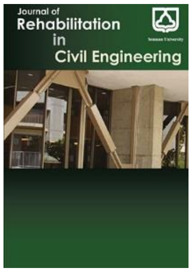
Journal of Rehabilitation in Civil Engineering 8-3 (2020) 01-14



journal homepage: http://civiljournal.semnan.ac.ir/

Developing a Feature Extraction of Existing Structures Using an Ambient Vibration Test

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ARTICLE INFO

Article history:
Received: 21 October 2019
Accepted: 05 February 2020

Keywords:
Structural Health Monitoring,
Data Acquisition,
Ambient Vibration,
Operational Modal Analysis,
Existing Buildings.

ABSTRACT

The paper aims to extract the dynamic properties of existing structures without utilizing the analytical models. The ambient vibration testing could be used on any type of frame such as concrete, steel and masonry to investigate the structural vulnerability. The method could be the first stage and necessarily for the retrofit process. To achieve this aim, the ambient vibration testing can also be employed. The experimental data obtained from the method can be used to monitor the health, evaluating, and damage detection structures at present. The achieved data can be compared in future with the recorded signals at different times. So, the ambient vibration test was carried out on the building of Imam Hossein Hospital at Mashhad. Then, its dynamic characteristics of the acceleration records are obtained by using Data Acquisition System with three accelerometers in two perpendicular coordinates. The method is more accurate and practical compare with analytical models of the existing buildings. The ambient vibration test prevents of several points such as destructive testing or may irreparable damage to the building as well as high cost. Even, the ambient vibration test maybe required for every couple of decayed, when noticed of any changes in the condition of buildings after construction. These type of changes could be quality of concrete or welding or some changes in the location of walls that can be affected the dynamic specifications of the building. The method provides real lateral load pattern and actual modes that can evaluate existing condition of the building compare with the time of construction.

1. Introduction

Today's, regarding the advancement of technology in a variety of fields, especially electronics and computers, the application and suitable use of them in various fields has become very common. In this matter, in

DOI: 10.22075/JRCE.2020.18982.1356

structural engineering, the use of structural health monitoring techniques in countries facing natural disasters (such as earthquakes and winds) is considered to be high, and in particular for buildings that require immediate occupancy during such disasters.

Among the functions of using this technique in buildings, one can mention the prediction of the structure condition, determination the amount of failure, remaining life of the structure, and identifying the health parameters of the structure [1]. Unfortunately, it is impossible to utilize either the experimental (empirical) modal or classical analysis (EMA)[1] method in the large civil engineering structures. This is why this method is not possible. Instead of the EMA, the (OMA)[2] for civil engineering structures is employed [2].

The modal parameters (including Eigen values, Eigen vectors and modal damping) can be estimated when the structure is stimulated by the environmental effects (such as wind, water flow, and etc.) or technology (traffic, pedestrian movement). Here, the white noise is the only condition that should be satisfied is to stimulate. An environmental stimulation is assumed as a continuous random frequency process with a flat frequency spectrum. It should be mentioned that the input-output methods contain some advantages of preventing the effects of noise on the structure response, in which only output methods do not have this advantage. However, the input/output solutions are more costly than the output solutions, and they usually interfere with the operation of the structure during the test. The output solutions can provide the ability to un-interruption and continuously monitoring the health of the structure because it can measure the response of the structure under the operational conditions. Nevertheless, the output methods have only some disadvantages, including excitation forces that are not known, and often not able to stimulate high-frequency modes of the structure [3].

Note that most local damage detection methods are not very practical to monitor the large construction structures [4]. Ideally, vibration-based health monitoring schemes are utilized sequentially and in combination with local damage detection techniques [5, 6]. There have been several past studies investigating the long-term performance of structures and superstructure and almost in all of them presence of non-destructive health monitoring system has been required. A recent study on full depth precast concrete deck panels shown that ambient vibration test could be an option for evaluating the bridge condition when they come to age [7, 8]. The vibration-based health monitoring is initially employed to investigate and analyze the overall damage to the structure, based on which the damage will be identified and positioned; local techniques will be applied to find the dimensions of the damage [9]. In this way, The displacement and acceleration sensors are the most common data-gathering tools for vibration-based damage detection [10]. These tools measure the time histories of either acceleration or structural displacement and then convert them into voltage signals. The mass and dimensions of the data acquisition system should be small compared to the mass of the structure so as

[1] Experimental Modal Analysis
[2] operational modal analysis

not to interfere with the output response. On the other hand, for building structures, the accelerometers are the most commonly used data acquisition tool. This is because these accelerometers have the ability to function in a wide range of frequency responses, simplicity, installation, and high measurement accuracy. Two types of accelerometers are available, one that uses acceleration based on capacitor power measurements, and another that uses piezoelectric deformations. Using the data obtained from the data acquisition device, various methods in the time domain or frequency domain can be utilized to obtain the dynamic properties of the structures.

