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Health monitoring of a historical monument in Jordan based on ambient vibration test

Khaldoon A. Bani-Hani*

Department of Civil Engineering, Qatar University Doha, Qatar

Hazem S. Zibdeh‡

Department of Mechanical Engineering, Jordan University of Science and Technology, P.O. Box 3030, Irbid, Jordan

Karim Hamdaoui‡†

Department of Structural Mechanics, University of Pavia, Pavia, Italy

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Abstract. This paper summarizes the experimental vibration-based structural health monitoring study on a historical monument in Jordan. In this work, and within the framework of the European Commission funded project "Wide-Range Non-Intrusive Devices Toward Conservation of Historical Monuments in the Mediterranean Area", a seven and a half century old minaret located in Ajloun (73 km north of the capital Amman) is studied. Because of their cultural value, touristic importance and the desire to preserve them for the future, only non-destructive tests were allowed for the experimental investigation of such heritage structures. Therefore, after dimensional measurements and determination of the current state of damage in the selected monument, ambient vibration tests are conducted to measure the accelerations at strategic locations of the system. Output-only modal identification technique is applied to extract the modal parameters such as natural frequencies and mode shapes. A Non-linear version of SAP 2000 computer program is used to develop a three-dimensional finite element model of the minaret. The developed numerical model is then updated according to the modal parameters obtained experimentally by the ambient-vibration test-results and the measured characteristics of old stone and deteriorated mortar. Moreover, a parametric identification method using the N4Sid state space model is employed to model the dynamic behavior of the minaret and to build up a robust, immune and noise tolerant model.

Keywords: vibration-based health monitoring; system identification; ambient vibrations; historical building.

1. Introduction

The richness of Jordan in archaeological sites and historical monuments suggests that many civilizations have flourished in this country. In addition of their vital role in the touristic and economic

*Associate Professor, on sabbatical leave, Jordan University of Science and technology
‡Professor, Corresponding Author, E-mail: hazemz@batelco.jo
‡†Ph. D. Student

life, cultural heritage structures are valued for their historical importance and attractive construction. Unfortunately, the majority of these structures are in continuous degradation due to aging, weathering and human factors. The desire to conserve these historical buildings for the future generations requires a high level of protection against any probable destructive event (Syrmakezis 2006).

Preserving ancient monuments is directly related to the amount of damage that the structure is expected to undergo through future earthquake actions. In civil engineering, this field is called "Structural Health Monitoring" (abbreviated SHM). It tries to monitor the condition of a structure's "health", which may be defined as the level of deterioration or damage within a building.

During the last twenty years, monitoring and repair has become an economically viable alternative to the demolition and replacement of old civil engineering structures (Rytter 1993). For this reason, various researchers have put considerable efforts into the development of new, more reliable and less time consuming detection methods (Kullaa 2003).

SHM methods are either based on the "on-line" or "periodical" measurements. The on-line measurements (Doebling, *et al*. 1996) category is the most reliable but also the most expensive one. Therefore, many scientists have concentrated their research on the development of reliable methods based on periodical inspection (Caicedo 2001).

An alternative to visual inspections, "Vibration-Based Health Monitoring" is being extensively investigated in various engineering disciplines (Fritzed 2005). It is based on the theory which states that each structure has its unique dynamic behavior which may be addressed as a vibrational signature, and any damage in the structure leads to deterioration in the load carrying capacity, consequently, changes in the physical properties (mass, stiffness or damping). That modification has a significant impact on the dynamic behavior of the whole structure.

The main advantage of SHM global techniques is that measurements in a limited number of locations are enough to assess the state of the whole structure. Also, they are very attractive to civil engineers because they can be used without having direct access to the structural members and without needing previous damage information for the structure, consequently, minimizing time and cost for the damage assessment of the structure.

In the present paper, experimental vibration-based structural health monitoring method is used to reach the goal of identifying the structural properties of the studied minaret. This research work seeks to achieve the following objectives

(1) Site investigation and measurements of the selected historical monument and determination of its current state of damage, if any.
(2) Development of Finite Element Model for the minaret using Sap2000.
(3) Carrying out an ambient vibration experiment for the monument with highly advanced equipment for system identification and vibration measurements.
(4) Vulnerability analysis of the structure using the updated finite element model based on the ambient vibration results.

2. General description of the case study

Ajloun mosque built in 1247 is one of the most ancient mosques in the region (Ghawanma 1986). This mosque is characterized by its minaret which arises at the north-east angle of the praying house, near the northern gate. The case study in this research is limited only to the minaret.

