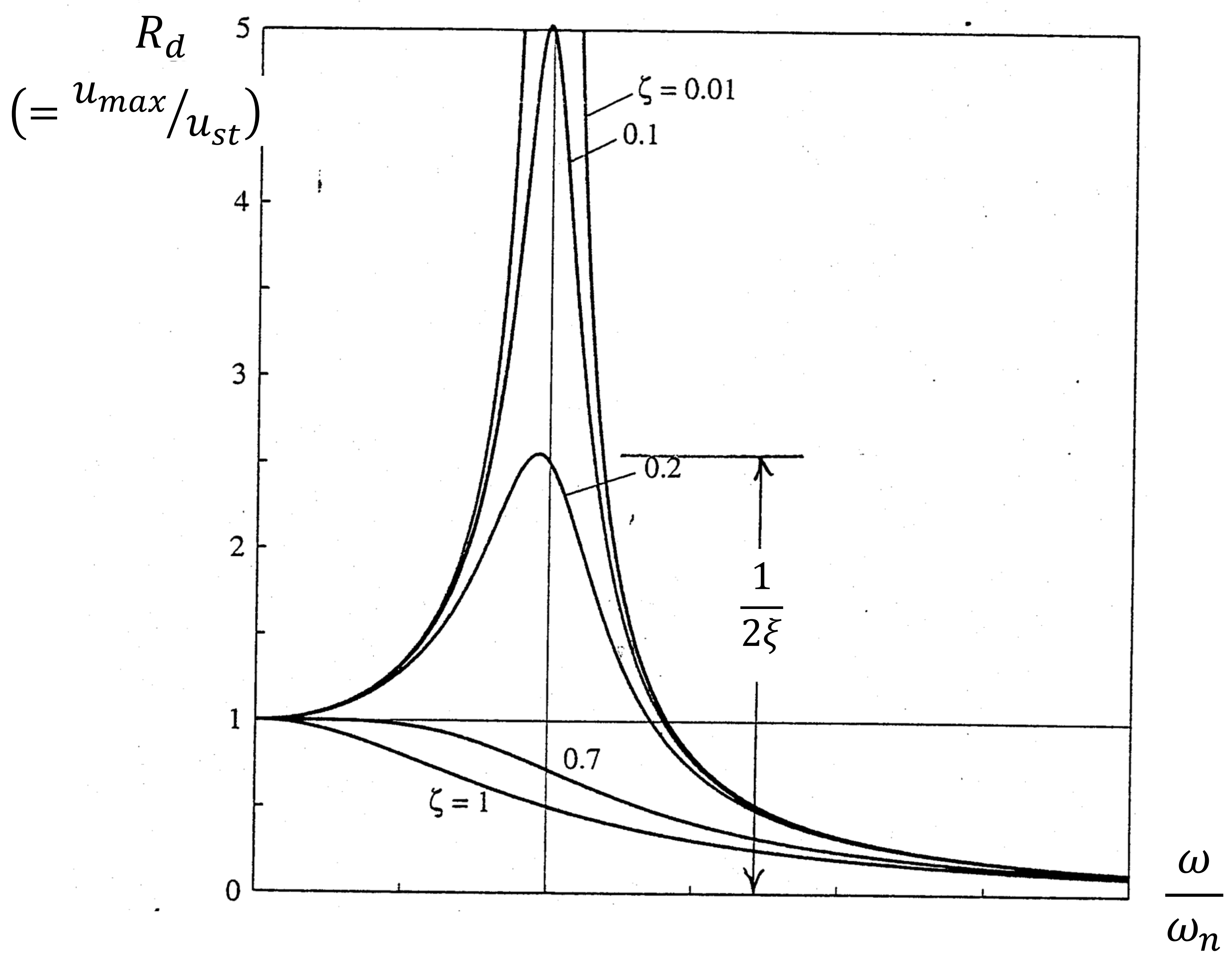
The constants ρ and θ are determined such that the given initial conditions $u(0)$ and $\dot{u}(0)$ are satisfied.

The transient response decays exponentially with time. So, the total response, as time goes on, approaches the steady-state response. However, the largest deformation peak may occur before the system has reached steady state.

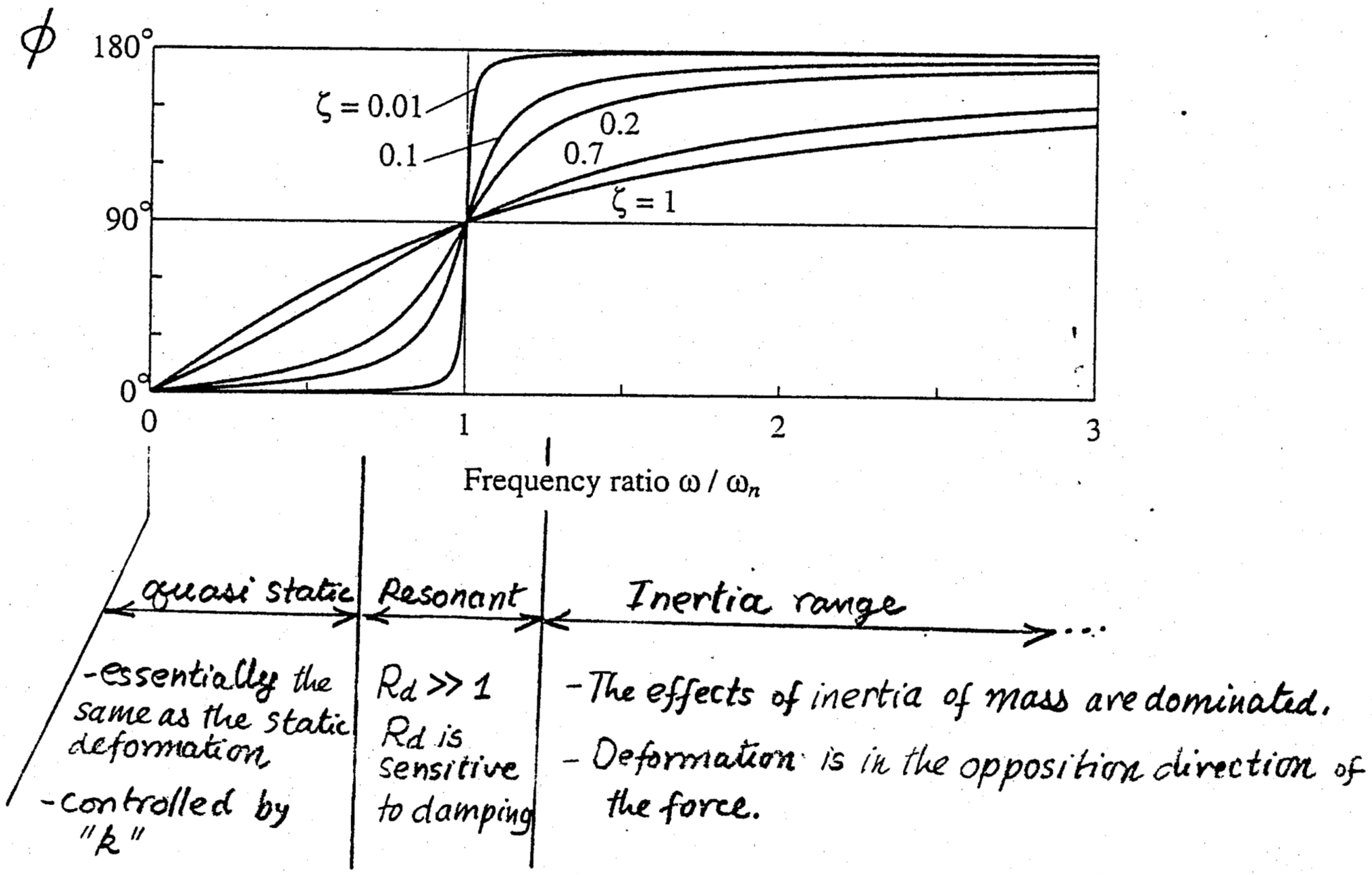


Response of a damped system to harmonic force; $\frac{\omega}{\omega_n} = 0.2, \xi = 0.05, u(0) = 0, \dot{u}(0) = \omega_n\, p_o/k$

Dynamic Response Factor and Phase Angle for Damped Systems Excited by Harmonic Force

