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AEROELASTIC STABILITY ANALYSIS OF WIND TURBINES CONSIDERING THE INSTABILITIES KNOWN FROM ROTARY WING DYNAMICS

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Abstract: Stability analysis of wind turbine is increasingly becoming a design critical subject in the wind energy industry. For small wind turbines with low rated power no aeroelastic instability was observed or registered but this had an end with increasing the size of the wind turbines to produce more electric power. The work presented in this paper consists of three parts. The first part describes the mechanism of some of well-known instabilities in the rotor dynamics e.g. blade flutter, rotor whirl-flutter and the instability due to the coupling of the rotor modes with the modes of the non-rotating structure. The possibilities of formation of these instabilities for a wind turbine are discussed. Furthermore, some wind turbine specific instabilities documented in the various literatures, e.g. blade edgewise instabilities (in and outside stall area), are as well highlighted. The second part introduces a stability analysis tool for rotating systems, MAESTRoS (MesH AeroElastic Stability analysis Tool for the Rotating Systems), which has been developed by the author and can be applied for the stability analysis of wind turbines. This tool makes use of the methods known from helicopter dynamics and aeroelasticity (e.g. application of multiblade coordinate system and Floquet theory). In the final part, the selected methodology of simulation of structure and control system and calculation of aerodynamic loads for the aeroelastic stability of a wind turbine is discussed. In the scope of this methodology, a wind turbine model is created in a multidisciplinary simulation environment using MBS-tool SIMPACK and SIMULINK. Aerodynamic loads are calculated using AeroDyn v13/ v15. For the (aero)-elastic stability analysis, a generic multi-megawatt wind turbine has been considered. On this paper, the emphasis is placed on prediction of rotor-tower coupling instability, an instability mechanism that can be related to the ground resonance phenomenon on helicopters. Demonstratively, the generic wind turbine has been scaled up (using the scale factor 2) applying the wind turbine similarity rule. Rotor-tower coupling instability of the scaled wind turbine was investigated and compared with the reference wind turbine (scale factor 1) results.
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1 INTRODUCTION

Stability analysis of wind turbine is increasingly becoming a design significant subject in the wind energy industry. For small wind turbines with low rated power no aeroelastic instability was observed or registered but this had an end with increasing the size of the wind turbines to produce more electric power [1]. The Observation of strong vibrations associated to aeroelastic instabilities on some of the commercial and research wind turbines has drawn the attention of wind turbine engineers to this field. By considering the aeroelastic similarity rules, one might be able to identify and prevent some of the known aeroelastic instabilities based on the stability analysis results available for the reference wind turbine. But for a new wind turbine design with innovative changes (e.g. aerodynamically modification of the structure) reliable stability analysis approaches are sought allowing to predict the stability of the wind turbine at: different operating points, parked (idling) and worst scenario conditions. In the next parts rotary wing aeroelasticity in general and aeroelasticity of wind turbines are briefly discussed.

1.1 Rotary wing aeroelasticity

Science of aeroelasticity in aerospace engineering, due to the earlier encounter of aircrafts and helicopters with instability problems, had an enormous progress. Mechanism of different aeroelastic instabilities, e.g. aircraft wing classical flutter, rotor/turboprop whirl-flutter and helicopter air and ground resonance, have been studied intensively and fully described for helicopter and aircraft applications. Criteria for the occurrence of some instabilities, e.g. correlation between reduced frequencies and occurrence of classical wing bending-torsion flutter, were defined by researchers and engineers. Different methods of analysis for the stability prediction of helicopters as a time periodic system are available [2]. Transfer of this knowledge and methods in order to predict the occurrence of the well-known aeroelastic instabilities for a wind turbine is an important step before studying and investigating any wind turbine specific aeroelastic problem.

For a helicopter, blade flap-wise instability, classical stall flutter (instability of pitch/torsion mode), classical flutter (torsion-flap modes coupling), pitch-lag and flap-lag instability (for both hingeless and articulated rotors at high trust or pitch angle), pitch-flap-lag instability, pitch-flap instability (rotor weaving, for helicopters with two bladed teetering rotor), torsion-lag flutter (articulated rotor, stall induced vibration), unsymmetrical rotor instability (rotor with anisotropic inertias and/or stiffness), rotor whirl flutter, helicopter ground resonance and air resonance are some known instabilities. Helicopter rotor wake/vortex in interaction with main rotor blades or tail rotor structure might induces strong vibration (e.g. helicopter tail shake phenomenon). In General, based on a selected criterium, known instabilities can be listed in the different groups. For example, based on the number of the involved modes in the instability mechanism, one can consider one-dimensional (e.g. stall flutter), two-dimensional (e.g. classical flutter) and multi-dimensional (e.g. pitch-flap-lag) instabilities. Other criteria could be involved components of the system structure (e.g. isolated blade for the blade flutter or rotor and rotor support for the whirl-flutter), linearity or non-linearity of unsteady aerodynamics (e.g. stall induced instability are characterized with non-linearity of unsteady aerodynamics), motion or wake/vortex induced vibration (e.g. aeroelastic buffeting as wake/vortex induced vibration). Mechanism and simulation requirements of the above-named instabilities can be found in different technical books and literatures [2-4]. Being aware of this information helps from one side to simplify the model required to predict a specific instability and from other side helps to identify easier the type of occurring instability. Mechanism of some of the selected rotor instabilities, which can occur for a wind turbine is discussed in the next part.

2 INSTABILITY MECHANISM OF WIND TURBINE

Stability of a system describes the response of the system after a disturbance from its equilibrium. Static/dynamic instability (e.g. wing divergence/flutter) describes the case, in which the system does not return to the equilibrium. Instabilities discussed here are dynamic instability, by which the system response includes oscillation with increasing amplitude. It is important to distinguish between self-excited and externally excited vibration (e.g. resonance). Instabilities discussed here are self-excited Instability. Classical aeroelastic stability analysis considers the interaction between aerodynamic, elastic and inertial loads (introduced by Collar's Triangle of Forces [5]). Wind turbine control system in interaction with structure motion and motion induced aerodynamic loads might also cause an instability (has been shown schematically on Fig. 1). An example of this instability is a control system induced instability including the tower fore-aft and blade pitch angle motion, which will be described in next part. For the stability analysis of a wind turbine, depending on the type of the wind turbine (onshore or offshore) and type of generator control system, additional forces (e.g. electrical and hydrodynamic forces) should also be considered.

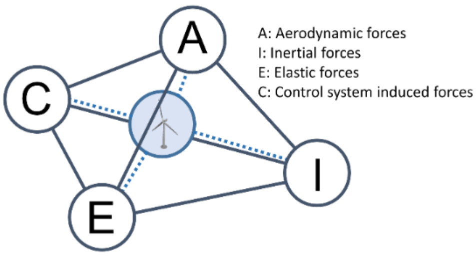

Figure 1: Aero(-servo)-elasticity of wind turbines and interaction of forces

Instabilities can lead to a rapid destructive failure of the structure or due to the existence of non-linearities (e.g. by stall flutter) to limit-cycle oscillation causing structural fatigue. Therefore, in design stage of a wind turbine, it is very important to identify all possible instabilities, which might occur for the wind turbine and try to prevent them with design modification (e.g. structural mode decoupling, selection of material with higher structural damping, movement of the position of the blade section center of gravity towards blade leading edge, especially in outboard area of the rotor blade) or application of any active or passive instability suppression methods (e.g. adding the structural damping with usage of local damper, application of vortex generators to delay the stall). In general, type of instabilities, which can occur for a wind turbine depends on the type of wind turbine (e.g. onshore or offshore), type of the main control (e.g. stall regulated, or pitch regulated with variable speed), wind turbine condition (e.g. operating or parked/idling condition). In the next parts rotor blade instabilities, instabilities due to the interaction between rotor and other components (e.g. rotor support or tower), control system induced vibration/instability, rotor/tower wake/vortex induced vibration and parametric instability are discussed [1,6-8].

