

3D-Multi Body Simulation of Wind Turbines with Flexible Components

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Abstract:

A new method and an example of a 3-dimensional simulation of the dynamic behaviour of wind turbine generator systems (WTGS) is presented. The essential feature is a multi body simulation of a complete 3-D model of the wind turbine including flexible elements (for example rotor and tower). By reducing the analysis to standard methods in multi body simulations (MBS) and finite element methods (FEM) the simulation model avoids programming errors. Both, motion and forces at any point of interest within the turbine can be represented by 3D animation, graphs or result files for advanced analysis. The 3-D animation guarantees an easy check of the reliability. The calculated example takes into account the FEM structures of the entire rotor blades and the tower and their flexible properties. The inertia effects of all structural elements (rotor, drive train, gearbox and generator) are implemented. A pitch and yawing control as well as a characteristic torque of the generator are modelled. The induced wind velocities and the local interaction of airflow and vibrations of the blades and the tower are calculated. The developed 3-D simulation permits a safe realistic forecast of normal operation- and extreme loads. The paper is part of a project supported by the government department for education and research (BMBF) of the Federal Republic of Germany.

1. Object of 3D-Simulation

In present simulation programs different types of wind turbines, especially different foundations of off-shore facilities, are modelled either by rough simplification or by additional programming susceptible to faults. Using flexible FEM-structures (for example foundation, tower, blades) within the simulation gives a better approach to reality. Local strain concentrations at discontinuities (end of struts, ribs) are covered realistically. In dynamic simulations the flexible blades are substituted up to now only by beams. The detailed structure of the blades and the local interaction of airflow and vibrations of the blades are often neglected. Most of the present simulation programs for WTGS permit only a limited optical check of the used calculation model, expressive 3D-animations are missing. A 3D-multi body simulation of WTGS can solve these problems (Fig. 1).

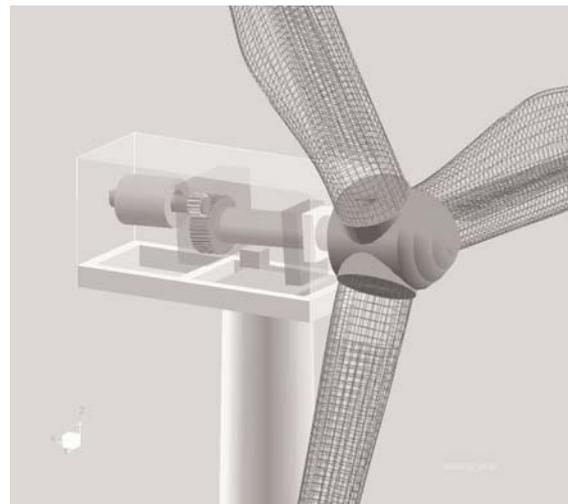


Fig. 1: Partial view of the wind turbine

It is not possible to model wind turbine generator systems using geometric based tools only. Aerodynamic loads must be calculated by additional programming. For that purpose undisturbed wind fields (IEC-61400-1 [11]) are processed from input data.

2. Flexible Components and Rigid Bodies

A flexible body in MBS is defined by a linear dynamic finite element model whose normal modes and static constraint modes have to be taken into account. Flexible properties are calculated by the finite element program ANSYS [10]. In order to build the multi body simulation model DADS [9] is used.

2.1 Multi body simulation, rigid bodies

A mechanism within a multi body simulation is described geometrically, the associated equations of motion are set up automatically and are solved in time domain. The results are represented graphically. A mechanism consists of (rigid) bodies, whose relative motions are restricted by constraints. Every body has a body fixed co-ordinate system. Its origin and orientation is described by independent generalised co-ordinates $\{\mathbf{k}\}$. The joints connecting the bodies are modelled by MBS standard elements. They define kinematic constraints in the following form:

$$\mathbf{Z}(\mathbf{k},t) = \begin{Bmatrix} z_1(\mathbf{k},t) \\ \vdots \\ z_h(\mathbf{k},t) \end{Bmatrix} = \mathbf{0}.$$

