WIND TURBINES AND EARTHQUAKES

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Abstract: Modern wind turbines have been mainly erected in regions where earthquakes are rare or normally weak. More recently wind farms in Africa, Asia ad southern Europe have been developed where stability under earthquakes becomes an issue. So far earthquake loads have been analyzed with methods adapted from civil engineering which may not be adequate for the dynamics occurring above the yaw bearing. In this talk we present results that have been obtained by taking into account ground accelerations in a state-of-the-art simulation code for wind turbines. Synthetic 3-dimensional accelerograms consistent with the relevant standards are generated and applied to the turbine foundation. The structural dynamics of a sample turbine, the Nordex N80 with 60m hub height, is analyzed, leading to a detailed picture of the loads occurring during earthquakes. A comparison with the design loads and an assessment with regard to the main components are carried out.

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1. Introduction

Wind turbines are designed to withstand aerodynamic forces that are exerted on the structure mainly via the rotor. Wind turbines consist of long flexible parts that tend to vibrate under the influence of external forces, and typically structural damping is weak. Especially in the presence of periodic or stochastic forces resonant oscillations can occur. These conditions have to be avoided or taken care of by appropriate security measures.

The development of wind turbines during the last 10 years has taken place mainly in areas like northern Europe where earthquakes are rare or normally relatively weak. As a consequence, the standards for wind turbine design [1] do not pay much attention to earthquakes. More recently, however, wind farm sites in other regions have been developed, where stability under earthquakes becomes an issue.

So far earthquake loads on wind turbines have been mainly analyzed with methods taken from civil engineering as for example the modal approximation [2]. As shown in the following, these methods are in general not adequate for loads on the turbine, especially those affecting rotor and nacelle. In particular, for sites with high peak ground acceleration, it seems necessary to take into account earthquakes in the framework of more sophisticated methods like time-domain simulation codes that are widely used in wind turbine development [3].

To this end, we have created a time series generator for ground acceleration in accordance with Eurocode 8 [4] that allows to simulate earthquakes in the framework of time-domain simulation codes. The results obtained are compared with the results of the modal approach. As an example we study the Nordex N80 (with 80 m rotor diameter and 60 m hub height) that was erected in Ryuyo-Cho (Japan), where the peak ground acceleration[1] is 0.3 g. With the methods described an approval of the stability of tower and foundation for the named turbine was carried out.

2. Modeling earthquakes

Essentially two independent methods will be applied and compared in this study. Firstly, a modal approximation as for instance applied in building construction will be used. The procedure is described in the textbooks as for instance in Ref. [2]. Its focus mainly lies on the loads on tower and foundation caused by horizontal ground accelerations.

Using the modal approximation, the starting point is a rather detailed description of the tower in form of sectional values for bending stiffness and mass distribution while the rest of the turbine (nacelle, hub and rotor) normally is approximated by a point mass on top of the tower. Then the complete system of tower plus point mass is mapped to a model of lumped masses connected by massless flexible rods. For this model the natural frequencies and eigenmodes (also called normal modes) can be obtained by standards methods[2] and elastic sectional forces can be calculated.

The starting point for the latter is the response spectrum of a single-degree-of-freedom (SDOF) system since each eigenmode behaves like a free oscillator. Earthquakes of a certain intensity generate a response acceleration in the SDOF system. Thus the peak response acceleration as a function of the oscillation period T[3] characterizes the influence of the earthquake on the SDOF system. From the peak acceleration the peak values of the elastic forces can be derived which, in turn, lead to the extreme loads. The latter have to be consistent with the design loads of the turbine.

The virtue of the modal approach is that the relevant degrees of freedom of the tower can be taken into account to any required precision because it is quite straightforward to calculate the necessary modes. A “rule of thumb” says that the sum of modal masses taken into account must exceed 90% of the system mass. An obvious disadvantage of the method is oversimplification of the turbine above the tower top. Machine loads cannot be assessed in this approach. Furthermore, the real turbine has more complicated system modes where for example tower and blade degrees of freedom “cooperate” that are not taken into account at all in the modal approach.