2.1 Rotor blade instabilities

Wind turbine rotors comparing to the known helicopter rotor types (articulated, bearingless and hingeless rotors) are like helicopter hingeless rotor. Differences arises from blade geometry, blade eigenfrequency and airfoil aerodynamic properties. It is advisable to study the different types of rotor blades instability for the different types of the rotor. In general rotor blade instabilities can be divided into two main groups (shown on Fig. 2). First group deals with the one-dimensional instabilities, by which due to the vibration induced aerodynamic forces one of the blade modes becomes unstable. For a wind turbine blade, this instability can be in edgewise, flapwise or in torsion direction. Mechanism of these instabilities are described below. Second group includes instabilities with two or multi modes involvement. During coupling of the modes, an unfavorable phase angle between the modes could cause the transfer of energy from the air to the blades and cause the increasement of the vibration amplitude and instability or when the motion in one direction induces aerodynamic force, which is in phase with vibration velocity in other direction, causing negative damping. Mechanism of this type of instability is also described below.

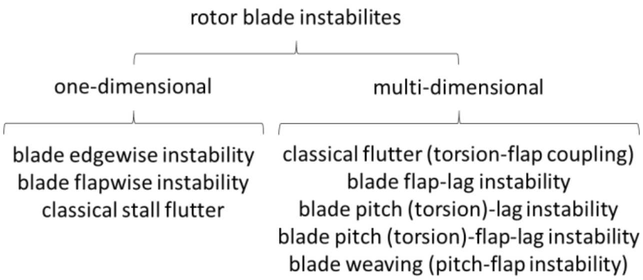

Figure 2: Possible rotor blade instabilities

2.1.1 Blade one dimensional aeroelastic instability

For a moving blade in air, any disturbance from its equilibrium state induces further aerodynamic loads (motion induced aerodynamic forces and moments), which affects the overall system damping towards higher positive value (stabilizing effect), lower positive value (destabilizing effect) or negative value (instability). Mechanism of blade one dimensional aeroelastic instability can be described easier with considering the motion of blade section as shown on Fig. 3.

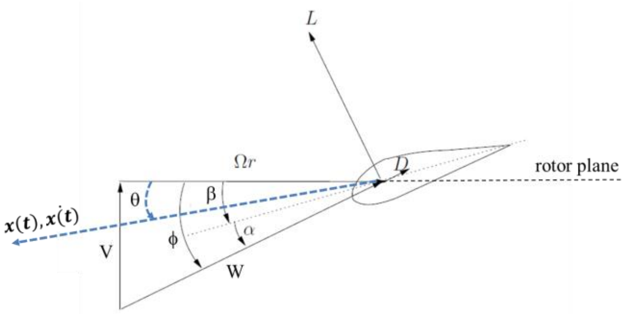

Figure 3: Rotor blade section with vibration in x direction

Vibration of this rotor blade section in “x” direction, shown on Fig. 3, induces additional wind velocity in this direction. With this induced velocity changes the total relative wind velocity “W” and effective angle of attack “α”. If we calculate the total aerodynamic forces along the “x” direction and linearize this force (considering a small deviation from equilibrium) we get the aerodynamic force along “x” as a function of vibration velocity $\dot{x}(t)$ as given by the following equation [1]:

$$F_x = F_0 - \eta\dot{x} \tag{1}$$

with

$$\eta = \frac{1}{2}\rho c W[c_d(3+\cos(2\theta-2\phi)) + c_{l\alpha}(1-\cos(2\theta-2\phi)) + (c_l + c_{d\alpha})\sin(2\theta-2\phi)] \tag{2}$$

According to the Eq. 1, a positive value of η affect against the vibration and has stabilizing effect and a negative value increases the vibration amplitude and has a destabilizing effect. This equation also shows that, the motion/vibration induced aerodynamic force is directly proportional to the total wind and vibration velocities. From Eq. 2, one can see that, negative $c_{l\alpha}$ (in stall area) leads to the reduction of aerodynamic damping. Special cases of blade vibrations are the vibrations in rotor plane and out of rotor plane. For the blade vibration in the rotor plane $(\theta = 0)$, blade lead-lag motion, Eq. 2 is simplified to:

$$\eta = \frac{1}{2}\rho c W[c_d(3+\cos(2\phi)) + c_{l\alpha}(1-\cos(2\phi)) - (c_l + c_{d\alpha})\sin(2\phi)] \quad (3)$$

The first term of this equation shows that, airfoil damping has an obvious stabilizing effect. The second term will be positive and have a stabilizing effect when the blade section is not in stall area ($c_{l\alpha} > 0$). The third element shows, increasing the lift has a destabilizing effect.
For the blade out of rotor plane vibration ($\theta = \pi/2$), blade flap motion, Eq. 2 is simplified to:

$$\eta = \frac{1}{2}\rho c W[c_d(3-\cos(2\phi)) + c_{l\alpha}(1+\cos(2\phi)) + (c_l + c_{d\alpha})\sin(2\phi)] \quad (4)$$

This equation shows that, blade flapping motion for the case $c_{l\alpha} > 0$ is always stable, because all the three terms of the aerodynamic damping are positive. Flap motion in stall area can become unstable depending on the airfoil aerodynamic characteristics.

Another blade one-dimensional instability is the classical stall flutter. By this instability, blade torsion mode motion becomes unstable [9]. As its name says, this instability occurs in the stall area and considered as a stall induced instability. In the stall area, increasing of blade angle of attack due to a disturbance (e.g. cause by gust) causes the reduction of lift that in turn causes the reduction of angle of attack. Reduction of angle of attack causes increasing of the lift and respectively increasing of the blade torsional deformation which leads to the increasing of angle of attack. Depending to the wind velocity (proportional to the available energy) and blade torsional stiffness the described loop can become unstable. Blade instability in stall area is a non-linear instability. Dynamic response of the blade is characterized as limit cyclic oscillation (LCO). This instability starts with exponentially increasing the vibration amplitude and is bounded to a constant value. If the resulted structure loads don't exceed the maximum permitted static loads, then the structure might encounter a fatigue failure. For a correct prediction of classical stall flutter and LCO, considering a high-precision unsteady aerodynamic model including the dynamic stall effect is very significant.

As described above, depending on the direction of blade vibration, wind turbine operating point (e.g. near stall) and aerodynamic characteristic of the blade airfoil, vibration induced aerodynamic loads could result in a negative damping. Frequency of this vibration is not an instability influence factor. Modification of airfoil aerodynamic characteristics or selecting different airfoil could be one solution to prevent the instability. From structure side, stiffening the structure or increasing the structural damping helps to prevent the instability. In general, aerodynamic damping for the vibration in rotor plane is lower than the vibration in out of rotor plane vibration. Coupling of these two modes using aeroelastic tailoring lets to use the aerodynamic damping in flap direction for stabilizing the vibration in lead-lag direction. However, this coupling might lead to another type of instability which is described in next part.

