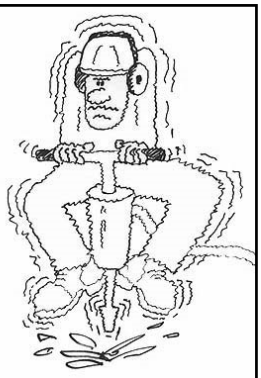

機械振動學課程
Introduction and Overview

Prof. Kuo-Shen Chen
Department of Mechanical Engineering
National Cheng-Kung University
Feb. 14 and 17, 2023

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任課老師介紹: 陳國聲教授

- Education
  - BS. Power Mechanical Engineering
    - National Tsing-Hua University
  - Ph.D. Mechanical Engineering
    - Massachusetts Institute of Technology (MIT)
- Specialty
  - Vibration control, precision machine design, structural analysis, MEMS, nanomechanics, machine tool monitoring & diagnosis

3

Vibration Related Faculty at NCKU ME

- Prof. S. Y. Lee (李森墉教授)
  - Ph.D. State Univerity of New York at Buffalo (1984)
  - Vibration, applied mathematics, creative design
- Prof. L. W. Chen (陳聯文教授)
  - Ph.D. Rensselaer Polytechnic Institute (RPI) (1980)
  - Elastic stability, photonic crystals
- Prof. C. H. Liu (劉至行教授)
  - Ph.D., Georgia Institute of Technology (2009)
  - Topology optimization, structural dynamics, robotics
- Prof. C. J. Lan (陳重德教授)
  - Ph.D., NCKU ME (2003)
  - FEA, Fracture Mechanics, Energy Harvesting

4

基本資料

- 選修年級: 3, 4
- 學分: 3
- 上課時間:
  - 週二(7,8) 15:10 – 17:00; 週五 (8) 16:10-17:00.
- 上課地點: 91204
  - 助教: 楊博丞, 張珈銘 RM 91A07
  - 分機 62272

基本資料

- 課程網站: Moodle? And http://klab.me.ncku.edu.tw/
- Facebook: klab course
- 先修科目
  - 應用力學 (II) (動力學)

評分標準

- 作業:　　約 8次, total 25 Pts
- Quiz :　　三次, ~ 25 pts each
- Possible Term project: 10 Pts

- Total 110 Points

Possible Term Project (~2人/組)

- To be announced later
- Probably a modal testing project

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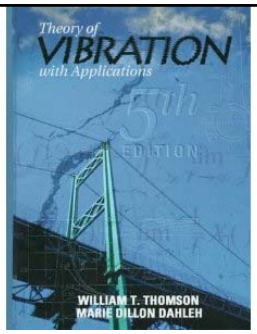
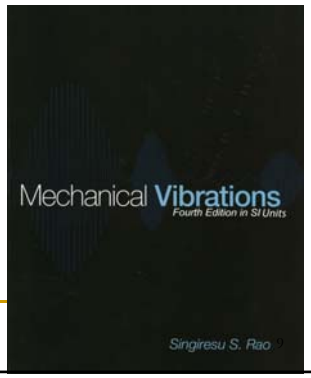
Books

- Thomson and Dahleh, Theory of Vibration with Applications,5th Ed. Prentice-Hall



- S. Rao, Mechanical Vibration, Pearson



Motivation *The Millennium Bridge* a Recent Vibration Problem (2000-1)

10

Modeling and Degrees of Freedom

11

Outline of the Entire Course (I)

- Single Degree of Freedom System
  - Mass-spring systems; mass-spring-damper systems, natural frequencies
  - Free and forced responses
  - Frequency-responses
  - Resonance
  - Shock and vibration isolations
  - Case studies

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Outline of the Entire Course (II)

- Multiple Degrees of Freedom Systems
  - Normal mode analysis
  - Natural frequencies and mode shapes
  - Vibration absorber
  - Modeling techniques
  - Introduction to finite element method
  - Case studies

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Outline of the Entire Course (III)

- Continuous Vibrations
  - Modeling of cable, bar, and shaft
  - Solution scheme
  - Modes and natural frequencies
  - Modeling of beam
  - Engineering examples
  - Case studies

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Outline of the Entire Course (IV)

- Experimental Vibration
  - General procedure
  - Vibration test instruments
  - Modal testing theory
  - Failure diagnostics
  - Case studies

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Outline of the Entire Course (V)

- Integrated Topics (簡介)
  - Vibration control
    - Feedback control
    - Passive vibration control
    - Active vibration control
    - Noise issues
    - Case studies
  - Advanced vibration topics (簡介)
    - Nonlinear Vibration
    - Random Vibration
    - Rotordynamics

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Outline of This Lecture

- Introduction
- Vibration related background
- Engineering vibration applications
- A first look on vibration analysis
- Vibration testing and control

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Part I: Vibration: Brief Introduction

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Theory of Vibration

- Study the science, mathematics, and engineering of objects with oscillatory motion and the force associated with them
- Oscillatory motion
  - Any motion that repeats itself after an interval of time
  - Vibration frequency, vibration amplitude,…

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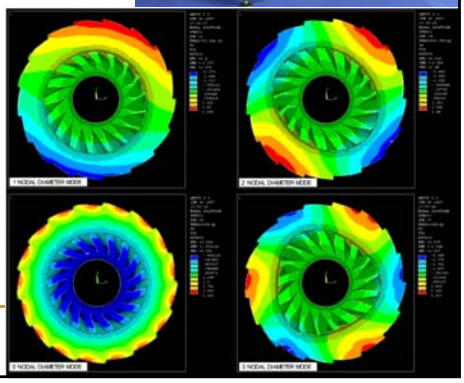
振動學應用範圍

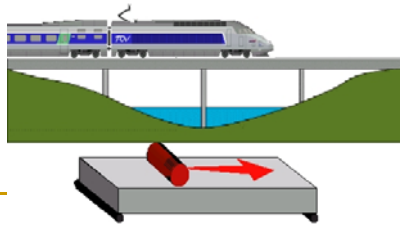


- 消除振動
  - 機械消音, 機械減振,
- 維持振動
  - 震盪器電路設計
- 鑑別系統動態行為
  - 模態分析

振動相關問題

- 地震與抗震
- 精密機械之定位
- 噪音與消音
- 振盪電路
- 汽車懸吊
- 衝擊

- 渦輪引擎之旋轉振動
- 橋樑/高速鐵路振動
- 中華一號衛星共振問題
- 流體誘發振動
- 材料疲勞與結構穩定
- 模態分析



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Delta II Rocket

Payload

22

晉陞探空火箭「飛鼠一號」

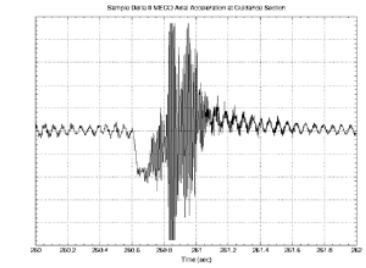
23

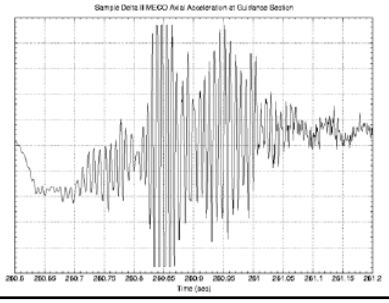
Main engine cut off

Mechanical Systems Analysis Branch/Code 542
Goddard Space Flight Center

MECO Transient Description

- **Approximately 4g's input at 115 Hz - 125 Hz**
- **Short duration transient event lasting about 0.2 secs**
- **Event seen on all previous Delta II flights**
- **Higher magnitude and longer duration with newer main engines - Approximately 8 flights**
- **No known launch anomalies associated with event**
- **Is this event a driver for payload design????**





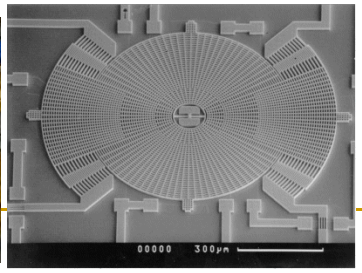
Part II: Vibration Related Courses / Books