The alternative to the modal approach is the inclusion of earthquake loading in a wind turbine simulation code. For this study we employ the simulation code Flex5 [6], which simulates horizontal axis wind turbines as a mechanical model with up to 28 degrees of freedom. The dynamics is defined in the time domain in a space of generalized coordinates that consists of modal amplitudes (tower, blades) and angles (tilt, torsion, etc.). Especially for the tower, two bending modes in each direction are taken into account. In order to extend the program to include ground acceleration, a simple coordinate transformation is used to map the ground acceleration on an effective external force that is added to the gravitational force and applied to each mass element of the model.

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[1] Peak acceleration reached on average once during a period of 475 years. By definition there is a logarithmic dependence between peak ground acceleration and the magnitude of the earthquake on the Richter scale.

[2] In this study we have used the Myklestad method described in Ref. [5]

[3] Normally the oscillation period is used instead of the frequency

Additional efforts have to be made to generate appropriate accelerograms that are consistent with the requirements of appropriate standards. The present study is orientated at the European standard Eurocode 8 [2].
The virtue of the simulational approach is a much more detailed picture of the behavior of the whole machine during an earthquake. Not only tower loads but also blade and various sectional loads can be computed. The disadvantage is that without extensions of the code, the number of degrees of freedom is limited. Normally higher tower modes that are only weakly exited by the wind turbulence become potentially important for parts of the tower during an earthquake.

3. Calculation of earthquake loads

3.1. The modal approach

The tower is characterized by its diameter, wall thickness and local masses (for example flanges) as a function of height. From these data a system of lumped masses and bending stiffnesses, a discrete model of the tower, is derived. For the sample turbine, the Nordex N80 with 60 m hub height, the lumped mass model is represented in Table 1 and illustrated in the sketch to the right of the table.

i	**H_i**	**L_i**	**M_i**	**$E*I_i$**
[-]	[m]	[m]	[kg]	[Nm^2]
1	1.284	1.284	2058.93	1.735E+11
2	1.285	0.001	4144.32	1.662E+11
3	4.084	2.799	4144.19	1.570E+11
4	4.085	0.001	3794.50	1.481E+11
5	6.885	2.8	7529.12	1.396E+11
6	9.685	2.8	7413.72	1.334E+11
7	12.484	2.799	3678.93	1.274E+11
8	12.485	0.001	3589.38	1.198E+11
9	15.49	3.005	7114.82	1.122E+11
10	18.494	3.004	3527.82	1.067E+11
11	18.495	0.001	3081.77	9.970E+10
12	21.405	2.91	6108.04	9.308E+10
13	24.314	2.909	3028.37	8.843E+10
14	24.315	0.001	2708.12	8.229E+10
15	27.225	2.91	5366.24	7.643E+10
16	30.134	2.909	2659.97	7.251E+10
17	30.135	0.001	2353.84	6.712E+10
18	33.045	2.91	4717.65	6.196E+10
19	36.024	2.979	2365.41	5.862E+10
20	36.025	0.001	2064.78	5.385E+10
21	39.005	2.98	2064.68	4.929E+10
22	39.006	0.001	1731.21	4.490E+10
23	41.915	2.909	3428.17	4.079E+10
24	44.824	2.909	1698.14	3.850E+10
25	44.825	0.001	1428.54	3.473E+10
26	47.735	2.91	2827.03	3.116E+10
27	50.644	2.909	1399.54	2.933E+10
28	50.645	0.001	1598.69	3.078E+10
29	53.554	2.909	1598.68	3.213E+10
30	53.555	0.001	1343.48	2.894E+10
31	56.465	2.91	1717.17	2.592E+10
32	58.104	1.639	131987.00	2.225E+11

