Wind Turbine Rotors with Active Vibration Control
This thesis presents a framework for structural modeling, analysis and active vibration damping of rotating wind turbine blades and rotors. A structural rotor model is developed in terms of finite beam elements in a rotating frame of reference. The element comprises a representation of general, varying cross-section properties and assumes small cross-section displacements and rotations, by which the associated elastic stiffness and inertial terms are linear. The formulation consistently describes all inertial terms, including centrifugal softening and gyroscopic forces. Aerodynamic lift forces are assumed to be proportional to the relative inflow angle, which also gives a linear form with equivalent stiffness and damping terms. Geometric stiffness effects including the important stiffening from tensile axial stresses in equilibrium with centrifugal forces are included via an initial stress formulation. The element provides an accurate representation of the eigenfrequencies and whirling modes of the gyroscopic system, and identifies lightly damped edge-wise modes. By adoption of a method for active, collocated resonant vibration of multi-degree-of-freedom systems it is demonstrated that the basic modes of a wind turbine blade can be effectively addressed by an in-blade ‘active strut’ actuator mechanism. The importance of accounting for background mode flexibility is demonstrated. Also, it is shown that it is generally possible to address multiple beam modes with multiple controllers, given that these are geometrically well separated. For active vibration control in three-bladed wind turbine rotors the present work presents a resonance-based method for groups of one collective and two whirling modes. The controller is based on the existing resonant format and introduces a dual system targeting the collective mode and the combined whirling modes respectively, via a shared set of collocated sensor/actuator pairs. The collective mode controller is decoupled from the whirling mode controller by an exact linear filter, which is identified from the fundamental dynamics of the gyroscopic system. As in the method for non-rotating systems, an explicit procedure for optimal calibration of the controller gains is established. The control system is applied to an 86m wind turbine rotor by means of active strut actuator mechanisms. The prescribed additional damping ratios are reproduced almost identically in the targeted modes and the observed spill-over to other modes is very limited and generally stabilizing. It is shown that physical controller positioning for reduced background noise is important to the calibration. By simulation of the rotor response to both simple initial conditions and a stochastic wind load it is demonstrated that the amplitudes of the targeted modes are effectively reduced, while leaving the remaining modes virtually unaffected.