Operational modal analysis of two wind turbines with foundation problems

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ABSTRACT: Towers and foundations of wind turbines are subject to fatigue damage due to the variable wind loading, which they are exposed to during their working life, particularly if they are located at places were very turbulent wind is acting. In the investigation described here, operational modal analysis is applied to identify the dynamic behaviour of a wind turbine showing an anomalous vibration level under normal wind conditions as well as appearance of fatigue cracks at the foundation. With the aim of avoiding these deficiencies, reinforcement of the transition between tower and concrete foundation was decided on. In order to validate the effectiveness of the repairing procedures, operational modal analysis was performed on the wind turbine before and after the foundation reinforcement.

1 INTRODUCTION

Wind turbines are structures being subject of continuous vibration-induced forces throughout their working life. Wind turbulences and the periodic excitation due to the blade's rotation are the most important loadings to consider in the design. Thus, the turbine operational frequencies should be sufficiently separated from the structural natural frequencies in order to avoid very high dynamic forces, which could cause immediate malfunctioning and possible progressive fatigue damage of the foundation.

The first excitation frequency, corresponding to the constant rotational speed, is usually referred to as 1P. For a wind turbine with three blades, the rotor harmonic of 3P has the potential to excite a fundamental mode close to the operating speed of the rotor. The effect of the harmonics 6P , 9P and 12P should also be considered.

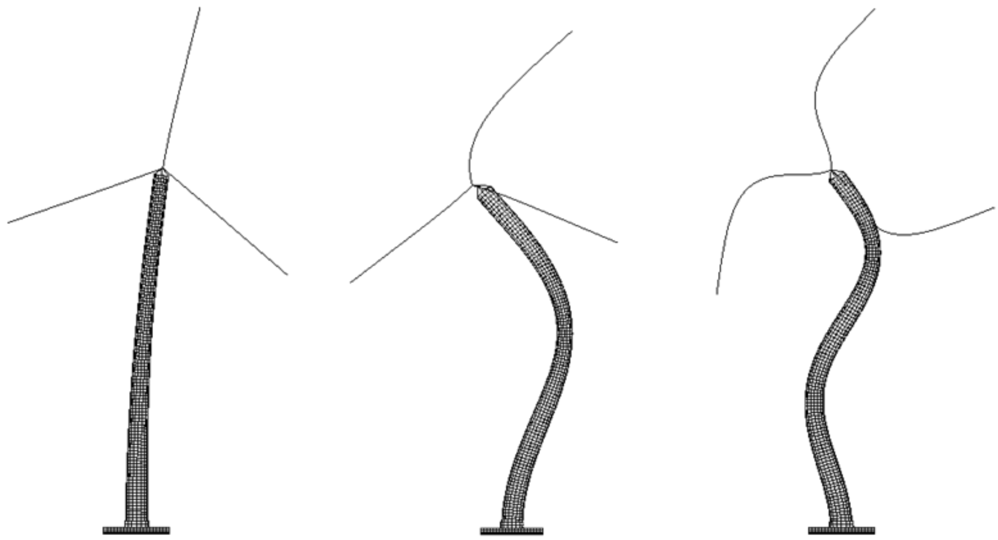
It is said that a wind turbine is very stiff if the natural frequency is greater than 3P, soft-stiff if the natural frequency is in the range 1P-3P, and soft if the natural frequency is less than 1P (Van Der Tempel and Molenaar 2002). Soft structures require less steel and are therefore cheaper. However, dynamic phenomena need to be identified and dealt with throughout the design, installation and operation steps.

In this investigation, the dynamic behavior of three wind turbines, denoted as A, B and C here, is analyzed. The steel tower of the turbines is built as a 60 m high cylindrical tube with a diameter of approximately 3 m at the bottom. The square-shaped concrete foundation has approximate dimensions 10 x 10 m for turbines A and C and 9 x 9 m for turbine B, respectively. All three foundations have a depth of 1.10 m. All the turbines are in a mountainous environment.