The program calculates the mass matrix \mathbf{M} , Jacobian $\mathbf{Z}_{,k}$, a term $\gamma(t,k,l)$ resulting from the constraints for k and uses the applied forces $\mathbf{Q}^A(t,k,l)$ and Lagrange multipliers λ for constraint forces in order to formulate the equations of dynamics

$$\begin{bmatrix} \mathbf{M} & \mathbf{Z}_{,k}^T \\ \mathbf{Z}_{,k} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{k}} \\ \ddot{\mathbf{e}} \end{Bmatrix} = \begin{Bmatrix} \mathbf{Q}^A \\ \gamma \end{Bmatrix}.$$

2.2 Flexible bodies, normal and constraint modes

In general all important flexible components of a WTGS are available as FEM models. The presented example of a blade [2] has been created parametrically. Local flexible displacements \mathbf{u} are combinations of fixed interface normal modes Φ_n and constraint modes Φ_c , which are determined within the FEM code. Normal modes (Fig.2) with fixed displacements at the interfaces are calculated from the eigenvalue problem

$$[-\omega^2 \cdot \mathbf{M} + \mathbf{K}] \Phi_n = \mathbf{0}.$$

Constraint modes Φ_c are static deformations with normalized displacements at nodes coupling to the rigid bodies. The modes have to be transformed, so that they are orthogonal and decouple the equations of motion [6]. Moreover rigid body modes have to be removed. Both is done in the multi body code. The modal coordinates $\mathbf{q}_n(t)$, $\mathbf{q}_c(t)$ define the local displacements of the flexible components where unchanged terms for the transformed modes were used.

$$\mathbf{u}(t) = [\Phi_n, \Phi_c] \begin{Bmatrix} \mathbf{q}_n(t) \\ \mathbf{q}_c(t) \end{Bmatrix},$$

2.3 Flexible bodies in a moving mechanism

The description of flexible bodies in MBS will be illustrated with the example of a beam (Fig. 3). The motion $\mathbf{x}_N(t)$ of a node N of the flexible beam is described by superposing its rigid body motion and flexible relative displacement \mathbf{u}_N represented by the modal coordinates \mathbf{q} . The rigid body motion of the node is expressed by generalised coordinates of position \mathbf{R} and orientation \mathbf{p} of the undeformed structure and the relative position \mathbf{r}_N in the body-fixed reference frame.



Fig. 2: Third normal mode of the blade

$$\mathbf{x}_N(t) = \mathbf{R}(t) + \mathbf{r}_N(t) + \mathbf{u}_N(t) = [\mathbf{I}; \mathbf{E}(\mathbf{r}_N); \mathbf{A} \cdot \Phi] \begin{Bmatrix} \mathbf{R}(t) \\ \mathbf{p}(t) \\ \mathbf{q}(t) \end{Bmatrix}$$

\mathbf{I} denotes the identity, $\mathbf{E}(\mathbf{r}_N)$ \mathbf{p} describes a rotation using Euler parameters \mathbf{p} and \mathbf{A} is a transformation to global co-ordinates.

The rigid-body and flexible-element motions influence each other according to the following equation of dynamics:

$$[\mathbf{M}] \begin{Bmatrix} \ddot{\mathbf{R}} \\ \ddot{\mathbf{p}} \\ \ddot{\mathbf{q}} \end{Bmatrix} = - \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{K}_{qq} \end{bmatrix} \begin{Bmatrix} \mathbf{R} \\ \mathbf{p} \\ \mathbf{q} \end{Bmatrix} + \mathbf{Q}^A - \mathbf{Z}_{,k}^T \cdot \lambda$$

3 Modelling Steps

The necessary steps to work out a simulation of a wind turbine under operating conditions are described in the following chapters.

3.1 Mechanical system

The blades and the tower have been built as parameterised finite element models. The fixed interface normal modes and the constraint modes are calculated by ANSYS. The finite element model and the computed modes are transferred via the interface implemented in the MBS code. The rigid components (hub, shaft, nacelle), their joints and connections are modelled with standard DADS elements. The aerodynamic coefficients are fed into the program and linked with the blade data.

