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Module 2

Lecture 5 : Vibration-based SHM scheme.

Civil Engg structures – with the recent advancement of sensors actuators and computational capabilities have become smart structures

- Intelligent enough to undergo a self-diagnosis so as to develop early warnings in case of any critical health state.

SHM methods – should address certain basic themes/purposes

✓ - To deal with reliable, functional components to avoid malfunction of the scheme and thus ensure public safety

- SHM methods should be effective and efficient such that functional losses to the structural system can be avoided

- structural system, if not functioning properly will face a down-time for repair
  - can lead to economic loss

- SHM method should enable to revisit the design principles towards light-weight structure
  - maintenance & assessment are more effective in light weight structures.

Considering the factors such as

- causes for the damage
- material and functional degradation
- load paths shifting etc

a damaged structure can be expressed in terms of

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general, non-linear, time-varying, spatially discrete and a coupled system as below:

$$M(\theta_d, \theta_e, x, t)\ddot{x} + g(x, \dot{x}, \theta_d, \theta_e, t) = f_{op}(t) + f_{exp}(t) \quad \text{——} (1)$$

where $[M]$ is the mass matrix

g is the force vector, which is a function of Elastic damping forces depends on vel, displacement & time.

θ_d damage parameter (for example, crack length, loss of stiffness, loss of mass etc)

θ_e indicates influence of environmental forces and operation conditions on the structure's health

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for example, temperature, humidity, change of mass distribution etc.

f_{op} - operational load

f_{ext} - experimental loads (scaled magnitude of operational loads)

- Damage function (θ_d) is non-linear and can be expressed as below:

$$\theta_d = \Gamma(\theta_d, \theta_e, x, \dot{x}, t) \quad \text{———} \quad (2)$$

while doing such analysis,
evaluation of damage (damage identification)
and dynamic response of the system under damaged
condition takes place in 2 different time scale

one may be slowly time-varying
other may be rapidly varying with time

$\therefore$ It is necessary that Θ_d shall account for such variations carefully

- Damage identification in Linear System

Dynamic response of 'n' dof system can be expressed as:

$$M\ddot{x} + c\dot{x} + kx = f(t) \qquad \text{———} \quad (3)$$

If the system is undamped (or practically, lightly damped), then the characteristic features of the structural system (like ω_n, ϕ_n) can be determined using classical Eigensolver Theory

$$(K - \omega_n^2 M)\,\phi_n = 0. \qquad \text{——— (4)}$$

Alternatively,

correction parameters to represent modal changes is the element level of the structural system

This can be expressed as below:

$$\left.\begin{aligned} \Delta k &= \sum_j k_j \, \Delta a_j \\ \Delta c &= \sum_j c_j \, \Delta a_j \\ \Delta m &= \sum_j M_j \, \Delta a_j \end{aligned}\right| \qquad \text{——— (5)}$$

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Where general damage parameter (θ_d) is now replaced with linear matrix correction Δa. (correction parameter)

The correction parameter, which localizes and Quantifies the damage, can be determined by solving the 'Inverse problem' which is

Minimizing the weighted sum of components of data Error, ϵ

Minimizing, the following function with ϵ

$$J = \epsilon^T W_\epsilon \epsilon + \Delta a \, W_a \, \Delta a \qquad (6)$$

$$\epsilon = S\Delta a - r$$

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Where S is the sensitivity matrix, which can be computed from the first order partial derivatives of dynamic Quantities with respect to correction parameter, a.

W_ϵ, W_a. weighted matrices

Vector v represents change of measurement data

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Damage detection by frequency-based method

FBDD - Frequency-based damage detection

A single damage index, for j^{th} member of any structural system is given by:

$$DI_j = \left[\sum_{i=1}^{NM} e_{ij}^2 \right]^{-1/2} \qquad (7)$$

where DI - damage index (indicator) @ the j^{th} element of the structure

NM - # of vibration modes considered for the analysis

e_{ij}^2 - localization error for i^{th} mode, is the j^{th} element of the structural system

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which is given by:

$$C_{ij} = \frac{Z_i}{\sum_{k=1}^{NM} Z_k} - \frac{F_{ij}}{\sum_{k=1}^{NM} F_{kj}} \quad \text{--- (8)}$$

$$Z_i = \frac{\delta\omega_i^2}{\omega_i^2} \quad \text{--- (9)}$$

Where Z_i indicates fractional change which is caused by the damage is the i^{th} Eigen value

$$\delta\omega_i^2 = \omega_i^{*2} - \omega_i^2 \quad \text{--- (10)}$$

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F_{ij} = Fraction of Modal strain energy for i^{th} mode, which is stored in the j^{th} element of the structure

F_{ij} is given by the follg expression:

$$F_{ij} = \frac{\{\phi_i\}^T [K_j] \{\phi_i\}}{[\phi_i]^T [K] \{\phi_i\}} \qquad (1)$$

where $\{\phi_i\}$ is the i^{th} mode shape vector

$[K]$ = system stiffness matrix

K_j - contribution of j^{th} element to the system stiffness matrix

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Once Z_i is determined experimentally,

F_{ij} - can be determined numerically.

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Specific advantages of using vibration-based SHM

- Basic feature of vibration-based SHM

  Changes in structural characteristics, such as mass, stiffness and damping, caused by presence of damage will affect the global vibration response of the structural system

Therefore,

By examining the changes in the measured values of structural (vibration) characteristics & then solving the inverse problem shall help to quantify the unknown changes in the original st system

Vibration-based SHM consists of 5 steps:

step # 1 : Measurement of structural dynamic response in terms of acceleration & displacement

- This is carried out by set of sensors, acquisition system & transmission of data
- Acc, vel, displ are key issues in the measurement. - They will generate a big volume of data
- Acquisition & transmission (data storage) should be carefully designed to avoid loss of data

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Step #2: characterization of initial structural model through both static & dynamic tests

- Initial characterization provides the base line for comparing the response of the structure, before and after damage
- While the vibration characteristics of the functional structure are obtained by continuous monitoring, data acquired will be compared with the base line model

Step #3

continuous monitoring and damage localization of the structure

- data acquired/stored continuously should be analyzed for its comparison with the base line model
- Any significant change in the vibration characteristics can be leading to a damage localization

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Step #4

Detailed Finite Element Analysis to update the structural model with the input from the observed damages

There is a constant update of FE Model is required to be carried out

Step #5

Evaluation of the structural performance of the updated model

– The updated model shall reveal the health status of the present structure

Summary

- details of vibration-based SHM
- vital steps involved in vibration-based monitoring, which can lead to damage localization
- necessity of high quality/reliable sensing system, acquisition/communication system with data storage & retrieval + powerful analytical tools to update FE model

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