2.1.2 Blade multi-dimensional instabilities

This group includes blade instabilities involving two or more blade modes. Interaction between the involved modes at the instability condition is in a way that, energy from air stream can be transferred to the structure and causes the rapidly increasing (exponentially) the vibration amplitude. Following instabilities are considered as rotor blade known multi-dimensional instabilities: classical flutter (involving the torsion-flap modes), blade flap-lag instability, blade pitch (torsion)-lag instability, blade pitch (torsion)-flap-lag instability, blade weaving (pitch-flap instability). With increasing the size of the rotor by multi-megawatt wind turbines, safety margin between classical flutter speed and rotor operating speed are reduced. This shows, for a new designed multi-megawatt wind turbine, occurrence of classical flutter in operating point and extreme conditions should be checked. Pitch regulated turbines with long slender blades are more likely to experience this instability. In this part among the above-named instabilities, the classical flutter is selected, and the mechanism of this instability is discussed. Blade classical flutter is a self-excited dynamic instability. This instability occurs, when blade modes (e.g. first torsion and first or second flap mode) are coupled and rotor speed is high enough to reduce the net damping (sum of the structural and aerodynamic damping) of the coupled modes to a negative value. For the development of the classical flutter, the phase angle between flap mode and torsion mode is very significant parameter. If the flapping and torsional motion are in phase, then the energy balance during one period of structure oscillation will be zero. For the case where the torsion mode is 90 deg in advance relative to the flap mode the energy balance becomes subsequently positive. That means the structure gets energy from air stream and this leads to the reduction of net damping and respectively the augmentation of vibration amplitude. Classical flutter happens above a certain relative speed on the blade. The possibility of occurrence of this instability increases, when the frequency ratio between flapwise bending and torsional modes is sufficiently low. Preconditions for this instability are: attached flow, which means the increase of the effective angle of attack leads to increase of the lift, high blade tip speed ratio and specific range for reduced frequencies. For a fixed wing, empirically determined, the classical flutter for the reduced frequency (with half of the chord length as reference length) above $\kappa \approx 1$ cannot occur [10]. For the fixed wing the reduced frequency is calculated with Eq.

$$k = \frac{\omega l_{ref}}{V_\infty} \tag{5}$$

For the rotary wings the reduced frequency is normally calculated at 75% radius, as given by the following equation:

$$k = \frac{\omega \frac{c}{2}}{0.75R\Omega} \tag{6}$$

Extent of the aerodynamic unsteadiness can be also assessed with the value of the reduced frequency [11]. Blade classical flutter typically occurs at the reduced frequencies, by which the unsteadiness of the aerodynamic is not neglectable, if the accuracy of the flutter speed prediction is important. Generally, in most cases the quasi-steady aerodynamics leads to a conservative prediction. For a rotating blade, stiffening effect (increasing of the blade flap mode eigenfrequencies with increasing the rotor rotational speed) due to the centrifugal force, ,torsional stiffening of the blade due to the propeller moment and finally gyroscopic effect changes the classical flutter and static divergence boundaries known for a fixed wing (non-rotating blade).

To prevent the classical flutter an uncoupling the torsion and flap motion is fundamental. Chordwise offsets of aerodynamic and mass centers relative to shear (elastic) center, one can control the coupling between flap and torsion motion and respectively control the occurrence of the instability. Movement of the blade section center of gravity towards the leading edge, special at outboard part of the blade, has a stabilizing effect. High torsional stiffness, high difference between torsion and flap mode frequencies and higher values for stiffness to mass ratio increase the safety margins. Airfoil modification is another way to affect the instability margin. There are also active damping methods (e.g. application of trailing edge flaps) to suppress the flutter.

In conjunction with the classical flutter, it has been shown for a swept wing airplane that a backward swept wing (upwards bending pitches down the wing) is less stable than forwards swept wing. Such a similar behavior has been also observed for a rotor blade with aeroelastic tailoring (structural coupling of flap-torsion for the last reduction): blade with positive coupling

ratio (ratio between bending and torsion deformations) is more stable than negative coupling ratio [12].
For a correct prediction of instability margin or determination of flutter speed consideration of blade deformation in equilibrium is very significant [13]. For the flatter analysis, we need to calculate the motion induced aerodynamic loads after a disturbance and these loads are dependent to the shape of the blade modes. Rotor blade instabilities can be calculated in simplest form by an isolated rotating blade, however from an accuracy standpoint, considering the coupling of blade modes through hub is important.

2.2 Instabilities due to the interaction between rotor and other components

Due to the interaction between rotating rotor and other rotating or non-rotating wind turbine components (e.g. rotor shaft, rotor support, drive train, nacelle, tower and platform for offshore wind turbines) different types of aeroelastic instability could occur. Some of the known rotary wing instabilities which belong to this group are: unsymmetrical rotor instability, helicopter ground resonance [14,15], helicopter air resonance and whirl-flutter [16,17]. Unsymmetrical rotor instability is a simple form of rotor instability (mechanical instability, aerodynamic can be neglected) which can occur for a rotor with anisotropic inertias and/or stiffnesses. One important point for this instability is that, due to the anisotropy of the rotor, the stability analysis method using multiblade coordinate transformation, as described later in this paper, is not valid. For a wind turbine additionally an instability or strong vibration of drivetrain torsion mode could be an issue. Here the following certain type of type of wind turbine instabilities classified in this group are discussed:

- whirl-flutter
- rotor-tower coupling instability
- drivetrain torsion mode vibration/instability

2.2.1 Whirl-flutter

Whirl flutter is an aeromechanical instability occurring in a flexibly mounted propeller-nacelle or rotor [16,17]. Considering a rotating rotor or propeller with an axial air stream, tilting or yawing movement of rotor (axis of rotation) induces aerodynamic moments and forces at the rotor or propeller hub. The induced aerodynamic loads, depending on the properties of the structure including stiffness and structural damping, can cause an instability which is called whirl-flutter. By this instability rotor hub starts to whirl around rotor axis with increasing amplitude. The whirl motion can be in direction of rotor rotation, the so-called forward whirl, or against the direction of rotor rotation, the so-called backward whirl. To understand the mechanism of this instability we consider a simplified whirl flutter model. This includes the rotor and rotor support system shown on Fig. 4.

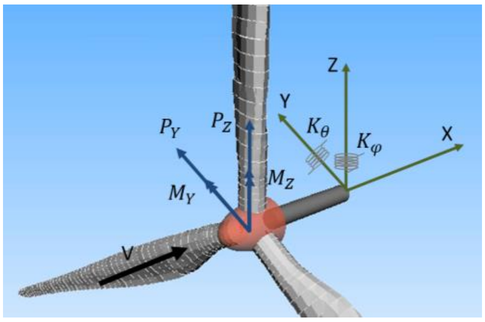

Figure 4: Simplified model of wind turbine rotor for the whirl flutter analysis

In this model the rotor is supported horizontally by a rigid shaft that is pivoted at the end to the remained structure. The stiffnesses (rotational springs) at the pivoted point defines the elasticity of the rotor support. The whole system can tilt or yaw at the pivot point. In General, there are two possibilities for the location of pivoted point: It is located on a rotating component or on a non-rotating component. Depending on this location, the dynamic equations of motion of the system can become time-periodic or time-invariant. The dynamic equations of motion of this system are given by following equations:

$$I_Z\ddot{\varphi} + C_\varphi\dot{\varphi} + K_\varphi\varphi + I_X\Omega\dot{\theta} = \sum M_\varphi = M_Z - h \cdot P_Y \tag{7}$$

$$I_Y\ddot{\theta} + C_\theta\dot{\theta} + K_\theta\theta - I_X\Omega\dot{\varphi} = \sum M_\theta = M_Y + h \cdot P_Z \tag{8}$$

