Aeroelastic analysis of wind turbines applying 3D CFD computational results

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Abstract. This document describes the enhancement of the aeroelastic stability analysis with the program system ARLIS [1] by applying aerodynamic results obtained from 3D CFD computations. As a main goal a coupling between the CFD-solver and ARLIS by exchanging aerodynamic loads and deformations is envisioned.

1. Introduction
Because the power captured by wind turbines is proportional to the square of the rotor diameter, the size of wind turbines has constantly increased. In addition, the trend for current wind turbine development is to go offshore, where wind turbines have a higher energy potential because of the higher wind speeds. Due to the combination of high wind speeds and large size of the turbines, tremendous loads are caused in the structure. Therefore, an important research area is the understanding, modelling and control of the loads on wind turbines.

Recently, several tools for investigating the linear aeroelastic stability of wind turbines have been developed and improved under the European STABCON project [2], [3]. In these tools different approaches for the structural and aerodynamic modelling are employed, leading, amongst others, to the possibility of predicting the damping of wind turbines during operation. In the framework of this project, the program-system ARLIS has been reactivated, refined and validated against other tools and measurements. The program-system was specifically developed for the stability analysis of horizontal axis wind turbines.

The dynamics and response of a wind turbine during operation depends significantly on the total damping of the turbine, which is a combination of the structural and aerodynamic damping. Usually the structural contribution to the damping is well known. On the other hand, the aerodynamic part can be very uncertain, however, it might result in severe vibrations that eventually can lead to structural failures of wind turbines. Thus, the need for improving prediction tools to avoid such stability problems is obvious.

2. ARLIS
ARLIS is the acronym for Aeroelastic analysis of Rotating LInear Systems. The program system was designed for the linear dynamic and aeroelastic analysis of horizontal axis wind turbines and was originally written in ANSI FORTRAN IV by Bertold Kirchgässner. Applying Floquet’s Theory it is capable to handle wind turbines with one, two and more blades. It is, however, restricted to constant r.p.m. of the wind turbine.
2.1. Short Description of the Program Concept
For the dynamic analysis of the coupled rotor - tower - system the separated systems are described by finite element models, using any appropriate FE-Program System, e.g. ASKA [4]. The eigenmodes are calculated for both systems separately, which are then reduced via condensation to small systems with only a few generalised degrees of freedom (eigenmodes) which are assumed to be sufficient for the description of the dynamics and the stability of the system. The displacements are assumed to be small enough to work with linearised equations of motion. The validity of this assumption can be checked by the dynamic response of the system. In the case of large stationary displacements the stability analysis can be conducted around the equilibrium state of the deformed structure. Tower and rotor are connected via one nodal point (coupling point) with 6 degrees of freedom. The drive train is modelled by a simple FE-model allowing a ”stiffness and/or damping coupling to ground” of the generator, thus allowing a modelling of synchronous and asynchronous generators. ARLIS takes over the matrices of the condensed systems and builds up the matrices of the linearised coupled rotor - tower - system, including quasisteady aerodynamics based on the blade element momentum theory (BEM). Since, in general, the matrices of the coupled system have periodic coefficients the stability analysis is carried out using Floquet’s theory. Furthermore, steady-state and transient response of the coupled system can be calculated taking into account loads due to deadweight, wind shear, gusts, unbalance, etc. The generalised displacements are given back to the Finite Element System, where nodal point displacements, stresses, forces etc. are computed in the usual manner.

3. Stability Analysis Compared to Measurements
In this section simulation results are compared to the outcome of experiments both conducted within the STABCON project.

3.1. Standstill Comparison
In order to validate the structural modelling of the wind turbine, standstill measurements are compared to results achieved from stability analysis with ARLIS. From Table 1 one can see that there is a good agreement between the computed and measured eigenfrequencies, with an average deviation of about 2.95%. Due to some assumptions that had to be made to build a common basis for all stability tools used within the project, even the largest relative difference of nearly 5% is considered acceptable. One conclusion to be drawn is, that the structural dynamics building on finite element models is well covered within ARLIS.

