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In Situ dynamic system identification of historic masonry monuments based on non-destructive testing

Ömer DABANLI[1], Yegan KAHYA[2], Feridun ÇILI[3]
[1] odabanli@fsm.edu.tr • Department of Architecture, Faculty of Architecture and Design, Fatih Sultan Mehmet Vakif University, Istanbul, Turkey
[2] kahya@itu.edu.tr • Department of Architecture, Faculty of Architecture, Istanbul Technical University, Istanbul, Turkey
[3] cilif@itu.edu.tr • Department of Architecture, Faculty of Architecture, Istanbul Technical University, Istanbul, Turkey

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Abstract

Istanbul is home to numerous architectural heritage which are in a great variety built by Byzantine and Ottoman period. On the other hand, cultural heritage buildings are faced with serious earthquake risks which require the investigation of the structural behaviour of cultural heritage buildings and the taking of necessary conservation measures to preserve and transfer them to the future in a sustainable way. This article describes an experimental in-situ investigation of an 18th century historic masonry monument, Nur-u Osmaniye Mosque in Istanbul by the non-destructive testing. Dynamic system identification study based on operational modal analysis (OMA) tests which include two different test setups in terms of locations and numbers of accelerometers. The extracted dynamic parameters of structure such as natural frequencies, mode shapes and as well as damping ratios obtained from two different test setups compared. In addition, the results of non-destructive in-situ tests used for the 3D Finite Element (FE) model updating by comparing and calibrating numerical and experimental characteristics. The paper presents an in situ dynamic identification procedure of an historic masonry monument based on operational modal analysis and compares dynamic properties obtained from experimental and numerical studies and gives the results of FE model updating of the structure.

Keywords
Historic masonry, Non-destructive testing, Nur-u Osmaniye Mosque, Operational modal analysis, System identification.

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1. Introduction

Experimental methods provide important information for understanding the behaviour of structures, especially when examining historic buildings whose behaviour is generally difficult to fully understand without using diagnostic techniques (Gentile et al., 2015; Makoond et al., 2020). Structural Health Monitoring (SHM) which is one of the most the popular research area for structural engineering of modern structures, as well as historic buildings is very beneficial for identification of the behaviour of historic buildings (Alvandi and Cremona, 2006; Zhou et al., 2010; Chen et al., 2011; Gunaydın, 2020; Baraccani, 2021; Ghandil et al., 2021). Generally, historic masonry buildings need to be monitored because of having probably several damages in the history, which is crucial to maintaining long-term building safety (Moropoulou et al., 2019). Early warnings on damages and operational safety or preventing the deterioration can be managed by structural health monitoring with a specific system installed and analysed (Binda et al., 2000; Pallarés et al., 2021).

One of the most popular dynamic system identification technique is operational modal analysis (OMA). Ambient vibration measurement can be effectively used to estimate the dynamic parameters of the structure, as well as to calibrate the finite element (FE) models (Feng et. al., 1998; Gunaydın, 2020). For identification of modal parameters of structures such as bridges, towers, historic buildings ambient vibration tests are performed (Xu and Zhan, 2001; Brownjohn, 2007; Ramos et al 2010; García-Macías, and Ubertini, 2020; Borlenghi et al., 2021).

For evaluation of dynamic structural characteristics of historic masonry structures, Operational Modal Analysis is an eminently useful tool, because of its non-destructive character and advantages based on the ambient vibrations of the investigated structure (Diaferio, 2011; Gentile et al., 2015; Pieraccini, 2014). The highlighted advantage of operational modal analysis is as follows:

- Operational modal analysis provides a full-scale testing of the structure. Therefore, it is possible to take into consideration the previous damages, repairs and any changes or problems in the historic structure.
- As a non-destructive test, operational modal analysis has a major advantage in diagnostic studies on historic buildings because of some existing limitations and prohibition about the destruction or taking samples from the historic buildings according to international conservation principles.
- In operational modal analysis test, there is no need for any external excitation force, because depending on ambient vibration case. So, it offers cheap and fast solutions in comparison with experimental modal analysis which requires expensive and invasive excitation force input for shaking the structure.
- Since it is non-destructive test, the application does not require to interrupt the function of the building. Considering the critical and intensive functions of the historic monuments, it may be rather crucial to be able to perform some tests without any disturbance to users and as well as visitors.

Since the successful practices of operational modal analysis in masonry structures, the interest in dynamic identification based on ambient vibration testing increased (Ramos and Aguilar, 2007; Ramos et al., 2010; Diaferio, 2011). For the ambient vibration test, it is rather sufficient to take a record of structural vibrations approximately for 1 hour after the test devices are installed in the building. Thus, the required ambient vibration data can be obtained in one day for the dynamic identification of the structure. In order to increase the reliability of the numeric analysis results of finite element (FE) models, the fundamental dynamic parameters such as free vibration frequencies, mode shapes and damping ratios which can be calculated based on ambient vibration data, should be used for the calibration process (Costa et al., 2015; Salvatore and Eleonora, 2020). Although the vibration source for operational modal analysis survey is ambient noise such as weak ground motions due to both natural and anthropogenic sources, wind, atmospheric perturbations and road traffic, the technique also provides very beneficial information in case of a seismic sequence in structural health monitoring status (El-Shafie et al., 2012).

There are several research on ambient vibration testing and operational modal analysis of buildings and the effectiveness of ambient vibration measurement at a small number of locations are presented to predict finite element (FE) model parameters (Feng et al., 1998; Gunaydin, 2020; Borlenghi, 2021). Although several computational approaches are available in the literature, the restoration of historic masonry structures remains a challenge to modern engineers (Teza et al., 2015). Because of some irregularities such as empty volumes, imperfections related with initial construction and repair, damages such as cracks and out of plane displacements and rotations, variability in material strength and stiffness, historic masonry structures contain many unknown as well as uncertainties. However, it is claimed that finite element (FE) techniques have been accepted as an effective tool for structural performance investigations of historic masonry buildings if the the models are calibrated based on data obtained by some diagnostics techniques like in situ ambient vibration assessment of the historical structures (Gentile et al. 2015, El-Shafie et al. 2012, Teza et al. 2015, Gunaydın 2020).