Here, "h" is the distance between the propeller and the pivot point. In these equations on the left side, the first term is a moment due to the inertia, the second term introduces the structural damping, the third term is a structural moment due to the elastic deformation of the system and finally the last term gives the gyroscopic moment. Due to the gyroscopic moment, when the rotor rotational speed is non-zero, tilt motion and yaw motion are coupled. On the right side of the Eq. 7 and Eq. 8, motion induced aerodynamic moments are considered. Considering a small deviation from equilibrium, motion induced aerodynamic moments can be defined as sum of linear aerodynamic stiffness moment (proportional to the tilt and yaw angles) and linear aerodynamic damping moment (proportional to the tilt and yaw angle rates) as given by the following equation:

$$\begin{bmatrix} M_Z \\ M_Y \end{bmatrix} = \begin{bmatrix} 0 & -K_{aero} \\ +K_{aero} & 0 \end{bmatrix} \begin{bmatrix} \varphi \\ \theta \end{bmatrix} + \begin{bmatrix} -C_{aero} & 0 \\ 0 & -C_{aero} \end{bmatrix} \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \end{bmatrix} \tag{9}$$

To understand this equation, it is easier to consider each state $(\varphi, \theta, \dot{\varphi}, \dot{\theta})$ isolated and separately. For instance, considering a positive yawing of the rotor, one can see the blade effective angle of attack on the upper part of the rotor plane increases and on the lower part decreases. This generates a positive moment M_Y. Eq. 9 shows three important points:

- aerodynamic stiffness matrix couples the pitch and yaw modes (aerodynamic coupling in comparison to the gyroscopic coupling).
- aerodynamic stiffness matrix is an antimetric matrix, which can cause an instability of the system and is a driving factor for the whirl-flutter instability
- aerodynamic damping matrix effects stabilizing

For the calculation of motion induced aerodynamic moments, quasi-steady aerodynamic model is enough for a conservative prediction. For a wind turbine with elastic blades, forces P_Y and P_Z in Eq. 7 and Eq. 8 can have their origin also from blade deformation and blade-hub coupling (will be described in next part). This means, the flexibility of the blades should be included in the formulation of whirl-flutter mechanism [18]. A critical condition happens, when blade lead-lag frequency is close to one of the rotor tilt-yaw frequencies. For a wind turbine system, the eigenmodes with lowest frequencies and involving the rotor tilt and yaw motion are normally tower first torsion, second and third fore-aft bending mode. Considering these eigenfrequencies, one can calculate the location of pivot point and torsional stiffnesses of the simplified whirl-flutter model shown on the Fig. 4. Simplified model has the advantage of possibility of easily parametric studying. With solving the Eq. 7 and Eq. 8 considering an initial condition, one can determines the whirl mode stability of the system.

For a propeller-nacelle-system, when the flexibility of the blades is neglected, the backward whirl-mode is often the unstable one, when the whirl flutter occurs, however, when the flexibilities increases, an instability in the forward mode is possible. Whirl-flutter is strongly dependent on stiffness and damping of the rotor support and rotor tip speed ratio (for helicopters or propellers: advance ratio). Most critical state is reached, when the stiffness of the rotor support in tilt and yaw directions are equal (isotropic support). Polar inertia of the rotor is another system parameter, which has effect on whirl-flutter stability characteristics. Distance between the rotor hub and the pivot point, shown on Fig. 4 is another parameter, which influences the whirl-flutter characteristics. Increasing of this distance has a stabilizing effect on whirl-flutter instability.

2.2.2 Rotor-tower coupling instability

Rotor-tower coupling instability is a self-excited (aero)-dynamic instability caused by the interaction of the blade modes (mainly lead-lag modes) with the tower modes (e.g. first or second side-to-side bending mode) and results a violent damage of structure. This instability depends on the blade lead-lag frequency und damping and tower mode frequencies and damping. Due to the dependency of the rotor lag frequency on the rotational velocity of the rotor, it is possible that for a range of rotor speed the wind turbine becomes unstable. The mechanism of this instability is like the helicopter ground resonance instability, where the rotating rotor modes are coupled with the fuselage modes and cause an instability [14,15]. Main reason of the rotor-tower coupling instability is periodically movement of the rotor center of gravity and excitation of a system mode with eigenfrequency near to the excitation frequency. For example, an out of phase movements of the rotor blades in rotor plane, due to an external excitation, causes the periodically movement of the rotor center of gravity. To understand the mechanism of roto-tower coupling instability, a simple wind turbine rotor, shown on Fig. 5, is considered.

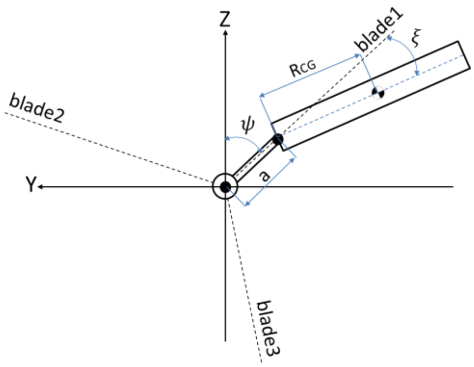

Figure 5: Wind turbine rotor with edgewise displacement/deformation of the blades

To simplify the equations, just the first lead-lag mode of the blades is considered. For this model, the position of the center of gravity of a blade (exemplary in "Z" direction) is given by the following equation:

$$Y_{CG,k} = -\mathrm{a}\cos\,(\psi_k) - R_{CG}\cos\,(\psi_k + \xi_k) \tag{10}$$

Considering a small blade lead-lag deformation, Eq. 10 is written in new form:

$$Y_{CG,k} = -(\mathrm{a} + R_{CG})\cos\,(\psi_k) - R_{CG}\xi\cos(\psi_k) \tag{11}$$

To calculate the rotor center of gravity, we average the positions of blades center of gravity, as given by the following equation:

$$Z_{CG,rotor} = \frac{-(\mathrm{a} + R_{CG})}{3}[\sin\ (\psi) + \sin(\psi + \frac{2\pi}{3}) + \sin\ (\psi + \frac{4\pi}{3}) - \frac{R_{CG}}{3}[\xi_1 \cos\ (\psi) + \xi_2 \cos(\psi + \frac{2\pi}{3}) + \xi_3 \cos\ (\psi + \frac{4\pi}{3})] \quad (12)$$

Eq. 12 is then simplified to:

$$Z_{CG,rotor} = -\frac{R_{CG}}{3}[\xi_1 \cos\ (\psi) + \xi_2 \cos(\psi + \frac{2\pi}{3}) + \xi_3 \cos\ (\psi + \frac{4\pi}{3})] \quad (13)$$

Considering the blade lead-lag frequency equal to $\kappa\Omega$ [rad/s], blade free response (vibration) due to a disturbance can be given by the following equation:

$$\xi = \xi_0 \sin(\kappa\psi) \quad (14)$$

Due to this vibration, rotor center of gravity starts to oscillate. Substitution of Eq. 14 in Eq. 13 results in:

$$Z_{CG,rotor} = -\frac{R_{CG}\xi_0}{3}[\sin(\kappa\psi) \cos\ (\psi) + \sin \kappa\left(\psi + \frac{2\pi}{3}\right) \cos(\ \psi + \frac{2\pi}{3}) + \sin \kappa(\psi + \frac{4\pi}{3}) \cos\ (\psi + \frac{4\pi}{3})] \quad (15)$$

considering the following equation:

$$\sin(a) \cos(b) = \frac{(\sin(a + b) + \sin(a - b))}{2} \quad (16)$$

Eq. 15 can be written in the following form:

$$Z_{CG,rotor} = -\frac{R_{CG}\xi_0}{6}[\sin((\kappa + 1)\ \psi) + \sin((\kappa - 1)\ \psi) + \sin((\kappa + 1)\ (\psi + 120) + \sin((\kappa - 1)\ (\psi + 120)) + \sin((\kappa + 1)\ (\psi + 240)) + \sin((\kappa - 1)(\psi + 240))] \quad (17)$$

Eq. 17 gives the frequencies of the oscillation of the rotor center of gravity, due to blade lead-lag vibration. These frequencies are: $(\kappa + 1)\Omega$ and $(\kappa - 1)\Omega$. These two frequencies are also corresponded to the eigenfrequencies of the rotor modes in non-rotating coordinate system (multiblade coordinate system), the so-called "progressive mode" or **A**dvanced **I**n **P**lane mode (AIP) and "regressive mode" or RIP. Instability can occur, when tower eigenfrequencies are near these frequencies. Interaction of rotor regressive mode with tower modes, provides condition, in which energy exchange between rotor mode and tower modes occurs. Receiving energy by a mode means reduction of its damping and increasing of its vibration amplitude. This instability can be considered as a mechanical instability, because the effect of aerodynamic on this instability is neglectable. To prevent this instability, active or passive damping of the blade lead-lag mode is the best way. Blade lead-lag vibration can be also suppressed by the control system.