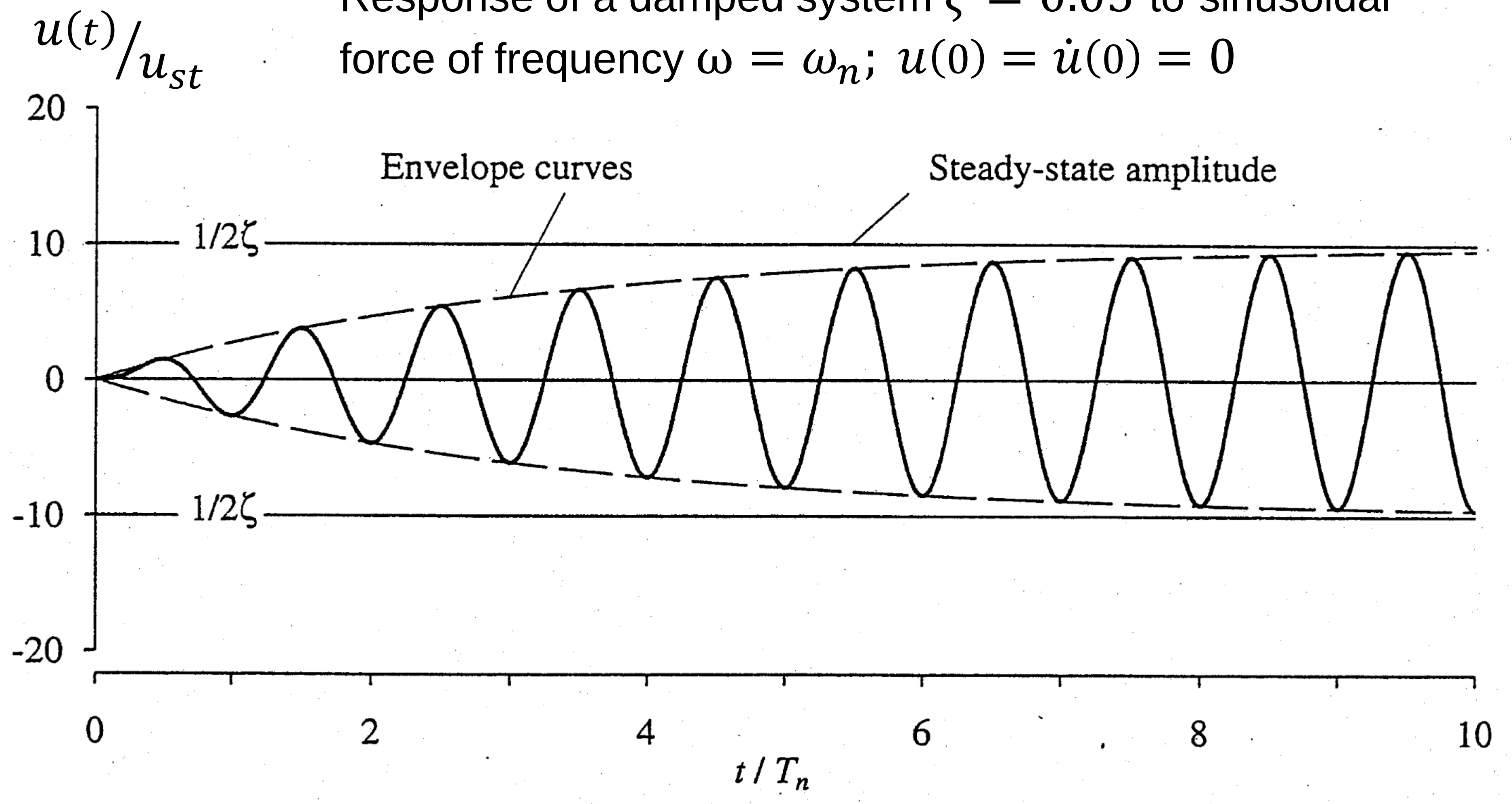


Dynamic Response Factor and Phase Angle for Damped Systems Excited by Harmonic Force



Though the dynamic response factor at $\omega \approx \omega_n$ is very large for a system with low damping, a very long time period is needed before the deformation amplitude reaches the steady state. The amplitude has to build up gradually cycle by cycle as shown by the figure below:

Response of a damped system $\xi = 0.05$ to sinusoidal force of frequency $\omega = \omega_n$; $u(0) = \dot{u}(0) = 0$



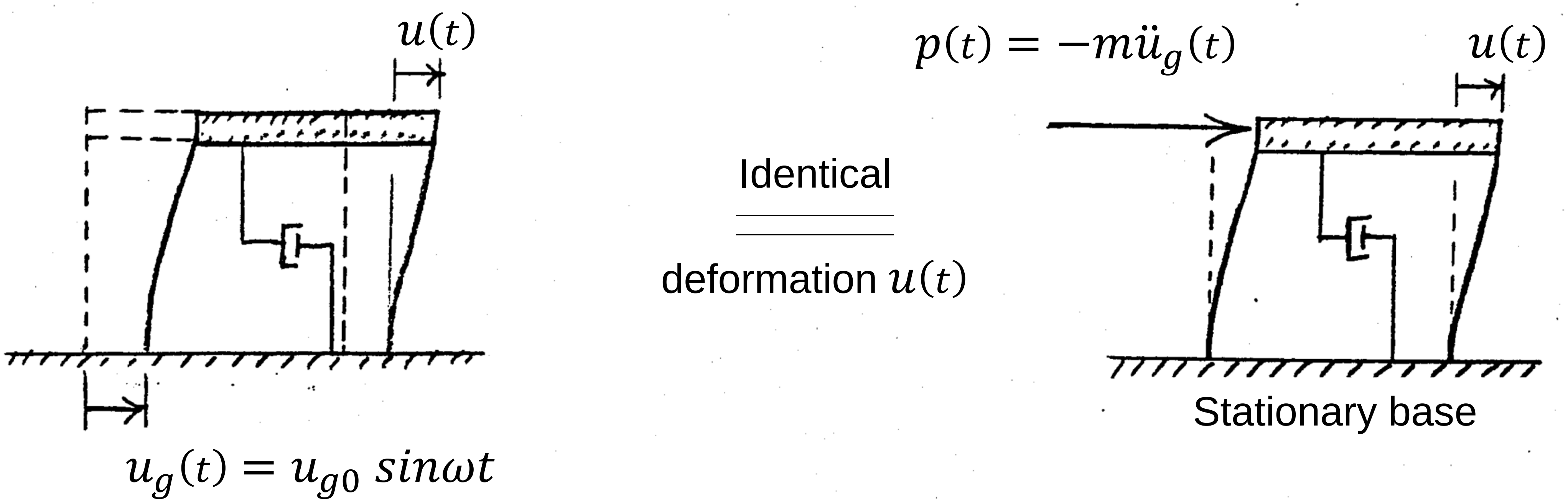
The number of cycles required to reach 95% of steady state amplitude is:

10 (cycles) for $R_d = 10$ (ξ = 0.05)

24 (cycles) for $R_d = 25$ (ξ = 0.02)

48 (cycles) for $R_d = 50$ (ξ = 0.01)

Response to Harmonic Ground Motion



Effective Force of Harmonic Ground Motion:

$$p(t) = -m\,\ddot{u}_g(t) = m\omega^2 u_{g0}\, sin\omega t \qquad (23)$$

The force $p(t)$ can be treated as a harmonic force, hence:

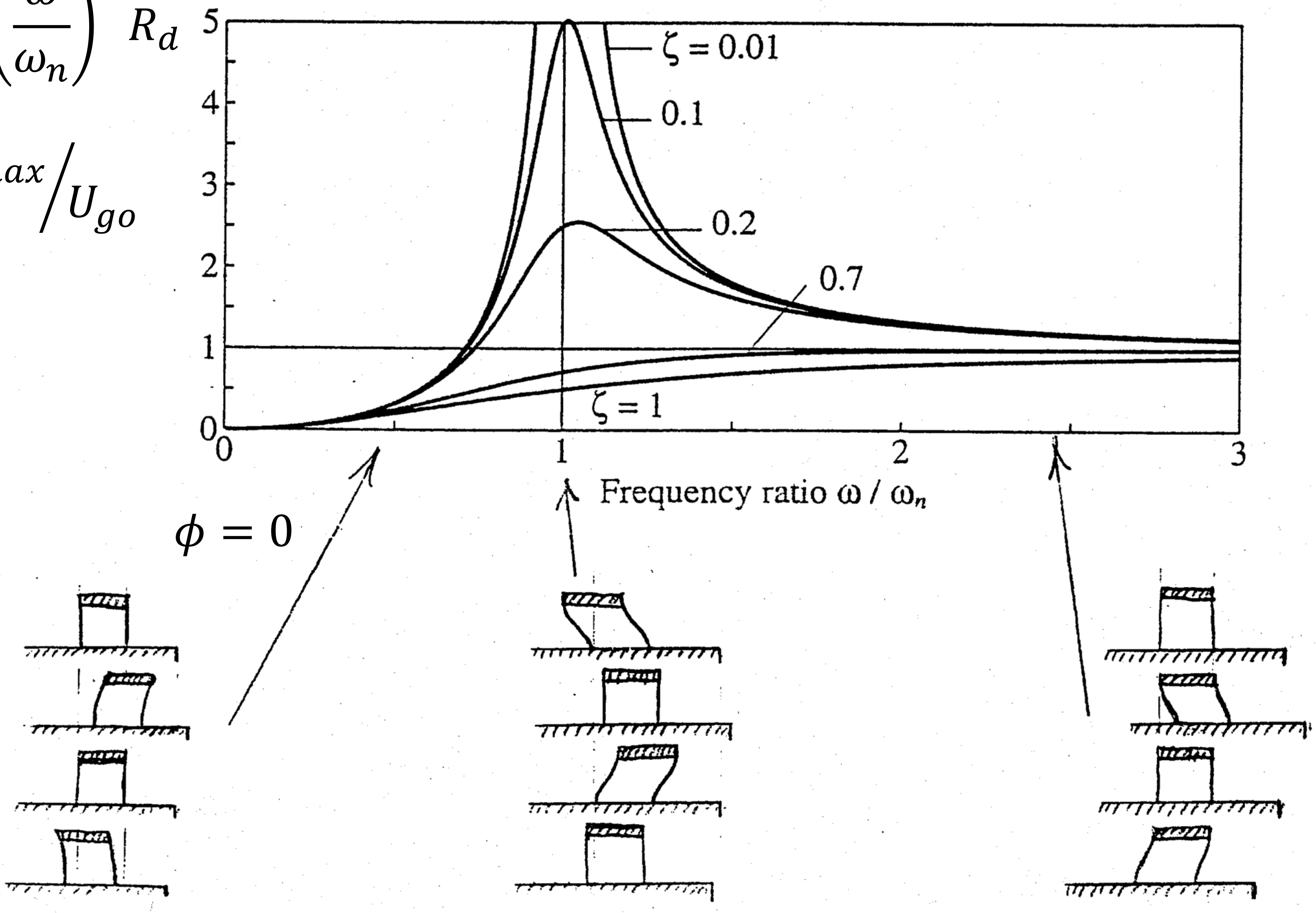
$$u(t)_{\text{at steady state}} = \frac{p_0}{k} R_d \; sin(\omega t - \phi)$$

$$= \frac{m\,\omega^2\,u_{g0}}{m\,\omega_n^2} \; R_d \; sin(\omega t - \phi)$$

$$\therefore \quad u(t)_{\text{at steady state}} = (\frac{\omega}{\omega_n})^2 \; R_d \; u_{g0} \; sin(\omega t - \phi) \qquad (24)$$

