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Subject: GAROS

1 Introduction

GAROS is a program for the aeroelastic- and rotordynamic analysis of wind turbines. Stability and dynamic response analysis can be done. Both horizontal and vertical axis turbines can be analysed.

The program is based on a modal coupling method of tower and rotor. The structures are idealised by finite elements and the modes are calculated by the finite element program NX Nastran. The modal model contains the fully coupled rotor dynamic matrices. Also the geometric stiffness matrix is included. In the stability analysis the quasi steady linearized aerodynamic stiffness, damping and mass matrices are considered. The static deformation of the blades can be accounted for in order to calculate the stability behaviour for different operating conditions. Also the true unsteady aerodynamic forces including the Theodorsen function which describes the time lag between motion and force can be accounted for. In that case a non-linear iteration is applied for the solution of the complex eigenvalues. For rotors with two blades the eigenvalues are calculated by the Floquet method because the equations contain periodic terms.

In addition to the stability analysis also dynamic response analysis can be done. In order to check the results of the stability analysis a sweep with increasing rotor speed and wind velocity can be performed. Aerodynamic forces due to wind gradient, tower influence, oblique flow, gusts and turbulence can be accounted for. Centrifugal and gravity excitation forces are also included. The results can be plotted as function of time or as polar plots as function of rotor angle. Nodal displacements and element forces can be recovered. The aerodynamic induction factor can be accounted for horizontal axis rotors.

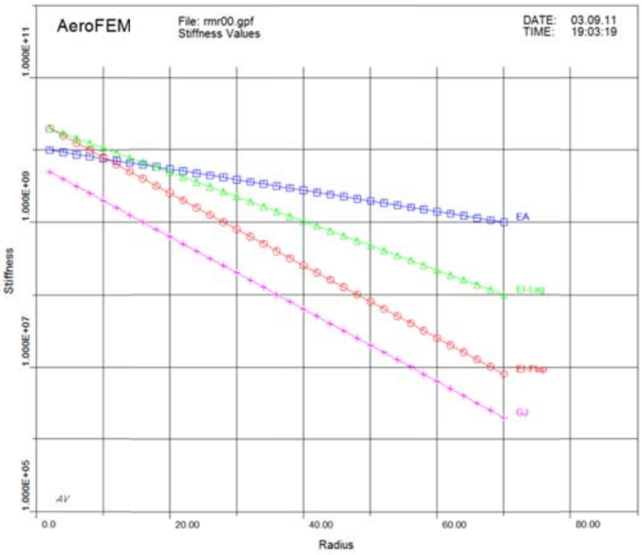
Many useful programs are included in the GAROS suite of programs.

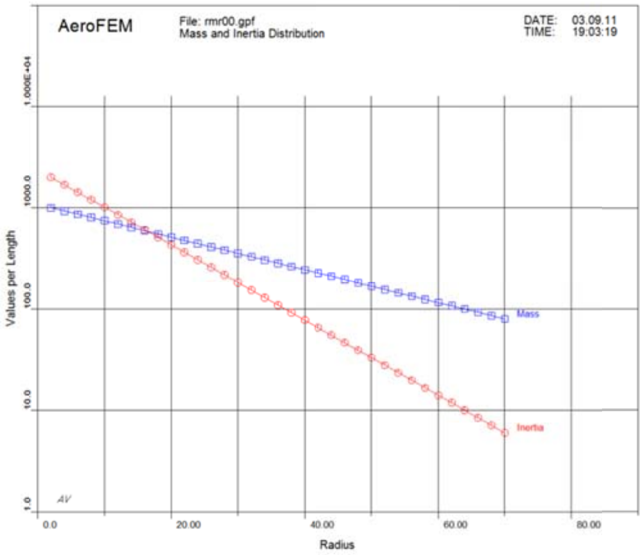
The theory will be published in the book:

Arne Vollan, *AeroFEM GmbH, Switzerland*; Louis Komzsik, *Siemens, Cypress, California, USA:*
Computational Techniques of Rotor Dynamics with the Finite Element Method
CRC Press Taylor and Francis Group, ISBN: 9781439847701
To appear 08.02.2012

