UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

STRUCTURAL HEALTH MONITORING & MANAGEMENT

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Definition of *SHM*

Structural Health Monitoring (SHM) is the process of implementing a <u>damage detection strategy</u> for engineering infrastructure.

Usage monitoring (UM) Measure inputs to and responses of a structure before damage so the onset of damage and deterioration can be identified.

Prognosis is the coupling of information from SHM, UM, environmental and operational conditions, component and system level testing, and modeling to estimate condition and useful life.

Doebling, S W, C R Farrar, et al (1996) Damage Identification and Health Monitoring of Structural and Mechanical Systems From Changes in Their Vibration Characteristics: A Literature Review, LA-13070-MS Los Alamos National Laboratory http://www.lanlgov/projects/ei/shm/publicationsshtml

Definition of *damage*

Damage is defined as changes introduced into a system that adversely affects its current or future performance.

- Damage is not meaningful without a comparison between two system states, one is often an initial or undamaged state.
- System changes include material and/or geometric property changes, changes in boundary conditions, and changes in system connectivity.

Sohn, H., C. R. Farrar, et al. (2004). A Review of Structural Health Monitoring Literature form 1996-2001,. LA-13976-MS. Los Alamos National Laboratory. http://www.lanl.gov/projects/ei/shm/publications.shtml.

SHM analogy with HHM

Classical (*occasional and in situ*) control methods

Visual methods
Direct visual inspection; Long-term video monitoring

Magnetic methods
Magnetic flux leakage (MFL)

Mechanical wave/vibration methods
Acoustic sounding; acoustic emission; impact –echo (IE); Impulse response; ultrasonic imaging; ultrasonic guided wave (GWT); global vibration response

Electromagnetic wave methods
Infrared thermography (IR); Impulse Radar (GPR)

Electrochemical methods
Half-cell potential; Linear polarization resistance (LPR); Electro-impedance sprectroscopy (EIS); Electrochemical noise

Penetrating radiation methods
Radiography; X-ray diffraction

Other methods
Direct pre-stress measurement

Example of classical control methods – ultrasonic systems

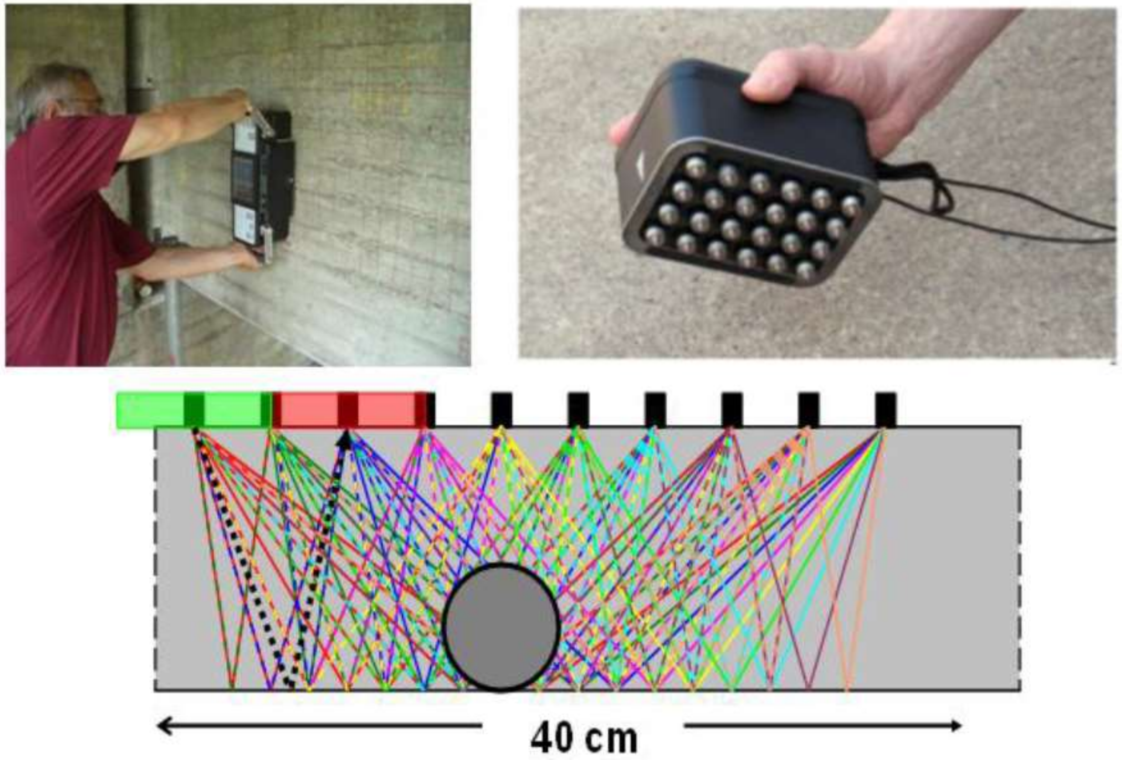


Figure 3.4: Illustration of ultrasonic s-wave array equipment (top) and data collection scheme (bottom)

