Structure Dynamic Characteristics Measurement & Structure Health Evaluation adopting Operational Modal Analysis Technique

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Introduction

The objective of **OMA** is to extract modal properties (frequencies, damping ratios , mode shapes) of a structure under its operating conditions.

OMA is frequently called output-only modal analysis because only output are measured. In a typical dynamic characteristic evaluation session, the subject structure might be excited under natural operating conditions from variety of excitation sources which are not measured but are assumed to be 'broadband random'.

Operational Modal Analysis Framework are as shown in Figure 1:

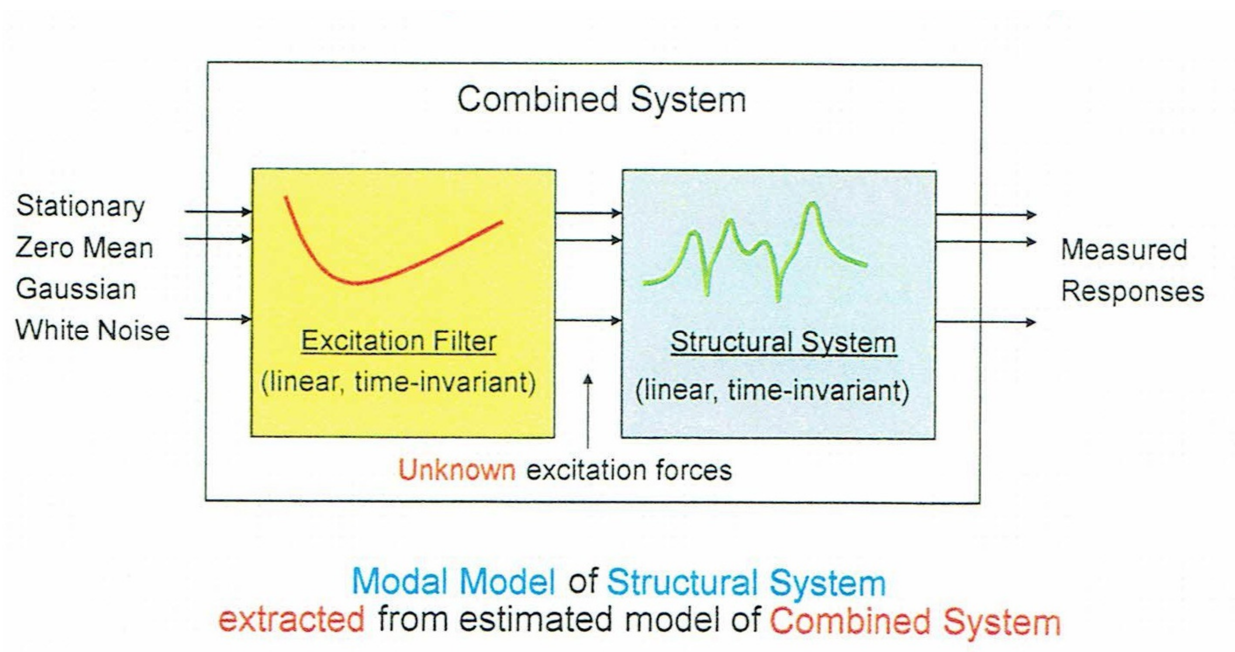

Figure 1 Operational Modal Analysis Framework

This paper describe one of the commonly adopted Operational Modal Analysis method: the subspace-based system identification (time domain) and frequency domain decomposition (frequency domain).

Subspace-based system identification

In this section we will recall the basic principles of stochastic subspace-based system identification and damage detection methods in relation to a health monitoring of vibrating structures.

Consider a linear and time-invariant discrete-time system represented in a state space as

$$\mathbf{x}_{\mathrm{k}+1} = \mathbf{A}\mathbf{x}_{\mathrm{k}} + \mathbf{v}_{\mathrm{k}}$$
$$\mathbf{y}_{\mathrm{k}} = \mathbf{C}\mathbf{x}_{\mathrm{k}} + \mathbf{w}_{\mathrm{k}}$$

where $\mathbf{A} \in R^{nxn}$ is the state transition matrix, $\mathbf{C} \in R^{rxn}$ is the observation matrix, $\mathbf{x_k} \in R^{n}$ are the states and $\mathbf{y_k} \in R^{r}$ are the outputs. The number of sensors, here accelerometers, is represented by r and n denotes the pairs of the complex conjugate poles of the system. Since the actual excitation is unmeasured, it is assumed to be Gaussian white with a properties, such as covariance, estimated during the identification step. In eq. (1), the unmeasured white noise input is denoted as $\mathbf{v_k}$ and $\mathbf{w_k}$ is the measurement noise due to disturbances and modelling inaccuracies.

A key theorem of the data-driven SSI states that the optimal prediction of a system response, formulated as a conditional mean between the past and future horizons of the block Hankel data matrix $\mathbf{H}_{p+1,q}$, can be factorized into a product of the observability matrix, $\mathbf{O}_{p+1,q}$, and the Kalman filter states $\widehat{\mathbf{X}}_{\mathrm{k}}$, where

$$\mathbf{O}_{p+1,q} = \begin{bmatrix} \mathbf{C} \\ \mathbf{CA} \\ \vdots \\ \mathbf{CA}^{p} \end{bmatrix}, \widehat{\mathbf{X}}_{k} = [\hat{\mathbf{x}}_{k} \quad \hat{\mathbf{x}}_{k+1} \quad \cdots \quad \hat{\mathbf{x}}_{k+j-1}].$$

From the $\mathbf{O}_{p+1,q}$ the system matrices $\mathbf{A}$ and $\mathbf{C}$ can be recovered by regression. The modal parameters, natural frequencies, damping ratios and mode shapes, are estimated from the poles of $\mathbf{A}$ and $\mathbf{C}$.