After a few years of operation under normal wind conditions, wind turbines A and B began to show an anomalous vibration level with excessive relative displacement between tower and foundation. As a possible way to identify the reason for such a behavior, operational modal analysis was considered before deciding on the repairing method to be used for the concrete foundation of these wind turbines. In addition, operational modal analysis was foreseen on the repaired wind turbines in order to determine the effectiveness of the repairing and strengthening of the foundation. Wind turbine C, located in the same area as the wind turbines A and B and working correctly up to present without exhibiting neither damage in the foundation nor high vibration levels, was also tested as a reference for comparison. For all of these wind turbines, the first operational frequency (1P) is 0.513 Hz (30.8 rpm).

2 FINITE ELEMENT MODELING

A simplified finite element model (FEM) was assembled in ABAQUS to estimate the three first modes of the wind turbine. The tower and foundation were discretized using quadratic solid elements with 20 nodes and reduced integration (C3D20R) whereas for the blades beam elements (B32) were used. The first three modes of the tower are shown in figure 1. These modes are in pairs (closely spaced or repeated modes) due to inherent symmetry of the geometry of wind turbines.



F = 0.7464 Hz   F = 5.0625 Hz   F = 13.07 Hz

Figure 1 : First three modes of the Wind turbines obtained with a FEM model.

3 TESTING DESCRIPTION

3.1 Testing description

Considering the goal to be achieved, measurement points were concentrated on the foundation region. In their usual state of operation, the concrete foundations are covered by a layer of loose soil material of about 1 m depth. To allow access to the foundation this layer was partly removed. Possible sensor locations were therefore limited to the free foundation surface.

The tower behavior was determined by disposing two bi-axial horizontal measurement points at heights of 35 m and 9 m above ground, respectively. As a consequence, several modes with different frequency but quite similar shape in the tower region were identified. To separate such modes according to their shape, a higher number of measurement points in the tower and in the blade's region would have been necessary.

3.2 Instrumentation

Twelve acceleration sensors were used simultaneously. Eight of them were 10V/g sensitivity sensors (PCB 393B31) used at the foundation and the lower part of the tower. The remaining four were 1V/g sensitivity sensors used at the tower at a height of 9 m and 35 m, respectively.
Specially designed steel supports were used to attach the sensors through screwing at the suitable locations. These sensor steel supports were fixed to the concrete foundation surface using sealing-wax. Magnet-bases allowed fixing of the sensors to steel surfaces inside of the tower.

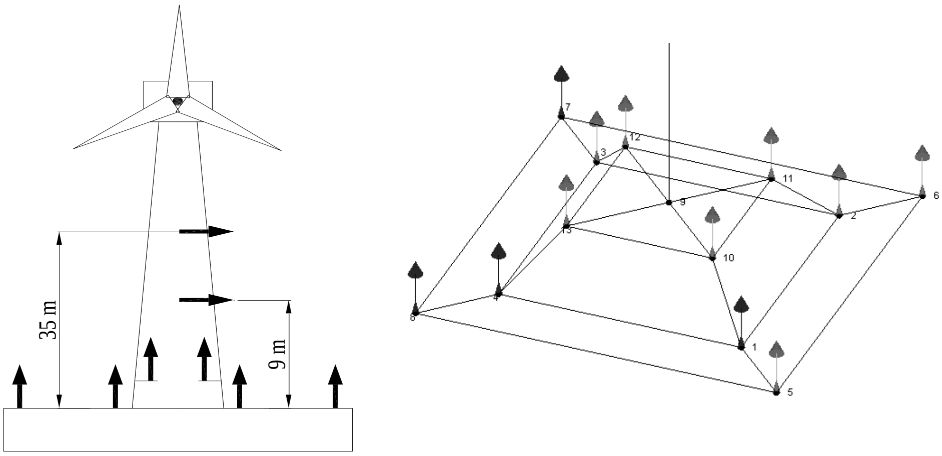


Figure 2 : Measurement points at wind turbines tested.