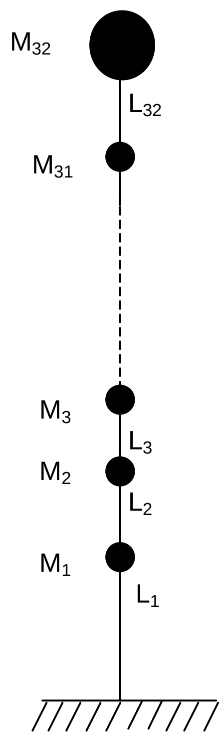

Table 1: *System of lumped masses and flexible rods representing the wind turbine, where H_i and M_i are height and mass of i-th element, L_i and $E*I_i$ the length and bending stiffness of the i-th rod.*

The last line in Table 1 represents the data of nacelle and rotor. Eigenmodes for this system are depicted in Fig.1. They have been obtained with the Myklestad method [5]. The corresponding eigenfrequencies are also given in the Fig. 1.

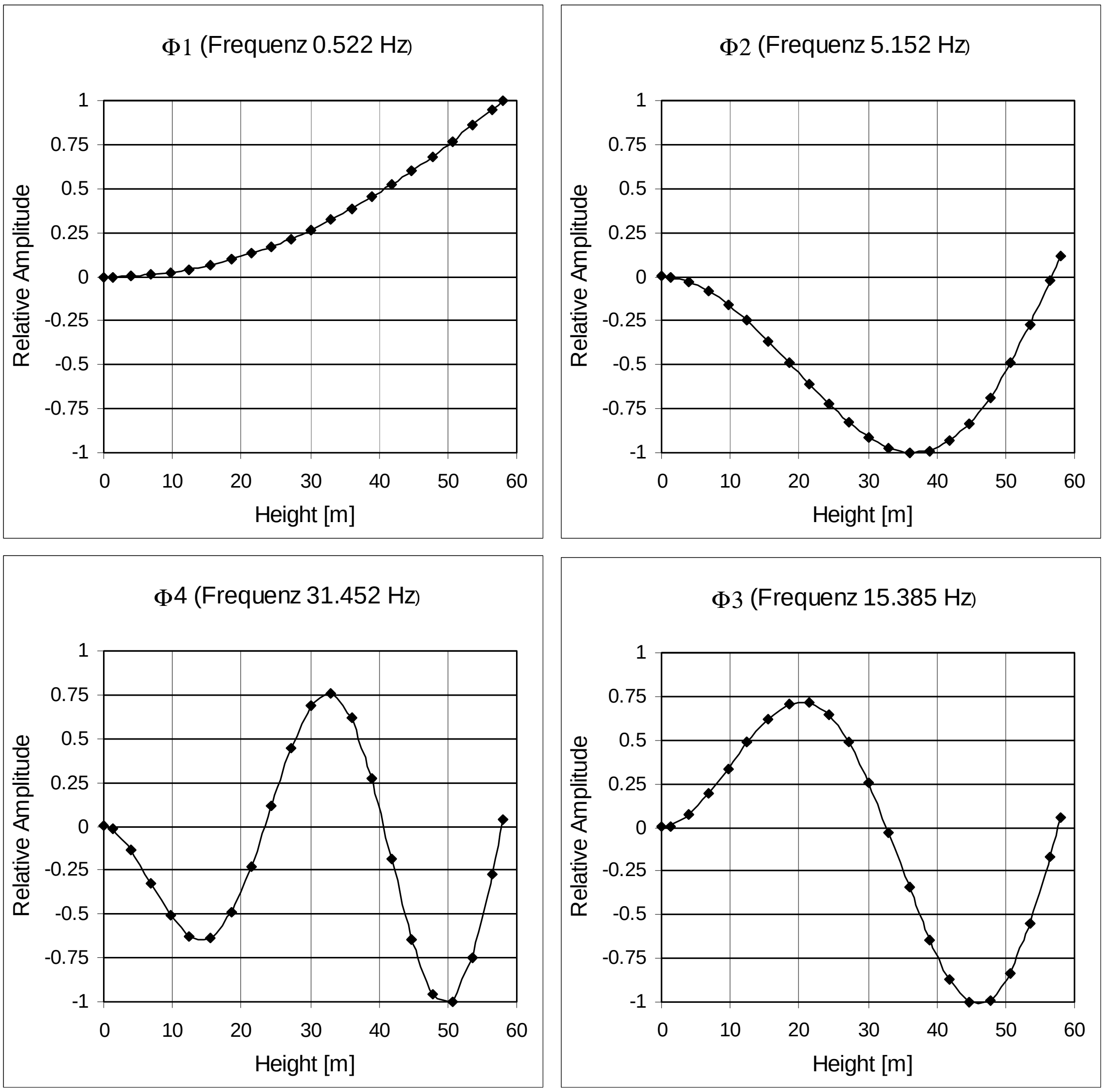

Fig. 1: *Normal modes and corresponding frequencies. The modes are normalized such that the maximum modulus of the amplitude is 1.*

The modes approximate the turbine by a system of uncoupled oscillators. The sum of the first four modal masses in the present case amounts to roughly 92 % of the total turbine mass. The SDOF oscillator response spectrum used here is taken from Eurocode 8 [4] and is depicted in Fig. 2. With this spectrum, the sectional forces and bending moments can be obtained. The contributions of the four modes of Fig. 1 are summed up by the square method [2]. An additional factor of 1.3 is multiplied to the sectional bending moments to take into account the transversal component of the earthquake acceleration.

On top of the earthquake loads reasonable assumptions have to be made concerning additional wind loads exerted on tower and rotor. In the following it is assumed that during the earthquake an emergency shut down is triggered. Additionally for the wind speed the cut-out value of 25 m/s is assumed and the thrust on the tower is calculated from

$$F = \frac{\rho}{2} \cdot c_D \cdot A \cdot v^2$$

where the air density is ρ =1.25 kg/m³, the drag coefficient is c_D = 1.0, A is the projected area of the tower (section) and v is the wind speed (here 25 m/s). For the rotor thrust acting on the tower top during the earthquake we use the extreme value obtained with Flex5 (without earthquake). Further, to take into account effects of nacelle and rotor to a certain extent, the extreme bending moment at the height of the azimuth bearing is added to the sectional moments.