From the first inspection, one can deduce that the minaret is composed of two parts: an original one made of heavy and large stone blocs, and a new extension made of the same material as the mosque. The original part of the minaret was made by the Sultan Addaheir Bebers, 16 years (1263) after constructing the mosque.

The minaret was built by red carved stone; it consists of 4.50 × 4.50 meters square base, carrying a vertical shaft that changes in cross section from a square in the original part to octagonal with a top cap of conical form in the new extension (Fig. 1 and 2). From the inside, a cylindrical shaft of constant inner diameter of 1.60 m extended from the level +6.00 m to the end of the original part (level +21.00 m). This shaft continues to extend up to the level of the upper balcony in the extension part but its diameter changes to 1.40 m (from level +21.00 m to 32.45 m) then to 1.30 m (from level 32.45 m to level 39.30 m). A helical stones stair begins at level +6.00 m. It is interlocked with the stones of the inner cylindrical shaft and is resting at its center on a common stone column of 25 cm diameter at the center of the minaret. A new similar stair was made to climb into the added extension.

The minaret has a small rectangular access of 1.35 × 0.72 meters situated in the western side, in addition to three windows in each side. The interior and the middle ones are wide in the outside and narrow in the inside to admit light and for surveillance and defense purpose, at the same time. The third

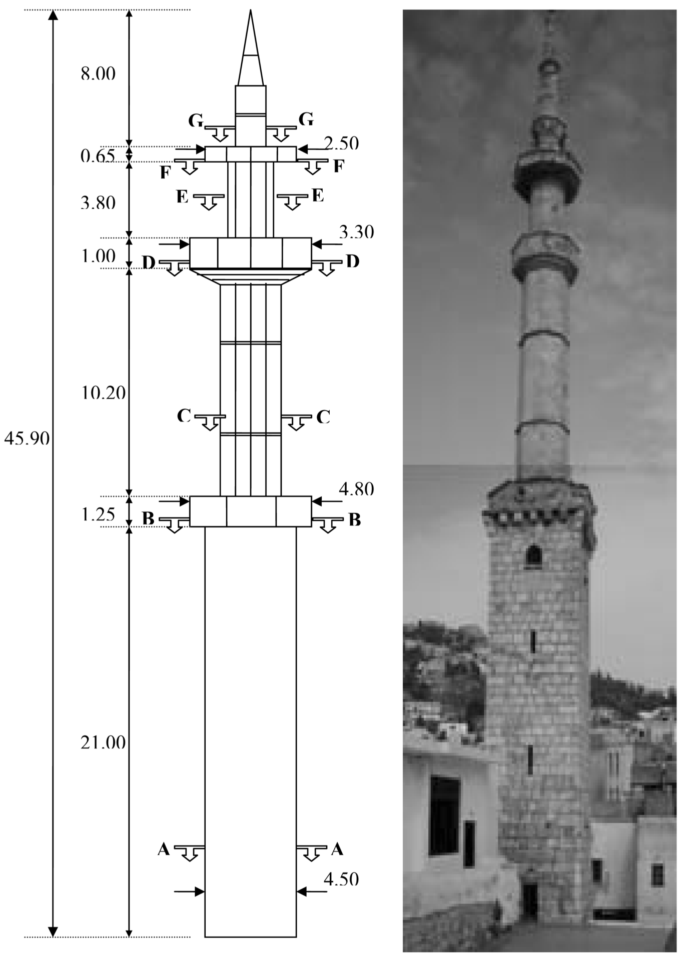


Fig. 1 Ajloun mosque minaret

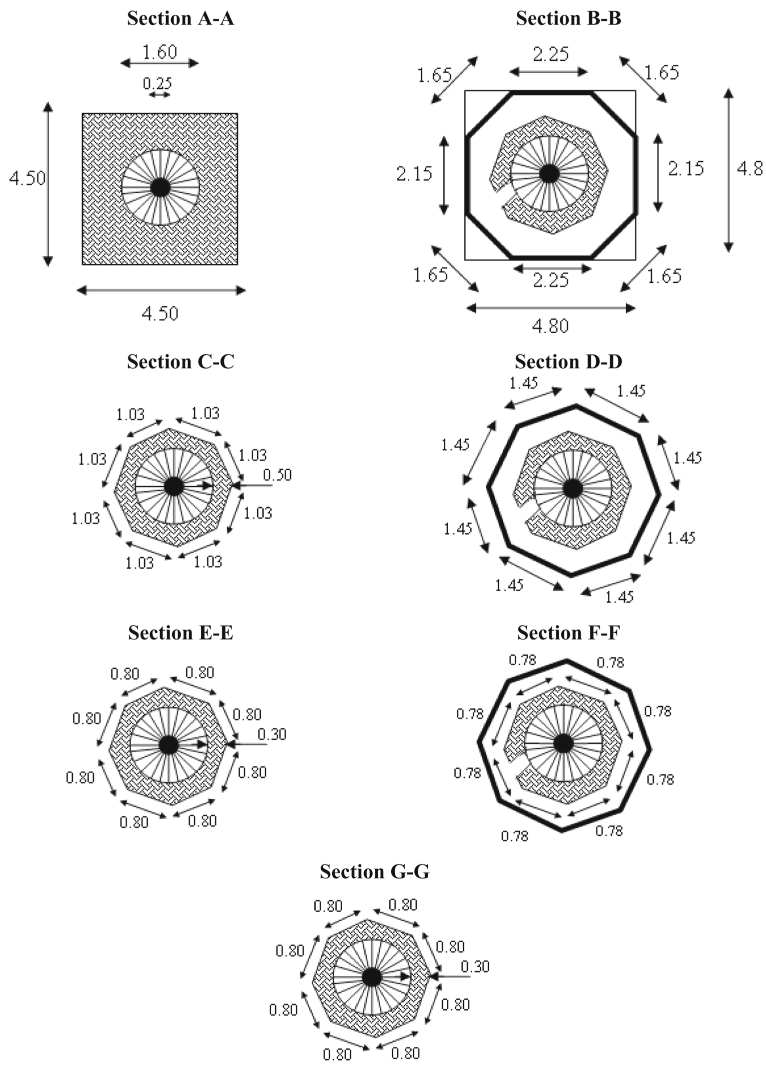
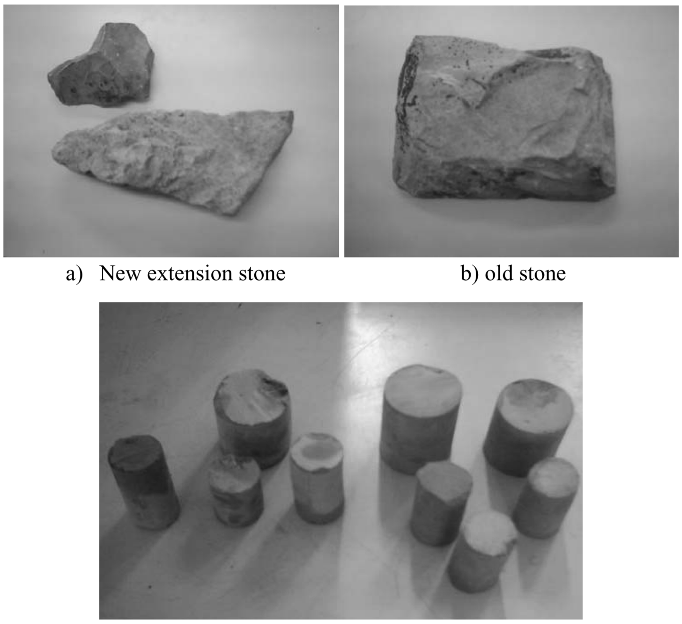


Fig. 2 Different section of the minaret

window is large and vaulted; it is placed at the end of the minaret.