3.3 Signal Acquisition System and Processing

With the damaged wind turbines, the acceleration signals were recorded with a 24 channel LMS Pimento acquisition system whereas a 16 channel TEAC-LX 120 was used with the repaired ones (see figure 3).

The sampling rate was chosen to Fs=200 Hz and the length of the time window per setup to 40 minutes or 2400 seconds, approximately. This period of time was based on the minimum ‘‘necessary’’ length of 1000 times T for an adequate modal parameter identification analysis. T is the fundamental period of the tower that was initially considered as T=2 seconds, so the minimum period length is surpassed slightly.

The input voltage was adapted to the requirements and the analogue-to-digital conversion was performed using a 24 bit (LMS) and 16 bit (TEAC) resolution respectively.

Signal processing was performed using the LXNAVI Teac software, MATLAB and the ARTeMis Software suite.

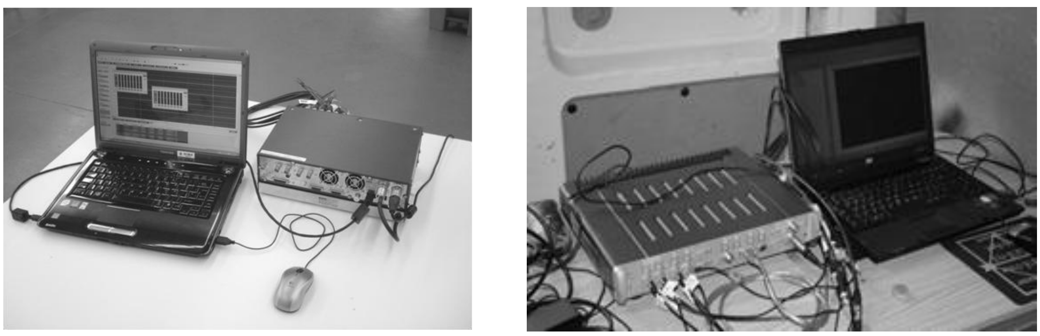


Figure 3 : Acquisition equipment used in testing.

4 TESTING PROCEDURES AND ANALYSIS

4.1 Testing procedure

Fourteen measurement points were defined on the structures. Two of the 14 measurement points corresponded to 2D-horizontal points on the tower (9 m and 35 m), 4 of them were 1D-vertical points inside of the tower (at the foundation level) and the remaining points were 1D-vertical points at the foundation. Figure 2 presents an overview of the measured DOF's. The remaining 8 roving points were covered with 2 setups roving four sensors.

4.2 Analysis

The results discussed here have been obtained using the ARTeMis Extractor EFDD routine (Brincker et al 2000) with the following parameters: No decimation, no filtering and 2048 frequency lines.

For the damaged wind turbines (A & B) the EFDD SVD diagrams resulting from the analysis in the frequency range $0 < f < 15$ Hz are presented in Figures 4 and 6, respectively, whereas the same EFDD SVD diagrams for the repaired wind turbines (A & B) are presented in Figures 5 and 7, respectively. The EFDD SVD diagram of healthy wind turbine (C) is presented in Figure 8. Figures 4 to 8 show that many of the modes exhibit two different shapes at basically the same frequency.

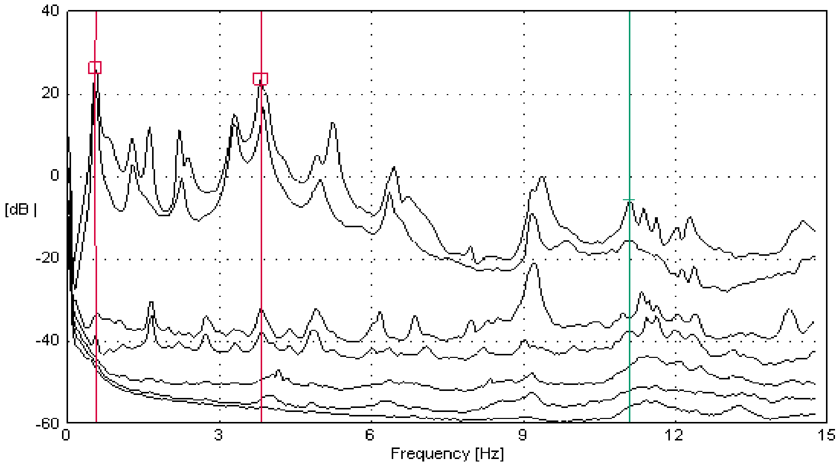


Figure 4 : EFDD SVD diagram for the damaged wind turbine A.

