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VIBRATION-BASED SYSTEM IDENTIFICATION OF A REINFORCED CONCRETE SHEAR WALL USING FREQUENCY DOMAIN METHODS

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Abstract: In last few decades, vibration-based Structural Health Monitoring (SHM) has played a significant role to study different parameters of a structure. Frequency Domain Decomposition (FDD) plays important roles to identify system properties, such as: modal frequencies, mode shape and damping ratio. The focus of the present research is to identify modal frequencies of a scaled down RC shear wall in laboratory conditions using wired PCB Piezotronics sensor network. For signal decomposition, FDD has been utilized to get modal frequencies of the experimental shear wall using ambient vibration data. Detailed experimentation mechanisms are shown in the work. From the analysis results, different modal frequencies are obtained at different phase of the experiment. It is concluded that wired sensor network is very effective for vibration-based system identification, at the same time PSD with the FDD in combination with SVD can provide an important tool for estimation of modal frequencies and corresponding mod shapes from noisy vibration response.

Keywords: vibration, Structural Health Monitoring, Frequency Domain Decomposition, modal frequencies, RC shear wall, PCB Piezotronics sensor

1 INTRODUCTION

Modal analysis is an important technique for extraction of modal parameters from vibration-based response of a structure. In Operational Modal Analysis (OMA) or Output Only Modal Analysis (OOMA) estimation of the input forces is not required. OMA is a popular technique to perform modal analysis of civil engineering structures; including buildings, bridges etc. While performing experimental tests under ambient or natural conditions the test results are often very noisy and sparse. Thus it becomes very difficult to extract modal information. This is one of the challenges in OMA and some understanding of the nature and the characteristics of the excitation forces are therefore very important in order to interpret and understand the results and be able to derive a proper modal model [1-3].

This paper gives an overview of the detailed experimentation technique for OMA and extraction of modal information from the structural response. A structural prototype of a RC shear wall has been tested at the Building Dynamics Laboratory at CSIR – Central Building Research Institute, Roorkee, India; wired PCB Piezotronics sensors have been used during the experimentation to collect the structural response in ambient condition. Later, Frequency Domain Decomposition (FDD) technique has been utilized to extract the modal information from the vibration response data of the structure.

2 DATA ACQUISITION AND INSTRUMENTATION

For sensing and data acquisition PCB Piezotronics wired accelerometers and data acquisition system is used as shown in Figure 1. Specifications of the sensor and the accelerometers are shown in Table 1 and Table 2. As these sensors can capture data with very high sampling frequency, test data was recorded with different sampling frequency to record the ambient response of the structure accurately with less noise in the signal.

Table 1: Wired accelerometers from National Instruments specification

Sensor type	**PCB Piezotronics Wired Accelerometers (Model: 393B12)**
Sensitivity	(±10%) 10000 mV/g (1019.4 mV/(m/s^2))
Broadband Resolution	0.000008 g rms (0.00008 m/s^2 rms)
Measurement Range	0.5 g pk (4.9 m/s^2 pk)
Electrical Connector	2-Pin MIL-C-5015
Weight	7.4 oz (210 gm)
Frequency Range (±5 %)	0.15 to 1000 Hz
Frequency Range (±10 %)	0.10 to 2000 Hz
Frequency Range (±3 dB)	0.05 to 4000 Hz
Transverse Sensitivity	≤7.0 %
Temperature Range	-45 to +82 °C
Base Strain Sensitivity	≤0.005 (m/s^2)/με

Table 2: Wired data acquisition from National Instruments specification

Data Acquisition type	**PCB Piezotronics Wired Data Acquisition System (Model: cRIO-9043)**
CPU	Intel Atom E3930
Number of cores	2
CPU frequency	1.3 GHz (base), 1.8 GHz (burst)
On-die L2 cache	2 MB
Supported operating system	NI Linux Real-Time (64-bit)
Supported C Series module programming modes	Real-Time (NI-DAQmx) Real-Time Scan (I/O Variables) LabVIEW FPGA
Application software	LabVIEW
Driver software	NI CompactRIO Device Drivers December 2017 or later
Maximum cabling distance	100 m/segment
Communication rates	10 Mb/s, 100 Mb/s, 1000 Mb/s auto-negotiated

Sampling frequency for the data acquisition system is considered as 4K Hz. A total of five accelerometers were used to perform the experimentation. Instrumentation of the sensors have been done along the height of the shear wall (Figure 2). The dimensions of the shear wall are shown in Table 3. Following experimentation is a part of the dynamic study of the shear wall to be performed in future.