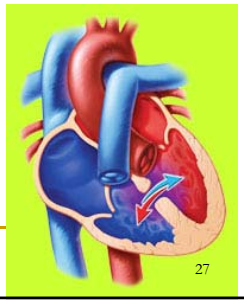
振動相關進階應用課程

- 結構動力學 (structural dynamics)
- 系統動態分析與控制器設計 (system dynamics analysis)
- 旋轉體動力學 (rotor dynamics)
- 微機電系統 (MEMS design)
- 非線性動力與混沌系統 (nonlinear vibration)
- 隨機振動 (random vibration)

振動相關進階應用課程

- 聲學 (Acoustics)
- 空氣彈性力學 (Aeroelasticity)
- 結構控制 (structural control)
- Intelligent materials and structures





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振動學所需基礎

- 牛頓力學
  - 應用力學 (II)
- 工程數學
  - 常微分方程 (Ordinary Differential Equations)
  - 線性代數 (Linear Algebra)
  - 富利葉分析 (Fourier Analysis)
  - 偏微分方程 (Partial Differential Equations)
  - 數值分析 (Numerical analysis)

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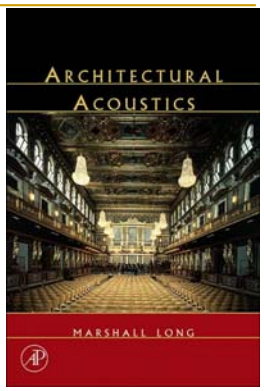
Part III: Vibration in Engineering Applications

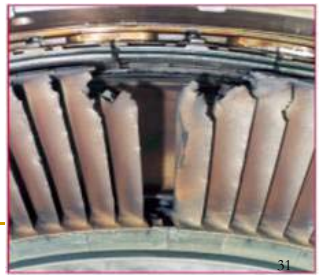
振動力學應用範圍: 機械領域

- 機械設計
  - machine element design
  - structural dynamic analysis
  - High speed rails
- 航空工程
  - Aeroelasticity , rotor dynamics
- 生物力學
  - Structure-fluid interaction
  - Hemodynamics

振動力學應用範圍: 機械領域

- 聲學相關應用
  - Noise control of optical storage devices
  - Speaker and microphone design
- Diagnostics
  - Failure analysis
  - Fatigue





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振動力學應用範圍: 電機領域

- 維持振動
  - Oscillator / resonator design
- 音響, 樂器, 揚聲器設計
  - Musical instrumentation with right resonant frequency and high Q

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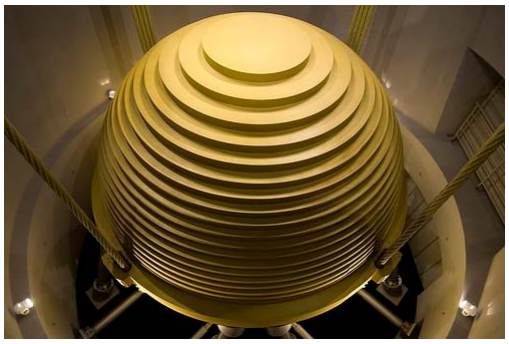
振動力學應用範圍: 土木領域

- 結構工程
  - Structural dynamics of buildings and bridges
- 地震工程
  - Earthquake engineering



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振動力學應用範圍:　系統與控制領域

- 系統建模
  - modeling of dynamic systems
- 結構控制
  - Active control of flexible systems
- 隨機系統
  - Random vibration

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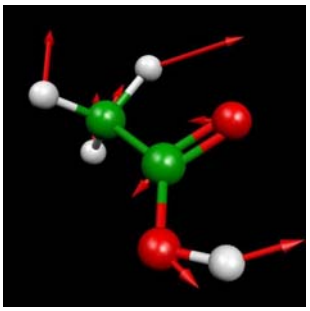
振動力學應用範圍: 微奈米領域

- 晶格振動
  - phonon
- 分子光譜
  - IR spectrum
- 感測器設計
  - Gyroscope
  - Accelerometers
  - Mass/ chemical sensors



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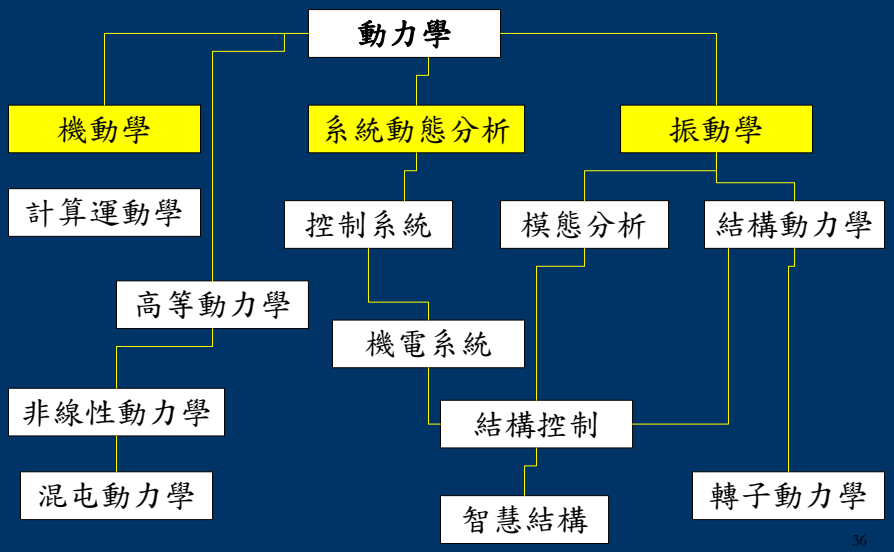
動力學後續相關領域介紹



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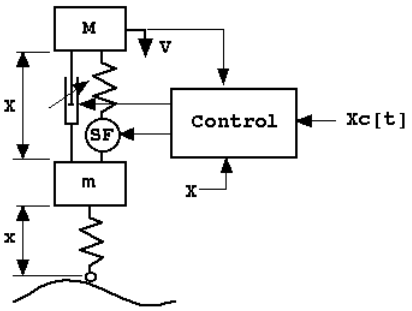
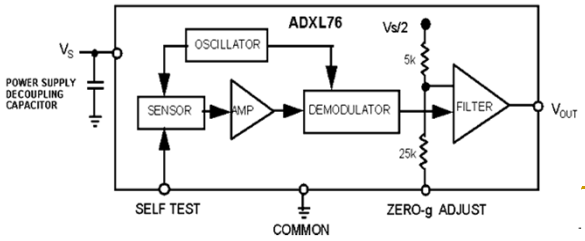
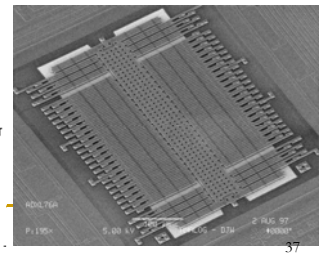
系統動態分析







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高等動力學

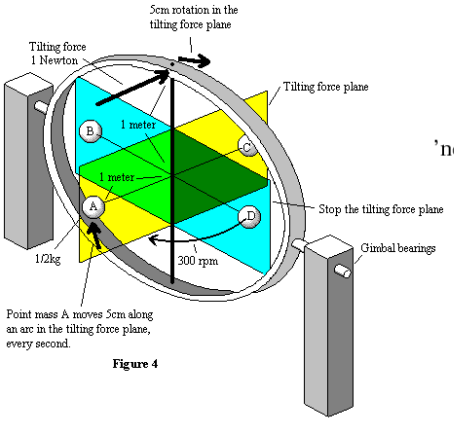
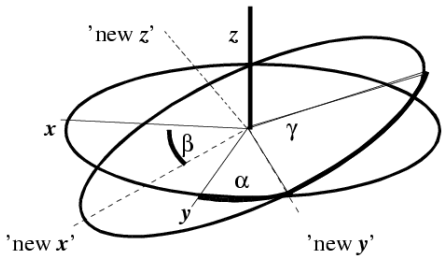