The structural assessment of historic masonry buildings has been gaining importance for sustainable conservation and heritage management. To evaluate the effects of building material degradation, damages and corresponding repairs of past earthquakes on structural behaviour and to determine possible damage locations and critical zones are needed to be identified to maintain structural safety and for sustainable protection (Costa et al., 2015; Gentile and Saisi 2007; Borlenghi 2021). The number of cultural heritage buildings in Turkey is large, especially in Istanbul, which was both the Byzantine and Ottoman capital that has several famous historic masonry monuments. Restoration and conservation of historic structures requires diagnostic monitoring to determine dynamic characteristics and detect possible damages in the future. Since natural frequencies, damping and modal shapes are directly related to structural integrity, stiffness and behaviour of the structure, the operational modal analysis is a beneficial technique in terms of evaluating changes of modal parameters as well as possible damages and deteriorations (Teza et al., 2015; De Stefano, 2016). Churches and mosques can be evaluated as finest architectural heritage and each of these assets requires specific structural investigations and diagnostic studies based on field survey and non-destructive tests such as operational modal analysis to have a correct numerical model (Carpinteri, 2005; Lacannaa, 2016).

Istanbul has experienced several devastating earthquakes throughout its long history. Various architectural monuments were damaged due to major earthquakes that occurred approximately for one hundred years period in Historic Peninsula of Istanbul. If a monument is still intact while plenty of buildings are damaged by earthquakes, it should be a pretty attractive research topic for a researcher. The Nur-u Osmaniye Mosque, which was built in the 18th century as a unique monument of Ottoman Architecture, has survived almost undamaged despite it is located in a region with major earthquake risk and experienced some devastating earthquakes in 18th, 19th and 20th centuries. Moreover, despite its exceptional earthquake performance, there was no exhaustive research on the structure of the monument and why it was not damaged. Therefore, the characterization of structural system of the mosque is an extraordinarily intriguing and as well as challenging task. In this context, in order to identify dynamic characteristics, as well as structural behaviour of the mosque, an in-situ experimental research program was conducted. This article discusses the dynamic system identification process and the characterization of structural dynamic system of Nur-u Osmaniye Mosque based on performed in-situ operational modal analysis tests which implemented for ambient vibration cases with different test configurations. The paper also mentions about calibration of finite element model using the results of the experimental study.

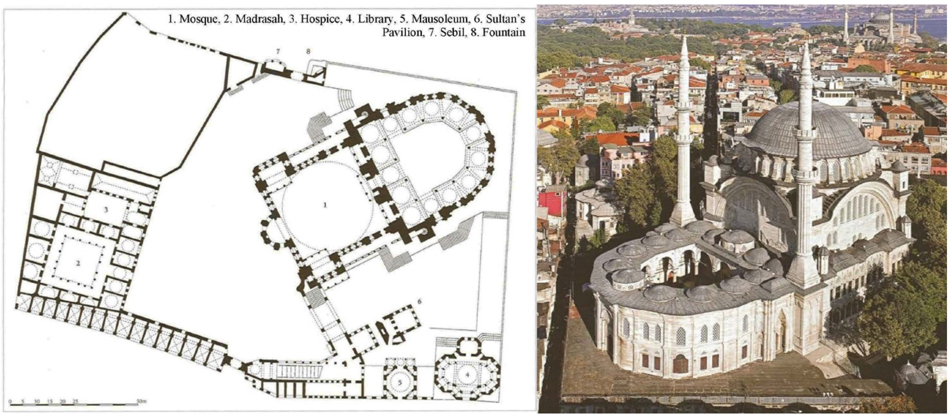


Figure 1. *Plan layout of Nur-u Osmaniye Complex and view of mosque (Kuban, 2007).*

2. Investigated monument: Nur-u Osmaniye Mosque

Nur-u Osmaniye Mosque is one of the most fascinating monuments of Istanbul. It was started to build by Sultan Mahmoud (I) the first and finished by Sultan Osman (III) the third between 1748 and 1755 in Istanbul. The mosque was first introduced Baroque Architecture in a religious complex in the 18th century. As the most significant representative of the new era and so it is also called the Ottoman Baroque, because of its style that synthesized the new art and architecture such as magniloquent details and elliptic courtyard as well as traditional elements of classical Ottoman Architecture. The mosque is located next to the Cemberlitas area of Historic Peninsula, around where there was the famous Constantinus Forum of Byzantine period (Sav, 2012). Among several buildings of the complex such as madrasah, hospice, library, mausoleum, Sultan's pavilion, and fountain, the mosque is the most important monument in the Kulliye (*Islamic Ottoman Social Complex*) as presented in Figure 1.

The mosque stands for the quality of technical approach and level of knowledge of the Ottoman Architects in the period. The unique synthesis of architectural style, design properties of structural system and building techniques are fascinating points of the mosque among the Ottoman monuments (Figure 1). Furthermore, the mosque represents a peak point of structural iron usage in the masonry construction as a result of the increase in line with the production and trade opportunities of the 18th century.

Design principle of the structural system of the mosque is also very simple and clear. The main sanctuary place of the mosque rises on a classic ~27m square baldachin plan covered by a single main brick dome and the famous elliptic courtyard and portico are also covered by petty brick domes. The main dome which is roofing the main sanctuary is supported with four main masonry arches which have highlighted profiles on both inside and outside. Moreover, there are pendants on the corners as transition elements. Under the main arches, the window openings on masonry walls provide transparency and light for interior space.

Regarding the substructure, which is invisible on the courtyard, the structural design of the mosque is very significant. The huge substructure sustains the superstructure of the mosque and forming a platform under the courtyard. However, it is completely hidden in the ground with the only exception of the northwest façade where side shops are located (Figure 2). The load bearing walls of the substructure consist of the roughly cut natural stones such as local limestone and tuffs. The roofing system of the substructure is brick vaults which were built with traditional *Khorasan*, a kind of lime mortar containing brick particles as aggregates. At the bottom of the substructure there are stone masonry foundations which were placed on a masonry platform constructed on wooden grillages and piles almost reaching main rock.