(a) (b)

Figure 1: NI wired sensing instruments; (a) accelerometer, and (b) data acquisition

Figure 2: Instrumentation technique

Table 3: Details of the shear wall

Parameter	Details
Dimensions	1.85 m x 0.30 m x 2.26 m
Composition	Pre-cast concrete shear wall

3 MODAL PARAMETERS ESTIMATION

3.1 Signal Processing

Modal parameter estimation from structural response depends on the amount of noise in the signal. Highly noisy signal requires filtration or pre-processing of the data. On the other hand, possible requirement of filtering of the data also depends upon the spectral distribution of the response signals. The first step of the analysis is therefore to calculate the Power Spectral Densities (PSD) of the response signals to check the amount of noise in signals. Further processing of signal can be done either in frequency domain or in time domain. For the following work, Frequency Domain Decomposition (FDD) method has been considered for modal parameters estimation [4-5].

3.2 Frequency Domain Decomposition Technique

The Frequency Domain Decomposition (FDD) technique is often called the Peak-Picking technique. The FDD technique estimates the modes using a Singular Value Decomposition (SVD) of each of the Spectral Density matrices. This decomposition corresponds to a Single Degree of Freedom (SDOF) identification of the system for each singular value. In the following the most important relationships for understanding the FDD technique are given [4-7].

The relationship between the input *x(t)*, and the output *y(t)* of a linear system can be written as following [4-7]:

$$\left[G_{yy}(\omega)\right] = [H(\omega)]^{*}\,[G_{xx}(\omega)]\ \ [H(\omega)]^{T} \tag{1}$$

where, $[G_{xx}(\omega)]$ is the input spectral matrix, $[G_{yy}(\omega)]$ is the output spectrum matrix, and $[H(\omega)]$ is the Frequency Response Function (FRF) matrix.

Another way to understand the response signals is from their decomposition into participations from the different modes $[\Phi]$ expressed via the modal coordinates $q(t)$ [4-7]:

$$y(t) = [\phi]q(t) \tag{2}$$

Using the expression mentioned in Eq. (2) using correlation technique and Fourier Transform it can be written as [5]:

$$\left[G_{yy}(\omega)\right] = [\phi]\left[G_{qq}(\omega)\right]\ [\phi]^{H} \tag{3}$$

where, $[G_{qq}(\omega)]$ is the spectrum matrix of the modal coordinates.

The FDD technique is based upon the SVD of the Hermetian response spectrum matrix at each frequency and for each set of data [4-7]:

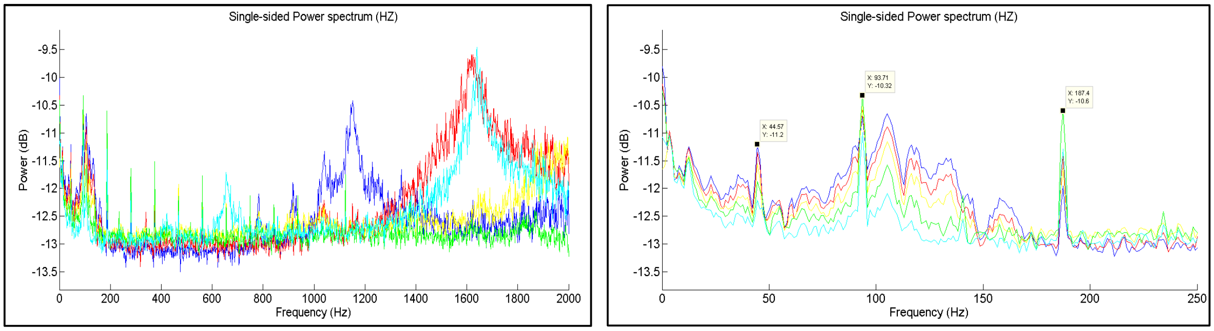
$$\left[G_{yy}(\omega)\right] = [V]\,[S]\,[V]^{H} \tag{4}$$

Where *[S]* is the singular value diagonal matrix and *[V]* is the orthogonal matrix of the singular vectors. The singular vectors (the columns in *[V]*) are orthogonal to each.

Eq. (4) can be explained that the singular vectors present estimations of the mode shapes and the corresponding singular values present the response of each of the modes (SDOF systems) expressed by the spectrum of each modal coordinate The assumptions are that $[Gqq(\omega)]$ is a diagonal matrix, i.e. the modal coordinates are uncorrelated, and that the mode shapes (the columns in $[\Phi]$) are orthogonal. The simple peak picking technique gives frequency and associated mode shape at the selected frequency. The peaks in the SVD plot should be used as explained above [7].