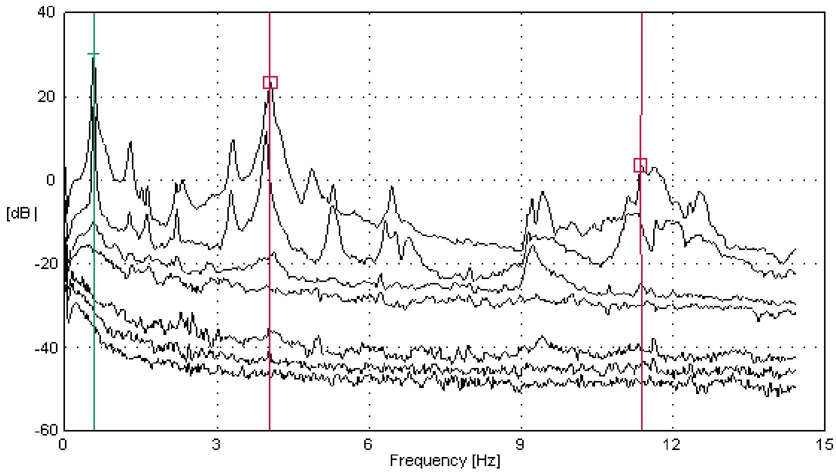


Figure 5 : EFDD SVD diagram for the repaired wind turbine A.

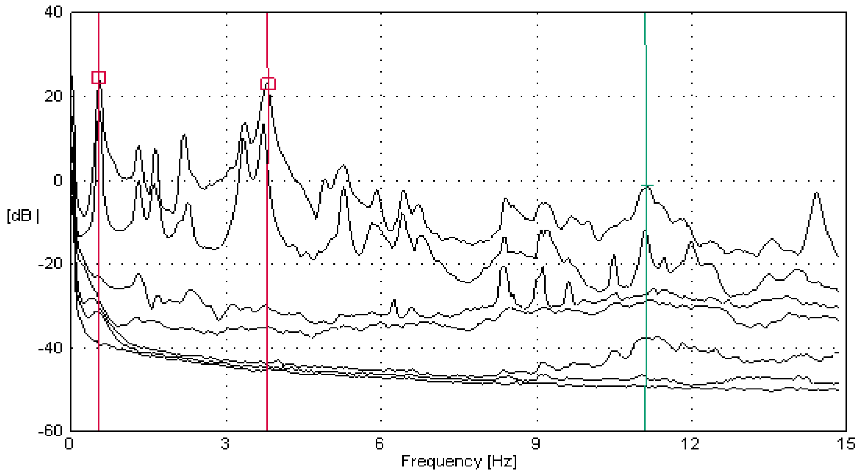


Figure 6 : EFDD SVD diagram for the damaged wind turbine B.