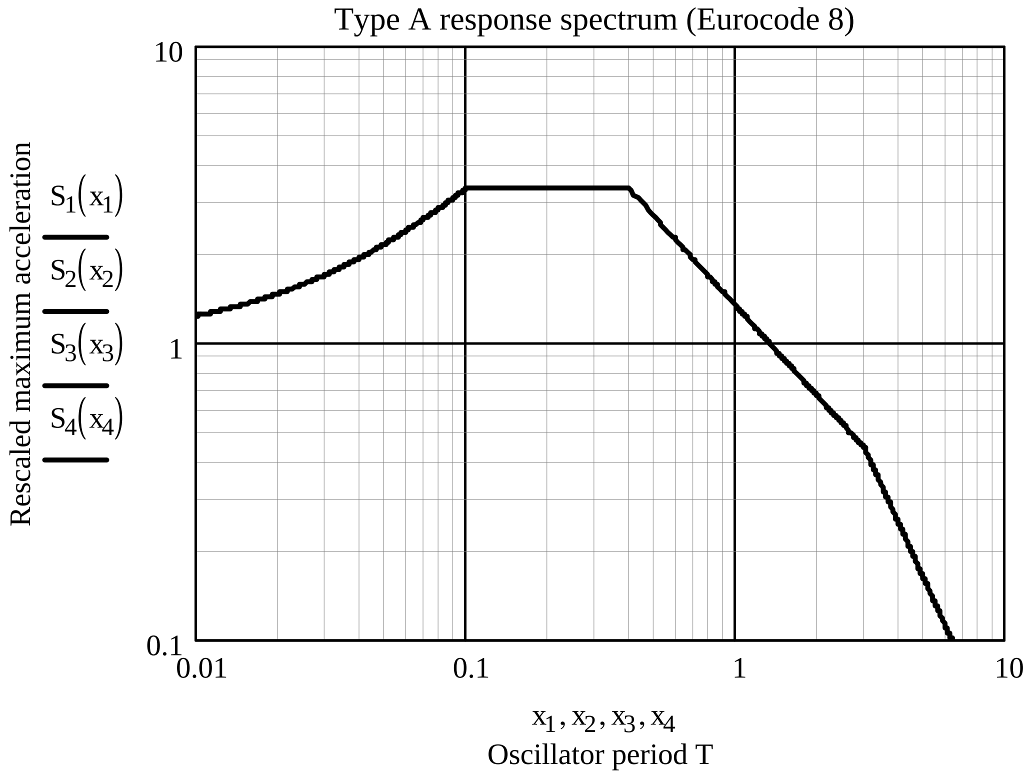

Fig. 2 *Response spectrum for SDOF oscillator according to Eurocode 8 [4] for subsoil class A (firm ground).*

3.2. The time-domain approach

In the simulation code the influence of the earthquake is taken into account in form of an 3-dimensional effective force acting on the mass elements of the model. The effective force is obtained by a transformation from an inertial system to the accelerated ground coordinate system. The time series for the acceleration have been generated by a separate software tool in accordance with Eurocode 8 [4]. The required properties of the synthetic accelerograms are specified in the Eurocode and an algorithm for obtaining time series that are consistent with the standard is described in Ref. [2].
For each direction, statistically independent time series have to be generated, where the vertical component is weaker (in the sense of peak acceleration) than the horizontal components. A typical horizontal accelerogram is shown in Fig. 3.

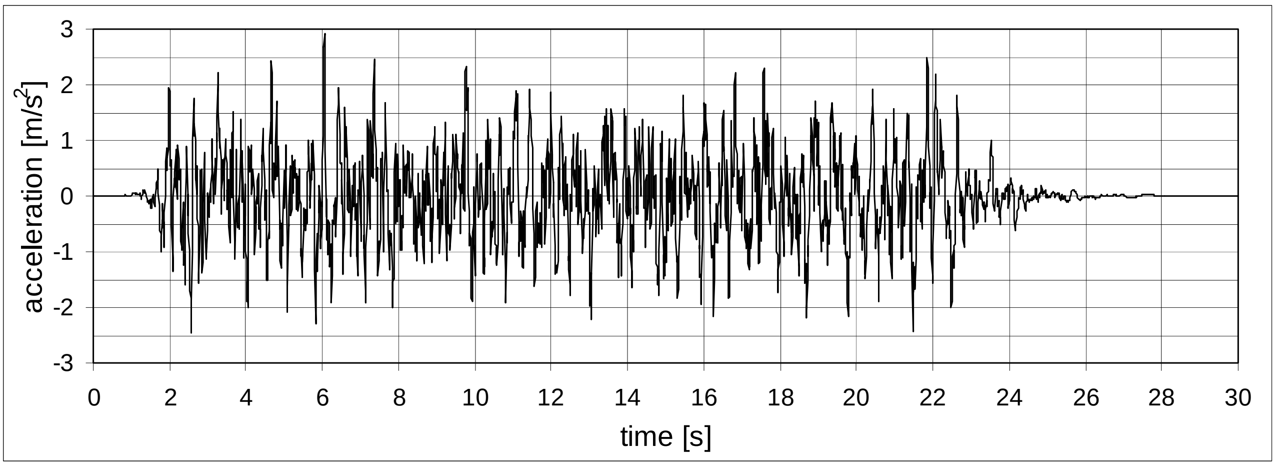

Fig. 3: *Typical accelerogram applied in the load cases with a peak acceleration of 0.3 g or 2.94 m/s².*

In order to simulate the earthquakes influence on the turbine, ten load cases have been considered, where the direction of the of the epicenter in the horizontal plane varies in steps of 36° from 0° to 324° with respect to the longitudinal direction of the turbine. As in the modal approach, an emergency shut down during the earthquake is triggered after ten seconds. The average wind direction is 0° and the turbine is oriented upwind assuming zero yaw error. All aerodynamic forces on rotor, nacelle, and tower and resulting sectional forces in the structure are taken into account by Flex5 and need not to be treated by separate additions.
From the ten earthquake load cases the extreme values have been determined. As usually, to take into account possible uncertainties and statistical fluctuations, a safety factor of 1.1 is multiplied to all loads[4]. All results shown in the next section include this factor.