4 OVERVIEW OF RESULTS

As mentioned before, PSD of the five channels of the response signals of the structure is performed to understand the amount of noise, shown in Figure 3. First, the total sampling range of the frequencies are checked, and then modal frequencies are estimated from the PSD diagram (Table 4). The obtained frequencies are quite high due to higher amount of stiffness in the structural prototype. From the PSD diagram it is seen that harmonics are present in higher modes, although first three modal peaks are quite identifiable from the entire spectra.



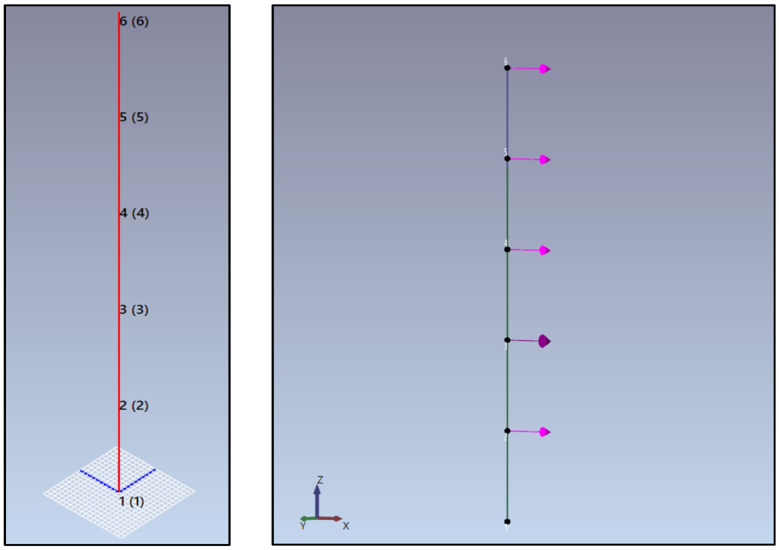
(a) (b)

Figure 3: Power Spectral Densities; (a) entire sampling range, and (b) range until 250 Hz

Table 4: Modal frequencies from PSD

Mode no.	Frequency (Hz)
1	44.57
2	93.71
3	187.4

The structural response is analyzed using FDD technique by employing the signals in ARTeMIS Operational Modal Analysis software [8]. A vertical cantilever 2D model simplified model is constructed in the ARTeMIS software, and the 5 degrees of freedoms have been assigned. (Figure 4).



(a) (b)

Figure 4: ARTeMIS model; (a) geometry of the model, and (b) degrees of freedoms

Modal frequencies are obtained through FDD analysis by picking the peaks of the SVD plot (Figure 5). Several peaks appear very clearly in the SVD, especially in the low frequency range below 100 Hz. Variable peeks are obtained at higher frequency levels, which are expected to be caused by structural resonance due to external noise associated with the signal. Structural frequencies and modal complexities are shown in Table 5.

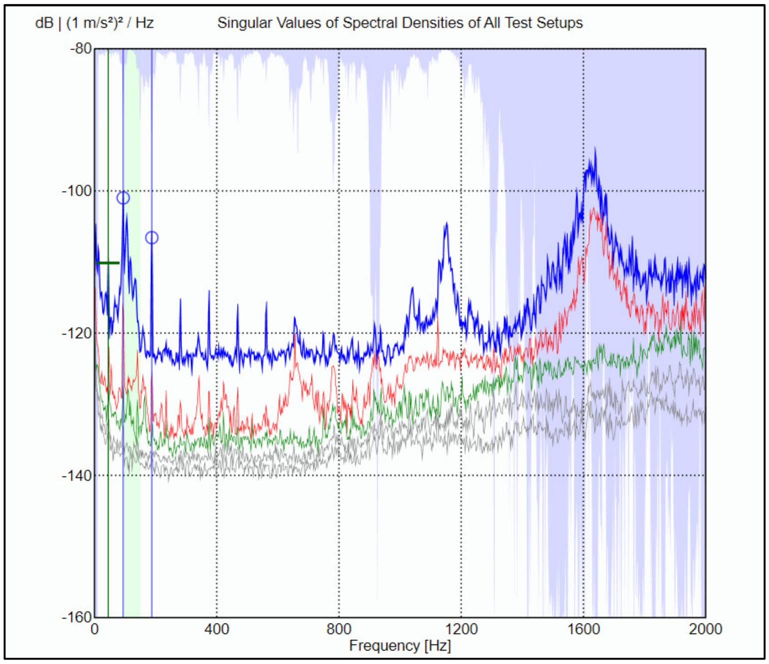


Figure 5: Singular Value Decomposition (SVD)

Table 5: Modal values from SVD

Mode no.	Frequency (Hz)	Complexity (%)
1	44.92	0.265
2	93.75	27.12
3	187.50	7.39

Modal Assurance Criteria (MAC) values for the estimated modal values are displayed in Figure 6.

