Systematic modelling of wind turbine dynamics and earthquake loads on wind turbines

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We present results on an ongoing project to develop a new computer simulation code for (horizontal-axis) wind turbine dynamics and structural loads. This fully independent, self-contained program constitutes a multi-body system with a strictly modular structure. All flexible components of the turbine are modelled by a variable number of modes which can be adjusted by the user to his needs. Special emphasis has been laid on the interaction of foundation and ground. A ground response model has been implemented. This offers users the possibility to get useful information like the bearing pressure distribution directly from the simulation.

Validations with measured data have been carried out. As an application we present results on earthquake loads on a wind turbine, where we can fulfill the requirements concerning of the relevant wind energy and building standards concerning both the quality of the mechanical model and the form of the synthetic ground acceleration. Further efforts will be made to extend the code to offshore wind turbines with general foundation structure and wave loads with the final aim to provide a full-fledged commercially available design code for on- and offshore wind turbines.

1. Load simulations and design process – the virtual wind turbine

Computer simulation plays an increasingly important role in the design process of wind turbines. As illustrated on the right-hand-side of Fig. 1, load simulation is one of the first steps in the design process, just after the turbine concept, main dimensions and the crucial elements of operation and control management have been defined. Further, examination of the load assumptions is one of the first steps in the certification procedure. Thus, for the developer it is extremely important to have a good simulation tool at hand that takes into account external influences, structural dynamic effects and aeroelastic interactions with sufficient precision, with the final aim to be endued with a tool that can be viewed as a virtual prototype.

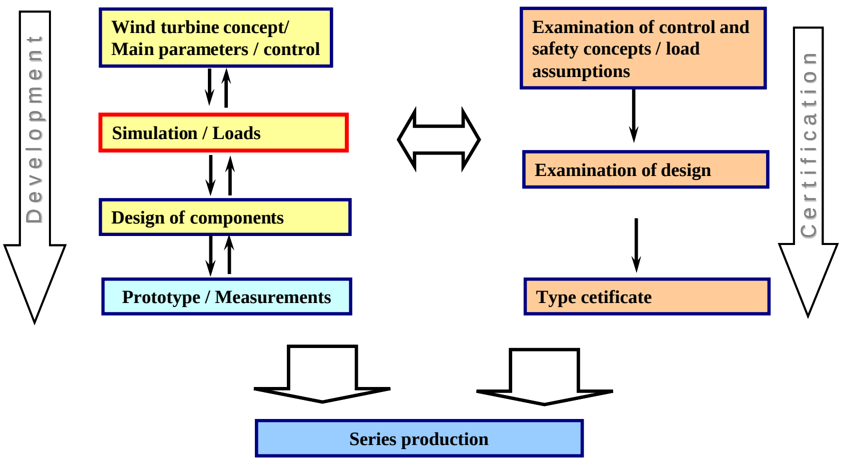

Fig. 1: Role of wind turbine simulation in development/certification process

Currently valid standards for the design of wind turbines [1], taken at face value, require for load calculations about 30-40 hours simulated real time subdivided in about 300-400 load cases. Thus it is important that the simulation is running fast enough in order be able to check and compare design iterations (as illustrated in Fig. 2) on reasonable time scales. In our work we have aimed at a ratio of 1:10 between simulation and real time.

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As far is the model approach is concerned, the two basic requirements formulated above, precision and speed, favour the approach called multi-body simulation with flexible parts. In this approach certain parts of the turbine like blades and the tower are modelled by a limited number of modes, which keeps the number of degrees of freedom whose equations of motion have to be integrated low. Other methods like finite elements or the straightforward multi-body approach are still too slow in order to provide the basis for a fast efficient virtual prototype

