Monitoring the structural response of historical Islamic minarets to environmental conditions

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ABSTRACT: This paper summarizes the findings of site measurements conducted to study the natural structural behavior of historical minarets due to variation in architectural configuration (height and cross-section). The examined minarets were belonging to Al-Azhar historical mosque located in Cairo-Egypt and were constructed with different architectural configurations at different epochs. They included: 1) Qaitbay minaret constructed in 1432 with 37.86 m height; 2) Al-Ghuri minaret constructed in 1509 with 52.5 m height; 3) Aqbaghawya minaret constructed during Mamluk period with 34.62 m height; and 4) Bab Al-Shorba and Saida twin minarets built during the Ottoman dynasty with 33.12 m height. Aging and environmental conditions may affect their behavior. Low-g accelerometers were utilized to monitor the tilting of these minarets under environmental and different climatic conditions for 651 continuous days (1.8 years).

The measured results showed that all minarets suffered from limited daily oscillations in horizontal plane, with slight increase with annual variations. In addition, it indicated that the maximum and minimum limits of oscillation were showing repetitive trend over a period of time.

1 INTRODUCTION

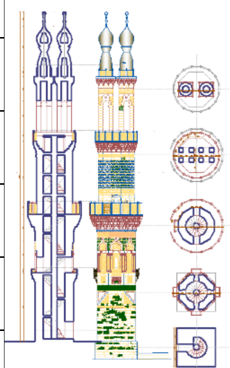
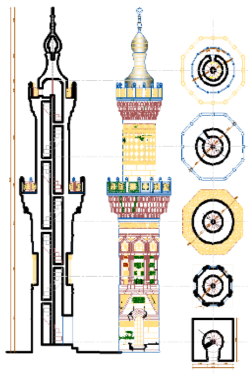
Minarets are considered historic symbols and evidence of prosperity of past rulers and kingdoms. Each minaret has its own unique shape and design that express the architectural style dominated construction within a certain era. Preservation of these minarets requires studying their response under the influence of different environmental and climatic conditions. Al Azhar mosque with its five minarets constructed at different epochs represents an ideal case for such kind of study. It provides an adequate number of test subject minarets that belong to Mamluk and Ottoman eras with different shapes and designs as shown on Figure 1.

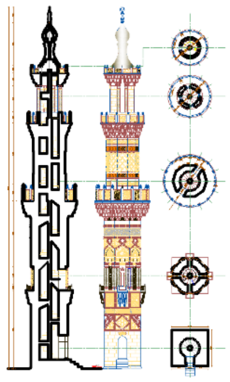
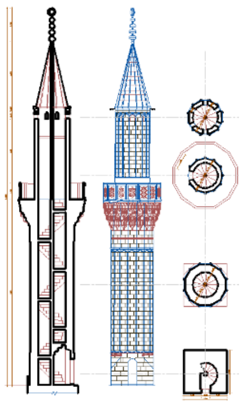
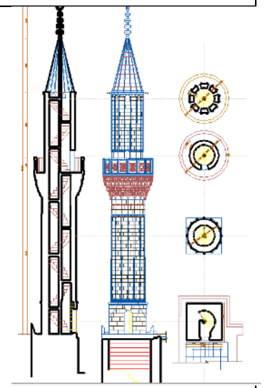
Al Azhar mosque, beacon of Islamic teachings in modern and ancient times was originally built by the Fatimids in 972 A.D., since then it has seen numerous renovations and additions at the hands of successive rulers. Presently there are three minarets located on the Northwestern court of the mosque and belonging to different eras within Mamluk period. They are; 1) Madrasa Aqbaghawya Minaret which is the first minaret built in Egypt by using carved stone. It was built by Amir Alauddin Aqbugha along with building his madrassa, i.e. school; 2) The minaret located on madrasa Taybarsiyya which was built by Sultan Ashraf Qaitbay and referred to in this study as Qaitbay minaret; and 3) The double ornament minaret which was built by Sultan Qansah Al Ghuri. On the eastern part of the mosque, there are two ottoman style minarets, the one located at the Southeastern corner and referred to as Saida minaret and the one located at central east of the mosque and referred to as Shorba minaret. Both minarets were built by Governor Abdurrahman

Katkhuda, during the Ottoman Dynasty. Table1 provides the architectural description for these studied minarets.

