

Simulating dynamics, durability and noise emission of wind turbines



Introduction

In many countries, governments increase the share of renewable power generation, through ecologic targets and resolute choices for 'green' energy that is clean, indigenous and inexhaustible. Wind energy is predicted to meet approximately 25% of Europe's power demand in the year 2030 and wind turbine markets are also growing fast in the United States and in Asia.

The drivetrain forms the very heart of a wind turbine. The wind power is converted via the blades into mechanical power on a slow-speed shaft. This power is scaled via a very large gearbox to a high-speed shaft and finally transformed via a generator into electrical power. The wind turbine control system together with the power converter guarantee a clean and steady output voltage at constant frequency, irrespective of varying wind conditions.

Engineering challenges

To obtain certification of a wind turbine, manufacturers have to ensure full system reliability under real-life operating conditions. Noise emissions must remain within prescribed tolerances. Moreover, durability must be assessed to provide a 20-year lifetime with small operation and maintenance costs. Overcoming these challenges involves extensive engineering efforts from the initial concept designs up until the final wind turbine validation and certification. Since extensive tests on full scale wind turbines are extremely expensive and often dangerous to conduct, manufacturers heavily rely on simulation throughout the development process.

To optimize the design of the gearbox, manufacturers make use of simulation tools to predict the torques that the different shafts need to transmit along the drivetrain from the blades to the generator. This can be done using simplified codes which only account for one torsional degree-of-freedom. However, detailed 3D multi-body simulation allow for more in-depth studies, capturing the dynamic behavior of the overall system and its components. For example, the engineering of bearings and gear contacts provides a true challenge to gearbox manufacturers and clearly illustrates the advantages of 3D multibody simulations. Bearings have to endure very high loads and therefore are critical in the reliability of the complete system. In-service misalignment of the shafts - as small as a few thousands of a degree - caused by the compliance of those bearings, influences the gear contact forces and cause unwanted wear on the gear teeth. In order to avoid this wear, gearbox manufacturers can optimize the gear geometry (lead crown and involute crown) based on virtual simulation.

An integrated Simulation process

Using LMS Virtual.Lab Motion, wind turbine engineers can accurately model contacts between gearbox components. This allows them to efficiently predict the transmission of loads between components like gears, shafts or bearings, while taking the flexibility of these components into account. Based on the wind load cases, LMS Virtual.Lab evaluates the stresses on each component and predicts their structural static reliability. Using the same Virtual.Lab simulation environment, users can perform durability, vibration and noise analyses in a straightforward way (Fig.1). In addition, the seamless integration and the preserved associativity within LMS Virtual.Lab avoid time-consuming and error-prone transfer of data and allow development team to perform fast optimization loops.

