INNOVATIVE CAE/TESTING SOLUTIONS FOR WIND TURBINES

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Rezumat. O provocare majoră a omenirii secolului 21 este asigurarea durabilă şi accesibilă a energiei necesare, fără poluare şi în condiții de siguranță. A crescut foarte mult, în special în Europa, interesul înlocuirii combustibililor fosili cu surse de energie regenerabilă cum este energia eoliană. Există mai multe motive care explică această tendință: poluarea, dependența economiilor europene de importul combustibililor fosili, resursele limitate ale acestora şi considerarea energiilor regenerabile ca o alternativă durabilă. Autorii prezintă aspecte ale modelarii şi simulării proceselor pentru o descriere cât mai aproape de realitate a sistemelor complexe din turbinele eoliene. Este utilizată ingineria hibridă, în care sunt abordate simultan diferite domenii fizice: structuri mecanice, probleme de zgomote şi vibrații, elemente de acustică, dinamică şi durabilitatea sistemelor. Inițial este realizată modelarea şi simularea componentelor, iar în final este analizată comportarea globală a turbinei eoliene. Model Based Systems Engineering (MBSE) permite analiza simultană a modelelor matematice precum şi proiectarea şi testarea sistemelor de comanda şi control asociate echipamentelor complexe ale unei turbine eoliene. Materialul din lucrare abordează următoarele aspecte tehnice ale unei turbine eoliene: analiza multi-corp (MBS – multi-body systems), estimarea durabilității componentelor şi simularea problemelor acustice.

Cuvinte cheie: turbină eoliană**,** durabilitate structurală, sisteme multi-corp, zgomote şi vibrații

Abstract. A major challenge to mankind in the 21st century is to supply a sustainable, clean and affordable energy in a safe manner. The interest for replacing fossil fuel in the energy mix partly by renewable energy sources, such as wind energy, has increased, especially in Europe. This trend is driven by the following motives: pollution aspects, the dependence of the European economy on the import of fossil fuel, the fossil fuel has limited resources on earth and the renewable energy can be considered as a durable alternative. The authors present the development of a consistent modeling and simulation approaches to correctly describe the realistic behavior of wind turbines. The Hybrid Engineering allows simulation and optimization of the performance of mechanical systems for structural integrity, noise and vibration, acoustics, system dynamics and durability, from the initial concept to the complete modeling and simulation of components and the full wind turbine. MBSE Engineering lets to create and run multi-physics simulation models to analyze and design the associated complex control systems. The following wind turbine problems are briefly presented: Multi-body simulation, Durability simulation, Acoustics simulation.

Keywords: Wind Turbine, Structure Durability, Multi-Body System, Noise and Vibration

1. INTRODUCTION – POWER FROM THE WIND

A wind turbine is a device that converts kinetic energy from the wind, also called wind energy, into mechanical energy in a process known as wind power. If the mechanical energy is used to produce electricity, the device may be called a wind turbine or wind power plant. If the mechanical energy is used to drive machinery, such as for grinding grain or pumping water, the device is called a windmill or wind pump.

The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range of vertical and horizontal axis types.

The wind wheel of Heron of Alexandria marks one of the first known instances of wind powering a machine in history. However, the first known practical windmills were built in Sistan, an Eastern province of Iran, from the 7th century. These were vertical axle windmills, which had long vertical driveshaft with rectangular blades. Windmills first appeared in Europe during the middle ages. The first historical records of their use in England date to the 11th or 12th centuries and there are reports of German crusaders taking their windmill-making skills to Syria around 1190. By the 14th century, Dutch windmills were in use to drain areas of the Rhine delta.

The first electricity-generating wind turbine was a battery charging machine installed in July 1887 by Scottish academic James Blyth to light his holiday home in Marykirk, Scotland. Some month's later American inventor Charles F Brush built the first automatically operated wind turbine for electricity production in Ohio, Figure 1. In 1931 the French aeronautical engineer, George Darrieus was granted a patent for the Darrieus wind turbine which uses vertical-axis airfoils to create rotation and a 100 kW precursor to the modern horizontal wind generator was used in Yalta, in the USSR. In the fall of 1941, the first megawatt-class Smith- Putnam wind turbine was synchronized to a utility grid in Vermont, Figure 2. In 1956 Johannes Juul built a 200 kW, three-bladed turbine in Denmark. In 1975 the United States Department of Energy funded a project to develop utility-scale wind turbines. The NASA wind turbines project built thirteen experimental turbines which paved the way for much of the technology used today.