2.2.3 Drivetrain torsion mode vibration/instability

A typical wind turbine drivetrain includes rotor hub, main shaft, main bearing, gearbox, torque arm supports, brake, coupling, generator and bed plate. In general, torsional vibration of the drivetrain is more in concern and it is the main component of the drivetrain dynamic response in comparison to the lateral and axial vibration. Drivetrain modes can be excited by internal high frequency excitation arise from gearbox (e.g. excitation with gearbox second stage gear mesh frequency) or by external low frequency excitations come from rotor structure or rotor aerodynamic. Drivetrain torsional modes can also be excited by excitation from generator side arising from generator rotor structure, electro-magnetic torque of the generator or control system. For example, turbulent wind from rotor side or voltage/frequency disturbance from electrical side can excite the torsional modes of the drivetrain. Damping of the drivetrain mode vibration in interaction with the rotor modes and/or the generator torque (applied from control system) can be reduced. This reduction leads to a strong vibration of the drivetrain or in worst case to an instability of the drivetrain torsion mode. Drivetrain mode shapes involves the lead-lag motion of the rotor blade. Flexibility of the rotor blades, torsional stiffness of the main shaft, meshing stiffness and damping and meshing error of the gears in the gearbox, bearing stiffness and damping are the parameters which effect on the drivetrain modes (frequencies/damping). Bearings are in the drivetrain the main components to control the drivetrain vibration.

2.3 Control system induced vibration/instabilities

Unfavorable interaction between control system, structure motion and motion induced aerodynamic loads can lead to reduction of overall damping and consequently to an instability. An example of this type of instability is the unstable coupling of blade pitch angle and platform motion by an offshore wind turbine [19]. In general, any motion of wind turbine (elastic or rigid mode motion), which includes the fore-aft motion of the rotor, causes changing of the relative wind velocity in the rotor plane, which in turn cause changing the rotor trust. Rotor trust has a stabilizing effect on the fore-aft motion and prevents the vibration. When rotor moves upwind or respectively downwind, relative wind velocity and consequently the thrust increases or respectively decreases. Increasing or decreasing the thrust acts against this fore-aft motion. Now, let us consider a condition, in which the wind turbine is working above the rated speed. Any increase or decrease of the relative wind velocity causes increase or respectively decrease of the trust and the rotor speed. Control system reacts to this changing and decreases or respectively increases the blade pitch angle to decrease or respectively increase the thrust. This changing of the thrust through control system has a destabilizing effect (reduction of aerodynamic damping) on the fore-aft motion of the rotor. In an unfavorable situation (negative overall damping), the wind turbine can become unstable. Considering the rotor motion (e.g. using the data from hub or tower top motion) in the blade pitch control methodology is a way to prevent this instability. Neglecting the rotor dynamics in design phase of wind turbine control system might also leads to an unstable closed-loop response. Therefore, considering the structure dynamics and tis interaction with the control system is an important step to prevent any unforeseen control system induced instability. Modern control system of pitch regulated variable speed wind turbine should also regulate the disturbance by the grid frequency. The grid frequency regulating system might interact with the structure dynamic and excite vibration or cause an instability. Different part of a control system, e.g. wind turbine main control system and voltage or frequency regulating control system, can interact with each other and effects on the overall damping of a structure mode (e.g. drivetrain torsion mode) [20].

2.4 Rotor/tower wake/vortex induced vibration

Wake/vortex induced vibration is a subject, which has application in many engineering disciplines (e.g. civil and structural engineering). Collapse of Tacoma bridge in Nov. 7, 1940, was due to a wake/vortex induced vibration. When the vortex-shedding frequency approaches or get near to the natural frequency of the structure, this leads to a strong vibration (similar to resonance). Possibility of occurrence of vortex induced vibration by wind turbines is becoming more, due to the increasing size of tower and blade [21]. Even if the vibration might not be directly destructive, failure of the structure due to the fatigue could be an issue. Knowing the Strouhal number (function of Reynolds number) and the characteristic length of the structure, one can calculate the frequency of the shedding vortex produced by the structure at different wind velocity. Eigenfrequencies of the structure should not match the shedding vortex.

2.5 Parametric instability

Time variation of a parameter inside a system changes the dynamic characteristic of the system (e.g. from time-invariant system to a time-period one) and might provoke an instability. An example of such a system is a pendulum with periodically moving of the pivot point. Another example is periodically changing the position of center of gravity on a swing. For a wind turbine the possibility of parametric instability is unlikely but not impossible. Time periodic variation of control system parameters might lead to an unwanted strong vibration or instability. Lead-lag vibration of a rotor blade in interaction with movement of the rotor hub in the rotor plane might lead to a blade lead-lag instability.

2.6 Summary of wind turbines instabilities

Table below summarized the wind turbine possible instabilities and gives the minimum requirements necessary for the simulation/analysis and prediction of the instability.

Table 1: Possible wind turbine instabilities and minimum simulation/prediction requirements

				Aerodynamic Model (Wind Turbine)		Linearized System Property			
No.	Type of Instability	Helicopters	Wind Turbines	Quasi-Steady	Unsteady	Time-Periodic	Time-Invariant	Eigenvalue Analysis of Linearized System	Time Domain Simulation
1	blade edgwise instability	yes	yes	Yes (low frequency)	yes (moderate to high frequency)	no	yes	yes	yes
2	stall flutter/ (flapwise or torsion)	yes	yes	no	yes (dynamic stall model needed)	non-linear methods		no	yes
3	blade torsion-flap (classical flutter), pitch-flap (blade weaving)	yes	yes	Yes (C(K)=1)	yes (moderate to high frequency)	no	yes	yes	yes
4	blade flap-Lag/ torsion-lag /pitch-lag flutter	yes	yes	yes (attached flow condition)	yes (if stall induced, dynamic stall model needed)	no	yes	no (if stall induced)	yes
5	blade pitch-(torsion)-flap-Lag	yes	yes	Yes (low frequency)	yes (moderate to high frequency)	no	yes	yes	yes
6	instability due to the coupling of rotating rotor with other rotating/non-rotating components	yes (e.g. ground resonance, air resonance, unsymmetrical rotor instability)	yes	yes (low frequency, aerodynamic can be neglegted depending on the shape of the involved blade modes)	yes (if aerodynamic is not neglectable, moderate to high frequency)	yes	no	yes	yes
7	whirl flutter	Yes	yes	yes (conservative instability prediction)	yes (moderate to high frequency)	yes (for two-bladed rotor)	yes (for 3- or more- bladed rotor and axial inflow)	yes	yes
8	blade pitch control system induced instability	yes	yes	yes	no	yes	no	yes	yes
9	parametric instability	yes	unlikely but not impossible	no	no	yes	no	yes	Yes
10	wake/vortex induced Vibartion (buffeting)	yes	yes	no	yes	non-linear methods		no	yes

3 MESH AEROELASTIC STABILITY ANALYSIS TOOL FOR ROTATING SYSTEMS

For the stability analysis of rotating system and in specific case wind turbines, different methodologies were selected and implemented in an in-house tool named MAESTRoS [22]. In the next part the selected method of simulation and process of stability analysis is described.

