AERO-ELASTIC SIMULATION OF A WIND TURBINE AND DRIVE TRAIN RESONANCE ANALYSIS USING THE MULTI-BODY SIMULATION CODE SIMPACK

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Summary

In a close cooperation, the company Intec GmbH together with the Endowed Chair of Wind Energy at the University of Stuttgart are currently developing an add-on module for the non-linear multi body system (MBS) modelling software SIMPACK. This module extends the capability of SIMPACK for the simulation of wind turbines. This paper comprises a description of the parametric wind turbine model including a detailed parameterised drive train model, the coupling of SIMPACK and an aerodynamic rotor module, as well as results from the validation tests and a resonance analysis, in form of a Campbell diagram.

1. Introduction

The structural dynamics of wind turbines are presently simulated with special software codes, developed solely for this application. The majority of these simulation codes use a modal approach that considers only a rather limited number of natural modes, e.g. in most cases only one ore two modes are available for modelling the entire drive train dynamics. For detailed component analysis other programs have to be used, which are in general not coupled to the wind turbine simulation tools and are therefore not able to accurately capture the dynamics of the whole system. To overcome these shortcomings the non-linear multi body system (MBS) modelling software SIMPACK has been extended to perform detailed resonance analyses and full time domain aero-elastic simulations of wind turbines with an arbitrary number of degrees of freedom. The degrees of freedom can be adjusted according to the user's requirements, allowing rough but fast as well as more detailed but time consuming simulations.

2. Objectives

The aim of this project is to develop a software code that is capable of simulating wind turbine components in detail without neglecting the effects of couplings to other structural components and rotor aerodynamics. This is important especially for gearbox design studies, because most state-of-the-art wind turbine simulation codes are not capable to capture the correct loadings for gearbox design. It was a costly experience for wind turbine and gearbox industry that gearboxes cannot be designed without taking the wind turbine dynamics into account.

Since the non-linear multi body system (MBS) modelling software SIMPACK is able to capture the interactions between coupled bodies, the decision has been taken to use this code as a basis and extent it according to the objectives.

3. Wind Turbine Multi Body Model

3.1 Tower and Rotor Blades

As a first development step a simple multi-body model has been implemented in SIMPACK which reflects the structural dynamics comparable to a standard wind turbine simulation code. Fig. 1 shows the topology of this model.

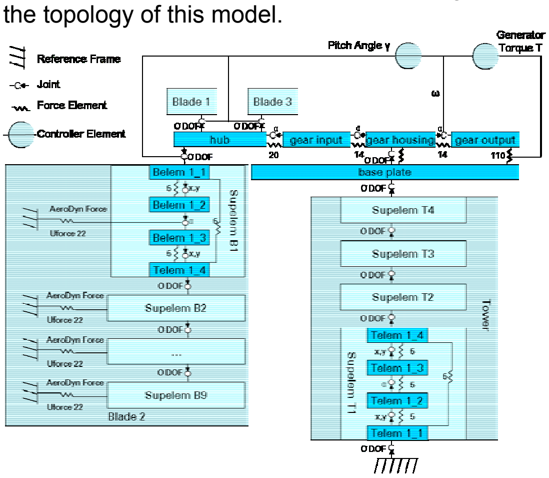


Fig. 1 Topology of Rotor and Tower Model

The multi-body model uses a stiff body approach. This means, that only stiff bodies are used in the model and component flexibility is modelled with flexible linkages between bodies. The theory used for this approach is called the super element approach and is described by Rauh [1]. Although SIMPACK has the capability to generate flexible beam structures and import flexible components from FE models, for the time being the blades and the tower are modelled with bending and torsional flexibility using the quoted approach.

The drive train flexibility is modelled very rough by only taking the fundamental torsional degree of freedom into account. Both, the low-speed and the high-speed shafts are designed flexible in torsion and the whole gearbox dynamics is combined in a gearbox model with a stiffness-damper element, including the gearbox ratio. For more detailed analysis the sophisticated gearbox model introduced in the next chapter can be used.

3.2 Gearbox Model

The detail of the virtual gearbox model should be chosen according to the phenomena under investigation. Too much detail leads to long simulation times and difficulties in interpreting the results, while too little detail will fail to include the desired effects. SIMPACK enables gearbox models with a large range of diversity and complexity to be easily interchanged to suit the current analyses [2].