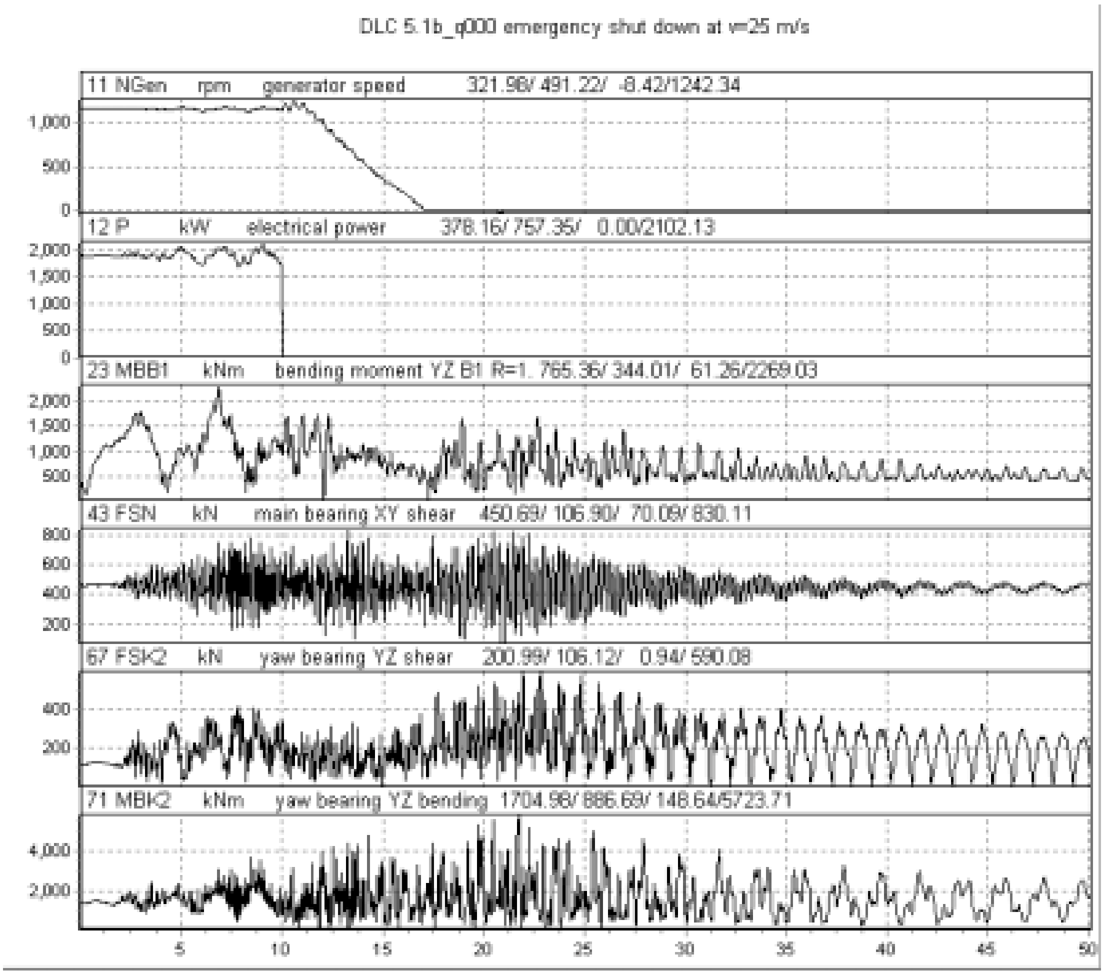

Fig. 4: *Selected time series that give an impression of the behavior of the turbine during an earthquake. They are taken from the load case with epicenter in 0°-direction. The first two plots show rotational speed and power. The corresponding ground acceleration was illustrated in Fig.1. The earthquake starts at zero, and the shut down takes place after 10 seconds. The effects of the earthquake can be clearly seen in the resulting sectional loads shown in the plots.*

4. Results

All earthquake loads shown in the following have been obtained with response spectra and accelerograms according to Eurocode 8 subsoil class A (firm ground) [4].

