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Numerical Assessment of Building Vibration Techniques Using Laboratory Models

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ABSTRACT

Experimental Modal Analysis (EMA) is one of the most attractive engineering fields nowadays, which specifies in the studies of modal parameters of existing small buildings under forced vibrations. This study aims to experimentally validate the modal parameters by comparing results obtained from accelerometers with those measured using Linear Variable Differential Transformer (LVDT). Numerical methods such as Fourier transform, peak picking, and the frequency domain decomposition (FDD) technique were used for modal parameters extraction and validation. Finite element modeling of the laboratory model, including the support flexibility, was investigated. In addition, a novel method for modal parameters' identification from the decomposed modal responses recorded by LVDT, was introduced. The experimental results showed that the natural frequencies obtained are in good agreement with the finite element method (FEM) and numerical methods. The validity of the proposed method paves the way for more effective output-only modal identification for the assessment of existing concrete buildings.

Keywords: Experimental Modal Analysis, Operational Modal Analysis, Impact Testing, FDD, LVDT.

1.INTRODUCTION

One can divide modal testing into two main categories: experimental modal analysis (EMA) that utilizes controlled input forces; and operational modal analysis (OMA) that utilizes operation forces. During the last two decades, both forced vibration and in-operation forces have been used, and they clearly showed their capability of determining the dynamic characteristics of structures.

The concept behind OMA testing techniques is that the structure to be experimentally measured is being excited by some types of excitations from different sources such as (wind, traffic, machinery, and the occupants of the building) not to mention it also contains white noise characteristics. That kind of excitation would give energy distributed over a wide range of frequencies, which depends on the capacity of the recording instruments. It should simply cover the frequency range of the modal fundamental mode shapes of the building to be tested. The most crucial issue in OMA is that all the required modes shapes of the tested building are adequately excited so that the utilized measurement method can acquire their energy contribution [1].

There are numerous reasons for performing vibration measurement. One of those reasons is to monitor the status of a given structure under various loading conditions. That would be useful for damage detection and control for existing buildings' structural health monitoring (SHM). Moreover, building vibrations is measured to identify the natural frequencies for a given structure to verify the analytical models and identify the dynamic response under different environmental conditions [2].

In-operation forces rely on forces of nature (wind and traffic) to excite the structure, but one setback in this method is that the sensor sensitivity should be very high to capture low vibration (Ambient Vibration) measurements. Many researchers have extensively studied this point in the last few decades. Gavin et al. [3] collected ambient vibration measurements to study the behaviour of four flat-plate reinforced concrete structures on Manhattan island in New York City. The buildings range from 27 to 52 floors, with aspect ratios ranging from 2.1 to 5.3. They developed ambient vibration analysis software based on the fast Fourier transform.

They concluded that ambient vibration (AVT) measurement analysis of a high-rise structure is beneficial in revealing the difference between the as-built characteristics of the building and its design representation.

Lee et al. [4] have evaluated the reliability of code formulas such as those of the Korean Building Code, UBC 1997, NBCC 1995, and BSLJ 1994 for estimating the fundamental periods of RC buildings with shear-wall dominant systems. That study relies on full-scale measurements of fifty RC apartment buildings ranging from 10-25 floors besides ambient surveys. Then, they proposed an improved formula based on regression analysis of the measured period data; for estimating the fundamental periods of apartment buildings with shear-wall dominant systems. In Europe, after introducing the capacity design principles in seismic regulations, the periods of vibration obtained for modern buildings were far less than their older equals [5]. In CA, USA, Celebi has identified dynamic characteristics for an undamaged case study building and its nearby free-field site; for strong and weak motions [6]. For that building, there have been numerous studies of several sets of vibration data. For that building, there have been numerous studies of several sets of vibration data. Furthermore, he has summarized variations of dynamic characteristics; for strong and weak motions for four additional buildings. He has concluded that dynamic characteristics of buildings; identified from weak motions cannot be generally used instead of those identified from strong shaking.

The fundamental period of vibration depends on the distribution of the mass and the stiffness of the structure. The evolvements of structural analysis techniques reveal to structural engineers the shortcomings of their representation of the structural behavior under lateral loading. For instance, the misrepresentation of nonstructural elements and the effect of soil during modeling will make the structure looks as if it is less stiffened than after construction. The contribution of the masonry infills walls to the lateral response of buildings should not be overlooked, as it can drastically change the lateral response of RC framed buildings by increasing the total mass and stiffness of the building; which can change the estimation of its natural period, hence affect the total-shear base force calculated [7] and [8].

Vibration analysis can give a good idea about the contribution of nonstructural elements in increasing the overall stiffness of the structure during various stages of construction. One can consider many other parameters; as the type of foundation and the soil underneath the structure. One can perform modal analysis for buildings by representing the combined structure-foundation system as a unit structural model. In this case, the base stiffness is represented by a series of translational and rotational discrete springs [9].