Figure 4



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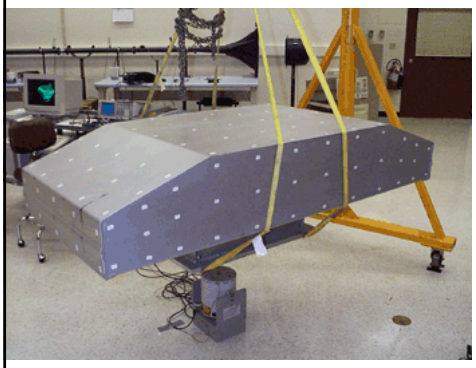
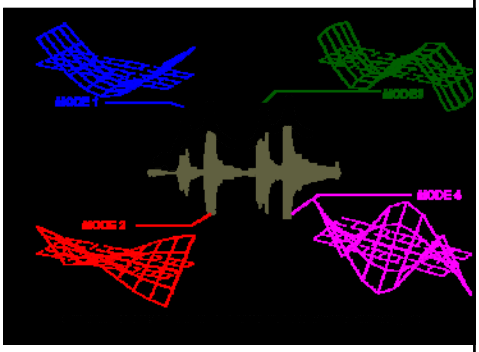
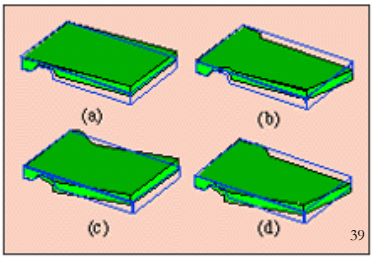
模態分析 (Modal Analysis)







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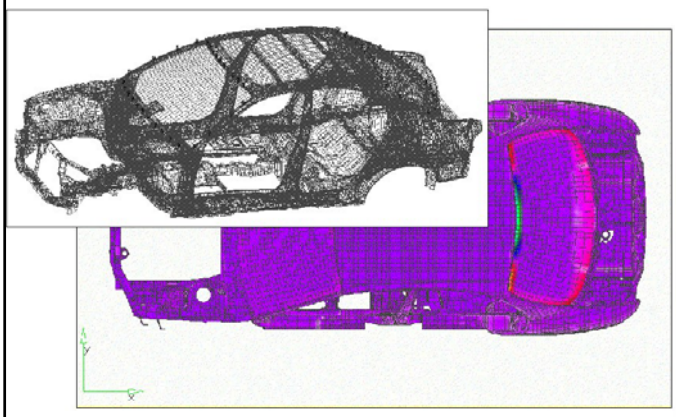
結構動力學 (Structural Dynamics)



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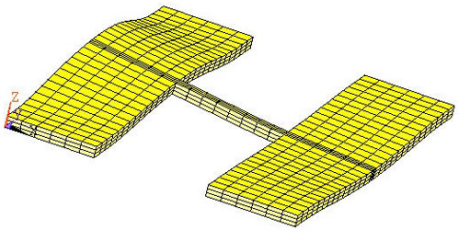
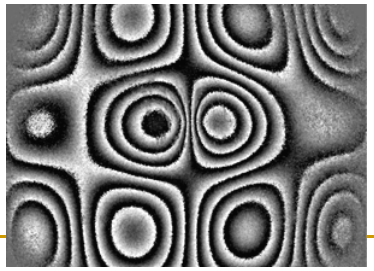
結構動力學 (Structural Dynamics)





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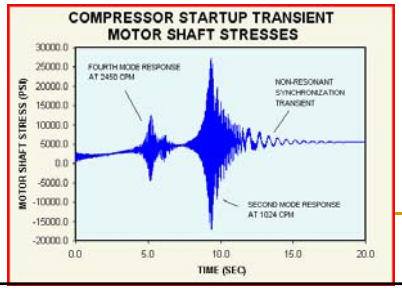
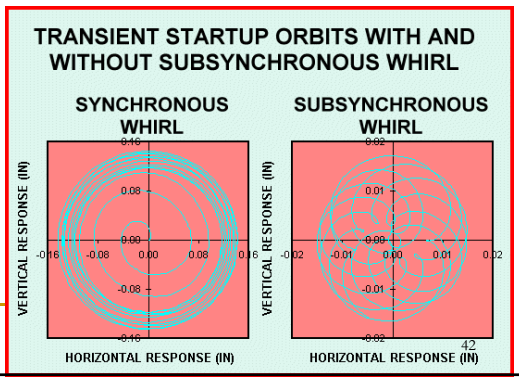
轉子動力學 (Rotordynamics)





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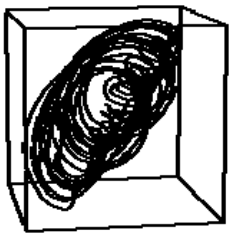
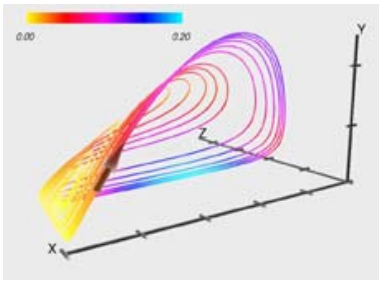
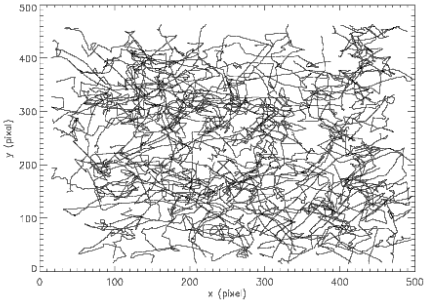
非線性動力學 (Nonlinear Dynamics)







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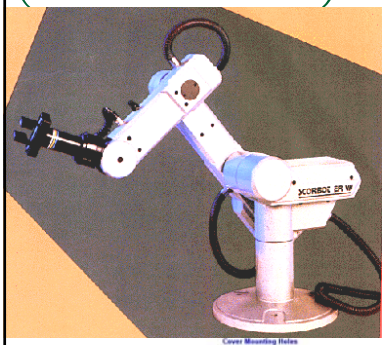
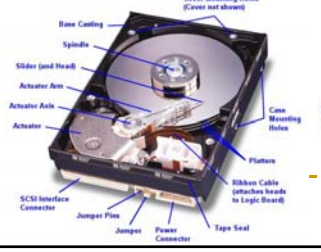
機電系統 (Mechatronics)





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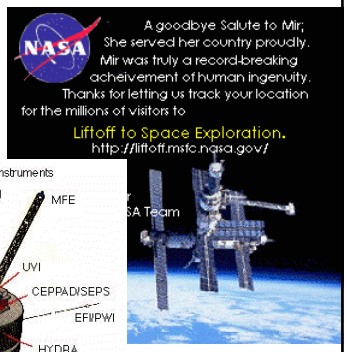
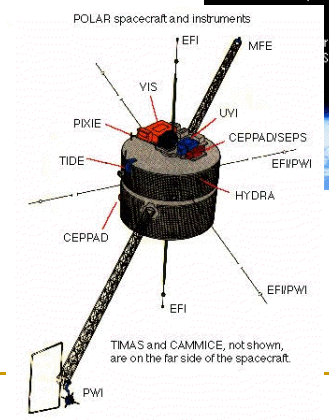
太空動力學 (Space Dynamics)