2. Operational Modal Analysis

There are many methods of frequency and time domain modal analysis technology in technical literature. For instance, the simplest technique, called PP[3], extracts the natural frequency of the structure by finding the peak of the response spectrum. In theory, each peak is proportional to the natural mode of the structure. The main limitation of this technique is the inability to distinguish between the frequencies of modes that are very close in terms of quantity [11].

Moreover, the use of this technique is possible for those structures that have low damping values. The second group of modal analysis techniques, the use of the frequency domain, is the partitioning of the singular of the matrix, which includes the transverse response of the structure response. This method is called (FDD)[4]. After the (SVD)[5] is implemented, the shape of the scaled modes and frequencies is achieved. The methods of SVD also provide the possibility of extraction of modal damping. These methods contain some advantages over peak picking methods, which will not cause relatively low natural frequency distances and not large damping drops. The third group of modal analysis techniques, used in the frequency domain, is the (LSCF)[6], which makes it possible to extract the mode shapes and the frequency through an approximation [12].

3. The Specification of the Studied Structure

The ambient vibration test was carried out on the structure of Imam Hossein Hospital in Mashhad that has six floors by area thirty thousand square meter which is shown in Figure 1(a). The building has been used on lead rubber bearing and High damping rubber bearing which is shown in Figure 1(b). In this building, from 55 isolators with lead core and 80 high damping isolators are used. The diameter of the isolators used is 80 cm and their lead core is 20 cm in diameter. Isolators are placed on large concrete columns and are used on the steel moment frame which is shown in Figure 1(b). 4. Ambient Vibration Test

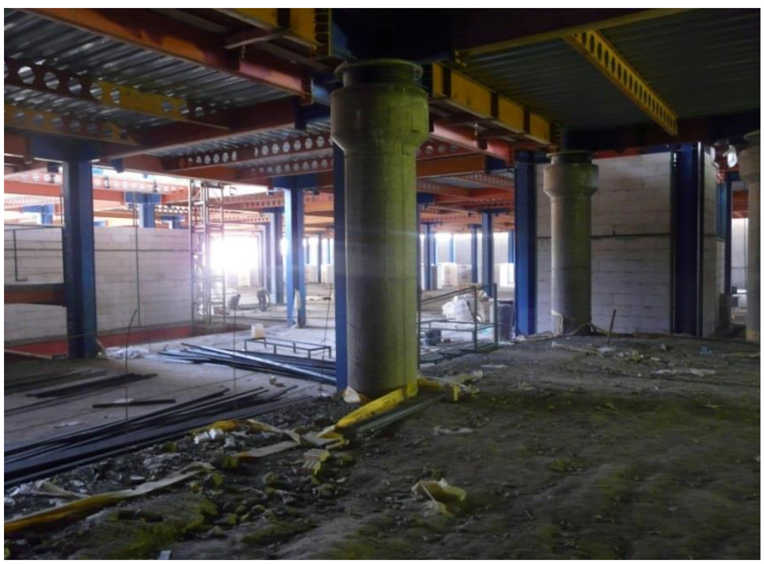
Now, to implement the ambient vibration test, data acquisition device which is shown in Figure 2(a) and the specifications in Table 2 with three-axis and one-axis acceleration sensors which are shown in Figure 2(b) and the specifications in Table 1, which was utilized with calibration confirmation.

Regarding the reference to the sources, it was determined that the duration of the record of

[3] Peak Picking
[4] Frequency Domain Decomposition
[5] singular value decomposition
[6] Least Squares estimate of the Complex Frequency domain

the ambient vibration test for the extraction of the dynamic characteristics of the structure should be between 1000 and 2000 times of the period in the first mode. The sampling frequency for construction works is usually considered to be 100 or 200 Hz based on the Nyquist criteria, which was assumed to be 100 Hz in this test.

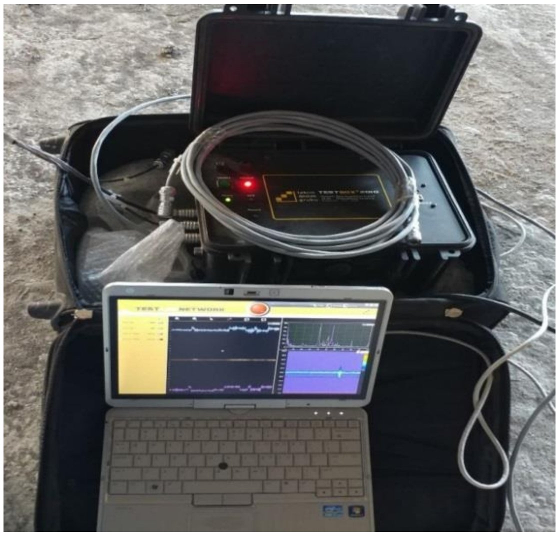
(a)



(b)

Fig. 1. (a) the Hospital Building, (b) Isolated Structure.

