EVOLUTIONARY PROCESS OF OMA METHOD BASED ON NATURAL FREQUENCY AND DAMPING RATIO

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Abstract
In this paper, we explore OMA (Operational Modal Analysis) development, delineate various OMA methods, investigate the key issues in OMA methods, and review the literature. Our goal in this paper is to explore and investigate the most important OMA methods. In doing so, we first review the basic concepts of OMA methods and then present two case studies in three modes. The evaluation parameters addressed in this study are natural frequency and damping ratio. According to evaluation results, new EFDD and FEM were founded to be above and below the diagrams in almost all cases.
Keywords: OMA Method, natural frequency, damping ratio

Introduction

Modal analysis plays a significant role in many industries and applications. It is widely used in design, optimization, health supervision, seismic control and failure detection in structures, bridges, and the like. With the development of vibration measurement systems and analysis methods, OMA has been preferred over EMA (Experimental Modal Analysis) in many applications as mentioned above. The major distinction between OMA and EMA lies in the source of applied forces. Unlike EMA, which tests the system under applied forces and measures input forces, OMA tests the system in real working situation under the forces applied in modal ambient, without input forces being measured. That is why this method is sometimes called Natural Excitation Modal Analysis, Modal Ambient Analysis, and Output Only Modal Analysis.

Since 1990, OMA was paid special attention in civil engineering, mechanical engineering and aerospace engineering, the reason being the following advantages. Modal ambient analysis is less costly than EMA and doesn’t need boundary condition simulation. OMA achieves dynamic features in the entire system, not only a part of it. Due to application of real random force to different points of the structure, a linear model is achieved under operational conditions rather than experimental conditions. Since the analysis made in this method is basically a MIMO analysis, repetition modes and close modes are easily identified. Therefore, OMA is an efficient method for complicated and difficult structures. Thanks to online application, OMA can be used to control structure vibration, detect failure, and supervise the health. In this paper we attempt to classify different OMA methods, review the history of OMA development, and compare two case studies.

LITERATURE REVIEW

In this part, we discuss the history of the most important OMA methods:

Natural Excitation Technique (NExT)

NExT was innovated by [1]. In this method, correlation function (COR), which is obtained from random response of the structure owing to modal ambient excitation, can be written as a group of decrement sine. Each decrement sine has a damped natural frequency, damping ratio and mode shape coefficient relating to one of the structural modes. In MIMO systems, therefore, COR can be used instead of Impulse Response Function (IRF) in order to obtain system modal parameters. This makes the necessary arrangement for the development and use of EMA techniques in OMA. NExT-based OMA methods consist of two main steps: the first step is to achieve a time response function (TRF) and the second is to identify modal parameters by one of the common TD methods (time domain). Two methods have been proposed for obtaining TRF in OMA, the first being to use COR (correlation function) and the second being to use the time function obtained from random decrement (RD) technique. RD technique, which averages time sections of a random time response, was innovated by [2]. However, [3] was the first to use this technique in modal analysis. He asserted that RD is the outcome of free system vibration. But [6-7] rejected [4] assertion, demonstrating that RD is the outcome of COR (correlation function).

Using RD technique, one can obtain COR from random response data of the structure and can use it to identify modal parameters in OMA based on NExT. This approach opened a new window for researchers to propose their techniques and develop OMA knowledge. [8] employed RD technique to estimate Reciprocal Correlation Function (CCOR) and Auto Correlation Function (ACOR) and then investigated three different methods to identify modal parameters. He [9] also compared the speed and accuracy of RD technique with FFT method and found that the former was 100 times speedier than the latter. In ACOR estimation, RD was also more accurate than FFT. In CCOR estimation, however, FFT method was more accurate than RD technique. In RD-based modal analysis methods, if ACOR and CCOR are concurrently used, high noise level in CCOR would cause errors in modal parameters. If only ACOR is used, phase information would be lost and mode shape would not be identifiable. To solve this problem, [5] proposed Vector Triggering RD method (VRD). In VRD method, the requirements for selecting start point of time sections are defined by a vector. This method maintains and protects phase data. In the same year, [16] investigated VRD method through simulation of four degrees of system freedom as well as an experimental test of a bridge model. [9] conducted a comparative study on FRF, RD and FFT methods and found that FRF had less leakage and noise than RD and was speedier than it.