Stairs terminate in a balcony that is supported on five stone-beams at each side, in addition to a stone-corner-beam at each corner. The minaret had an upper part "Cap" (the "Mabkhara") at the top of its original part, but it was demolished to introduce the new octagonal extension. This new extension has an intermediate balcony and terminates with a helmet of conical form.

The material properties of the stone used in the minaret is found experimentally. Due to monument historical value, sampling is allowed only in places that don't affect the monument value. Therefore, all samples were taken from debris stones near the windows. As stated earlier, the minaret body was made of two distinct flat-faced limestone blocks: The first material represents the original old part and the second one is for the new extension (Fig. 3). The samples were tested in compression to determine the compressive strength and the modulus of elasticity of each material; the results are shown in Table 1.



a) New extension stone b) old stone

Fig. 3 Two stone samples taken form the old and new part of the minaret

Table 1 Stones mechanical properties

Property	Old Material	New Material
Elastic Modulus (Mpa)	2100	1700
Specific Gravity (KN/m^3)	26.6	22.3
Compressive Strength (Mpa)	19	17
Poisson Ratio	0.2	0.2

3. Experimental analysis

3.1. Ambient vibration test

Measurement of structural parameters can be best made on by a structure subjected to strong earthquake and being able to conduct strong motion recordings of the input forces and of the response through instrumentation (Magpantay 2006). However, this requires continuous monitoring of a structure since predicting the occurrence of earthquakes is, up to now, unattainable by science. Fortunately, several experimental techniques are available now to excite artificially the structures. The basic idea of tests such as forced vibration, shaking table, transient vibration, micro-tremor excitations, ambient vibration and free vibration (Aghakouchak, *et al.* 2000) is to apply sufficient magnitude of force to the structure in order to produce useful response amplitudes, and study their dynamic characteristics.