Regarding the restriction on the number of sensors (two single-axis sensors and a three-axis sensor) as well as the length of the cables that interconnected the data acquisition device with the sensors, here, only three sensors was employed in the same direction in one direction. Afterwards, data recording was carried out in the direction of the initial direction by rotating the sensors to a further 90 degrees. By considering the number of floors in the building, and considering that in each record, the data would be recorded for each direction in the total height of the structure. as a result, the sensors is settled in center of each floor. Moreover, because the diaphragms were rigid, so the position of sensor settlement on the floor are not important for extracting bending vibration modes. The most commonly used modal identification technique for ambient frequency transduction tests is frequency domain decomposition and peak picking and in time domain is the SSI[7] [13].



(a)

(b)

Fig. 2. (a) Data acquisition device used in testing, (b) Tri-axial Accelerometer.

Table 1. The sensors specification used in hospital testing.

SENSBOX 7021, +-3g, 130 dB @ 0.1-120 Hz 135 dB @ 0.1-10 Hz, Uniaxial Accelerometer
SENSBOX 7023, +-3g, 130 dB @ 0.1-120 Hz 135 dB @ 0.1-10 Hz, Triaxial Accelerometer

[7] Stochastic Subspace Identification

Table 2. Specifications of the DAQ system used in the test.

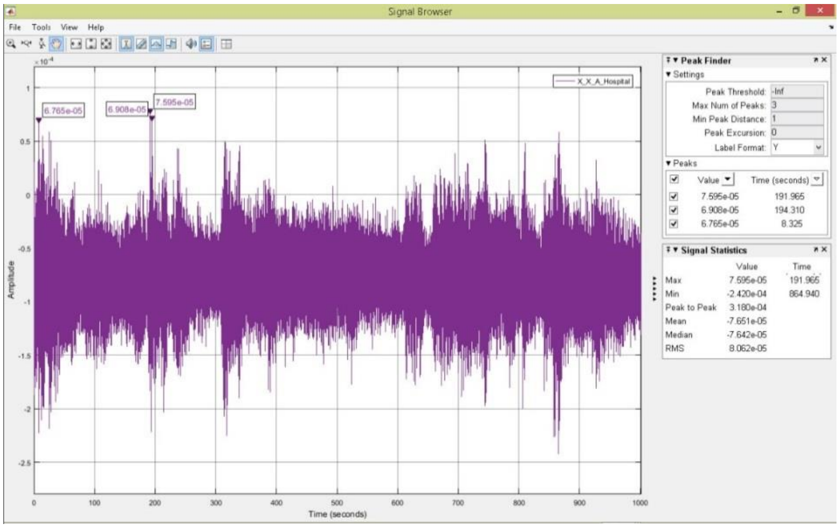
Resolution:	24 Bit
Communication Interface:	Ethernet
No of Channel:	4/8/16 Channels in one box
Type of Measurement:	Differential
Synchronization:	True Simultaneous
Sampling Rate:	2 KHz (2000 sps) / Channel
Filtering:	Anti-Aliasing / Low Pass
Dynamic Range:	140 dB
Measurement Range:	+-5.5V(ATT version) +-17.2mV
Channel Gain:	1/8,1/4,1/2,1,2,4,8,16,32,64,128- Each Channel can be set.
Sensor Excitation:	+5V, +12V, -12V
Power:	12V DC, maximum 40W
Connector Structure:	9-pin circular IP67 pull connector
Enclosure:	Ex-proof mobile casing complies with “NATO Cage Code A7423”
Memory Option:	Limited by USB flash disk capacity
Microprocessor:	ARM Cortex, embedded Linux operating system