In the simplest form, a gearbox model may include only one or two natural modes of rotation. Detail can be enhanced by including separate bodies for the input and output shafts and the gear box housing which may either be rigidly or freely mounted with appropriate force elements depicting the mounting bushings. Multiple variations can be easily generated by changing the degrees of freedom of the housing and detail of the support arm mounts, for example by including the non-linear and frequency dependent stiffness. A large range of detail for torque conversion also exists.

A library of kinematical converters exists from simple direct torque to torque conversion to planetary gear layouts. Other elements may be used to include the effects of gear wheel meshing with backlash, stiffness and damping. For highly detailed simulation a gear wheel force element, developed initially for Formula1 engine applications, may be used.

An analytical force element built to the DIN 3990 standard is used to build up complex drive trains. Helical gears both internal and external can be modelled. Backlash, dynamic separation distance, multiple tooth contact and material properties are all taken into account. Automatic graphical representation of the geometrical gear parameters enables easy visualisation and inspection (Fig. 2).

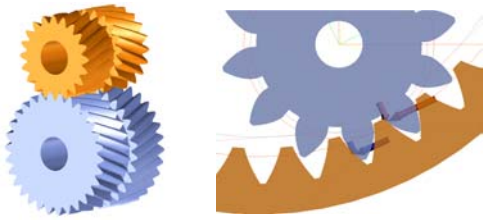


Fig. 2 Graphical representation of gear wheels

The non-linear jump phenomena in the frequency response according to G. W. Blankenship and A. Kahrman [3] is easily verified. Fig. 3 depicts the frequency curves of a gear pair for a constant run-up and run-down simulation.

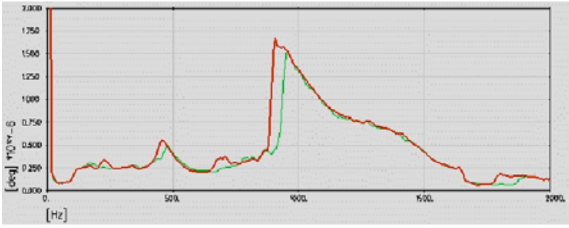
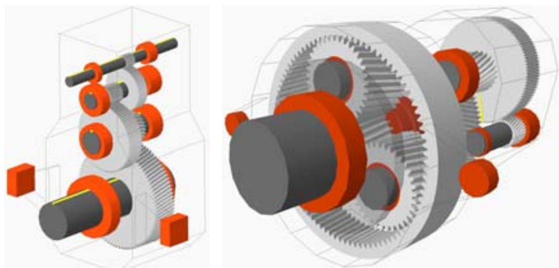


Fig. 3 Gear pair frequency sweep of a constant run-up and run-down simulation

The detail of the gearbox may be further enhanced by incorporating the flexibility of selected bodies. Structures comprising of straight beam elements, ideal for the shafts, are created directly in SIMPACK using an internal FE code. More complex flexible structures, such as the gearbox housing, may be imported from FEA programs.

Completely parameterised models of detailed gearboxes have been built up in SIMPACK. The separation of the parameters from the model enables easy access and modification of the data by non-SIMPACK users. Pre-defined batch jobs of analyses can then also be carried out with virtually no SIMPACK experience. The individual parameters within the files are clearly documented. The data origin is also documented and can be easily updated which facilitates project work. Variations of substructures, e.g. neglected axial and radial shaft DOFs, are easily generated.



Jahnel-Kestermann (used by Komai) SIMPACK Database

Fig. 4 Models of detailed gearboxes. Bearings and bushings highlighted in red.

Before a model is imported into a complete virtual wind turbine, model verification is carried out using virtual test rigs. Linear and non-linear analyses are used to inspect and validate input data. Resonance analyses, described in Chapter 5, can also be used.

4. Aerodynamic Rotor Module

One of the most important extensions to SIMPACK is the implementation of rotor aerodynamics and wind field generation. The aerodynamic module AeroDyn [4] developed by NREL is coupled to SIMPACK to include both the rotor aerodynamics and the wind field generation. The software code AeroDyn provides the calculation of aerodynamic forces on a wind turbine rotor when subjected to different wind conditions, while the non-linear wind turbine kinematics are calculated by SIMPACK. The wind fields are generated with an AeroDyn pre-processor [5] and can be deterministic or stochastic.