For complex, large and heavy civil engineering structures, the artificial excitation is simply impossible (as in the case of tall buildings, towers, bridges etc.). This intricate task can be avoided by using methods that identify the structure exclusively on the basis of measurements of the output caused by ambient vibration (Wenzel and Pichler 2005). For this kind of tests, only output vibrations are recorded.

Because of their cultural value, touristic importance and the desire to preserve them for the future, experimental modal analysis of historical structures (El-Borgi, *et al.* 2005) is generally carried out using non-destructive output-only measured data. Furthermore, these structures are generally more difficult to model than others, and are constructed from inhomogeneous materials that have nonlinear behavior under heavy load.

3.2. Description of the measurement equipments

Ambient vibration response of Ajloun minaret was determined by using the following measurement equipments:

(1) The K2 Strong Motion Digital Recorder (Fig. 4)

(2) A three channels conjunction box (Fig. 5)

(3) Three forced balance accelerometers of model “FBA ES-U2” (Fig. 6)

(4) Three Cables of 20, 20 and 10 metres long

(5) A laptop computer as Central Processing Unit.

The K2 data digital recorded is three channels full-featured Digital Recorder (Fig. 4) designed to meet a wide range of earthquake monitoring applications (K2 Digital Recorder 2006, Kinemetrics 2002).

Uniaxial force balance accelerometers are used to convert the physical excitation into electrical