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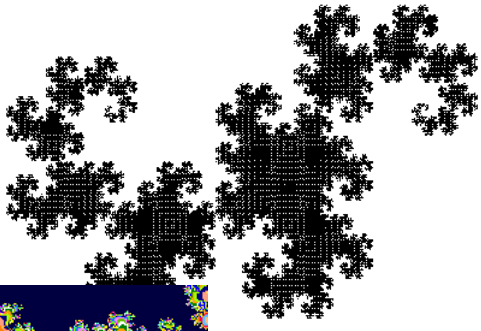
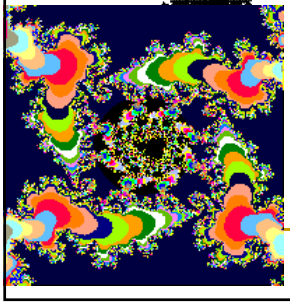
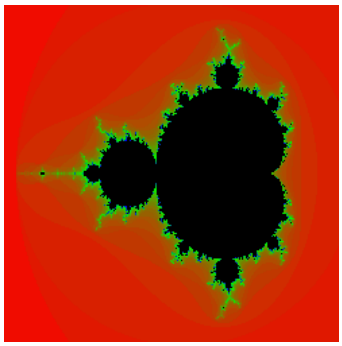
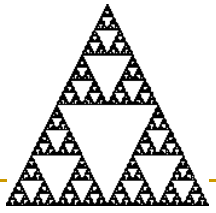
混屯動力學 (Chaotic Dynamics; Dynamical Systems)









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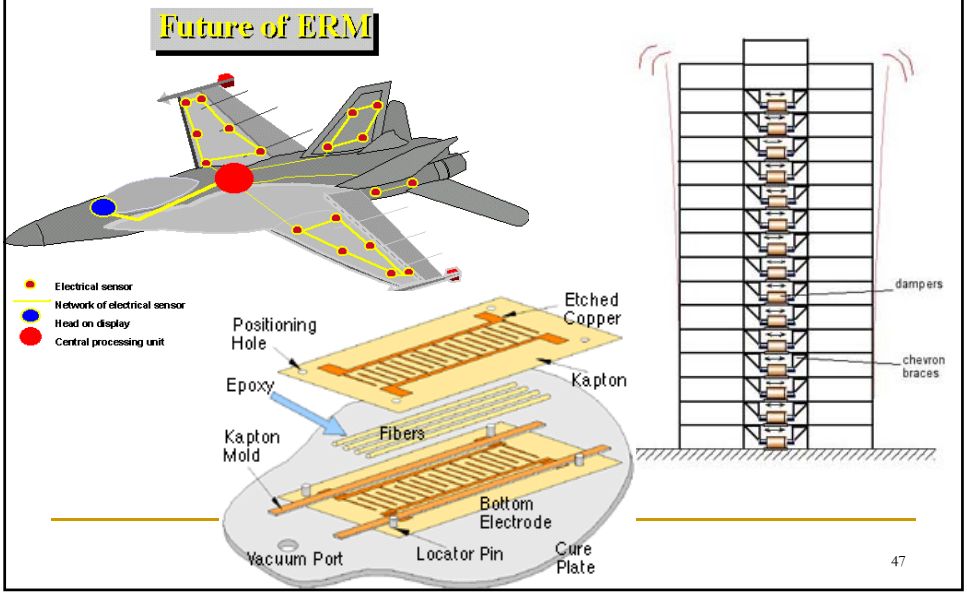
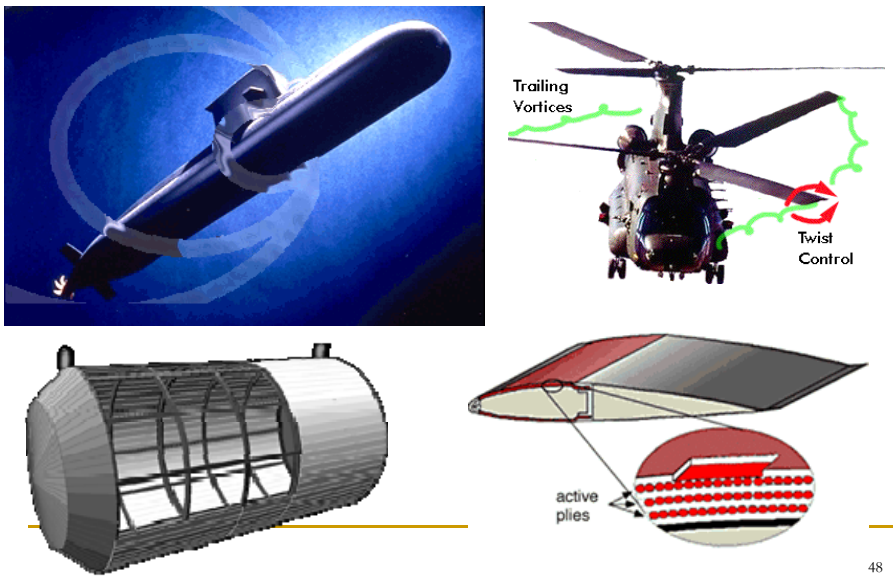
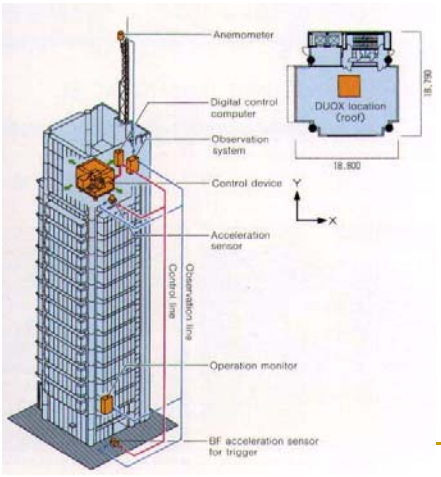
智慧結構 (Intelligent Structure)



結構控制 (Structural Control)



Tall Building



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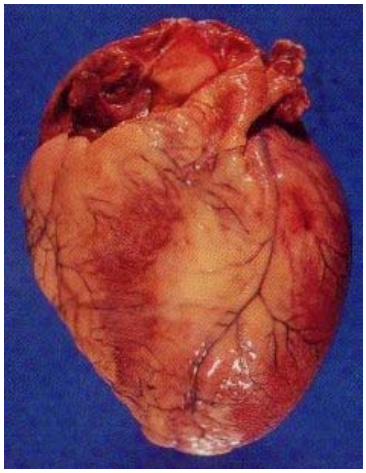
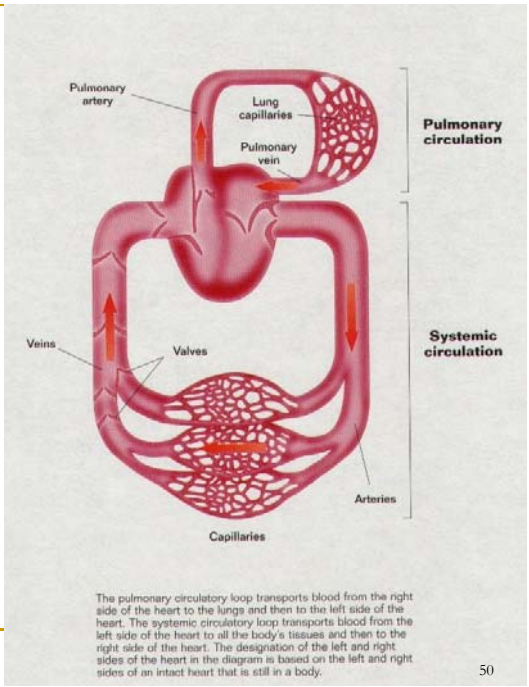
Biomechanics Example





50

Biomechanics Example

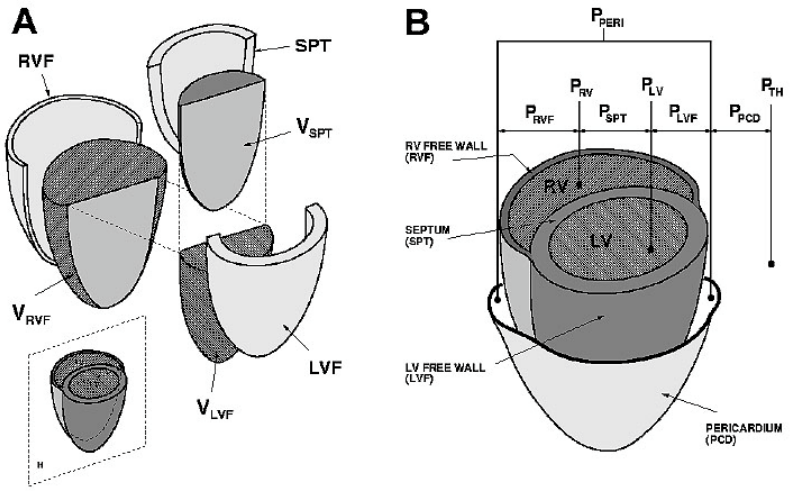


FIG. 1. Components of ventricular model: (A) volume distribution within the ventricles; (B) Force balance for coupled ventricles within pericardium. *Source*: Chung *et al.* (6).

