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FIELD DYNAMIC TESTING AND MODELLING OF ZAFARANA WIND TURBINE TOWERS INCLUDIMG MODELLUS OF SUBGRADE REACTION

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ملخص البحث

حدث فى فى الاونة الاخيرة تقدم كبير فى تكنولوجيا انشاء وتصنيع توربينات الرياح. وفى مصر نجد مزرعة الرياح بالزعفرانة وهى من اكبر مزارع الرياح وتولد طاقة كهربائية بقدرة 517 ميجا وات مما يجعلها واحدة من اكبر مزارع الرياح فى العالم. وتقع مزرعة الرياح بالزعفرانة فى نطاق سيزمى على الجانب الغربى من خليج السويس. وبالتالى دراسة تحليل المخاطر السيزمية لهذه المزرعة ضرورى فى التصميم الانشائى وتصميم الاساسات لتوربينات الرياح الموجودة بالمزرعة. يقيم هذا البحث السلوك الديناميكى وكذلك رد فعل التربة المتبادل لاساسات توربينات الرياح من نوع Vestas V47 من خلال الاختبارات الحقلية الديناميكة والتحليل العددى بهدف تقييم ديناميكى لتوربينات الرياح لتقييم رد فعل التربة الراسى والافقى المستخدم فى حسابات قدرة تحمل التربة لاساسات توربينات الرياح. ممن هذه الدراسه وجد ان اختبار الاهتزاز غير المحيط قادر بنجاح على عمل كل من التحليل السجلى الترددى والتحليل السجلى الزمنى المستخدم فى تحديد الخواص الديناميكية لبرج توربينات الرياح, وكذلك كل من التحليل المودى ونسبة الخمود الديناميكى لبرج توربينات الرياح . وتم استخدام ايضا طريقة العناصر غير المحددة ببرنامج ANSYS 3D لعمل تحليل لرد فعل التربة المتبادل وكذلك حساب رد فعل التربة الراسى والافقى لاساسات توربينات الرياح. . وقد اثبت التحليل العددى المستخدم ببرنامج ANSYS 3D ان رد فعل التربة المتبادل هو المتحكم الاساسى فى تقدير كل من رد فعل التربة الراسى والافقى المستخدمين فى تقدير قدرة تحمل التربة لاساسات توربينات الرياح.

ABSTRACT

Wind turbine technology has developed tremendously over the past years. In Egypt, the Zafarana wind farm is currently generating a capacity of 517 MW, representing one of the largest onshore wind farms in the world. It is located in an active seismic zone along the west side of Gulf Suez. Accordingly, seismic risk assessment is demanded for studying the structural integrity of wind towers under expected seismic hazard events. The present paper describes the dynamic performance investigation and soil structure interaction of an existing Vestas V47 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 and the soil structure interaction to evaluate the modulus of subgrade reaction for tower foundation. Field dynamic testing of the full-scale tower was performed using ambient vibration techniques (AVT). Frequency domain and time domain methods were utilized to identify the actual dynamic response of tower as built in the site. The natural frequencies, their corresponding mode shapes and damping ratios were successfully identified using AVT. A vibration-based finite element model (FEM) was applied using ANSYS 3D software including soil structure interaction of tower foundation, and to evaluate the modulus subgrade reaction in vertical and horizontal directions. The results show that identification of the actual dynamic properties of the existing tower was successfully performed based on AVT. Also, using ANSYS 3D to evaluating the modulus of subgrade reaction shows that soil structure interaction is expected to govern the

calculated vertical and horizontal subgrade reactions to estimate the bearing capacity of wind turbine towers foundations.

Keywords: Ambient vibration test, modulus of subgrade reaction, numerical modelling, Vestas V47, wind turbines towers

1. INTRODUCTION

Wind energy has gained popularity worldwide as many countries aim to increase the production of clean energy. Egypt has ambitious targets in the field of renewable energy. Its target is that 20% of the country's electricity should come from renewable source by 2020 [1,2]. The largest wind farm in Egypt was constructed in 2001- 2010, Zafarana wind farm hosts 545 MW of grid connected wind power, to become the largest wind farm in Africa and the Middle East. For a wind turbine, the tower is considered one of the major components in wind turbines generator with a contribution to cost of energy of 8 to 12% [1]. It has been lately reported that many wind turbine damage occurs due to the structural failure of wind turbine towers and geotechnical failure [2]. When dealing with wind turbines, very field tests have been performed on the supporting structure [3]. It is essential to rely on field dynamic testing when there is a demand for studying actual seismic performance through vibration based tuned numerical models. The ambient vibration testing (AVT) is a kind of an only output response dynamic test method. This field dynamic testing has an advantage of being cost-effective since no equipment is needed to excite the structure. It is also regarded as a non-destructive test being harmless to the integrity of the tested structure [4]. Ambient vibration testing (AVT) has also shown to be an efficient tool for identifying the real dynamic behavior of different structures. Recent researches incorporated AVT for modal analysis of wind turbine towers in both parked and operating conditions. The field results were mainly used to provide good simulation for the vibration modes of the wind turbine towers and their rotors [5- 10]. 3 D numerical modelling is very effective tools to evaluate the soil structure interaction in wind turbine towers. The use of soil structure interaction (SSI) in design is usually restricted to buildings in seismic zones. However, wind turbines contain moving parts and must sustain continuous vibration-induced forces throughout their operational life. Recent researches [11-17] showed that the response of a structure when subject to a dynamic wind loading can be affected by SSI. Flexible soil-foundation system (V_s < 500 m/s where Vs is the shear wave velocity of soil under foundation level) can have the effect of reducing a wind turbine's fundamental natural frequency and introduces a considerable amount of damping to the system. Comparing fixed-base and flexible-based foundation models showed that, inclusion of the soil-foundation system can affect the dynamic response of the turbine.