3.2. Frequencies and Damping During Operation
As a second step, the predicted natural frequencies and modal damping of the rst tower bending and edgewise rotor whirling modes are compared to the estimations from the experiments on the turbine. In order to extract these modal damping and frequency estimates from a real operational turbine, a method called operational modal analysis (OMA) has been developed by other partners in the course of the project [5]. This method made it possible to get a good estimate for comparison, however, it must be noted that the experimental results contain several uncertainties e.g. the effect of the active controller during the measurements.

The used aerodynamic profile coefficients for the predictions were given in the project and are corrected for 3D effects already. The data were derived as a result of the load verication of the wind turbine. This means that the lift and drag coefficients for the different tables were adjusted to obtain the best possible match between calculations and measurements of power and loads.

3.2.1. Tower Modes In Figures 1 and 2 one can see a fairly good agreement between predicted and measured frequencies and damping for both tower modes. There is an under-prediction,
Table 1. Computed and measured natural frequencies of the 10 lowest turbine modes at standstill.

| No. | Name                      | Mode             | Frequency [Hz] | Measured | USTUTT | Deviation [%] |
|-----|---------------------------|------------------|----------------|----------|--------|---------------|
| 1   | st lateral tower bending  | 1st              | 0.437          | 0.452    | 3.44%  |
| 2   | st longitudinal tower bending | 1st              | 0.444          | 0.463    | 4.29%  |
| 3   | st shaft torsion          | 1st              | 0.668          | 0.690    | 3.31%  |
| 4   | st yaw                    | 1st              | 0.839          | 0.855    | 2.00%  |
| 5   | st tilt                   | 1st              | 0.895          | 0.908    | 1.44%  |
| 6   | st symmetrical flap       | 1st              | 0.955          | 0.959    | 0.44%  |
| 7   | st vertical edgewise      | 1st              | 1.838          | 1.905    | 3.63%  |
| 8   | st horizontal edgewise    | 1st              | 1.853          | 1.945    | 4.97%  |
| 9   | nd tilt                   | 2nd              | 2.135          | 2.229    | 4.38%  |
| 10  | nd yaw                    | 2nd              | 2.401          | 2.440    | 1.64%  |

Average deviation: 2.95%

Both, in frequency and damping, which is acceptable especially in case of damping. The good agreement in the tower modes can be explained due to the small aerodynamic influence on the tower behaviour. This also explains a slightly larger deviation in damping for the longitudinal tower bending mode, where the aerodynamic influence is expected to be slightly higher.

3.2.2. Rotor Modes In contrast to the tower bending modes, an over-prediction in frequency and damping for the edgewise whirling modes of the rotor can be seen in Figures 3 and 4. Also the mean deviation is found to be higher compared to the tower modes. Since the modelling of unsteady aerodynamics is not yet implemented in ARLIS, the differences were even expected to be larger, especially in case of damping. There are of course other possible sources for discrepancies, however, experience from the project leads to expect improved results by enhancing the aerodynamic modelling within ARLIS.

Figure 1. Frequencies of the first two tower modes predicted with ARLIS (V2) and estimated from OMA.

Figure 2. Damping of the first two tower modes predicted with ARLIS (V2) and estimated from OMA.
4. Inclusion of Unsteady Aerodynamics

The state of the art aeroelastic codes used today rely on above described models based on the BEM method. Although quite simple, the BEM method leads to accurate predictions for the aerodynamic loads, provided that sound lift and drag curves are used for the airfoils. The question is how these data are obtained. It is common experience that the use of 2D airfoil data may lead to serious discrepancies between measured and predicted loads. One way to tackle the problem is the use of correction models, e.g. models to account for the effects of rotation (e.g. [6], [7]), dynamic stall models (e.g. [8], [9]) and dynamic inflow models (e.g. [10]). Another approach which just started to appear in literature is to extract local airfoil characteristics from 3D CFD computations of the rotating blades that, however, have still the problem to accurately handle turbulence effects, e.g. dynamic stall. In the future this may lead to fully coupled aeroelastic computations where the interaction between the rotor blades and the tower on a wind turbine are investigated using CFD methods.

As an extension of the ARLIS-code the implementation of engineering models for dynamic stall [11] and 3D-effects due to the rotation of the blades [12] have been taken into consideration and are currently ongoing. The qualification “engineering” is meant to indicate that the model can be implemented in PC or Workstation based programs without unduly increasing the run time.