51

Biomechanics Example

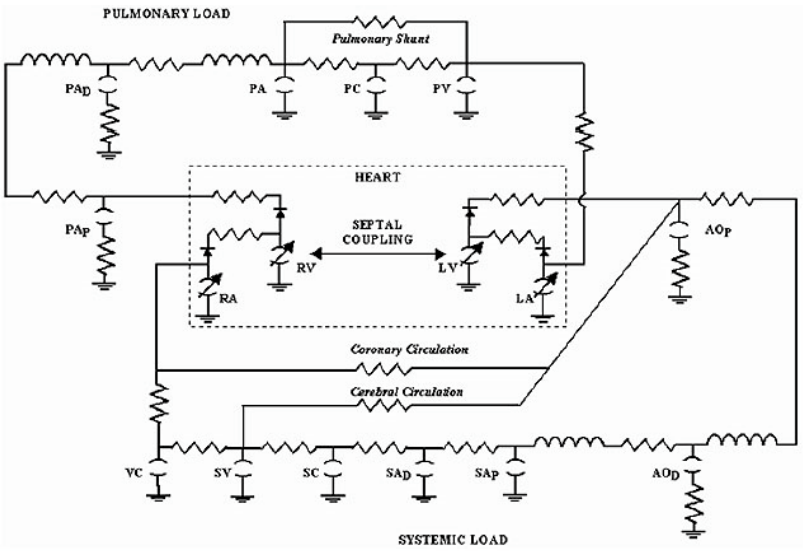


FIG. 3. Hydraulic equivalent schematic representation of the closed-loop circulatory model. Model parameters are listed in Table 1 and Appendix B.

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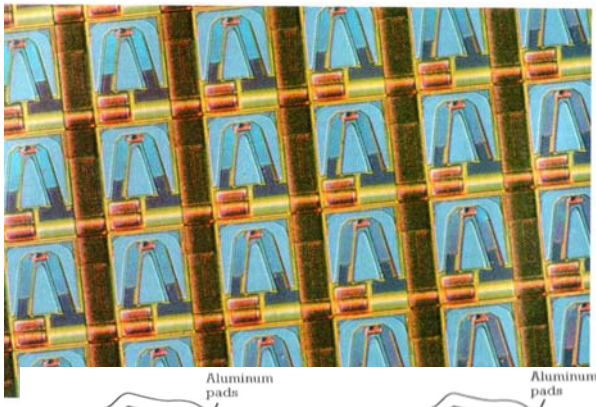
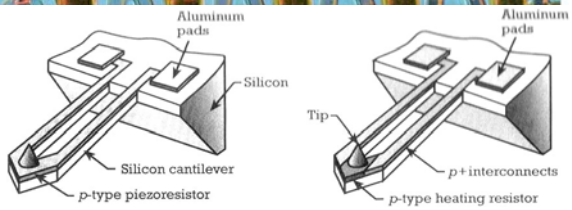
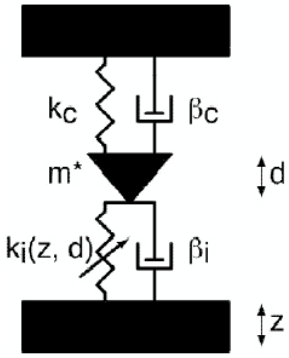
AFM/SPM Example





Piezoresistive (reading) cantilever Heater (writing) cantilever



53

Part IV: A Quick Scan on Mechanical Vibration

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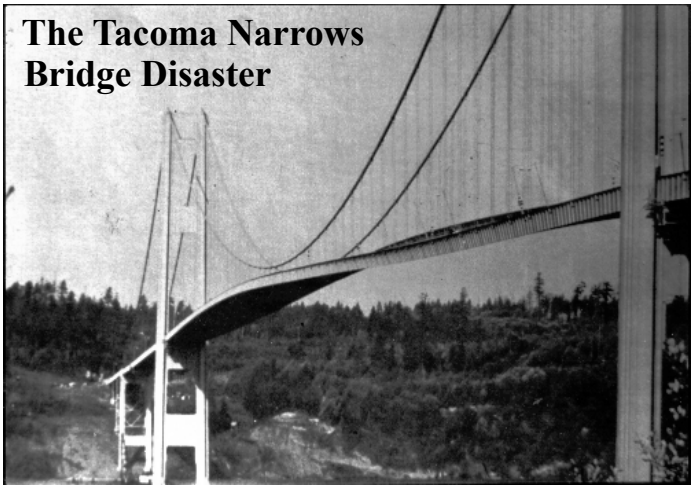
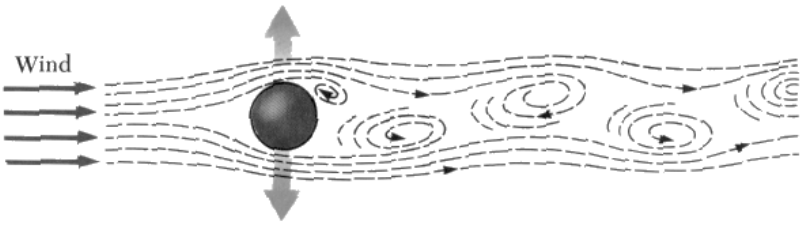
Example: Flow induced vibration