In the present paper, first part is focused on collected data during an ambient vibration test of two full-scale wind turbine towers, then analyzing of these data in order to characterize the towers bending and torsional vibration modes. The collected data was processed with time and frequency domain modal identification methods based on AVT techniques.

Second part is to model wind turbine towers foundations using 3D ANSYS software for Vestas V47wind turbine tower foundation . Simplified dynamic structure analyses of a steel tower of Vestas V47 wind turbines towers foundations using numerical model, and including soil structure interaction is presented. This simplified dynamic analysis is 3D finite element method (FEM) by ANSYS 3D software, and including the soil structure interaction effect to calculate the vertical n and horizontal modulus of subgrade reactions.

The results showed that identification of the actual dynamic properties of the existing tower was successfully performed based on AVT. On the other hand using ANSYS 3D to evaluate modulus of subgrade reaction shows that soil structure interaction is expected to govern the calculated vertical and horizontal subgrade reactions for the designed bearing capacity of wind turbine towers foundations.

2. ZAFARANA WIND FARMS

Zafarana wind farm site was analyzed as part of this research to study the structural behavior and soil structure interaction using ambient vibration testing, and numerical modelling for Vestas N47 at Zafarana Wind Farm (3). Figure1 shows Zafarana Wind Farms, which are consist of eight wind farms over an area round of 12 X 18 km.

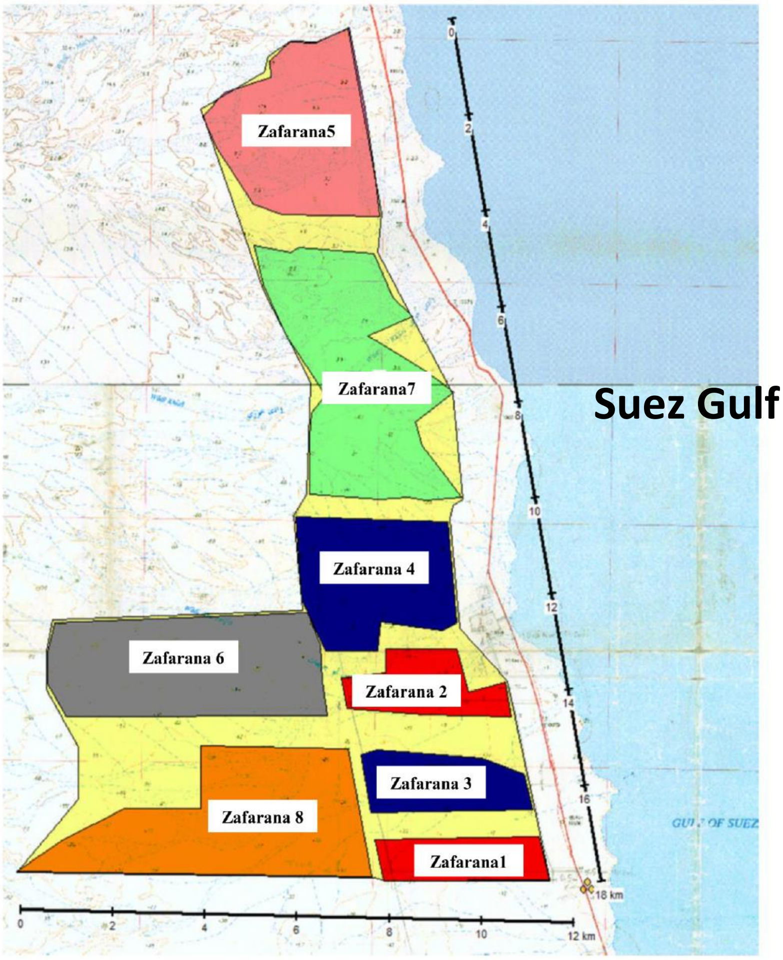


Figure 1: Layout of Zafarana Wind Farms including Zafarana Wind Farm (3).

3. ZAFARANA EARTHQUAKE ZONES

The Egyptian code for loads version 2012 divides Egypt into five main zones according to the seismic impact [18]. Figure 2 presents the seismic zones considering the assumed returned time of earthquake is 475 year. From Figure 3, Zafarana wind farm located at the coast of the red sea at the red zone. According to the colored scale at the right of the map, the red zone represents the third zone. So the design ground acceleration is taken as 0.15g. (The ground acceleration is considered 9.81 m/s^2)

