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ORIGINAL RESEARCH

Seismic response of a full-scale wind turbine tower using experimental and numerical modal analysis

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Abstract Wind turbine technology has developed tremendously over the past years. In Egypt, the Zafarana wind farm is currently generating at a capacity of 517 MW, making it one of the largest onshore wind farms in the world. It is located in an active seismic zone along the west side of the Gulf of Suez. Accordingly, seismic risk assessment is demanded for studying the structural integrity of wind towers under expected seismic hazard events. In the context of ongoing joint Egypt–US research project "Seismic Risk Assessment of Wind Turbine Towers in Zafarana wind Farm Egypt" (Project ID: 4588), this paper describes the dynamic performance investigation of an existing Nordex N43 wind turbine tower. Both experimental and numerical work are illustrated explaining the methodology adopted to investigate the dynamic behavior of the tower under seismic load. Field dynamic testing of the full-scale tower was performed using ambient vibration techniques (AVT). Both frequency domain and time domain methods were utilized to identify the actual dynamic properties of the tower as built in the site. Mainly, the natural frequencies, their corresponding mode shapes and damping ratios of the tower were successfully identified using AVT. A vibration-based finite element model (FEM) was constructed using ANSYS V.12 software. The numerical and experimental results of modal analysis were both compared for matching purpose. Using different simulation considerations, the initial FEM was updated to finally match the experimental results with good agreement. Using the final updated FEM, the response of the tower under the AQABA earthquake excitation was investigated. Time history analysis was conducted to define the seismic response of the tower in terms of the structural stresses and displacements. This work is considered as one of the pioneer structural studies of the wind turbine towers in Egypt. Identification of the actual dynamic properties of the existing tower was successfully performed based on AVT. Using advanced techniques in both the field testing and the numerical investigations produced reliable FEM specific for the tested tower, which can be further used in more advanced structural investigations for improving the design of such special structures.

Keywords Wind turbine tower · Ambient vibration test · Zafarana wind farm · Time history analysis · Seismic response

Introduction

In 2003, a detailed wind atlas was published for Egypt's Gulf of Suez coast, concluding that the region has an excellent wind regime with wind speeds of 10 m/s and the potential to host several large-scale wind farms. The Zafarana wind farm (see Fig. 1) by the Red Sea coast has been constructed in stages since 2001, in cooperation with Germany, Denmark and Spain. The installed modern wind turbine systems consist of three basic components (rotor, nacelle and tower) as shown in Fig. 2. The rotor for a typical utility-scale wind turbine includes three high-tech blades, a hub, and a spinner. The nacelle of a wind turbine is the box-like component that sits at the top of the tower

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Fig. 1 Nordex wind turbine towers at the Zafarana wind farm

and is connected to the rotor. The nacelle contains components of the wind turbine such as the gearbox, generator and mainframe. The nacelle and generator are mounted on top of a high tower to allow the blades to take advantage of the best winds.

Wind turbine steel towers are vulnerable to aerodynamic loadings, and the identification of their actual dynamic properties is a crucial step in understanding its dynamic behavior. That is necessary to improve design guidelines and to predict the structural behavior under any expected future loading. A recent study conducted an experimental modal testing on full-scale wind turbine prototype model using a shaking table facility (Prowel et al. 2008). Their research presented the experimental results from an initial series of full-scale shake table tests of a 65 kW wind turbine with a 23 m hub height. Using the experimental results, a calibrated finite element model was developed to investigate and highlight the salient characteristics of the wind turbine's seismic response. Their model was subjected to a number of earthquake records from California. Five high-intensity historical input motions, which produced significant response in the turbine, were used to investigate the difference in seismic demand of a parked turbine for uni-axial and bi-directional excitation scenarios. Molinari et al. (2010) described the results of AVT conducted on a two bladed wind turbine tower. Its spectral response to wind excitation was identified both in operation and with the rotor at rest. The outcome of the experiment suggests that the vulnerability to fatigue of that model of turbine is very sensitive to its modal behavior, depending on the mechanical admittance of the foundations. Dai et al. (2013) conducted ambient vibration test using a laser Doppler vibrometer (LDV) as a remote sensor. The tested wind turbine is a three-bladed turbine system. The supported tower is a 63 m-height tubular steel structure. The study investigated the efficiency of using a laser-based remote sensor to measure the dynamic properties of an existing wind turbine structure. The natural frequencies and damping ratios of the 1.5 MW wind turbine were identified. It is indicated that the tubular steel tower is flexible with low damping. Bazeos et al. (2002) and Lavassas et al. (2003) presented extensive finite element models for prototype turbines with power ratings of 450 kW and 1 MW, respectively. Both studies employed simple single-degree-of-freedom models with the rotor and nacelle mass lumped at the top of the tower. Prowell and Veers (2009) presented an insightful analysis of the literature describing various simplified and full-system wind turbine models that have been published and used for the seismic analysis of turbines.