The past research also showed how complex the study of forced vibration could be, especially for significantly large structures [1]. For those latter, it would be very complicated to generate the force required to excite the building. For example, the exciting force may be induced by generating a ground motion, by a blast produced from an explosive buried in a hole away from the structure. Moreover, this type of excitation might be risky as it can cause permanent damage to the building; if not controlled appropriately. For small-size buildings: and for laboratory experiments, it would be a different situation, as will be shown later in this paper [10] and [11].

The results of the operational modal testing test conducted by researchers from the University of British Columbia at the Heritage Court Tower (HCT) Two buildings have been presented by Brincker and Ventura [12]. Furthermore, they have presented three other complementary case studies that illustrate many important aspects of OMA testing. The first case shows how OMA can be used to determine the dynamic properties of a building under construction; the second case illustrates the use of OMA to determine the dynamic properties of a large complex cable-stay bridge, and the third case shows the results of studies done on a cargo ship.

The present research focuses on determining the dynamic characteristics of small-size buildings by forced vibration testing or the EMA method. Large-size buildings are not the subject of this research because of laboratory limitations. In the present work, the tested structural model is excited throughout a controlled-predefined input force. Sensors are placed at selected locations on the model; in such a way that obtaining the needed information is possible. Then, the structural response is measured in terms of acceleration time histories to determine the dynamic characteristics of the model. Those results can be used to compute the frequency response functions (FRFs), from which the natural frequencies, damping values, and mode shapes of the structure can be computed; based on well-established mathematical formulas.

This research is concerned with some points that need further investigation. Firstly, validation of extracting modal parameters of a structure under ambient vibrations by numerical techniques by LVDT and any available commercial FE package such as SAP 2000 [13]. Secondly, this study accounts for the interaction between the structure and underlying soil. Thirdly, the ambient vibration of the laboratory model is assessed. Finally, the results obtained through the study are discussed, and the main conclusions are given.

2.EXPERIMENTAL WORK

The purpose of laboratory testing is to validate the numerical methods utilized for extracting modal parameters; analytically. Besides, the reliability of the devices used for vibration measurement will be calibrated. Then, the calibrated devices and validated numerical methods; will be utilized in further future investigations concerning the fundamental period for RC buildings.

2.1.Laboratory Model

The laboratory model includes a two-floor space steel frame shown in Figure (1). As given in Table (1), the columns were four rectangular steel columns of 5 × 50 mm cross-section and 400 mm; floor height (H). The floor slab was a (400 × 300 × 2) mm steel plate; supported along all sides on edge beams of 5 × 50 mm cross-section. All structural members were rigidly connected by proper welding. The foundation of the laboratory model was a (500 × 400 x 80) mm concrete slab; bedded by a sand layer of 50 mm thickness to compensate for any irregularity of the footing shape. The columns were hooked at the base and embedded in the concrete footing.

***Table 1** Steel sections forming the laboratory model elements*

Element	Section Type	Section Size
Columns	Plates	5×50×H mm
Beams	Plates	5×50×B mm
Floors	Plates	400×300×2 mm
Add. Weight	Concrete cubes	Each cube weighs 8 kg

***Figure 2** A 2-story space frame (Laboratory Model) during placement of concrete for foundation slab.*

***Figure 1** Wit-motion accelerometer.*

2.2.Description of the Accelerometer

The device used in measurements is Witmotion triaxial force balanced accelerometer, Figure (2). It has the following characteristics: high Module integrates high-precision gyroscope, MPU 9250 geometric sensor, high-performance microprocessors, and advanced dynamics solves dynamic Kalman filter algorithm to quickly solve the current real-time movement of the movement attitude [14]. The use of advanced digital filtering technology can effectively reduce the measurement noise and improve measurement accuracy. Besides, it can measure acceleration in x,y, and z-axes. Its range is ±16g (g equals the gravitational acceleration) along with a maximum sampling frequency of 50 Hz, which means it can read a sample each 0.02 sec. This device will capture the structural response in the form of acceleration records in three different axes (x,y,z), Figure (3).

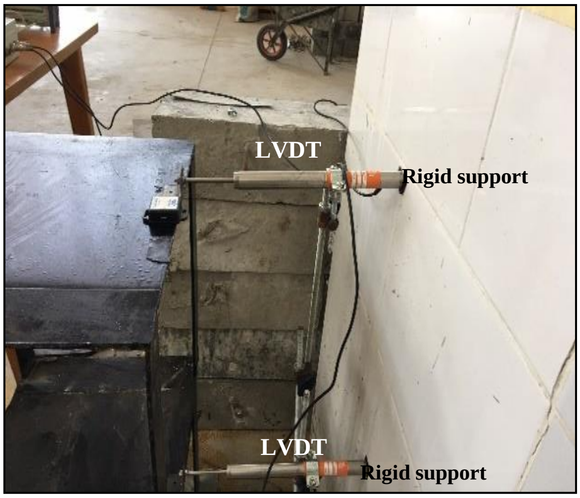

***Figure 3** LVDT and Accelerometer setup.*

2.3.Description of Mobile Sensor

The mobile sensor used is (Bosch MBA280). It has the following characteristics: a 3-axis accelerometer, accelerometer range of ±16g; along with a maximum sampling frequency of 100 Hz; which means it can read a sample each 0.01 sec.