$\left(\frac{\omega}{\omega_n}\right)^2 R_d$

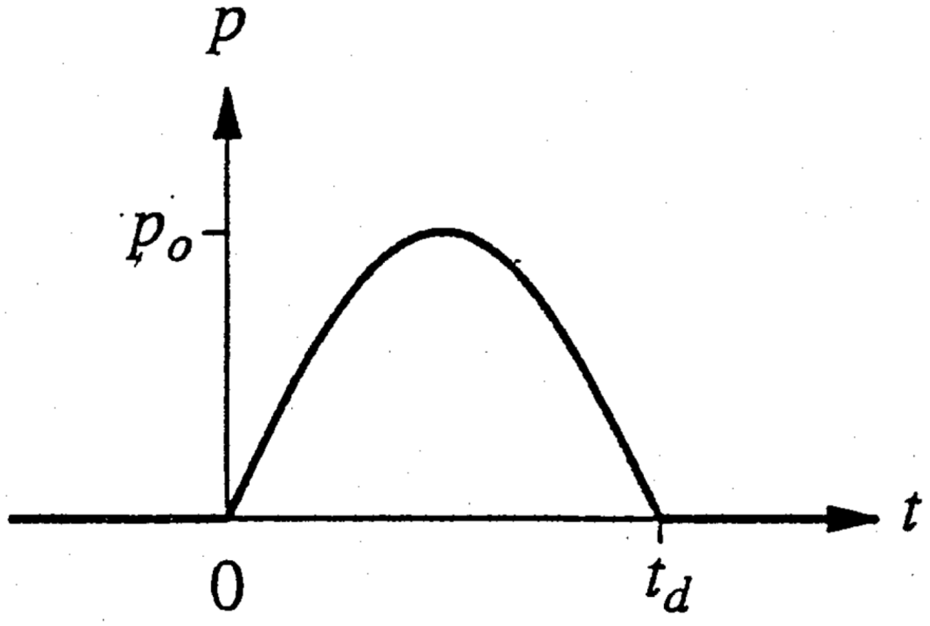
or U_{max}/U_{go}



Response to Half-Cycle Sine Pulse Force

Equation of motion:

$$m\ddot{u} + c\dot{u} + ku = \begin{cases} p_0 \sin\left({}^{\pi t}/_{t_d}\right) & t \le t_d \\ 0 & t > t_d \end{cases} \qquad (25)$$

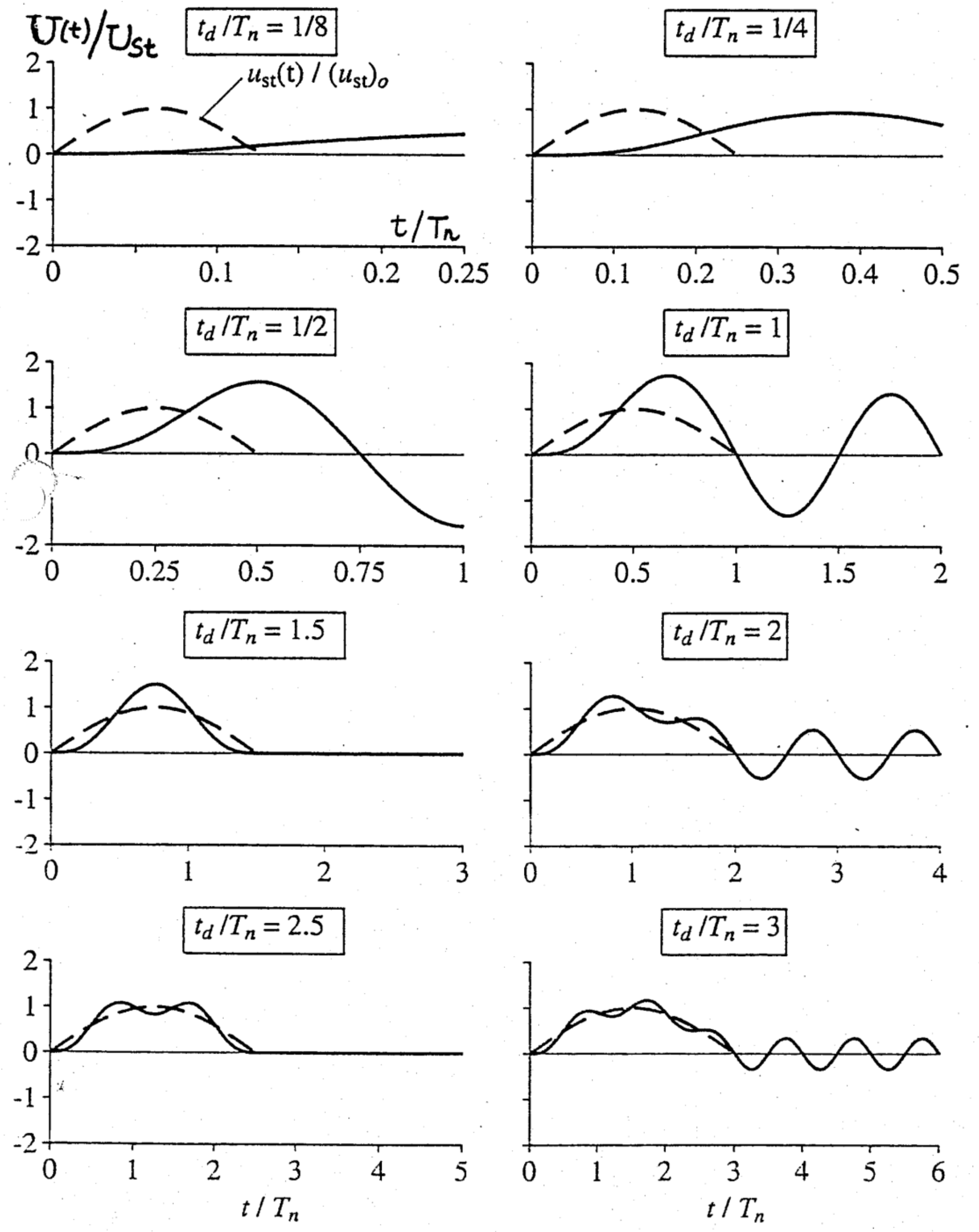


Initial Conditions:

$u(0)$ *and* $\dot{u}(0) = 0$ at rest condition

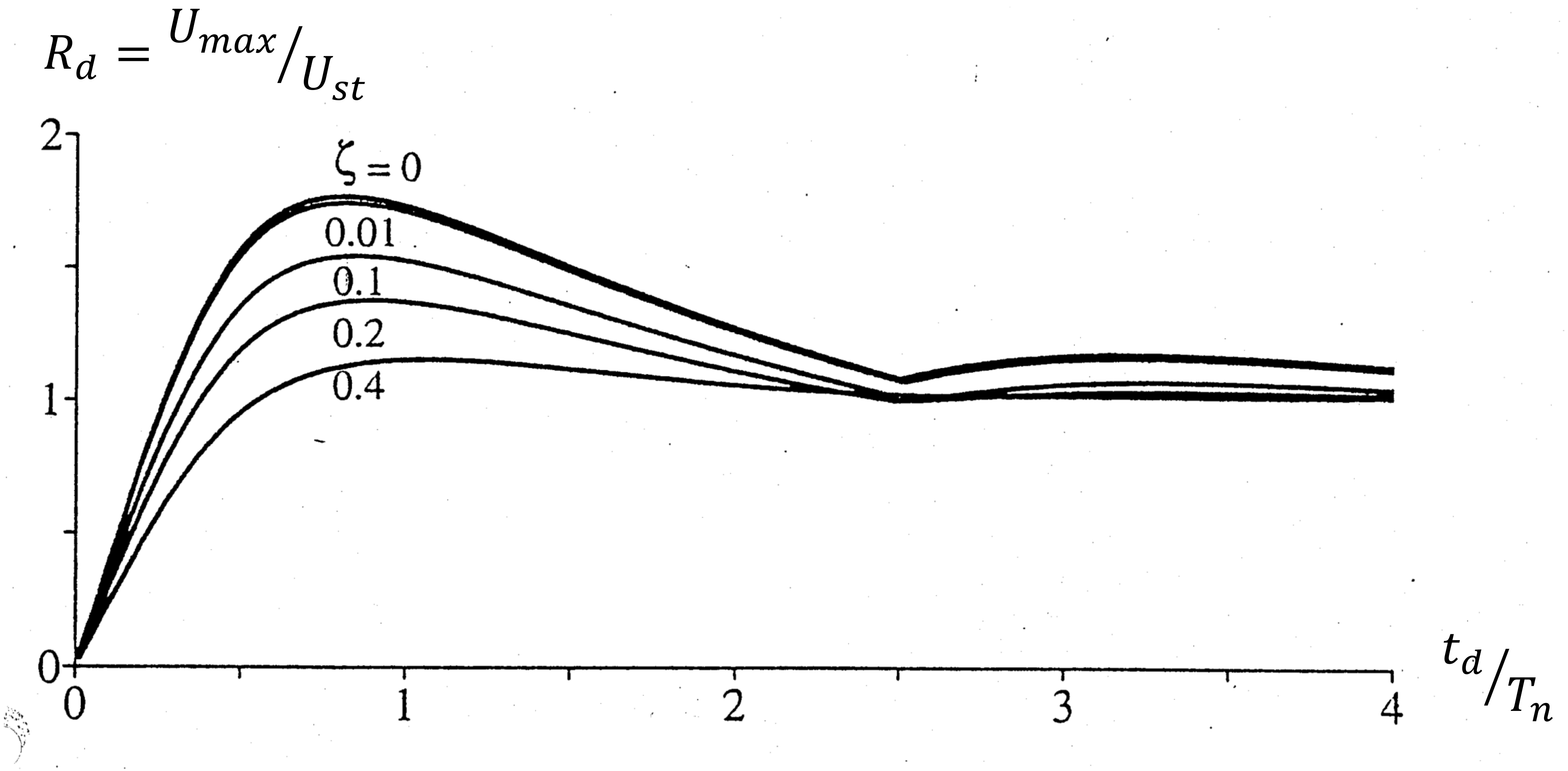
Solution: see figures in the next slide

Dynamic responses of undamped SDOF systems to half-cycle sine pulse force; Static responses are shown by dashed lines



- The normalized deformation $U(t)/U_{st}$ is a function of t/T_n. The characteristics of the function depend on t_d/T_n —the ratio of the pulse duration to the natural vibration period of the system.
- Since the response has not yet reached its steady state, the dynamic response factor is not as high as that of steady-state response to harmonic excitation.
- The dynamic response factor, U_{max}/U_{st}, is a function of t_d/T_n

Shock spectra for a half-cycle sine pulse force for five damping values



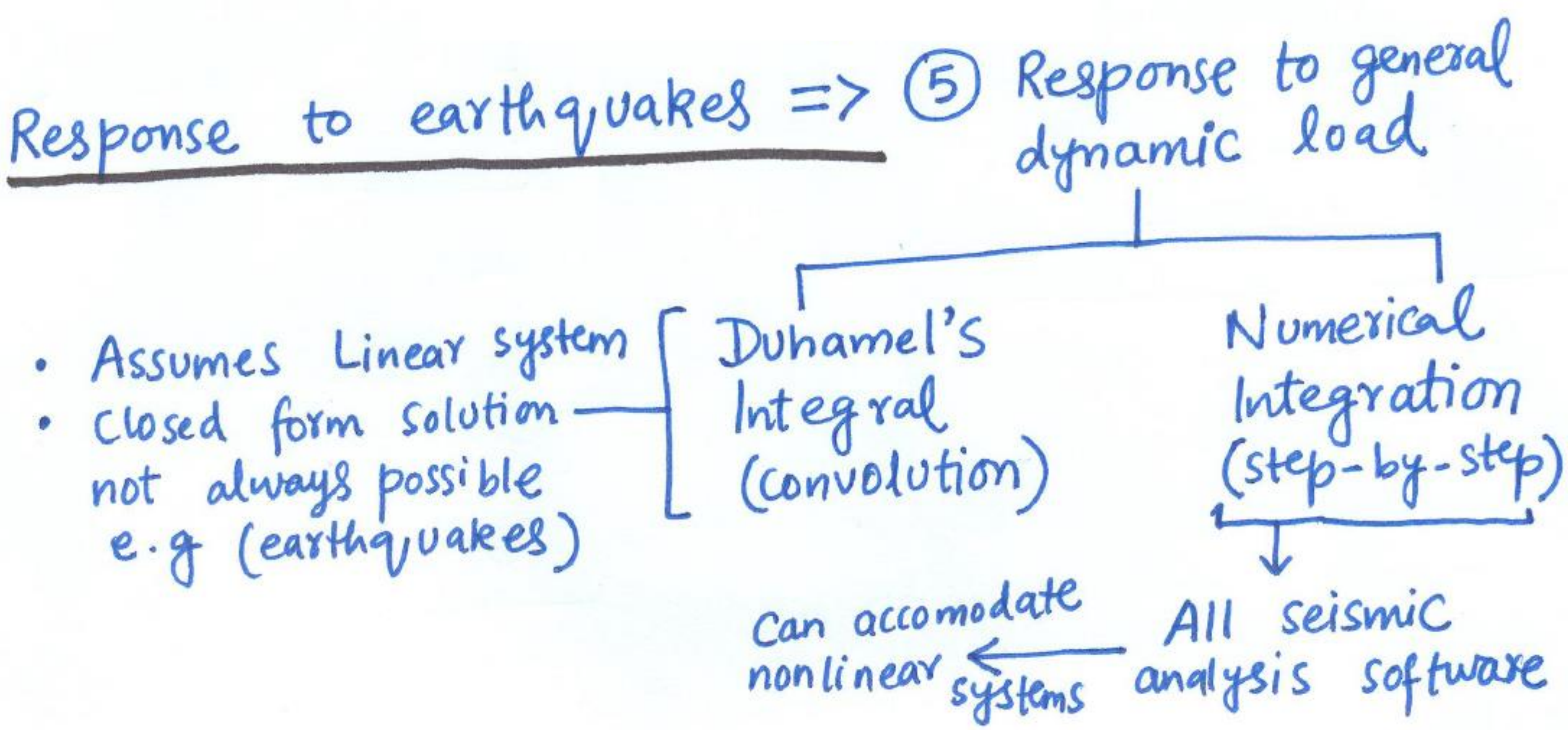
- A plot which shows the maximum deformation of a SDOF system as a function of the natural period T_n of the system (or related parameter such as ${t_d}/{T_n}$, for example) is called a '**response spectrum**'.

- When the excitation is a single pulse, the terminology '**shock spectrum**' is also used for the response spectrum.

- The effect of damping on the maximum response is usually not important unless the system is highly damped. This is different from the case of steady-state response of systems of harmonic excitation at or near resonance, where damping has significant influence.

- **Increase in damping ratio from 1% to 10% reduces the maximum deformation by only 12%.**

Dynamics of SDF Systems



Response to Arbitrary Force

Equation of motion: $$m\,\ddot{u} + c\,\dot{u} + k\,u = p(t) \qquad (26)$$

A force varying arbitrary with time

Initial Conditions: $$u(0)\ and\ \dot{u}(0) = 0$$ at rest initial condition

Solution: $$u(t) = \int_0^t p(\tau)\,h(t-\tau)\,d\tau \qquad (27)$$

The convolution Integral

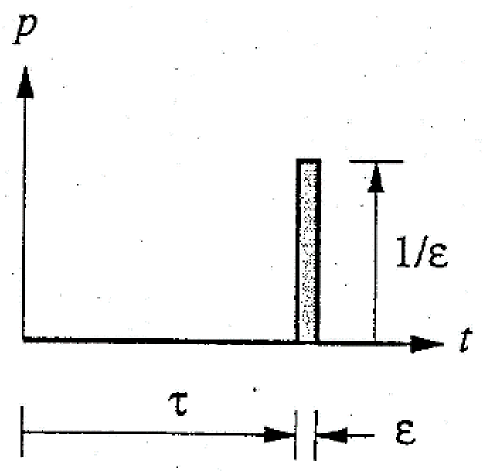
where

$h(t-\tau)$ is the response of the SDOF system to a unit impulse which occurs at time $t=\tau$, so

$h(t-\tau)$ is called “unit impulse response function”

$$h(t-\tau) = \begin{cases} \dfrac{1}{m\omega_D} e^{-\xi\,\omega_n(t-\tau)} sin[\omega_D(t-\tau)] & t \geq \tau \\ 0 & t < \tau \end{cases} \qquad (28)$$

(a)

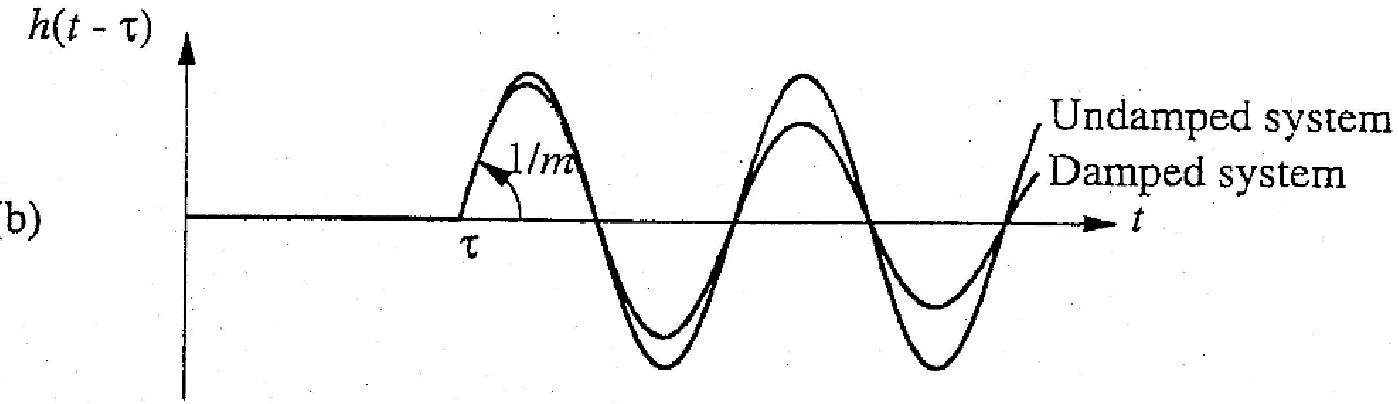


a unit impulse at $t = \tau$

$$\int_{\tau}^{\tau+\varepsilon} p(t)\, dt = 1$$ and ε is very small, that is, $\varepsilon \to 0$