Figure.1 Studied minarets

Table 1: Architectural description for Al Azhar mosque minarets

Ghuri	Base	Square Dim = 3.15 * 3.15	
	1st shaft	Octagonal with two supporting marble columns on each side, D = 4.72, W. Th. = 1.02	
	2nd shaft	12-sided polygon, D = 4.41, W. Th. = 0.93	
	3rd shaft	Dual rectangular shafts built of four stone columns	
	Ornament	Double onion shaped bulbs atop each shaft	
	height (m)	40.41 above mosque roof – 52 m from ground level	
Aqbaghawya	Base	Square, Dim = 2.68 * 2.71	
	1st shaft	Octagonal with two supporting marble columns at each corner, D = 2.71	
	2nd shaft	Cylindrical, D = 2.21	
	3rd shaft	None	
	Ornament	Single onion shaped bulb	
	height (m)	21.71 above mosque roof – 34.62 from ground level	

Qaitbay	Base	Square, Dim = 3.15 * 3.15	
	1st shaft	Octagonal with three supporting marble columns at each corner, D = 3.14,	
	2nd shaft	10-sided polygon, D = 2.75,	
	3rd shaft	Consisting of eight brick columns, each pair relate to bricks to provide support for the columns, D. = 2.13	
	Ornament	Single onion shaped bulb	
	height (m)	31.64 above mosque roof – 37.86 from ground level	
Shorba	Base	Square Dim = 2.43 * 2.57	
	1st shaft	16-sided polygon, D = 2.30	
	2nd shaft	16-sided polygon, D = 2.0,	
	3rd shaft	none	
	Ornament	Conical shaped spire	
	height (m)	22.93 above mosque roof – 33.12 from ground level	
Saida	Base	Square, Dim = 2.73 * 2.74	
	1st shaft	16-sided polygon, D = 2.6,	
	2nd shaft	12-sided polygon, D = 2.11,	
	3rd shaft	none	
	Ornament	Conical shaped spire	
	height (m)	24.13 above mosque roof – 33.12 from ground level	

2 BACKGROUND AND OBJECTIVES

Traditionally, Structural Health Monitoring (SHM) for archeologically valuable and historically significant minarets was applied through conducting Operational Modal Analysis (OMA) to identify initially minarets dynamic properties. For such purpose, usually the time span for monitoring is short term ranging from 5 minutes to maximum 6 hours Then, the OMA results are utilized later to calibrate and update mathematical finite element models for these minarets which are used to study the minarets structural response under different loading conditions (Altuni et al, 2010 and Bani-Hani et al, 2008). This approach, although provides information on the deformations and stresses within minarets bodies under certain loading conditions, it did not provide any indications on the influence of environmental and climatic conditions on minarets response. Surveying the available literature indicated that only in very limited cases (Hamed, 2009 and Gentile, et al. 2016) monitoring continued for long term which allowed for capturing the effects of environmental conditions on the structures. Therefore, in this study, we have adopted a different approach towards the application of SHM to Al-Azhar mosque minarets with the aim of understanding the response of the minarets to ambient excitation and different environmental conditions. This approach is based on utilizing low-g accelerometer collecting data at normal logging mode, which is ideally suited for tilt application due to low frequency of the events, to monitor the tilting of the minarets under environmental conditions continuously for 651 days. This allowed us to; 1) Study how the minarets operate and respond in their natural environment; 2) Study the variations of architectural and geometric properties and its effects on the behavior of the minarets; 3) Test the efficiency and suitability of a low cost integrated SHM system composed of a low-cost capacitance accelerometer, data acquisition and data logger system for long monitoring purpose.

3 STUDY APPROACH

For this study a low cost accurate capacitance accelerometers were utilized to effectively monitor the five minarets at nine different observation nodes. Table 2 shows the locations of these sensors in each minaret. The used sensors were HOBO Pendant Acceleration G Data logger (UA – 004 – 64). They are triaxial capacitance acceleration sensors, with following specifications: measurement range ± 3 g, Resolution 0.025g, Accuracy 0.075g @ 25 °C anFd 0.105g @ -20 to 70 °C. The microprocessor uses calibration data along with a transfer function to convert the input voltage to an equivalent acceleration value in G, where 1G = 9.8m/s². The loggers were fixed to minaret walls to measure the variation in ground acceleration in the three dimension of space (X, Y & Z). Tilt angle is later calculated as [tilt angle = 180° – Arc Cos (acceleration in G's)], assumes acceleration varies between -1G and +1G and generates corresponding angles between 0° and 180°. Recognizing that logger resolution are in range of ±0.025g ≅ ±1.4°, it can be clear that tilting less than ±1.4° are not sensed and data within this range are expected to be jumping up and down.