The building techniques are different for the substructure and the superstructure of the mosque. Masonry

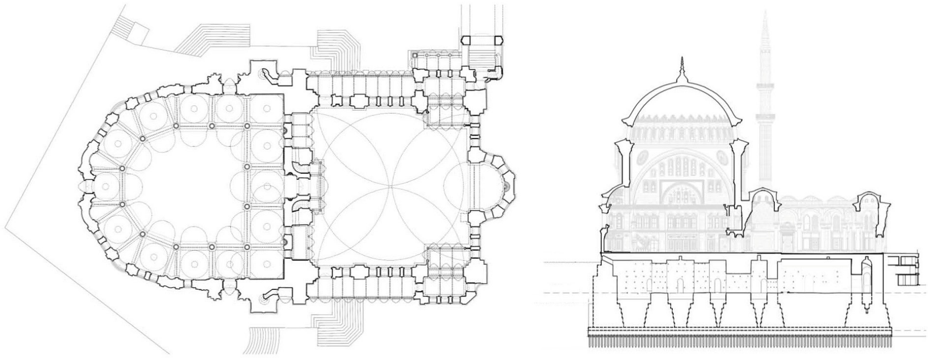


Figure 2. *Ground floor plan and section through courtyard-mihrab direction of the mosque.*

walls, pillars and arches were constructed with cut stone masonry technique using an organic limestone named as küfeki, which is widely used in the Byzantines and Ottoman monuments of Istanbul. Hammer-dressed stone masonry technique was used in the walls and the stones are tied with each other with iron clamps and mortises. Furthermore, during the construction, the structure was strengthened with double iron tie beams on each nine levels from the floor to the main dome. Some of the iron tie beams are observed on the spring level of arches while some are visible within the window openings of masonry walls. The rest of the tie beams are hidden in the wall and as well as dome. Thanks to Ahmed Efendi who was the clerk of the construction process in 18th century. He explained the tie beam usage, levels, and all construction details in his historic manuscript named The History of Nur-u Osmaniye Mosque (Tarih-i Cami-i Şerif-i Nur-u Osmani) (Ahmed Efendi,1918).

Natural stones obtained from local quarries and traditional brick are main building materials of the mosque. Also lime mortar consist of brick and limestone particles and dust as aggregate was used in masonry work of the building. In the sanctuary of the mosque, there are marble and granite columns supporting the gallery floor, however they are not the main elements of load-bearing system because of their location and size. There are bigger granite columns sustaining the brick domes of portico in the courtyard. The drum of the main dome consists of hammer dressed limestone and the rest of the main dome was built with traditional brickwork.

3. Experimental study: Operational Modal Analysis (OMA)

In order to identification of the dynamic structural system, the operational modal analysis performed in terms of two different test setups with different devices and configurations on the structure. The experimental study performed as full scale and non-destructive test considering the ambient vibration of the structure.

3.1. Setup 1 (OMA-1)

The first operational modal analysis test (OMA-1) in Nur-u Osmaniye Mosque was performed with two 24-channel digitizers, using seven triaxial force-balance type accelerometers. Ambient vibration data was recorded with 200 sampling rate using instruments connected with GPS to be able to acquire synchronized data. In order to determine the dynamic parameters of the building in both directions in the plan, the devices are placed on the north and south corners as located opposite to each other.

The best possible locations and cable routes were chosen, in order to keep the cable lengths as short as possible and to avoid the noise caused by the long cables to obtain a clear data. For instrumentation, three levels such as the ground floor level, the spring level of the main arches and the dome base level were selected from bottom to top, respectively. The accelerometers were put at each of the two corners (A and B) of the structure and recording was taken synchronically (Figure 3).

The acceleration – time history graphs obtained from the test and the ambient vibration data showed that the amplitudes decrease from top to bottom levels. Since the fundamental parameters defining dynamic response of a structure are the natural frequency and damping ratio, they are also the only parameters needed to determine the response of the structure subjected to earthquake loads (Şafak, 2010). For this reason, digital signal processing performed both in time and frequency domain. After applying the required filters, Fourier (FFT) and Power (PSD) spectrums were calculated to pick and compare the identified natural frequencies and corresponding modes. The frequency analysis was applied separately in both directions as perpendicular to Qibla direction (x), for northeast-southwest component and the main axis of the structure Qibla (towards Mecca)