4.3. Tower loads

Fig. 5 shows the extreme bending moments along the tower from the base at 0 m up to the yaw bearing at about 56.5 m. The results from the earthquake models are compared with the design loads.
Firstly, the earthquake loads of the independent approaches are of the same order of magnitude. Deviations can be observed mainly in the lower part of the tower. The earthquake results are covered by the design loads at most of the tower sections. Only close to the yaw bearing, the Flex5 result (diamonds) is slightly above the design loads. This is not a reason for concern, however, since the difference is marginal and the design in this part of the tower is normally driven by the fatigue loads.

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[4] The 1.1 is in accordance with the safety factor demanded by IEC 61400-1 (Ref. [1]) for abnormal load cases.

There is a significant difference between modal results (squares) and Flex5 results in the lower part of the tower below about 25 m above ground. In these sections the modal approach predicts much higher bending moments (which are, however, still covered by the design moments). A first guess would be, that this discrepancy comes from the fact that more tower degrees of freedom are taken into account in the modal approach (4 modes) compared with the Flex5 approach (2 modes). It is straightforward to demonstrate, however, that this is not the case, since reducing the number of modes to two in the modal approach yields a result that is somewhat smaller than the 4-mode result but still much higher than the Flex5 curve.
In any event, the maximum of both modal and Flex5 loads presumably represents a conservative measure for the earthquake loads. This maximum is just covered by the design loads in the present situation.

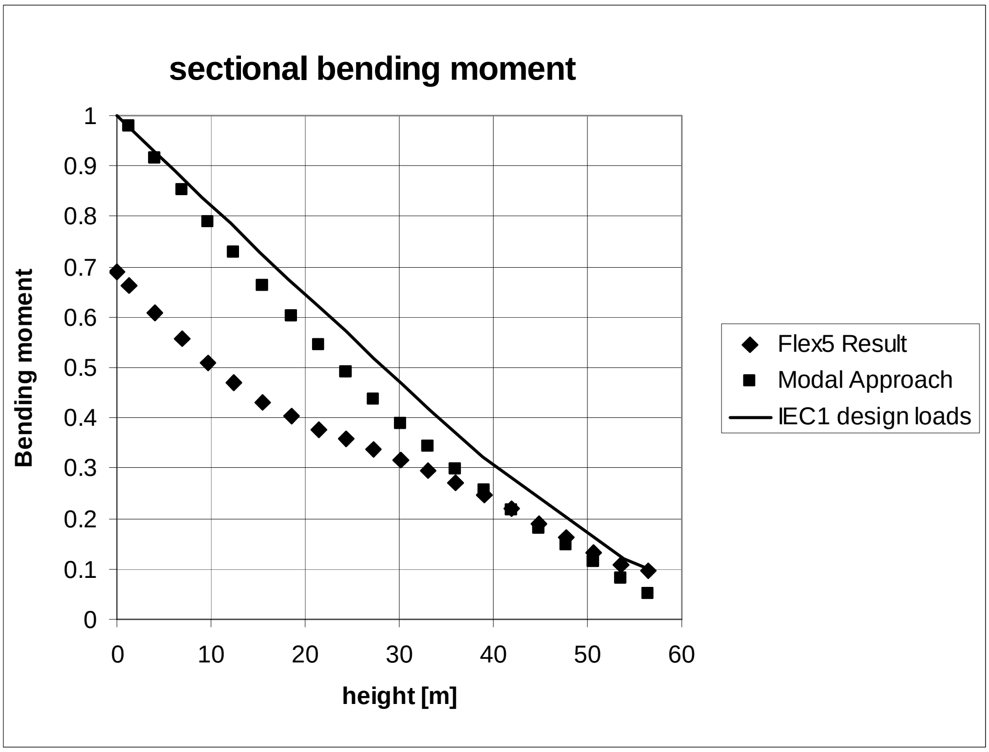

Fig. 5: *Results of the different methods compared with the IEC1 design tower loads. Results are given relative to the design moment at the tower base*