$a_g = 0.15g = 1.47\ m/s^2$ **Eq.1.0**

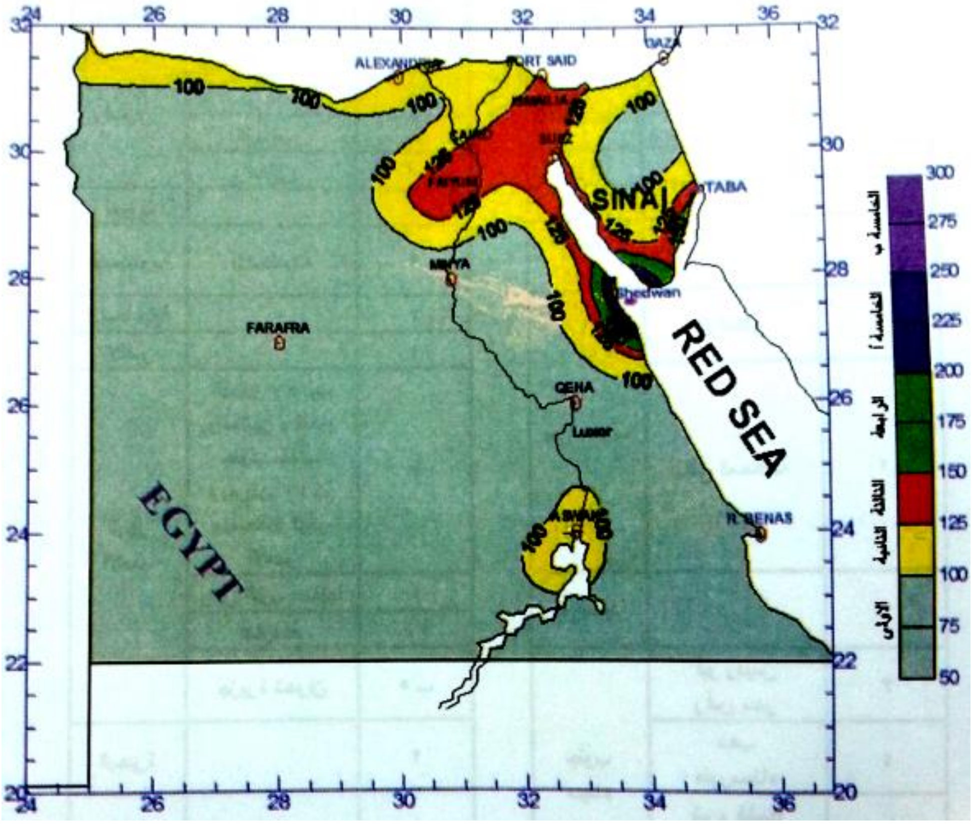


Figure 2: Seismic impact zones [18].

4. ZAFARANA GEOLOGICAL FORMATION

The geological features indicate that, area under study consists of coastal and wadi deposits. Based on the results of the previous site investigation and laboratory testing the soil formations encountered in the boreholes show five main formations, which are: Wadi deposits, Clay, Claystone, Sand and Sandstone. Groundwater is not encountered in any of the boreholes at the time of investigation to depth of 20 m and the foundation depth is 2.50 m.

The Egyptian code for loads classifies the soil underneath the foundation into five categories (A, B, C, D and E) based on the results of shear wave velocity Vs. According to the previous soil profile, SPT results indicate a very dense formation. However, all of the SPT results were affected by the cementation of the sand and reached refusal values. Category (A) represented rock or formations like rock have a very high SPT results. So the soil category at Zafarana wind farm (3) are taken as category (A) [18].

5. WIND TURBINE TOWER VESTAS V47/660

The Vestas V47/660 wind turbine tower as shown in Figure 3 was investigated for its dynamic modal behavior and static soil structure interaction using numerical modelling . The tower has 3-bladed, horizontal-axis wind turbine . Rotor diameter is 47 m and its height is 45.0 m. Tubular tower is formed as truncated cones with variable cross sections and shell thickness along its height . The access to the tower height is internal through aluminum ladder interrupted by one intermediate steel platform. The turbine tower is traditionally pre-fabricated in sections, and bolted together on site. The sections are connected by means of double flanges with preloaded bolts, where the flanges are placed in the inner side of the tower. The tower is fixed to a reinforced concrete foundation sitting on the strengthed bearing soil.

Figure 3: Vestas V47/660 wind turbine towers at Zafarana Wind Farm (3).

6. FIELD DYNAMIC TEST USING AMBIENT VIBRATION TEST

6.1 Ambient Vibration Testing and Signal Processing

The ambient vibration test was performed using a 18-channel data acquisition system consists of three B&K LAN-XI and 18 PCB 393B40 uni-axial piezoelectric accelerometers as shown in Figure 4 [19,20]. The locations of the accelerometers at the test points are shown in Figure 5. PCB 393B40 accelerometers have a sensitivity of 1000 mV/g, a measurement range of ± 5 g and frequency range 0.06 to 450 Hz. B&K LAN-XI system is a portable data acquisition unit with six input channels. LAN-XI data acquisition modules were distributed over the height of the tower and connected to a network switch with a single LAN cable each [19,20]. This supplies both power and assures perfectly sample-synchronized data acquisition where cable work is significantly reduced. The ambient response of the tower was recorded for 30 min at test frequency 800 Hz. It took about 7 hours for V47/660 tower to finish the test settings applied to capture both the bending and the torsional modes. For V47/660 tower, one setup using 18 channels was set to capture the bending modes, other setup of 12 channels was applied to capture the torsion modes [21,22,23] as shown in Figure 5. The arrangement of the accelerometers in test setup of V47/660 tower is shown in Figure 6, as implemented in ARTeMIS [10] , post-processing analysis was performed. The signal data were further decimated in time by a factor 10, giving a baseband for the analysis ranging to 40 Hz. The recorded data was processed in frequency domain. Power Spectral Density (PSD) was estimated using total time period with a frame of 8192 data points. Hanning windows are applied with 66.7 % overlapping by default. 4096 spectrum lines, with frequency resolution of 0.01 Hz, were obtained [21, 22, 23].

Figure 4: Test equipment (a) LAN-XI unit attached to the ladder

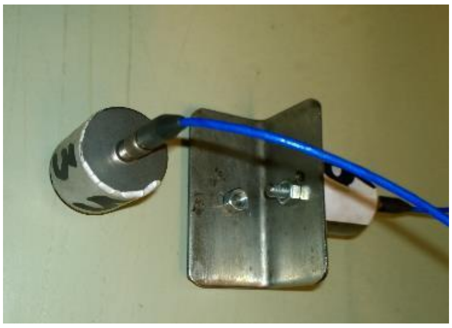


Figure 4: Test equipment (b) PCB accelerometers with magnetic mounting attached to the tower wall