3.1 Multibody and Multidisciplinary simulation of wind turbines

For an accurate prediction of stability boundaries of a wind turbine, accurate simulation of structure dynamic, aerodynamic and control system is an important step. Multibody simulation has been broadly used in wind energy industry and by wind turbine engineers. Our current modelling strategy is based on multibody simulation using SIMPACK. Following figure shows schematically a multibody representation of a wind turbine.

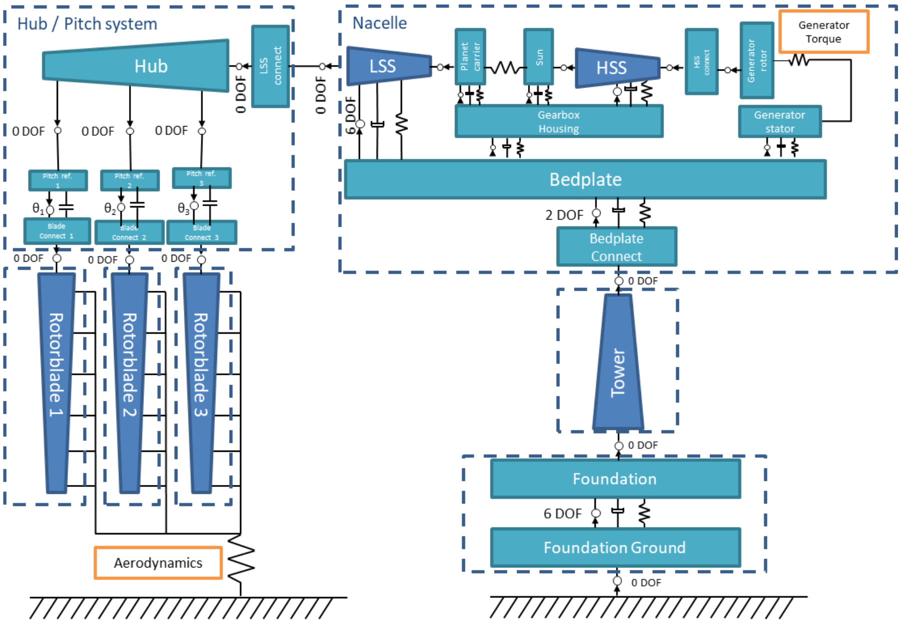

Figure 6: Multibody representation of a wind turbine

Components of the gearbox and generator can be modelled in detail, depending on the type of analysis (e.g. drive train resonance analysis) and if necessary. Wind turbine components can be modelled as rigid or elastic bodies. For the elastic bodies, number of considered modes for the calculation of elastic deformation can be defined by user. Aerodynamic loads are calculated using AeroDyn (based on blade element momentum and additional correction methods, using the Beddoes-Leishman dynamic stall model). Control System is generally simulated in SIMULINK, which is coupled to the structure-aerodynamic-model through co-simulation.

3.2 Calculation of equilibrium and linearization

For the stability analysis of wind turbine using a linear method, it is necessary to calculate first the periodic equilibrium and then linearize the system at the equilibrium. Calculation of dynamic equilibrium can be performed using a steady run-up simulation or time simulation with constant wind velocity. But this is quite challenging, specially near any instability. There are different methods available to calculate the periodic equilibrium of a rotating system. Discussion of these methods is a future work. After calculation of equilibrium, linearization and calculation of state-space representation of the wind turbine is the next step. For the case that, control system is modelled in SIMULINK, combination of linearized subsystems (wind turbine structure/aerodynamic and control system) allows generating an overall linear system with one state vector including all the states from structure-aerodynamic and control system.

3.3 Stability Analysis of wind turbines

Aeroelastic stability analysis of time-periodic systems can be evaluated by performing a nonlinear time domain simulation to calculate the transient response of the system. A disadvantage of this approach is the difficulty of getting quantitative information (e.g. modal damping) about the complete dynamics from the transient response. An alternative approach is to evaluate the stability using the methods which are based on linear system theory. For the stability analysis of wind turbine different approaches were selected and implemented in MAESToS.

Having a non-linear wind turbine system, periodic equilibrium is calculated at the different operating points. Wind turbine system is then linearized at the different points of the time-periodic equilibrium (time-periodic trajectory). Result of the linearization includes the state-space representation (e.g. linear system matrix) of the non-linear system at the linearization point. Linearization of a non-linear system at a time-periodic trajectory results in a time-periodic linear system. For the stability analysis of the determined time-period system two different linear approaches are used. The first approach is based on the application of multiblade coordinate transformation and the second approach applies the Floquet theory. Figure 3 shows schematically the described stability analysis approaches and illustrates the implemented linear methods.

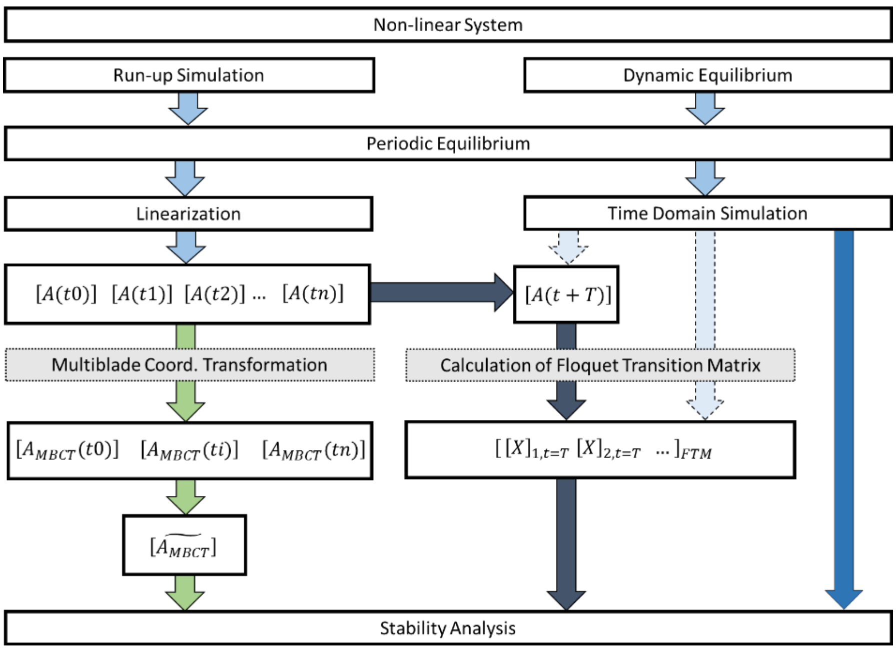

Figure 7: MAESTRoS: scheme of different selected stability analysis approaches

3.3.1 Stability analysis using multiblade coordinate transformation

Generally, equation of motion of a rotor is derived in the rotating frame, where each rotor blade is considered separately. But mostly the rotor responds to an excitation as an entire system. Changing the coordinate from blade rotating frame to rotor non-rotating frame (so called multiblade coordinate or MBC) allows considering the rotor as a whole system. Transforming the differential equations of the motion from rotating blade coordinate to multiblade coordinate (multiblade or Coleman transformation) has the following advantages: It simplifies the analysis and helps to understand the behavior of the rotating systems, especially when they are in interaction with nonrotating parts. In the case of linear time-periodic systems, this transformation reduces or eliminates the time periodic elements in the linear system matrix. A combination of multiblade transformation and time average approximation turns the linear system matrix to a time invariant one. In the implemented tool, linear system matrices of a time periodic system, generated at different instants of time inside a time period (different rotor azimuth angles), are read-in as input by a MATLAB script. This script transforms all the blade states (position, velocity, acceleration) from rotating blade coordinate in to the multiblade coordinate and calculated the transformed linear system matrices as shown on Fig. 8.