November 7, 1940

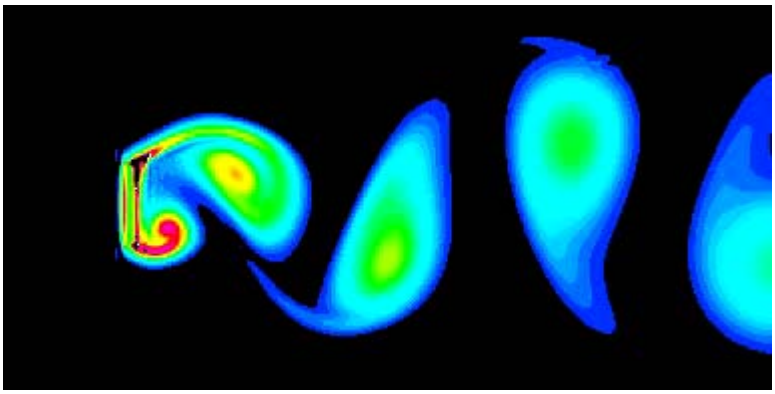
Vortex Shedding



…Caused Wind-Induced Vibration

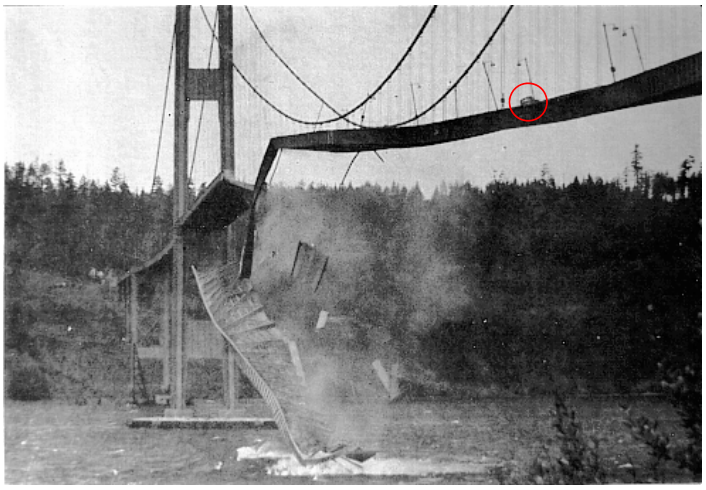
56

Vortex Shedding



57

Tacoma Narrows Bridge



~~11:02 A.M.~~ 600-ft span breaks away…

58

Part IV. A First Look on Vibration Analysis

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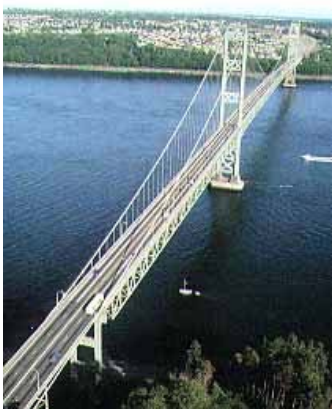
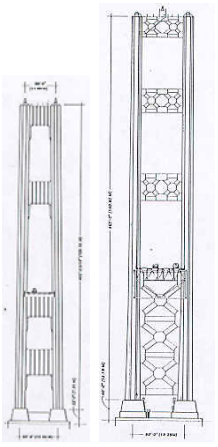
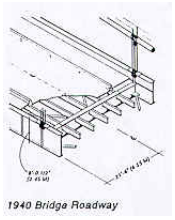
Today's Tacoma Narrows Bridge

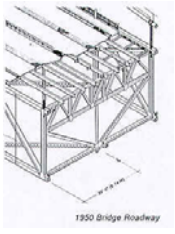




Old New



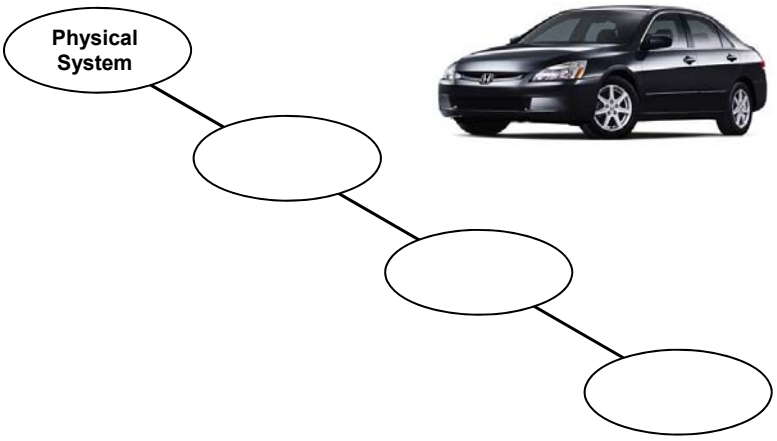
Old



New

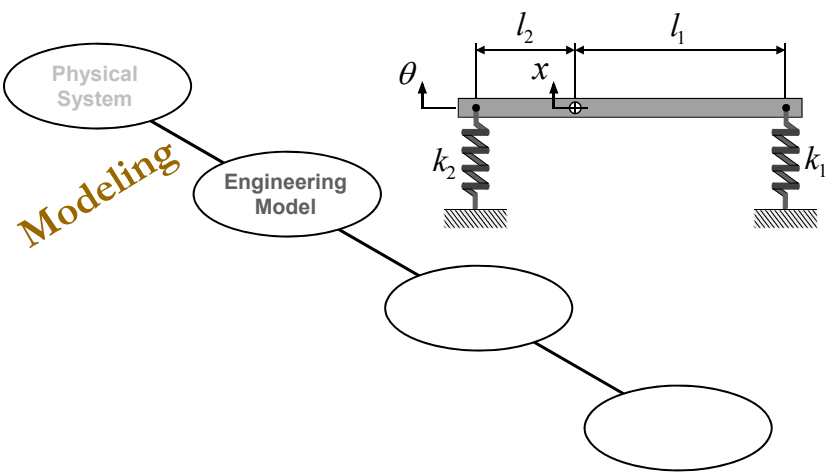
60

Analyzing Vibration



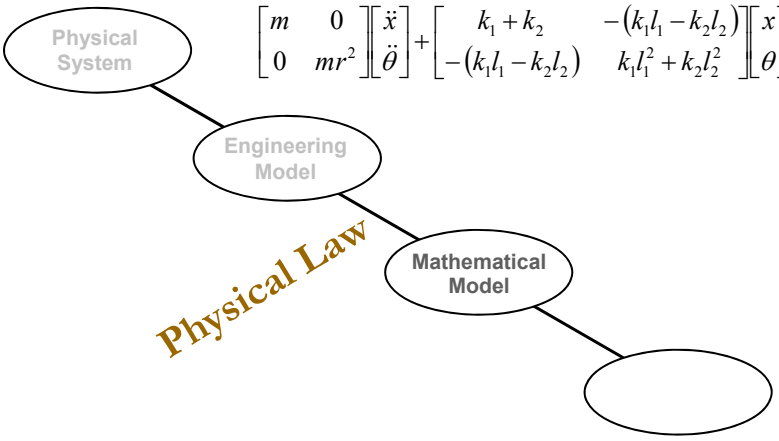
61

Analyzing Vibration



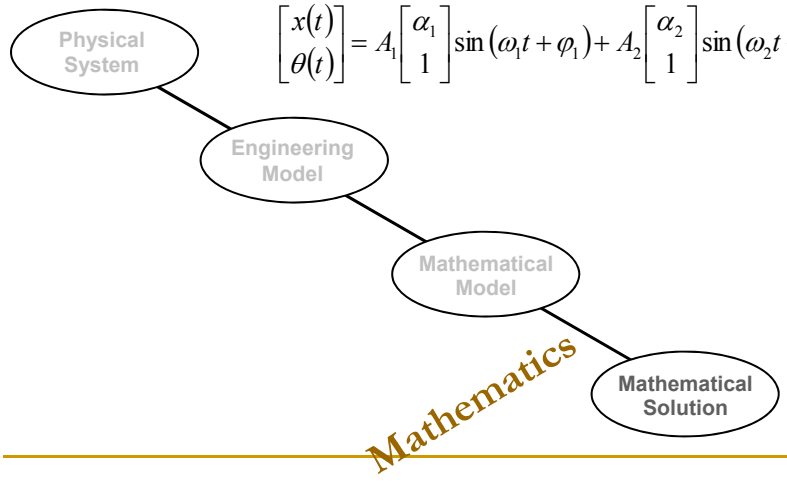
62

Analyzing Vibration



63

Analyzing Vibration



64

Modeling Vibration

The Ingredients:

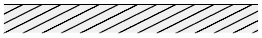
65

Modeling Vibration

The Ingredients:

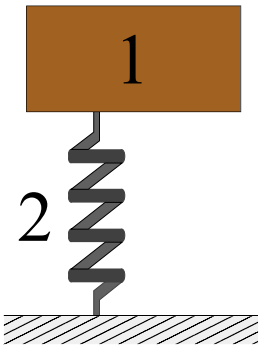
1

1. Inertia (stores kinetic energy)



66

Modeling Vibration

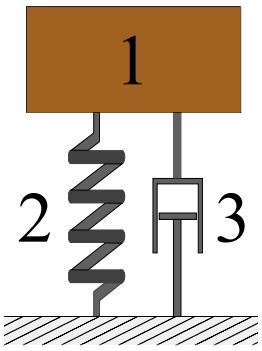


The Ingredients:

1. Inertia (stores kinetic energy)
2. Elasticity (stores potential energy)

67

Modeling Vibration



The Ingredients:

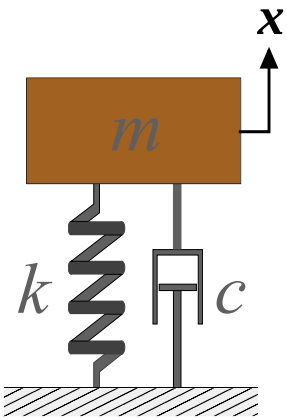
1. Inertia (stores kinetic energy)
2. Elasticity (stores potential energy)