4. The Record Characteristics

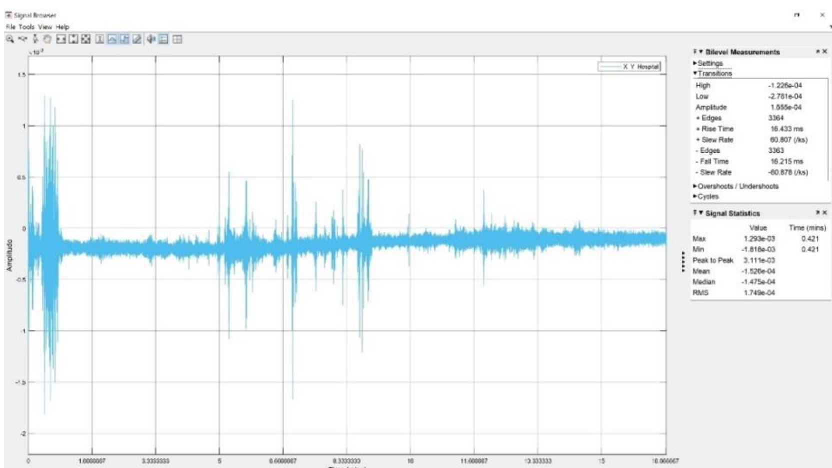
The acceleration records obtained from the hospital structure were taken in two directions perpendicular of the main directions of the structure with duration of 2000 seconds along with a time interval of 0.01 seconds. Three sensor were responsible to implement this test. In terms of two straight lines, a total of 6 records were obtained for this structure which is shown in Figure 3 (a to f). The position of the sensors attached in each floor of the structure, is shown in Figure 4.

By utilizing the frequency domain method for peak-picking, the authors received the values of the fundamental frequencies in both directions. The mode shapes is shown on

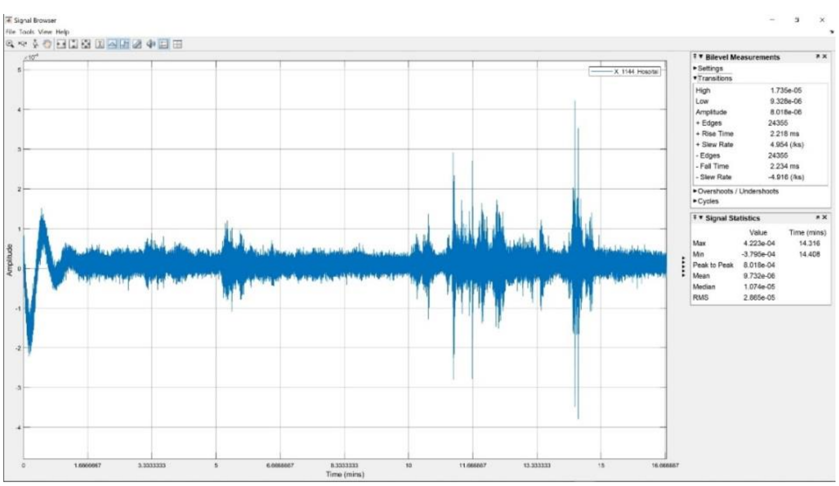
Figure 5 (a, b), in two main directions. Using the singular value decomposition of the power spectral density is obtained for Eigen values and Eigen vectors.



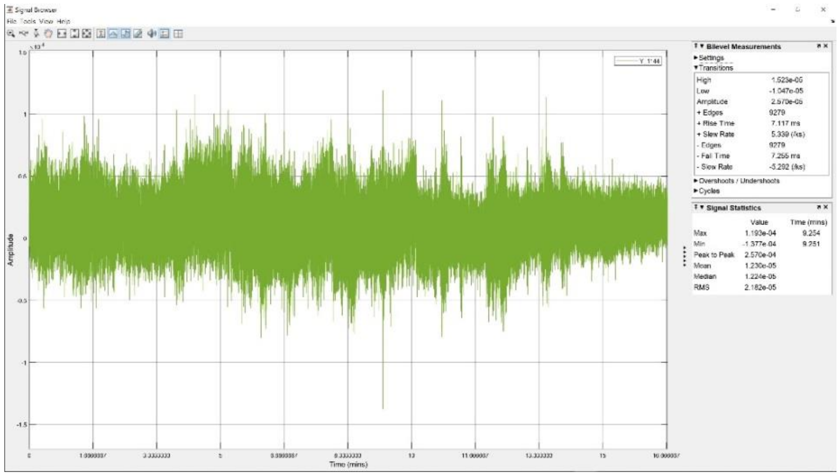
a) Sensor on the fifth floor of the longitudinal direction