3.2 Control and electrical system

The pitch control of the example is modelled by standard elements of DADS. It is also possible to create individual control algorithms with user defined subroutines. To simulate the electrical load of the wind turbine a file containing the generator characteristic curve is used as input to a standard control element.

3.3 Loads

The undisturbed turbulent wind field is computed in a separated program and has been made available for the MBS model. In an internal user defined subroutine the induced wind is calculated for each segment of the blade. The relative local wind speed takes into account the vibration of the tower and the blades. The forces calculated by the aerodynamic coefficients are transferred automatically to the corresponding finite element nodes and are used at the next time step. Thereby a direct aeroelastic coupling is coming about. The time step of the solver is automatically chosen by the program, the print interval is determined by the user.

An input file controls different load cases, e.g. normal operation, start up and shut down, gusts or operational conditions resulting from a failure.

4 Evaluation of Results

4.1 3D-animation, graphical evaluation

The dynamic behaviour can be displayed as animation. The view point can be any position in a local or global co-ordinate system. The viewer can move with any body of the wind turbine model. The reaction forces and moments at any position of the model are saved in a result file and can be used in further analysis.

4.2 Stress evaluation

Strain or stress in the flexible elements of the wind turbine are calculated by the orthogonalised deflection shapes used in the MBS formulation. The deflections are transferred back to ANSYS as static load cases. Additionally the time dependent modal co-ordinates are transferred to the FE-code and are used

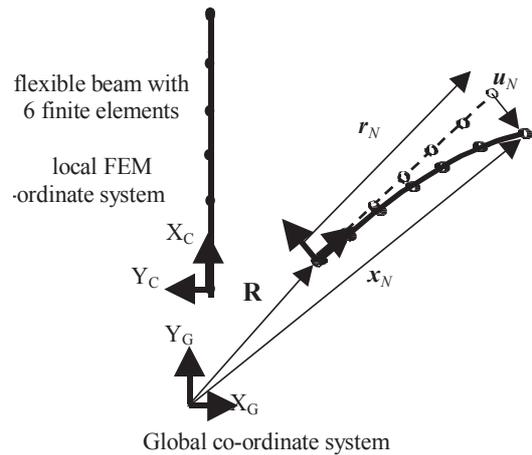


Fig. 3: Superposing rigid body motion and flexible relative displacements



Fig. 4: Snap-shot of the deflection; left side scaled by factor 25; right side scaled by factor 3

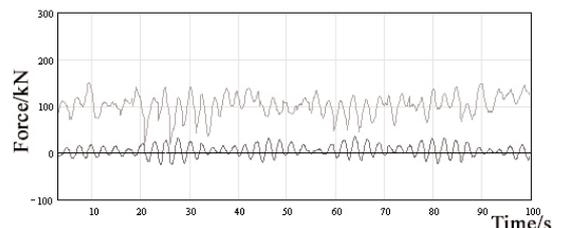


Fig. 5: Force components at the top of the tower

to superimpose the shapes describing the deflection of the finite element nodes. An ANSYS specific APDL program has been developed to calculate stresses and strains at arbitrary time steps. The resulting time histories can be used to analyse extreme loads and operational stability.

5 Summary

A new technique for analysing the dynamics and stresses of wind turbines is presented. The simulation is carried out with a complete 3-dimensional model of the wind turbine within a multi body simulation program using flexible elements. Models of different types of blades or towers need not to be simplified. Modelling is supported by optical checks. The analysis is reduced to standard methods in multi body simulations and finite element calculation. Strain concentrations at discontinuities within the flexible parts are covered realistically. The system's behaviour can be represented by 3D animation of the moving bodies. Forces or stresses (in the flexible parts) may be displayed at any point of interest within the turbine. The new method is to be extended to a software package for the simulation of wind turbines.



Fig. 6: Stress and deformation of a blade

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