[10] proposed a method for computing the variance and estimating the accuracy and length of RD in modal analysis. They also discussed how to use RD in OMA and to determine appropriate parameters in RD [20-22]. Shen et al. (2002) investigated NExT scientific development and proposed a method for identifying modal parameters in frequency domain using CCOR and common analysis methods in TD. They used Cross Power Spectral Density (CPSD) function instead of FRF in Frequency Domain Poly-Reference (FDPR) method and demonstrated the ability to use CCOR in FDPR by carrying out experimental tests on an airplane model.

RD technique was extended to other modal analysis methods in frequency domain [23-25]. [26] proposed a method for computing spectral density function by reshaping Furrier of RD function instead of time function. This method reduced the noise level by averaging and decreased the leakage thanks to sufficient length of time in RD. They tested their idea through an experimental model. Finally, [27] compared all methods in frequency and time domain through the review of studies. He also delineated the use of RD technique in OMA.

SSI Method (Stochastic Subspace Identification)

Stochastic subspace based method is a modal identification technique in time domain which has been developed and used in OMA. In 1990s, a new subspace based method for identification of system space conditions was proposed in the field of control and system engineering, which directly used the measured data. Based on this method, SSI method was proposed in 1993, which used random response of the measured structures [23-25]. Peeters et al. (1995) delineated SSI method and explored the relationship between vibration model and stochastic model of a system, using this relationship as a tool for modal analysis of a structure under modal ambient loads. In [11] employed this method to examine a sheet with a fixed electrical motor on it. They compared the results with those obtained from FDD method in frequency domain.

Thereafter, due to mathematical complexity of SSI method, [19] attempted to explain it more simply. They maintained that the steps of this method were mostly similar to other methods in time domain. In [24] proposed a new signal processing method from unfixed signals, which was called Empirical Mode Decomposition (EMD). Based on this method, they proposed a new EMD-based SSI method in operational modal analysis. In this method, they first transferred the measured data to modal response function through EMD and then applied SSI method to extract modal parameters completed [24] research and delineated how to use subspace based methods for extracting time series of modal coordinates. He asserted that this method did not have limitations of the past methods in which the number of modal coordinates was limited to the number of sensors. The subdivisions of this group are: Unweighted Principal Component (UPC), Principal Component (PC), and Canonical Variate Analysis (CVA).

FDD Method

FDD is an OMA method in frequency domain. OMA methods in frequency domain are based on a simple relationship between input and output power spectral density (PSD) of a stochastic process [29]. The simplest frequency domain method is Peak Picking (PP) method, in which natural frequency is obtained directly from picking the picks in PSD diagram. If modes are well separated from each other, this method produces acceptable estimations [30-31]. The major advantages of this method over TD techniques lie in the omission of computational modes as well as its simplicity and speed. However, PSD PP has some disadvantages including low accuracy (particularly in complicated structures) due to independence of PSD spectrum resolution result, extraction of operational deflection shape rather than natural mode shape of the system, low accuracy in computation of damping ratio, and the incapability to be used in close mode systems.

In [12] eliminated the above mentioned disadvantages and proposed frequency domain decomposition method (FDD). This method uses singular value decomposition of output PSD (power spectral density) in different frequencies as mode indicator function. In this method, not only different modes, especially close modes, are identified but also signal and noise spaces are separated. FDD method enables to obtain natural frequencies and mode shapes.

Enhanced Frequency Domain Decomposition (EFDD)

In 2001, [13] innovated Enhanced Frequency Domain Decomposition (EFDD) to estimate damping ratio. In this method, singular values in the vicinity of natural frequencies are transferred to time domain through inverse FFT and damping ratios are obtained by logarithm decrement techniques. In EFDD, only one separated part is transferred to time domain, so bias errors would possibly exist in damping ratio, particularly in close modes. To eliminate this problem, [31-39] proposed Frequency Space Domain Decomposition method (FSDD). Using a PSD promoted by singular vector, they extracted natural frequency and damping ratio through a degree of freedom curve fitting. Because of simplicity and efficiency of FDD method in OMA, [14-18, 50) proposed an auto FDD based modal identification instruction. This instruction can be implemented in commercial modal analysis software and therefore user intervention in production of results may be reduced. [13], considering the relationship between Complex Mode Indicator Function and FDD (frequency domain decomposition), proposed an enhanced mode indicator function as a substitute for EFDD (advanced frequency domain decomposition). A full description of NEW EFDD can be found in [22].