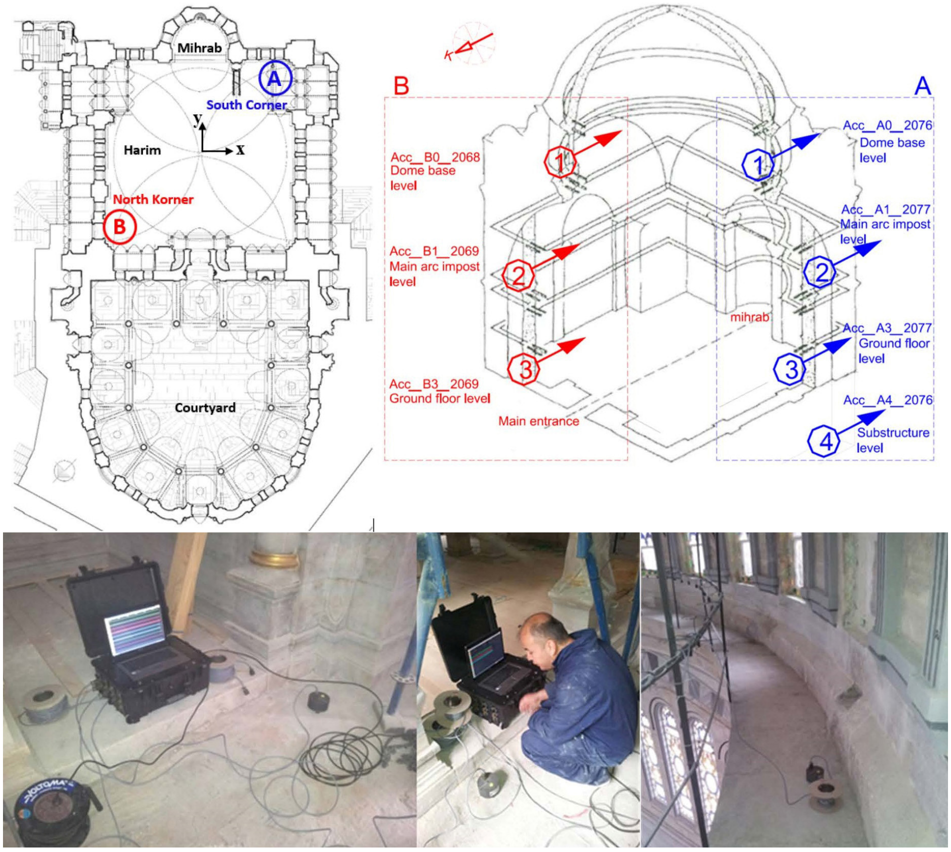


Figure 3. *Setup for OMA-1 on plan and axonometric view, and data recording.*

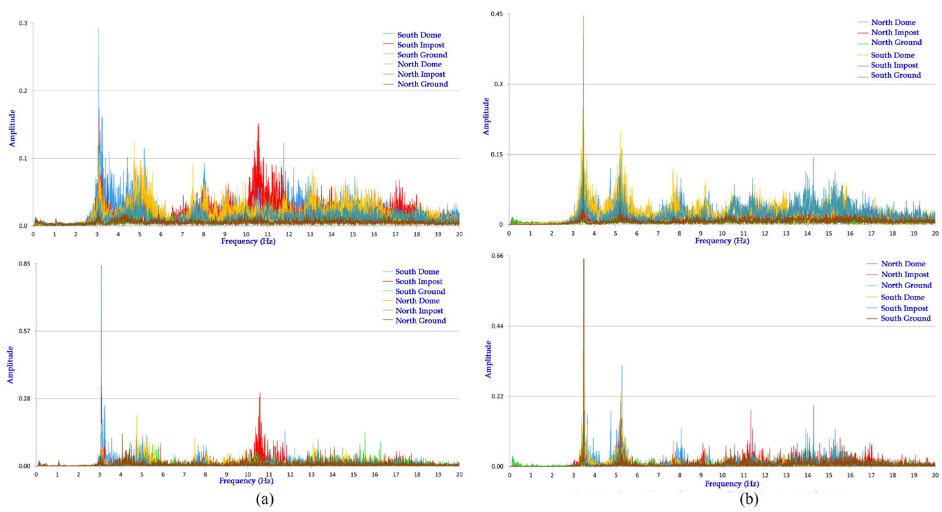


Figure 4. *Fourier (above) and Power (below) Spectrums, a) Perpendicular to Qibla-x b) Qibla-y direction, (OMA-1).*

Table 1. Identified natural frequencies in OMA-1, periods, and modes in x-y directions.

Mode	Direction-Number	Frequency [Hz]	Period [s]	Mode Shape and Direction
1	X_1	3.08	0.325	Translational movement – x direction
2	Y_1	3.49	0.287	Translational movement – y direction
3	$T_1 = XY_1$	5.22	0.192	Torsion
4	$T_2 = XY_2$	7.70	0.130	Torsion
5	$T_3 = XY_3$	9.17	0.109	Torsion
6	$T_4 = XY_4$	10.58	0.095	Torsion
7	Y_2	11.41	0.088	Translational movement – y direction
8	X_2	11.76	0.085	Translational movement – x direction

direction (y), for southeast – northwest component and consequently the natural frequencies of the main modes of the structure were identified (Figure 4 and Table 1). In direction perpendicular to Qibla, the first frequency calculated as 3.08 Hz while the second and third natural frequencies are 5.22 Hz, and 8.05 Hz respectively.

In Qibla direction (y), the main modes and corresponding natural frequencies of the structure were presented in Figure 4. The first frequency (3.49 Hz) in this direction shows that the behaviour of the structure is more rigid than the other direction's (3.08 Hz). Furthermore, Fourier and Power spectrums are purer in Qibla direction.

The natural frequencies obtained from the spectrums for the dome base level, the main arches' impost level and ground floor levels were calculated for the (x) component of all the acceleration, perpendicular to the qibla. The first frequency in the direction perpendicular to the qibla is 3.08 Hz. The second frequency obtained as 5.22 Hz while third one is 8.05 Hz. Moreover, the natural frequencies for qibla direction (y) are obtained from calculated spectrums by analysing the y direction of recorded accelerations and first three modes and natural frequencies in the direction are detected as, 3.49Hz, 5.22 Hz and 7.70 Hz, respectively.

Although natural frequencies can be determined from spectra, it is not possible to obtain an idea about mode shapes directly. Therefore, it is useful to compare the spectra of two direction by overlapping them in order to understand the modal shapes of the structure. When the spectra calculated for both directions are compared, it is determined that the peaks of the frequencies seen in the spectrum in only one direction correspond to the translational movement in the relevant direction, and the frequencies that coincide with each other in the spectra in both directions mean torsion motion and torsional mode shape.

Considering the spectra in both main directions, it is seen that, the frequencies belonging to a total of eight modes can be detected (Figure 5 and Table 1). Since four of the free vibration modes of the structure correspond to the torsion mode, it has been determined that there are two translation modes in the direction of the qibla and perpendicular to the qibla. The first three frequencies and modes determined by analysis are striking. It was determined that the first two modes (F1=3.08 Hz and F2=3.49 Hz) are translational movements perpendicular to the qibla and in the direction of the qibla, respectively. On the other hand, the third mode (f3 = 5.22 Hz) is the torsional mode. The obtained results from the OMA show that the dynamic behaviour of the structure is quite pure and smooth.