Monitoring of minarets started in March 13, 2014 up to December 12, 2015. The accelerometers were set to record a measurement every five minutes and produce an average for each hour. In total, there are 15650 measurement recorded. Interpreting this data necessitated the use of an averaging method that can preserve the trends and complex fluctuations while highlighting the behavior of each minaret.

Data recorded is hourly acceleration in the three orthogonal axes, measured in m/s^2 and using built in trigonometry equations, tilt is readily calculated in degrees. Simple statistical processes are performed on the acceleration data to allow for better feature identification from the data, such as; 1) Calculating the resultant of acceleration in horizontal plane; 2)Data Normalization by subtracting the minimum reading of the acceleration data at each node, therefore, relating all the measurements to the initial reading and remove the amplitude caused by any tilt in the structure prior to the setup of the monitors; 3) Calculating the daily average of each sensor, therefore, reducing the size of the data to 667 points while maintaining the patterns and trends on the data while allowing it to be more readable and easily displayed ; and 4) Representing the data in stacked area charts, enabling us to show the magnitude of change over time and draw attention to the total values across the monitoring span.

Table 2: Sensors locations indicated by arrows

				
Al Ghuri	Aqbaghawya	Qaitbay	Shorba	Saida

4 RESULTS AND DISCUSSION

The obtained measurements were in the form of tilting in the horizontal directions and acceleration in vertical direction. Figure 2 shows these measurement for the upper sensor at Qaitbay minaret. Analyzing these data indicated that Qaitbay minaret bulb showed a daily variation ranging in 1.6° through north-east/south-west (Y) which may increase to 4.5° in annual variation. Perpendicular direction of north-west/south-east (Z) daily variations goes up to 4.5°, while annual variation goes to 5.8°. Vertical oscillation of bulb showed daily variations in range of 0.026g while annual variation reached 0.052 g and rarely to 0.074g. It worth to mention here, that due to huge number of results, the data was averaged and represented by the black curve. Similarly, analyzing the data for Qaitbay down sensor showed a daily variation of 3° in (Y axis) north-east/south-west increasing to 4.4° in annual variation. Perpendicular direction of north-west/south-east (Z axe) goes to 3.8° in daily variation, while annual variation 4.6° and rarely to 7°. Vertical oscillation of minaret body shows daily variations of 0.025g while annual variation reach 0.076 g. The harmony between the data of upper sensor and lower one for this minaret indicated its stability. This was further proven by examining Figure 3 which shows the daily average resultant of horizontal acceleration as recorder from all sensors. As can be seen, the variation in the acceleration was minimal indicating the minarets stability. Similarly data for Aqbaghawya minaret indicated its stablity too. In general, both minarets, although have the same rigidity ratio (L/D) as can be concluded from Table 3, they still have smooth reduction in stiffness with height with no abrupt change, which result in recording lower acceleration values under normal conditions.

