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Simulating dynamics, durability and noise emission of wind turbines in a single CAE environment †

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Abstract

To optimize the design of their windturbines, manufacturers make use of simulation tools to predict the loads that the different components need to transmit along the drivetrain from the blades to the generator. Using detailed 3D Multi-body simulation allows for in-depth studies, capturing the dynamic behavior of the overall system. Multi-body simulation is used to assess the structural reliability of components such as the gearbox and to make sure they resist the extreme and unpredictable loads from the wind for a reasonable lifetime. LMS Virtual.Lab provides state-of-the art methods to model gearboxes and the meshing of gears with varying stiffness. It also provides capabilities to model the rotorblade as well as the generator. The complete system is built from the subsystems assembled in a versatile and modular way. Using LMS Virtual.Lab Motion, a dynamic simulation is finally performed to visualize the behavior of the system trough graphs and animations. The integrated simulation capabilities within LMS Virtual.Lab environment also offer an efficient solution to analyze and optimize the durability performance, noise emissions and overall yield 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. The environment enables to quickly analyze the effect of design changes on a specific performance attribute, which allows engineering teams to perform fast optimization loops from the early development stages onwards.

Keywords: Multi-body virtual simulation; Drivetrain; Windloads; Controls; Durability prediction; Noise prediction; Optimization

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1. 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, including the rotorblade, the transmission and generator. The wind power is converted via the blades into mechanical power on a slow-speed shaft. This power is scaled via a 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.

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2. Multi-attribute optimization of a full wind-turbine drivetrain system

2.1 Engineering challenges

To obtain certification of a wind turbine, manufacturers have to ensure full system safety 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 until the final windturbine 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 up 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, influence 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 results.

2.2 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 and using the same simulation environment, users can perform durability, vibration and noise analyses in a straightforward way (Fig. 1).

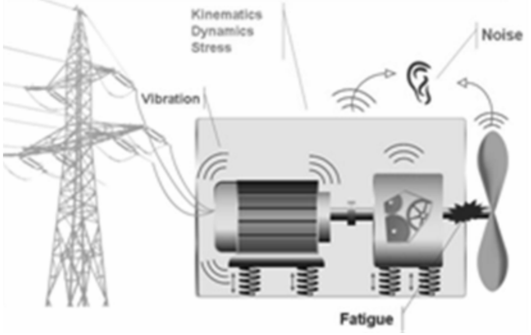

Fig. 1. the multi-attribute simulation of windturbines.

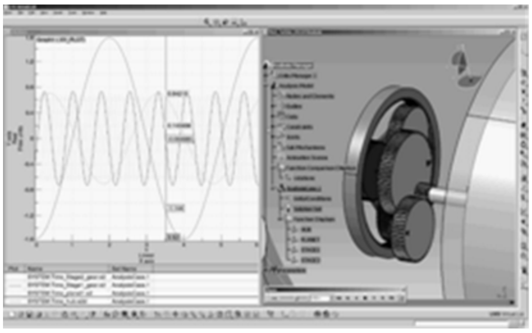

Fig. 2. a typical 3-stage gearbox design with planetary gears.

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 and multi-target optimization loops.

2.3 Multi-body simulation to assess dynamic behavior

In a standard 1.5MW wind turbine the huge input torque coming from the blades has to be transferred to realize a gear ratio between input and output shaft of more than 100 in order to match the needed rotational speed to generate electricity from the generator. Typically this is done through a 3-stage gearbox design (Fig. 2) with planetary gears offering a large gear ratio and a good load distribution.

The gearbox model includes gears, shafts, bearings and the housing. 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 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. An equivalent gear meshing stiffness is used, the force being derived based on a tooth meshing formula, idealized in that no local tooth to tooth contact is searched for. This results in 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 [1-3].

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 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 angle, 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.

A recent breakthrough for gear contact modeling has been realized by LMS Engineering Services to better account for the elastic deformation of the tooth under loading and for the micro-geometry correcting the ideal involute profile. In that state-of-the-art approach, a Finite Element static case is calculated once, applying unit loads on an existing mesh of the tooth in order to capture its material elasticity. The results of that case are stored and used by the analytical formulation. The micro-geometry - lead crown and involute crown – is too detailed to be included in that FE analysis and are therefore directly taken into account in the analytical formulation being used during the actual system level dynamic simulation.

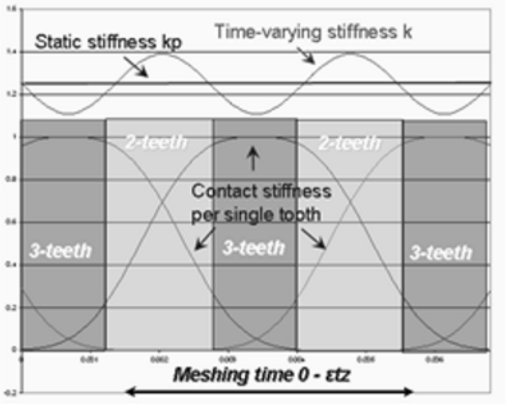

Fig. 3. a meshing stiffness variation with a 2.5 contact ratio.