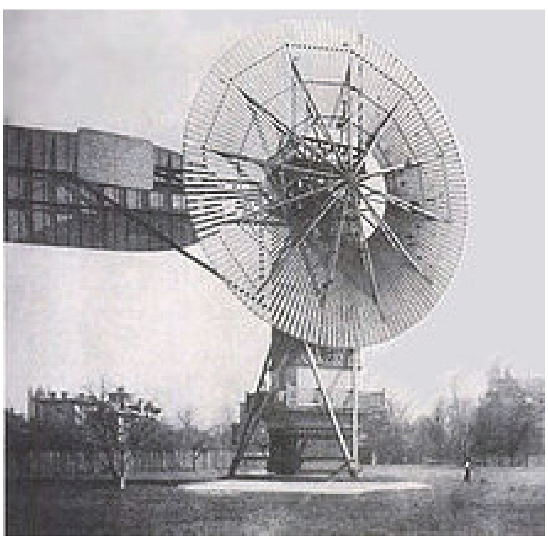


Fig. 1. The 12 kW DC Brush windmill with 144 blades and 17 m rotor diameter.

Fig. 2. The 1.25 MW Smith-Putnam wind turbine (1941).

A wind farm is a group of wind turbines in the same location used for production of electricity. A large wind farm may consist of several hundred individual wind turbines distributed over an extended area, but the land between the turbines may be used for agricultural or other purposes, Figure 3. A wind farm may also be located offshore.

Figure 3: Left – the Brazos Wind Farm in Texas; Right – the Shepherds Flat Wind Farm in the U.S. state of Oregon.

2. WIND POWERED ELECTRICITY - CURRENT STATE

A major challenge to mankind in the 21st century is to supply a sustainable, clean and affordable energy in a safe manner. For electricity generation there are various aspects, including the so-called energy mix. The interest for replacing fossil fuel in this mix partly by renewable energy sources, such as wind energy, has increased, especially in Europe. This trend is driven by the following motives: a) the dependence of the European economy on the import of fossil fuel was demonstrated during the oil crisis in 1973; b) to neglect the climate change due to CO2 emissions during the last centuries is an act of irresponsibility; c) the fossil fuel has limited resources on earth and the renewable energy can be considered as a durable alternative.

Worldwide there are now over two hundred thousand wind turbines operating, with a total nameplate capacity of 282482 MW as of end 2012. The European Union alone passed some 100000 MW nameplate capacity in September 2012, while the United States surpassed 50000 MW in August 2012 and China passed 50000 MW the same month.

A modern wind turbine has typically a horizontal axis and a three-bladed upwind rotor. This latter component is manufactured in lightweight material and often equipped with dedicated features, such as a pitch mechanism, vortex generators or lightning protection. The tower is mostly a tubular steel structure, which is designed to avoid resonance at the main excitation frequencies. The drive train converts the mechanical energy at the rotor hub into electrical energy at the generator. The grid connection can be direct or indirect, where the latter type implies that all produced electric power goes through a frequency converter towards the grid. The main parts of the modern wind turbine are shown in the Figure 4.

3. CAE AT DIFFERENT STAGES IN THE WIND TURBINE PRODUCT DEVELOPMENT

Any use of computer software to solve engineering problems means Computer-Aided Engineering (CAE). A typical CAE program is made up of a number of mathematical models encoded by algorithms written in a programming language. The natural phenomena being analyzed are represented by an engineering model. The physical configuration is described by a geometric model. The results, together with the geometry, are made visible via a user interface on the display device and a rendering model.