Operational Modal Analysis on a two story scaled Model Frame Structure

The geometry and dimension is as shown in Figure 2.

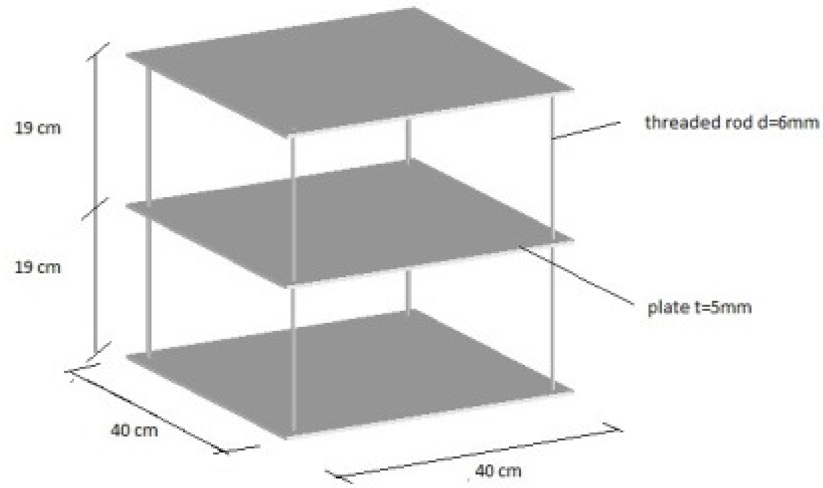

Figure 2 Dimension of the two-story scaled Model Frame Structure

The accelerometer sensors placement are as shown in Figure 3 . The data acquisition equipment can be observed at the lower left corner of Figure 3.

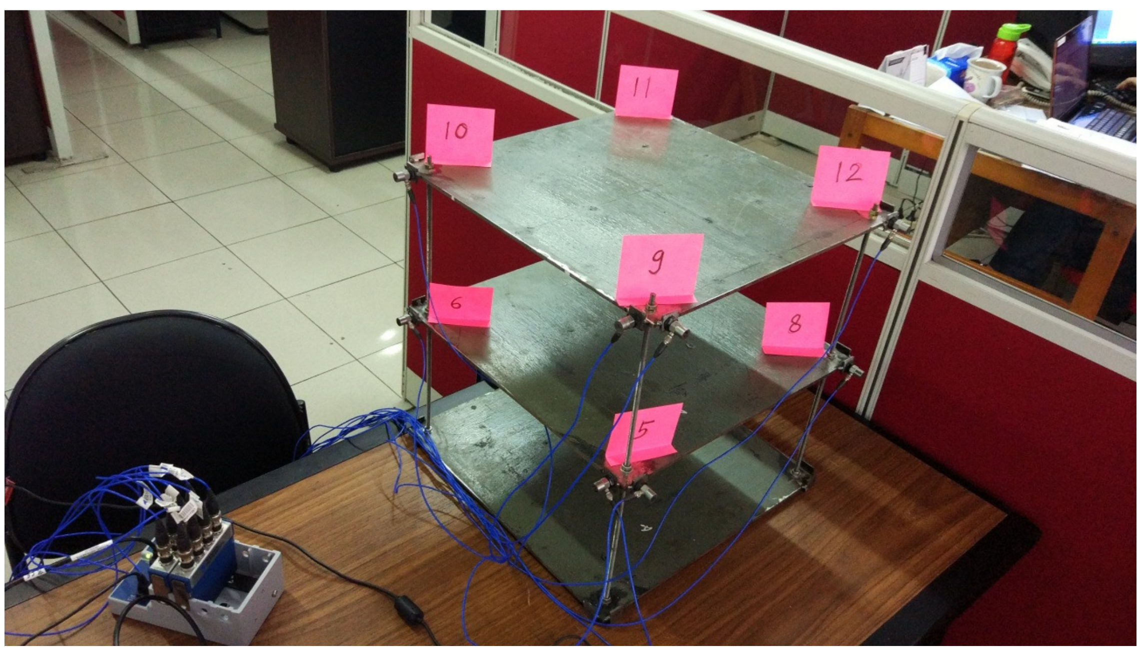

Figure 3 Accelerometer Sensors Placed at Selected DOF

The Numbering of Nodes and the corresponding channel number are as shown in Figure 4 where node 5 and node 9 have accelerometer sensors in both direction.