Another method in this group is Curve – Fit Frequency Domain Decomposition (CFDD). This method is a development of the existing FDD in ARTeMIS Extractor, which has been detailed in [27]. The major advantage of this method is higher accuracy in the estimation of natural frequencies and damping ratios in both fully random excitation and harmonic excitation. Using MAC, a frequency band is used around a picked pick in order to achieve the average value of singular vectors. Natural frequency and damping ratio are estimated by curve-fitting of SDOF (SDOF spectral bell) in frequency domain.

RESEARCH METHOD

The simulated structure is a 22-floor building with the height of 67.5 m. It has two main towers which are separated by a 10-cm seam designed for making a distance between dynamic responses of two structures in time of severe movements. Both towers are made up of a central RC shell (including elevators and staircases) and a big glass façade with RC sheets behind it, which are interconnected by columns. Both parts of the structure enjoy the same load bearing structure. Geotechnical explorations indicated high heterogeneity in the sediments settled below the structure. Geological situation of this valley takes intensifying local impacts on seismic waves stimulating the structure. In this study, we set the basic frequency of soil profile on below 2.7 Hz. The basic transverse and longitudinal frequencies were set on 1.20 Hz and 1.22 Hz respectively.

In order for continuous evaluation, we monitored the structure via 24 acceleration sensors in French Accelerometric Network (RAP). The sensors existed throughout the structure. Kephren station, placed in the basement (level 2), recorded these 24 channels. This network consisted of:

- 18 Episensor single-axis accelerometer, FBA ES-U2, in various classes
- 2 Episensor three-axis accelerometer, FBA EST, in basement

The receptors were set on ±1g sensitivity. The reports were recorded in 125 Hz sampling frequency and synchronized by a GPS Garmin 16.

Figures 1 and 2 illustrate the first three longitudinal modes together with natural frequencies and damping ratios. We computed these modes and natural frequencies based on tangent stiffness matrix (after applying gravity loads). They well matched the modes and natural frequencies obtained from ambient vibration data in undamaged test structure.

It should be noted that the higher natural frequency in the first mode of Case II corresponds to FE model with the properties of non-cracked concrete, while the equivalent frequency in Case 1 has been obtained from a sample with cracked concrete conditions. We compared the simulated acceleration and time history of displacement response with laboratorial counterparts, which had been reproduced for the same input seismic movements on vibration table, and confirmed the validity of non-linear FE model in test structure. For four historical earthquake movements used in vibration table test, peak ceiling displacements predicted for FE matched the related laboratorial results.

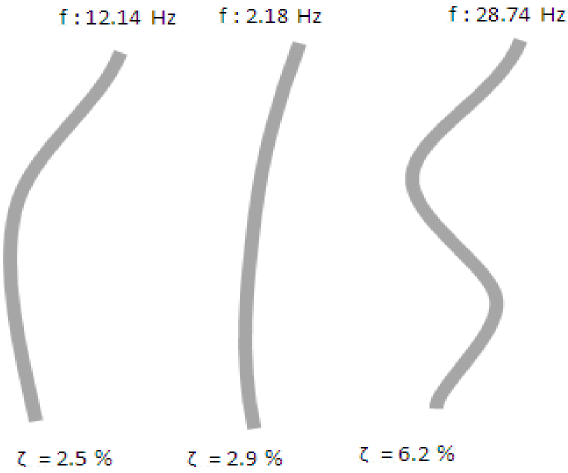


Figure 1. The first three longitudinal modes together with natural frequencies and damping ratio