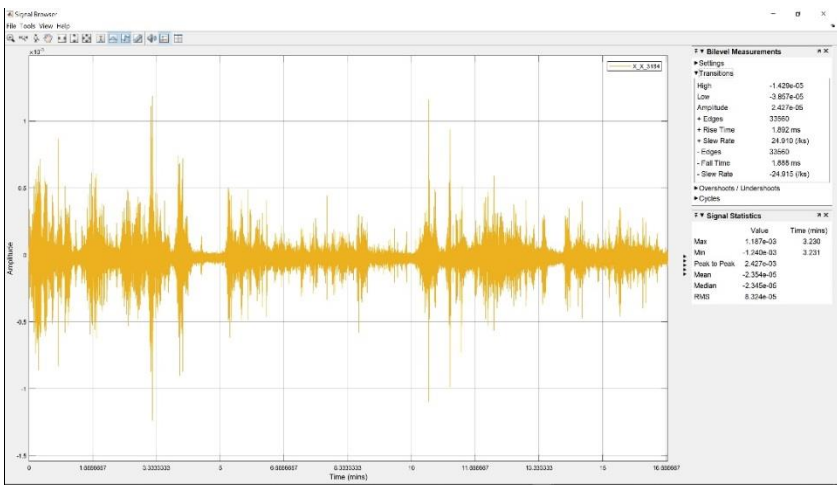
b) The sensor on the fifth floor



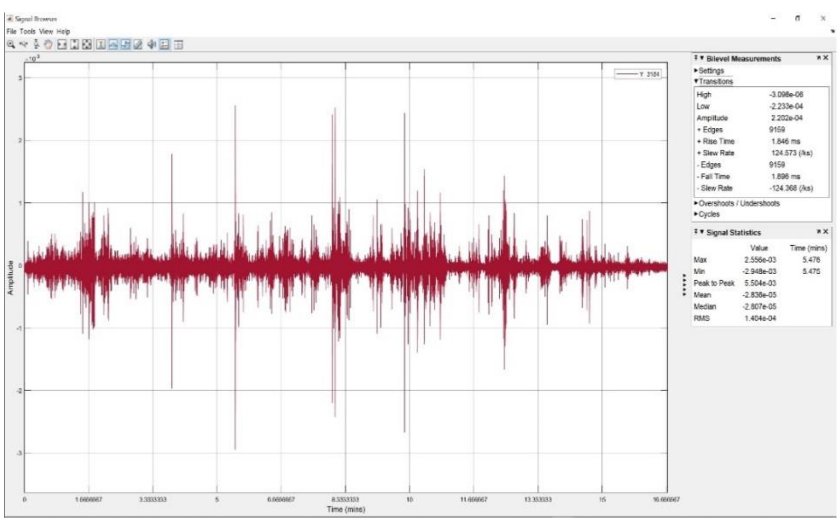
c) Sensor on the third floor along the longitudinal axis



d) The sensor on the third floor is transversal



e) The sensor on the first floor of the longitudinal direction



f) The sensor on the first floor is transverse

Fig. 3. Records taken from the hospital structure in two main directions of the building and in different floors (a to f).

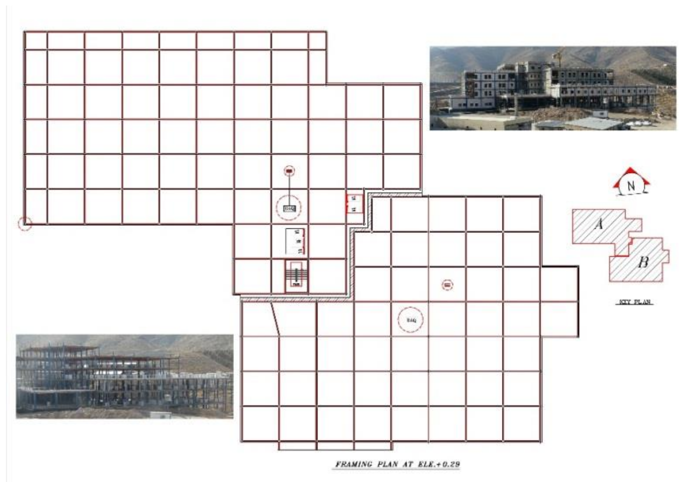
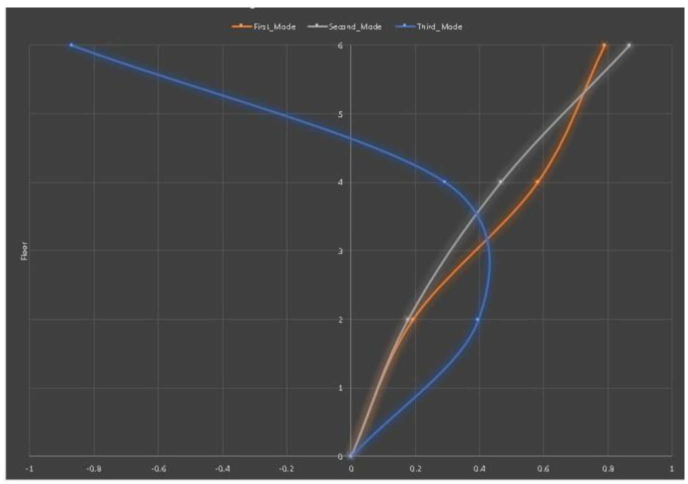
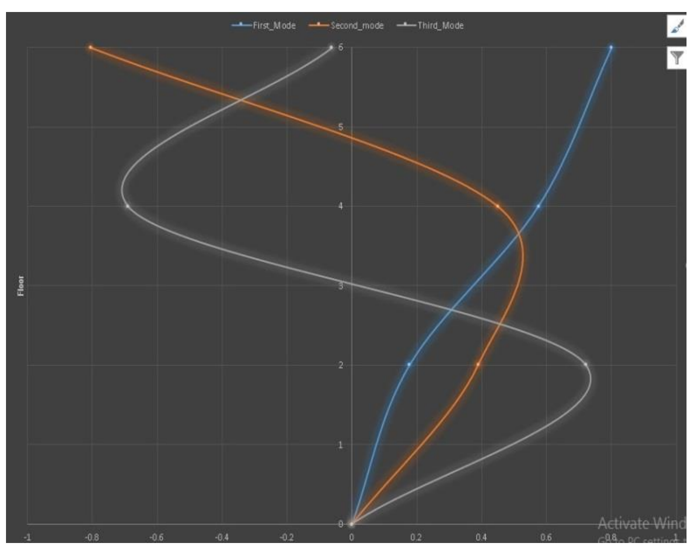