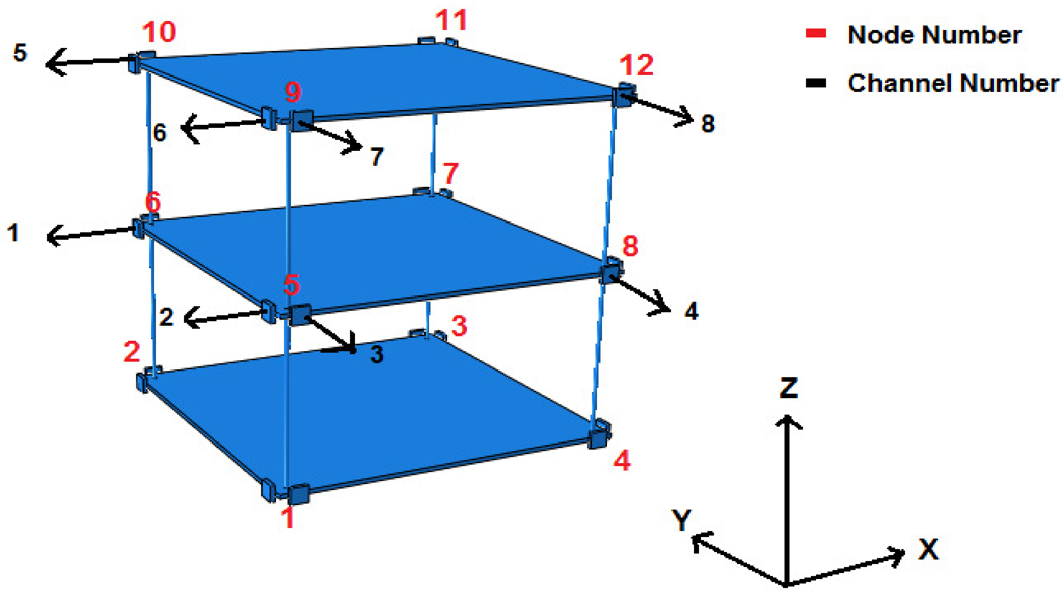

Figure 4 Node Number, Channel No

The extracted frequencies from measurement will then be compared with the calculation from a typical FE analysis. The FE Model is as shown in Figure 5:

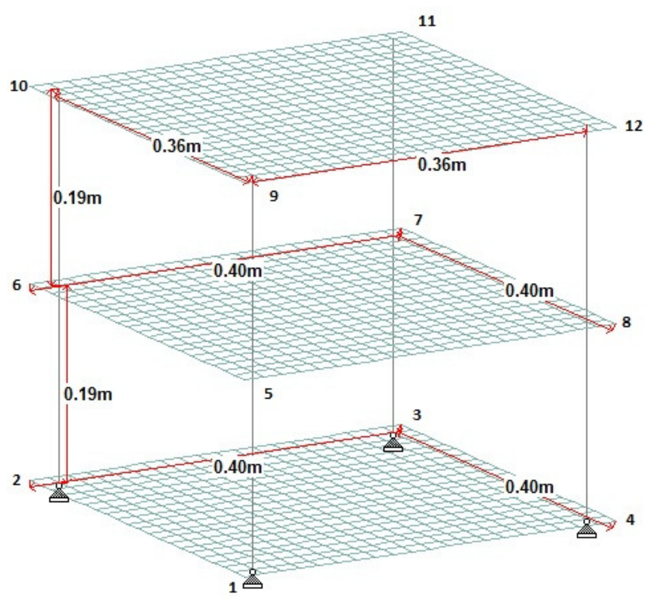

Figure 5 FE Model of the two-story scaled Model Frame Structure

Assignment of measurement Channel Number and Degree of Freedom (DOF) of the two story scaled Model Frame are shown in Table 1 :

Accelerometer Sensors			Node #	Direction	DOF (XYZ)
Model No.	Serial No.	Channel #			
352C33	LW196987	**1**	**6**	-X	(1,0,0)
352C33	LW196909	**2**	**5**	-X	(1,0,0)
352C33	LW197723	**3**	**5**	-Y	(0,1,0)
352C33	LW196914	**4**	**8**	-Y	(0,1,0)
352C33	LW197450	**5**	**10**	-X	(1,0,0)
352C33	LW196905	**6**	**9**	-X	(1,0,0)
352C33	LW196904	**7**	**9**	-Y	(0,1,0)
352C33	LW197705	**8**	**12**	-Y	(0,1,0)

Table 1 Assignment of Channel number , Sensors and DOF

The excitation on the two story model frame Structure is through tapping the model frame structure in random pattern to simulate “Broadband random” excitation.

Reference no 7 provide description on implementing OMA to a 35 meter span steel truss bridge where “broadband random” excitation was simulated by driving dump truck in random pattern along the two lanes driveway.

The dynamic response captured by the accelerometer sensors for all the Channels are as shown in Figure 6.