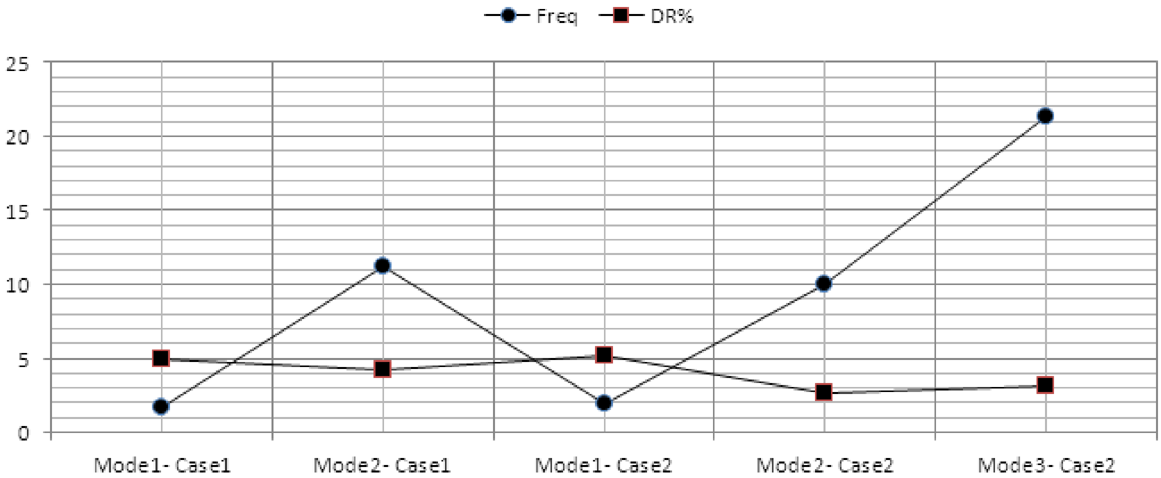


Figure 2. The first three modes with two case studies together with natural frequencies and damping ratio

To measure aluminum sheet vibration, we used sampling rate of f_s=4096 samples/s. Nyquist frequency was 2048 Hz, sufficiently above the intended frequency range (1000 Hz) for modal parameter excitation. Measurement duration was 30 seconds, so 122880 data points were obtained for each channel. As a general rule, the lowest natural frequency should exist in the data with at least 1000 cycles. This requirement was met in the lowest structural mode (around 70 Hz) with two times the number of required cycles. To record the data, we excited sheet vibration by random knocks of fingertip and pencil head. This was not a white noise but could be sufficiently random for the purpose of OMA algorithm. We made several measurements for each test setup and performed the test with different knocking techniques and excitation levels. Due to low weight of the sheet, excitation level showed most of accelerations to be too high, more than their nominal range for each short time period in the beginning of motions. Using the plastic part in the end of pen, we weakened the energy of high frequency bands so that they could overcome overloading. But the comparison of spectral results indicated no significant impact on general quality of the signal. Finally, we written the data in Universal File Format (UFF) text files and transferred them to analysis laptop in which ARTeMIS suite had been installed.

For the purpose of comparison, we carried out a numerical modal analysis with finite element method (FEM). In real projects, this type of analysis is usually performed before experimental test of real hardware. For the structures which are more complicated than a simple sheet, one of the primary goals in FEM analysis in the early steps of a project is to acquire a basic knowledge on dynamic behavior of the system. Based on this knowledge, sensor locations for precise experimental tools can be so defined that modal vectors in the test can meet the requirements.

In the case of simple rectangular sheet, basic shapes for flexural and torsional can be predicted without any FEM analysis before test. We carried out FEM analysis after the experimental test only for the validation of OMA algorithm and the use of software. In a real project, the comparison between FEM and experimental results is made for FE model validation and is used as a basis for model updates.

We modeled the sheet using Graphical Pre/Post Processing Software MSC Patran 2008 and MSC Nastran 2007 R1 as a real FE solver back-end. FE model included 1800 shell elements (QUAD4) and 12 and 13 concentrated mass elements (CONM2) which indicate accelerations. We modeled all three setups and performed the analysis by placing sensor masses in the setups. We didn’t model sensor cables and stabilizing tapes because their impact on structure stability was considered to be negligible. Total mass of the model was 584 g.

Since suspension by plastic part would separate sheet modes from any other suspended mode, the test could be considered to have free boundary conditions. For this reason, we designed FE model with free boundary conditions as well. This model is called a free-free model (the second “free” refers to the absence of load forces. In a numerical modal analysis, no loading is applied to the model).

We configured modal analysis solving sequence in order to obtain 20 specific values of the system. Due to free boundaries and lack of assembly, the first six specific values formed kinematic rigid body movements with natural frequency of 0 Hz. The remaining 14 modes are the desired sheet modes up to 1000 Hz. Based on sensor placement setup, we obtained 20 specific values by FE analysis.

RESULTS

Before inputting real measurement samples, we defined sheet geometry and sensor locations in ARTeMIS Testor. We inputted several measurement files into the project and determined some channels for geometric nodes. We transferred the merged data and measurement information to binary files to be analyzed in ARTeMIS Extractor. While it was possible to use UFF text data, binary files would make Extractor more stable. Among the advantages of binary files is smaller size and higher software processing performance.