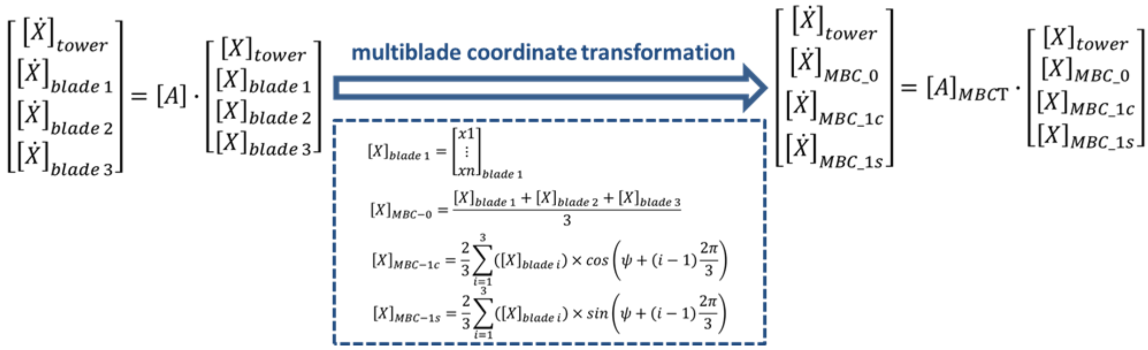

Figure 8: Multiblade coordinate transformation of three-bladed wind turbines

With multiblade transformation the linear system matrix might become time invariant. If this is not the case, an azimuthal averaged determination of the transformed matrices results in an estimated time invariant linear system matrix. Eigenvalue analysis of this matrix is then used for the stability prediction.

3.3.2 Stability analysis using Floquet Theory

Floquet theory is one of the widely used theory applied for the stability prediction of a linear system with time periodic coefficients. Based on this theory, stability prediction is performed with the evaluation of the eigenvalues of the Floquet transient matrix. In classical application of Floquet theory, this matrix is explicitly computed. The implicit Floquet analysis is another method that extracts the dominant eigenvalues of the Floquet transition matrix without the explicit computation of this matrix. Fig. 9 shows schematically the stability analysis approach based on application of Floquet theory which has been implemented in MAESTRoS.

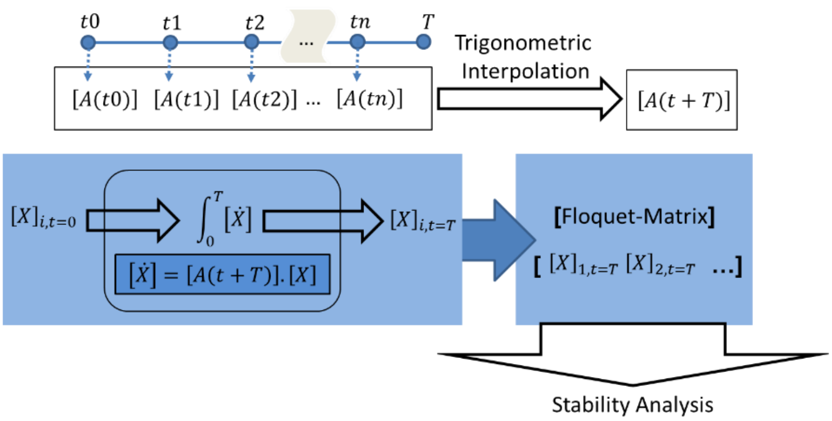

Figure 9: Scheme of stability analysis method based on Floquet theory

3.3.3 Stability analysis using time domain simulation

As mentioned above, stability of a system can be evaluated directly by the analysis of system response in the time domain. This makes more sense, when linear methods in the presence of strong structural or aerodynamic non-linearity are not valid (e.g. stall flutter). Time domain simulation can also be used for the calculation of state-space model using a linear system identification method or can be used for the direct calculation of Floquet transition matrix (accuracy of this method depends on the level of non-linearity). Implementation and verification of these latest approaches are future task and currently not available in MAESTRoS.

4 APPLICATION OF DEVELOPED STABILITY ANALYSIS TOOL

In the next part, methods described in the previous part are applied for the stability analysis of a selected reference wind turbine.

4.1 Stability analysis of a reference wind turbine

Exemplary and for the demonstration of the application of the developed stability analysis tool, a 3-bladed, 5-MW reference wind turbine [23] was selected and modelled in multibody simulation tool SIMPACK. Rotor radius and tower height of this wind turbine are 63 m and 87.5 m. For this wind turbine, the possibility of mechanical instability due to the coupling of the rotor modes and tower modes (rotor-tower coupling instability) was investigated. As for the formation of this instability mainly from rotor side the blade lead-lag modes are relevant, therefore for each blade just the first lead-lag mode was considered. For the tower the first and second tower fore-aft and side-to-side modes and first tower torsion mode were considered. Rotor-tower coupling stability of this model was investigated using both described methods. Stability prediction results using the method of multiblade coordinate transformation are shown on Fig.10.

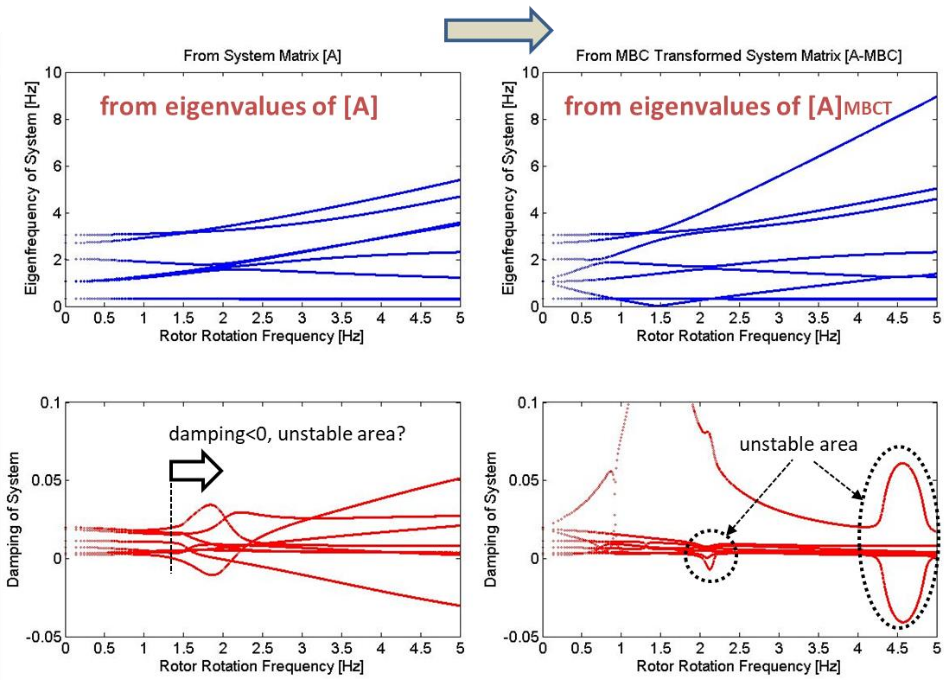

Figure 10: Eigenfrequencies and damping of the rotor-tower coupled modes

This figure shows the eigenfrequencies and damping of the wind turbine in both rotating coordinate (left) and non-rotating coordinate (right). As the linearized system (rotor-tower), due to the gravity, time-periodic characteristics has, the classical eigenvalue analysis of the linearized system is not valid. Application of this method (left damping diagram) leads to wrong instability prediction. Stability results in multiblade coordinate predict two instability areas, evolved due to the coupling of blade lead-lag regressive mode with tower first side-to-side and tower second bending mode. This instability areas are far from permitted operating frequency.