Fig. 4. The position of the sensors.



(a)



(b)

Fig. 5. (a) Mode shape in the longitudinal direction of the building, (b) Mode shape along the transverse side of the building.

The structural health monitoring algorithms can be categorized into two main classes, namely parametric and non-parametric methods. In the parametric health monitoring, the mathematical model governing the structural behavior is known and then intended to identify possible changes in structural parameters relative to the reference model to obtain as well as to determine the position of the defect [14]. On the other hand, the non-parametric methods map constructive inputs to outputs without any information about the internal structure of the structure. Damage is achieved by identifying changes made to the intrinsic parameters or non-physical model made [15]. However, non-parametric models cannot determine the position of damage without prior information. All probable damages and structural responses are available. Nevertheless, the outstanding score for health monitoring methods of non-parametric structures compared to parametric attitudes is their ability to consider the full dynamic of the structure, including simplified or unmodified dynamics [16].

Many other methods in either time domain or frequency are developed in the light of the theory of system Identification. The simplest of them is the frequency domain decomposition (FDD) while contains the separation of power matrices (spectral density) of power spectral density (for the systems of a degree of freedom) with a singular value. The Fourier power spectral density matrices of the correlation matrices are simultaneously between all the recorded signals, so that no model is preferable [17]. Spectral Density Matrices of Input Signals (Unspecified (and Output)), the functions of the angular frequency ω can be given as [X](ω) and [Y](ω), respectively [18].

The modal software is utilized as ARTeMIS Modal PRO. The results of three methods of FDD and three methods of SSI are compared and then analyzed with each other which is shown in Table 3, 4.

Table 3. Frequencies and damping obtained with different methods of frequency domain analysis with software ARTeMIS.

Modes	Method	Frequency(Hz)	Period(Sec)	Damping(%)
First	FDD	0.877	1.14	-
	EFDD	0.878	1.139	0.231
	CFDD	0.878	1.139	0.278
Second	FDD	0.923	1.083	-
	EFDD	0.926	1.08	0.369
	CFDD	0.926	1.08	1.181
Third	FDD	2.487	0.402	-
	EFDD	2.496	0.4	0.592
	CFDD	2.493	0.401	0.257
Fourth	FDD	4.146	0.241	-
	EFDD	4.146	0.241	0.095
	CFDD	4.165	0.24	0.048

Table 4. The frequencies and damping obtained by various methods of stochastic subspace identification with software ARTeMIS.

Modes	Method	Frequency(Hz)	Period(Sec)	Damping(%)
First	SSI/UPC	0.895	1.117	1.793
	SSI/CVA	0.895	1.117	1.138
	SSI/PC	2.201	0.454	2.749
Second	SSI/UPC	1.009	0.991	8.978
	SSI/CVA	2.156	0.464	2.501
	SSI/PC	2.542	0.393	1.934
Third	SSI/UPC	2.19	0.456	3.537
	SSI/CVA	2.529	0.395	1.696
	SSI/PC	3.142	0.318	2.162
Fourth	SSI/UPC	2.562	0.39	2.125
	SSI/CVA	5.026	0.199	2.49
	SSI/PC	5.051	0.198	1.943

5. Stability Diagram and Modal Assurance Criterion

The Stability Diagram is an effective way to display and identify the modes of a structure under test. Nowadays, the Stability Diagram is the standard method for the modal parameter identification stage. It provides a graphical representation of the system's poles (modes) at different mode orders during the modal parameter identification stage [19].

This diagram is utilized to identify the type of parameters. By increasing the order of the model, the values of the system's frequencies are obtained, which allows the selection of the real and actual modes from non-realistic and noise which is shown in Figure 6 (a, b).