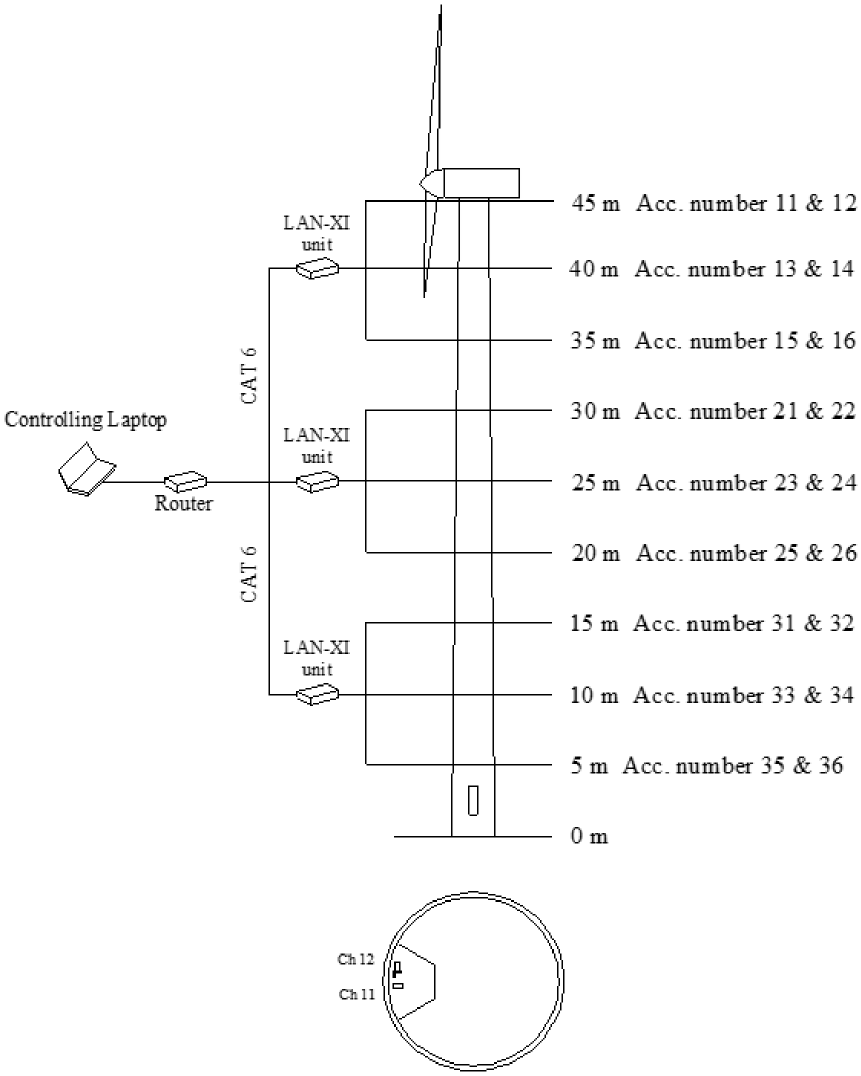


Figure 5: Test setup for dynamic testing.

Figure 6: Accelerometers arrangement at level 2 for Vestas N47 Test Setup.

6.2 Modal Identification

The Enhanced frequency domain decomposition (EFDD) method adds a modal estimation layer to frequency domain decomposition (FDD) method [21,22,23]. In the method, modes are selected by peak-picking located in singular value decomposition plots (SVD) calculated from the spectral density spectra of the responses. The single degree of freedom (SDOF) function is estimated using the shape determined by the previous FDD peak picking - the latter being used as a reference vector in a correlation analysis based on the Modal Assurance Criterion (MAC). A MAC value is computed between the reference FDD vector and a singular vector for each particular frequency line. If the MAC value of this vector is above a user-specified MAC Rejection Level, the corresponding singular value is included in the description of the SDOF function. In EFDD method, SDOF power spectral density (PSD) function, identified around a peak of resonance, is taken back to the time domain using the inverse discrete Fourier transform (IDFT). The natural frequency is obtained by determining the number of zero-crossing as a function of time, and the damping by the logarithmic decrement of the corresponding SDOF normalized auto correlation function.

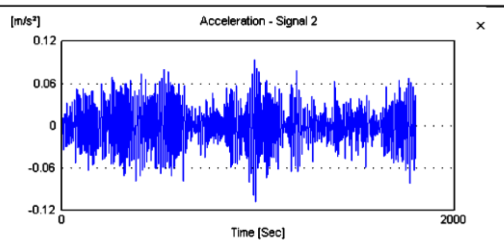
Modal models are estimated for the different state space dimensions up to a selected maximum state space dimension [21,22,23]. The setting of maximum state space dimension depends upon the number of modes, which is searched for, the excitation, the number of sinusoidal components in the response signals and the number of noise modes needed to fit (predict) the measured response signals. The results are achieved by a singular value decomposition of the full observation matrix, which is a matrix calculated from the measured responses, and extracting a subspace holding the modes in the model. A stabilization diagram for the modal models is used for selecting a model (at a certain state space dimension). If the responses are measured in a sequence of measurements (data sets), a number of reference Degrees of Freedom (DOF's) must be included in each measurement (data set) and the models from each measurement are linked together afterwards.

Applying the modal identification methods in ARTeMIS [24], The analysis produced the singular values plots (SVP) as shown in Figure 7. For the same tower, it is clear that, identical modal peaks were produced from analysing the tower response for test setup using EFDD. SSI method consumed a lot of time and effort to manually obtain the structural modes of the towers. The automatic estimation option of SSI-CVA identification in ARTeMIS [24] successfully identified the first side to side bending mode of Vestas tower as shown in Figure 8 that could not be detected by EFDD. This specific mode is at 0.259 Hz. For a steel flexible structure with first natural frequency less than 1 Hz, SSI technique is shown to be powerful to clearly identify it. As the Vestas tower is taller and it exhibited torsion bending coupled modes. The Vestas N47 tower revealed a dynamic behavior of close bending modes at the lower frequency range. For Vestas N47 tower 11 structural modes were successfully determined in the range 0 -25 Hz. The modal results for Vestas N47 towers are displayed in Figure 9.