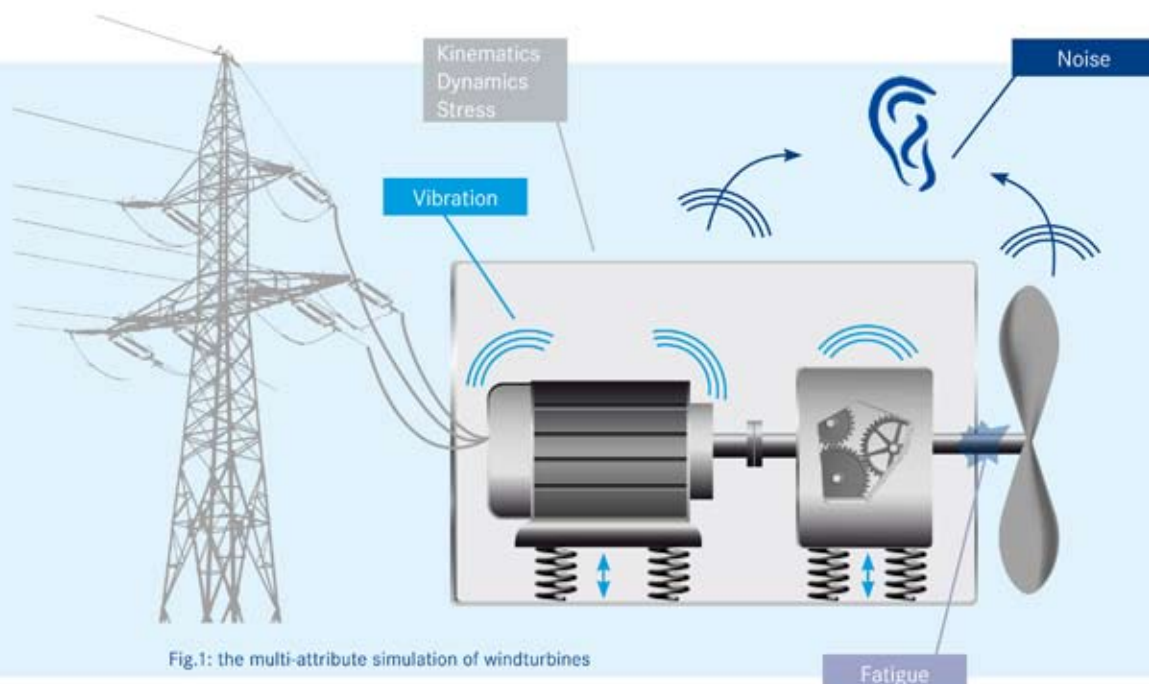


Fig.1: the multi-attribute simulation of windturbines

Multi-body simulation to assess dynamic behavior

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.

In a standard 1.5MW wind turbine the huge input torque of around 1000kNm 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 (Fig.2); 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 the first step of the process, the CAD geometry is imported or created within LMS Virtual.Lab Motion using the embedded 3D modeling capabilities. The model includes gears, shafts, bearings and the housing. 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. At this level a dynamic simulation is computed and the results can be visualized through 3D animations or 2D graphs from any variable in the model. 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. This allows an in depth understanding of the root causes of its behavior and enables engineers to minimize the risk of failure during subsequent assessment test on prototypes.

LMS Virtual.Lab provides several methods to model the meshing of gears. The most suited is the so-called "Gear contact force" element. It is applicable to any kind of gear system which is spur or helical, external or internal. The method also applies to planetary gears which are often used in wind turbines. In case of the "Gear contact force", the contact formulation is not computed based on one-to-one tooth geometry interpenetration. In stead, it is directly derived from the global gear theory for more efficient analytical solving and shorter calculation times. Moreover, it takes into account the variability of the stiffness which is due to the profile of one single tooth and to the instantaneous number of meshing teeth, according to the Cai and ISO formulations (see references 1, 2, 3).

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 below (Fig.3), assuming that the contact ratio is 2.5, meaning the number of contacting teeth varies from 2 to 3. The total contact stiffness consequently has a fluctuation nature (oscillation around a static stiffness) which introduces internal excitations to the gears that could cause whine noise and possible tooth separations under certain loading conditions. In the figure below the dependent variable is the stiffness and the independent variable is the meshing time, from 0 to ϵt_z where ϵ is the total contact ratio, t_z the meshing period for a single tooth, and ϵt_z the whole meshing period.