In extracting modal parameters, we employed all identification techniques available in ARTeMIS Extractor in order to become familiar with the software and to evaluate its applications. We analyzed three test setups with different sensor locations in each project as well as in a multi-test setup project. Frequency resolution for Fourier transform and consequently for singular value decomposition (SVD) plots was between frequency lines of 1 Hz. In each sensor setup, we identified 14-15 modes in frequency band of 0-1000 Hz.

We identified natural frequencies in different techniques. The fact that the difference between the lengths of columns in the diagram is easily identifiable indicates that standard deviation of these estimations is normally less than 1 Hz. Since the frequency resolution used for Fourier transform is only 1 Hz, the difference between estimations is desirable.

Damping ratio estimations indicated a more significant difference. This was no strange because estimation of damping ratio is the most difficult step in modal identification. This parameter is most influenced by the advantages and disadvantages of various techniques. If frequency domain decomposition (EFDD) technique failed to develop a high quality correlation function outside the selected frequency band, the weak logarithm curve fitting would result in a low quality damping ratio. This was the case in several modes. Likewise, curve-fit FDD (CFDD) estimation algorithm had some problems in close modes and the modes which had not been well excited.

Figures 3 and 4 illustrate the results by detail and by average. The estimated damping ratios are different not only in all identification algorithms but also in all modes, even similar modes in different measurement setups. The theory does not predict this for an isotopic sheet. The reasons for divergence of the theory are likely to lie in the sensors, connection lines and tape used for fixing, which may significantly increase damping ratio of the structure. These cases are present in sheet locations with high range for some modes and low range for the other, because they are located in or around modal line of other modes. Likewise, when sensor, cables and tape are relocated for setting up the precise instruments, damping ratio for the same mode will change.