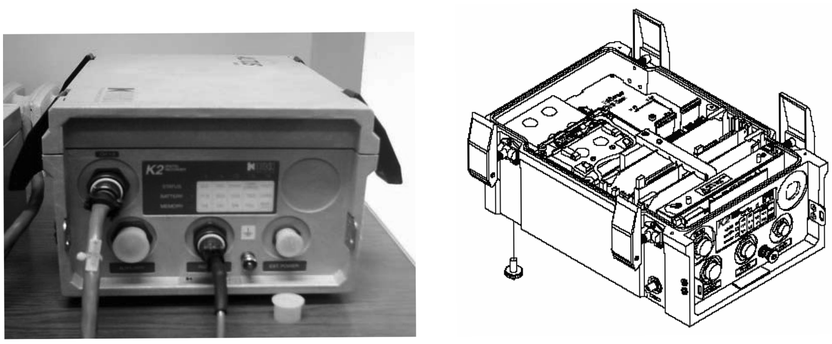


Fig. 4 The K2 digital recorder

Fig. 5 The three channels conjunction box

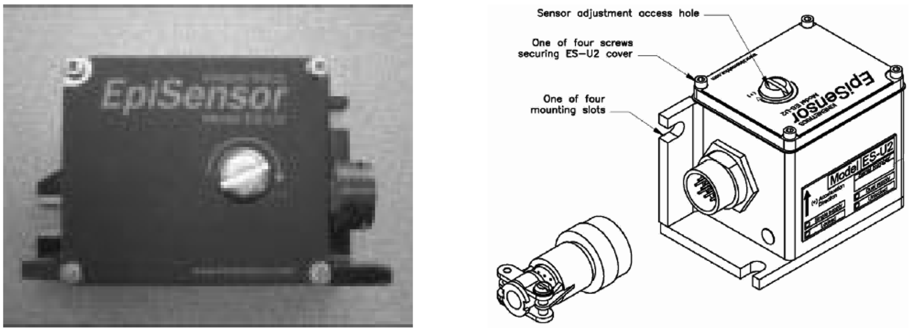


Fig. 6 The uniaxial force balance ES-U2 accelerometer

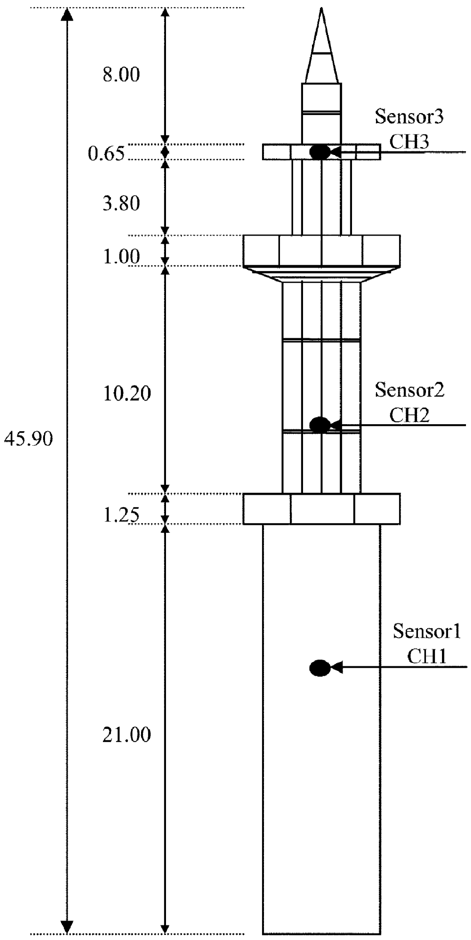


Fig. 7 Location of the three sensors

signals. In the experimental work, accelerometers of type "EpiSensor ES-U2" force balance were used (Fig. 6). They are a uniaxial surface package that can be used for measuring accelerations up to ±4g and down to the ambient noise level (EpiSensor 2006, Kinemetrics 2005).

Fig. 8 Data acquisition system

The uniaxial force balance ES-U2 accelerometer is extremely low-noise; it can detect motions of the ambient vibration field at most urban sites and civil structures from 1 Hz to 200 Hz. The output of the ES-U2 is an amplified, conditioned signal - it requires no external electronics other than data acquisition system.

3.3. Testing procedure

The experiment was conducted on the 31st of December 2005. First of all, the three sensors were placed at strategic locations on the minaret where the lateral motion is assumed to be sensible (Fig. 7). To facilitate their emplacement and detachment they were placed on wood plates that were fixed to the body of the minaret in a horizontal direction to measure the lateral ES accelerations. Each accelerometer was connected to the three channels conjunction box, then to the K2 data acquisition system using cables. In turn, the K2 was connected to the Laptop computer as a central processing unit (Fig. 8).

3.4. Data acquisition

As it was explained in the previous section, the minaret has been equipped with three accelerometers. The data has been sampled at 200 samples per second. To gather maximum data, the vibration readings were continuously recorded over 6 hours, 31 minutes and 35 seconds. This very long event file was then divided into seven parts to minimize the processing time, each of 30 minutes duration file, then selecting useful portions of 5 minutes measurement session, which implies that the final record length has N = 60000 points. This record length is assumed to be adequate in order to obtain accurate system identification. In Fig. 9, the data of one of the measurement sessions is presented for all three channels.

4. System identification

Recalling, the system identification problem is to estimate a model of a system based on observed data. Generally, its basic steps are (Ljung 1987):