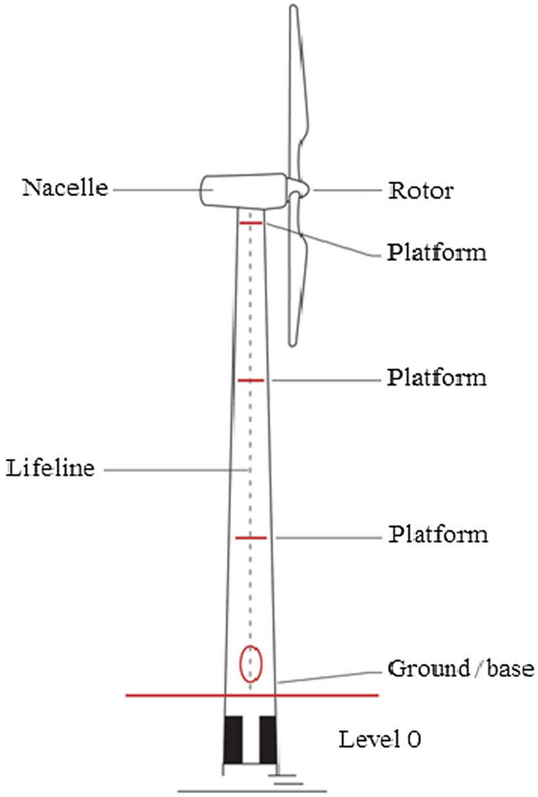


Fig. 2 Typical wind turbine system components

The actual dynamic parameters (frequencies, mode shapes and damping) of wind turbine were obtained from ambient vibration test and FE models were developed to simulate the tested tower. The tested structure is Nordex N43/600 tower of the Zafarana wind farm with a height of 40 m. The tower is a thin-walled steel tubular one which consists of two sections bolted together on the site. The top and bottom tower diameters are 1.56 and 3.178 m, respectively. The thickness of the tower varies from 15 mm at the bottom of the tower to 8 mm at the top. The nacelle, hub and rotor are supported by the tower. A reinforced concrete cylinder foundation is used to support the whole wind turbine system. The complete nacelle weight (including gearbox and generator) is 215 kN and the rotor weight is 140 kN. So the total weight mounted at the top of the tower is approximately 355 kN.

Experimental modal analysis

The last few decades have witnessed an exceptional interest in a better understanding of the structural dynamic behavior and identifying the modal parameters, namely the natural frequencies, damping ratios and mode shapes. This field of research is referred to as experimental modal analysis. It is based on determining the modal parameters of a linear, time invariant system by way of an experimental approach (Ewins 2000; Heylen et al. 1997; Maia and Silva 1997). The knowledge of the modal parameters can serve various purposes including structural modification (Maia and Silva 1997), assessment of the structural integrity and reliability (Melchers 1999), structural health monitoring (Doebling et al. 1998) and model updating (Friswell and Mottershead 1995).

Dynamic testing methods without any control on the input are classified as ambient vibration testing where the output-only response of the structure is measured. The popularity of this method is due to the convenience of measuring the vibration response while the structure is under service loading. The loading could be from either wind, waves, vehicular or pedestrian traffic or any other service loading. So ambient sources represent the true excitation to which a structure is subjected during its lifetime (Bergmeister et al. 2003). It is also considered as a non-destructive test being harmless to the safety of the tested structure (Endrun et al. 2010). It has been successfully performed on many existing buildings, bridges and other large civil structures (Abdel-Ghaffer and Scanlan 1985; Brownjohn et al. 1992; Chang et al. 2001; Cunha et al. 2001; Ren et al. 2001, 2004; Darbre and Proulx 2002; Jaishi et al. 2003; Pau et al. 2005; Gentile and Gallino 2008; Cantieni 2009; Saudi et al. 2009; Kyung-Won et al. 2013; Foti et al. 2011, 2012; Diaferio et al. 2015a, b). Still few types of experimental testing are used to obtain the actual dynamic parameters of wind turbine towers. Ambient vibration testing can be successfully used to identify these parameters from in situ measurements of full-scale wind turbine towers under the actual applied forces (Swartz et al. 2008; Bechhofer et al. 2012; Sheng and Veers 2011; Molinari et al. 2010; Marinone et al. 2014; Van der Valk and Ogno 2014; Kaoshan et al. 2015).

Measurement Instruments

The measurement system used for field dynamic testing consists of three units of LAN-XI—6 channels from Brüel nad Kjær as shown in Fig. 3. Sensitive accelerometers of type PCB Model 393B04 were used to capture the horizontal response of the towers as shown in Fig. 4.

Calibration of the measurement system

The actual sensitivity of each accelerometer has been determined using Calibration Exciter Type 4294 from Brüel and Kjær. For the laboratory checkup test, the accelerometers were attached to LAX-XI units in the same order as they would be attached at the site during the real test as shown in Fig. 5. That procedure considers the

Fig. 3 Six channel input module 50 kHz (data acquisition unit)

Fig. 4 High sensitivity PCB accelerometer model 393B04 and calibration instrument

Fig. 5 Laboratory checkup test before transporting equipment

influence of the cables on the sensitivity of the accelerometers.

Test procedure

Each accelerometer was connected to LAN-XI unit with a 20 m cable which is capable of transmitting electricity and data together. Using the new technology of Power over Ethernet IEEE-802.3, the units were connected through the cables of Type CAT6 to a suitable router to supply power to the mounted accelerometers at different heights of the tower. The router was then connected to the controlling laptop which was operated by the team manager at ground. The test grid inside the tower was set, so that the spacing between the tested points equal 5.0 m along the height of each as shown in Fig. 6. These positions were found to be the only accessible ones using the main ladder in reaching all the high levels. That allowed measuring the vibration response of the tower in the horizontal direction, which can be reliably used to identify the bending modes of the full tower.

To accurately mount the accelerometers at equidistance test points, a measuring tape was fixed at the top of the tower descending down the whole height till the floor level. Each level had a set of accelerometers which consisted of two accelerometers: one of them in the X direction and the other one in the Y direction as shown in Fig. 7. Every three consequent sets of accelerometers were connected to a LAN-XI unit as shown in Fig. 8 and all of the units connected to the controlling laptop through CAT6 cables and router unit. The ambient dynamic response of Nordex tower was measured using 16 accelerometers. The wind turbine tower was tested in the non-operating state (parked state). For 30 min, the vibration accelerations of the towers were recorded by the use of a data recorder. Figure 9 depicts some recorded signals of acceleration at heights 40 and 35 m of the tower.