3.2. Setup 2 (OMA-2)

In the second operational modal analysis test performed on the building, accelerations of the ambient vibration case were recorded to determine the dynamic parameters of the structure such as natural vibration frequencies, mode shapes and damping ratio and compare them with the results of first study. In this second study, the test set consisting of nine triaxial accelerometers (Sensebox, force-balance), two 16-channel data acquisition devices, integrated computer, GPS devices for time synchronization were used (Figure 6). For data acquisition, the crown points and the spring level of the main arches and the ground floor level were selected

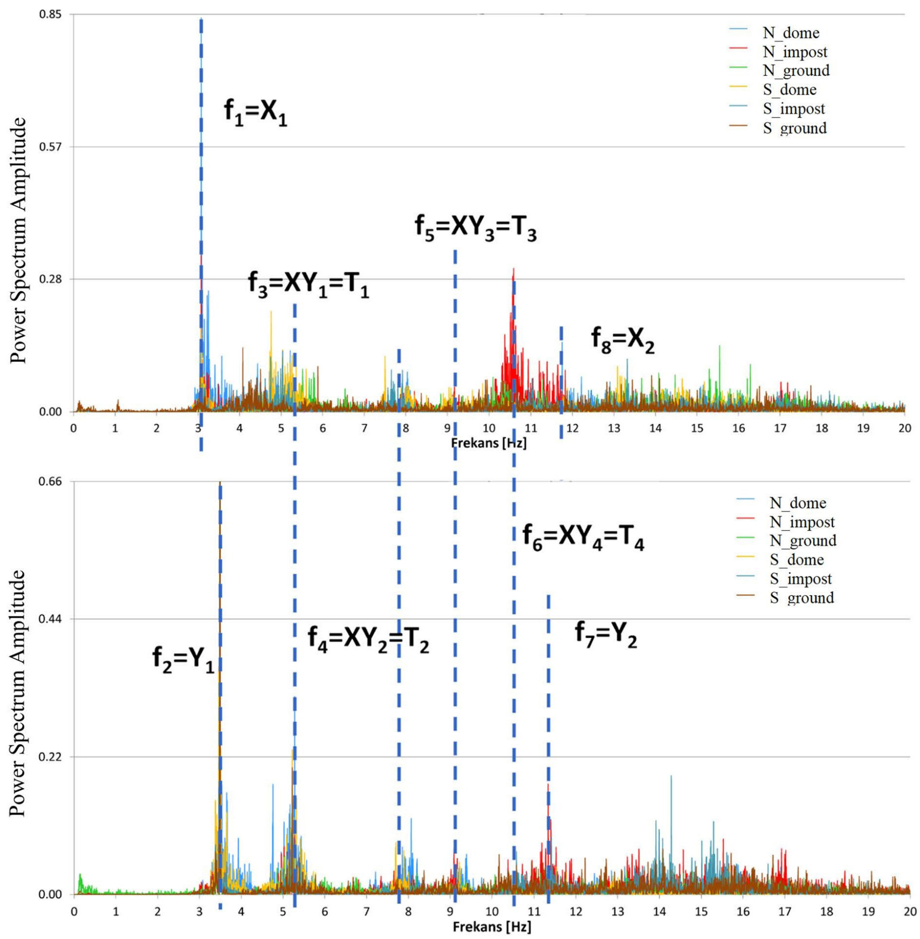


Figure 5. *Comparison and matching of the spectrums for x and y directions (OMA-1).*

from top to bottom respectively (Figure 6). Some locations of accelerometers were changed, and the number of devices increased with respect to the first study to be able to compare the results from the two setups. In the second test, x, y and z denotes the same directions as in the first test. In this case, the data acquired with 200 sampling rate analysed by using ARTeMIS (2016) software for dynamic diagnosis. The acceleration – time history graphs obtained from OMA-2 test are similar to those of the first study OMA-1, as the acceleration amplitudes, decrease from dome to the bottom levels.

In order to obtain mode shapes, accelerations from each device located in the building are defined in the relevant points on the simple representative building model created in the Artemis software. Each accelerometer data was associated with the same representative node on the model, and directions of the devices and model were matched. In this way, it is possible to display the modal vibrations as well as the mode shapes of the building via a representative geometric model simulation.

The natural frequencies, mode shapes and damping ratios were calculated using Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD) and Curve-fit Frequency Domain Decomposition (CFDD) methods of Artemis for both directions x and y. The calculated frequency and damping values by using three different techniques are very close to each other (Table 2). As generally expected, the damping ratios are low due to the ambient vibration data, and the largest ratio is around 2.2%. Also, the damping ratios in the first two modes with high participation is significantly higher than the other modes.

It has been determined that the identified frequencies based on ambient vibration data in OMA-1 and OMA-2 tests performed on the building are very close to each other (Table 2). The results of the first test were calculated