Response to the unit impulse
= Free Vibration with $u(\tau) = 0$ and $\dot{u}(\tau) = {}^{1}/_{m}$

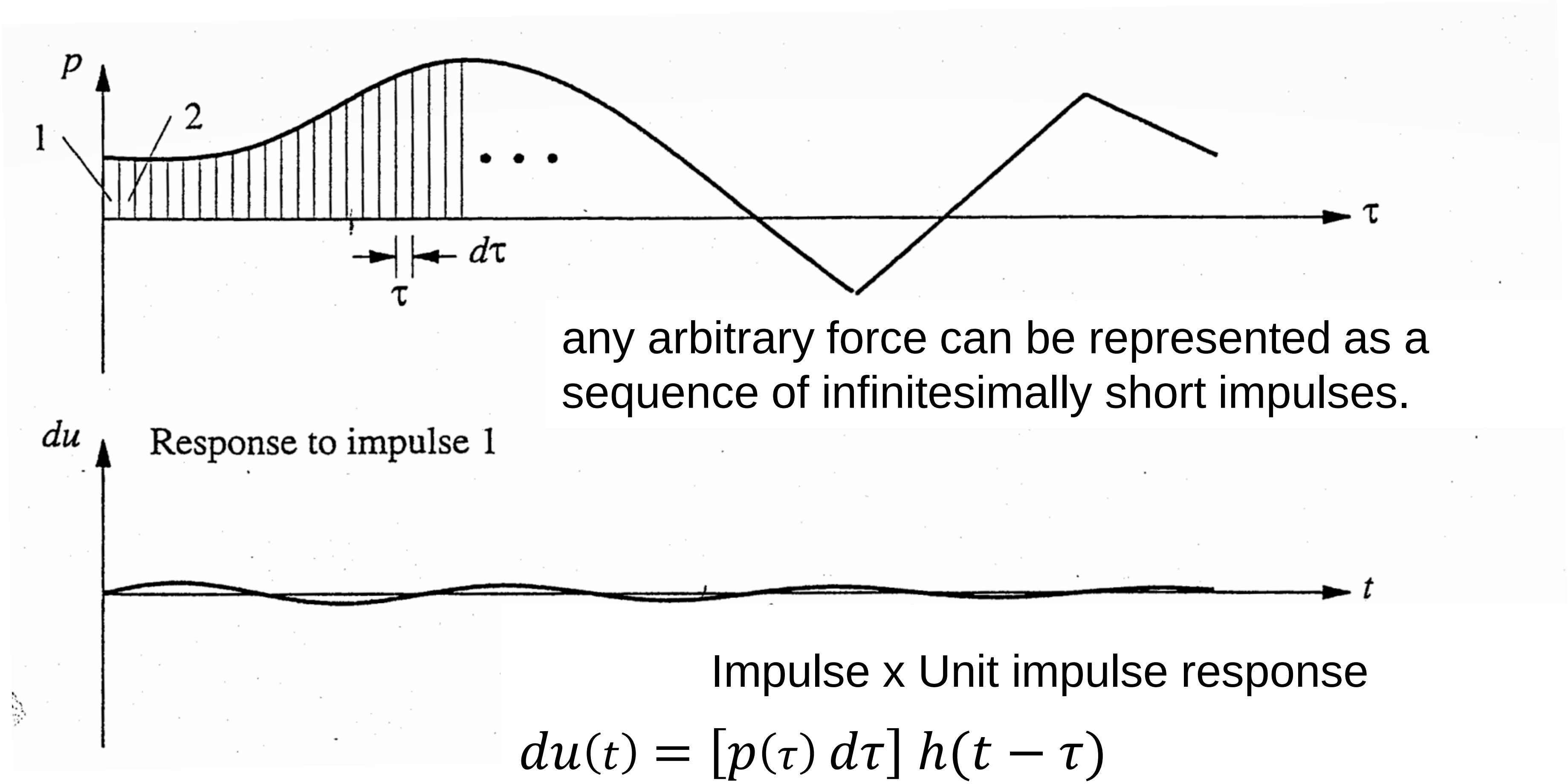
(b)



Impulse = change in momentum, so

$$1 = m\,\dot{u}(\tau) - m \times 0$$

Schematic Explanation of Convolution Integral



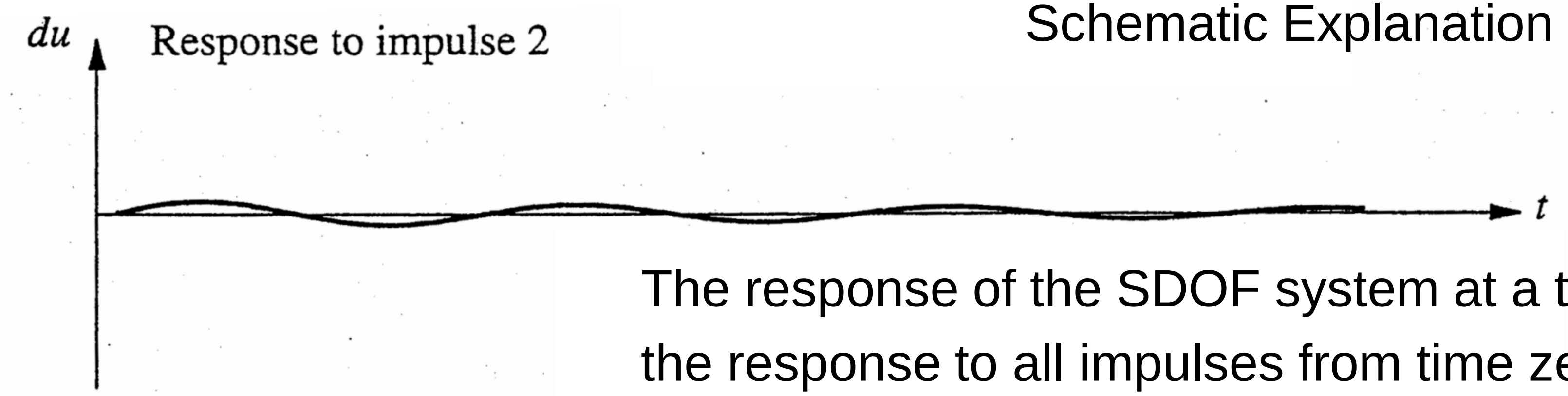
any arbitrary force can be represented as a sequence of infinitesimally short impulses.

Impulse x Unit impulse response

$$du(t) = [p(\tau)\, d\tau]\, h(t - \tau)$$

Response of a SDOF system to one of these short impulses – the one at time τ

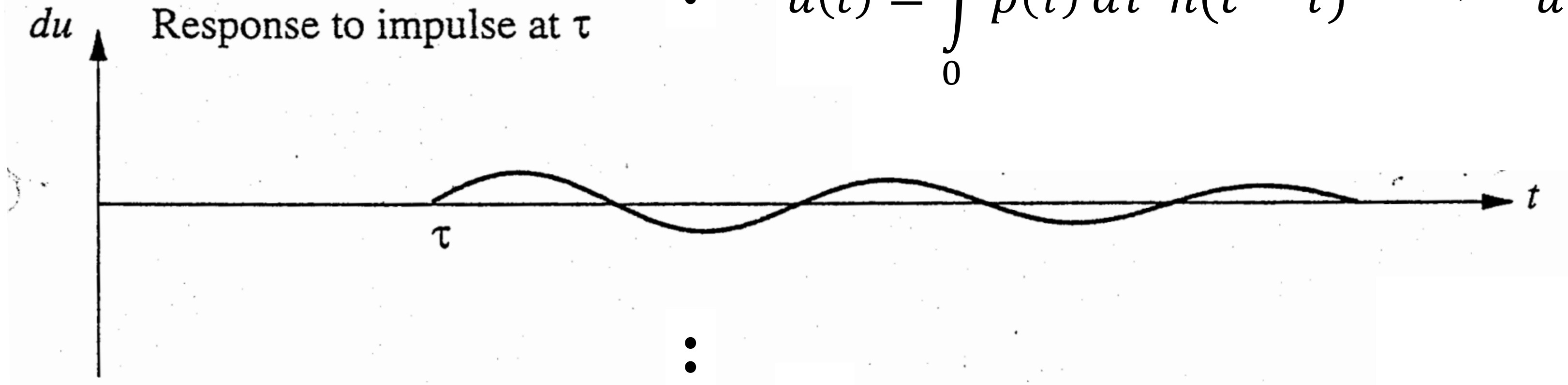
Schematic Explanation of Convolution Integral