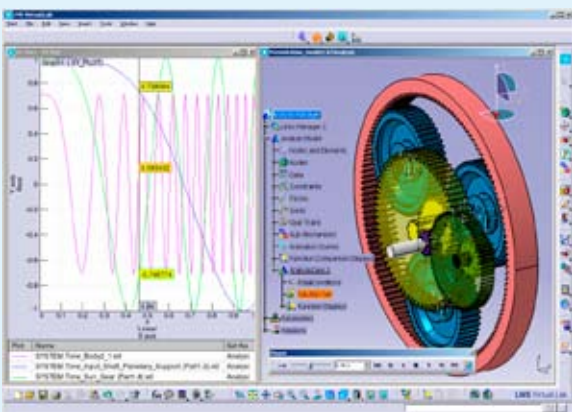


Fig.2: a typical 3-stage gearbox design with planetary gears

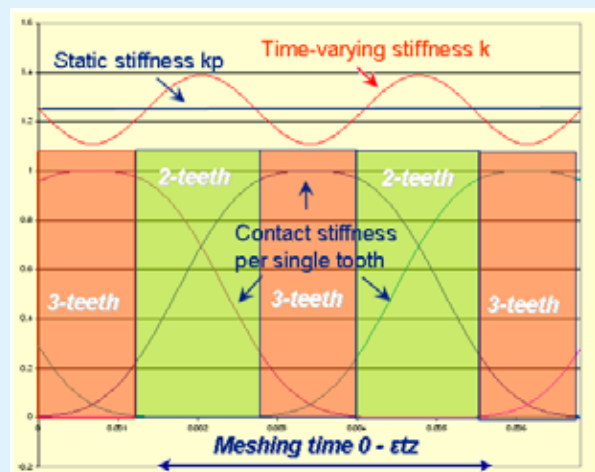


Fig.3: a meshing stiffness variation with a 2.5 contact ratio

Optimizing overall durability performance

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. The critical loads acting on a wind turbine are mainly due to fluctuations in speed and direction of the wind and by the starting and stopping of the system. The number of load cases typically varies between 50 and 500 and last up to ten minutes each.

LMS Virtual.Lab Durability provides the batch capability to efficiently analyze the different load cases independently or on remote CPUs with advanced monitoring capabilities and e-mail notifications at the end of the job. Starting from the external loads, Virtual.Lab computes internal loads acting on the components such as the rotor hub (Fig.6). A global load spectrum formulated from individual events is then used to simulate 20 years of use.

Traditionally, only the static loads and a maximum stress criterion are applied, not taking into account the unpredictable random forces, or the interrelationships of multi-axial forces. This oversimplification leads to inaccurate fatigue-life predictions, and the only way to secure the operational safety of the turbine was to over-design it. By ignoring the phasing relations, the conclusions may even identify the wrong hotspots.

LMS Virtual.Lab Durability provides accurate fatigue life prediction and results are calculated very efficiently. The time history approach uses all significant damaging events and automatically accounts for correct phase relations of load components and correct mean stresses. Because it can assess the entire model of the structure, hotspots are accurately and automatically identified, and the damage distribution is easily visualized. Furthermore, Virtual.Lab Durability provides the tools to understand the causes of fatigue problems - which events are the most damaging, what is the contribution of a load to a given hotspot - and to refine the design of the components. Using the integrated automation scripting methods, the complex setup of several hundred load events is constructed from a spreadsheet, the fatigue analysis is run in batch and a report is prepared in a fully automated way.

The unique capabilities of Virtual.Lab Durability include frequency based fatigue solutions that directly use random descriptions of the loads via power spectral densities and phasing information via cross correlations. The software also performs fast simulations of shaker table tests of sine sweeps and block sines.

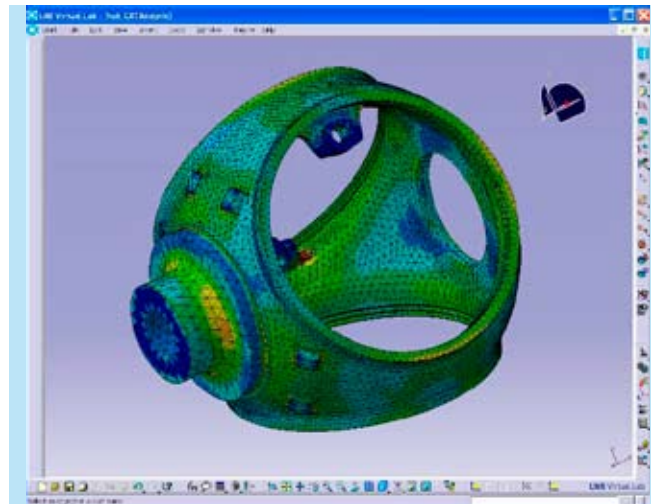


Fig 6 The software calculates the external loads on the blades and the resulting internal loads on the hub