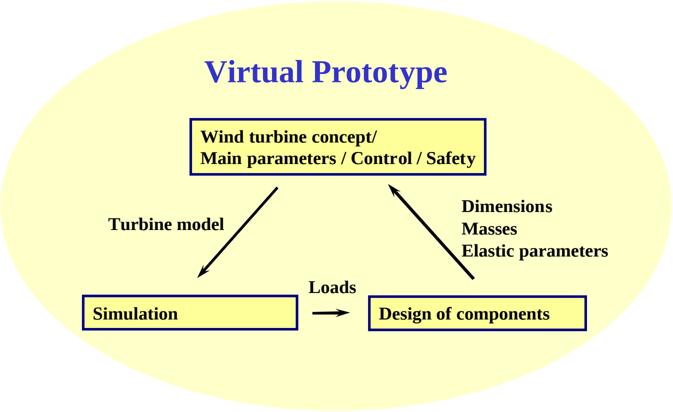

Fig.2: Basic steps of development with the virtual prototype

Motivated by a number of shortcomings of other existing and commercially available simulation codes, a project to develop a new simulation code was started about one year ago. In the following the code will be called SIWEC standing for simulation of wind energy converters. In the next section a description of the basic features of SIWEC is provided. Then an application to earthquake loads on wind turbines is reported.

2. Simulation code SIWEC

The aim of the project was to create a code (including pre- and post-processing) for fast and accurate simulation of the complete wind turbine. Complete means that all dynamically relevant effects should be taken into account by the model, starting from the interaction between the ground and the turbine foundation to the losses at the blade tips.

The advantage of newly-created software is that out-dated code elements like procedures for the management of small storage capacities that slow down simulations with some of the available codes considerably can be substituted by state-of-the-art code elements. So we decided to start from scratch, maintain a strictly modular design and use up-to-date algorithms from computational mechanics [2] for the mechanical model. A recently developed fast solver for systems of ordinary differential equations with a variable and easy-to-adjust number of degrees of freedom was implemented. Work on the aerodynamic model is still in progress.

Blades and tower can be described by a variable number of modes. Especially for the blades the pre-processing of blade structural data is arranged such that simplified flapwise and edgewise modes as well as more realistic complex vibration modes can be taken into account in the model.

Further, a detailed on-shore foundation model [3] including the ground-foundation interaction has been included. As an example we have for the vertical oscillation of the foundation the following equation

$$m_{eff}\,\ddot{z} + c\,\dot{z} + k\,z = P(t)$$

with

$$c = \frac{3.4\,r^2}{1-\nu}\sqrt{G\rho}, \qquad k = \frac{4\,G\,r}{1-\nu}$$

where r is radius of the foundation, a the properties of the ground are described by its shear modulus G is the Poisson number ν, and the density ρ. Further *P(t)* stands for the forces on the foundation. For example the ground acceleration due to an earthquake can be described by this term. According to [4] this model is quite accurate in the load-relevant frequency range. On the other hand it uses only a few ground-specific constants, which can in general be easily obtained for a specific turbine site.

A sketch with the degrees of freedom of the turbine model is provided in Fig. 3.

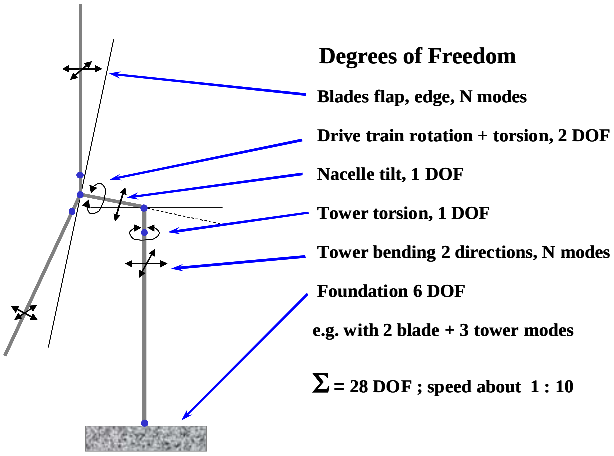

Fig. 3: Turbine model and its degrees of freedom

3. Earthquake loads on wind turbines

A first application of SIWEC is the simulation of structural loads due to earthquakes. Recently, many wind turbines have been erected in areas where strong earthquakes may occur. The stability of the turbines under earthquake conditions has to be proved according to local building standards as for example the Eurocode 8 [5]. For more details on wind turbines and earthquakes we refer to Ref. [6].