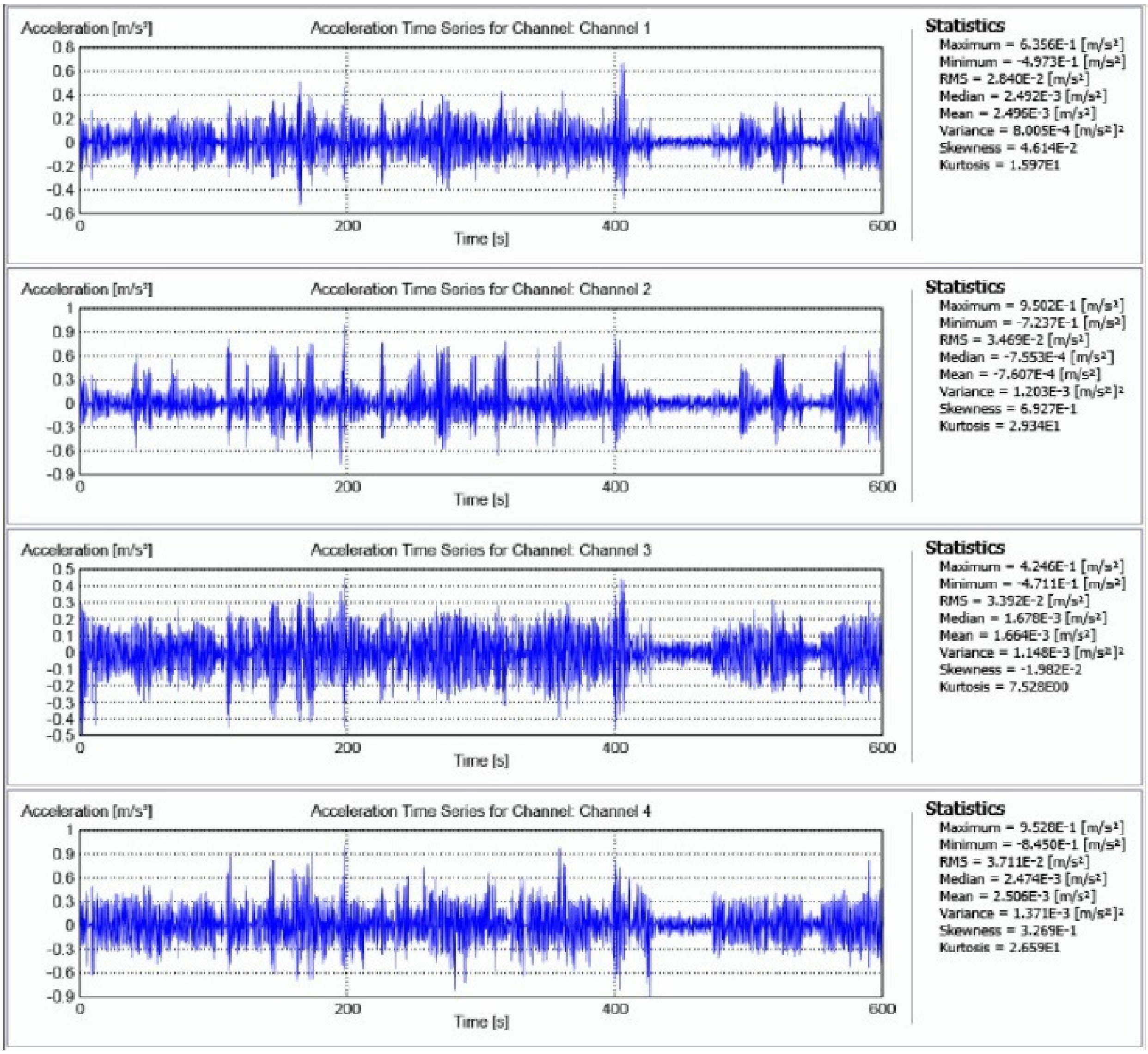

Figure 6 Accelerations data captured by the sensors

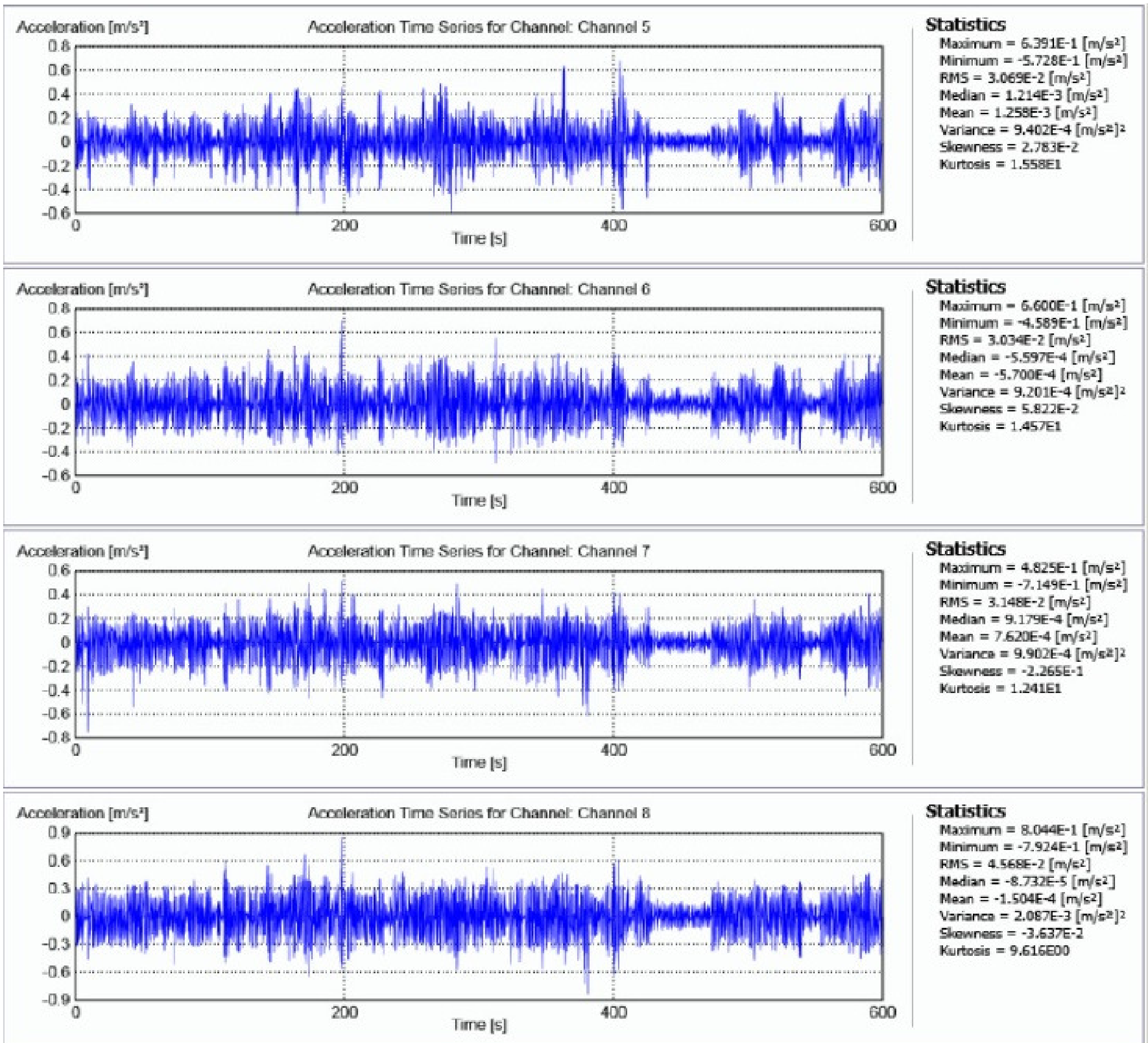

Figure 6 Accelerations data captured by the sensors (continued)