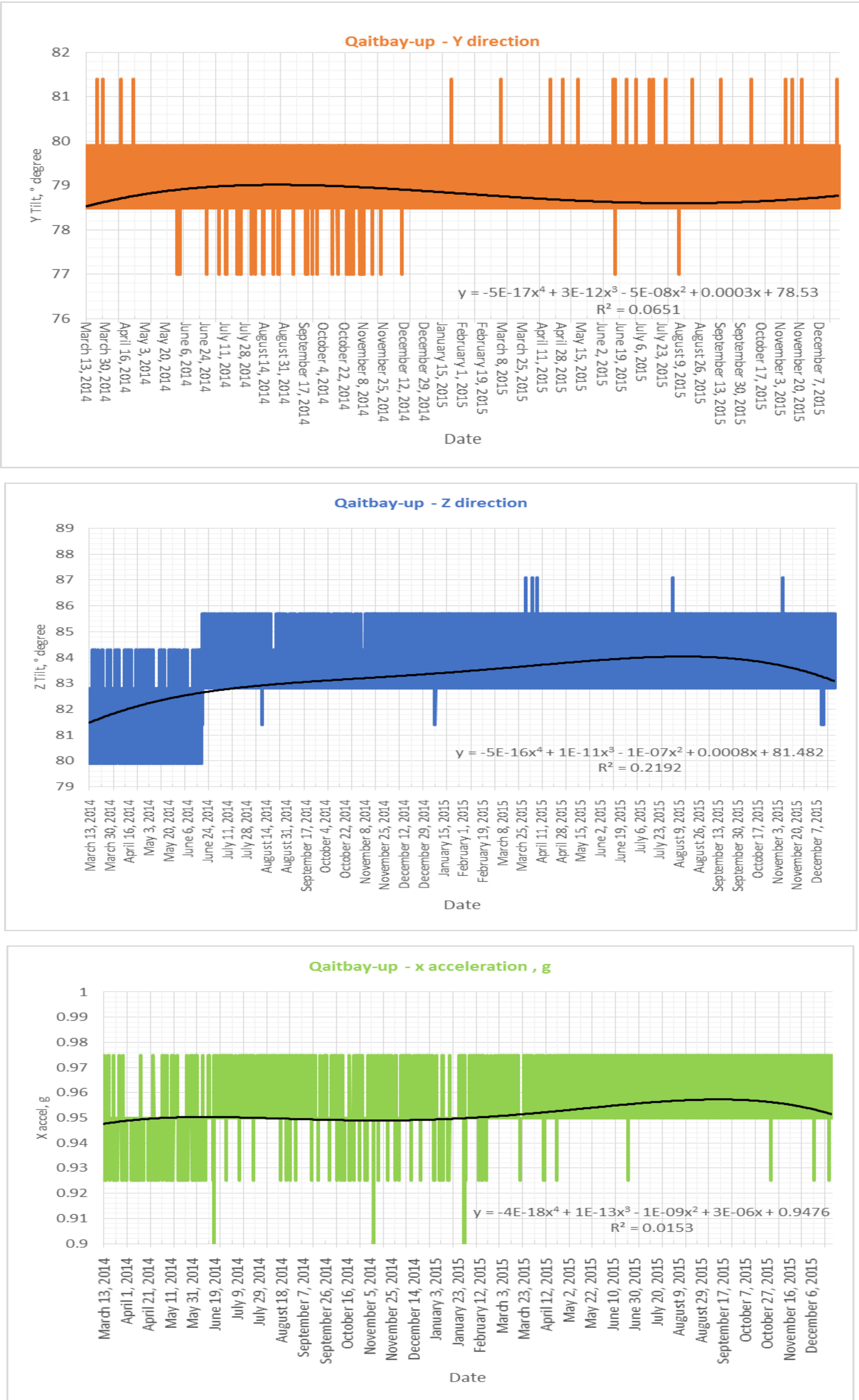


Figure.2 Tilt and acceleration results extracted from upper sensor located at Qaitbay minaret

Also, measured data displays a steady pattern of winter - summer cycles, where there is reduction in acceleration in summer and steady gradual increase of vibrations towards winter.

With regard to Al Ghuri minaret, the response was more complicated. Down sensor shows very high magnitude of acceleration compared to other minarets displaying unsteady blocky pattern, indicating that sources of excitation are constantly varying in magnitude. The location of the sensor may have caused the recording of this pattern, it is situated at the root of the dual third shafts of the minaret, and therefore, it is exposed to other sources of vibrations than the normal condition present in other minarets. This source is the vibrations from the motion of the dual shafts carrying the bulbs of the minarets. The bulbs of Ghuri minaret are susceptible to motion more than the bulbs of other minarets since they have a narrower base and higher length to diameter ratio, indicating lower rigidity and lower resistance to motion ,in addition, the distribution of stiffness is not gradual as in other minarets.

Table 2: Rigidity (length/diameter = L/D) and stiffness (inertia/length = EI/L) for studied minarets

Minaret	1st shaft		2nd shaft		3rd shaft		Ornament	
	L/D	EI/L	L/D	EI/L	L/D	EI/L	L/D	EI/L
Al Ghuri	2.21	1.32E	2.04	1.86E	Set of pillars		3.80	-
Qaitbay	2.49	0.53 E	2.50	0.36 E	2.04	0.15E	2.45	0.06E
Aqbaghawya	2.38	0.26E	2.69	0.18E	NONE		2.16	0.13E
Shorba	3.85	0.13E	2.70	0.12E	NONE		Conical	
Saida	3.67	0.22E	2.72	0.14E	NONE		Conical	