In order to analyze earthquake loads, often lumped mass models have been employed. In this approach the tower is described by a number of elastically connected lumped masses, while nacelle and rotor are substituted by an additional mass on top of the tower. From this model tower modes and related frequencies can be calculated and used straightforwardly to obtain an estimate for the earthquake loads with the response spectrum of a single degree of freedom (SDOF) oscillator. The SDOF spectra are normally provided by the standards (see [5]).

The disadvantage of this approach is that the vibration modes of the turbine are oversimplified and loads on certain components of the turbine as for example blade loads are neglected. As an example we consider a realistic wind turbine model with 80 m rotor diameter and 60 m hub height. Fig. 4 shows the eigenfrequencies of the lumped-mass model compared with the results of SIWEC. It becomes obvious that in the more realistic system the tower modes couple to other vibration modes (like the blade modes) which give rise to a much more complex vibration behaviour than in the lumped-mass model.

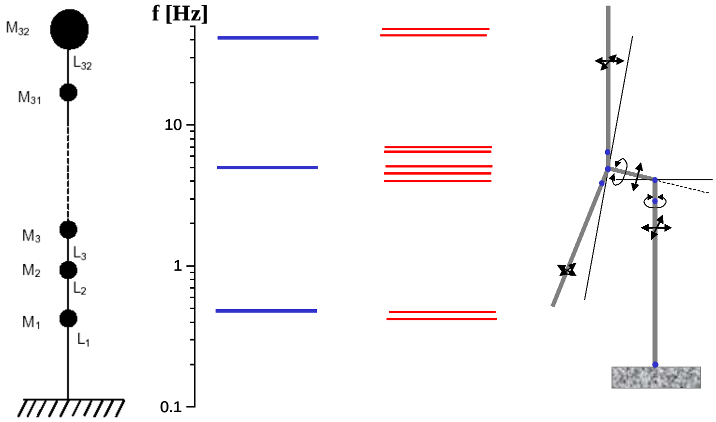

Fig. 4: Modes with lumped-mass model and with SIWEC

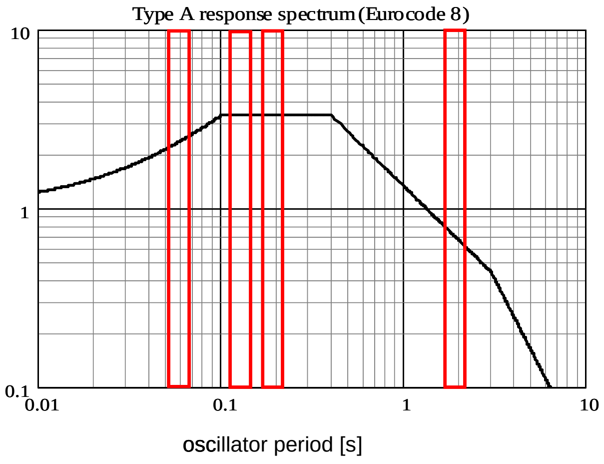

Fig. 5: Response spectrum of the SDOF oscillator according to Eurocode 8 (black line) and bands with system frequencies of the wind turbine (frequency ranges marked by beams)

In Fig. 5 the response spectrum of the SDOF oscillator according to Eurocode 8 [5] is displayed together with the bands where the structural eigenfrequencies lie. At least some of the low-lying bands are in a range where the response spectrum has its maximum. As a result, it is generally recommended to analyse the earthquake loads with a full turbine model that provides a realistic description of the turbine dynamics.

In order to analyze the earthquake loads with SIWEC, we need time-series for ground accelerations. According to the Eurocode [5] time-domain simulations for stability analysis are accepted provided the time series of ground acceleration is consistent with the SDOF spectrum. In order to fulfill this requirement (stated in a similar manner in other standards as well) we have created a program that generates 3-dimensional ground acceleration time series, where the peak ground acceleration and the SDOF spectrum displayed in Fig. 5 enter as parameters. An example for the synthetic ground acceleration is shown in Fig. 6. More details on this topic can be found in Ref. [6].