Spectral analysis and structural modal identification

The analysis was performed using ARTeMIS extractor program. The configuration of signal processing includes specifying the order of decimation (fraction of the original sampling frequency) and the number of spectral lines for the Fourier analysis. The software has the capability of applying a filter (bandpass, bandstop, highpass or lowpass) on the data to remove unwanted components that may obscure any curve fitting process in the analysis. The sampling frequency of 81.93 Hz and a Nyquist frequency of 40.97 Hz were chosen in configuration setting of the signal processing. The spectral estimation was performed using the modified averaged periodogram method (Welch's technique) with an overlap of 66.7 % and a Hanning weighting function. This ensures that all data are equally weighted in the averaging process, minimizing leakage and picket fence effects. The Welch method performs a splitting of the time series and then an overlap of the windowed segments before averaging them together. This technique minimizes the spectral noise and the effects of other artifacts. For signal processing setting, the number of frequency lines was chosen to be 2048 with frequency line spacing of 0.02 Hz.

Using the ARTeMIS Extractor, two techniques were used to perform the modal identification. The first technique is the enhanced frequency domain decomposition (EFDD) and the other is the stochastic subspace identification (SSI). Both techniques efficiently identified the modal properties of the tower. The results are shown in Table 1. Modal frequencies and damping are shown for each technique. Modal assurance criterion (Allemang 2002; Saudi 2015; Abo El-kheir 2015; Saudi and Kamal 2014) was used to study the correlation between these methods and the reliability of the identified properties. The results of the captured mode shapes are shown in Fig. 10. Bending modes in orthogonal directions were clearly identified in the range 0–18 Hz.

Finite element modeling

In the modern analysis of systems in engineering, a great deal of effort has been invested in the development of sophisticated computer models. Digital computers have been applied, particularly in the generation of numerical predictions from discrete models. However, when predictions are compared with experimental results, it is often discovered that the degree of correlation is not good enough to allow the application of the model with confidence. Thus, there is a need to correct (update) an FE model so that its vibration behavior matches with the experimental dynamic response. The procedure used to

Fig. 6 In situ systematic diagram of the test set and accelerometer locations

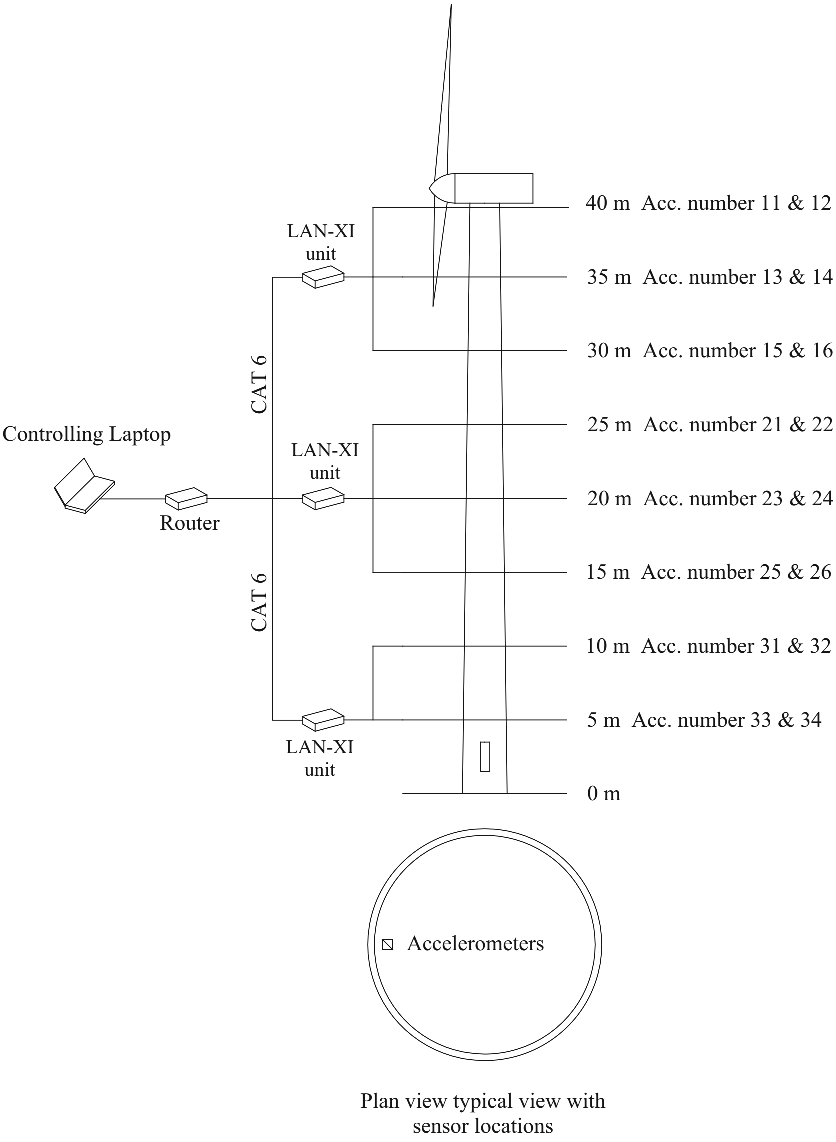


Fig. 7 Accelerometers used

update the FE model is called finite element model updating (FEMU) (Friswell and Mottershead 1995). For the Nordex tower, the model updating was achieved through building an initial three-dimensional FE model in ANSYS, which was then modified in successive steps to finally match the measured properties with good agreement.