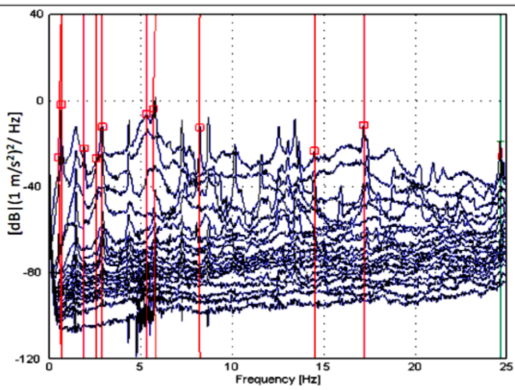
A three dimensional model of the tower was built in ANSYS. Fixed boundary conditions are assumed at the lower end of the tower for all the analyses. Shell elements (Shell63) are used for the tower wall. Six degrees of freedom Mass21 element was used to represent the mass of the whole components of the 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 s2/m. ANSYS calculates the own weight of the tower by defining the gravity acceleration g = 9.81 m/s2 and the material density was taken as 78 kN/m3.

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 [27]. 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.

Accordingly, it was clear that the structural system built in ANSYS does not require altering of the structural properties of the tower, where the results produced good agreement with the experimental data and adjustments were made to the distribution of lumped masses to represent the different antennas and their feed lines along the tower height as shown in Figure 10. Modal analysis was performed to determine the natural frequencies and mode shapes of the tower numerically. They are important for further dynamic analysis to perform a time history analysis. Block Lanczos method was used in ANSYS to achieve a faster convergence rate. The finally predicted modal frequencies are presented in Table (1).

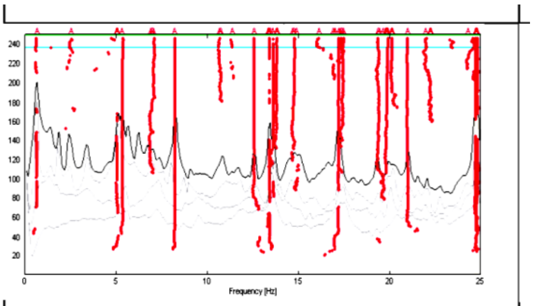


Example of measured response of V47 tower

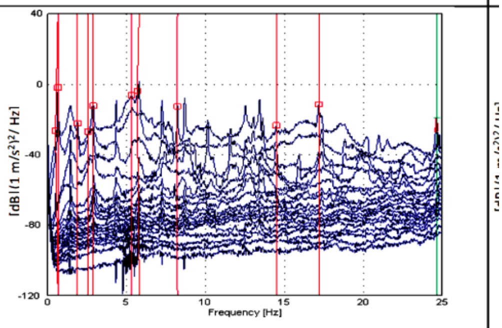


Identified natural frequencies of V47 tower using EFDD (Test setup No.1)

Figure 7: Modal identification analysis of Vestas N47 Wind Turbine Tower.



Stabilization diagram of V47 tower response



Identified natural frequencies of V47 tower using EFDD (Test setup No.2)

Figure 7: Modal identification analysis of Vestas N47 Wind Turbine Tower (Continued).

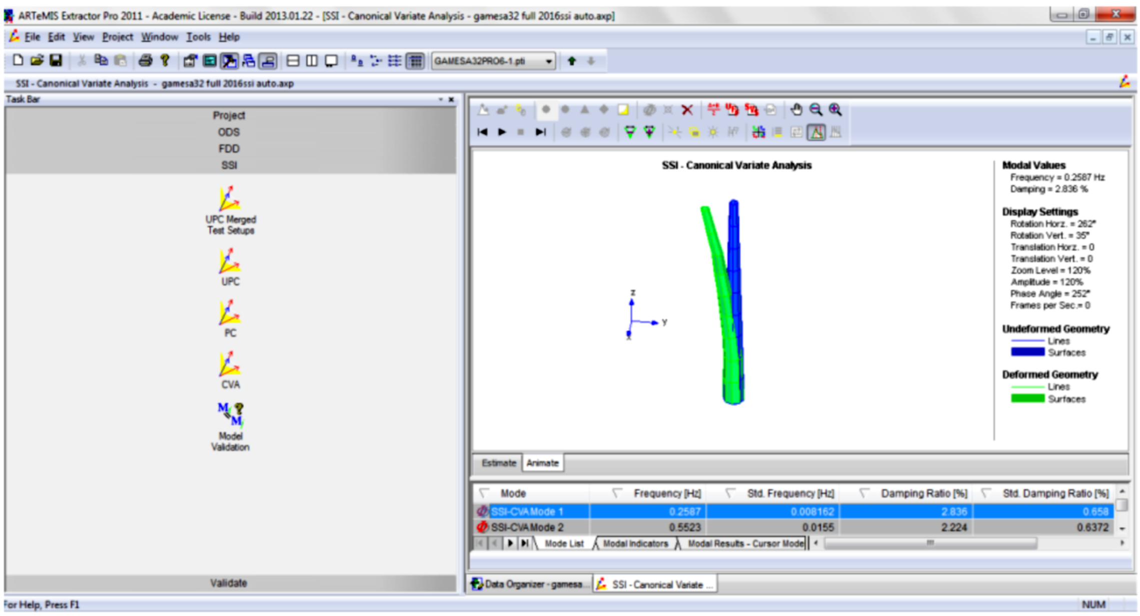


Figure 8: Identified side to side bending mode using automatic estimation SSI-CVA.