The extracted frequency and Mode Shape for Mode 1 to mode 6 are as shown in Figure 7

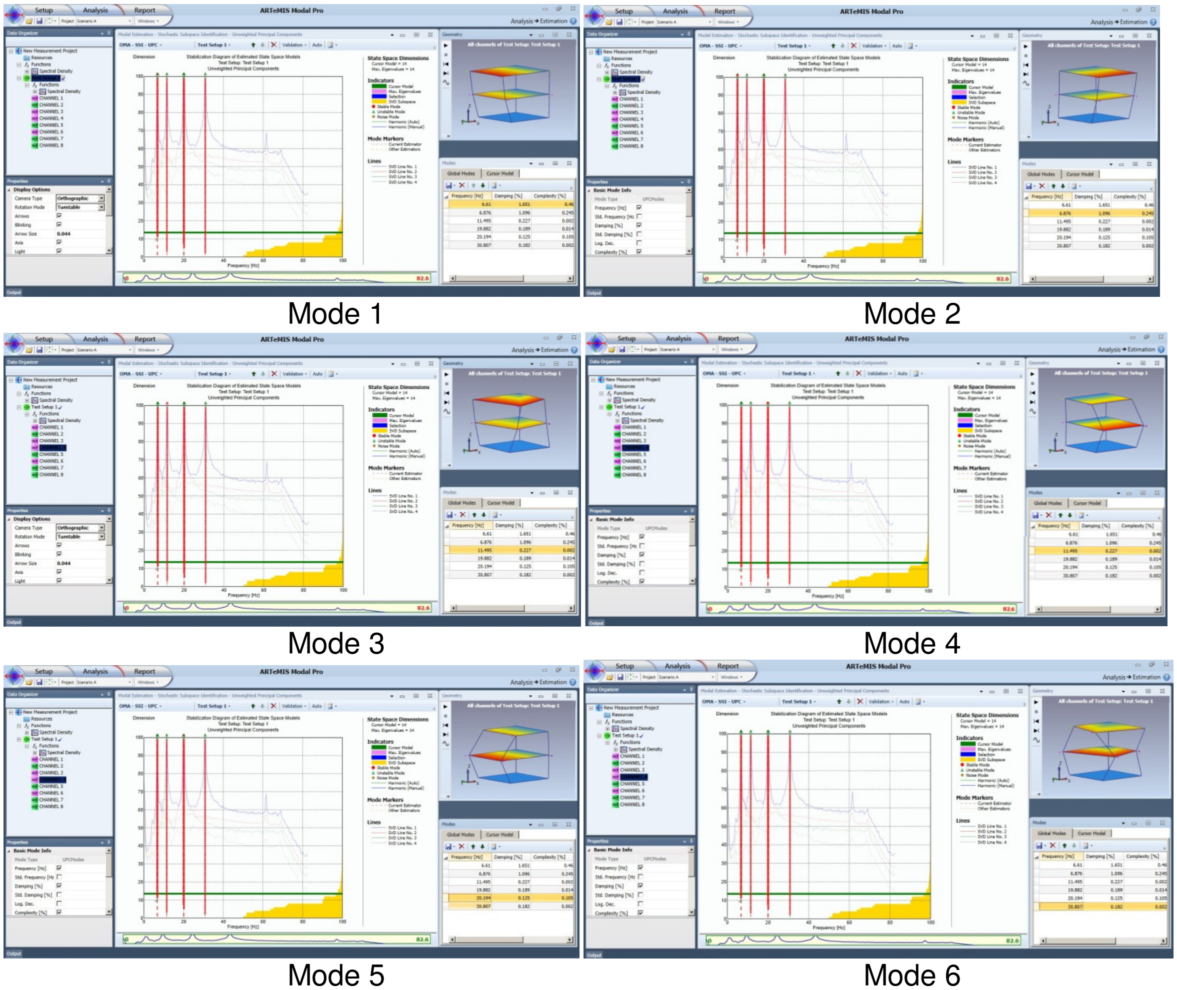

Figure 7 Frequencies, Mode shape extracted by OMA

Comparing Frequencies calculated using FE analysis with Frequencies extracted from OMA :