Initial finite element modal

The initial structural model of the tower is represented by an equivalently long, slender cantilever beam built from segments having different, but uniform cross-sectional properties. The tower is cantilevered to the ground and carries a concentrated mass at its free end, approximating the inertia properties of the nacelle/rotor unit. This mass is assumed to be rigidly attached to the tower top. The door opening was not considered at this stage. The dimensions of the model are the same as explained in "Experimental modal analysis" for describing the Nordex tower. Figure 11 shows the tapered cylindrical tower. Fixed boundary conditions are assumed at the lower end of the tower for all the analyses. Shell elements (*Shell63*) are used for the tower wall. Six degrees of freedom *Mass21* element was used to represent the mass of the whole components of the wind turbine (nacelle including the generator, gearbox, the hub and rotor). Mass was applied in 12 nodes at the top of the tower, so that each node has a mass of 3015 N s^2/m as shown in Fig. 10. ANSYS calculates the own weight of the tower by defining the gravity acceleration $g = 9.81$ m/s^2 and the material density was taken as 78 kN/m^3.

Fig. 8 LAN-XI unit fixed at the ladder

In the modal analysis module, Block Lanczos solver performance output was used to extract mode shapes and natural frequencies. The Block Lanczos method uses an assembled stiffness and mass matrix in addition to factoring matrices that are a combination of the mass and stiffness matrices computed at various shift points (ANSYS 2012). The numerical analysis gave a large number of natural frequencies and their corresponding mode shapes. The FE model produced about 100 modes of shapes in the frequency range between 0.1 and 1000 Hz. These mode shapes consist of local and global ones. Table 2 shows the comparison between the FEM results and the experimental results for the lowest six bending modes. The difference

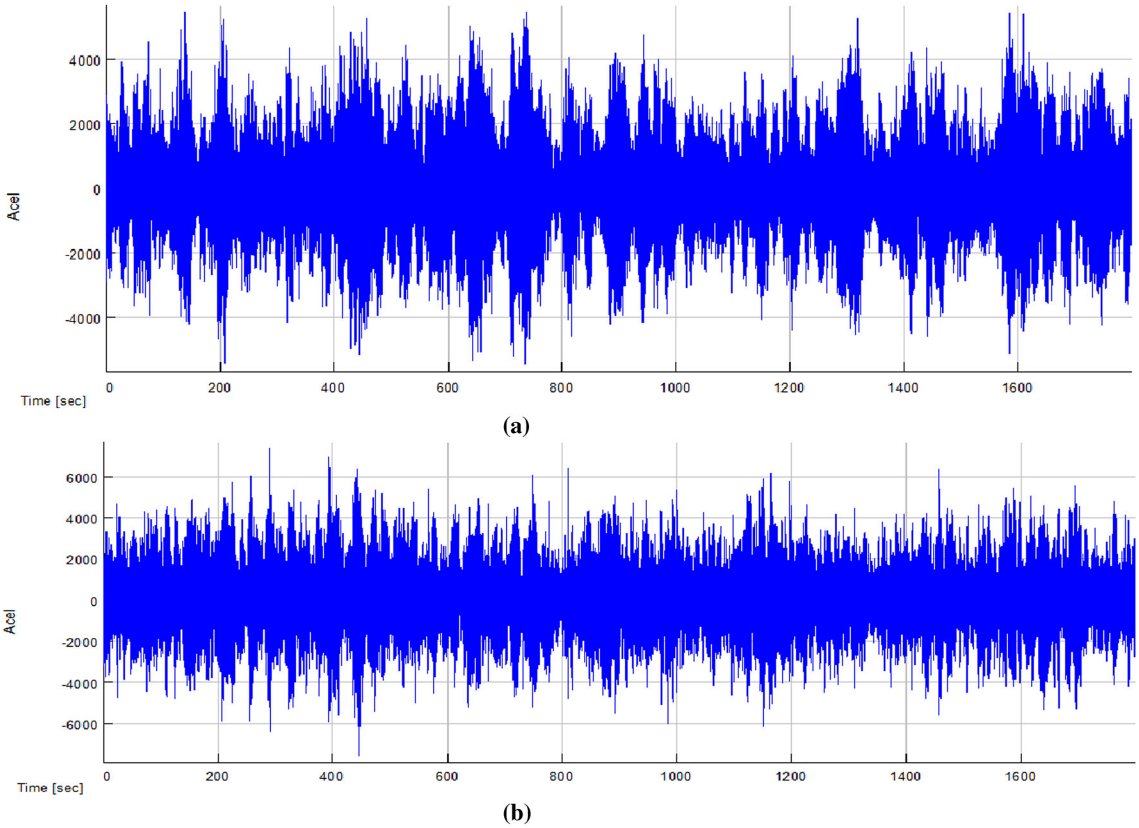
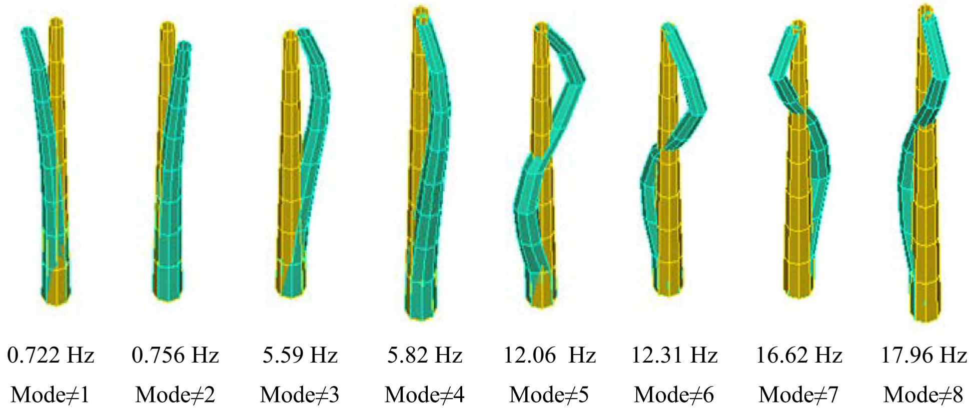