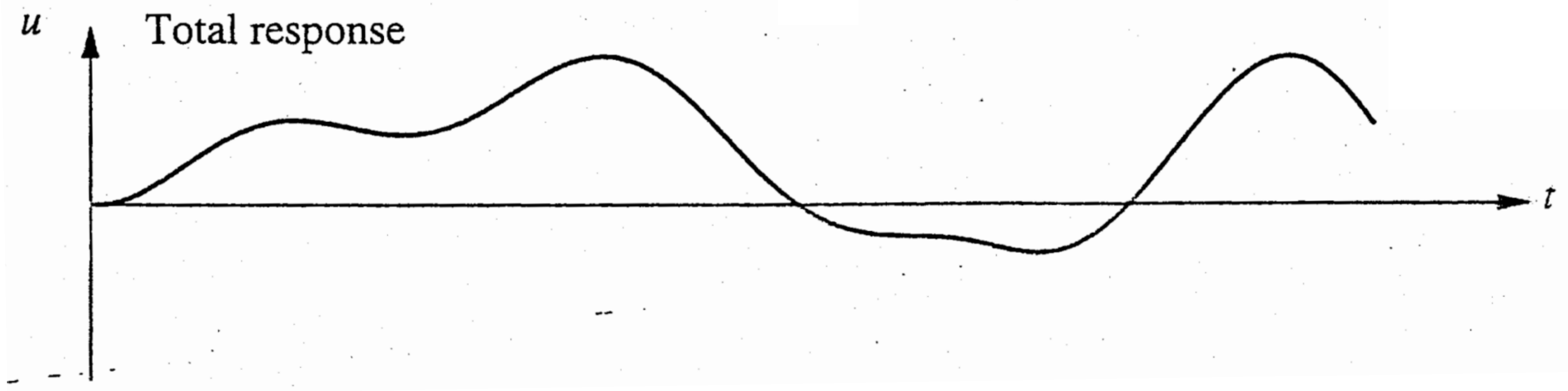
The response of the SDOF system at a time t is the sum of the response to all impulses from time zero to time t

⋮

$$u(t) = \int_0^{\tau} p(\tau)\, d\tau \;\; h(t-\tau) \longrightarrow u(t) = \int_0^{\tau} p(\tau)\, h(t-\tau) d\tau$$



⋮



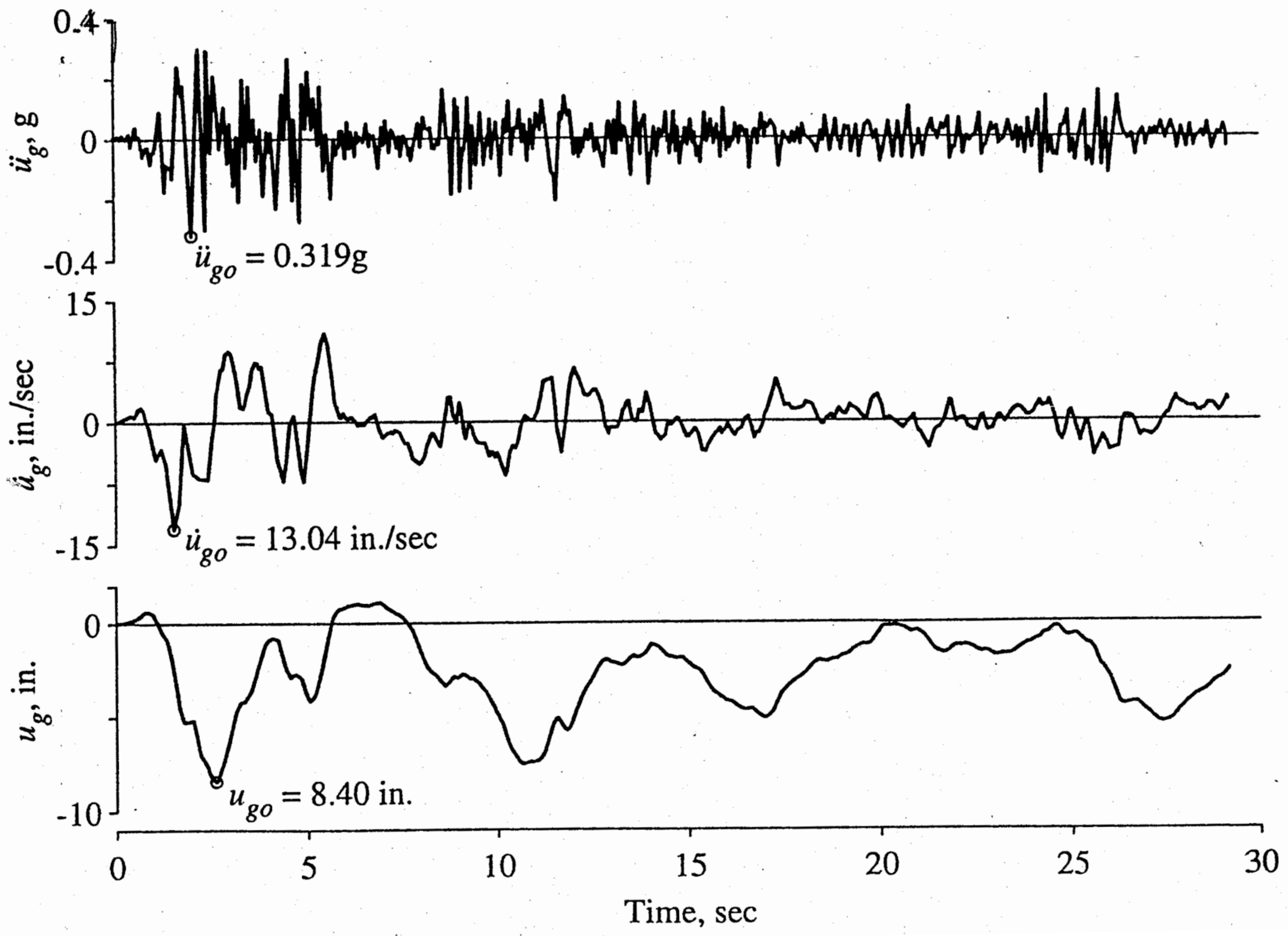
The convolution integral is restricted to linear systems because it is based on the principle of superposition. Therefore, it does not apply to the cases where structural deformations exceed their linearity elastic limit.

Ground Motion Accelerogram

For engineering purposes, the time variation of ground acceleration $\ddot{u}_g(t)$ is the most useful way of defining the shaking of the ground during an earthquake.

This is because $$P_{eff}(t) = -m\,\ddot{u}_g(t)$$

This basic instrument to record three components of ground shaking (up-down, N-S, E-W) during earthquakes is the strong-motion accelerograph which does not record continuously but is triggered into motion by the first waves of the earthquake to arrive.



North–south component of horizontal ground acceleration recorded at the Imperial Valley Irrigation District substation, El Centro, California, during the Imperial Valley earthquake of May 18, 1940. The ground velocity and ground displacement were computed by integrating the ground acceleration.

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GSR-12 / GSR-16 Strong Motion Recorder

Features

- ❒ Servo Force Balance Accelerometer
- ❒ Standard 2 GByte Removable Memory
- ❒ On-line Diagnostics and Self-Checking System
- ❒ LED and LCD Status Indication
- ❒ Detailed Analysis Tool with dedicated GeoDAS Data Analysis Package
- ❒ Compact and user-friendly
- ❒ Quick Installation
- ❒ Minimal Maintenance
- ❒ Broad Application Field

Outline

The **GSR-12/16** is an acceleration data acquisition system that represents the state of the art technology in earthquake monitoring. In combination with the high performance e.g. Servo (Force Balance) Accelerometer the GSR-12/16 brings a 72/96 dB dynamic range.

The sensor signals are captured by an A/D converter and digitally filtered to increase accuracy and to provide stable performance.

Various parameter settings allow you to configure the **GSR-12/16** very simply and specifically to your desired requirements.

A variety of trigger conditions can be selected to start data capture into a **Solid State Memory Bank** (SRAM) for later analysis. Recorded data can be conveniently transferred to the central station using the serial interface (PC/RS-232 port or modem).

Transferring data to PC while recording is possible and can be done also via modem

Optionally available is the dial-up system that allows the GSR to call automatically a predefined telephone number after an event has been recorded.

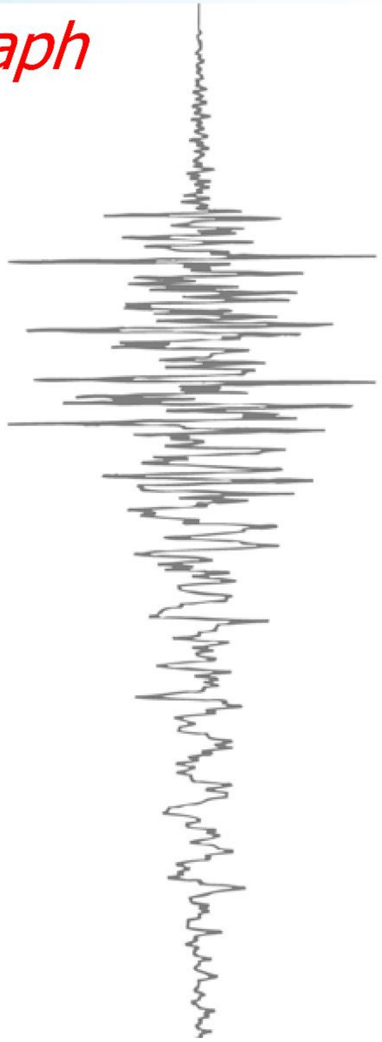
A comprehensive package of advanced, menu-driven analysis software is available. **GeoDAS** is included with the **GSR-12/16** and can be used on-site for a first impression of the recorded data. **GeoDAS Data Analysis Package** is a dedicated evaluation program especially designed by **GeoSIG** for earthquake and civil engineering data analysis. It contains all necessary functions and performances for detailed evaluation in the frequency domain functions (FFT, Power Spectrum, Response Spectrum). Additional include integration (acceleration-velocity and velocity-displacement), CAV (Cumulated Absolute Velocity), Space (Rotation, Display) and various data filters.