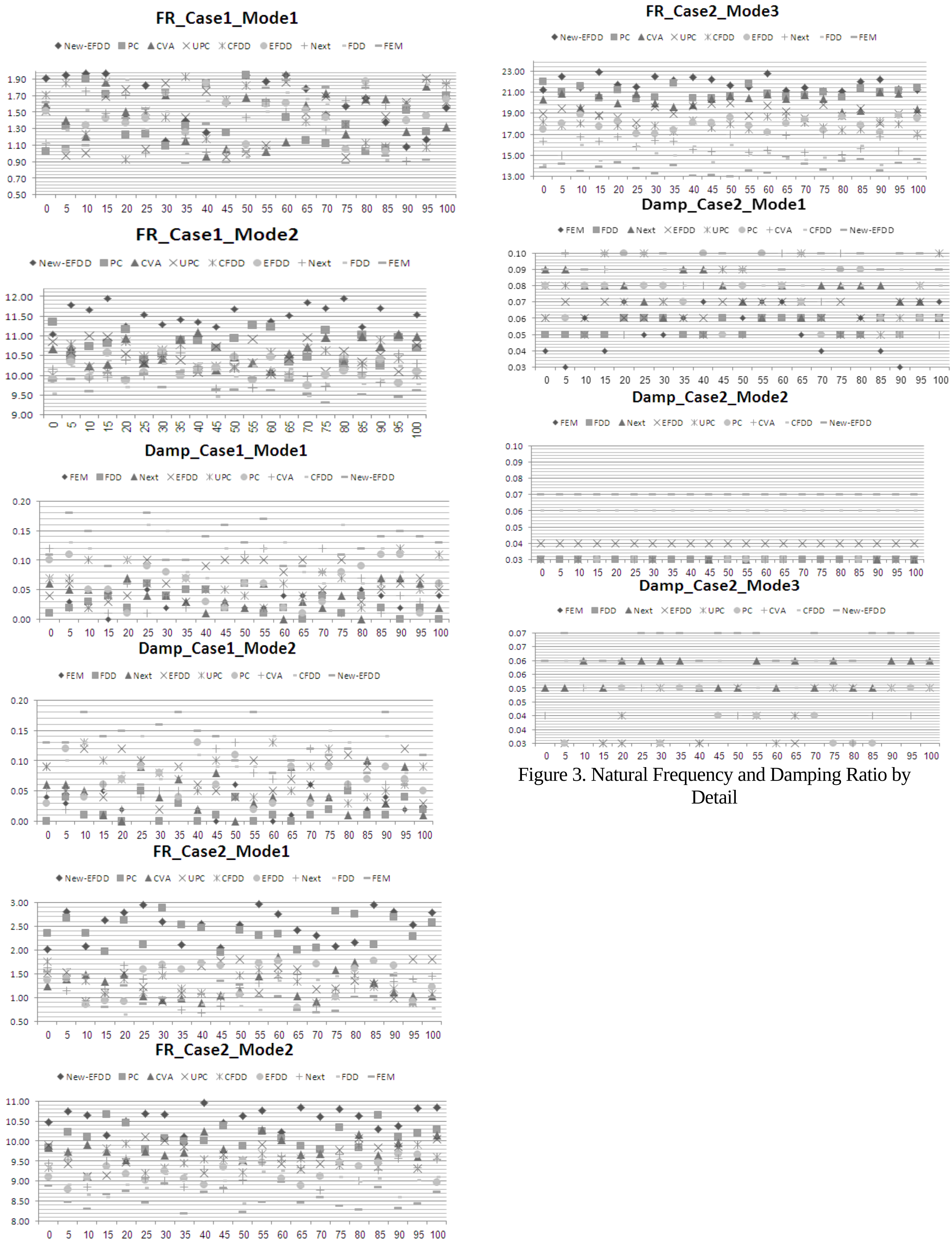
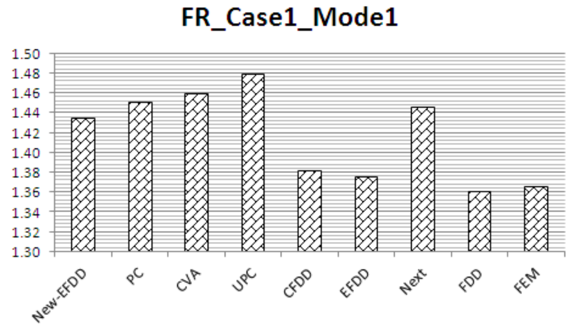
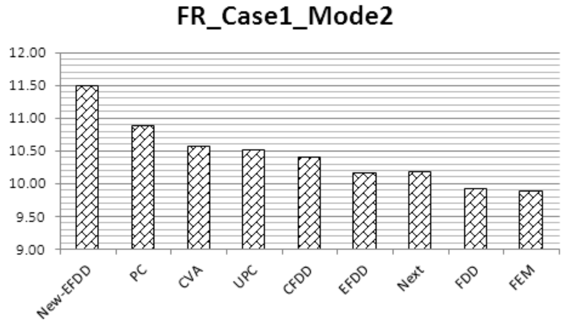
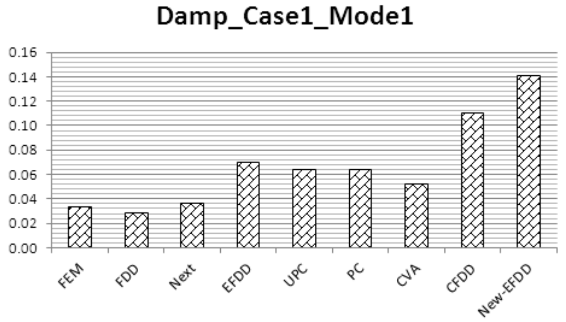
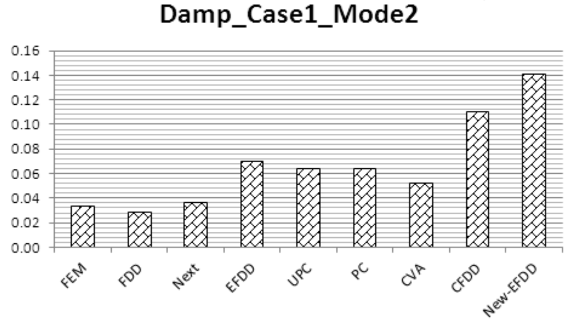


Figure 3. Natural Frequency and Damping Ratio by Detail


FR_Case1_Mode1
1.50
1.48
1.46
1.44
1.42
1.40
1.38
1.36
1.34
1.32
1.30
New-EFDD
PC
CVA
UPC
CFDD
EFDD
Next
FDD
FEM


FR_Case1_Mode2
12.00
11.50
11.00
10.50
10.00
9.50
9.00
New-EFDD
PC
CVA
UPC
CFDD
EFDD
Next
FDD
FEM


Damp_Case1_Mode1
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
FEM
FDD
Next
EFDD
UPC
PC
CVA
CFDD
New-EFDD