Fig. 9 Typical recorded signals at Nordex N43 tower. **a** Channel 1, **b** channel 2

Table 1 Experimental results identified using EFDD and SSI for Nordex N43 tower

Mode	Description	EFDD		SSI		MAC
		Freq (Hz)	Damping %	Freq. (Hz)	Damping %	
1	First bending fore—after	0.7223	0.63	0.7188	0.52	0.997
2	First bending side to side	0.756	0.85	0.756	1.42	0.974
3	Second bending fore—after	5.591	1.665	5.435	3.223	0.940
4	Second bending side to side	5.822	1.208	5.75	0.4439	0.941
5	Third bending fore—after	12.06	0.3328	12.07	0.383	0.950
6	Third bending side to side	12.31	0.246	12.31	0.260	1.00
7	Fourth bending fore—after	16.62	0.0661	16.71	1.51	0.962
8	Fourth bending side to side	17.96	1.041	17.86	1.583	0.973
9	Fifth bending fore—after	26.26	0.256	26.26	0.2561	0.741
10	Fifth bending side to side	25.8	0.321	25.84	0.3056	0.996
11	Higher bending fore—after	34.3	0.3465	34.33	0.4771	0.708
12	Higher bending side to side	34.59	0.343	34.57	0.343	0.932

Fig. 10 Nordex N43 identified mode shapes



ratio between the ambient vibration test and the initial FEM simulation does not exceed 3.13 % for the first and second mode shapes. The following four mode shapes have frequency differences varying from 24.01 to 63.18 % from the measured frequencies. Model updating of tower parameters was required to have a better simulation of the experimental results.

Updating finite element (ufem)

The initial FEM of Nordex N43 tower was modified where more elements were introduced to represent the nacelle and rotor parts. Beam4 element was employed to simulate the nacelle and rotor. The mass distribution was changed. First, the total mass of the wind turbine components was split into two masses. The weight of the nacelle is considered as 215 kN. The weight of the rotor and hub is considered as 140 kN. The first mass (Mass1) representing the weight of the complete nacelle was applied at 12 nodes at the top of the tower, so that each node had a mass of 1826 N s^2/m. The mass was applied in the three global directions (*x*–*y*–*z*), so that we can obtain the mode shapes and torsion of the tower in all directions. The second mass (Mass2) represented the weight of the rotor and hub. For more accurate representation, the mass of the hub and rotor (Mass2) was modeled using Beam4 element. The nacelle was simplified as 12 beams (Beam4) connected to the top of the tower. The hub was represented with a beam connected to the nacelle and Mass2 was applied as a concentrated mass at the end of the hub Beam4 element as shown in Fig. 12.

The door opening was simplified as a rectangular void with 2000 mm height and 700 mm width at a height of 3000 mm from the base. The modal analysis of the updated FEM predicted the dynamic behavior of the tower in terms of its modal frequencies and the corresponding mode shapes as shown in Fig. 13. Comparison between the results and the experimental findings is shown in Table 3 and illustrated in Fig. 14. The difference between the ambient vibration test and FEM simulation was 7.28 % for the first mode shape. The mode shapes have frequency

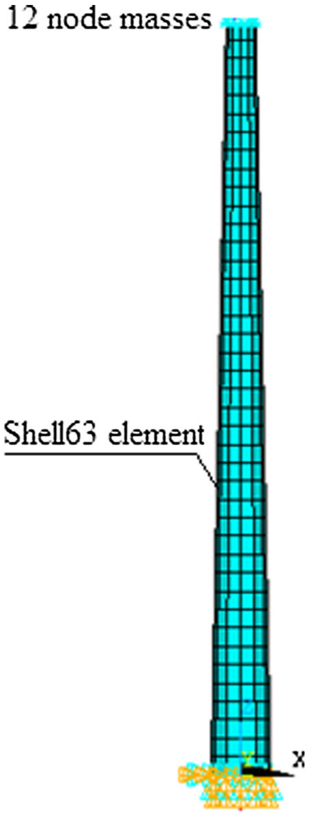


Fig. 11 The initial FEM in ANSYS software for Nordex N43 tower

differences varying from 0.05 to 9 %, except for the third mode at 12.23 %, from the experimentally identified frequencies. The improvement in matching the measured properties is evident as obtained from the UFEM. According to that, the updated FEM was considered to be a reliable representation of the existing tower, where further structural studies can be efficiently conducted.