The **GSR-12/16** is the ideal compact and most cost effective **12 and 16 Bit** approach.

KINEMETRICS

K2

Strong Motion Accelerograph



Strong Motion Accelerograph

KEY BENEFITS

- Dynamic range greater than 114 dB
- Modular design that allows multi-channel expansion to 6 or 12 channels
- Multi-tasking operating system that allows simultaneous data acquisition and interrogation
- Timing accuracy to ±0.5 ms due to synchronized sampling with optional GPS timing system
- Zero Channel Skew through the utilization of individual A/D converters for each channel
- Remote alerting capability for system event or auto-diagnostic failure
- Remote data acquisition with real time digital data output
- Interconnectivity with other Altus Family recorders for common triggering and shared GPS (option)
- Common user interface, file format, and support tools with other Altus family recorders

INTRODUCTION

The ***K2*** is a full-featured strong motion accelerograph designed with the end user in mind. Technical advances and innovative engineering have increased performance and flexibility of this recorder to offer a dynamic range greater than 114 dB. The high dynamic range and superior resolution offer significant advantages for applications where signal fidelity and data integrity are vital.

In order to provide the greatest flexibility in data storage, retrieval and communications, Kinemetrics has included two fully compliant PCMCIA card slots that support a wide variety of nonproprietary memory cards, hard disks and modems. This allows users to easily configure the ***K2*** for their specific applications.

Developed for Microsoft Windows™, our QuickTalk® and QuickLook® software provide a user-friendly environment, making system setup, communications and rapid data analysis quick and easy.

MAJOR APPLICATIONS

- Structural monitoring arrays
- Dense arrays, two and three dimensional
- Aftershock study arrays
- Local, regional and national seismic networks and arrays

Input Channels

Sensor channels: Up to 12 channels
Input level: Standard ± 2.5V

Data Acquisition

Type: Over-sampled Delta Sigma system with 24-bit DSP
Anti-alias filter: Brickwall FIR filter. Cut-off at 80 % of output Nyquist; 120 dB down at output Nyquist
Dynamic range: ~114 dB (200 sps 0-50Hz BW RMS noise/RMS clip
Frequency response: DC to 80 Hz @ 200 sps
Sampling rates: 20, 40, 50, 100, 200, 250 sps
Chan.-chan. skew: None – simultaneous sampling of all channels
Acquisition modes: Continuous, trigger
Output data format: 24 bit signed (3 bytes)
Parameter calculations: Calculations of key parameters in real-time
Real time digital output: RS-232 output of digital stream (contact factory for available formats)

Trigger

Type: IIR bandpass filter (three types available)
Trigger selection: Independently selected for each channel
Threshold trigger: Selectable from 0.01% to 100% of full scale
Trigger voting: Internal, external trigger votes with arithmetic combination
Additional trigger: STA/LTA

Storage

Type: Fully compliant PCMCIA storage system (two slots)
Compatibility: PCMCIA standard 2.1; sockets accept
Type I, II, III card formats
Type I or II modem

Storage primary slot: 32 MB Memory Card (minimum) Optional larger cards available.
Storage 2nd slot: Same as primary slot
Parallel 2nd slot: Accepts Type I or II modem with connectors
Recording capacity: Approximately 42 kB per channel per minute on Memory Card, of 24-bit data @ 200sps.
Recording format: Data is stored in DOS file system allowing cards to be read directly by PC.

RS-232 input: Full RS-232C interface with modem control
Aux. input: Mil-style connector for 4th channel input, IRIG out, IRIG in, clock sync., 1 pps out, trigger in, trigger out, alarm out, real time digital output (tx & rx), ext 12V out. Interface for interconnection of multiple units
EMI/RFI protection: All I/O lines are protected from both EMI/RFI emission and susceptibility problems by ferrite filters and transient suppressors

Power Supply

Type: High efficiency switched power supply and charger system
Input: Nominal 24 Vdc from charger
Operating range: 10.5V to 15V
Ext. charger voltage: 100-250 Vac 50/60 Hz
Charging voltages: Temperature compensated for lead acid gel cell, 2 outputs with separate protection circuitry allows unit to recharge flat battery and work with reversed or damaged battery in multi battery system
Fuses: Four 2 amp fuses for charger and batteries
Batteries: Internal battery 12V 12 Ah (standard); external battery (opt)
Current drain: 390 mA @12V (standard configuration)
Power autonomy: >36 hours with internal battery

Housing

Type: Lexan structural foam housing internally coated with EMI/RFI shielding material, 5/16" aluminum base support for mounting
Mounting: Single hole for 1/4" stud
Size: 10.1" (256 mm) W x 15.0" (381 mm) L x 7" (178 mm) H
Weight: 10.9 kg (24 lbs) including battery

Communications

RS-232 interface: Parameter setup, real-time telemetry and event retrieval.
PCMCIA modem: Remote access, initiated by user or by the K2. Optional
Ethernet interface: Connect the K2 directly to your IP based Wide Area Network (WAN). Optional
FTP via Modem: FTP transmission of events via dial-up ISP. Optional

Support Software

QuickTalk®*: Windows-based control and data retrieval program for easy setup and data retrieval by direct connection or modem.

Recording capacity: Approximately 42 kB per channel per minute on Memory Card, of 24-bit data @ 200sps.
Recording format: Data is stored in DOS file system allowing cards to be read directly by PC.

Firmware

Type: Multi-tasking operating system supports simultaneous acquisition and interrogation; boot loader allows remote firmware upgrades
System control: Configure sample rate, filter type, trigger type and voting, maintains communications and event storage
User interface: Packetized protocol and simple terminal loop control and data retrieval via RS-232 interface
Intelligent alerting: System can be configured to initiate communications when an event is detected or if an auto-diagnostic failure occurs
Auto-diagnostics: System can be configured to continuously check system voltages, temperature, RAM and code integrity, timing system integrity
Rapid setup: Unit can be configured from parameter file stored in PCMCIA memory card

Timing

Type: Free running disciplined oscillator (standard); GPS
GPS option: Integrates completely with system, providing timing, internal oscillator correction and position information
Shared GPS: Allows a group of interconnected Altus recorders to share one GPS module (option)
Timing accuracy: 5 microseconds of UTC with GPS
Power: Power cycling is software controlled
Power consumption: 110 mA at 12V (active)

I/O and Display

Display: Matrix of 8 LEDs. Display indicates acquisition mode, event, recording, battery voltage, memory capacity used
Power input: Mil-style connector for 24 Vdc charge input, external battery, standby power

Support Software

QuickTalk®*: Windows-based control and data retrieval program for easy setup and data retrieval by direct connection or modem.
QuickLook®*: Windows-based data retrieval program for rapid review of waveforms and event information. Also operates with DOS communication software
Antelope: Comprehensive commercial network operational and mgmt system for medium and large networks
Earthworm: Comprehensive public domain network operational and management system for medium and large networks
NMS: Commercial PC-based network management system for small to medium sized networks via modem or real-time data
SMARTS: Commercial open architecture user-extensible real-time data collection and processing software that runs on a variety of computers
PSD: Commercial Pseudo Spectral Density software for earthquake data analysis
SMA: Commercial Strong Motion Analyst software for earthquake data analysis and processing
*K2COSMOS**: Conversion software from Altus EVT file format to COSMOS v1.20 format
Format Converters*: Provides option to convert and store data in ASCII and other formats. Contact Kinemetrics for other options.