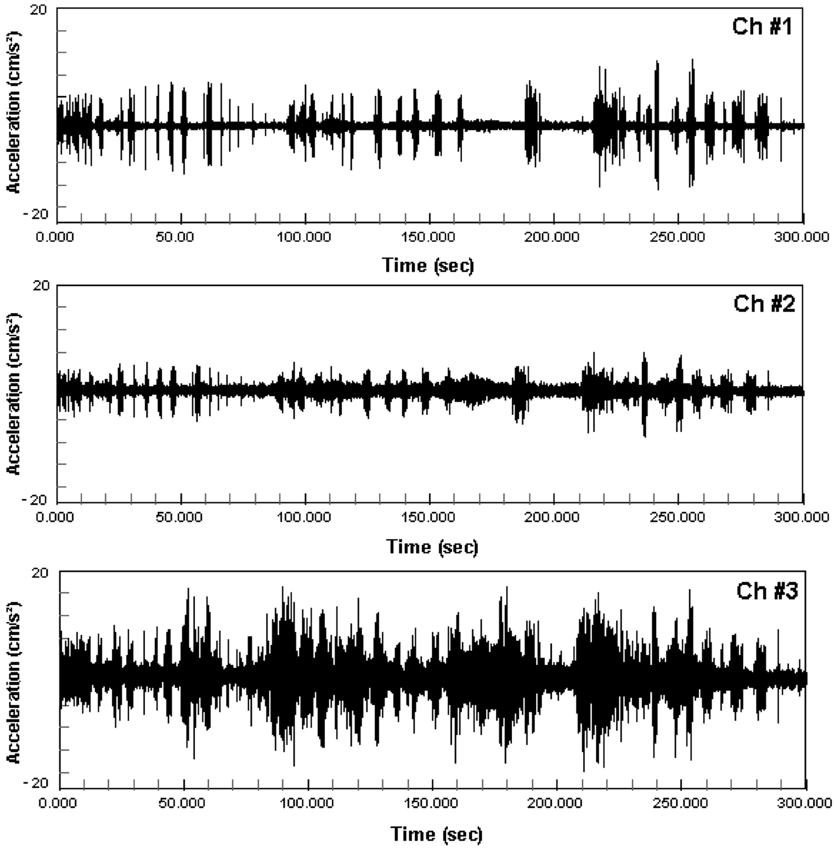


Fig. 9 Example of the measured accelerations of channels1, 2 and 3 respectively

(1) Data acquisition from the process to be identified.
(2) Examination of the data and signal processing so as removing trends and outliers, and selecting useful portions of the original data. Possibly applying filtering to enhance important frequency ranges.
(3) Selection and definition of a model structure (a set of candidate system descriptions) within which a model is to be found.
(4) Computation of the best model in the model structure according to the data and a given criterion of fit.
(5) Examination of the obtained model's properties.
(6) If the model is good enough, then stop; otherwise going back to Step 3. Possibly also to try other estimation methods (Step 4) or work further on the data (Steps 1 and 2).

To solve the complex non-stationary nature of the unmeasured excitation problem, different robust output-only modal identification techniques were developed like the improved Peak-Picking (Peeters and Ventura 2003), Frequency Domain Decomposition (Brincker, *et al.* 2000), Stochastic Subspace Identification (Van Overschee and De Moor 19996, Andersen and Brincker 2006), PolyMAX modal parameter estimation (Peeters and Van der Auweraer 2005), etc. Nowadays, these techniques are available in several software packages such as the ARTeMIS extractor (2006), the MATLAB computer program (Using Matlab Version 2006), etc. In this study, the N4Sid state space identification technique, available in the MATLAB computer program (version 7R14), is applied to extract the modal signature of the minaret.

4.1. MATLAB as foundation for output-only modal identification

The MATLAB (MATrix LABoratory) is an open environment that offers computation, visualization and programming tools. The basic package consists of general-purpose functions that can be used to make more application specific toolboxes (Peeters 2000). Most of the functions are accessible ASCII-files which are compiled at their first call in a session.

After finishing the step of data acquisition (Fig. 9), the examination of data and signal processing are performed using the Graphical User Interface (GUI) (Ljung 2001). It covers most of the toolbox's functions and gives easy access to all variables that are created during a session. The GUI is started by typing "ident" in the MATLAB command window.

Once converting the retrieved data shown in Fig. 9 to ASCII-file format, this data is imported to the MATLAB workspace, then using the system identification subroutines that exist in the system identification toolbox in MATLAB the whole process can be simulated and executed. Several steps of output-only modal analysis are to be performed: preprocessing the data so as to detrend it (by removing mean values) and filter it through a linear filter (to remove drift and high frequency noise), selecting a structural model, estimating it, examining dynamic properties, returning back to previous steps if the model is not good enough. Due to the use of in-plane measurements it is, therefore, expected to identify in-plane vibration modes only and any out-of plane modes can not be detected experimentally.

4.2. Modal identification results

In Fig. 10, the linear power spectra density of the three channels is shown. The first five fundamental frequencies can be easily seen as singular values in the plots.

Table 2 shows the measurement-based estimates of natural frequencies and its corresponding periods of the first five modes using the N4Sid state space identification technique available in the MATLAB.

5. Finite element model

Based on the ambient vibration measurement, a three dimensional finite element model of the minaret was developed and updated using the SAP 2000 (version 8) computer program [26]. Eight-nodded solid elements were used for modelling the selected structure including the helical stairs. Based on the geometric measurements, Fig. 11 shows the finite element model with a total of 29040 solid elements. In non-destructive ambient vibration tests, only small amplitudes are felt. For this reason, linear elastic analysis is adopted which is sufficient for the finite element modelling. The minaret material's behavior is assumed then to be linear elastic, homogeneous and isotropic.

The Finite Element model was updated iteratively by shifting the stone modulus of elasticity using the relationship depicted in Eq. (1).

$$E_{updated} = (T_{old}^2 / T_{updated}^2) E_{old} \tag{1}$$

Where (E_{old}, T_{old}) are the initial values of the modulus of elasticity and system period, respectively, and ($E_{updated}$, $T_{updated}$) are the corresponding updated values.

Fig. 12 shows the first 12 mode shapes of the minaret. It is noted that because of the symmetry of the minaret, mode shapes 1 and 2, 3 and 4, 5 and 6, 8 and 9 have the same dynamic properties.