Time history analysis under seismic load

The ground motion of Al Aqaba Earthquake 1995 which was recorded at Eilat Station was used in this study. The measured acceleration time history was recorded at the surface as shown in Fig. 15. This time history was applied to

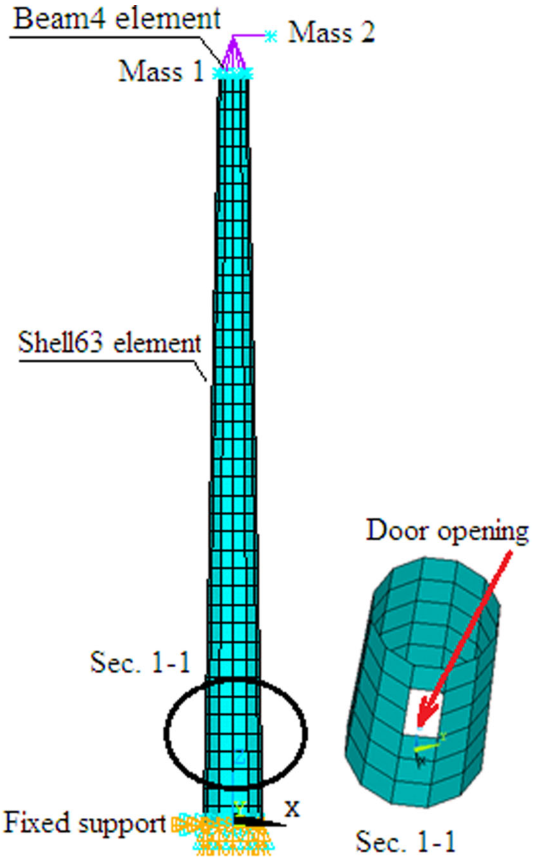


Fig. 12 The updated FE model

the tower FEM using ANSYS V.12. The damping was taken as 2.5 % for all modes. The FEM was solved through 12,000 time steps from 0.005 to 60 s that is the time history. Every time step is an independent solution step that has its time-varying results (Korea Institute of Nuclear Safety 2009). After those steps, the results are taken from several nodes and elements. Node 1 represents the hub in the *X* direction and Node 2 represents the hub in the *Y* direction at a height of 42 m for Nordex towers as shown in Fig. 16. Node 3 and Node 4 represent the middle of the Nordex tower at a height of 20 m. The maximum displacement is found at Node 1 and Node 2. The maximum stresses were located at the door level of the towers, 3 m from the base. “Introduction”

Table 2 Comparison between ambient vibration test and initial FEM results

Mode	Description	Freq. identified using EFDD (Hz)	Freq. identified using initial FEM (Hz)	% Difference
1	First bending fore—after	0.7223	0.745	3.14
2	First bending side to side	0.756	0.745	−1.46
3	Second bending fore—after	5.591	7.22	29.14
4	Second bending side to side	5.822	7.22	24.01
5	Third bending fore—after	12.06	19.68	63.18
6	Third bending side to side	12.31	19.68	59.87

Fig. 13 Mode shapes as obtained from the updated FE simulation results

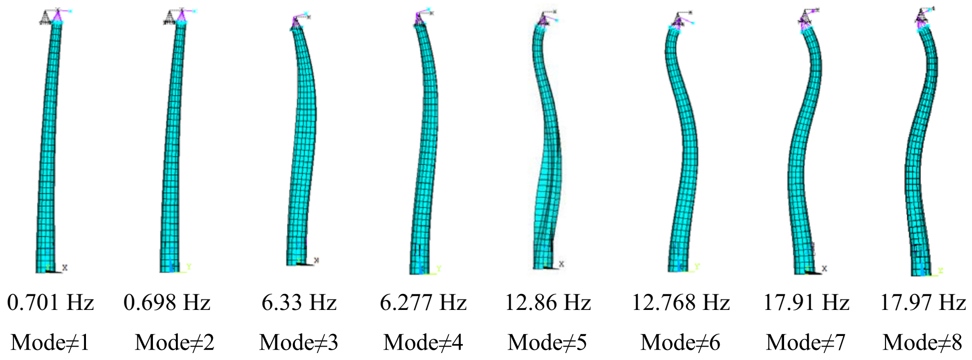
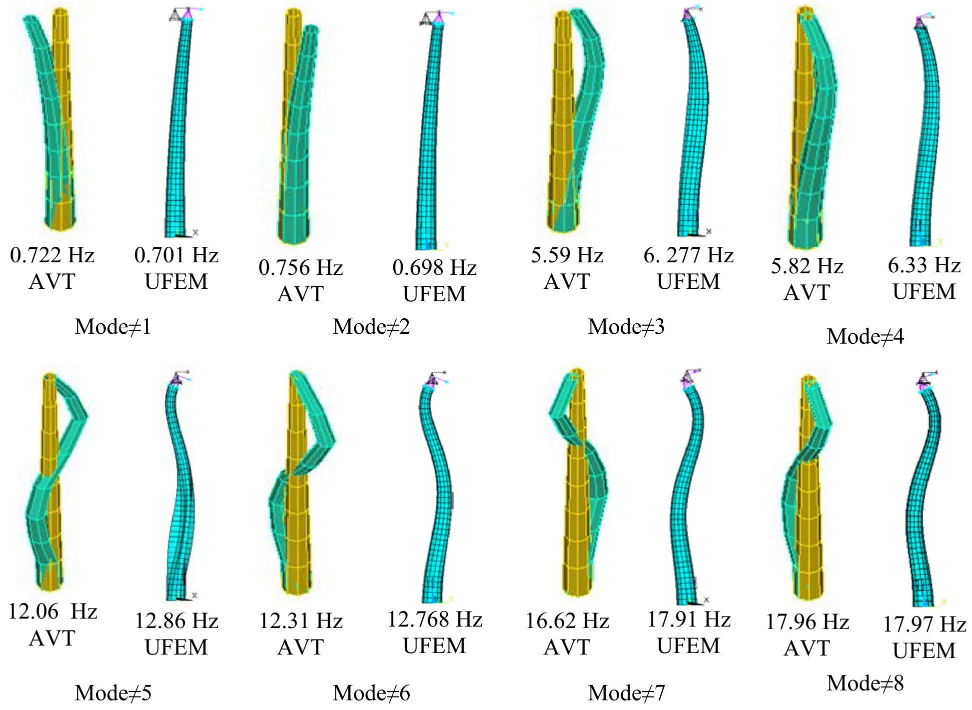