2.4. Description of the LVDT

LVDT is a common type of electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electric signal. Two units were mounted to measure the displacement at each floor. Each was mounted then connected to the floor by a tight setup to secure more accurate results, Figure (4).

Figure 5 *LVDT's connection to the model and fixation to the wall.*

A data acquisition box (DAQ) was connected to each LVDT. The DAQ had an individual channel specified for each port. The whole setup was connected to a computer software package, Figures 5 and 6.

Figure 6 *The connection between the LVDT - DAQ setup and the computer.*

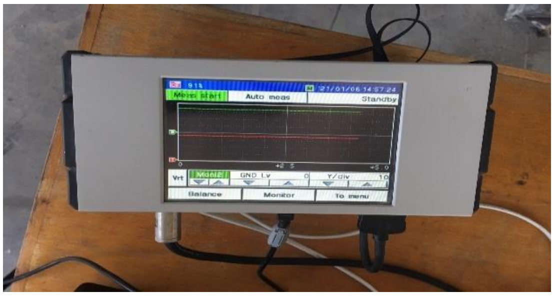

Figure 4 *The display monitor of the DAQ while recording measurements.*

Vertical Loading and Excitation Method

The current tested two-story space steel frame relies on a type of EMA (forced vibration-impact testing). Additional variable vertical floor loads in the form of concrete cubes were applied to increase the structure mass. The model was tested experimentally by different methods, and it was analyzed numerically by the FE commercial package (SAP 2000) to acquire its different mode shapes.

The concept was to impact the structure by an impact hammer and measure the structural response by an accelerometer (Wit Motion); in the form of acceleration records. For further identification, after impact displacements at floor levels were recorded via LVDT units; Figures 3 and 4. The recorded measurements were analyzed by Fourier transform, Peak Picking, and FDD methods. It ends to identify the natural frequency and mode shapes of the structure.

3.ANALYSIS OF LABORATORY EXPERIMENTAL RECORDS

The purpose of these calculations was to evaluate the reliability of the devices used in extracting the modal parameters via one of three devices; namely:

1. LVDT
2. Mobile Sensor (Bosch BMA 280)
3. Reference sensor (WitMotion 3-axis Accelerometer).

Each device has to acquire the input time history data. Data analysis was then carried out by the Fourier transform, based on the Peak Picking method along with the FDD method. Finally, it is possible to extract the natural frequencies and modes of the shape of the model. Our reference data for comparison were the results obtained by finite element analysis performed on the laboratory model.

The FE results were obtained by the commercial software package (SAP2000) in this work. These calculations were performed in two iterations, as shown in the following sections.

3.1.FEM Results

The columns were modeled as a frame element of 5 × 50 mm cross-section and assigned the material properties as steel (with a modulus of elasticity of $2x10^8\ N/mm^2$ and specific weight of $78.5\ kN/m^3$). Both floor steel plates and the concrete footing slab were divided into rectangular shell elements; with the appropriate material properties. Vertical additional loading was applied to each floor as a gravity load. For compensating for the rigidity, a body diaphragm was provided at each connection between the frame and area elements (at least at three different nodes), Figures 9 to 12. Both rigid and flexible conditions were assumed at the column bases throughout the analysis. In the latter case, the soil was represented by a series of translational and rotational spring elements. The spring constants were taken as 20000 kN/m2/m based on the elementary areas; and guidelines for the design of shallow foundations given by the Egyptian code of practice (ECP-202 part 3) [15].

Figure 7 *Test setup for the first trial with additional weight of 16 kg.*

The FE analysis was carried out for two trial floor loads; namely:

a) First trial: where the mass added at each floor was taken as 16 kg, Figure (7), and

b) Second trial: where the mass added at each floor was taken as 32 kg, Figure (8).

Figure 8 *Test setup for the first trial with additional weight of 32 kg.*

3.1.1. First trial

In this trial, each floor was loaded with two concrete cubes (8 kg each) , Figures 9 and 10. An excitation force was exerted to the floor center by a 25 kg weight impact hammer. The natural frequencies and modes of the shape for the test model were then obtained by the Fourier transform, based on the *Peak Picking method* along with the FDD method, Figures 13 and 14.