MODE	A= FE Analysis Hz	Measured Hz	(B-A)/A*100% (%)
1	7.798	6.833	-12.37%
2	7.798	6.943	-10.97%
3	11.98	11.526	-3.79%
4	20.989	20.054	-4.46%
5	20.989	20.445	-2.59%
6	32.23	31.069	-3.60%

Table 2 Extracted Frequencies from OMA compared with Calculated Frequencies

The Mode Shapes Generated from the FE Analysis are as shown in Figure 8:

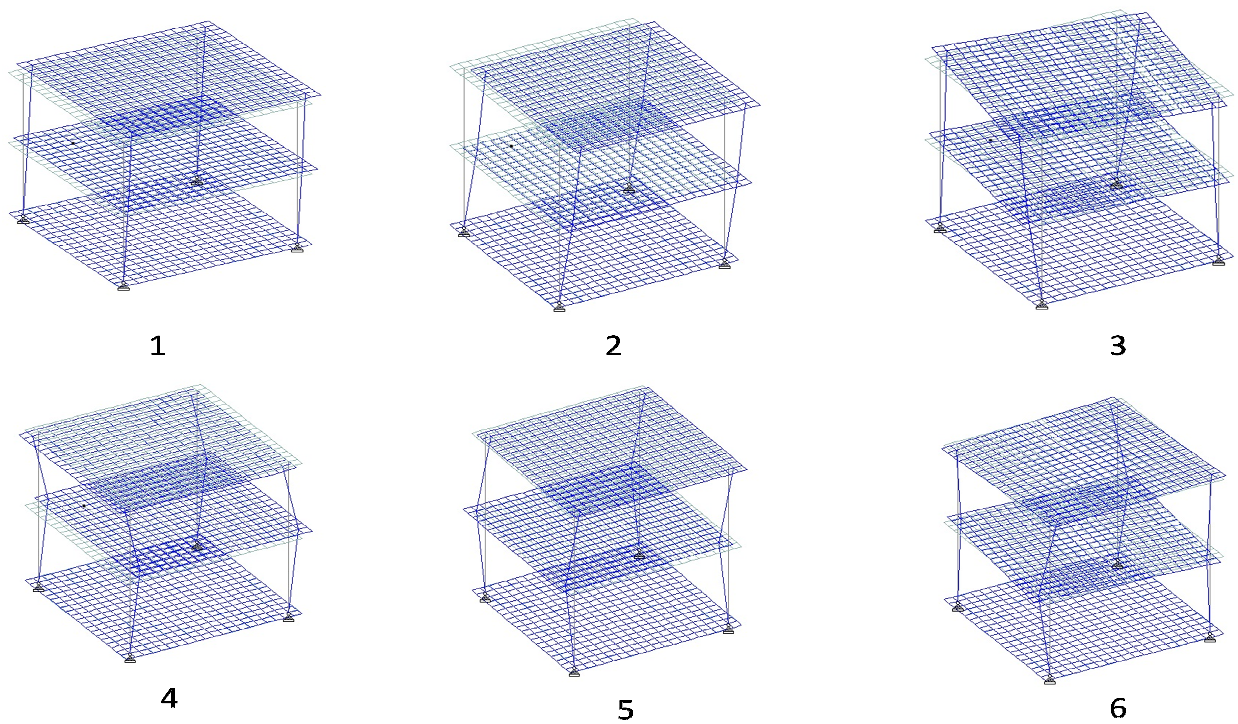

Figure 8 Mode Shapes generated from FE Analysis

The Screen captures of the Mode shapes extracted using Operational Modal Analysis consistently matches with the Mode shapes generated from FE analysis as shown in Figure 9. Reference 6 provide full details on capturing the dynamic response using acclerometer sensors, extracting frequencies and mode shapes.