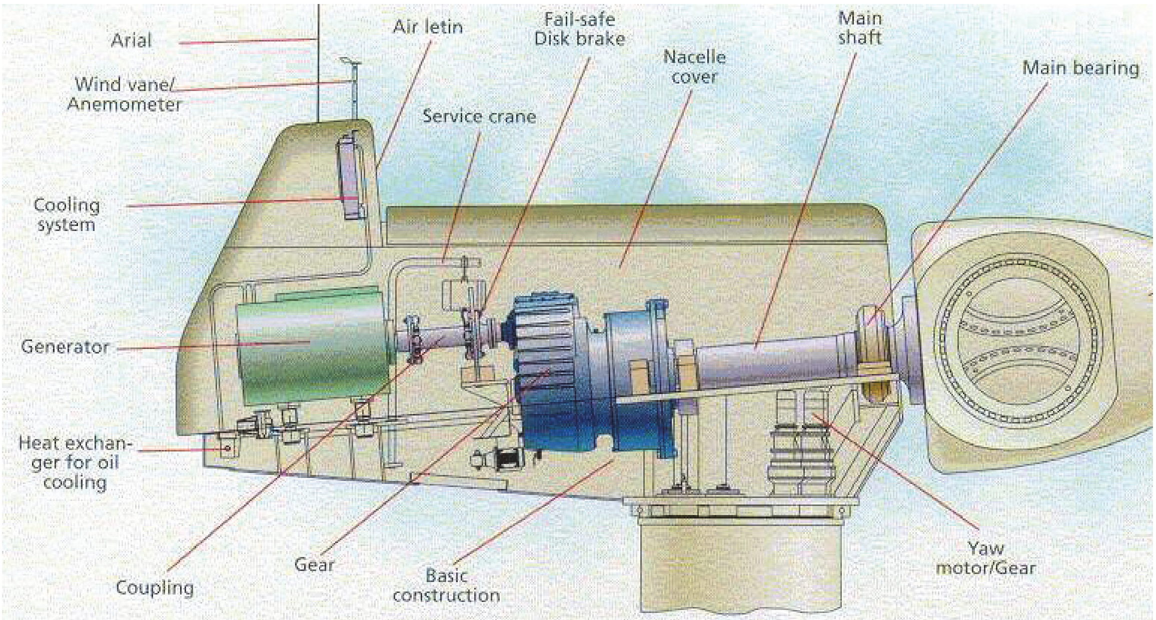


Fig. 4. Main parts of a modern wind turbine.

A wide range of technologies are used during different design phases in simulation driven product development, including structural finite element analysis, acoustics, crash analysis, fatigue and failure analysis, and computational fluid dynamics.

Wind turbine design requirements can be divided in two groups: structures and machinery requirements. Structures include blades, hub, main shaft, bearings and must sustain wind variable thrust forces and wind turbulence. Also have to keep structural integrity under exceptional wind loads. Machinery means shaft, bearings, gearbox and generator and sustains wind variable torque under extreme conditions with high reliability and availability.

The main aspects of simulation and testing solutions can be grouped as follows:

– *3D virtual simulation*: gear modeling; system modeling for noise, vibration and durability; fatigue life prediction;

– *1D multi-domain simulation*: electric architecture comparison; control strategies studies; power grid connection optimization;

– *testing solutions*: vibro-acoustic measurement and analysis; driveline operational measurements; gearbox noise path identification.

4. MULTI-BODY SIMULATION OF THE WIND TURBINE DRIVE TRAIN

Multi-body simulation is used to assess the structural reliability of the gearbox and to make sure it resists the extreme and unpredictable loads from the wind and doesn't break under high or concentrated stresses. Figure 5 shows a generic model of a modern wind turbine. The drive train has one main bearing integrated in the gearbox carrying the wind turbine rotor. The generator is a doubly fed induction generator and the gearbox design is a combination of two planetary stages with one high speed parallel stage. The wind turbine rotor is connected to the planet carrier of the first planetary stage. This stage has spur gears and its ring wheel is fixed in the gearbox housing. This housing is assumed to be rigid as well as its connection to the bed plate. The second gear stage in the gearbox is a helical planetary stage. Its planet carrier is driven by the sun of the first stage and its ring wheel is also fixed in the gearbox housing. The pinion of this stage rotates at the speed of the generator. A brake disk is mounted on this output shaft and a flexible coupling connects it with the input shaft of the generator.