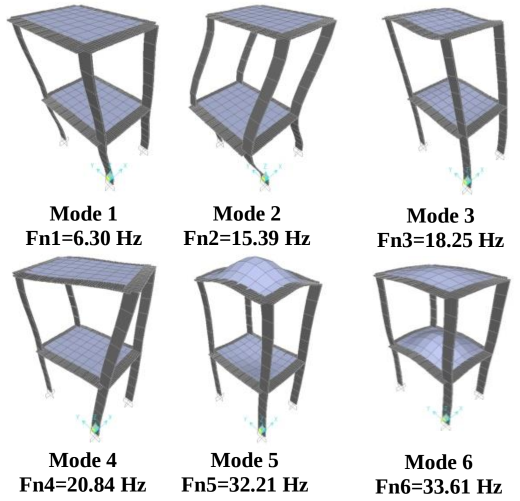

Figure 9 FE *Modal analysis results for the 16 kg trial (Fixed supports).*

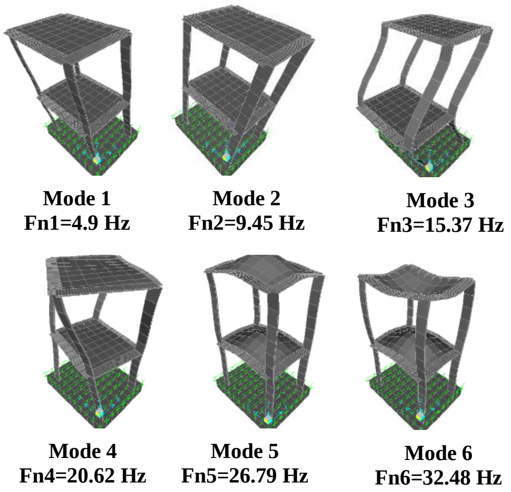

Figure 10 FE *Modal analysis results for the 16 kg trial (Elastic supports).*

3.1.2.Second Trial

In this trial, four concrete cubes (8 kg each) were added to each floor. The results are shown in Figures 11 and 12.

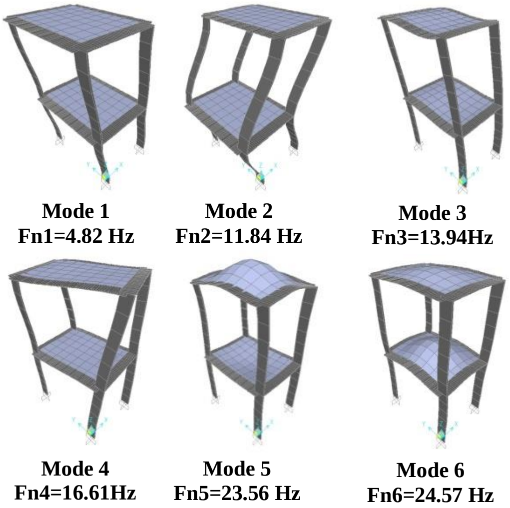
Mode 1 Fn1=4.82 Hz
Mode 2 Fn2=11.84 Hz
Mode 3 Fn3=13.94Hz
Mode 4 Fn4=16.61Hz
Mode 5 Fn5=23.56 Hz
Mode 6 Fn6=24.57 Hz

Figure 11 *FE Modal analysis results for the 32 kg trial (Fixed supports).*

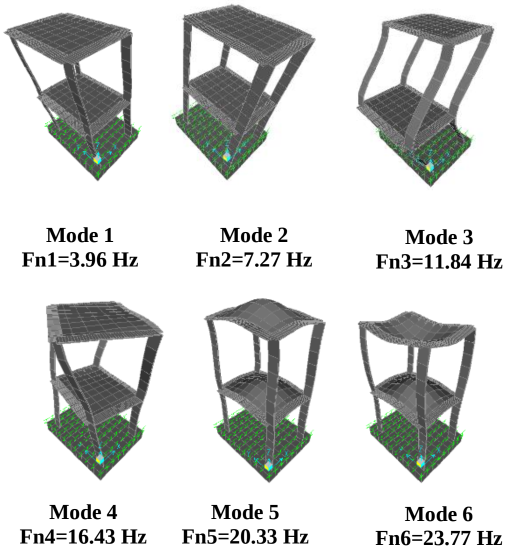
Mode 1 Fn1=3.96 Hz
Mode 2 Fn2=7.27 Hz
Mode 3 Fn3=11.84 Hz
Mode 4 Fn4=16.43 Hz
Mode 5 Fn5=20.33 Hz
Mode 6 Fn6=23.77 Hz

Figure 12 *FE Modal analysis results for the 32 kg trial (Elastic supports).*

3.2. LVDT Readings

An impact force was applied at a specific moment. Then, the resulting accelerations and displacements were recorded by LVDT. Figures 13 to 16 show the displacement-time curves; and LVDT's Spectrum. There is a spike in the data representing the forced response phase at the moment of impact. Then, the model oscillated freely, showing a decaying exponential wave. For the sake of comparison, the Mobile Sensor and Accelerometer were mounted to read the acceleration records simultaneously. The results obtained by those latter will be shown and discussed in the following sections.