Damp_Case1_Mode2
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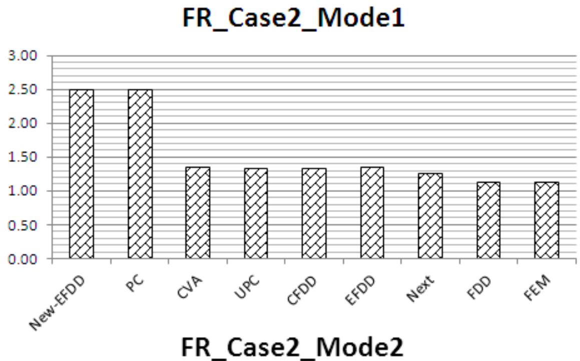
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
FEM
FDD
Next
EFDD
UPC
PC
CVA
CFDD
New-EFDD


FR_Case2_Mode1
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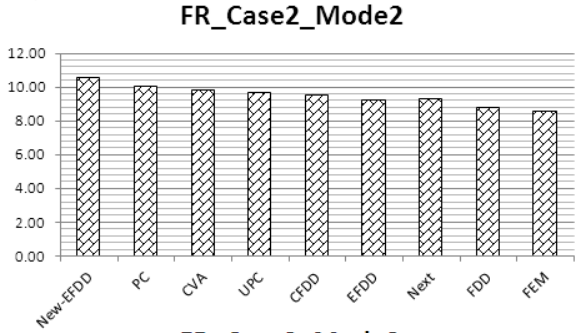
2.50
2.00
1.50
1.00
0.50
0.00
New-EFDD
PC
CVA
UPC
CFDD
EFDD
Next
FDD
FEM


FR_Case2_Mode2
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10.00
8.00
6.00
4.00
2.00
0.00
New-EFDD
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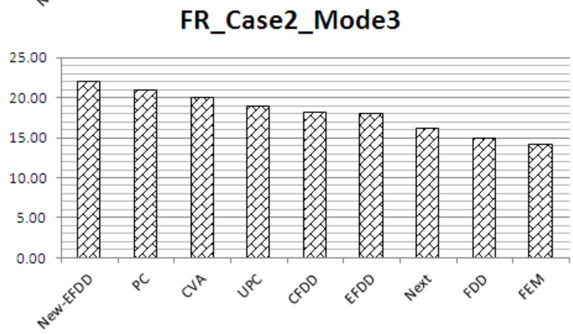
CVA
UPC
CFDD
EFDD
Next
FDD
FEM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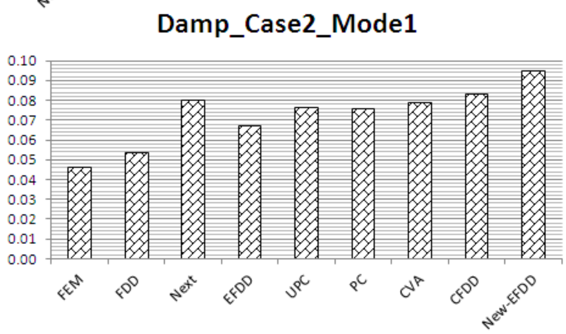
20.00
15.00
10.00
5.00
0.00
New-EFDD
PC
CVA
UPC
CFDD
EFDD
Next
FDD
FEM


Damp_Case2_Mode1
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
FEM
FDD
Next
EFDD
UPC
PC
CVA
CFDD
New-EFDD

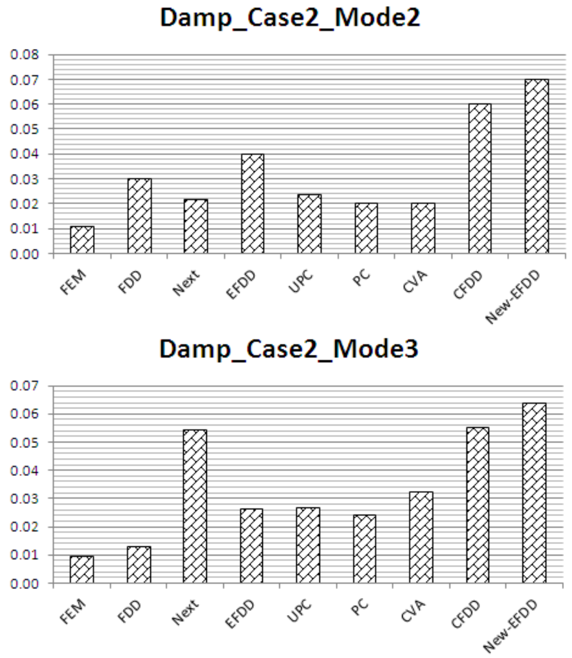


Figure 4. Natural Frequency and Damping Ratio by Average

In a project where damping ratios are essential (such as finite element (FE) model update), an agreement should exist between different parameters – considering which method has the best performance for a specific mode and which mode is significant for system performance. This example indicates the importance of proper model validation and the necessity of user experience.