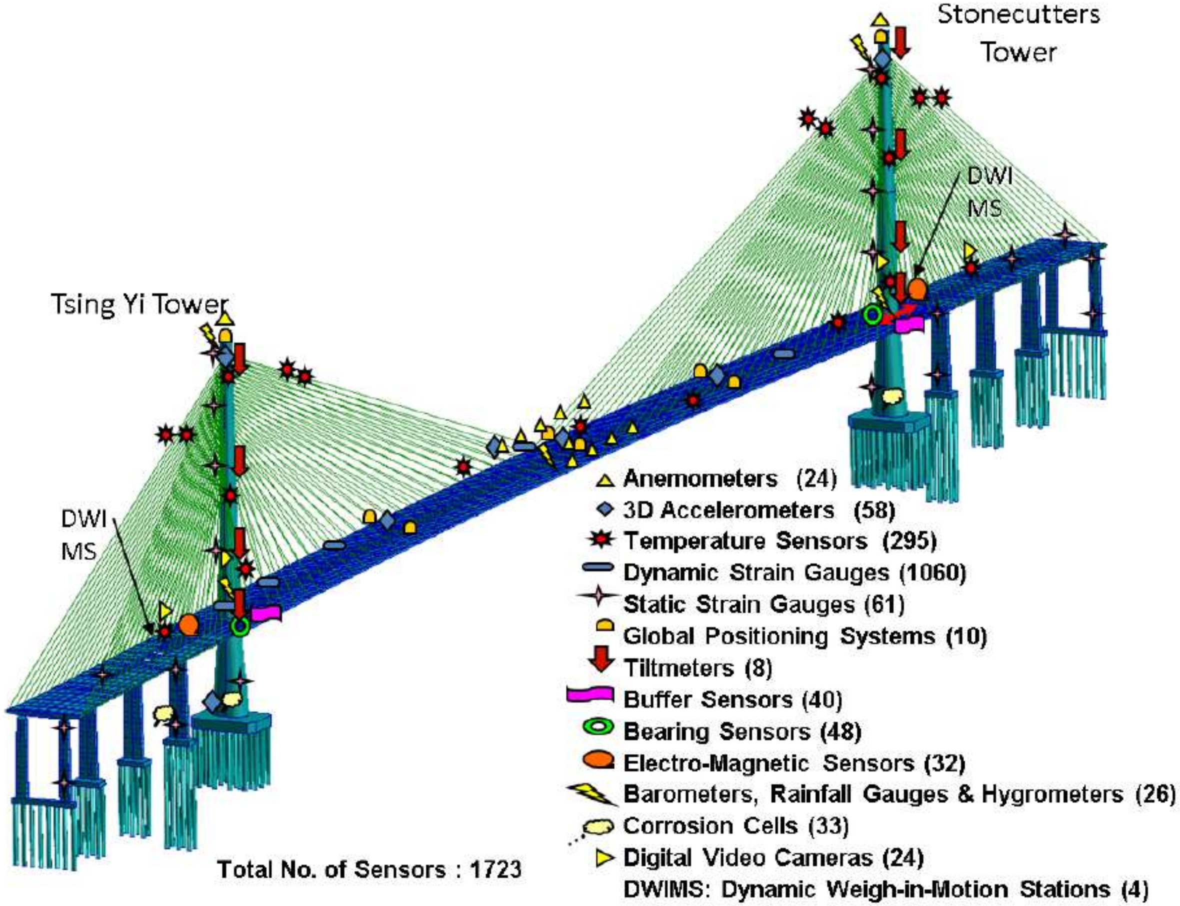
Modern (*continuous and remote*) structural monitoring

- The measurements can be used to refine the numerical/mathematical model of the structure to the actual conditions, allowing us to analyse its static and dynamic behaviours

- Any structural modification involves a variation in the static and dynamic responses. Such variations are analysed by specific algorithms for the identification of possible damages or related degradations

- The process is *continuous* and allows us to monitor the structure, to highlight potentially critical conditions, to suggest maintenance interventions

Example: structural monitoring of a bridge (Hong Kong)



Components of a SHM Process

1. Operational Evaluation

2. Data Acquisition, Fusion, and Cleansing

3. Feature Extraction and Information Condensation

4. Statistical-Model Development for Feature Discrimination

1. Operational Evaluation

Topics to address:

- Economic and/or Life-Safety Issues
- Definition of Damage
- Environmental and/or Operational Constraints
- Data Management

2. Data Acquisition, Fusion, and Cleansing

Sensing and collection issues:

- Excitation Methods
  - Forced Excitation
  - Ambient Excitation
  - Local Excitation
- Data Transmission
  - Wired Transmission
  - Wireless Transmission
- Sensing Structural Response
  - Strain
  - Displacement
  - Acceleration
  - Temperature
  - Wind
  - Other Measurement Quantities
  - MEMS Technology for Sensing Motion
  - Fiber-Optic Sensors
  - Sensor Placement
  - Other Issues

3. Feature Extraction and Information Condensation
Parameters and methods

- Resonant Frequencies
- Frequency Response Functions
- Mode Shapes (MAC and CoMAC)
- Mode Shape Curvatures
- Modal Strain Energy
- Dynamic Flexibility
- Damping
- Antiresonance
- Ritz Vectors
- ARMA Family Models
- Canonical Variate Analysis (CVA)
- Nonlinear Features
- Time-Frequency Analysis
- Empirical Mode Decomposition
- Hilbert Transform
- Principal Component Analysis or Singular Value Decomposition
- Finite Model Updating
- Wave Propagation
- Autocorrelation Functions
- Other Features

4. Statistical-Model Development for Feature Discrimination

- Supervised Learning
  - Response Surface Analysis
  - Fisher's Discriminant
  - Neural Networks
  - Genetic Algorithms
  - Support Vector Machines
- Unsupervised Learning
  - Control Chart Analysis
  - Outlier Detection
  - Neural Networks
  - Hypothesis Testing
- Other Probability Analyses