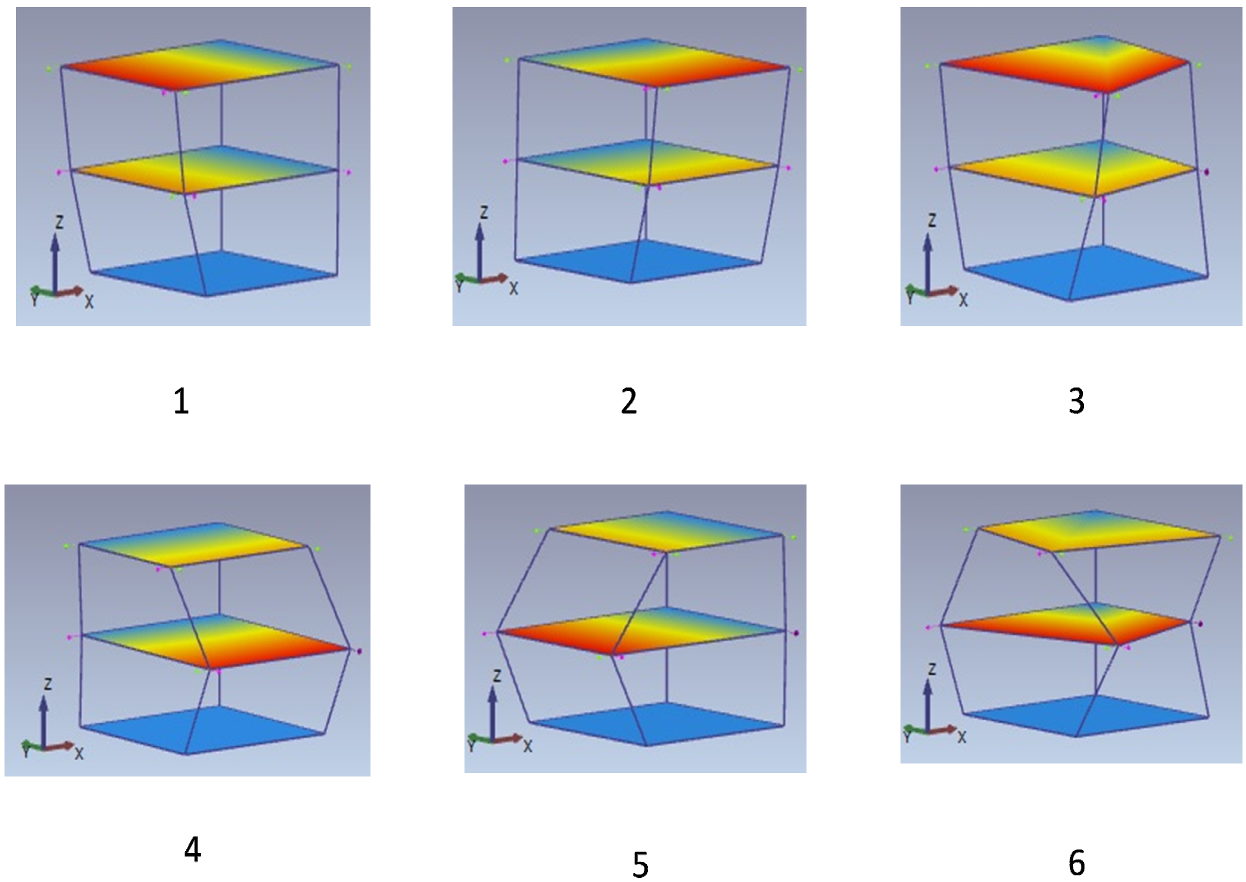

Figure 9 Mode Shapes extracted from OMA

Subspace-based damage detection

The vibration-based damage detection relates to identification of a damage-induced deviations in a damage-sensitive features of the responses collected from the structure. The deviations are defined by a relative comparison between the reference and operational states of the system during the monitoring period. A frequently used features for a modal-based damage detection are the modal parameters (natural frequencies, mode shapes and damping ratios) identified from the data. The subspace-based approach, however, is within the statistical methods that use the probability distributions of the deviations, which differ between the damaged and the undamaged states, hereby indicating faults in the system.

In relation to eq. (1), a perturbation in the structural properties of the system, mechanically manifested in the stiffness or mass, leads to deviations in the state matrices, what subsequently is reflected in $\mathbf{y_k}$. As a result, damage changes the eigenstructure of the state space model from eq. (1) and the damage-sensitive system property relates both to $\mathbf{A}$ and $\mathbf{C}$ as well as to $\mathbf{O}_{p+1,q}$ and consequently $\mathbf{H}_{p+1,q}$, based on the factorization property. As a result, the subspace-based damage detection test detects if the residual of the characteristic property of the reference (healthy) state of the system, based on fx. $\mathbf{H}_{p+1,q}$, is significantly different from zero using the χ^2-test.

Simulating the "Damaged State" of the two story scaled Model Frame Structure

The authors selected "non destructive" approach in simulating the "damage State" of the two story scaled Model Frame Structure by loosening the nuts in turn as shown in Figure 10. Two Scenario were tested:

- Test Scenario B1 : Loosening the nut at Node 5
- Test Scenario B2 : Loosening the nut at Node 5 and Node 6