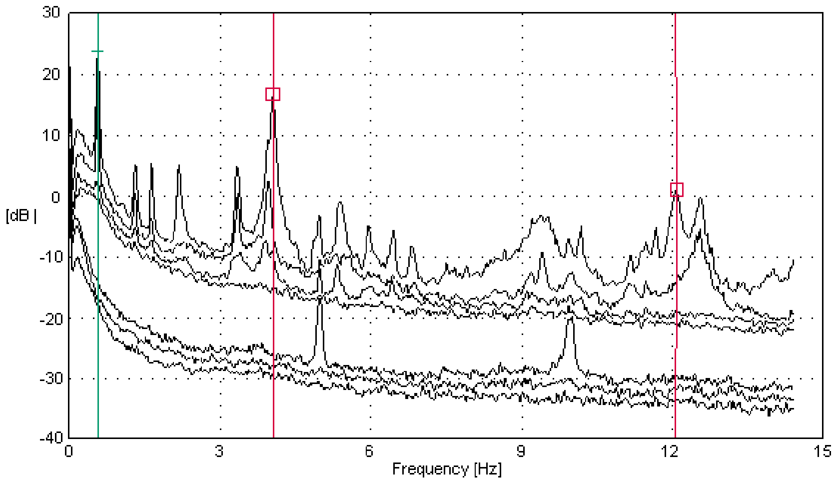


Figure 7 : EFDD SVD diagram for the repaired wind turbine B.

5 RESULTS

The natural frequencies and damping ratios of wind turbines A, B and C are presented in Table 1 and Table 2, respectively. In Table 1 it can be observed that the same modes have been identified in both operational modal tests performed before as well as after the reinforcement of the foundations. It can also be concluded that the natural frequencies of both damaged wind turbines (A and B) obtained in the tests carried out after repairing are higher than those corresponding to the previous test (before repairing) and exhibit practically the same natural frequencies as the undamaged wind turbine C. This evidences that the stiffness of the wind turbines has increased, in particular concerning the connection between the foundation and the tower. Thus, the reinforcement performed in the foundation is proven to be effective.

From Table 1 it can also be confirmed that the first natural frequency is close to the first operational frequency of the three wind turbines. This means that the wind turbines motion will be considerably amplified causing potentially progressive fatigue damage.

Regarding damping, it must be mentioned that a large uncertainty is inherent to the damping ratio identification in operational modal analysis, mainly in structures with closely spaced or repeated modes. In Table 2 it can be observed that damping has diminished for practically all modes in turbines A and B after repairing. Damping ratios which cannot be estimated with a reasonable accuracy have been omitted in Table 2.

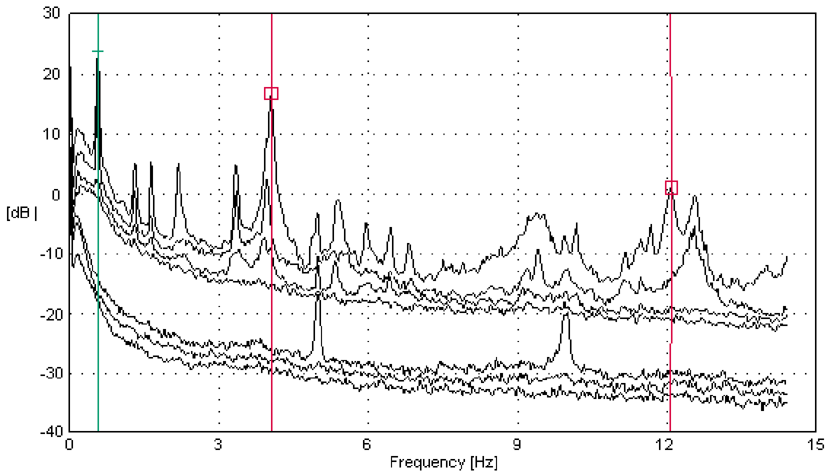


Figure 8 : EFDD SVD diagram for the healthy wind turbine C.

Table 1: Natural frequencies of the wind turbines.

	Turbine A		Turbine B		Turbine C
Mode No.	Before	After	Before	After	
	Frequency Hz	Frequency Hz	Frequency Hz	Frequency Hz	Frequency Hz
1	0.551	0.5652	0.543	0.5615	0.5647
2	1.27	1.294	---	1.294	1.29
3	1.61	1.627	1.63	1.637	1.663
4	2.2	2.199	2.18	2.153	2.238
5	3.29	3.296	---	3.327	3.246
6	3.81	4.051	3.78	4.048	4.056
7	5.25	5.313	5.24	5.391	5.349
8	6.44	6.497	6.42	6.438	6.316
9	9.36	9.434	---	---	9.439
10	11.09	11.38	11.09	12.06	11.98

For the damaged foundations, larger damping is expected because the possible damage in the concrete, predominantly in the proximity of the steel tower promotes higher damping. On the contrary, repairing and reinforcing the concrete foundation results in an enhancement of the connection between tower and foundation. Thus, a decrease of damping is likely to occur.