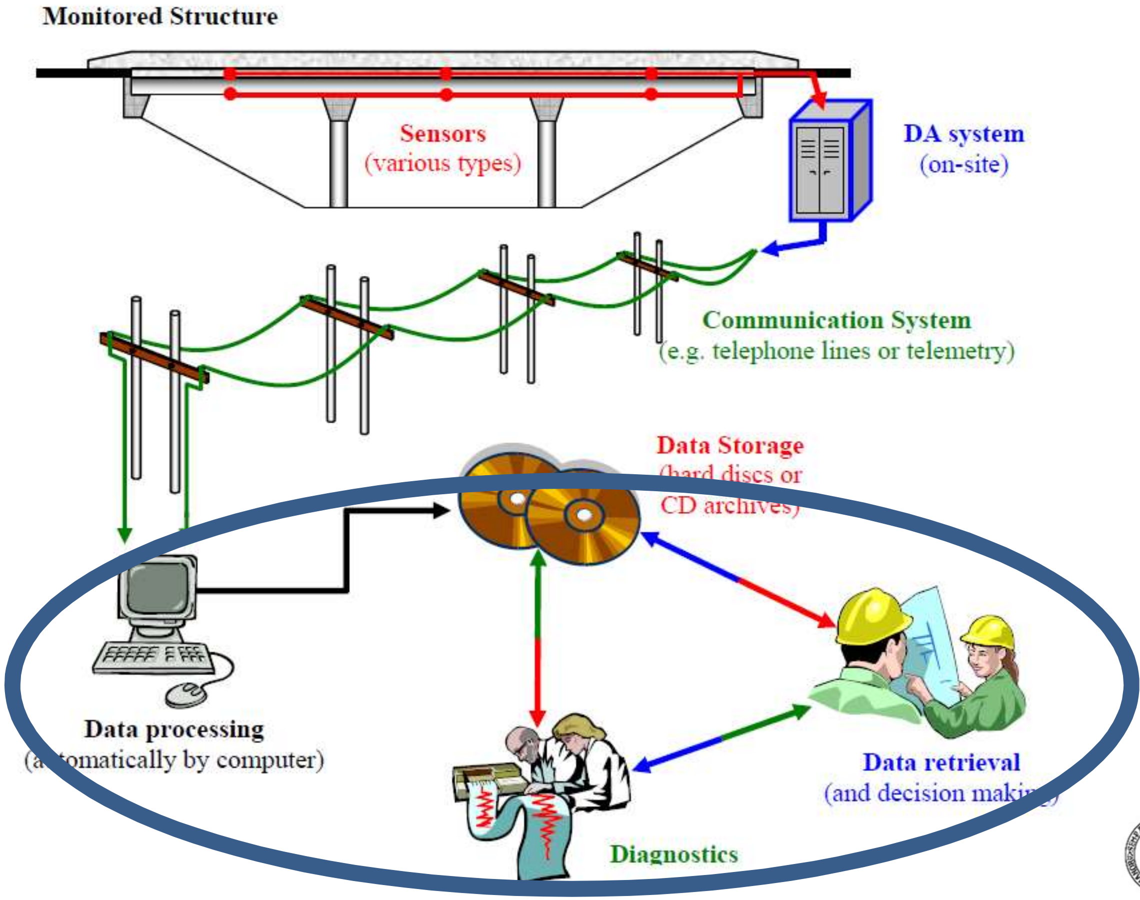
Structure monitoring: components

Sensorized structure, continuously monitored or on demand

The signals are acquired, stored, and elaborated by specific algorithm

Damage indicators highlight potential critical issues, or evolving situations that need attention

A structural (mathematical) model allows us to identify and localize the critical points, the relevant incoming issues and gives indications for the '*on condition*' maintenance



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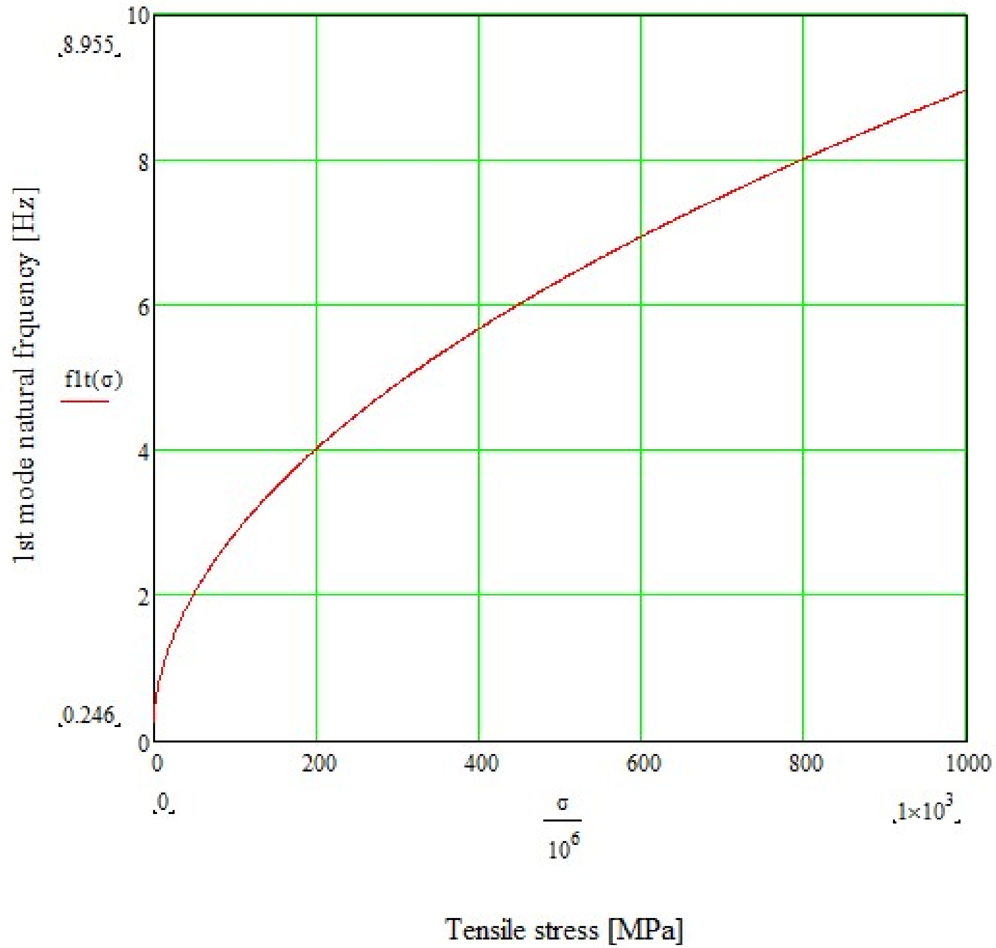
Example: Strays monitoring

The 1st mode natural frequency variation with the stray tensile stress



Representing dynamic mechanical systems

There exist various methods of constructing and representing dynamic mechanical models: transfer function form, state space form, modal form, state space modal form, etc.

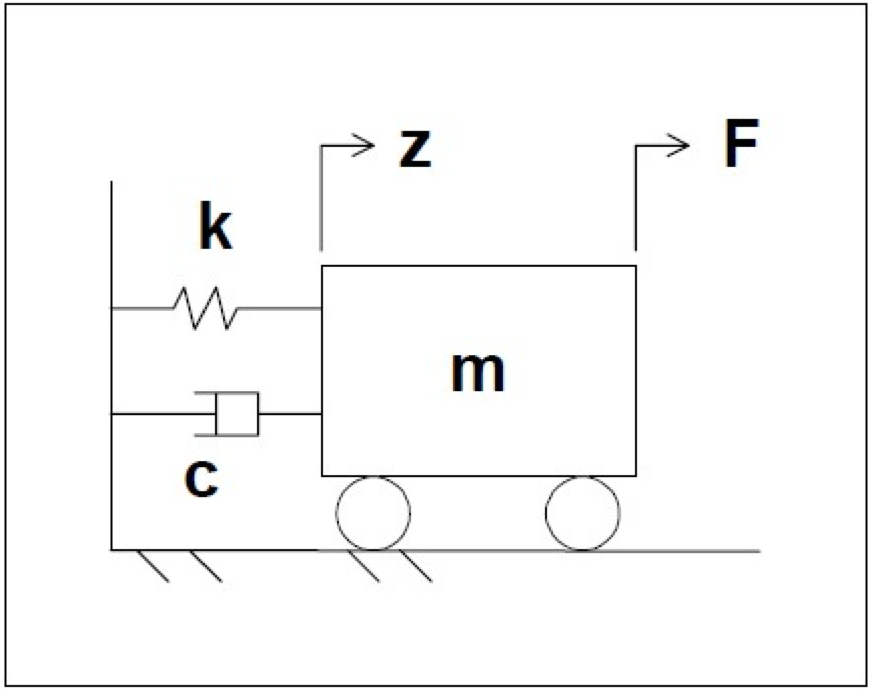
The nature of damping in the system will determine which representation will be required.