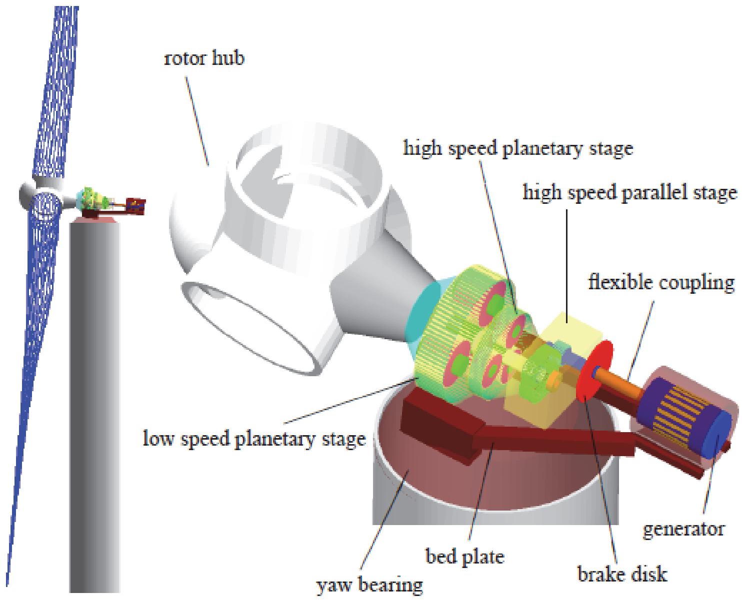


Fig. 5. Simplified representation of the three bladed wind turbine with a zoom on its drive train.

In a standard 1.5 MW wind turbine the huge input torque of around 1000 kNm coming from the blades rotating at 15 rpm has to be transferred to realize a gear ratio between input and output shaft of more than 100 in order to match the rotational speed needed to generate electricity from the generator. Typically this is done through a 3-stage gearbox design, Figure 6, a first stage with planetary gears (offering a large gear ratio and a low weight of the gears) and two subsequent parallel gear stages. Next to the gears themselves, the bearings have to be modeled in detail because of the very high loads they support and their key impact on the overall reliability of the wind turbine.

In order to switch from a pure kinematic analysis to a dynamic analysis, the gearbox model is then extended with flexible bodies (with inertial parameters), connections between them (joints, constraints, forces) as well as controls. Various alternatives of the design (from CAD or dynamic parameters) are compared in order to optimize the system with regards to any specific performance attribute.

The equivalent meshing stiffness between the two gears is the sum of the contact stiffness over the number of contacting teeth, which varies in time according to the contact ratio. Each single tooth equivalent stiffness is also varying during the meshing time, since the bending is bigger at the top than at the root of the tooth. An example of the meshing stiffness variation is shown in Figure 7 above, assuming that the contact ratio is 2.5, meaning the number of contacting teeth varies from 2 to 3. In the figure above the dependent variable is the stiffness and the independent variable is the meshing time, from 0 to εtz where ε is the total contact ratio, tz the meshing period for a single tooth, and εtz the whole meshing period.

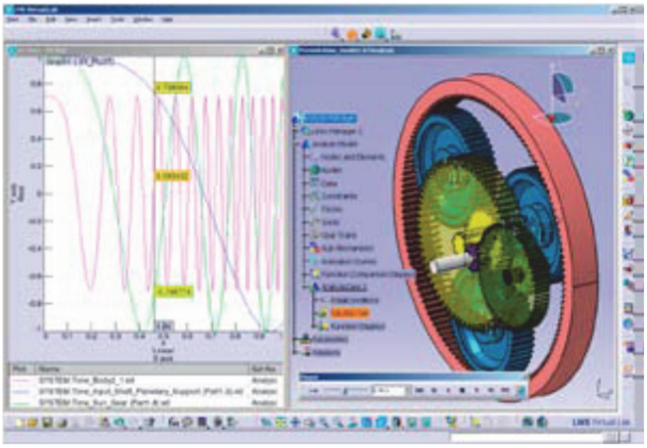


Fig. 6. A typical 3-stage gearbox design.