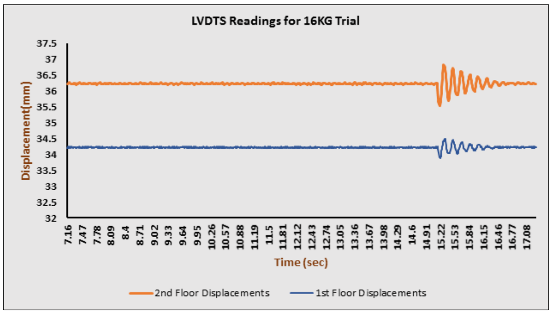

Figure 13 *The displacement-time curve for the 16 kg trial (first trail).*

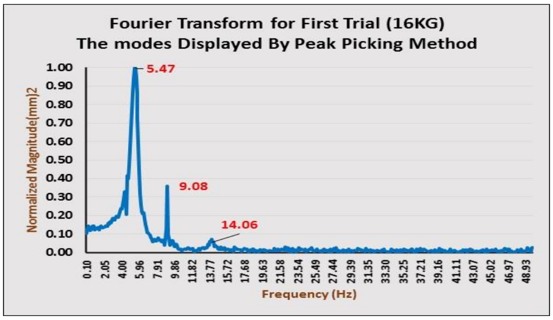

Figure 14 *LVDT's Spectrum for the first trial.*

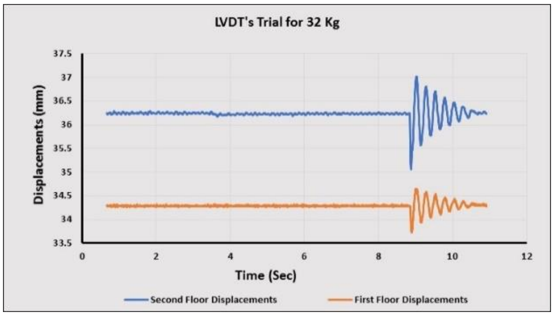

Figure 15 *The displacement-time curve for the 32 kg trial (second trail).*

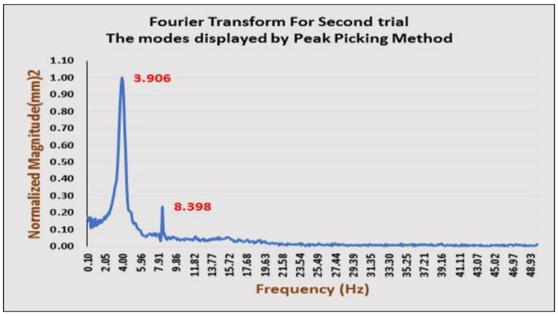

Figure 16 *LVDT's Spectrum for the second trial.*

3.3.Mobile Sensor and Accelerometer Readings

The Acceleration – time relationships and spectrum obtained by the mobile sensor for the two trial floor masses (16 kg and 32 kg), respectively, are depicted in Figures 17 through 20. Corresponding results obtained by the Accelerometer are given in Figures 21 through 24.

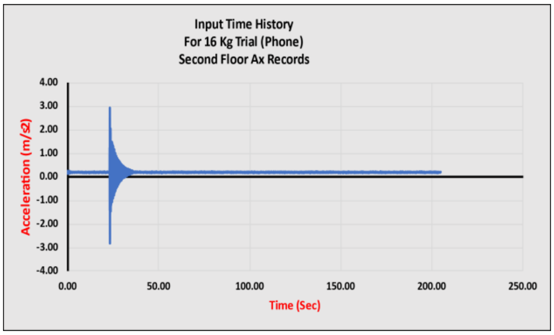

Figure 17 *Acceleration –time relationship for the first trial by mobile sensor.*

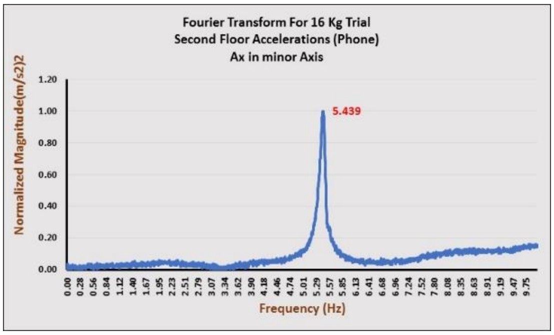

Figure 18 *Mobile sensor spectrum for the first trial.*

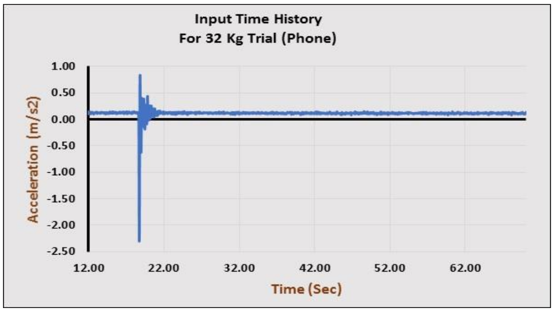

Figure 19 *Acceleration – time relationship for the second trial by mobile sensor.*