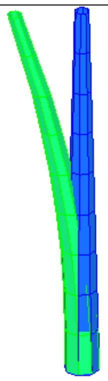
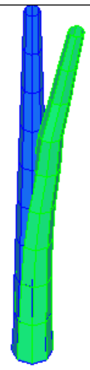
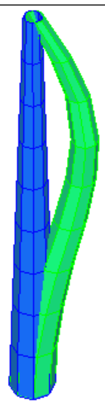
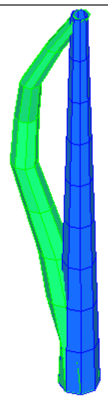
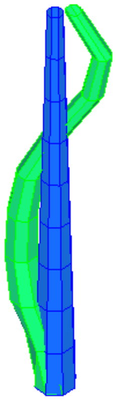
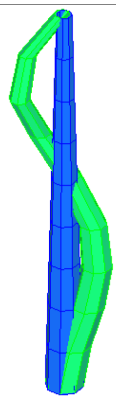
 **First Bending mode Side to side** **Freq. = 0.638 Hz, Damping 3.7%**	 **First Bending mode fore-after** **Freq. = 0.638 Hz, Damping 1.67 %**
 **Second Bending mode Side to side** **Freq. = 5.292 Hz, Damping 0.673%**	 **Second Bending mode Fore -after** **Freq. = 5.787 Hz, Damping 0.293%**
 **Bending mode fore-after Freq. = 14.49 Hz, Damping 0.7123 %**	 **Bending mode side to side** **Freq. = 16.42 Hz, Damping 1.662 %**

Figure 9: Identified structural modes of Vestas N47 wind turbine tower experimentally .

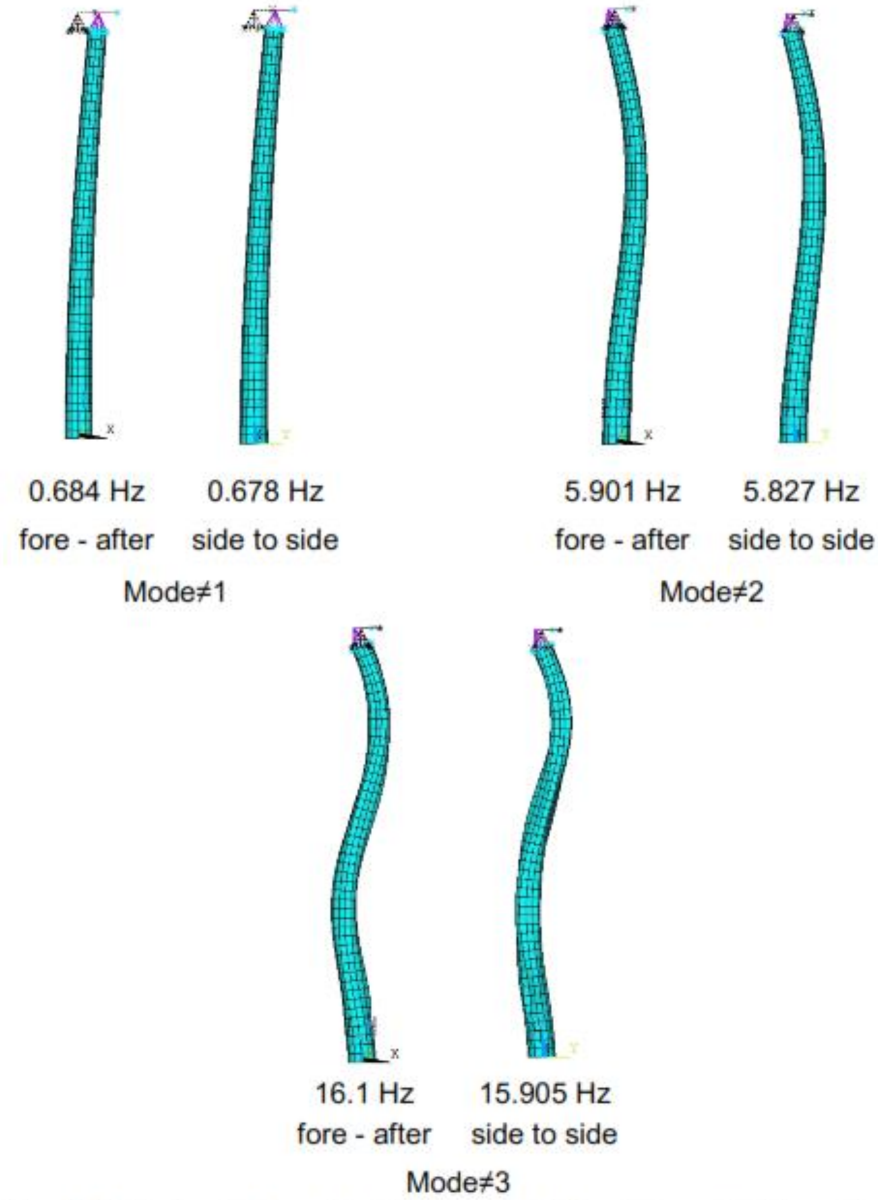


Figure 10 Vestas V47 mode shapes as obtained from FEM results

Table 1: Comparison between experimental and FEM results for Vestas V47 model

Mode	Description	Freq. Identified Using EFDD	Freq. Identified using FEM	% Difference
1	First bending fore-after	0.647	0.684	5.72
	First bending side to side	0.647	0.678	4.79
2	Second bending fore-after	5.486	5.901	7.56
	Second bending side to side	6.156	5.827	-5.34
3	Third bending fore-after	17.25	16.1	-6.67
	Third bending side to side	17.4	15.905	-8.59

6. MODELLING OF EVALUATE MODULUS OF SUBGRADE REACTION

The base of the Vestas N47 Wind Turbine Tower was designed as a reinforced concrete base (tapered one), where depth is varied between 1.00m at the region under tower and to 0.80 m at the base edge, as shown in Figure 11 (a,b). To simplify the modelling, the base was modelled using and constant-average depth that was equal to 0.90 m with the material properties that are represented in Table (2).

Table 2: Material properties of the base.

Material Type	Density (kN/m^3)	Elastic Modulus (N/m2)	Poisson Ratio
Reinforced Concrete	2500	2.1E10	0.25

The base is adopted through the FEM model to apply the Soil-structure interaction on the lower face of the base. SHELL163 element was used to model the base of the tower as shown in Figure 12. Where, this element is a 4-node element with both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has 12 degrees of freedom at each node: translations, accelerations, and velocities in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes as shown in Figure 13 [25,26,27].

The base is meshed to small areas (4-nodes-mesh) of 1.0m x 1.0m as shown in Figure 13 to apply the subgrade reaction at each node, that will be described in the following section.