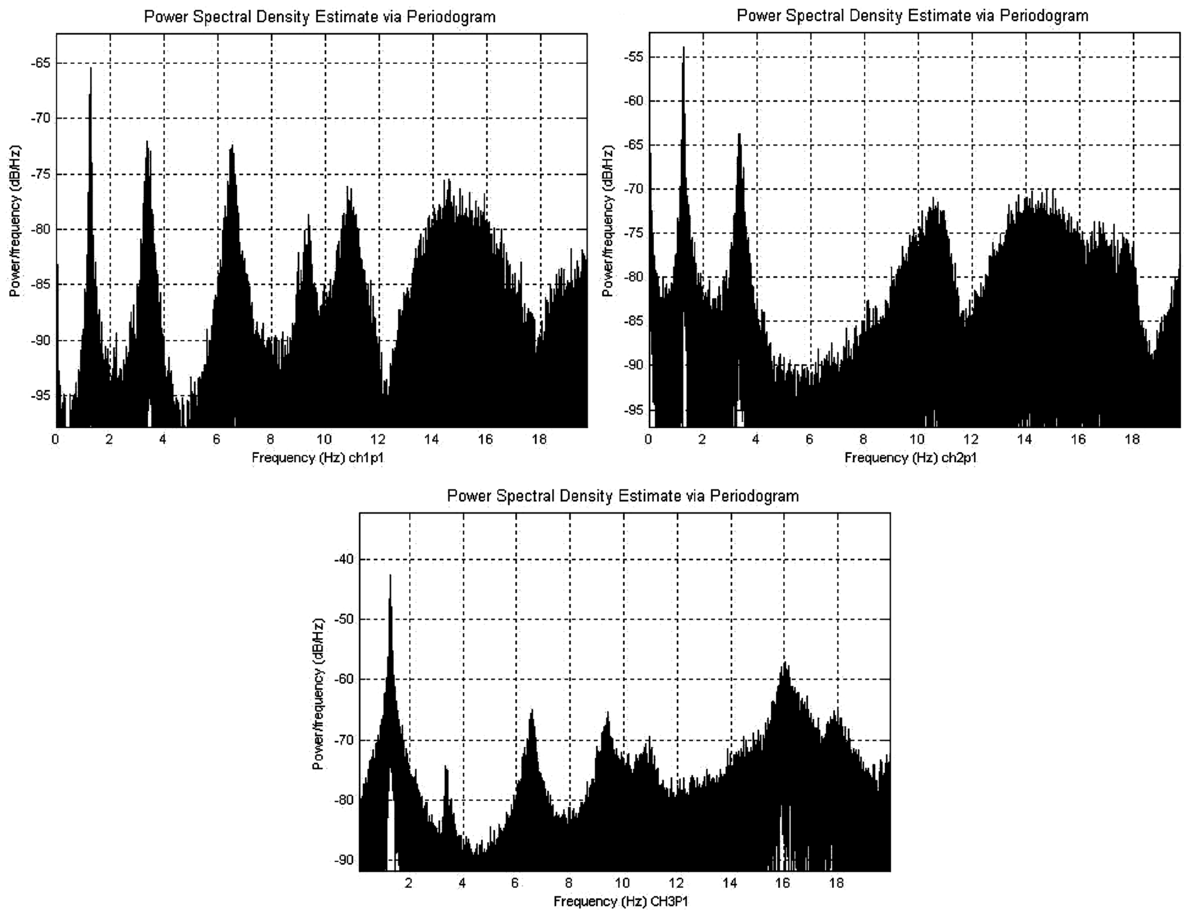


Fig. 10 Power spectra density plot for the three channels

Table 2 Measured natural frequencies and corresponding periods

Mode	Frequency (Hz)	Period (Seconds)
1st	1.278	0.782
2nd	3.408	0.293
3rd	6.517	0.153
4th	9.474	0.106
5th	10.968	0.091

6. Comparison with experimental results

The initial FE model produced inaccurate natural frequencies therefore an updating procedure is carried out as explained in Eq. (1). This process is performed several times to match the identified modes from the ambient vibration results to the FE model results. Table 3 shows the initial modelled frequencies compared to final updated results.