In lightly damped structures, we will be able to use "modal analysis," enabling us to restructure the problem in terms of individual modes of vibration with a particular type of damping called "proportional damping."

For systems which have significant damping, as in systems with a specific "damper" element, we will have to use the original, coupled differential equations for solution.

Illustrative example: 1dof system

The first step in analyzing a mechanical system is to sketch the system, showing the degrees of freedom, the masses, stiffnesses and damping present, and showing applied forces.



Illustrative 1dof example: equation of motion

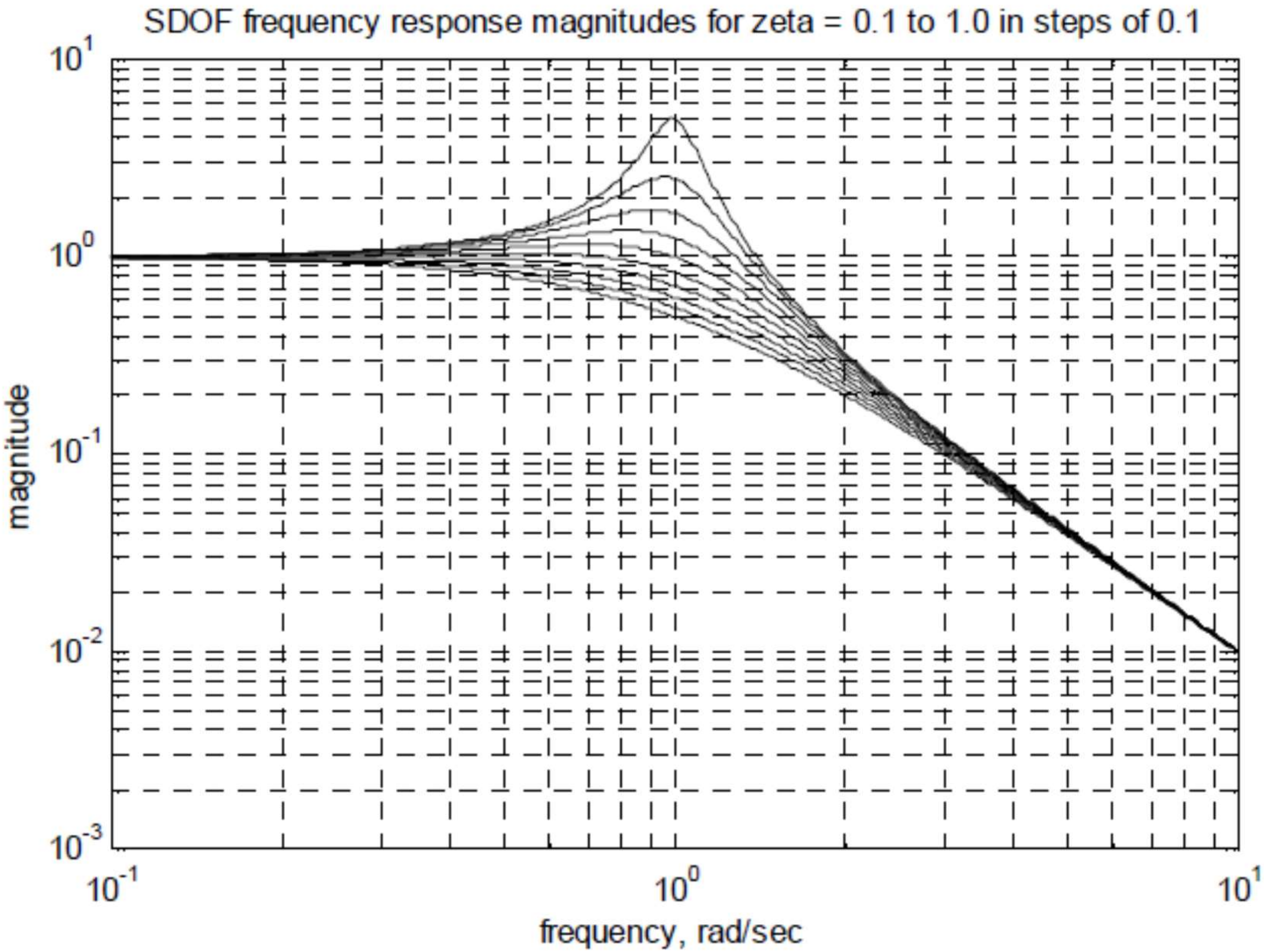
The equation of motion for our problem is given by:

$$m\ddot{z} + c\dot{z} + kz = F$$

$$\frac{z(s)}{F(s)} = \frac{1}{ms^2 + cs + k} = \frac{1/m}{s^2 + \frac{c}{m}s + \frac{k}{m}}$$

$$\frac{z(s)}{F(s)} = \frac{1/m}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Illustrative 1 dof example: frequency response



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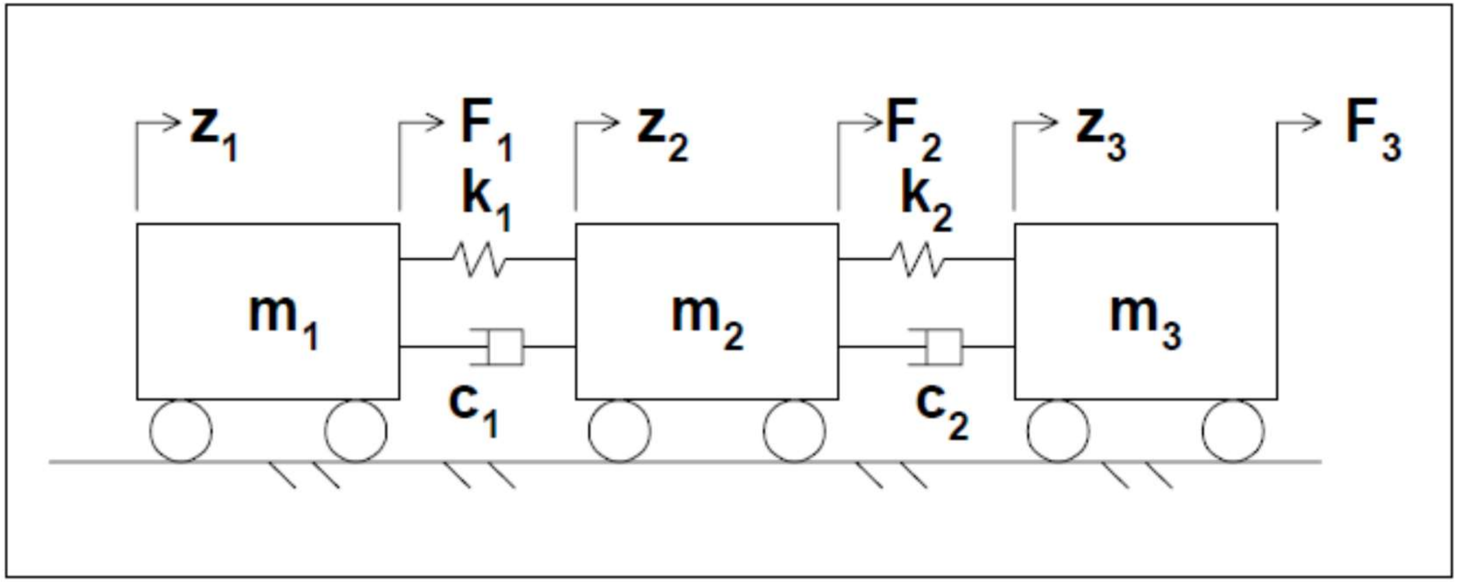
Illustrative example: 3dof system