4.4. ***Machine loads***

Concerning the machine loads, results for extreme values have been compared with design loads. In most of the components the results of the earthquake simulation lie significantly below the design loads. Especially blade loads are generally significantly smaller. The only components that are above the design quantities are the vertical force components and the tilt moment.
Firstly, the vertical component has not been taken into account at all in the modal approach. In the formalism developed in Ref. [2], the vertical component of the earthquake acceleration is not considered, probably because in building construction the vertical component normally can be disregarded (except in extremely strong earthquakes) or can be calculated straightforwardly from the vertical acceleration without any additional dynamical model.
Concerning the wind turbines the situation is somewhat different since bearings are loaded and vibrations of parts of the turbine (blades, nacelle tilt) in vertical direction can be provoked. Since wind alone does not lead to high vertical force fluctuations, it is seen very easily that the vertical extreme values reached during a earthquake are normally higher than the loads reached under extreme wind conditions or fault situations, even for weaker earthquakes than the ones analyzed in the present study. Furthermore, tilt vibrations are generated by the vertical acceleration.
In the present case the somewhat higher vertical forces do not pose a problem for the design. The extreme tilt moment is just covered by the design loads.

5. Summary and Conclusion

In this talk, a method to take into account earthquakes in the framework of a time-domain simulation code for wind turbines was described. As an example, a wind turbine Nordex N80 with 60 m hub height was studied at a site with peak ground acceleration 0.3 g.

In order to analyze earthquake loads, we have applied and compared two different methods:

- In the modal approach, four oscillation modes of the combined system tower+nacelle+rotor (where nacelle an rotor were approximated by a point mass on top of the tower) were taken into account. In this approach, the earthquake response spectrum as specified in the Eurocode [4] can be applied straightforwardly, and sectional bending moments as extreme values for the given peak ground acceleration can be obtained.
- In the time-domain approach, the full-scale mechanical model of the wind turbine is studied under the influence of synthetic acceleration time series. Tower modes are taken into account up to second order. The time series were generated in accordance with a rather detailed prescription given in the Eurocode [4] with an algorithm described in Ref. [2].

As the results, the tower loads are just covered by the design loads. The modal approach yields relatively conservative results near the tower base. The somewhat lower Flex5 results can be considered as more realistic, although one has to keep in mind that Flex5 takes into account only two vibration modes. As discussed in the previous section, however, in the modal approach the third and fourth mode do not influence the results very much such that a major correction of the Flex5 results due to higher tower modes or other dynamic effects seems unlikely.

As seen in Fig. 5, the Flex5 loads are greater than in the modal approach close to the tower top. This is clearly caused by tilt oscillations of the nacelle-rotor system that are not taken into account by the modal approach. In the present case, these loads are still covered by the design loads.

As a conclusion, the envelope of modal and Flex5 approach should yield a reliable measure for the tower loads. Since this is just covered by the design, the peak acceleration of 0.3 g may be considered as the limit for this turbine configuration as far as the tower is concerned. For the machine loads mainly the peak values of the vertical forces are generically higher than the design values but do not pose a problem since these force components are not dimensioning. Especially for the blades, where the design driver is typically the 50-years gust, the earthquake loads are much lower (about 70 %) than the design loads.

The approach presented here is generally applicable for wind farm projects in regions where earthquakes have to be taken into account. It enables the manufacturer to design suitable turbines or to approve an existing design.

References

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