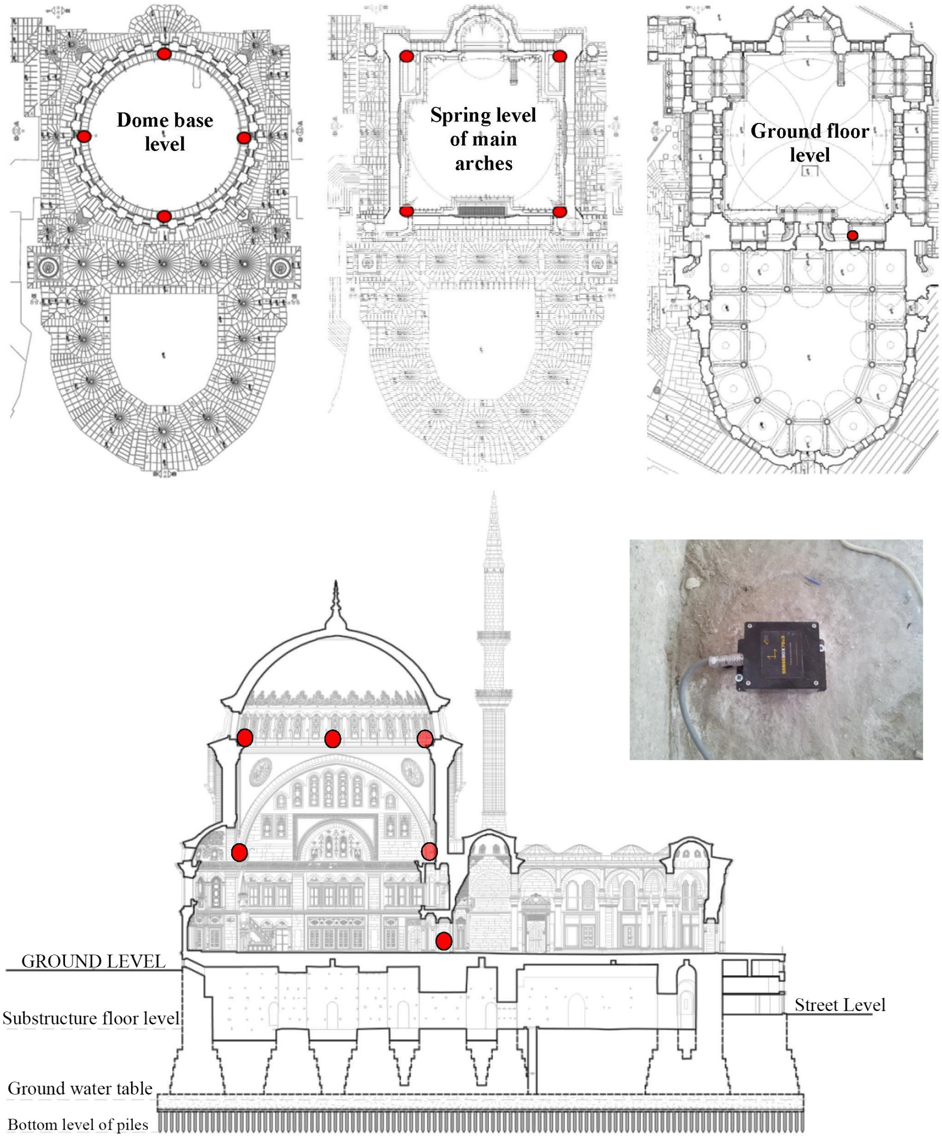


Figure 6. *The locations of accelerometers on the plan and section of the mosque for OMA-2 test setup.*

Table 2. *Calculated frequencies and damping ratios and comparison of OMA-1 and OMA-2.*

Mode	OMA -1	OMA-2						
	FFT	FDD	EFDD		CFDD		Average	
	Frequency [Hz]	Frequency [Hz]	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]	**Damping [%]**	**Frequency [Hz]**
1	3.080	3.101	3.097	0.685	3.100	1.324	1.005	3.099
2	3.490	3.442	3.454	1.185	3.458	2.217	1.701	3.451
3	5.220	5.176	5.168	0.448	5.175	0.921	0.685	5.173
4	-	7.397	7.384	0.212	7.380	0.561	0.387	7.387
5	7.700	7.861	7.850	0.099	7.861	0.269	0.184	7.857
6	9.140	9.106	9.122	0.254	9.121	0.575	0.415	9.116
7	-	12.231	12.235	0.440	12.235	0.666	0.553	12.234

by FFT and PSD method, while the data acquired by the second test were analysed by the software using FDD, EFDD and CFDD tools. It was determined that the calculated frequencies by the analysis of the data obtained from different device locations, numbers and types have resulted in almost the same values and the two tests confirmed the results of each other.

The mode shapes and modal assurance criteria (MAC) results determined by the analysis are displayed on the model representing the mosque (Figure 7). It is observed that the first mode shape corresponds to the translational movement in the direction perpendicular to the qibla (y), while the second mode shape to the translational movement in the qibla direction (x) and the third mode to a torsional shape as predicted in the first test (Figure 7). The first three are the dominant modes of the building and greatly mobilize the building mass while the fourth and fifth modes are torsional modes that involve complex motion. The sixth mode shape is the opening of the main dome in the short direction and the seventh mode has a shape that corresponds to the entire expansion movement of the dome. The results of mode shapes obtained by comparing the frequencies determined in the both direction of main axis of the structure in the first test (OMA-1) were confirmed by the numerical and graphical results obtained in the second test (OMA-2). In this sense, it was concluded that the modes and frequencies determined in both tests were nearly the same, as well as the determined mode shapes.

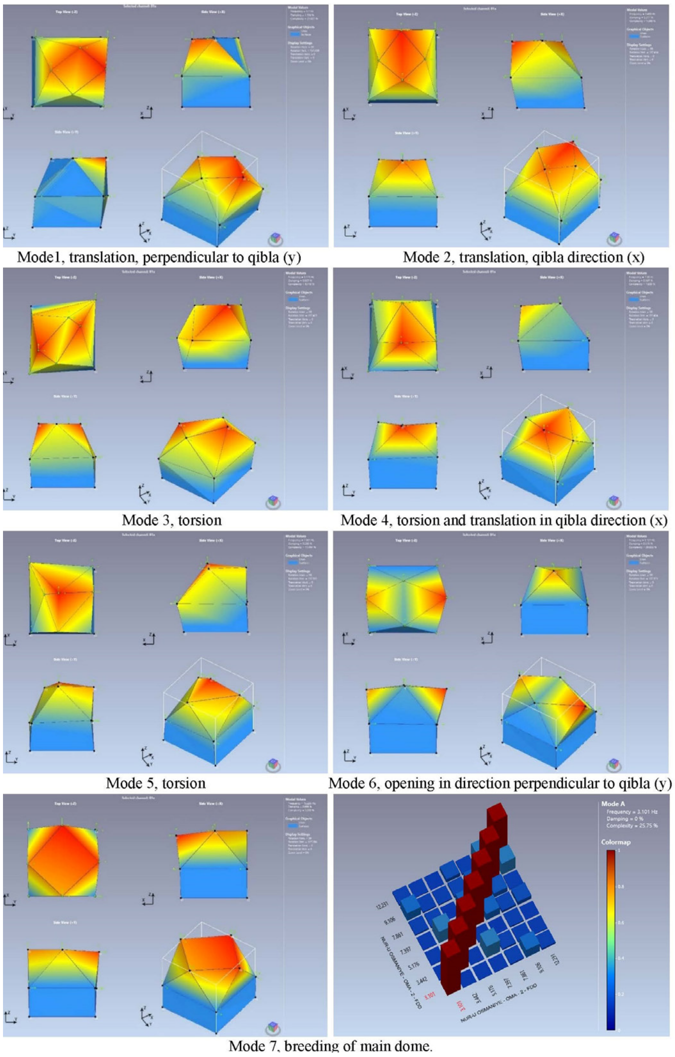
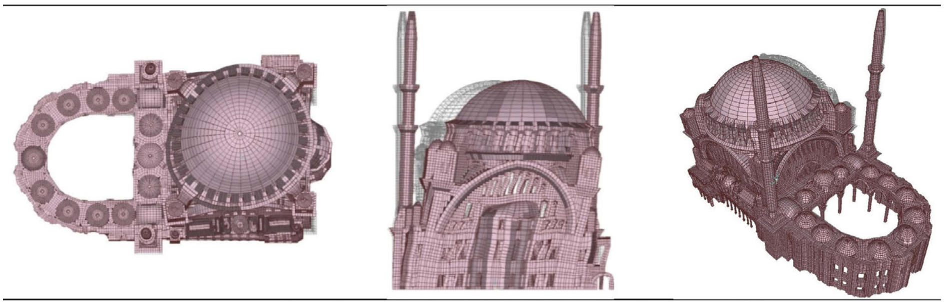