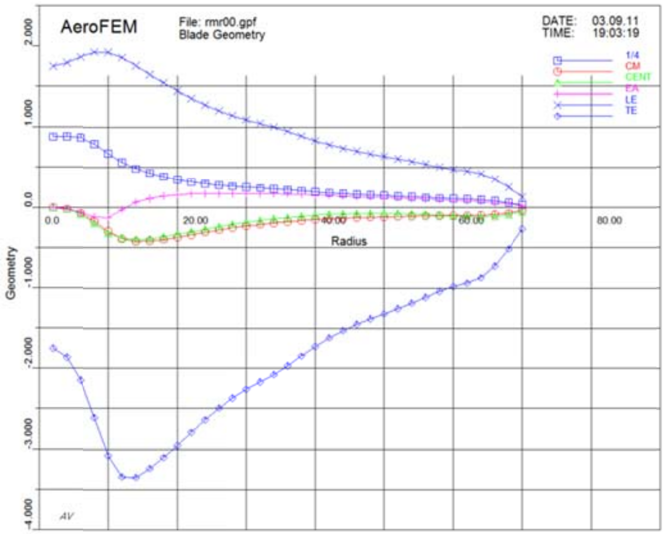
2 The model

The program contains a model builder where the finite element model of the rotor can be established from the stiffness-, mass-, inertia- and geometric data.

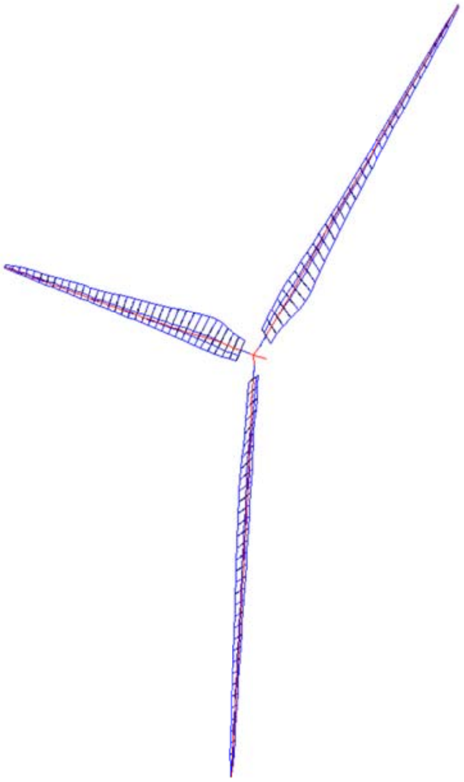




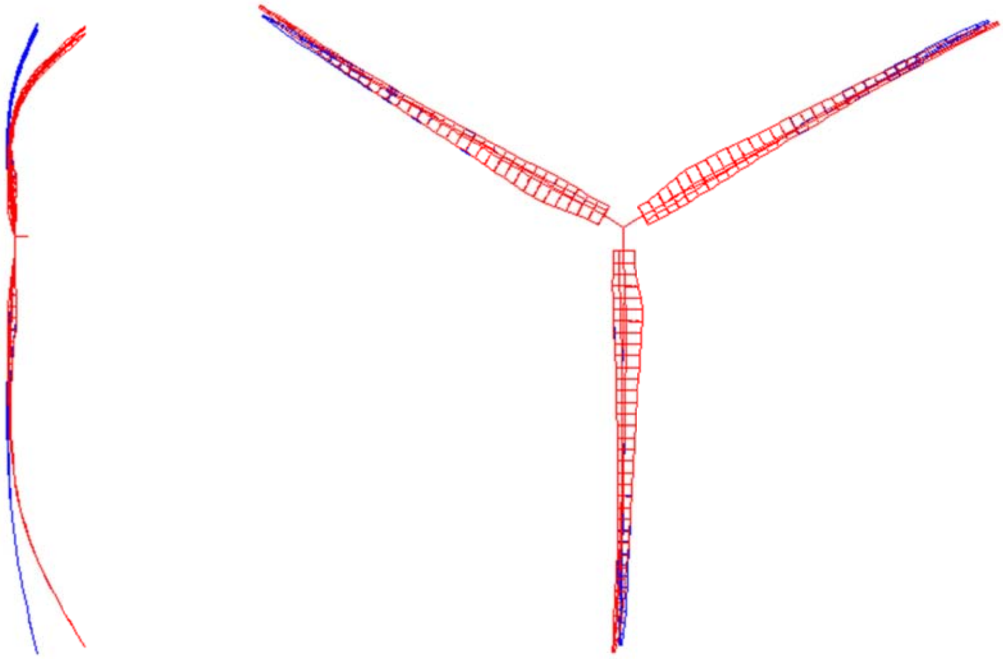
Examples of stiffness and inertia data of a wind turbine blade are shown in the plots.