Based on a geotechnical study for the soil under the Vestas V47 wind turbine, the net allowable bearing capacities and values of subgrade reactions are estimated and represented in Table 3 using Meyerhof' equations [28] for comparison, as shown in Table 3.

The ANSYS 3D analysis is carried on considering the properties of zone 3 which Vestas V47 wind-turbine tower, that is located in zones 3 and 4, the analysis is conducted using the data of zone 3. The soil-structure interaction is modeled using the spring action. The subgrade reactions are assigned to each node of the base of the tower. Since, the area mesh of the base is equal to 1.0m x 1.0m, each node is assigned with 3 values of subgrade reaction; one in the vertical direction (z-direction) with the value of 3,800kN x 1.0m x 1.0m, and the two others are in the plane directions (x and y-directions) which are calculated as a ratio of the vertical subgrade reaction. Table 4 shows the calculated vertical and horizontal modulus subgrade reactions from ANSYS 3D analysis for Vestas V47 wind turbine tower.

Table 3: Net Allowable bearing capacitates and corresponding modulus of subgrade reaction calculated from Meyerhof' equations.

Zone	Net Allowable Bearing Capacity (kPa)	Vertical Modulus of Subgrade Reaction kN/m3
Zafarana (3)	180	3,600

Table 4: Corresponding modulus of vertical and horizontal modulus subgrade reactions from ANSYS 3D analysis.

Wind Tower	Zone	Vertical Modulus of Subgrade Reaction kN/m^3	Horizontal Subgrade Reaction kN/m^3
Vestas V47	Zafarana (3)	3,600	1,080

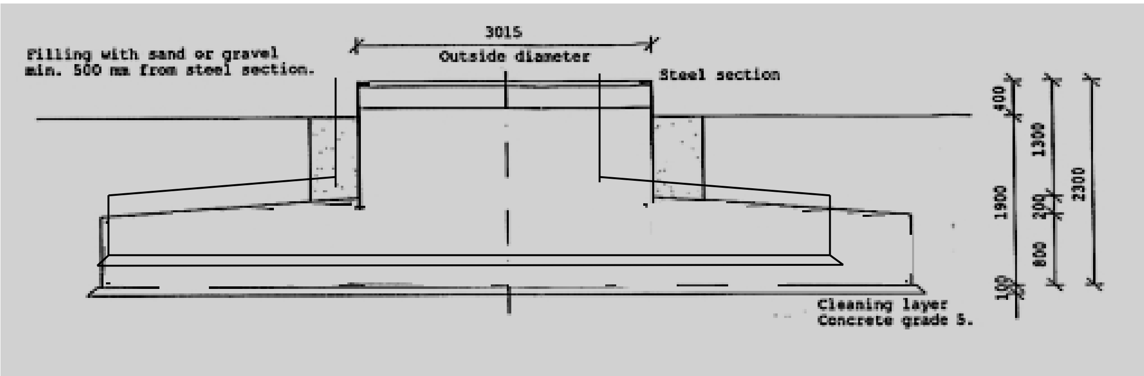


Figure 11: (a) Side-Section of the base.

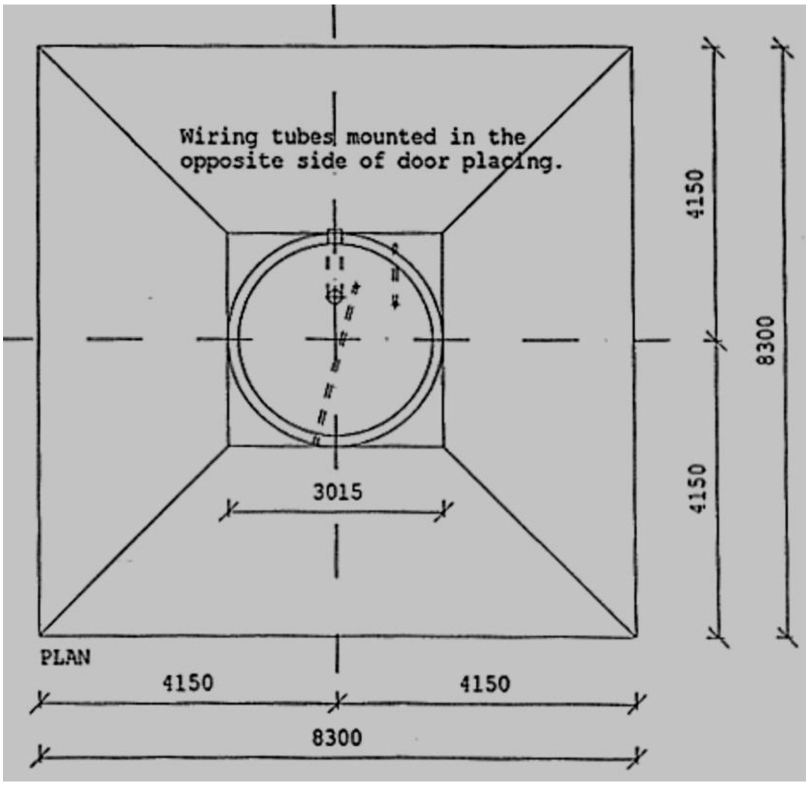


Figure 11: (b) Plan layout of the base.

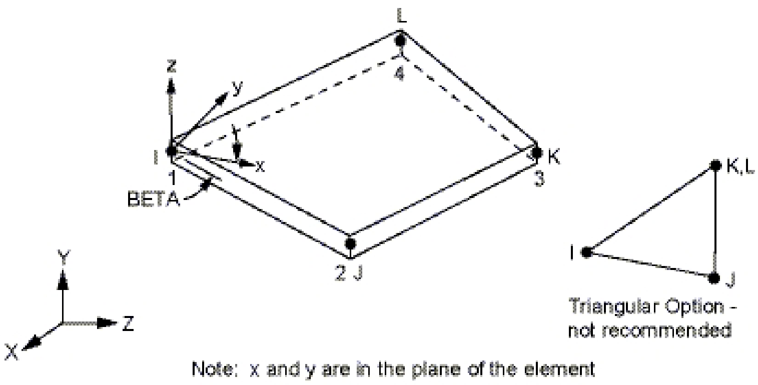


Figure 12: SHELL163 element description [10].