Fig. 11 shows the rotor-tower coupling stability analysis results determined using the Floquet theory and comapre the predicted instabiliy areas with thouse predicted by multiblade coordinate transformation.

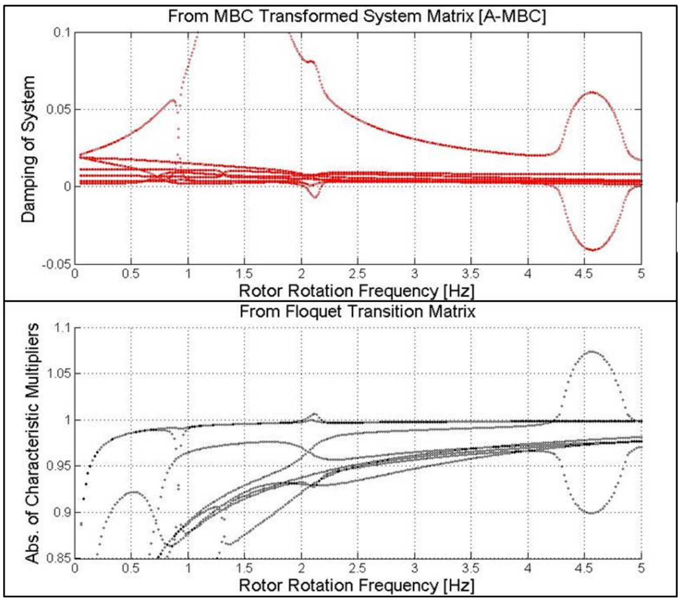

Figure 11: Comparison of rotor-tower coupling instability prediction using MBC and Floquet

4.2 Rotor-tower coupling instability of a scaled reference wind turbine

Tendency of wind energy industries toward making larger wind turbines for producing more power from one side and from other side building a smaller model (e.g. wind tunnel model) to test a wind turbine brought engineers and scientists to the thought of defining scaling and similarity rules. In general, aerodynamic similarity and structural dynamic similarity (for both up- and down-scaling) are two important criteria for the consistency of the aeroelastic similarity. In general, for aeroelastic similarity (e.g. same stability at the same flow condition) between a scaled model and reference model (e.g. full aircraft) the following six dimensionless characteristic numbers should be equal: density ration, reduced frequency, Cauchy number, Mach number, Froude number and Reynold number. A simultaneous fulfillment of the conditions of equal Mach number, Froude number and Reynolds number are generally not possible. For a scaled rotor, to have same aeroelastic responses comparing to the reference rotor, following five nondimensional parameters should maintained invariant: frequency scaling, lock number, advance ratio, Froude number and Mach number. By a classical scaling of a wind turbine assuming the same flow condition, tip speed ratio, blade profile, number of blade and the material used should be maintained and all dimensions (rotor radius, profile chord, spar size) are proportionally adjusted [24].

Using these similarity rules, the 5MW reference wind turbine model used in the previous section was scaled up to a 20MW wind turbine. For the scaled-up wind turbine the possibility of the rotor-tower coupling instability was investigated. Following figure compares the frequencies (in both rotating and not-rotating coordinate) of the reference and scaled-up models. From this comparison, it can be seen, that the mode coupling mechanism after scaling remains unchanged. This means, for the scaled-up wind turbine, the rotor-tower coupling instability can be predicted by using the stability results of the reference model.

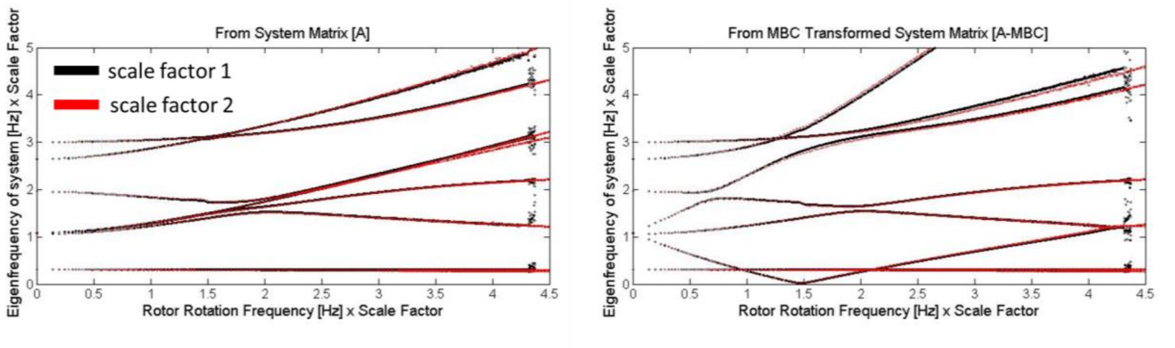

Figure 12: Eigenfrequencies of rotor-tower coupling modes: reference model vs. scaled model

5 CONCLUSION

Similarities between wind turbines and other rotating systems (e.g. helicopters) from aeroelasticity point of view were highlighted. Possible wind turbine instabilities were listed and the mechanism of certain type of instabilities were discussed. It was concluded that the blade lead-lag mode is a critical mode which can become unstable in both attached flow and stall conditions. For the blade lead-lag motion low aerodynamic damping is available, therefore structural damping or any active or passive damping methodology could be beneficial. Although generally different type of instabilities occurs in different range of reduced frequencies, but blade lead-lag instability or strong vibration could provoke other type of instabilities including the lead-lag mode (e.g. blade flap-lag instability, rotor-tower coupling instability and even whirl flutter). Mechanism of formation of whirl flutter for a wind turbine was discussed. It was shown the main sources of the whirl flutter instability are the gyroscopic and aerodynamic coupling of the rotor modes. Mechanism of rotor-tower coupling instability was also discussed. It was shown that the blade edgewise motion of a rotating rotor can excite the tower modes (first or second tower side-to-side eigenmodes) and become unstable. This instability can be associated to the helicopter ground resonance. Finally, some other type of wind turbine instabilities (e.g. instability of drivetrain mode, control system induced instability, parametric instability) were shortly discussed. For each type of wind turbine instability, it was additionally highlighted how to prevent the instability and what are the (minimum/conservative) requirements for the simulation and prediction of the instability. Table 1 summarizes these perceptions.

For the stability analysis of a wind turbine, modelled in a multibody and multidisciplinary simulation environment, a stability analysis tool in MesH Engineering GmbH has been developed. This in-house tool (named MAESTRoS) applies the well-known linear methods for the stability analysis of time-periodic systems (Floquet theory and multiblade coordinate transformation) and therefore it is currently limited for the analysis of aeroelastic instabilities, which can be predicted applying linear methods. For a non-linear instability analysis (e.g. stall flutter) time domain simulation is used. Simulation of wake/vortex induced vibration is another limitation of MAESTRoS. This limitation arises form the capability of AeroDyn, which is used for the calculation of aerodynamic loads. The methodologies used in MAESTRos in conjunction with the application of Floquet and MBC transformation were described in the paper. Rotor-tower coupling instability of an exemplary 5MW reference wind turbine was investigated. Instability prediction were performed using both multiblade coordinate transformation and Floquet theory. Both methods predict the same range where the rotor-tower coupling instability is an issue. The instability zones are far from the maximal permitted rotor speed. At the end, aeroelastic similarity rules of rotors and wind turbines were briefly argued. Based on these rules the 5MW reference wind turbine was scaled up and the rotor-tower coupling instability of this wind turbine was investigated. It was shown that, the stability of the scaled-up model could also be predicted using the stability prediction results of the reference model.

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