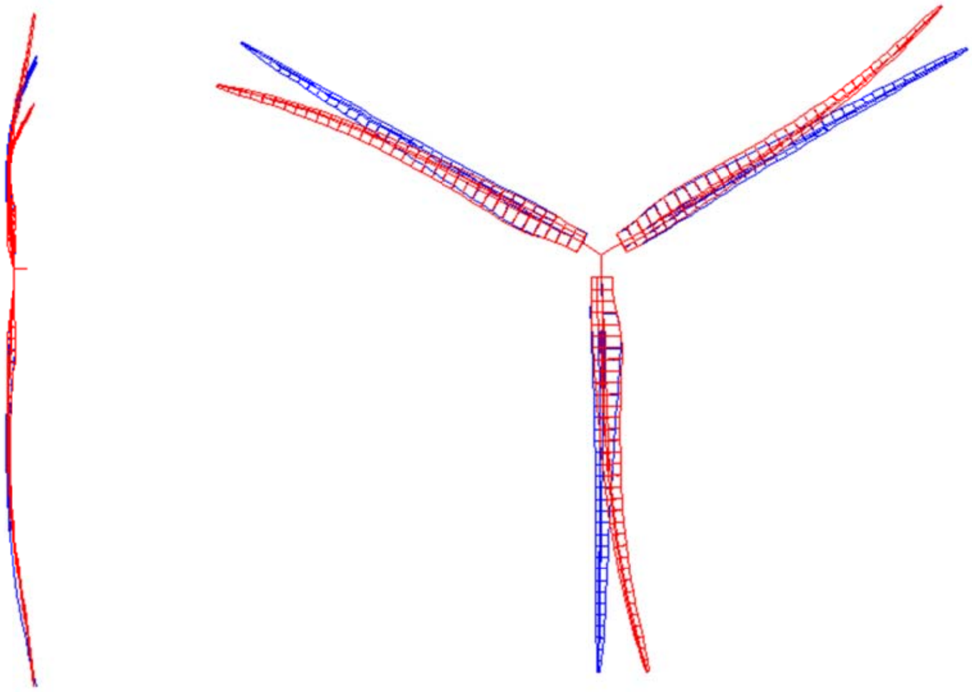
The position of the shear centre and the centre of mass together with the position of the aerodynamic reference point is important for the aeroelastic stability analysis. The picture above shows the blade geometry.



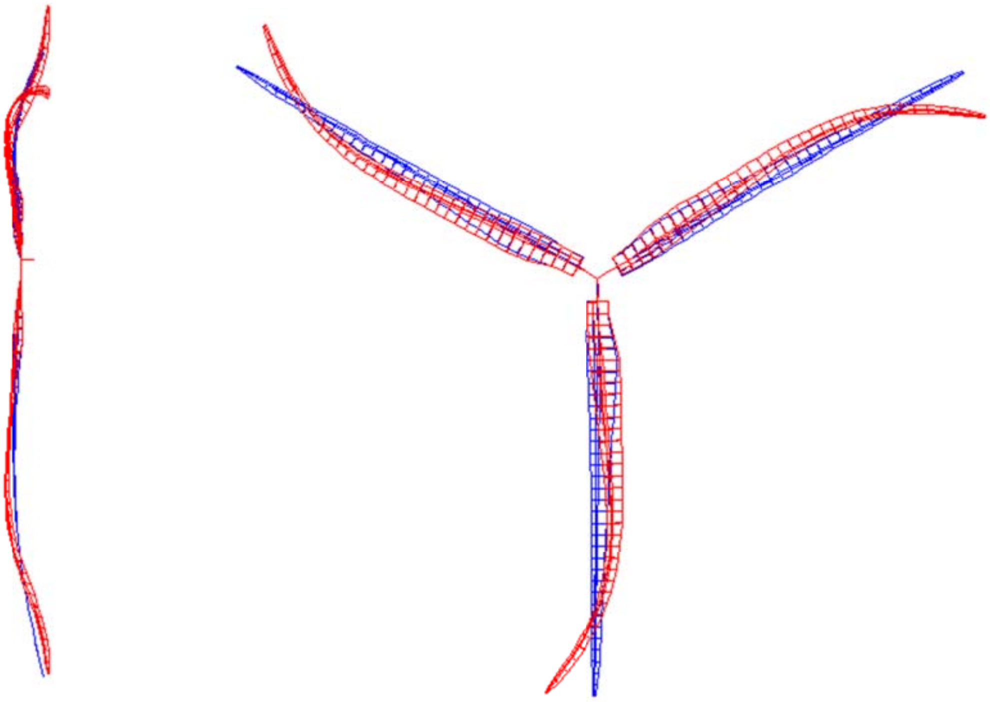
The finite element model contains tapered beam elements, discrete masses and plot-elements without stiffness for the visualisation.