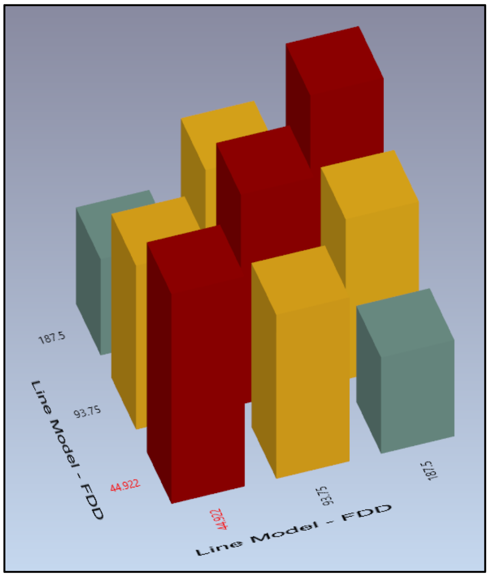
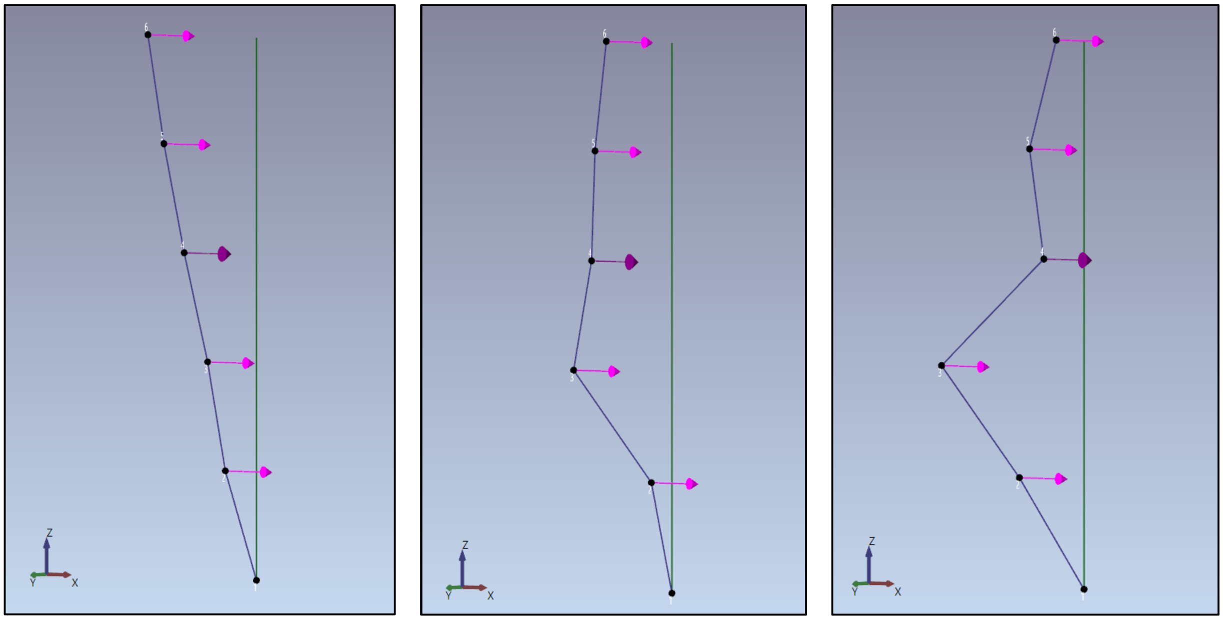


Figure 6: Modal Assurance Criteria (MAC)

The displacement mode shapes at different modal frequencies are shown in Figure 7.



(a) (b) (c)

Figure 7: Displacement mode shape; (a) First mode, (b) Second mode, and (c) Third mode

5 CONCLUSION AND FUTURE WORKS

The present work demonstrates that PSD with the FDD in combination with SVD can provide an important tool for estimation of modal frequencies and corresponding mod shapes from noisy vibration response. Frequency values shown in Table 4 and Table 5 are quite close to each other. Although, further validation is required from the time domain decomposition, where manual peak picking errors can be avoided, the work clearly shows the efficiency of the wired sensor to estimate modal properties of the system with a higher sampling frequency in ambient condition neglecting closely separated modes. Further experimentation is to be done to study the dynamic behavior of the shear wall, and numerical model is to be constructed to study nonlinear time history analysis.

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