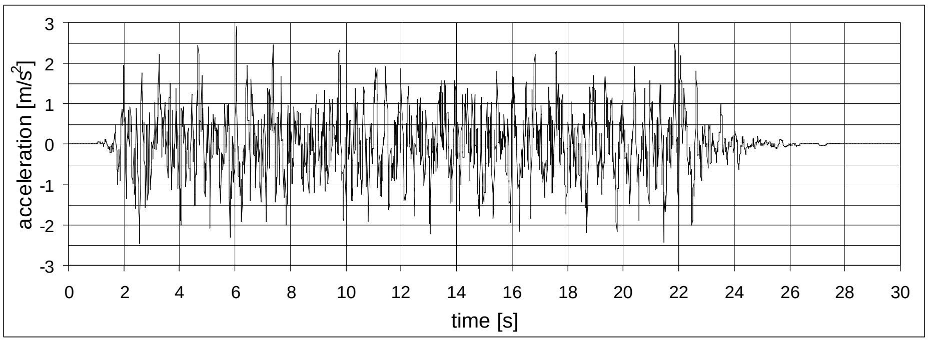

Fig. 6: Synthetic ground acceleration for earthquake with peak ground acceleration 3 m/s².

Using SIWEC equipped with the generator for synthetic accelerograms, we are able to:

- fulfill requirements of the standards, as for example that 85% of the overall system mass being taken into account by the vibration modes used as the approximation for the flexible parts,
- obtain a detailed picture for the vibration modes of the system,
- obtain accurate results for the tower/foundation dynamics and loads and the acceleration in tower and nacelle, and
- obtain detailed information about machine and blade loads due to earthquakes.

Fig. 7 shows an example for the results of a typical earthquake load case. The rotor speed and the results for the cross acceleration in the nacelle are displayed. Before the earthquake, the turbine operates at about 13 m/s wind speed. At t=82 sec the earthquake (peak ground acceleration 3 m/s²) starts. At t=87 sec the turbine is shut down.

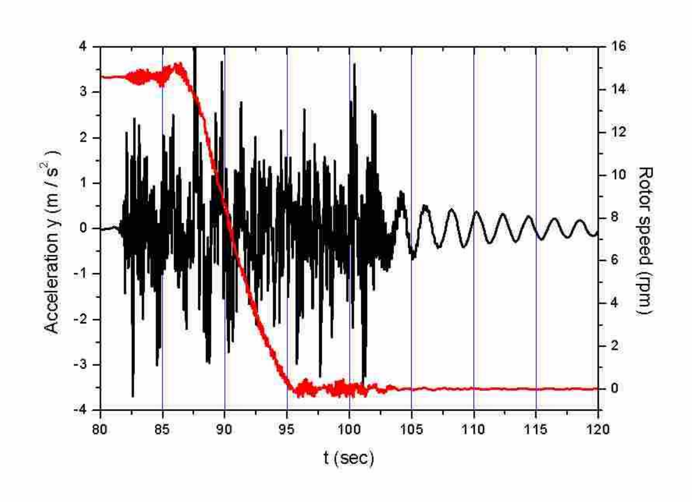

Fig. 7: Result for cross acceleration in the nacelle (left scale) and rotor speed (right scale) in a typical earthquake load case (see text).

In Fig. 8 the amplitudes of the first three tower modes are displayed, rescaled by the average amplitude during normal operation before the earthquake. From this picture it becomes clear that the relative increase in amplitude is much stronger in the higher modes than in the first mode.