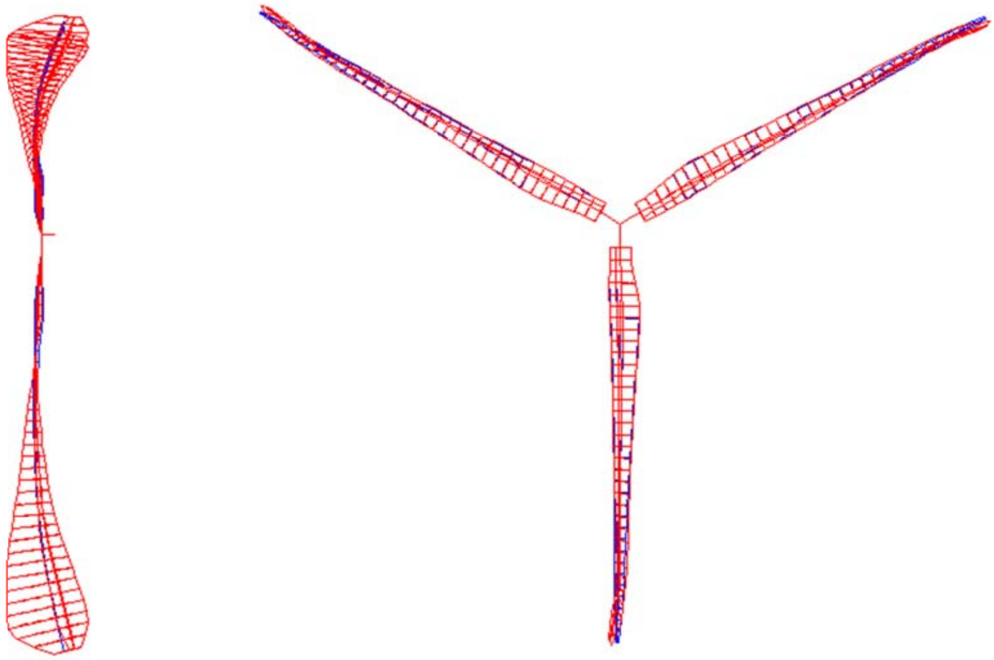
First symmetric flap mode of the deformed blade