This method allows for example to calculate the required lead or involute crown to be manufactured in order to compensate for existing misalignment of axis as small as a few thousands of a degree. The use of ideal involute profiles under axis misalignment would indeed cause high vibrations and excessive wear of the tooth that is unacceptable from the fatigue life point of view.

For the overall dynamic behavior of the gearbox, use is made of the gear contact force element. The sun gear is positioned between the three planet gears and is connected to the low speed shaft through a spline joint allowing small relative movement along and around its longitudinal axis. The low, intermediate and high speed shafts are supported by the housing through bearings whose behavior is globally depicted by 6dof's matrices with non-linear stiffness and damping coefficients. Once the gearbox virtual model has been constructed, input and output torques are modeled in order to capture its real-life dynamic behavior. The wind creates aerodynamic forces on the blades and the resulting torque is applied on the hub. On the other side of the gearbox, the generator generates a resisting torque depending on the actual speed of the high-speed shaft.

Using LMS Virtual.Lab Motion, a dynamic simulation is finally performed to visualize the behavior of the system trough graphs and animations. These enable engineers to compare several design variants through graphs and 3D animations and to select the most suited one. The so-called design tables provide an extremely easy and efficient way to parameterize the system. Each design table - a MS Excel or ASCII file - contains one line per parameter and one column per configuration, i.e. a set of parameters with a prescribed value (geometry of a component, material properties, dynamic properties, enabling/disabling of any element …).

The complete system is built from various subsystems (blades, gearbox, generator, nacelle, tower …) being easily assembled thanks to the submechanisms approach. In that approach, each submechanism is loaded from a separate file contained in a library and provided by the corresponding design department. The parameterization of the model and the sub-mechanism approach enable users to develop a new variant of a wind turbine from an existing model in very short time. The parameters of the new model can be further optimized to reach specific targets, e.g. in terms of minimizing the loads or stresses on critical components.

2.4 Validating 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. 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.

LMS Virtual.Lab Durability provides the batch capability to efficiently analyze the different load cases. Starting from the external loads, Virtual.Lab computes internal loads acting on the components such as the rotor hub (Fig. 4). A global load spectrum formulated from individual events is then used to simulate 20 years of use.

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.

2.5 Complying with noise regulations

Furthermore, 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 originates from mechanical and electrical equipment due to the rotation of components as the gearbox and the generator. These dynamic forces cause local surface vibrations, which distribute noise to the surrounding area through radiation (Fig. 5). 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 and provides the means to investigate noise transfer paths.

2.6 Energy management and yield optimization

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

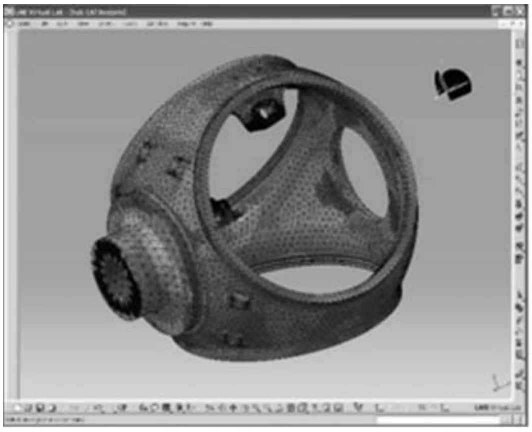

Fig. 4. fatigue on the hub loaded from blades and main shaft.

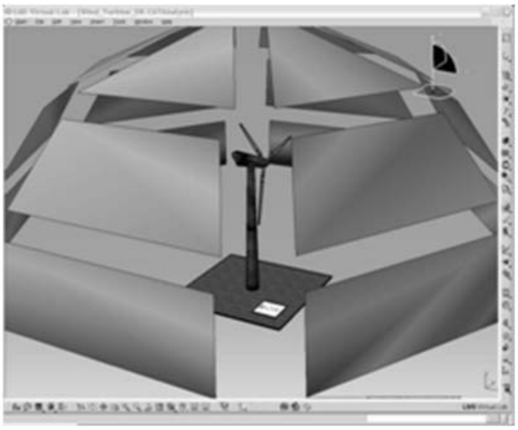

Fig. 5. gearbox noise radiated from a wind turbine.

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 asses 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. 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 efficiency of the wind turbine, which depends on a reduced speed parameter, is integrated in the model. When the wind speed is low, the turbine is not efficient. If the turbine rotates too fast, its efficiency is not optimal either. On top of efficiency issues, control systems for load reduction are more and more used in the industry as breaking components imply huge maintenance cost, especially for off-shore windturbines. The design of the 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.

3. Conclusions

The integrated simulation capabilities within LMS Virtual.Lab 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 gear 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 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, which 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.

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Guillaume Lethé received his Master's degree in Mechanical Engineering from the Université Catholique de Louvain-la-Neuve, Belgium, in 2005. He then received his Master's in Science of Management degree from the same University, in 2006. Ir. Guillaume Lethé is currently Manager at the LMS International Company, Belgium, for the Virtual.Lab Motion software for Multibody dynamic simulations. His research interests include mechatronic systems for on- and off-road vehicles as well as dynamic simulations of windturbine systems.