The mode Assurance criterion is defined as a scalar constant that correlates the degree of compatibility (linearity) between one modem and another reference method in the following [20].

$$MAC_{cdr} = \frac{\left|\{\psi_{cr}\}^T \{\psi^*{}_{dr}\}\right|^2}{\{\psi_{cr}\}^T \{\psi^*{}_{cr}\} \{\psi_{dr}\}^T \{\psi^*{}_{dr}\}} \quad (1)$$

The mode assurance criterion takes a value of zero, which indicates that there is no matching compatibility and one that represents the similarity of the corresponding. In this matter, if the surveyed mode vectors correctly show both similarity and linearity, the mode assurance criterion should be close to one while the mode factor can be considered reasonable. In spite of the intercalation calculations, it should be noted that the mode assurance criterion is normalized by the size of the measurements and therefore is limited only to zero and one.

The mode assurance criterion can only show the similarity while it cannot display the validity and interchangeability of the devices. If errors, randomness, or bias exist in the estimation of all modifier vectors, these errors cannot be displayed in the mode assurance criterion. Mainly, the invalid assumptions usually cause this type of potential error. Although the mode assurance criterion is one, these assumptions that do not include system estimation techniques or modal parameters, are not necessarily correct. These assumptions may cause the similarity errors in all modal vectors under all approved test conditions by the mode assurance criterion [21].

For most concrete or steel structures, a proportional damping model is usually a good estimation. In such cases, the shape of the motions is real, which means that the maximum and minimum values occur during the movement of the shape during movement. If the shape of the modes was complex, it could be interpreted due to one or more of the following reasons:

- Non-proportional damping;
- Either inappropriate measurements or poor estimation of modal parameters;
- Contradictory data, e.g. variable time conditions;

Another way to see this is to look at all the components of the mode shape on the complex plane. This kind of diagram is called complex plotting. Each component of the mode shape, which starts from (0.0) and indicates to the real value and imaginary component of mode shape. The component that has the real value must be generated in the horizontal direction. Therefore, the complex amount is represented by the vertical component. There is a standard for mode complexity criterion, which can be said to be specified as follows for a modulus:

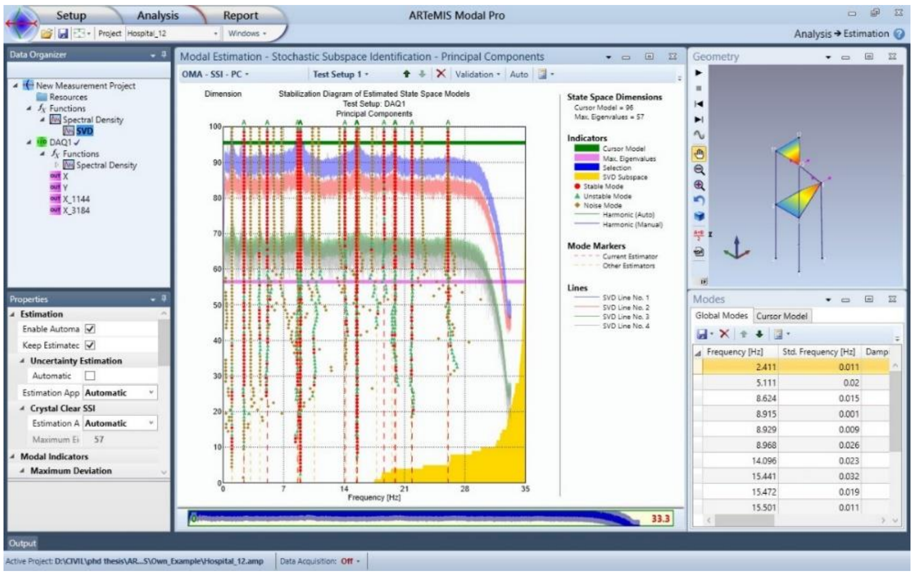
$$MCF_r = 1 - \left[\frac{\left\{\left(S_{xx} - S_{yy}\right)^2 + 4 * \left(S_{xy}\right)^2\right\}}{\left(S_{xx} + S_{yy}\right)^2}\right]$$