First symmetric lead-lag mode



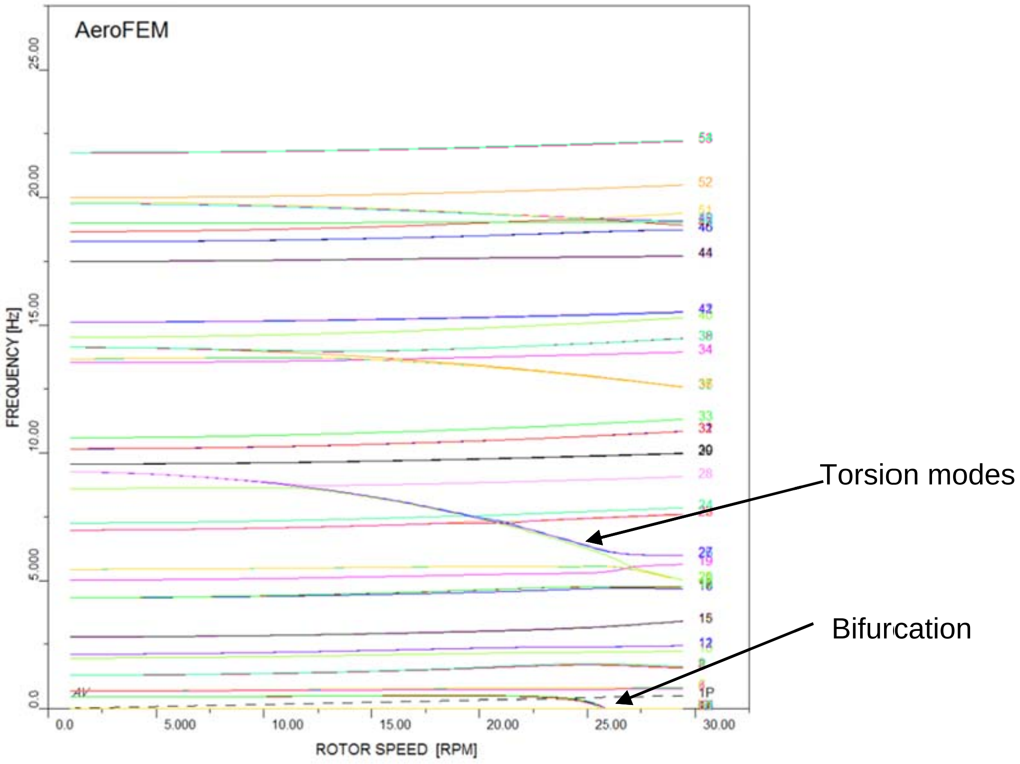
Second symmetric lead-lag mode of the deformed blade contains also torsion



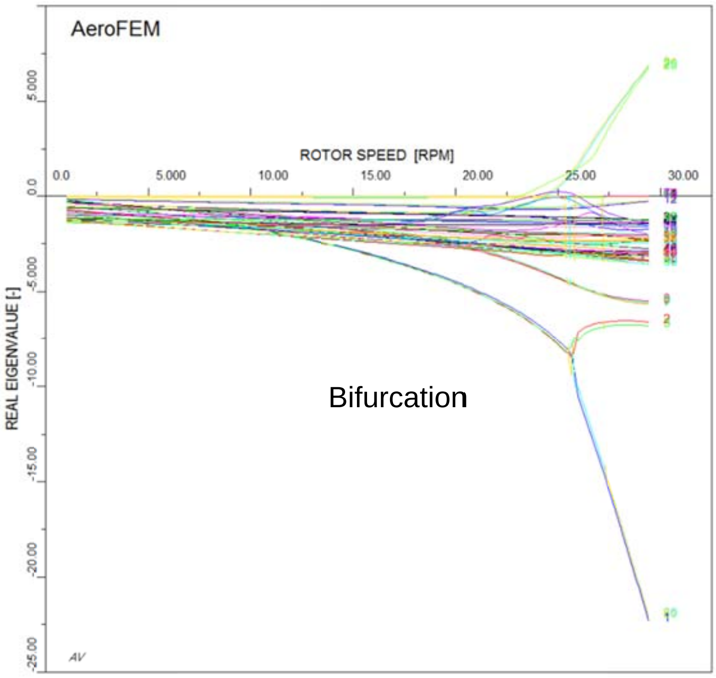
First symmetric torsion mode

3 Stability analysis

Stability analysis for a rotor with three blades is shown. The rotor blades are 70 m long. The eigenfrequencies of the torsion modes decrease with rotor speed due to the aerodynamic stiffness. The bifurcation point for the flap bending modes occur around 26 RPM. This is a blade divergence but the motion is strongly damped and the motion is stable. For propeller and transport aircraft the divergence instability occurs shortly after the bifurcation point.