Table 3 Comparison between ambient vibration test and UFEM results

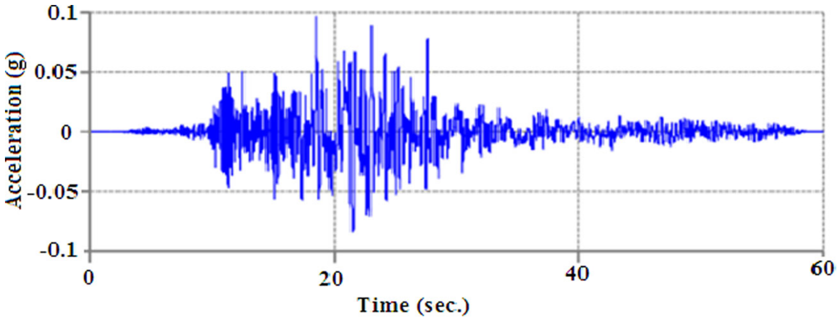
Mode	Description	Freq. identified using EFDD	Freq. identified using UFEM	% Difference	MAC
1	First bending fore—after	0.7223	0.701	−2.95	1.0
2	First bending side to side	0.756	0.6982	−7.65	0.998
3	Second bending fore—after	5.59	6.277	12.27	0.999
4	Second bending side to side	5.822	6.33	8.73	0.992
5	Third bending fore—after	12.06	12.86	6.63	0.979
6	Third bending side to side	12.31	12.768	3.72	0.982
7	Fourth bending fore—after	16.62	17.91	7.76	0.988
8	Fourth bending side to side	17.96	17.97	0.06	0.997

Fig. 14 Ambient vibration test and UFEM results for the Nordex N43 tower



shows the elements around the door of the towers where the maximum stresses are in the *X* and *Y* directions. The maximum displacement and stress obtained from the El Aqaba earthquake time history are shown in Table 4. The time-varying results for the hub, middle point and door level are shown in Figs. 17, 18, 19, 20, 21 and 22.

Fig. 15 Time histories of the Aqaba earthquake in 1995



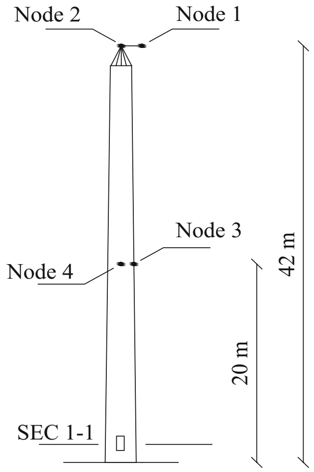


Fig. 16 Location of selected nodes and elements for spectrum analysis

Table 4 Maximum displacement and stress as obtained from the El Aqaba earthquake time history

	X direction	*Y* direction
Maximum hub displacement (mm)	10.10	10.11
Middle displacement (mm)	1.907	1.91
Maximum stress at door level (MPa)	2.661	2.615

Conclusions

This work presented was one of the pioneer studies concerning the investigation of the structural dynamic performance of a full-scale wind turbine tower under seismic load in Egypt. Both ambient vibration test at site and numerical modeling using advanced modules were used in this study. The seismic response of the tower was investigated using the time history analysis under the AQABA earthquake record. Both the displacement and stresses at key points along the height of the tower were presented. The conclusions from the current study can be summarized as follows:

1. Ambient vibration test was shown to be an efficient technique for obtaining the dynamic parameters (frequencies, mode shapes and damping) of wind turbine towers. Clear spectral peaks were produced from the modal analysis and were successfully interpreted in terms of the dynamic behavior of the tower.
2. Eight bending mode shapes were clearly identified in the range 0–17.96 Hz using the modal identification techniques for ambient vibration.
3. The tower exhibited a dynamic behavior characterized by well-separated modal frequencies where bending mode shapes were captured in the main horizontal directions *X* and *Y*. Each structural mode has a defined representation in these directions up to the fourth bending mode.

Fig. 17 Time history of displacement at the hub of Nordex N43 FEM in the *X* direction (Node 1)

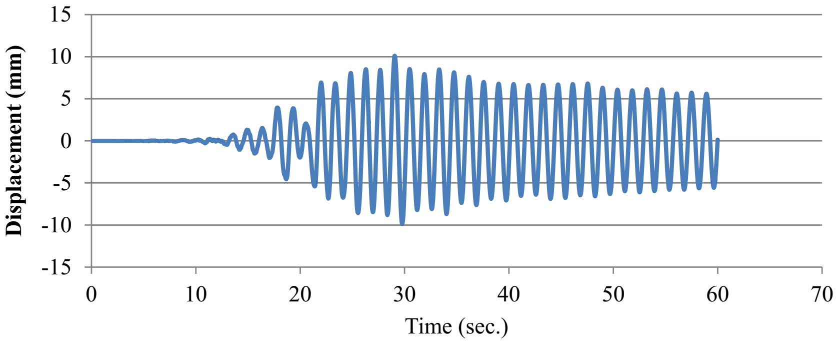


Fig. 18 Time history of the middle point displacement for the Nordex N43 FEM in the *X* direction (Node 3)