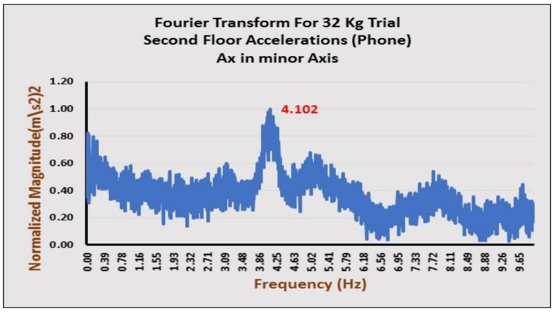

Figure 20 *Mobile-sensor Spectrum for the second trial.*

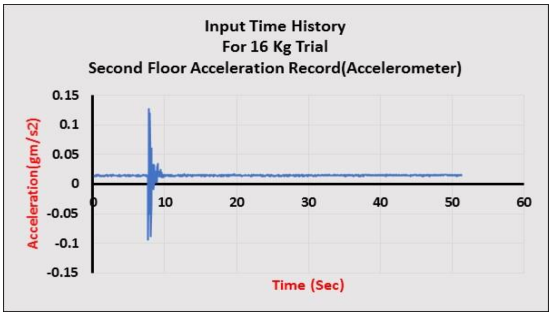

Figure 21 *Acceleration –time relationship for the first trial by accelerometer.*

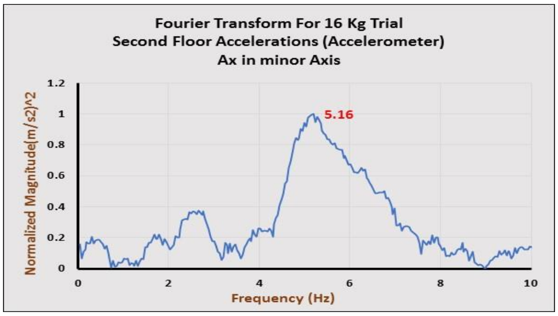

Figure 22 *Accelerometer spectrum for the first trial.*

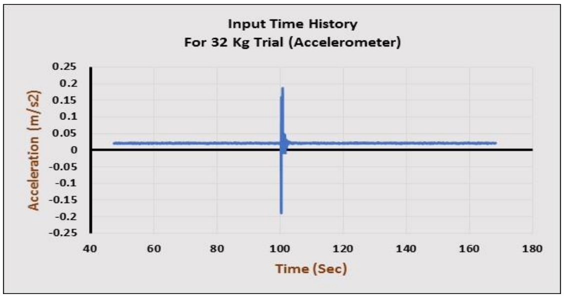

Figure 23 *Acceleration –time relationship for the second trial by accelerometer.*

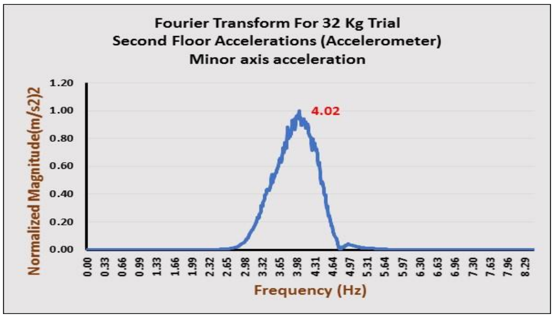

Figure 24 *Accelerometer spectrum for the second trial.*

3.4. Frequency-Domain Decomposition (FDD)

The frequency-domain decomposition (FDD) technique is formulated based on singular value decomposition (SVD) of the spectral density (SD) matrix. FDD technique is very useful when analyzing cases having two closely spaced modes. Hence, it takes the classical frequency-domain approach some steps further. Besides, the FDD approach makes the frequency-domain technique more user-friendly because it concentrates all information in one single plot; that is the plot of singular values of the SD matrix.

The technique was introduced by Brincker et al. and has been widely used for OMA mainly due to its user-friendliness and the implementation in the Artemis Extractor software [17]. The technique is closely related to the complex modal indicator function (CMIF) introduced by Brown and co-workers [18], which was based on an SVD of the frequency response function (FRF) matrix and presentation of the singular values as a function of frequency. Nevertheless, some considerable differences between the CMIF and the FDD techniques are worth mentioning. The most noticeable difference is that the modal decomposition of the spectral matrix follows a different approach than the decomposition of the FRF matrix.