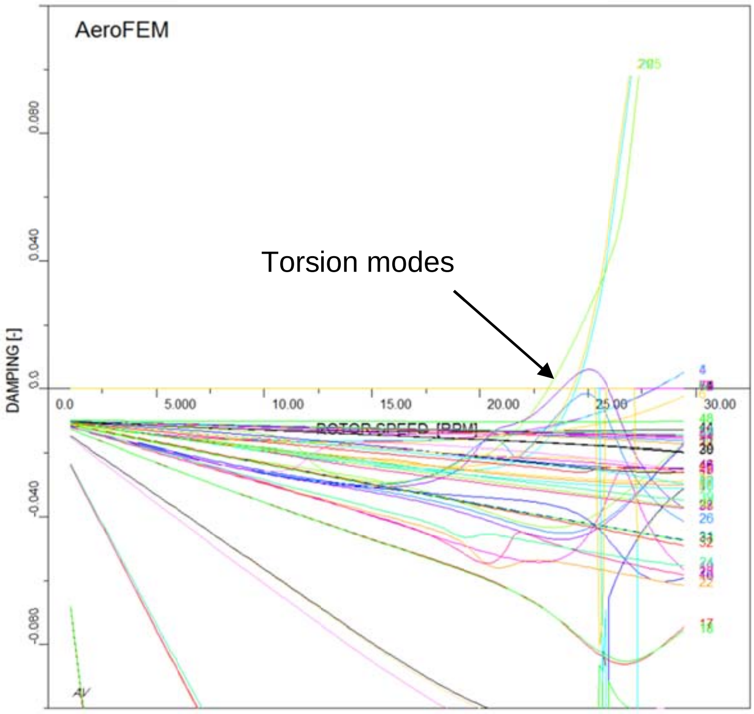


Eigenfrequencies for the rotor with deformed blades



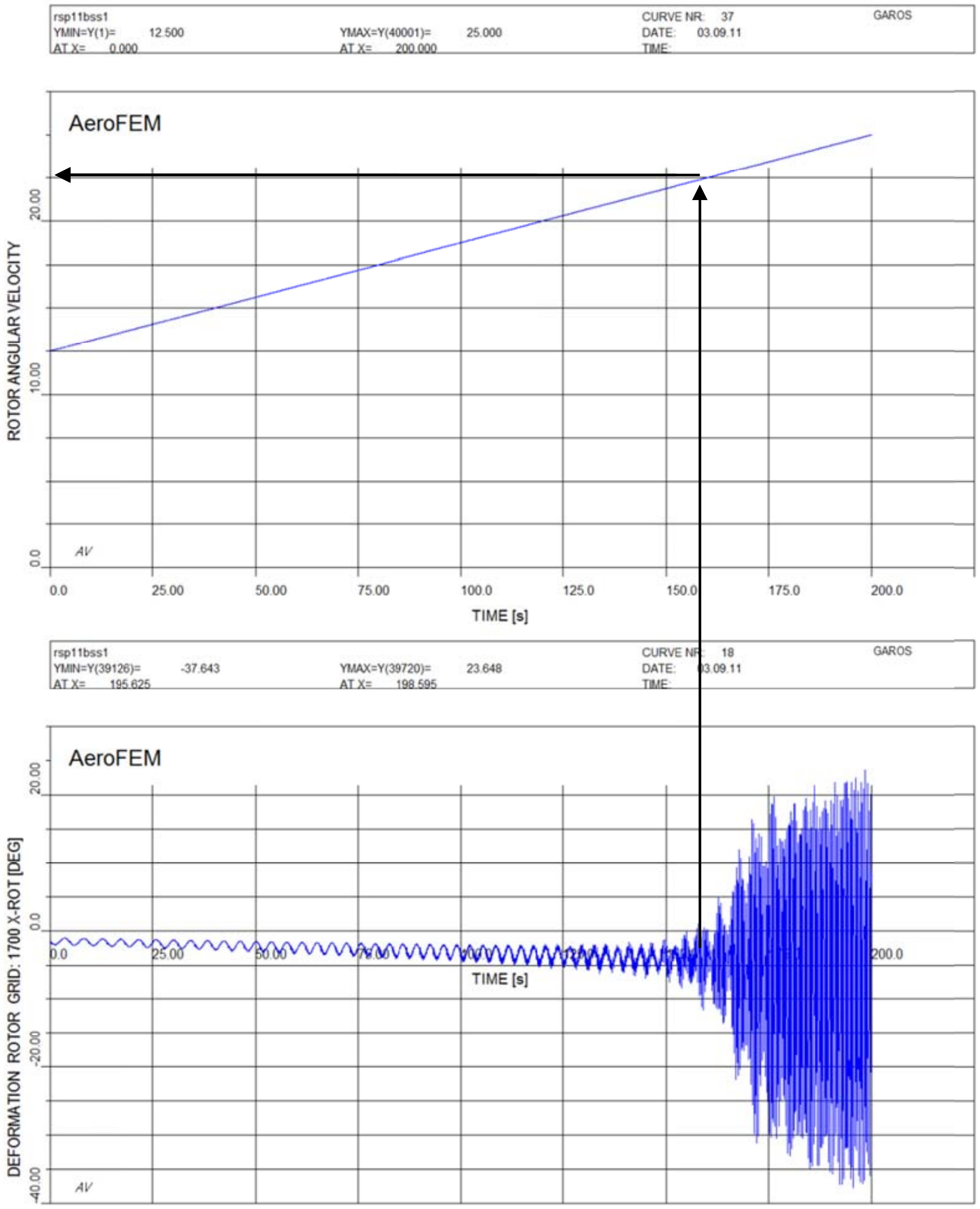
Bifurcation

The real parts of the eigenvalues show a stable system after the divergence bifurcation.



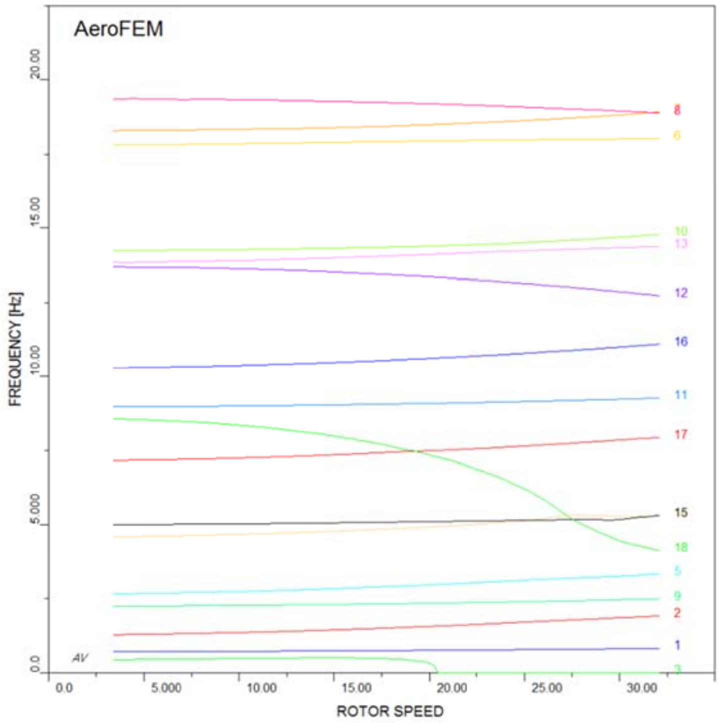