The review of FEM modes indicates that the experimental analysis has identified all modes between 0 and 1000 Hz. Natural frequencies identified in OMA show a good correlation with the frequencies obtained from FEM analysis. In all modes, the frequencies of FEM modes were only a few Hertz above the measurement values, which indicated that not only FE model had a small volume but also it was very strong. The phenomenon of mode change due to sensor displacement can be investigated by FE analyses for all three schemes. Also, the changes in the measured frequency is more significant than what had been measured. The tendencies and changes in mode order are according to test results.

We measured the natural frequency and damping ratio for the existing EFDD technique as well as for EFDD technique with omitted harmonic component. If harmonic components are present in the function, the existing EFDD technique will give improper estimations of modal parameters. In the natural frequency with harmonic component, damping ratio was estimated to be very low. Using the existing EFDD technique, natural frequencies were estimated with a good accuracy. This was the case in damping ratios as well, although more deviation occurred when harmonic component were close to natural frequency.

Some of the advantages of new EFDD method are:

- Accuracy: harmonic components are accurately identified and their impact can be omitted, even in cases where a harmonic component is located exactly in a structural mode. It is necessary to use a frequency with high resolution or polynomial proportion.
- No knowledge is needed (such as knowledge on harmonics and their frequencies)
- Easy to use: This method has been automated based on EFDD technique
- Speed: This method is based on efficient computational algorithms

There was an agreement between the values obtained from OMA techniques, with a small standard deviation in different approaches. The important characteristics of these techniques included simplicity in BFD, clear interpretation in FDD, and efficiency and stability in SSI. It is also possible to combine different methods to improve the results [22]. FEM is able to produce the modes of this tall irregular reinforced-concrete structure. Experimental and numerical similarity of modal shapes demonstrates their proper identification. Natural frequency values measured by FEM showed a good conformity with the frequencies obtained from the recorded reports.

Using the recorded reports of ambient vibration, we employed OMA techniques to obtain dynamic properties of the tower. There was a good agreement between the parameters extracted from three different techniques (BFD, FDD and SSI). Finite element model was able to produce the frequencies and mode shape of the irregular structure under study. Using FE model, we investigated the impact of relationships between independent dynamic parts in the structure (which had been separated by seismic seams and connected by non-structural elements). The validity of dynamic properties enables to use this model for evaluation of structure response to seismic movements.

In many OMA applications, the presence of dominant harmonic components in the measured responses is inevitable. This may have severe impacts when using EFDD technique because harmonic components need to be determined out of the function. Compared with modal results which had been obtained by fully stochastic excitation of the same structure, New EFDD showed a good conformity in terms of natural frequency, damping ratio and mode shape. If a high frequency resolution is used, one can omit even a harmonic component which is exactly located in the peak of a structural mode and achieve a good modal estimation. Using a polynomial proportion rather than simple linear interpolation which was used in the primary execution, one can improve the results. Among other advantages of this method are the unneeded prior knowledge on harmonic components in terms of frequencies or levels, high computation efficiency, and easiness of use.

CONCLUSION

We investigated various OMA methods and explored their key issues. In doing so, we first studied the main group of OMA methods including NExT, SSI, FDD and FEM. For this purpose, we examined a structure piece of RC shear wall with full scale on NEES vibration table. We employed three output-only system identification methods to extract modal parameters (natural frequency, damping ratio and mode shape) of the structure under study. These three methods were Eigensystem Realization Algorithm (NExT-ERA), Data-Driven Stochastic Subspace Identification (SSI-Data), and Enhanced Frequency Domain Decomposition (EFDD). In this study, we analyzed the changeability or uncertainty of system identification methods in two steps. The first step was when the methods were applied to the measured response of the structure. The second step was when the methods were applied to the response of the structure simulated using a three-dimensional nonlinear finite element model which had been calibrated and confirmed. After applying variance analysis in system identification results based on the experimental data measured in the first step, we achieved the final results as follows:

Natural frequency: New-EFDD, PC, CVA, UPC, CFDD, EFDD, Next, FDD, FEM

Damping ratio: FEM, FDD, Next, EFDD, UPC, PC, CVA, CFDD, New-EFDD

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