As a second approach to improve the analyses with ARLIS, a coupling to CFD methods is envisioned. Although more expensive with respect to cpu-time, improvements in the physical understanding of the flow around the rotor and more accurate results in the stability analysis are expected. As a first step this could be achieved by using local airfoil characteristics extracted from those computations. A future step could be a coupling by exchanging aerodynamic loads and deformations between the CFD-solver and the response calculations within ARLIS. So far CFD-calculations of the rotor only were conducted, using the DLR FLOWer code to solve the 3D, unsteady Euler or RANS equations. The numerical procedure is based on structured meshes.

4.1. Notes on Grid Generation

The rotor blade that is the object of this numerical analysis has a radius of roughly 40 meters. The power control method of this 3 bladed horizontal axis variable speed wind turbine is by pitch regulation. In designing a computational model of the rotor the aim was to stay as close to the original geometry of the turbine while allowing the simulation of a multitude of operational conditions. Both hub and blade were first modelled using the CAD software CATIA, Figures 5 and 6. On the basis of the data provided within the STABCON project a CAD model was
created then used as a basis for grid generation using the software GRIDGEN.

![Figure 5. CAD model of the hub](image)

![Figure 6. CAD model of a rotor blade](image)

![Figure 7. Cuts through grid blocks - blade grid](image)

![Figure 8. Cuts through grid blocks - hub grid](image)

The computational grid of the rotor blades is based on a C-topologie, Figure 7. Each blade grid contains close to 1 million points. An additional block which is based on an O-topology has been designed for the hub which has been closed off with a tear shaped terminator in order to minimise aerodynamic discontinuity behind the rotor, Figures 8. The hub grid consists of 3.3 million points. Applying the Chimera-technique, the three blade grids and the hub grid are placed inside a background grid which covers the whole computational domain and contains 3.9 million points. The cell distribution in the shear layer has been done according to equation (1) which according to experiences from other projects delivers good results.

\[
\Delta s = 5,5 \cdot Re_{\text{ref}}^{-\frac{2}{3}} \cdot L_{\text{ref}} \cdot y^+ 
\]  

(1)

The maximum of the estimated Reynolds numbers at the trailing edge was selected as the reference reynolds number \(Re_{\text{ref}}\). The dimensionless wall distance \(y^+\) in the innermost cell layer should be approximately one. Examination of the true values for \(y^+\) at the grid points on the blade surfaces show that the Reynolds numbers have been underestimated especially for high angles of attack. \(y^+\)-values for the first cell layer range between one and ten.

Chimera decomposes complicated configurations into simple components for each of which a grid is then generated. Those grids have to overlap each other; cells can be excluded from calculation in component grids by defining holes that are cut from those grids which is necessary if those cells lie within solid body volumes of other component grids. Thus the rotor blade cuts a hole in both hub grid and background grid, Figures 9 and 10. The hub grid cuts a hole only in the background grid, since no cells of the blade grid lie within the hub body. The data transfer between grids takes place by trilinear interpolation at the grid and hole boundaries. This approach has the advantage that the blades can be connected to the hub at a variable pitch angle. The numerical solution of the RANS equations is done with the solver FLOWer using the k-\(\omega\) SST turbulence model.
4.2. Extraction of local airfoil characteristics from 3D CFD computations

To obtain the local airfoil characteristics a Fortran routine has been written, which can calculate these searched values from the output-files of the CFD computation. The pressure forces are integrated using the surface normals and pressure values at each node over one frame. Similarly the friction forces are calculated using the surface velocities and friction coefficients and are added to the resulting total force. Projection of the resulting force onto the chordwise direction and perpendicular to it leads to the tangential force $F_T$ and the normal force $F_N$. These two forces are rotated by $\alpha_{eff}$ to the lift $L$ and drag $D$ vector:

$$ L = F_N \cos(\alpha_{eff}) - F_T \sin(\alpha_{eff}) $$
$$ W = F_N \sin(\alpha_{eff}) - F_T \cos(\alpha_{eff}) $$

The effective angles of attack $\alpha_{eff}$ are extracted from the CFD computations according to [13]. In order to receive the airfoil characteristics the lift $L$, the drag $D$ and the momentum $M$ around the quarter chord point are standardized with the dynamic pressure, the area around the corresponding airfoil and the arm of lever.