*No charge

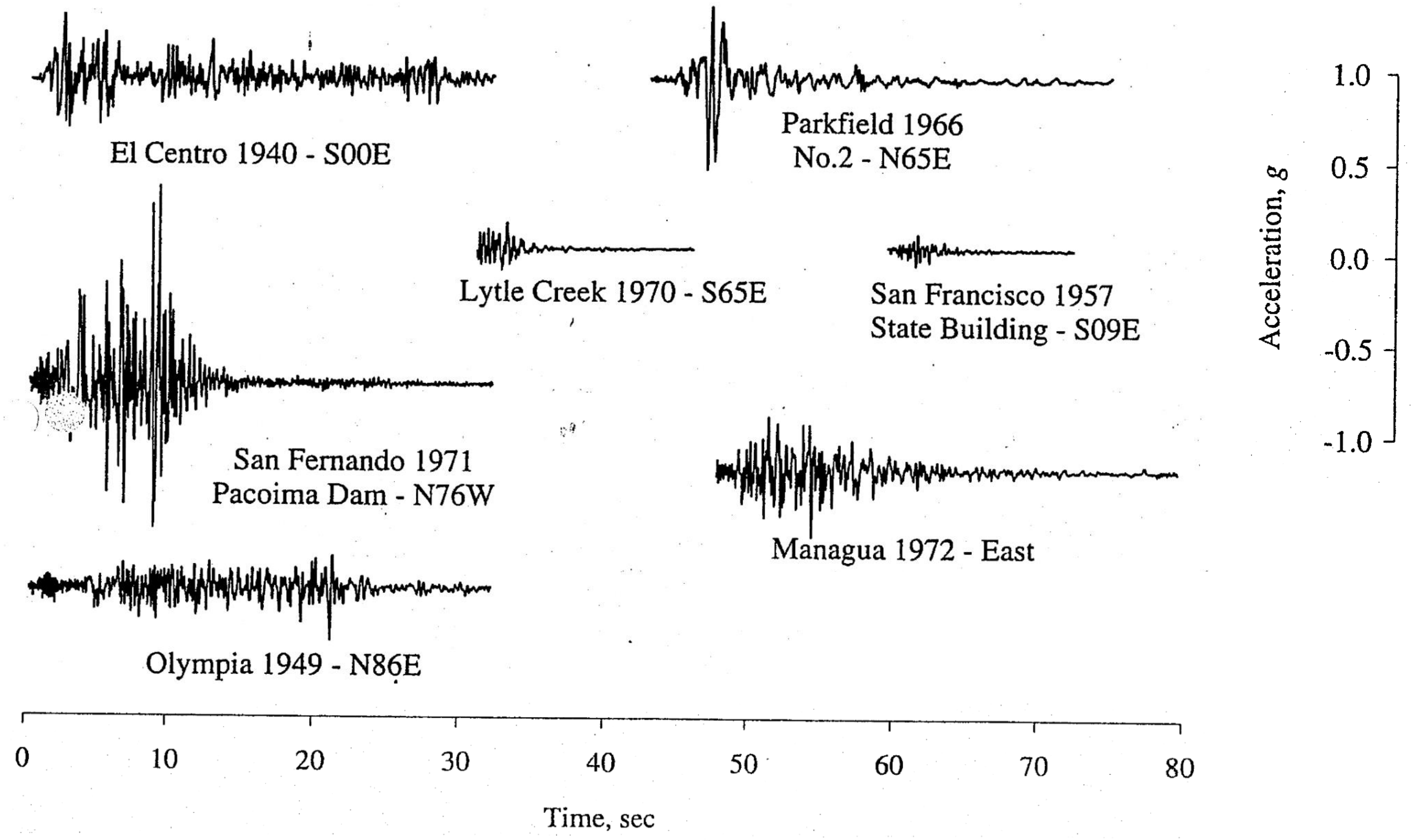
Environment

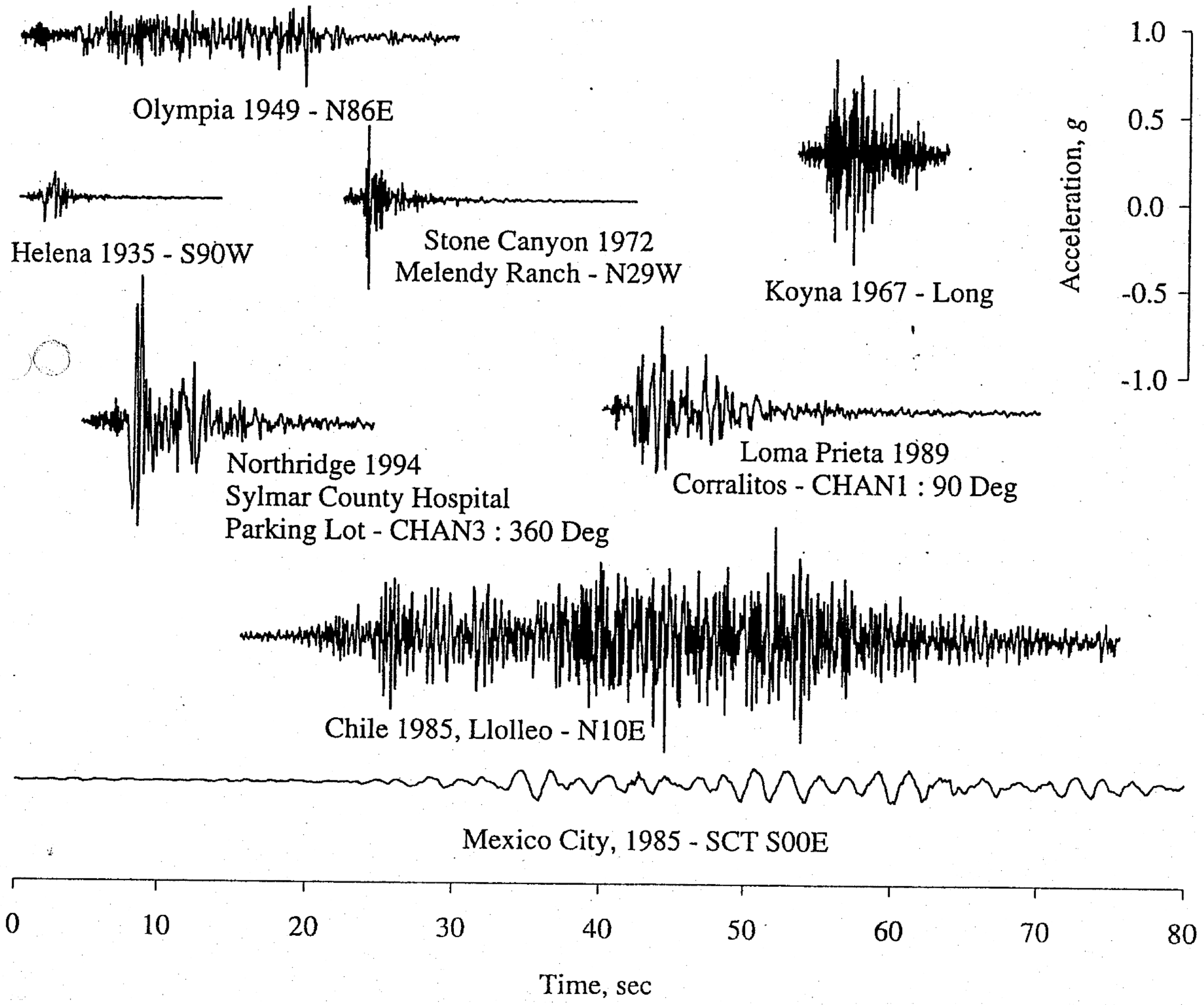
Operating temp.: -20° to 70°C
Humidity: 0-100% RH

Ground motions recorded during several earthquakes:

-highly irregular

-wide variety of amplitude, duration, frequency content and general appearance of different records can be clearly seen.




Olympia 1949 - N86E
Helena 1935 - S90W
Stone Canyon 1972
Melendy Ranch - N29W
Koyna 1967 - Long
Northridge 1994
Sylmar County Hospital
Parking Lot - CHAN3 : 360 Deg
Loma Prieta 1989
Corralitos - CHAN1 : 90 Deg
Chile 1985, Llolleo - N10E
Mexico City, 1985 - SCT S00E
1.0
0.5
0.0
-0.5
-1.0
Acceleration, g
0
10
20
30
40
50
60
70
80
Time, sec

Dynamics of MDF Systems

Lets consider the most simple case : Free vibration Response + Undamped

$$\mathbb{M}\ddot{\mathbb{U}}(t) + \mathbb{K}\mathbb{U}(t) = \mathbb{O}$$

Free-vibration response of a SDF system, $u(t) = a\sin(\omega t+\theta)$

a → arbitrary amplitude as per the initial conditions.

ω = natural circular frequency.

So by analogy,

$$\mathbb{U}(t) = \phi \sin(\omega t+\theta)$$

ϕ → an N-vector that represents the shape of vibration

Putting in above equation and Solving,

$$\mathbb{K}\phi = \omega^2 \mathbb{M}\phi$$

$$[\mathbb{K} - \omega^2 \mathbb{M}]\phi = \mathbb{O}$$

ω^2 → Eigen-value

ϕ → Eigen-vector

Dynamics of MDF Systems

For $\mathbb{A}\mathbb{X} = \Phi$, The equation has non-zero Solution of $\mathbb{X}$ if and only if Det $\mathbb{A} = 0$ (Cramer's Theorem)

$$\text{So Det}(\mathbb{K} - \omega^2 \mathbb{M}) = 0$$

This will yield "frequency equation" — an nth degree polynomial (n = DOFs) with "n" roots $\omega_1, \omega_2, \omega_3, \text{-----} \omega_n$ — (frequencies of n modes of vibration)

For each $\omega_i \rightarrow$ a corresponding ϕ_i can be calulated using above equation.

ϕ_i is a "free vibration mode shape" of an ith mode of vibration.

Modal Analysis for Forced Vibrations Response (Mode-superposition method)

The dynamic response of a MDF system to external forces $P(t)$ can be computed by modal analysis.

① Define structural properties

a) $\mathbb{M}$, $\mathbb{K}$,

b) estimate ξ

② Determine ω_n and modes ϕ_n

③ Compute response for each mode

a) solve $M_n \ddot{q}_n(t) + C_n \dot{q}_n(t) + K_n q_n(t) = P_n(t)$

or $\ddot{q}_n + 2\xi_n \omega_n \dot{q}_n + \omega_n^2 q_n = \frac{P_n(t)}{M_n}$

for $q_n(t)$

b) Determine nodal displacements using $U_n(t) = \phi_n \times q_n(t)$

c) Determine element forces associated by nodal displacements $U_n(t) \longrightarrow \gamma_n(t)$

(i) Using element stiffness properties

(ii) Using Static analysis at each time step, under equivalent static forces $f_n = K U_n(t)$

$f_n = \omega^2 m \phi_n q_n(t)$

④ Combine all modal contributions.

$$U(t) = \sum_{n=1}^{N} U_n(t) = \sum_{n=1}^{N} \phi_n q_n(t)$$

$$\gamma(t) = \sum_{n=1}^{N} \gamma_n(t)$$

Thank you