COMBINE14 (Spring-Damper) element was adopted to simulate the subgrade reaction springs as shown in Figure 14. This element has either torsional or longitudinal capability which could be adopted in 1-D, 2-D, or 3-D applications. The torsional option is a rotational element that got three degrees of freedom at each node: x, y, and z axes rotations without any axial loads or bending consideration. The longitudinal option is a purely uniaxial tension compression element without consideration of bending or torsion. Its degrees of freedom are up to three at each node: translations in x, y, and z directions [26,27]. The detail of the base for both towers with the subgrade reactions are represented in Figure 15.

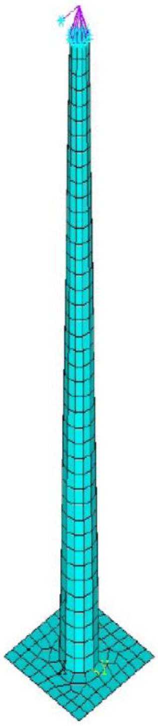


Figure 13: Base modelling and meshing of Vestas V47 Tower.

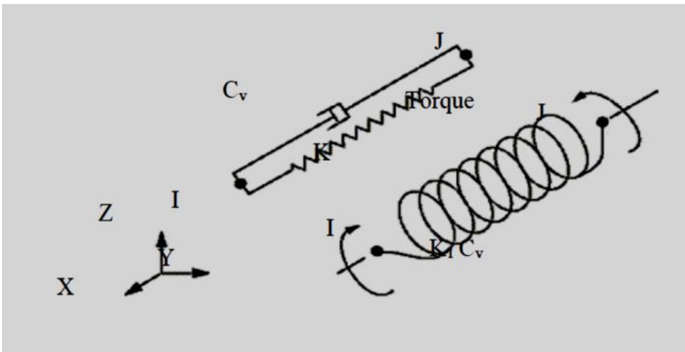


Figure 14: Combin14 spring - damper element [26,27].

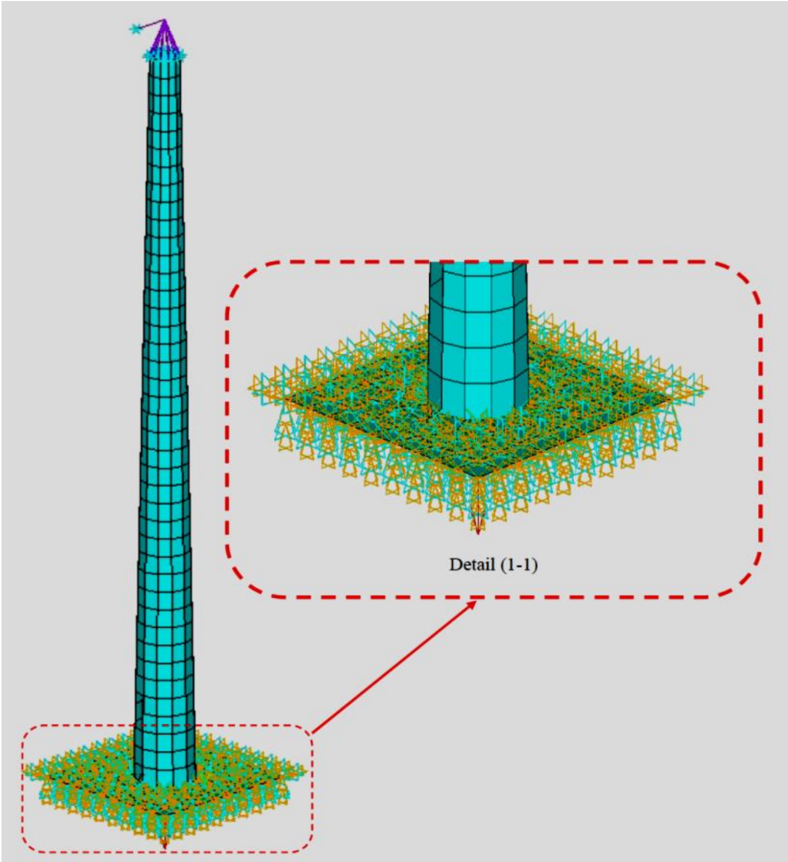


Figure 15: Details of base with soil subgrade springs in the 3-directions.

7. CONCLUSIONS

This work presents one of the pioneer studies concerning the investigation of the structural dynamic performance of a full-scale wind turbine tower of Vestas N47. The study is including dynamic testing using ambient vibration test, and numerical modelling based on field test using ANSYS 3D to evaluate modulus of subgrade reactions in vertical and horizontal direction.

1. In ambient vibration test the dynamic characteristics of the towers were extracted using EFDD and SSI-CVA methods. It could be deduced that both methods are successful in determining the modal properties of the full-scale wind turbine towers.
2. Static structure interaction method by ARTeMIS was found to be more powerful in identifying the first side to side bending mode at 0.638 Hz of Vestas N47 tower which couldn't be identified using EFDD method.
3. Both bending and torsion structural modes of the towers were successfully identified in the range 0-25 Hz. The dynamic behavior of wind towers is characterized by close bending modes in the lower frequency range up to 3 Hz.
4. Soil structure interaction is expected to govern the calculated vertical subgrade reactions and horizontal subgrade reactions for the designed seismic bearing capacity and settlement analysis of wind turbine towers foundations.
5. Morevoer, increasing the vertical and horizontal subgrade reactions lead to increase the settlement under the wind turbine towers foundations based on previous results by the same other.

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