3.4.1.Mode Shape Estimation

In FDD the mode shapes are estimated from the singular vectors of the SVD of the spectral density matrix. Nevertheless, An SVD is given for each frequency where the SD matrix is known because one can perform the SVD for all known frequencies. Accordingly, if we have the same number of modes as we have sensors, then in principle, all mode shapes can be found at one single frequency line. Of course, this is not a correct way to perform the estimate, and we need to consider more carefully how we obtain the estimate accurately.

3.4.2.FDD for Laboratory Model

This technique is best applied by multiple accelerometers taking readings concurrently to capture the model response at different excitation levels, where we can get the energy contribution of each mode in one set of measurements but with multiple locations. Unfortunately, due to lack of resources, the measurements were taken by a single accelerometer held at different locations (8 times to be exact). In each case, the direction of the impact force was perpendicular to the device location. For each measurement, the excitation should be induced at a specific time (after 100 sec of running the measurement). Instead of using Artemis modal software, we utilized a built-in MATLAB code for running this technique [16].

The acceleration records had to be analyzed thoroughly. Even though sensors'-readings were not synchronized, the results were fascinating as shown in Figure (25). It was compared with FEM results in Tables 6. The results will be compared in the next section.

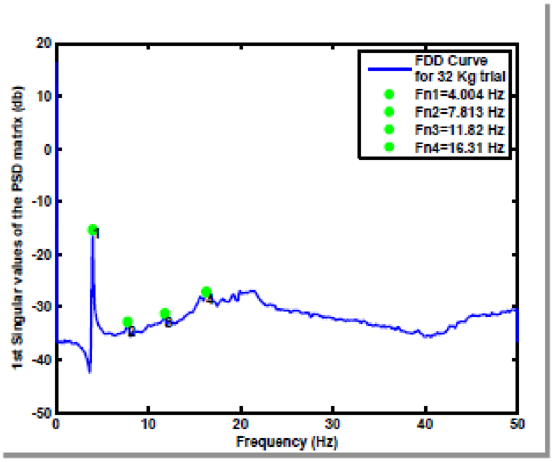

Figure 25 *First singular values of the PSD matrix – FDD technique for laboratory model*

4.DISCUSSION OF RESULTS

Table 2 compares the FE modal analysis results for different modes of the laboratory model for variable conditions at the supports. The natural frequency results are given for both fixed and elastic support conditions. The natural frequency is generally lower for frames with flexible supports. The differences are noticeable. Accordingly, one can say that it is better to introduce more realistic conditions at the supports throughout the modal analysis of structures.

Table 2 *Comparison between FEM results for frames with fixed and elastic supports*

	Natural frequency [Hz]

Method Mass	FEM with fixed supports	FEM with elastic supports	difference
	Mode 1		
16 kg	6.3	4.9	28.5%
32 kg	4.82	3.96	21.7%
	Mode 2		
16 kg	15.39	9.45	63%
32 kg	11.84	7.27	63%
	Mode 3		
16 kg	18.25	15.37	19%
32 kg	13.94	11.84	18%

Tables 3, 4, and 5 compare the modal parameters of the first fundamental mode; obtained by FEM and those obtained experimentally via LVDT, accelerometer, and mobile sensor, respectively. In all three cases, the *Peak picking technique* was utilized to obtain the modal parameters. It is worth mentioning that the first fundamental mode is preferable for depicting the results as it has the same direction of excitation used in the experiments. Moreover, the experimental program includes two stages to raise confidence in the results. In all cases, one can see that the bigger the tested mass, the lower the natural frequency of the frame and its percentage error.

Table 3 *Comparison between the FEM results and LVDT experimental measurements (Mode 1)*

	Natural frequency [Hz]		
Method Mass	FEM	LVDT	Error
16 kg	4.90	5.47	11%
32 kg	3.96	3.906	1.30%

Table 4 *Comparison between FEM results and experimental Accelerometer measurements (Mode 1)*

	Natural frequency [Hz]		
Method Mass	FEM	Accelerometer	Error
16 kg	4.90	5.16	5.36%
32 kg	3.96	4.021	1.5%

Table 5 *Comparison between the FEM results and Mobile Sensor experimental measurements (Mode 1)*

	Natural frequency [Hz]		
Method Mass	FEM	Mobile Sensor	Error
16 kg	4.90	5.439	11%
32 kg	3.96	4.102	3.60%

Table 6 compares the modal parameters obtained by FEM and accelerometer using the *Frequency Decomposition Technique*; for a test mass of 32 kg. The table shows the natural frequencies for four different fundamental modes of vibration. For all vibration modes except for the second (where the error reaches 7.4%), one can find an excellent agreement between the FEM and FDD experimental results. Therefore, it is better to use the *FDD* than the *Pick-Peaking technique* to obtain the modal parameters throughout the laboratory work.