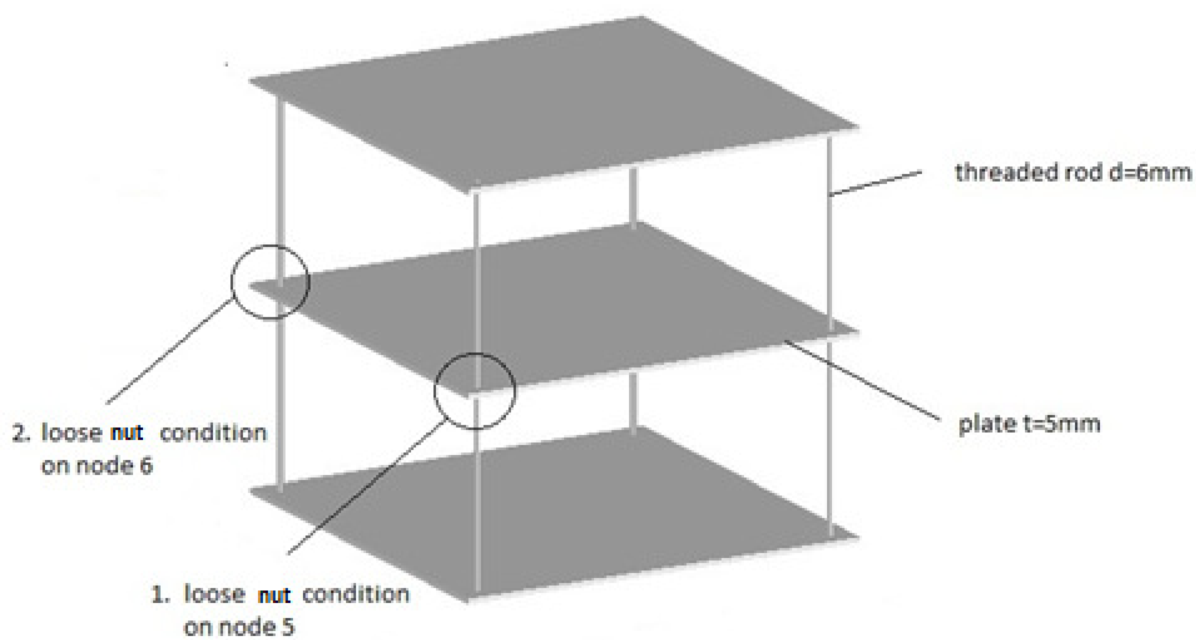

Figure 10 Simulating "Damage State by loosening nuts at Node 5 & 6

The extracted Frequencies for Test Scenario B1 and B2 are compared with the Test Scenario A which is the “un-damaged State” :

Mode	Scenario A			Scenario B1 (Loose nut at Node 5)			Scenario B2 (Loose nut at Node 5 & 6)		
	Sesi 1	Sesi 2	Sesi 3	Sesi 1	Sesi 2	Sesi 3	Sesi 1	Sesi 2	Sesi 3
1	6.61	6.93	6.96	6.263	6.318	6.316	5.109	5.18	5.341
2	6.876	6.955	6.997	6.497	6.555	6.57	5.644	5.69	5.729
3	11.495	11.545	11.539	10.904	10.947	10.948	9.577	9.652	9.735
4	19.882	20.147	20.132	19.629	19.635	19.644	19.34	19.344	19.368
5	20.194	20.589	20.552	19.944	19.944	19.931	19.719	19.724	19.73
6	30.807	31.191	31.21	30.38	30.371	30.391	29.769	29.765	29.836

Table 3 Extracted Frequencies for Screnario A, B1, B2

The subspace-based damage detection application provided the damage indicators of the “damaged state “ of the test structure as shown in Figure 11 :

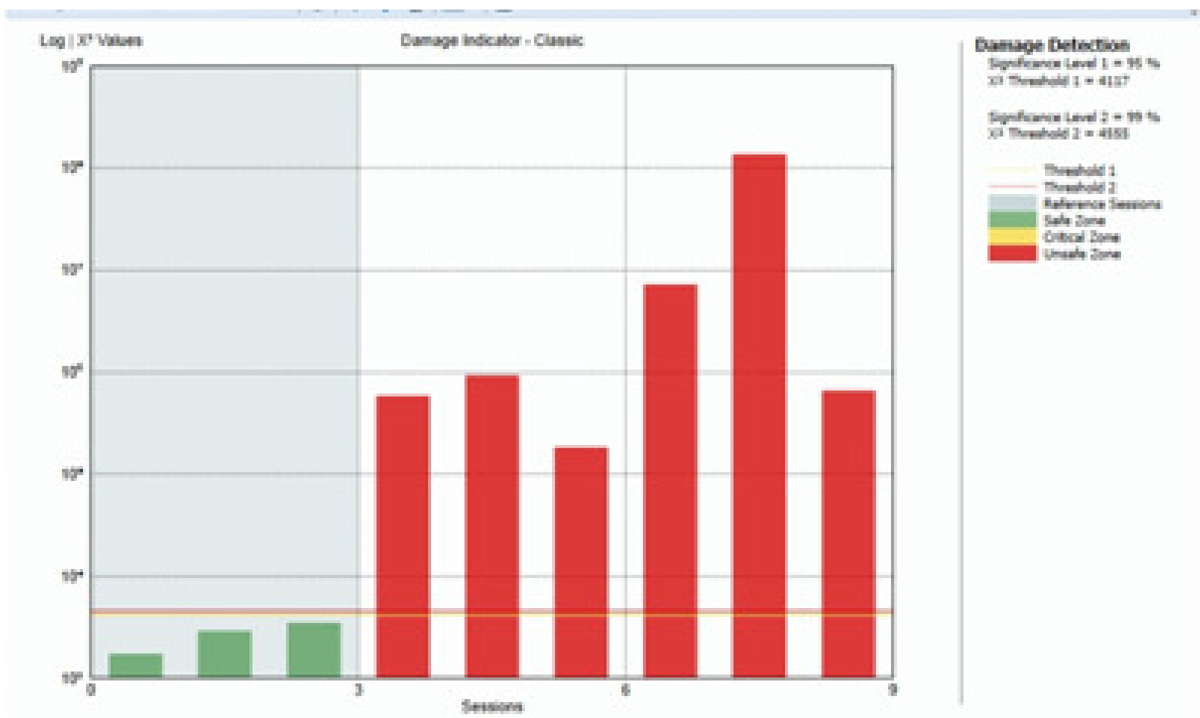

Figure 11 Damage Indicators for Test Scenario A, B1, B2

Conclusions:

Operational Modal Analysis Technique adopting subspace-based system identification and Damage detection techniques offer a practical alternative as compared with forced-vibration technique to evaluate structure health under operational condition by analyzing the changes of dynamic characteristics over the design life span of the structure.

References:

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