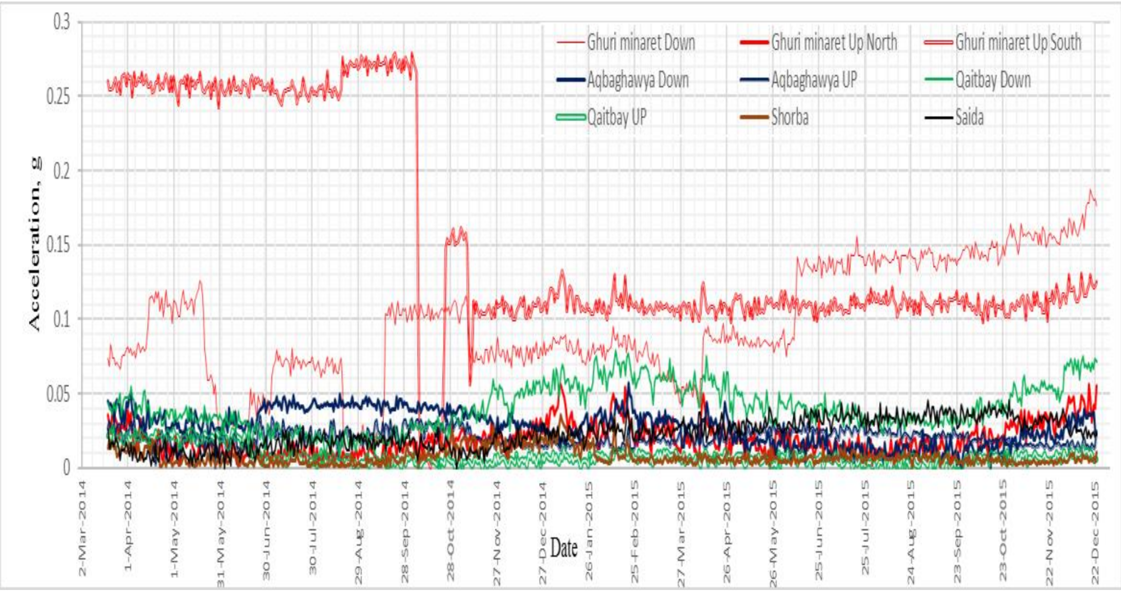


Figure 3: Daily average resultant of horizontal acceleration from all sensors

Shorba and Saida minarets, displayed a typical example of the winter – summer oscillation pattern, the profile is prominent and obvious. When comparing the second-year cycle to the first, we can identify the same trend and behavior of the minaret, however, we can also observe the magnitude of acceleration has slightly increased. This can be explained by the change in the wind strength within the same season in the following year.

When comparing the daily variations of Saida and Shorba minarets, we can see the effect of rigidity on acceleration, through comparing the length to diameter ratios of both minarets. Shorba minaret prevails in both rigidity ratio for the 1st and 2nd shafts. Furthermore, it appears that Shorba minaret is less prone to motion than Saida. The difference in magnitude of both acceleration data is understandable and may be caused by the following reasons; 1) Minarets location, since Shorba minaret is present within the mosque complex and is well shielded from traffic excitations, unlike Saida minaret which is accessible from the side streets and more prone to traffic than Saida minaret; and 2) Sensor location, since location of sensor in Saida minaret is at the balcony level, while in Shorba minaret is at the base of the conical spire. This is enough to produce a difference in acceleration magnitude as the center section of the minaret is more prone to vibration than the top end, as seen in Qaitbay and Aqbaghawya and Ghuri minarets.

5 CONCLUSION

Integrated low g-accelerometer (low cost) system used in this article has proven a reasonable efficiency in providing detailed data suitable for long term monitoring of tall structures. Simple statistical processes of normalization and jumping averaging are enough to reduce the enormous amount of data into a manageable extent and still be able to illustrate and differentiate between the long term and short term responses. Overall, the information available is considered sufficient for understanding and comparing the structural health of masonry minarets, and may be applied in future to other more complex structures.

Moreover, minarets oscillation is thought to be of a constant behavior induced by ambient environmental forces. In some cases, there may be short term anomalies mainly produced by nearby human activities and construction works. The observed behavior of the masonry minarets is considered linear elastic. Normal oscillation is controlled mainly by the seasonal wind forces. Monitoring location must be hidden and protected from any direct wind forces. Minarets with constant stiffness along the height such as shorba and saida minarets or with uniform transition in stiffness such as Qaitbay and Aqbaghawya minarets response in smooth way under normal conditions, however, those with non-uniform stiffness respond in hazard manner even under normal environmental conditions

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