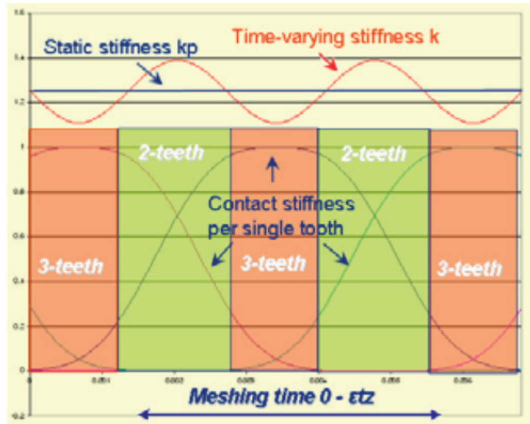


Fig. 7. A meshing stiffness variation with a 2.5 contact ratio.

5. WIND TURBINE DURABILITY PREDICTION

Wind turbines are designed to cover a 20-year lifetime with low operating and maintenance costs, and to withstand the high variability of wind forces. To meet these targets, engineering teams apply durability analysis using loads measured through testing or obtained from dynamic simulation.

Variable wind loads require durability analysis on large number of wind turbine components: hub, transmission, gear boxes, tower and blades. The following steps must be completed in the component fatigue analysis: loading, stress analysis and fatigue analysis, Figure 8. Depending on the fatigue target, the material and loading type fatigue simulation accumulates the damage.

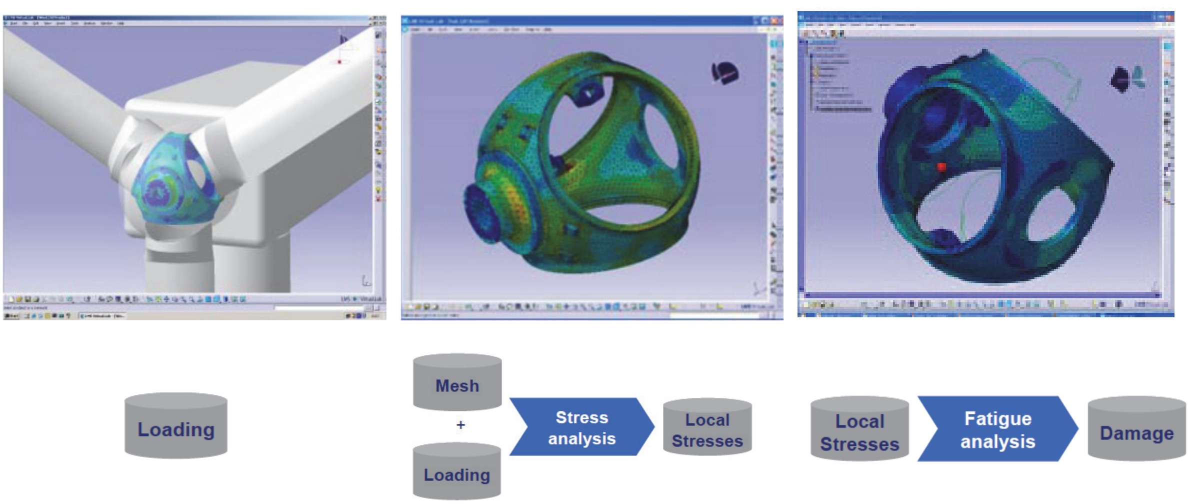


Fig. 8. Three steps of the component fatigue process analysis.