The first step in analyzing a mechanical system is to sketch the system, showing the degrees of freedom, the masses, stiffnesses and damping present, and showing applied forces.



Illustrative example: 3dof equations of motion

The matrix equations of motion for our problem is:

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{bmatrix} \ddot{z}_1 \\ \ddot{z}_2 \\ \ddot{z}_3 \end{bmatrix} + \begin{bmatrix} c_1 & -c_1 & 0 \\ -c_1 & (c_1 + c_2) & -c_2 \\ 0 & -c_2 & c_2 \end{bmatrix} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix}$$

$$+ \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & (k_1 + k_2) & -k_2 \\ 0 & -k_2 & k_2 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix}$$

Illustrative 3dof example: transfer functions

$$\frac{z_1}{F_1} = \frac{m^2s^4 + 3mks^2 + k^2}{s^2\left(m^3s^4 + 4m^2ks^2 + 3mk^2\right)}$$

$$\frac{z_2}{F_1} = \frac{(mks^2 + k^2)}{s^2\left(m^3s^4 + 4m^2ks^2 + 3mk^2\right)}$$

$$= \frac{k(ms^2 + k)}{s^2(ms^2 + k)(m^2s^2 + 3km)}$$

$$= \frac{k}{s^2(m^2s^2 + 3km)} \quad \text{(note cancelling of pole/zero)}$$

$$\frac{z_3}{F_1} = \frac{k^2}{s^2\left(m^3s^4 + 4m^2ks^2 + 3mk^2\right)}$$

$$\frac{z_2}{F_2} = \frac{m^2s^4 + 2mks^2 + k^2}{s^2\left(m^3s^4 + 4m^2ks^2 + 3mk^2\right)}$$

Illustrative 3dof example: undamped vs damped model

z11 Undamped Zero/pole/gain:

$$\frac{(s^2 + 0.382)(s^2 + 2.618)}{s^2 (s^2 + 1)(s^2 + 3)}$$

z11 Damped Zero/pole/gain:

$$\frac{(s^2 + 0.0382s + 0.382)(s^2 + 0.2618s + 2.618)}{s^2 (s^2 + 0.1s + 1)(s^2 + 0.3s + 3)}$$

z21 Undamped Zero/pole/gain:

$$\frac{(s^2 + 1)}{s^2 (s^2 + 1)(s^2 + 3)}$$

z21 Damped Zero/pole/gain:

$$\frac{0.1 (s+10)(s^2 + 0.1s + 1)}{s^2 (s^2 + 0.1s + 1)(s^2 + 0.3s + 3)}$$

z31 Undamped Zero/pole/gain:

$$\frac{1}{s^2 (s^2 + 1)(s^2 + 3)}$$

z31 Damped Zero/pole/gain:

$$\frac{0.01 (s+10)^2}{s^2 (s^2 + 0.1s + 1)(s^2 + 0.3s + 3)}$$

z22 Undamped Zero/pole/gain:

$$\frac{(s^2 + 1)^2}{s^2 (s^2 + 1)(s^2 + 3)}$$

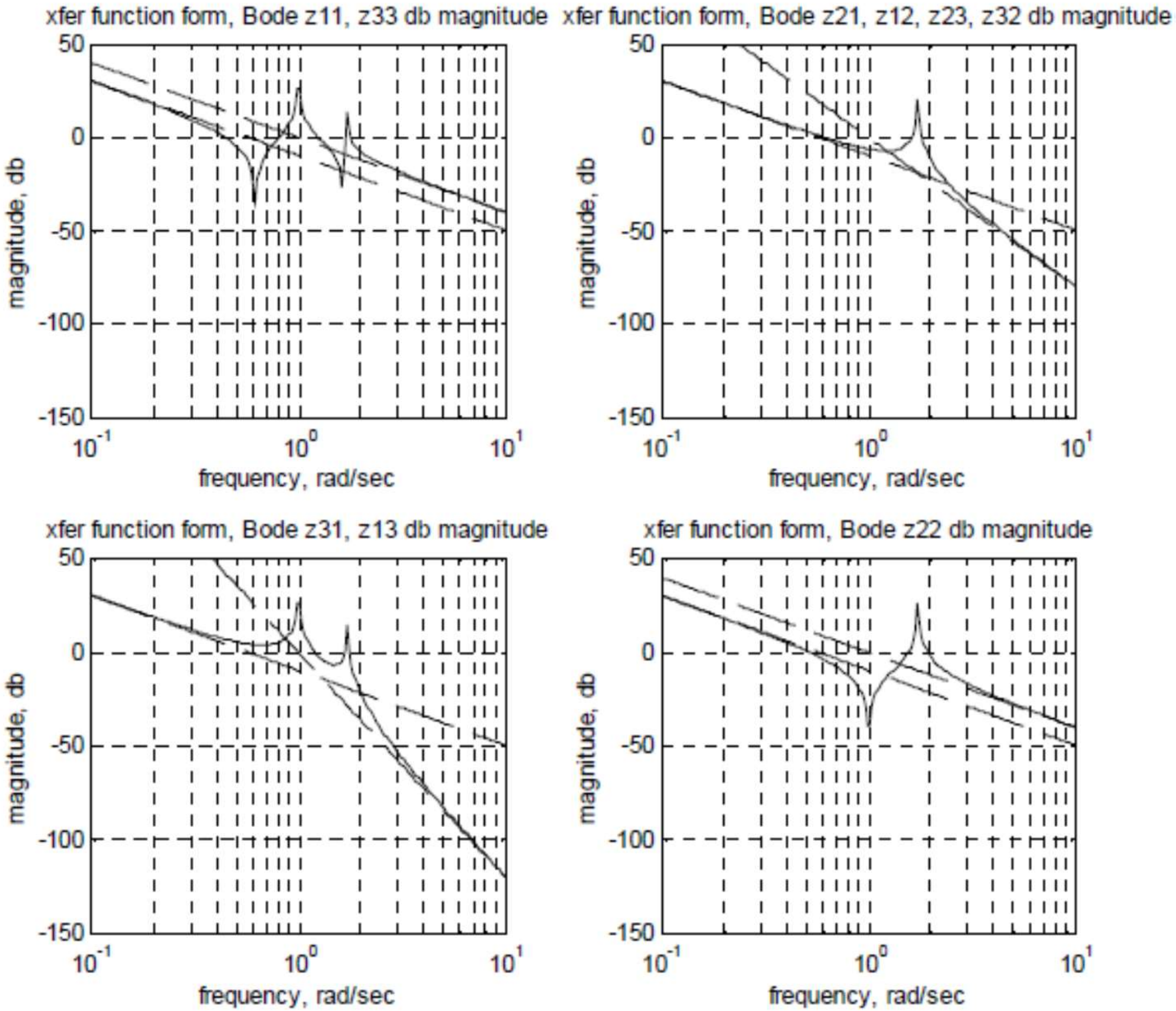
z22 Damped Zero/pole/gain:

$$\frac{(s^2 + 0.1s + 1)^2}{s^2 (s^2 + 0.1s + 1)(s^2 + 0.3s + 3)}$$

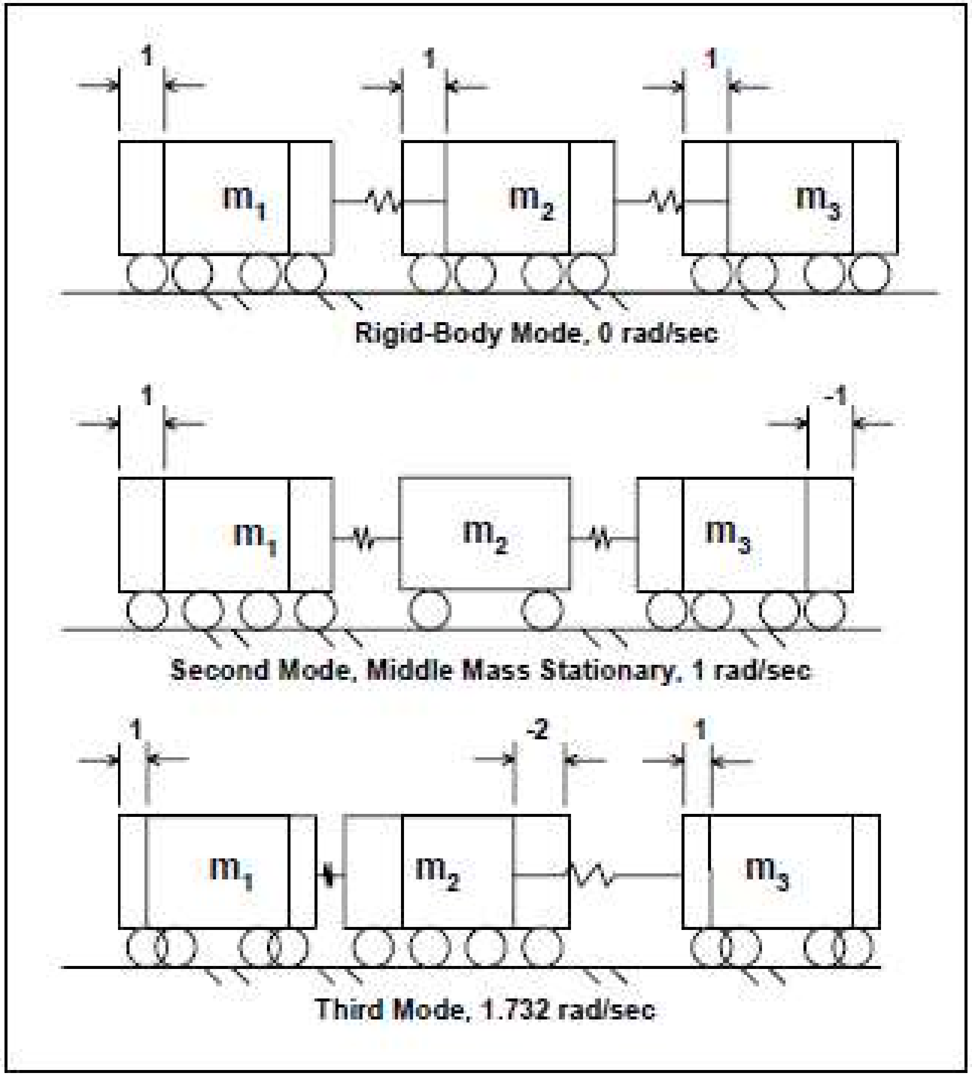
Modal analysis

- Lightly damped structures are typically analyzed with the "normal mode" method which serves one well in both performing analysis and in understanding test data.
- All "real" or "normal" modes means that at certain frequencies all points in the system will vibrate at the same frequency and in phase, i.e., all points in the system will reach their minimum and maximum displacements at the same point in time.
- They are computed by solving the undamped eigenvalue problem, which identifies the resonant frequencies and mode shapes (eigenvalues and eigenvectors).