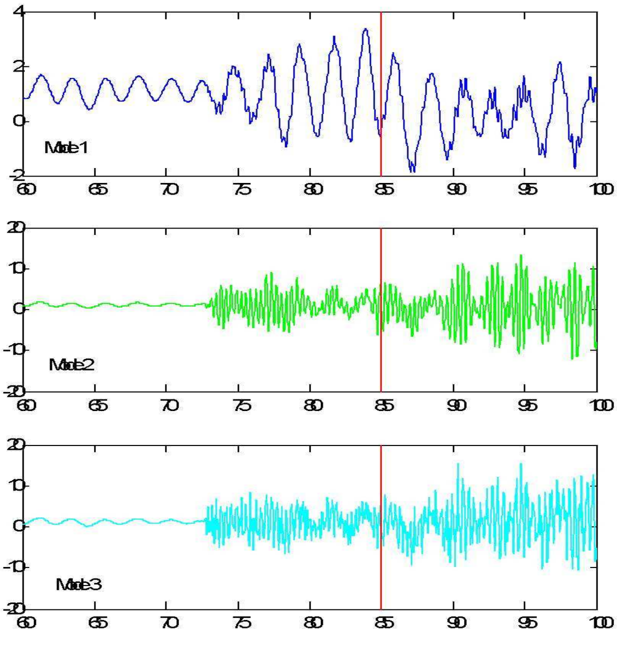

Fig. 8: Excitation of tower modes during earthquake. The amplitudes are rescaled by the average amplitude during normal operation before the earthquake.

Finally, Fig. 9 shows the modal energies of the first five tower modes for normal operation at rated wind speed (13 m/s) and during an earthquake with peak ground acceleration 3 m/s². In normal operation 93% of the total vibration energy is contained in the first and second mode. During the earthquake the first two modes contribute only 84% implying that taking into account higher tower modes in earthquake analyses is actually necessary in order to obtain reliable results for loads.

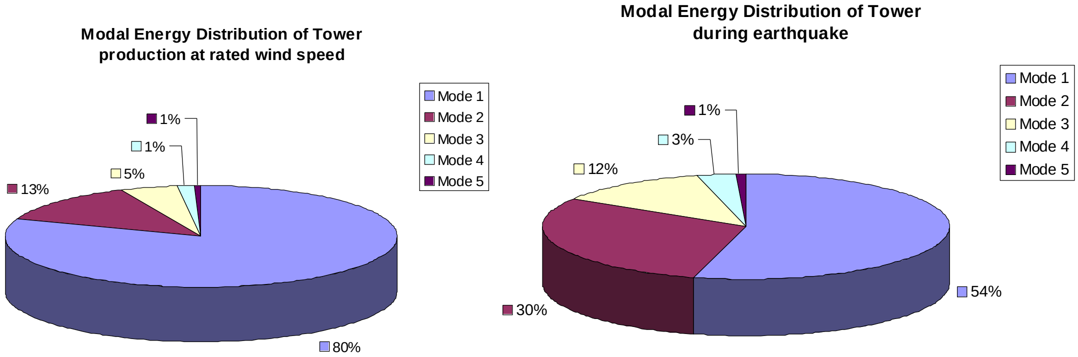

Fig. 9: Modal energies of tower modes for power production at rated wind (13 m/s) and during the earthquake with 3 m/s² peak acceleration.

4. Summary and Outlook

In this paper we presented results on an ongoing development of a simulation code for wind energy converters (SIWEC) with horizontal axis. The aim of the project is to develop a fast and accurate simulation tool that can be employed effectively for load calculations and virtual prototyping. Concerning the mechanical model, the wind turbine is described by a multi-body system with flexible parts (tower, blades) described by a variable number of modes. The number of modes can be chosen by the user to fit the actual needs. The integration of the resulting equation of motion is carried out by a state-of-the-art solver for ordinary differential equation with variable step and effective error control.
As a first application we studied earthquake loads on wind turbines. Starting from the frequency spectra of the ground acceleration required by building standards, we found that higher tower modes are much more important in earthquake analyses than in normal operation conditions.
Work on the aerodynamic model is still in progress. Further efforts will be made to extend the code to offshore wind turbines with general foundation structure and wave loads.

References

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