Figure 7. *Identified mode shapes and MAC graphics for OMA-2.*

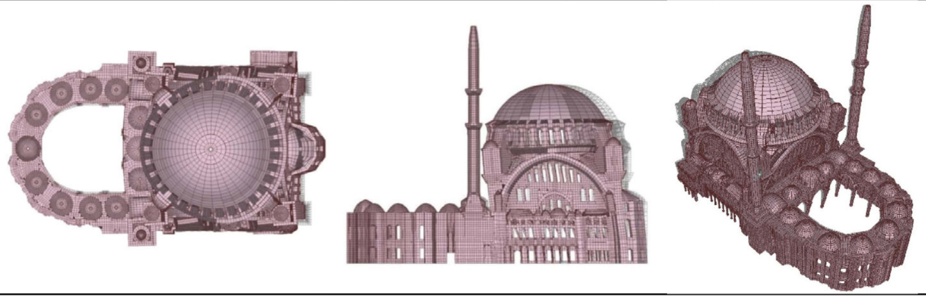
4. Numerical analysis and calibration

The field survey allowed assessing the main frequencies of Nur-u Osmaniye Mosque. Calculated frequencies from operational modal analysis tests were used to calibrate the 3D numerical model which is generated by using finite element method using the data obtained by a long field survey. In the 3D model, totally 95866 solid element (masonry walls, pillars, arches, domes, and vaults) and 162162 joints are generated by considering natural stone sizes. Iron ties are modeled to be effective only in case of axial loadings. The substructure of the building is excluded from the model because this part of the building is extremely rigid and completely buried in the ground.

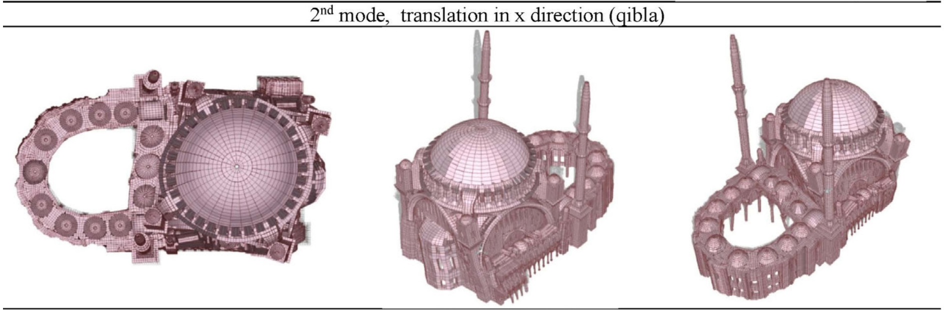
As a result of the laboratory experiments carried out on the main building material, the limestone (kufeki) samples, it was determined that the natural unit volume weight is 2.40 g/cm^3, and the ratio of the open pores is approximately 9 %. Also, uniaxial compressive strength of the cylindrical kufeki stone samples were determined as 26 MPa which is corresponding to 29 MPa as equivalent cube strength. The modulus of elasticity of the main building stone, organic limestone kufeki, was found to be around 28000 MPa in the laboratory tests which performed using core samples taken from building. For this organic shell limestone, which is the main building material of the monuments in Ottoman and Byzantine architecture, there are findings very close to the result obtained in the scope of this study in the research of the relevant literature (Arioglu and Arioglu, 1999; 2005). However, the natural stone blocks are assembled in the masonry elements such as walls, arches, and piers by combining them with Khorasan mortar and metal elements such as clamps and mortises. The binder of traditional Khorasan mortar is air lime putty. Brick and limestone particles which have diameter under 10mm and 6mm respectively, are used as aggregates. The binder/aggregate ratio is approximately 1/3. The metal elements fixed with lead into the stone blocks. In this case, it should be expected that only the values of the natural stone material obtained in the laboratory are not valid, and the in-situ



1st mode, translation in y direction (perpendicular to qibla)



2nd mode, translation in x direction (qibla)



3rd mode (torsion)

Mode	*FFT Frequency* [Hz]	*FE Model Frequency* [Hz]	*Difference* %
1	3,080	3,165	2,76
2	3,490	3,201	8,28
3	5,220	4,681	10,33

Figure 8. *The first three mode shapes of calibrated FE model and comparison of experimental and numerical results.*

masonry structure exhibits a different behaviour than stone. Since it is not possible to use only the values of the material determined in the laboratory, the actual values must be found by a deductive method by verifying the dynamic characteristics of the structure.