Comparing the experimental results with those of the finite element model, it was possible to determine that the modes 1, 6 and 10, correspond to the first three modes of the tower. According to Table 1, it follows that these modes are the ones in which the natural frequencies changed the most.

From the mode shapes (Fig. 9) it becomes apparent that under ambient excitation conditions still some relative movement persists between the steel tower and the concrete foundation in all undamaged and repaired wind turbines tested. This relative movement can practically be identified irrespective of the modes. This can only be explained if the tower and the foundation are not rigidly but elastically connected. Thus, the constructive solution adopted does not provide a totally rigid connection between tower and foundation.

Table 2: Damping ratios of the wind turbines.

	Turbine A		Turbine B		Turbine C
Mode No.	Before	After	Before	After	
	Damping ratio %	Damping ratio %	Damping ratio %	Damping ratio %	Damping ratio %
1	---	---	---	---	---
2	---	---	---	---	---
3	2.34	1.101	2	0.4322	0.9999
4	1.39	0.8707	1.88	1.671	0.622
5	1.49	---	---	0.6312	1.337
6	1.07	0.8062	---	0.5554	0.7339
7	1.04	0.3658	0.99	0.6466	0.5083
8	0.68	0.8818	0.73	0.7176	0.4327
9	0.66	0.7092	---	---	0.7327
10	0.5	0.3508	0.95	0.7282	0.8068

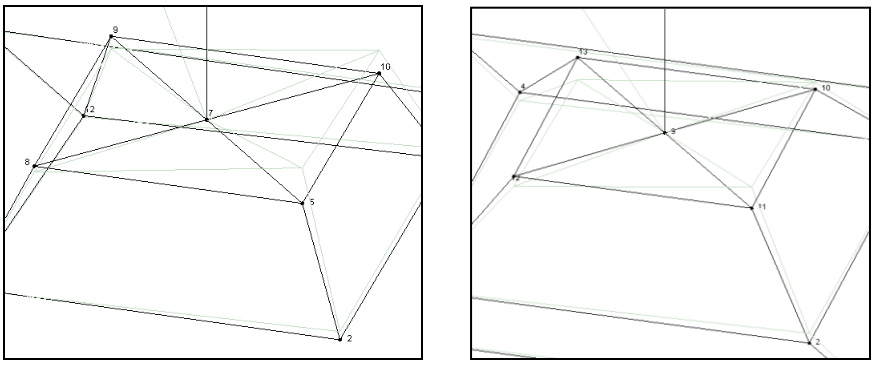


Figure 9 : Detail of mode shape 6 for damaged wind turbine B (left) and for healthy wind turbine C (right).

6 CONCLUSIONS

- Operational modal analysis has been applied to two damaged wind turbines in order to determine their dynamic behaviour under ambient working conditions, and to study the effectiveness of a subsequent reinforcement. In order to have a reference system to compare the results, operational modal analysis was also applied to an undamaged wind turbine C.
- The turbines' first natural frequency is quite close to the first operating frequency for all three wind turbines, which means that the wind turbines motion would be amplified.
- The repaired wind turbines A and B exhibit practically the same natural frequencies as the undamaged turbine C. This implies, practically, that they exhibit the same dynamic behaviour which means that the repairing of the foundations of turbines A and B has been effective.
- From the mode shapes it becomes apparent that some relative movement persists between the steel tower and the concrete foundation for all undamaged and repaired wind turbines tested. This can only be explained if the tower and the foundation are not rigidly connected. Thus, the constructive solution adopted does not provide a totally rigid connection between tower and foundation.

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