$$S_{xx} = Re\{\psi_r\}^T Re\{\psi_r\}$$

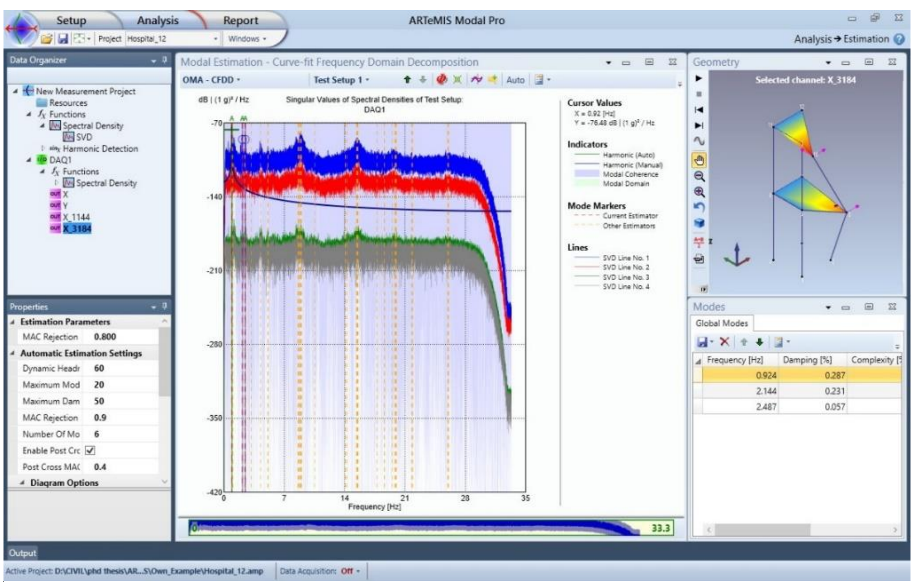
$$S_{yy} = Im\{\psi_r\}^T Im\{\psi_r\}$$

$$S_{xy} = Re\{\psi_r\}^T Im\{\psi_r\} \quad (2)$$

This value is between zero (real modes) and one (imaginary modes), which is illustrated in the form of a percentage. The first mode in one direction of the structure, is shown in Figure 8. Therefore, for real modes, this factor should be almost zero.



(a)



(b)

Fig. 6. (a) The results of the stochastic subspace identification method, (b) The results of frequency domain analysis.

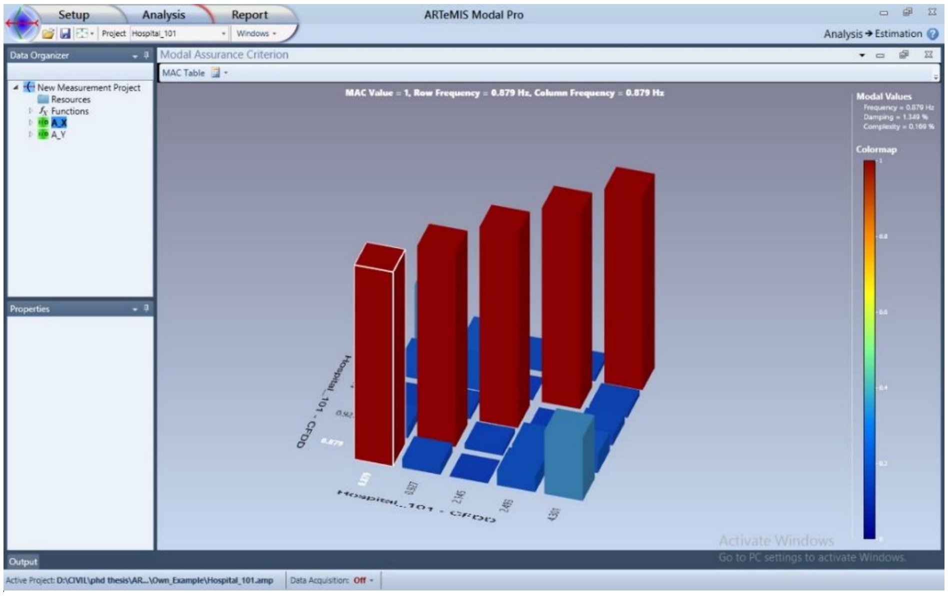


Fig. 7. Modal assurance criterion.

Fig. 8. The First Mode Complex Criterion Ratio for the Structure.

6. Conclusion

The limitation of number of sensors compels us to study only limited number of vibration modes. So, the bending vibration modes were studied when the first few modes are dominant vibration modes. Therefore, the bending modes in two perpendicular coordinates that have significant modal participation factors in dynamic behavior of the building where studied.

The interpolation was performed just for presenting schematic of mode shapes which can be used for verification of odd floors phases in mode shapes. In fact, no interpretation was presented in the manuscript for the missing stories of the mode shapes. Actually, the focus has been on the natural frequencies and damping ratios of the building that estimated by the ambient vibration test. In the isolated structure, due to the horizontal stiffness of the lead core and the level of excitation in the ambient vibration, it is not the difference between fixed-supported and isolated structures. Of course, if the lead core isolators were not used, there are possibility of movement of the isolators. but it is conflicted with the design philosophy of the equipment.

The critical damping ratio for the devices in the FDD and SSI are different, which could be due to the filter used in the time domain analysis method, when the important part of the signal energy was eliminated.

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