4.1 Theory of Aerodynamic Rotor Module

The software code AeroDyn provides a state-of-the-art blade-element-momentum approach (BEM) [6] with empirical corrections to calculate the rotor aerodynamics. These empirical corrections are needed to overcome the simplicity of the BEM theory which is based on the assumption uniform induction on radial annuli, steady 2D aerodynamics and for example neglects the interdependence of the airflows at adjacent radial blade sections.

The empirical corrections consider the losses caused by the airflow around the blade tip and at the rotor hub. The effect of turbulent-wake-state that occurs if the rotor strongly decelerates the axial airflow is also considered as well as unsteady airfoil aerodynamics and wake inertia or 3D-effects such as stall delay.
An alternative approach to the BEM method also available in AeroDyn is called the generalised-dynamic-wake-theory (GDW) [4]. This theory is used to take the significance of dynamic inflow into account.

AeroDyn is capable of generating a wind field with deterministic wind shear, tower shadow and yawed flow and a stochastic representation of the temporal and spatial structure of 3D atmospheric turbulence.

4.2 Coupling of Aerodynamic Module and SIMPACK

The aerodynamic module AeroDyn is coupled to SIMPACK by a newly developed interface. This interface controls the calculation of the aerodynamic forces in the AeroDyn module and the exchange of data. Fig. 5 shows a flowchart of the coupling.

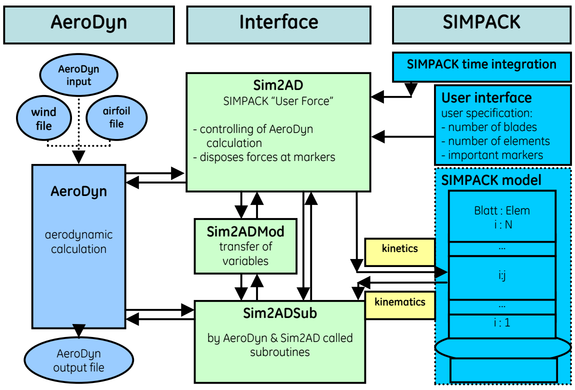


Fig. 5 Schematic illustration of the coupling

The module AeroDyn needs three input files. These files contain general calculation parameters, an airfoil dataset and wind field data. These input files are provided for AeroDyn without any participation of SIMPACK.

For the actual aero-elastic calculation of aerodynamic forces at the blade elements, the instantaneous kinematics of the blade elements has to be taken into account. For this reason the blade element kinematics is measured in the SIMPACK interface that controls the aerodynamic calculations performed in the software code AeroDyn. The interface provides the kinematics to the aerodynamic module. The loads, as calculated by AeroDyn, are then transferred back to the SIMPACK multi-body model and are applied at the structural rotor blade elements. The described coupling is partly based on the same concept as the link between another multi-body code and AeroDyn [7]. The complete coupling to AeroDyn including the module AeroDyn itself is accessible in SIMPACK as a so-called force element. This is an easy way for the consideration of rotor aerodynamics.

4.3 Results from Model Tests

The coupling between SIMPACK and the aerodynamic module AeroDyn has been tested against the commercial state-of-the-art wind turbine simulation code Bladed [8] to a preliminary extent. For this purpose a model of a typical variable speed, pitch controlled 1.5MW wind turbine is employed. As illustration Fig. 6 shows the power curve, calculated in SIMPACK and the reference power curve calculated under steady-state conditions.

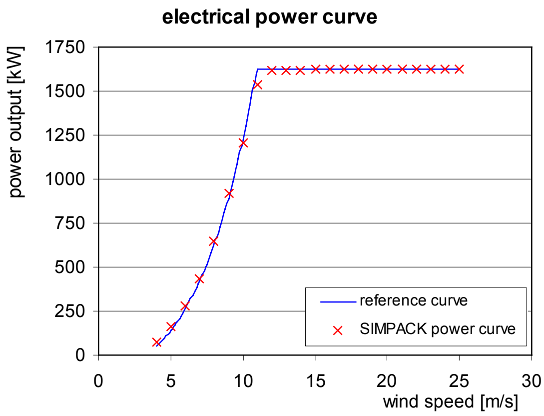


Fig. 6 Power curves from validation

The variation of the SIMPACK power curve from the reference curve is small in partial load. At full load the differences are even less. It is believed that the main reasons for the deviations are differences in the control algorithms in both programs as well as different empirical corrections for the blade element momentum theory.
The small power deviations appear due to differences in the definitions of blade elements, empirical BEM corrections and in pitch controller model in the two used simulation codes. Dynamic simulations with turbulent inflow demonstrate the numerical stability of the coupling of AeroDyn and SIMPACK and a correct representation of turbine dynamics. Further benchmark tests of dynamic load cases are currently under preparation. Based on the present validation exercises we can state that the SIMPACK coupling with the aerodynamic module appears to be reliable.