From Table 4, it can be seen that natural frequencies and natural periods from the finite element

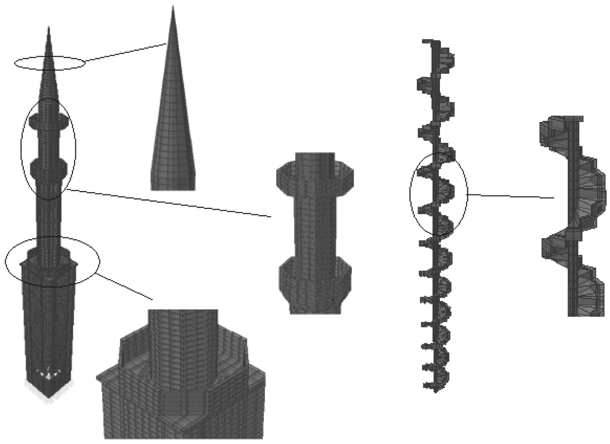


Fig. 11 Datails of three dimensional finite element model of the minaret

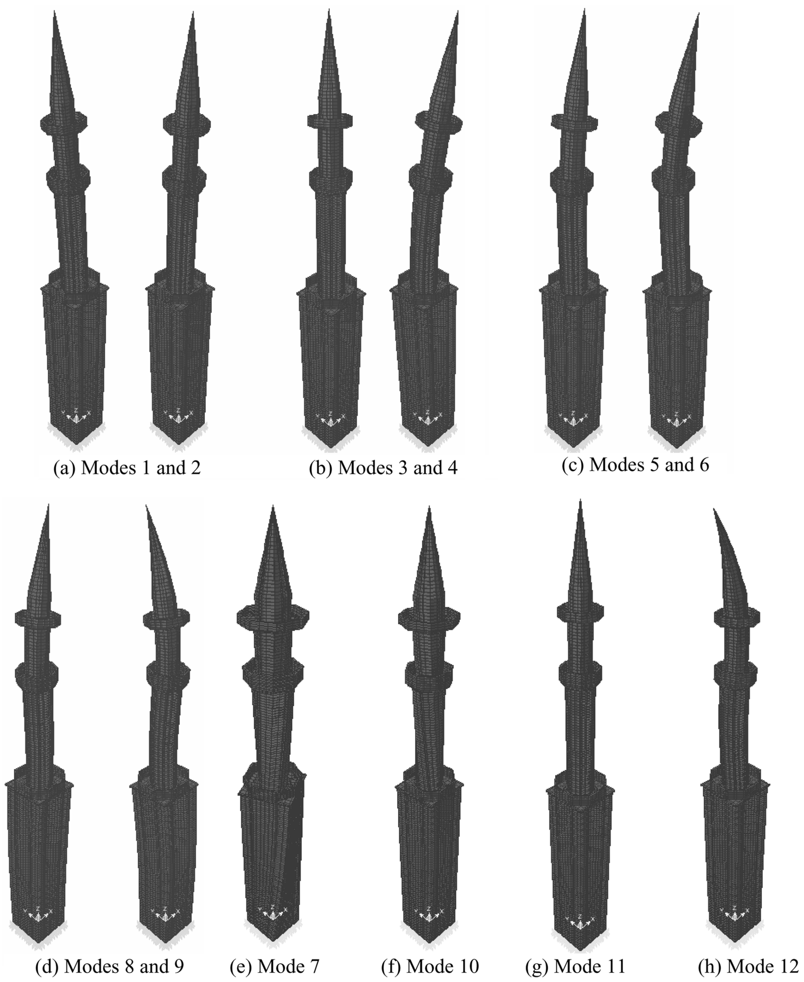


Fig. 12 Analytical first 12 mode shapes

Table 3 Comparison between initial natural frequencies and the final updated results

Mode	Frequency (Hz)	
	Initial model	Updated results
1st	1.069	1.265
2nd	2.432	2.755
3rd	5.795	6.965
4th	8.114	9.513
5th	11.345	12.161

Table 4 Comparison between the measured and analytical dynamic characteristics

Mode	Frequency (Hz)		Relative Error
	Measured	F.E. Model (SAP)	
1st	1.278	1.265	1.01%
2nd	3.408	2.755	19.2%
3rd	6.517	6.965	6.8%
4th	9.474	9.513	3.6%
5th	10.968	12.161	13.3%

model are very close to those obtained from the experimental ambient vibration test.

The relative error in the second mode is slightly high; this indicates that the FE model was to some extent approximate in this mode. However, the first mode has the main contribution for a high cylinder structure as our case study, therefore, in FE updating the first mode was given the priority.

7. Conclusions

The dynamic signature of Ajloun minaret was determined experimentally using ambient vibration tests. The results were compared with analytical ones obtained using finite element model and found to be in good agreement. The experimentally obtained periodic modal parameters provide information about the structure's state of damage during its existence since they are directly related to the mass and the stiffness. The main purpose of the present study was to obtain a relatively faithful linear elastic model of the historical monument based on the measured modal signature. This consists of the measurement of the dynamic characteristics of the structure during its life time, and their use as a basis for identification. Hence, the comparison of the extracted results of this study with future series of sets of modal parameters will provide us an idea about the structure's health.

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