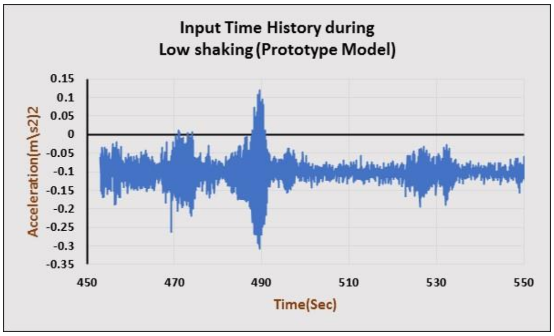

Figure 27 *Time-acceleration history of laboratory model during Ambient Vibration.*

Table 6 *Comparison between the FEM and accelerometer test using FDD technique for different Modes (Mass=32 kg)*

	Natural frequency [Hz]		
Method Mode	FEM with elastic supports	Accelerometer with FDD technique	Error
Mode 1	3.96	4.004	1.11%
Mode 2	7.27	7.813	7.40%
Mode 3	11.84	11.82	0.20%
Mode 4	16.43	16.31	0.80%

4.1.Ambient Vibrations Testing for Laboratory Model

Although impact testing with forced vibrations is the best for small structures, ambient vibration is essential under certain circumstances. Therefore, the laboratory model was placed in open terrain during very high winds. The wind speed on the day of testing was 50 km/hr. The duration of testing was at least 4 hours. A complete setup was made for recording the structural response under

Figure 26 *Laboratory model setup during ambient vibration experiment.*

ambient vibrations, Figure (26). The structural response was traced by recording the time-acceleration history and spectrum, Figures 27 and 28. Table (7) compares the results of FEM, EMA, and OMA experimental work (mobile sensor) under ambient vibration. The natural frequencies obtained experimentally for EMA, and OMA are considerably close to one another. Both are approximately 4% higher than the FEM results.

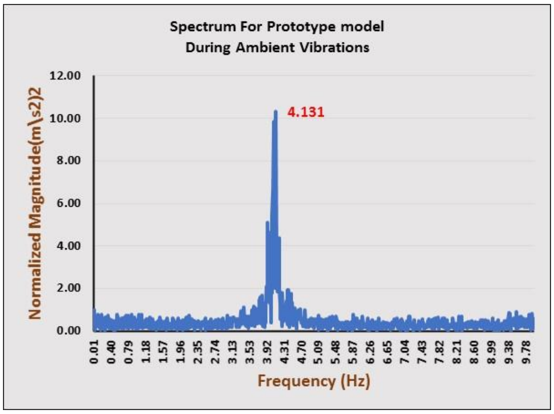

Figure 28 *Spectrum of laboratory model during Ambient Vibration.*

Table 7 *Comparison among the natural frequencies of FEM, EMA, and OMA experimental work under ambient vibration (Mass 32 kg, Mode 1).*

Method	Natural frequency [Hz]		
	FEM	Mobile Sensor	Error
EMA	**3.96**	**4.102**	**3.60%**
OMA	**3.96**	**4.131**	**4.30%**

5.CONCLUSIONS

Based on the numerical and experimental studies conducted in the current work on a two-story space steel frame model, the following could be concluded:

5.1. Laboratory model

1) Experimental modal analysis (EMA) is an effective method for identifying a structure's modal parameters, especially by impact testing.
2) The modal parameters obtained by LVDT, accelerometer, and mobile sensor were noticeably close to each other.
3) The maximum difference between the extracted frequencies by LVDT and accelerometer reached 5 %.
4) The difference between the extracted frequencies by EMA and OMA was less than 1%.
5) The higher the gravity load, the smaller the difference between the numerical and experimental results.
6) The higher the gravity load, the lower the natural frequency of the test model frame.

5.2. Numerical methods

1) The FDD is a perfect method for identifying the modal parameters for a structure, especially when having two closely modes of shape.
2) To avoid statistical errors during data analysis, more devices should be utilized.
3) The effect of support rigidity on the structural response is pronounced. For the model under consideration, the difference in natural frequency reached 28.5 % higher when support flexibility was neglected.

Authorship Contribution Statement

Moataz Elrayes: Writing - original draft, Formal analysis, Software, Investigation, Visualization. **Ezzaat Sallam**: Conceptualization(supporting), resources, Writing - original draft (supporting), Writing - review and editing, Supervision**.** **Emad Abdel Galil:** Conceptualization, Supervision, writing -review and editing.

Declaration of Competing Interest

There have been no involvements that might raise the question of bias in the work reported or in the conclusions, implications, or opinion stated.

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