5. Resonance analysis

For a quick overview of possible excitations of undesirable vibrations, resonance analyses are carried out on the entire virtual wind turbine (Fig. 7). For the first step eigenfrequencies at various rotational speeds of the 'settled' system are plotted in a Campbell diagram to show the possible resonance frequencies of eigenmodes excited by the rotating shafts and meshing gears and higher orders thereof.

Before the eigenfrequencies can be calculated for a defined rotational speed the model must be brought into a state of quasi-static equilibrium. All transient states such as the gear wheel chatter must first be eliminated.
Initial rotational speeds of the shafts are easily set by making all initial rotational speeds dependent upon one shaft speed input, by means of parameterisation. A simple non-linear input function is used to model the reaction torque of the generator which is dependent upon the rotor's rotational speed. Knowing the reaction torque of the generator and the rotational speed of the main shaft enables the input torque on the system, exerted on the hub, to be automatically calculated and applied by means of a function expression.

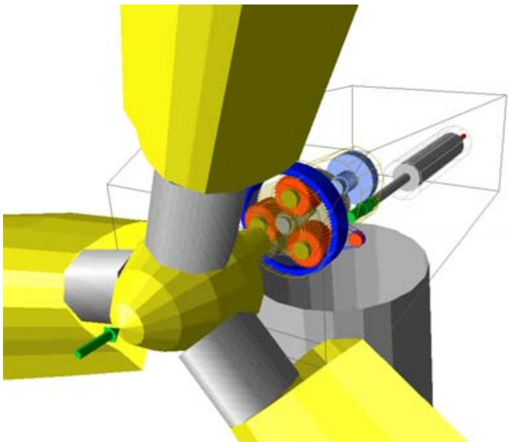


Fig. 7 Complete virtual wind turbine

For a given rotational speed a non-linear time integration is carried out until all transients have dissipated. The end states of the integration are copied to the linearisation state at which point an eigenfrequency analysis is performed. All frequencies are entered for the specified rotation speed and the process is repeated for a different speed. This process can be completely automated using batch commands and scripting. For initial design investigations of drive train dynamics the coupling of the rotor blades with the aerodynamic model is normally not considered.
Generally the rotor blades and main shaft all include flexibility for resonance analyses. Addition shafts and other components (e.g. tower, base plate and gearbox housing) may also be modelled as flexible if deemed necessary.

An indication of the magnitude of resonance can be acquired by carrying out order analyses. A run-up is

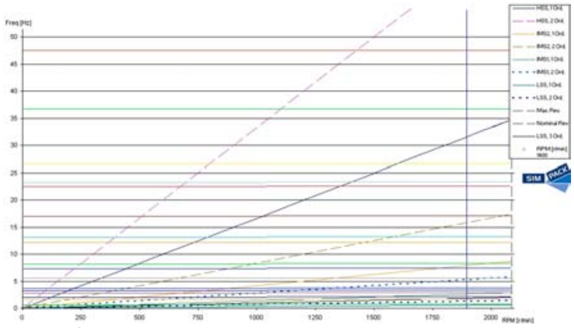


Fig. 8 Campbell Diagram

simulated in the time domain. The turbine is started at still stand and then driven through the complete range of velocities by increasing the torque applied at the hub. The order analysis can then be plotted for any output signal (e.g. force, acceleration, etc). All orders may be plotted together forming a Campbell diagram. Other excitations, in addition to the gear meshing, can be applied to the system (e.g. unbalanced shafts, square wave force signals, etc.) in order to excite various vibration modes.

6 Conclusions

With the new SIMPACK extensions it is possible to perform aero-elastic wind turbine simulations and detailed resonance analysis for all rotational speeds (Campbell diagrams) with adapted degrees of freedom. Among others parametric gearbox models, rotor aerodynamics and turbulent wind field input are offered. Further capabilities are under development.

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