In order to calibrate the dynamic behaviour of the numeric 3D model, iterative solutions were obtained by changing the modulus of elasticity of the masonry material. By monitoring the effects of changes in material properties on the modal analysis results, the modulus of elasticity that provides the frequencies obtained from the operational modal analysis tests was determined. Thus, it was detected that the modulus of elasticity value of 8000 MPa for natural masonry material provided the closest values to the operational modal analysis test results. This value of modulus of elasticity corresponds to approximately 1/3 of the value obtained in the laboratory tests of natural stone and is in accordance with the studies in the literature (Bartoli, 2013).

Operational modal analysis tests results show that the period of the first main vibration mode obtained in y-direction or perpendicular to qibla is 0.316 seconds (3.165 Hz) as shown in Figure 8. In this mode, the cumulative mass participation ratio is calculated as 48% due to the asymmetric structure of the main body and the courtyard with respect to y-axis. If the courtyard mass was not considered, the total mass participation ratio increases to 65%.

The second main vibration mode of mosque is calculated in the x-direction (parallel to qibla) and corresponding period of the mode was calculated as 0.312 seconds (3.205 Hz). The mass contribution of the courtyard was relatively small by comparing it to the main structural body of the mosque. The contribution of the courtyard in the total mass participation ratio was calculated to 52%. If the courtyard is ignored, the ratio is enhanced to 65%.

The third main vibration mode consists of torsional displacements. Figure 8 shows the main torsional effects of mode-3 with 0.214 seconds period (4.67 Hz). In total, 15 mode were calculated to reach a satisfactory total mass participation ratio (~95%) by using the Ritz method. Twelve of the free vibration modes is related with the x and y direction movements with different frequencies. One of three remaining vibration modes is breeding of main dome and the others two are torsional modes of mosque. Especially, as the contribution in mass participation ratio of the first three modes exceeds 50 %, it can imply that a large part of the structural mass moves together.

Figure 8 presents frequency results which are calculated using data obtained by the operational and the numerical modal analysis. The differences between the frequency results of experimental and numerical analysis are below 3%, 8% and 11 % for the first 3 modes, respectively. The highest difference is calculated for the mode 3, however, the highest difference is situated approximately 10%.

5. Conclusion

The study has focused on a multidisciplinary work consisting of a field survey, monitoring, operational modal analysis, signal processing, finite element modelling and numerical analysis to assess main dynamic characteristics of Nur-u Osmaniye Mosque. The results of two operational modal analysis tests were used to a generate calibrated finite element model to be able to determine the dynamic behaviour and to perform earthquake analysis of the structure.

In experimental study, two separate operational modal analysis setups (OMA-1 and OMA-2) carried out on Nur-u Osmaniye Mosque. The device types, numbers and locations on the structure were selected in a different way to examine the effect of the test setups. Dominant natural vibration frequencies, periods and mode shapes, which are the basic dynamic parameters of the structure, were determined as a result of the evaluation and analysis of the acquired vibration data caused by the environmental effects without any excitation in the building.

In the first operational modal analysis test (OMA-1), by using the calculated Fourier and power spectrums from the acceleration records acquired from the building, the modes in the direction of both main axes of the building and the corresponding free vibration frequencies were determined. As a result of the analyses, it has been determined that the first mode (frequency 3.08 Hz) and the second modes (frequency 3.49 Hz) are translational modes in direction perpendicular to the qibla and in the direction of qibla, respectively. Moreover, the third mode (frequency 5.22 Hz) is a torsional mode while other modes are more complex and less dominant than the first three modes.

The results of the second operational modal analysis test (OMA-2) obtained by using Artemis software with three different techniques are nearly the same in comparison with the first test (OMA-1). It has been determined that the identified frequencies based on ambient vibration data are very close to each other in OMA-1 and OMA-2 tests which have different device locations, numbers and types. As two tests have resulted in almost the same values for frequencies and modes, two tests confirmed the results of each other. Furthermore, in terms of the mode shapes obtained by the analysis comparing the frequencies determined in the direction of both main axes of the structure in the first test (OMA-1) were confirmed by the numerical and graphical results obtained in the second test (OMA-2). For this reason, it was concluded that the modes and calculated frequencies in both tests were nearly the same, as well as the determined mode shapes.

Considering the operational modal analysis results, the first two main modes are translational in the direction of principal axes of the structure and the third dominant mode in the form of torsion shows that the structure has a very smooth structural system and dynamic behaviour. According to the operational modal analysis results, the structure displays a more rigid behaviour in the direction of the qibla than the direction perpendicular to it. The reason for the stiffness difference seems to be the presence of courtyard and minarets in the direction of qibla. Minaret bases and the courtyard are thought to make the structure more rigid in the qibla direction. The structure displays a clearer dynamic behaviour in the qibla direction than the direction perpendicular to the qibla. This situation can be explained by the symmetry that the structure has in the qibla direction. Since it is not completely symmetric in the direction perpendicular to the qibla the structure exhibits a more complex dynamic behaviour with the effect of the sultan's mahfil, courtyard and as well as minarets.

In order to obtain the same frequencies as the experimental results, the finite element model calibrated according to the results of operational modal analysis. For this purpose, the modulus of elasticity values of the *küfeki* named shell limestone which is the main building material, were changed and it was determined that the value giving the closest result was 8.000 MPa. This value corresponds to approximately one third of the modulus of elasticity (28.000 MPa) obtained in the laboratory test of organic limestone. Because the natural stones used in the building are combined with mortar and iron clamps and mortises in masonry, the structural elements which are assembly of the used materials have turned into a stiffness of approximately one third.

Finally, as the natural frequency is the main dynamic characteristic of the structures, it is possible to use the any change in natural frequency as a damage indicator. Therefore, the earthquake analysis can be carried out on the finite model which is calibrated according to the frequencies obtained in this study. In addition, in case of future earthquakes, the damage assessment of the structure can be made by examining whether the frequency values obtained in this study have changed or not. In this regard, the results of the experimental study can be considered as a "documentation of behaviour" of the structure.

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