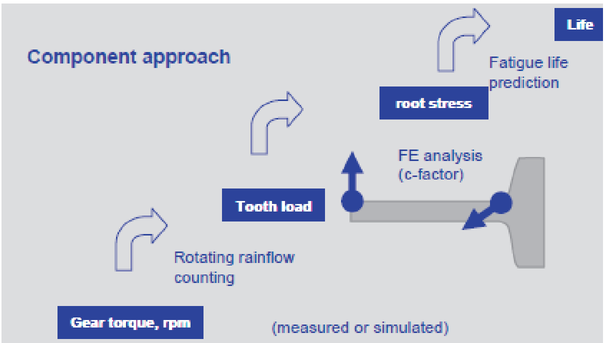
Fatigue life prediction for gears based on component, Figure 9*a*, and system-level approach, Figure 9*b*, includes features for rotating components. Gear fatigue is typically performed in 4 steps:

– simulate the gear torque;

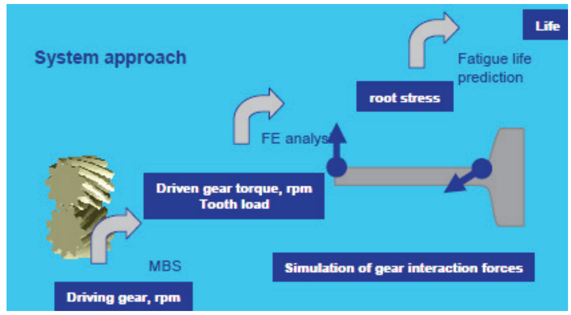
– apply a specialized rotating counting algorithm to account for the fact that each tooth sees the load once per rotation;

– get stresses at gear tooth for a given torque;

– perform a fatigue analysis using the rotating count.



a)



b)

Fig. 9. Fatigue life prediction for gears:
a – component approach; *b* – system approach.

Component fatigue allows for different methods for stress: quasi-static (superimpose elastic pseudo stress, no rigid body motion and loads do not excite natural frequency), inertia relief (accounts for rigid body motion), modal superposition (accounts for the excitation of natural frequencies), flexible bodies (system level approach, automatically accounts for rigid body motion and the excitation of natural frequencies), transient analysis (large deflections and complex geometrical nonlinearities – contact), vibration based – random fatigue (stationary process, estimate local stress distribution).

Powerful stress fatigue post-processing allows for better understanding of impact of loads and events on fatigue life. It helps to verify solution design simulation process by comparing measured strains to simulated strains. Understanding the influence of different load cases allows simplifying and fastening up tests and to optimize the design for maximize the fatigue life.

6. OPTIMIZING WIND TURBINE ACOUSTICS THROUGH VIRTUAL SIMULATION

The noise wind turbines generation is influenced by many factors, including blade size and design; drivetrain operation as well as the orientation, force and turbulence of the wind. There are two types of wind turbine noise:

– ***Blade aerodynamic noise*** which has a broadband and a low frequency spectra, Figure 10. It depends on blade aero-dynamic design, on atmospheric wind turbulence and on blade operating conditions.

– ***Rotating machinery noise*** which has a deterministic noise spectrum (RPM) and can be divided in two principal groups:

- *airborne noise* – represented by direct acoustic radiation from machinery housing (gearbox, generator and accessories).
- *structure borne noise* – specific tonal noise components occur as a result of dynamic forces that come into play inside the gearbox (teeth meshing), the generator (electro-mechanical poles interaction), and system hydraulics equipment; the noise generated by driveline

rotating machinery also propagates directly through structural noise paths as it is shown in Figure 11; these dynamic forces cause local housing surface vibrations, which distribute the noise to the surrounding area through radiation, Figure 12.

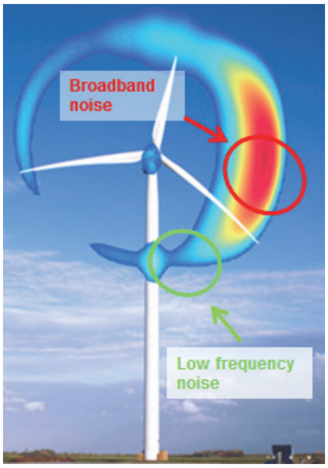


Fig. 10. Blade aerodynamic noise.