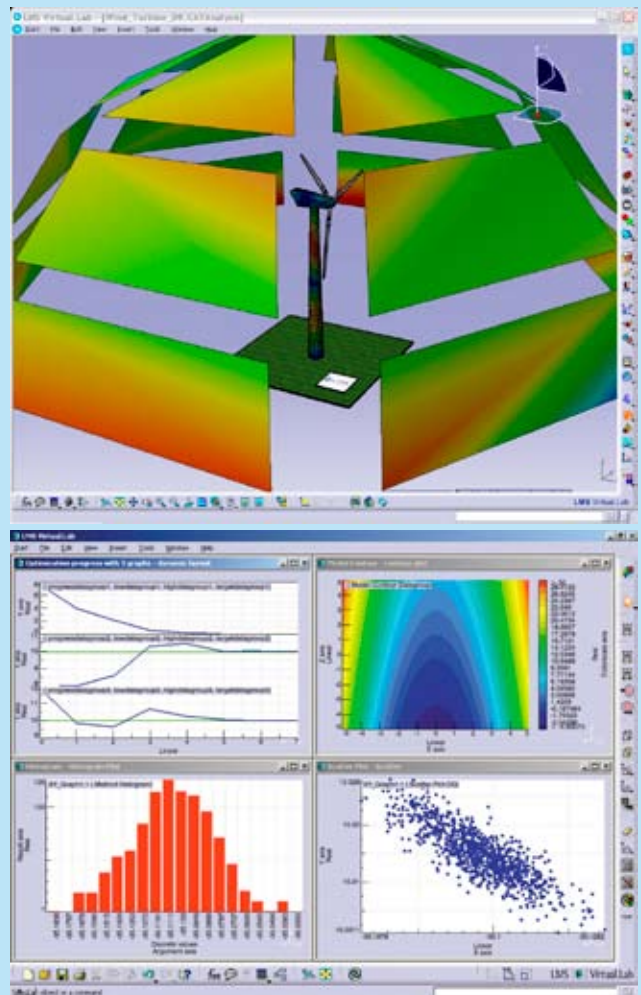


Fig.7: noise radiated from a wind turbine and optimization tools

Complying with noise regulations

To comply with the restrictive regulations, wind turbine development teams have to perform noise and vibration analyses. The noise generated in wind turbines consists of broadband and tonal components. Broadband noise mainly originates from aerodynamic phenomena like the flow of air around the blades, hub and tower. Tonal noise tends to originate from mechanical components and electrical equipment like the gearbox and the generator. The rotation of these components and the resulting dynamic forces cause local housing surface vibrations, which distribute noise to the surrounding area through radiation (Fig.7). The noise generated by driveline rotating machinery also propagates directly through structural noise paths.

While it is relatively easy to predict performance at the component level, most noise and vibration problems are only discovered at the full system level. From the early concept development stages onwards, LMS Virtual.Lab Noise and Vibration captures all critical process steps to systematically improve the noise and vibration characteristics of a complete assembly. The loads can be imported from measurements, from multi-body or acoustic simulations or from generic loading sources. LMS Virtual.Lab Noise and Vibration offers a wide range of visualization and analysis tools to quickly investigate transfer paths and efficiently assess the noise and vibration contribution of individual system parts.

Optimizing the overall wind turbine system behavior

The performance of advanced mechanical system designs like wind turbines relies on an optimal interaction of subsystems of different nature. Wind turbine engineers have to carefully optimize the coupling between mechanical subsystems like the turbine blades and gearbox on one hand, and the electrical generator and the power grid on the other hand. Electronic controllers, mechanical components and powered actuator subsystems all relate to different physical domains and a different engineering logic. This makes it very challenging to assess the multi-domain, overall system-level behavior of a complete wind turbine system. Dedicated simulation tools can optimize the individual systems but cannot take into account the interaction with other systems of a different nature. Testing the full system behavior on a wind turbine prototype is often used as a costly and time-consuming solution.

LMS Imagine.Lab AMESim offers a complete 1D simulation platform to model and analyze multi-domain, intelligent systems and to predict their multi-disciplinary performance. The AMESim software models critical systems like the turbine blades, the gearbox, the electrical

generator and the power grid as analytical or tabulated models. It studies the performance of the individual subsystems and the coupling between the subsystems in the overall system configuration.