Illustrative 3dof example: bode plots for the undamped systems



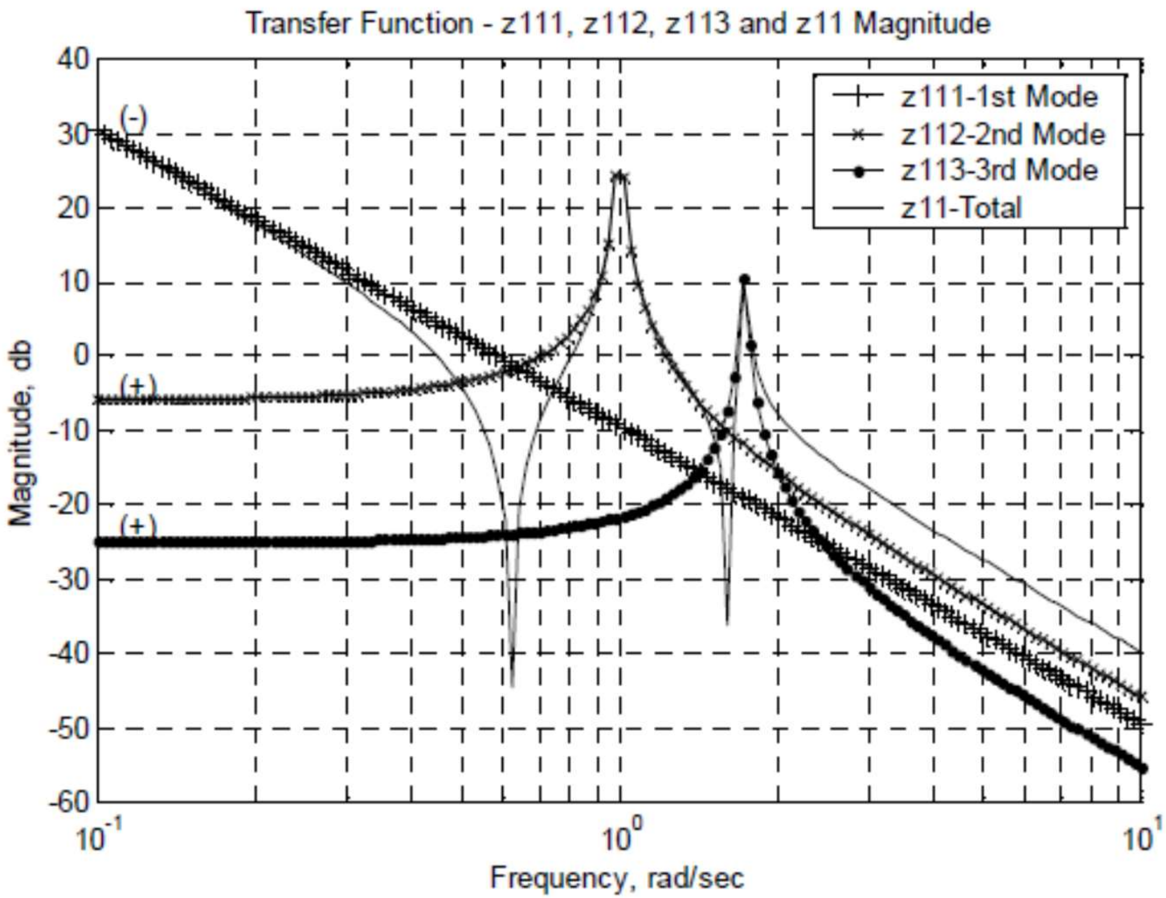
Illustrative 3dof example: mode shapes (eigenvectors)



- At each natural frequency, the eigenvector defines the relative motion between degrees of freedom.
- Since eigenvectors define the **relative** motion between degrees of freedom, we need to choose a degree of freedom against which to measure the other motions.

Illustrative 3dof example: normal modes

- **Poles** represent the resonant frequencies of the system
- **Zeros** are related to the anti-resonant frequencies of the system (modes combine with appropriate phases at some frequencies to have no motion).



Poles and zeros of the transfer function

- The poles knowledge is crucial: they represent the resonant frequencies of the system, and for each resonant frequency a mode shape can be defined to describe the motion at that frequency.
- The poles for a system depend only on the distribution of mass, stiffness, and damping throughout the system, not on where the forces are applied or where displacements are measured.

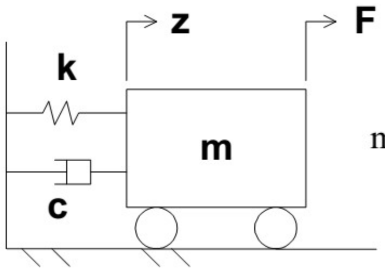
- We have seen from our frequency response analysis that at the frequencies of the zeros, motions approach or go to zero, depending on the amount of damping present.
- All the individual modes of vibration can combine at specific frequencies to create zeros of the overall transfer function.

The problem of damping

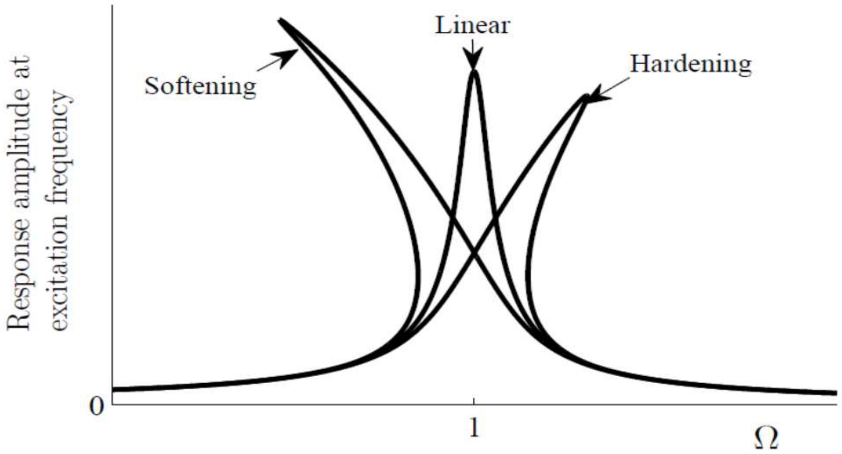
- Damping in complex built-up mechanical systems is impossible to predict with the present state of the art.
- The presence of damping usually implies the presence of “complex modes”, in which all points in the system do not reach their minimum and maximum displacements at the same point in time.
- In order to have “normal modes” in a damped system, a sufficient condition for the existence of damped normal modes is that the damping matrix be a linear combination of the mass and stiffness matrices.

System identification

The dynamical system



$$m\ddot{z} + c\dot{z} + kz = F$$



The problem is to identify the parameters of a mathematical model (*m*,*c*,*k*) which represents well the physical system using the input and output signals of the system.

