State estimation in elastic mechanical structures under unknown excitation on the example of wind turbines

Summary of the doctoral thesis submitted by Johannes Luthe

The design of modern wind turbine structures is based on conservative load assumptions compared to the actual load conditions at the designated erection sites. As a consequence, structural reserves are very likely at the end of the turbines' approved life time. In the light of ecological and economical aspects, it is only reasonable to further exploit these reserves. To achieve this, it is necessary to record the actual load and strain history of the support structures during wind turbine operation by means of an adequate monitoring system. Traditionally, direct strain measurements are utilized as an intuitive sensor concept. As downsides, however, interesting points of high strain concentration are not necessarily accessible or directly suitable for strain gauge application. In addition, strain measurements tend to be associated with a high metrological and cost-intensive effort. In contrast to that, so-called *Inertial Measurement Units* (IMU), essentially a combination of accelerometers and gyroscopes, convince through their vibrational robustness and comparably low cost. Motivated by these considerations, the collaborative research project *DynAWind*^{2} (funding code 0325228E/F/G) was initiated in 2019 aiming to develop a fatigue monitoring system for a specific wind turbine based on a minimal network of inertial sensors. Emerging from investigations within the named research project, the present thesis introduces a thorough and consistent framework for model-based estimation of elastic deformations in wind turbine support structures which is solely based on IMU measurements. The analyses presented are in fact driven by but not restricted to wind turbine systems, since fundamental aspects similarly apply to general elastic mechanical structures.

In contrast to existing strain-based fatigue estimation schemes, the IMU-based sensor concept requires thorough and careful signal processing to extract information on the structural deformation fields. As a central idea of the developed framework, the wind turbine support structure is divided into individual mechanical substructures for the tower and the rotor blades. Recovery of deformation fields is then performed for each subsystem independently by means of a classical state observer scheme which requires a suitable mathematical model of the substructure under consideration. A model representation is regarded suitable in this context if it is able to represent the structural dynamics of the relevant wind turbine components and provide consistent stress and strain recovery. Therefore, the promising *Nodal-based Floating Frame of Reference* (NFFR) formulation is pursued and analyzed in detail within this thesis, as it allows to derive the corresponding *Equations Of Motion* (EOM) for each substructure based on standard data provided by every commercial finite element software environment. As an important advantage for the state observer design, it is shown that the generally nonlinear rotor motion of the wind turbine can be considered in terms of a rheonomic constraint, finally yielding EOM that are in fact linear w.r.t. to the sought elastic deformation coordinates. The rheonomic constraint, however, causes time-dependent coefficient matrices in the equations of motion, whose impact on the dynamic behavior is analyzed in detail.

A further important challenge in the state observation process is the existence of unknown and also immeasurable system excitation by turbulence and wind gusts. Instead of designing a state observer directly based on the derived substructure EOM, the principle of modal decomposition is employed. This idea allows to formulate a set of kinematic differential equations that express the substructure dynamics in terms of reduced, generalized coordinates. As a major benefit, these equations do not contain any unknown excitation quantities. Yet, an appropriate set of reduction modes is necessary to reproduce the dynamic behavior with sufficient accuracy. Apart from this, the measured inertial accelerations and angular velocities provided by IMU sensors need to be mapped to the underlying mathematical model for each substructure. For this reason, extensive mapping relations are derived in the context of this thesis.

Under ideal conditions, the developed sensor-model mapping equations may be directly solved for the sought set of reduced generalized coordinates by applying numerical integration schemes. However, unaided time integration is not feasible in practice due to numerous unknown influencing factors. These include discretization errors of the numerical integration process and unknown initial conditions. Apart from that, sensor measurements are typically contaminated by bias and noise effects. In this context, the concept of integrated motion measurement is adopted as a stabilizing framework that is capable of tolerating these imperfections to some degree. Different numerical and experimental case studies ultimately confirm the high performance of the entire process chain and point out specific limiting factors that may degrade the estimation quality in practical applications.

In summary, this thesis successfully provides a hollistic framework for state estimation and deformation recovery in elastic mechanical structures under unknown excitation. In addition, the general proof of concept for the entire process chain is vividly demonstrated in relevant numerical as well as experimental case studies. Overall, these results are considered a significant milestone towards the economical application in terms of a versatile and cost-effective fatigue monitoring system.