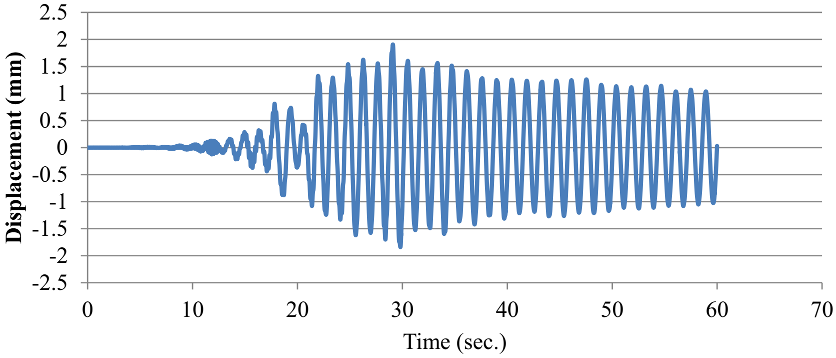


Fig. 19 Time history of the maximum stress of Nordex N43 FEM in the *X* direction

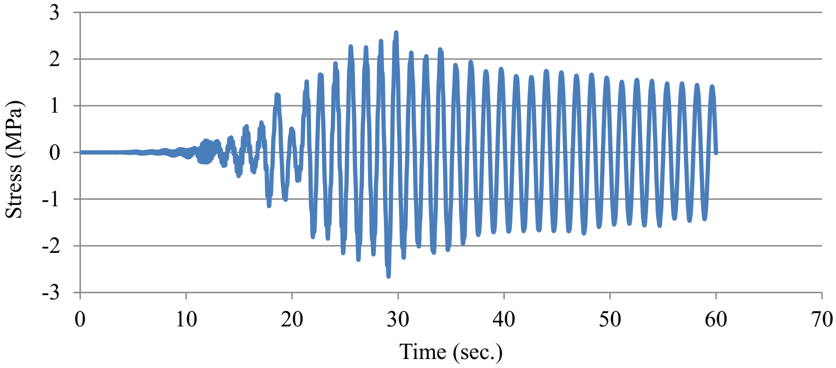


Fig. 20 Time history of displacement at the hub of Nordex N43 FEM in the *Y* direction (Node 2)

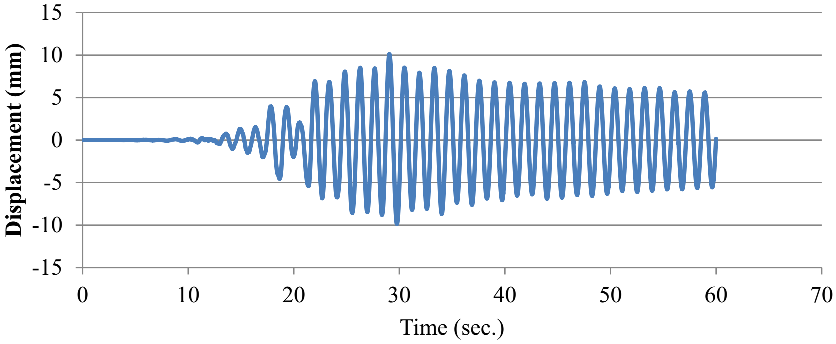
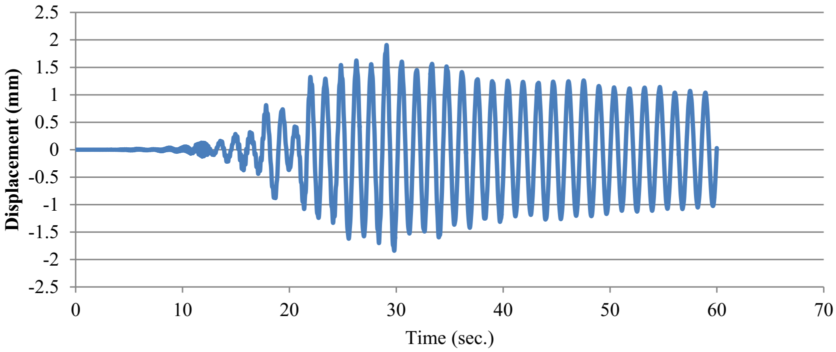


Fig. 21 Time history of middle point displacement for Nordex N43 FEM in the *Y* direction (Node 4)



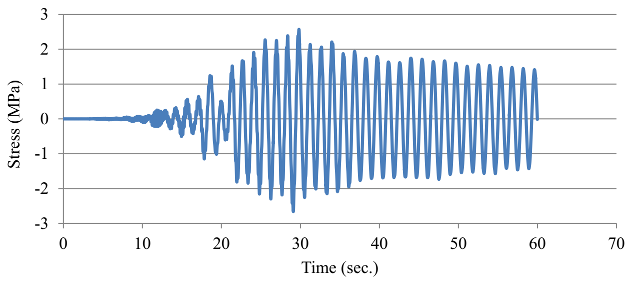


Fig. 22 Time history of maximum stress of Nordex N43 FEM in *Y* direction

4. The numerical simulation of the tower in ANSYS was successful where the difference between the measured and computed properties of the final updated model was within 7 %. This is considered quite acceptable in the context of model updating for large structures.
5. The zone of the tower around the opening door is the most affected where the stresses were found to be higher than the other tower parts. This highlights the importance of the careful design of the tower at such zones where the concentration of stresses is highly expected.
6. All the data being realistic from structural field testing and current seismic records in region of Red Sea. More confidence in the obtained results was gained. Accordingly the final updated model of the tower represents a reliable baseline model that can be utilized in further structural studies under different loading conditions including wind loads.

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