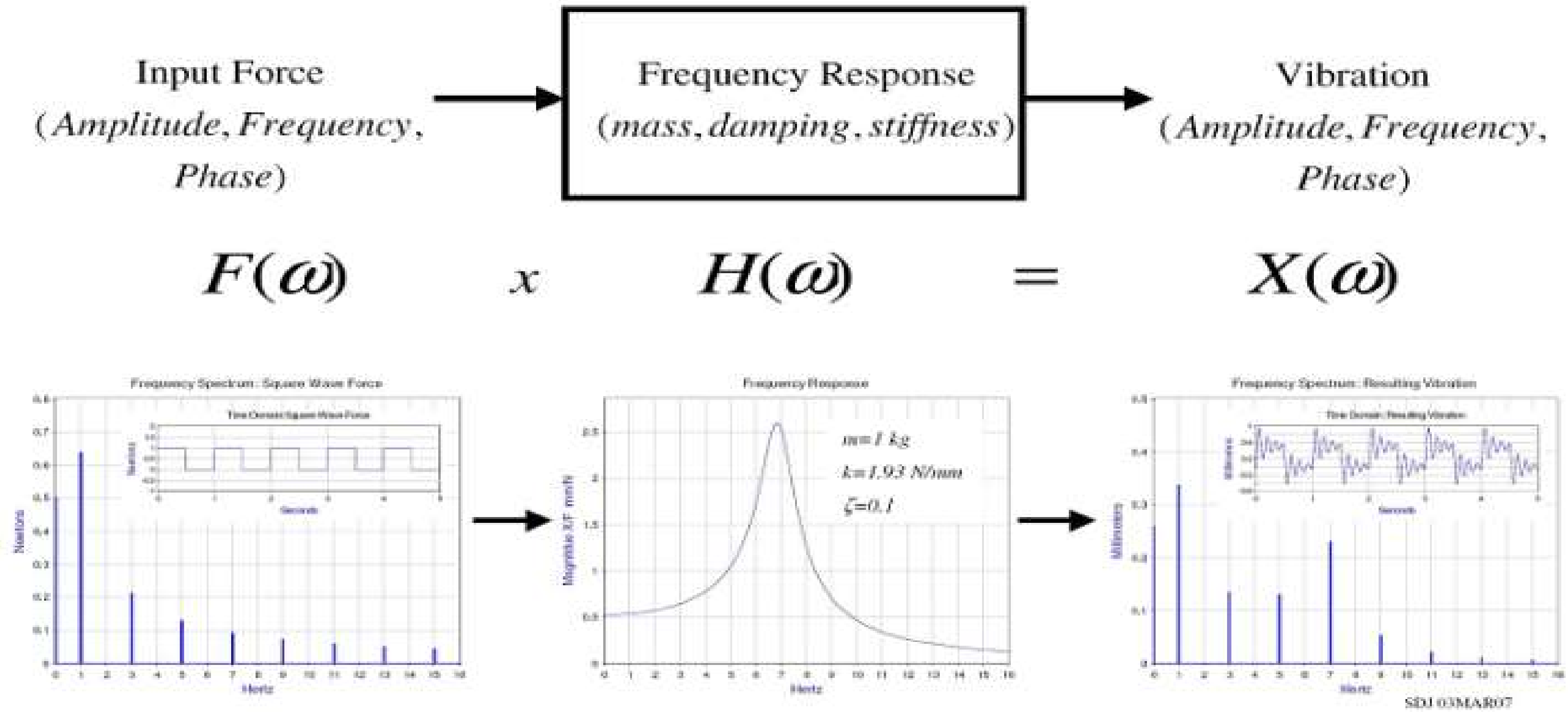
$$\frac{z(j\omega)}{F(j\omega)} = \frac{1/(m\omega^2)}{\left[\left(\frac{\omega_n}{\omega}\right)^2 - 1\right] + j2\zeta\left(\frac{\omega_n}{\omega}\right)}$$

In general, each mechanical system is nonlinear, but within certain limits it is possible to consider it as a linear system.

System identification

The dynamical system

For the analysis of the measured signals, an identification algorithm can be employed to estimate the parameters of the system based on a dynamical modeling



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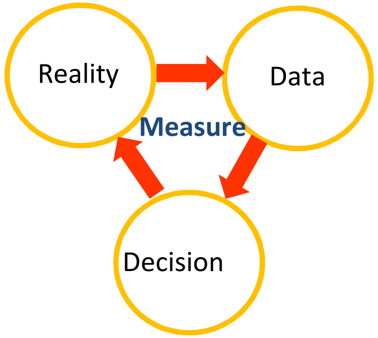
SHM State of the art

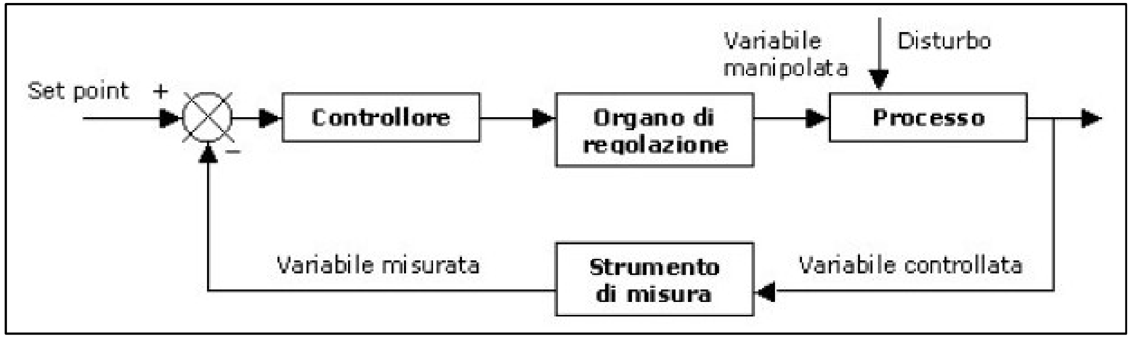
- Many techniques exist for the identification and location of damage. No method solves all problems in all structures.
- Techniques have damage related sensitivities. A sensitive technique may produce false-positives. A less sensitive technique may give false-negatives.
- Defect size has a noise floor.
- Researchers are exploring multiple detection strategies.
- Exploration of non-linear parameters is increasing.

Final comments

- The quantification of damage and prediction of the remaining lifetime are the most difficult issues, particularly the latter.
- Most traditional detection methods are based on appreciable reductions in rigidity of a structural element
- Must relate reduction in rigidity to a decrease in strength or life. Prognosis must still deal with this.
- Statistical methods have seen considerable development in dealing with experimental errors, incompleteness, and environmental and operational conditions.
- Statistical pattern recognition techniques that allow for a reduction in sensors still requires considerable further work.

The problem of control: data management automation





Measurements

- Precision
- Accuracy
- Resolution
- Sensibility

Database building

Decision chain traceability

More reliable decisions

Control

- Instability
- Saturation
- Non Linearity
- Adaptation

Conflicting and hasty decisions - Chaos

Decisions influenced by the past

Decisions without considering drift phenomena

Conclusions

- The continuous structural monitoring offers a wide range of possibilities for monitoring the structure health during its operation
- Through a suitable selected sensors network and dedicated algorithms it is possible to highlight the critical points in the structure. When supported by numerical models the monitoring allows us to perform a detailed diagnosis
- Moreover, the information obtained by the monitoring allows us to perform inspections and maintenance ***on condition***, i.e. when actually needed, thus reducing the exercise costs without changing the safety conditions

Thank you for your attention!!