Realistic Addition:

3. Energy Dissipation

68

Modeling Vibration



The Ingredients:

1. Mass, m
2. Stiffness, k

Realistic Addition:

3. Damping, c

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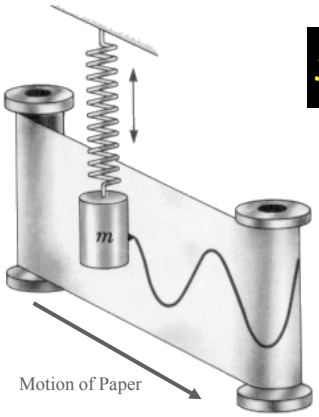
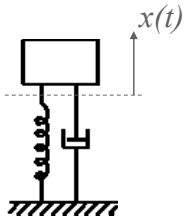
Simple Harmonic Motion

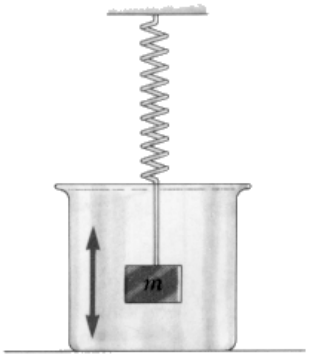


$$x(t) = A\sin(\omega_n t + \phi)$$



70

Simple Harmonic Motion with Damping

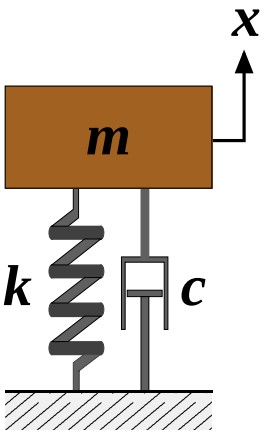


- Energy is converted to heat, sound, etc.

$$x(t) = Ae^{-\frac{t}{\tau}} \sin(\omega_n t + \phi)$$

71

How is this model useful?



Can be used to model a:

- Motor vehicle
- Water tower
- Floating object

…and lots more!

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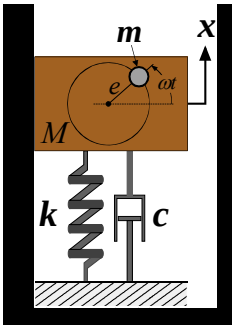
Forced Vibration

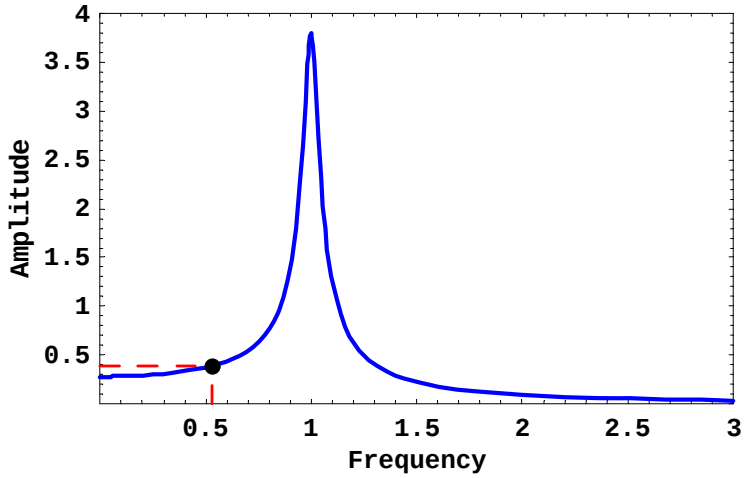


Steady-state Response:

$$x(t) = \frac{me\omega^2}{\sqrt{\left(k - M\omega^2\right)^2 + (c\omega)^2}} \sin(\omega t - \phi)$$

73

Forced Vibration



Low Frequency ⇒ Small Amplitude

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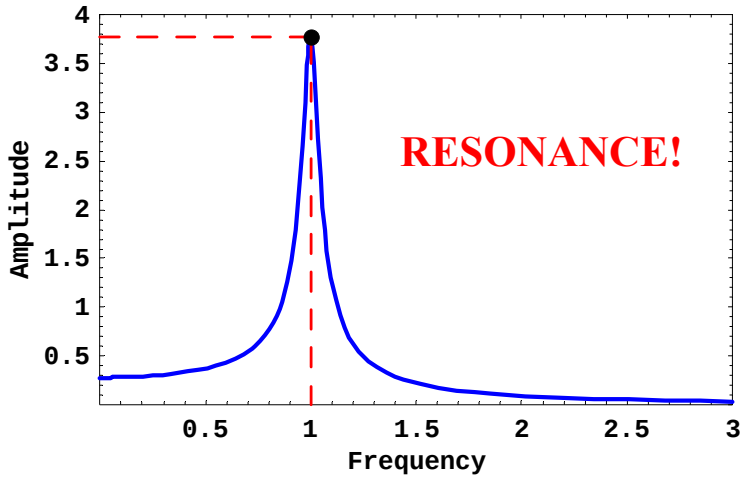
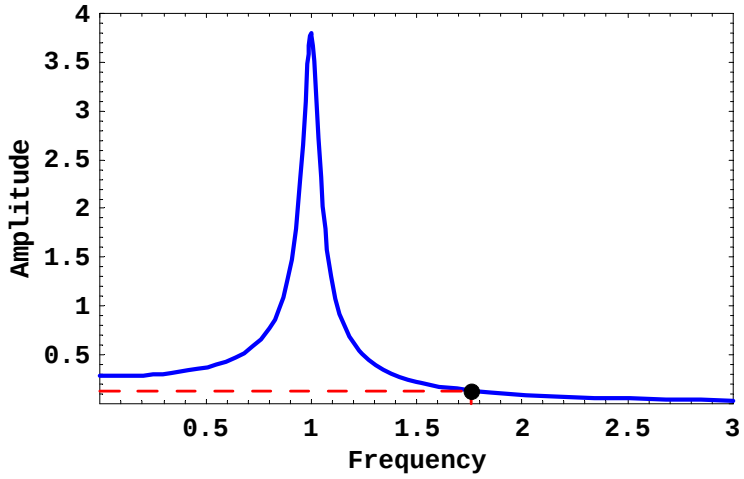
Forced Vibration



Resonant Frequency ⇒ **Large Amplitude**

75

Forced Vibration



Large Frequency ⇒ Small Amplitude

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Mode Shapes

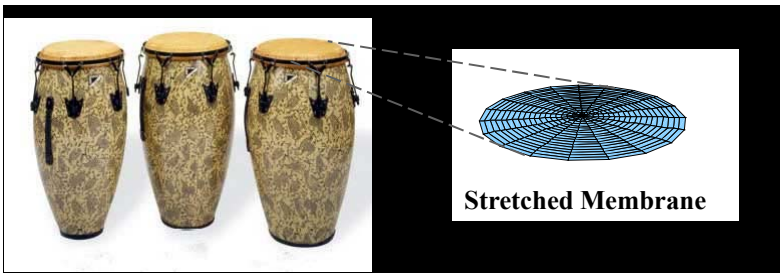
"Characteristic Geometry" of Vibration

77

Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 1:



Bongo Drums

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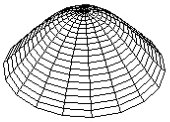
Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 1:

Bongo Drums



Mode 1

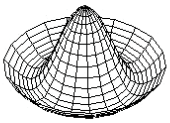
79

Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 1:

Bongo Drums



Mode 2

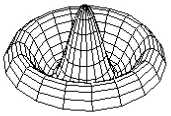
80

Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 1:

Bongo Drums



Mode 3

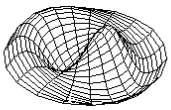
81

Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 1:

Bongo Drums



More complex modes…

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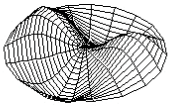
Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 1:



Bongo Drums **More complex modes…**

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Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 2:

Acoustic Guitar

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Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 2:

Acoustic Guitar **Mode 1**

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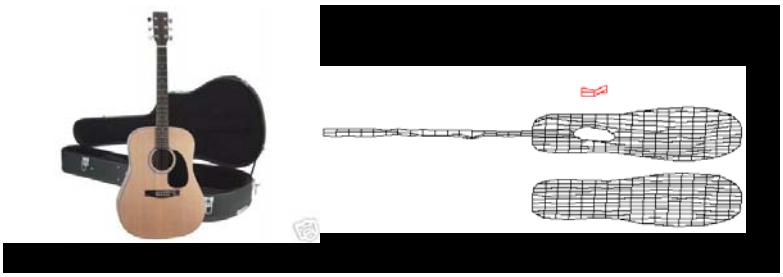
Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 2:



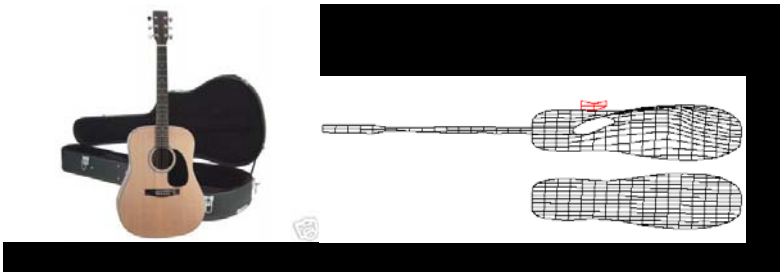
Acoustic Guitar **Mode 2**

86

Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 2:



Acoustic Guitar **Mode 3**

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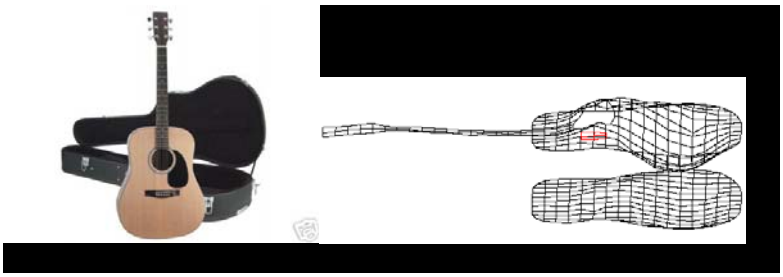
Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 2:



Acoustic Guitar **More complex modes…**

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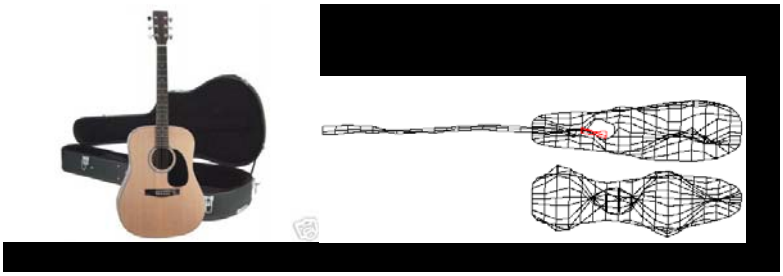
Mode Shapes

"Characteristic Geometry" of Vibration

EXAMPLE 2:



Acoustic Guitar **More complex modes…**

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Part V: Vibration Testing and Control

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Modal Testing and Analysis

- Natural frequencies
- Mode shapes
- And their related applications
  - Material properties
  - NDT

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振動學實驗儀器簡介

加速規

衝擊錘

92

振動學實驗儀器簡介

- 激振器 (shaker)

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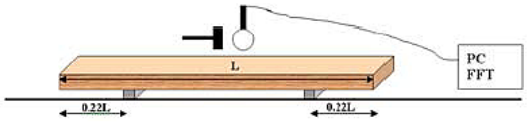
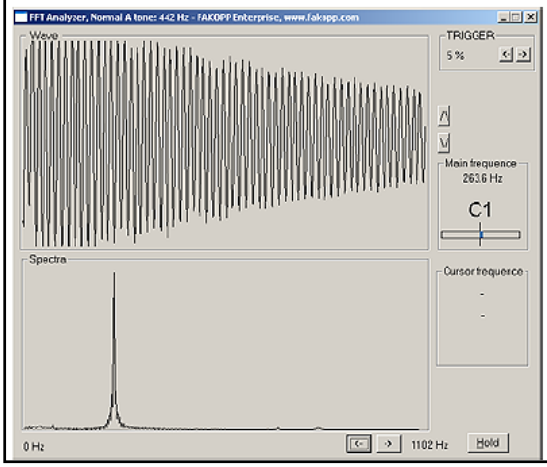
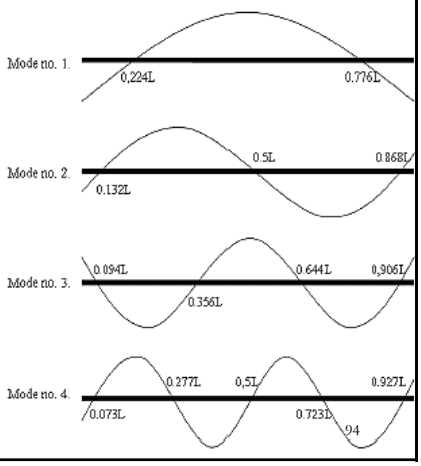
Dynamic MOE determination by bending vibration



$$MOE_{dyn,bending} = \left(\frac{f_n}{C_n}\right)^2 \frac{mL^3}{I}$$





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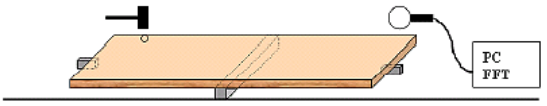
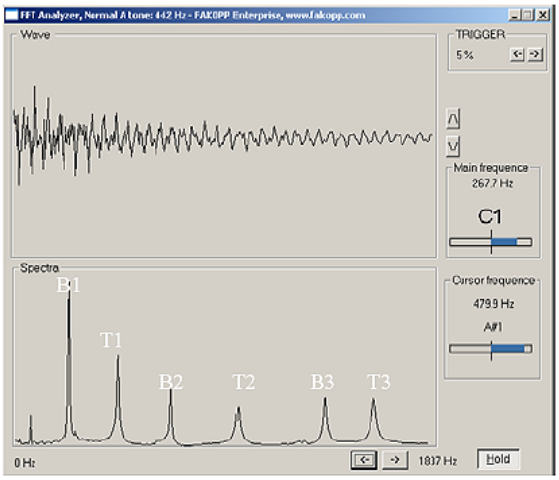
Determination of shear modulus by torsion vibration



$$G_{dyn,torsion} = \left(\frac{2Lf_n}{n}\right)^2 \frac{\rho I_p}{K_t}$$



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Laboratory demonstration of active vibration isolation

isvr

University of Southampton

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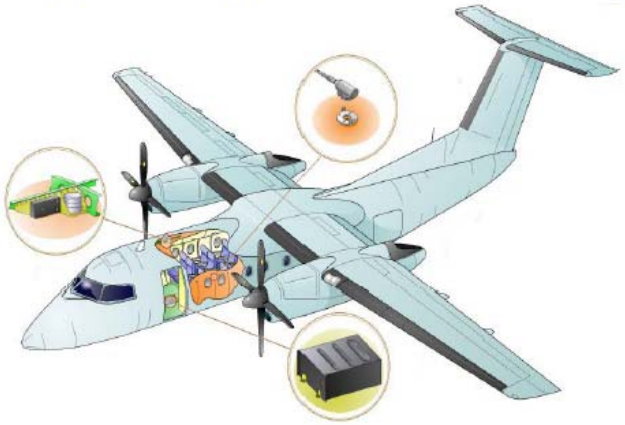
Control System for Propeller Aircraft Active Noise System



Centralised digital system made by Ultra Electronics controls 5 harmonics with 48 structural actuators at 72 acoustic sensors, distributed throughout cabin.