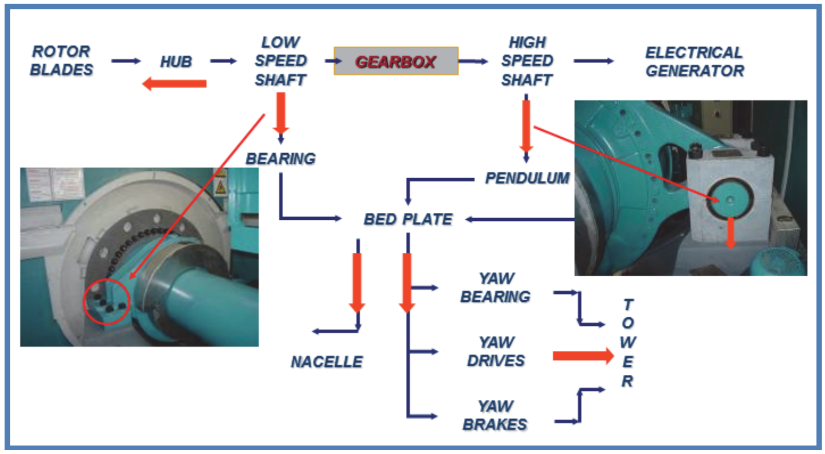


Fig. 11. The propagation of the driveline rotating machinery noise through structural path.

Based on the structural full-system FE model, it is derived a Boundary Element (BE) model of the wind turbine through a dedicated „skinning" procedure. The acoustic BE model makes it possible to simulate the acoustic power generated by the wind turbine through local surface vibrations of various system parts. This information serves as input for the Acoustic Transfer Vector (ATV) method that accurately and effectively translates the acoustic power into far field noise emissions. Transfer Path Analysis (TPA) is used to evaluate the contribution of the different structure borne and airborne transfer paths between a given source and target locations. TPA uses transfer functions between the target and the forces at all considered transfer paths and combines these with estimates of the forces acting on the considered paths during operational conditions or transient operating conditions. These operating forces are either available as experimental data or have to be determined indirectly.

One of the major advantages of this deterministic acoustic simulation approach is that it supports different kinds of analyses that provide detailed insight into particular noise sources. Through post-processing, it is possible to trace the modal contribution of specific system parts, or analyze the effect of individual panels and loads on overall noise radiation. The engineering information resulting from these investigations is vital for driving development improvements and new wind turbine development. Deterministic acoustic simulations were performed up to a frequency of 200 Hertz, which allowed significant structure-borne noise phenomena to be traced and tackled with sufficient reliability.

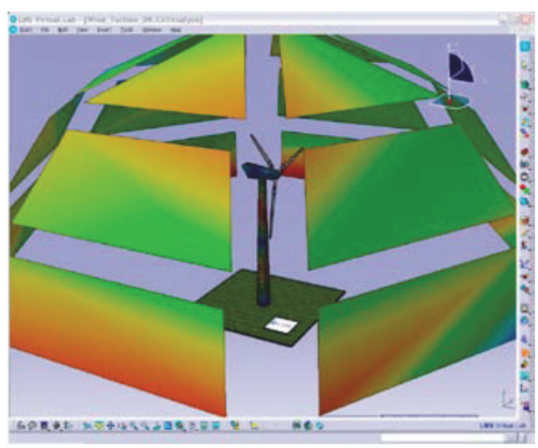


Fig. 12. Simulation of the noise radiation to the wind turbine surrounding area.

7. CONCLUSIONS

Increasingly development of the production of electricity using wind resource is determined by a balanced relationship between expectations and requirements for wind turbines. There are customers and manufacturer expectations. As customer requirements can be listed: site integration and environmental friendly, wind park profitability, low annual cost of energy, guaranteed reliability and a long term service agreements up to 20 years. Manufacturer's expectations are: high performance and reliability, minimal development cost, minimal production cost and environment friendly. These expectations generate the following engineering challenges: extreme dimensions, limited yearly production rates, high cost of physical testing and high accuracy of CAE.

Efficient simulation permits to simulate all events in batch and to identify the important loading. Also it is possible to analyze design parameters sensitivities to performance and to optimize the design and refine the structure. At the end it is validated the performance of the whole installation.

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