The blades model transforms the wind energy into mechanical energy on a rotating axis. The efficiency of the wind turbine, which depends on a reduced speed parameter, is integrated in the model. This efficiency has a bell shape curve. When the wind speed is low, the turbine is not efficient. If the turbine rotates too fast, its efficiency is not optimal either. The AMESim software offers a wide range of modeling levels for the gearbox: from a simple efficiency ratio model up to a detailed model that simulates the teeth backlash with variable contact stiffness. Dedicated libraries are available to model the electrical components like the generator, the inverter and the power grid. The design of control rule can be done directly in AMESim, or by using Matlab/Simulink. In the latter case, the control model can easily be linked back into AMESim

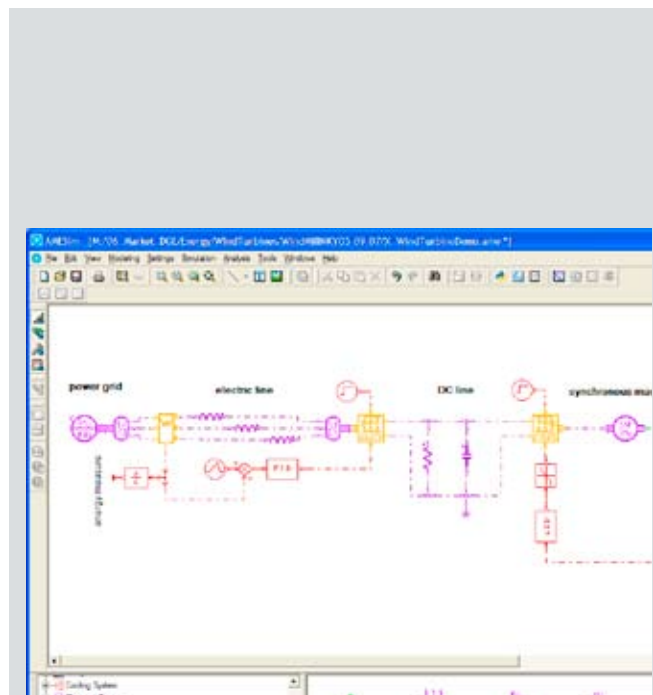


Fig.8: windturbine model in the LMS Imagine.Lab AMESim environment

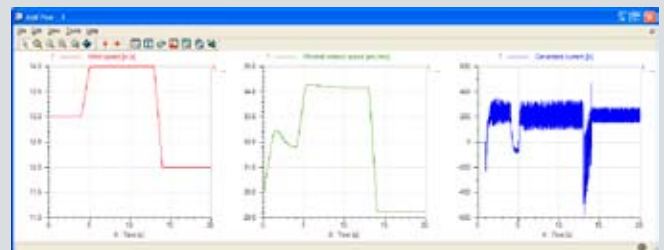


Fig.9: typical results in function of the time

The AMESim software allows the engineering team to interactively assemble the overall system model, and to simulate key system-level performance criteria. As an example, the software can simulate the rotating velocity of the wind turbine and assess the electrical power that is generated, in function of the input wind velocity (Fig.9). The developed model of the overall intelligent system allows to

- compare the use of a synchronous machine or induction machine
- compare the use of a mechanical reducer or machine with high number of pole pairs
- study different alternative control rules
- optimize energy management
- detect potential online failures

Conclusions

The integrated simulation capabilities within LMS Virtual.Lab and LMS Imagine.Lab AMESim offer an efficient solution to analyze and optimize the dynamics, durability performance and noise emissions of wind turbines. Accurate loads are easily generated with LMS Virtual.Lab Motion thanks to state-of-the-art contact formulations suited for system level analysis. Those loads lead the engineers to evaluate the stresses occurring in each component and the vibrations generated in the structure. To assess the fatigue life of the components, either the computed stresses or measured stresses are then used in Virtual.Lab Durability. Virtual.Lab Noise and Vibration helps engineers to evaluate the noise emitted by the system and to understand its components and origin.

Using the same LMS Virtual.Lab environment to perform all of these analyses eliminates the need to transfer data and models between different tools, which saves time and avoids errors. Moreover, the single integrated environment enables to quickly analyze the effect of design changes on a specific performance attribute. This allows engineering teams to perform fast optimization loops from the early development stages onwards.

The multi-domain system approach of LMS Imagine.Lab AMESim helps engineers to model critical subsystems, to study their performance and to assess the coupling between the subsystems in the overall system configuration. ■

References

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2. Cai, Y. and Hayashi, T.: 1994, The linear approximated equation of vibration of a pair of spur gears (theory and experiment), The ASME Journal of Mechanical Design 116, 558 – 564.
3. ISO Standard 6336-1, Calculation of Load capacity of Spur and Helical gears part 1: Basic Principles, Introduction and General Influence Factors.