For further use within ARLIS airfoil characteristics were extracted from the following URANS computations shown in Table 2:

Table 2. Performed URANS computations.

| wind speed $[\text{m} / \text{s}]$ | rot. speed $[\text{rad} / \text{s}]$ | pitch angle $[\text{o}]$ | turbulence model          |
|-------------------------------|------------------|----------------|--------------------------|
| 5                             | 1.267            | -30 -25 -20 -10 0 5.3 10 15.4 20 | $k$-$\omega$ SST         |
| 10                            | 1.806            | x x x x x x x x | $k$-$\omega$ SST, Baldwin-Lomax |
| 15                            | 1.806            | x x x x x x x x | k-$\omega$ SST, Baldwin-Lomax |
| 20                            | 1.806            | x x x x x x x x | k-$\omega$ SST           |

5. Stability analysis results

In order to investigate the effect of the profile coefficients on the stability analysis with ARLIS predictions have been performed using the airfoil data given within STABCON, 3D CFD
extracted data, as well as 2D data collected from the book by Abbott and von Doenhoff [14]. In Figure 11 the lift coefficients over $\alpha$ are exemplarily shown for two radial positions, where the 3D-CFD curve was extracted from computations at $10\text{ m/s}$ wind speed.

The resulting lift curves were then used for the stability analysis computations in ARLIS. As expected this change in airfoil data has no influence on the frequency and damping of the two tower modes.

Regarding the two considered edgewise whirling modes the results do not match the expectations. There is no visible change in the frequency and damping curves. In fact the differences between the predictions based on the different airfoil coefficients are negligible. E.g. in Figures 12 and 13 one can see comparisons of the predicted damping and frequency for the first edgewise mode. The curves are based on the airfoil data given within STABCON (V2), 3D CFD extracted data (3D-CFD) and 2D data (2D) and are again compared to measurements (OMA).

The stability analysis was performed as usual for normal operational conditions of the investigated turbine. Depending of the wind speed the local effective angles of attack during those operational conditions have been found to always range in the linear region of the lift curve. E.g. at a wind speed of $10\text{ m/s}$ the local angles of attack vary between $1.65^\circ$ at the tip and $15.3^\circ$ at 20% radius of the blade. Since the lift coefficient curves are very close together and since the slope of the curves is almost matches in the linear region, no influence can be expected on the calculation of aerodynamic loads based on those lift curves.

**Figure 11.** Lift coefficients for radial positions 24.1m and 37.2m at 10m/s wind speed.

**Figure 12.** Comparison of frequencies over windspeed for the first edgewise whirling mode.

**Figure 13.** Comparison of damping over windspeed for the first edgewise whirling mode.
6. Conclusions
In the framework of the European STABCON project the program system ARLIS has been successfully reactivated and refined. Being the only code able to apply Floquet’s Theory, ARLIS has been tested and has shown to be computationally efficient and to provide acceptable results, without having to eliminate the periodic coefficients in the resulting linear equations. However, a need to improve the aerodynamic modelling has been found. The implementation of 'engineering models' to consider unsteady aerodynamic effects has been investigated. Especially in case of dynamic stall, the implementation would require a complete new buildup of the program system in which the gain is not certain. Experiences from the project show, that the stability results vary a lot depending on the dynamic stall model used. Therefore, a second concept has been presented in which a weak coupling to CFD methods is envisioned.

The investigations described above have shown however, that the use of airfoil characteristics extracted from 3D URANS computations does not lead to the anticipated enhancements of ARLIS. At least during normal operational conditions of the investigated turbine, the influence of the extracted airfoil characteristics is negligible. So the problem of enhancing aerodynamic modelling within ARLIS still remains.

Although not leading to the expected enhancements of ARLIS the presented CFD computations, especially the extraction of local airfoil characteristics from 3D URANS computations still do look promising, in this case fully coupled computations are prepared as a next step using the inhouse code DYNROT to solve the structural dynamics of the blades.

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