Torsion modes

Damping curves for the rotor. The symmetric blade torsion gets unstable around 23 RPM

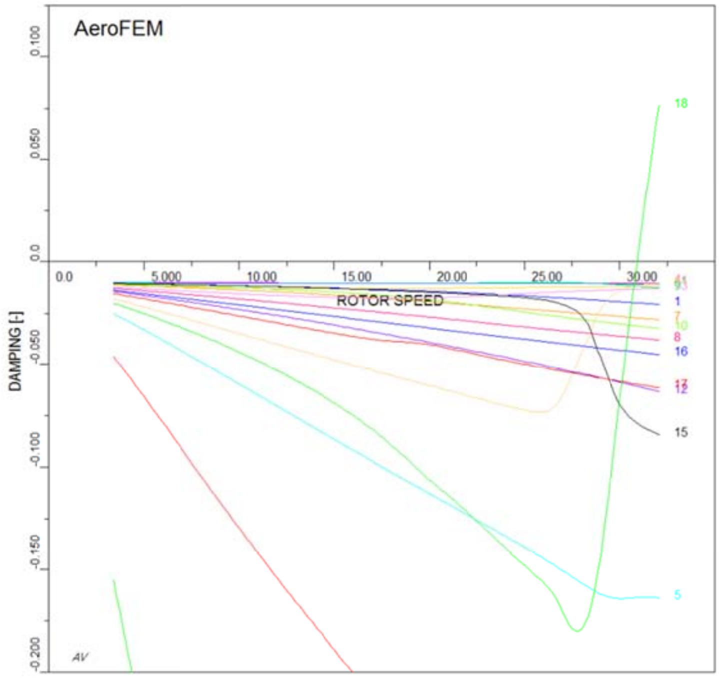


Result of a sweep analysis showing the torsion instability shortly below 23 RPM which is in good agreement with the stability analysis

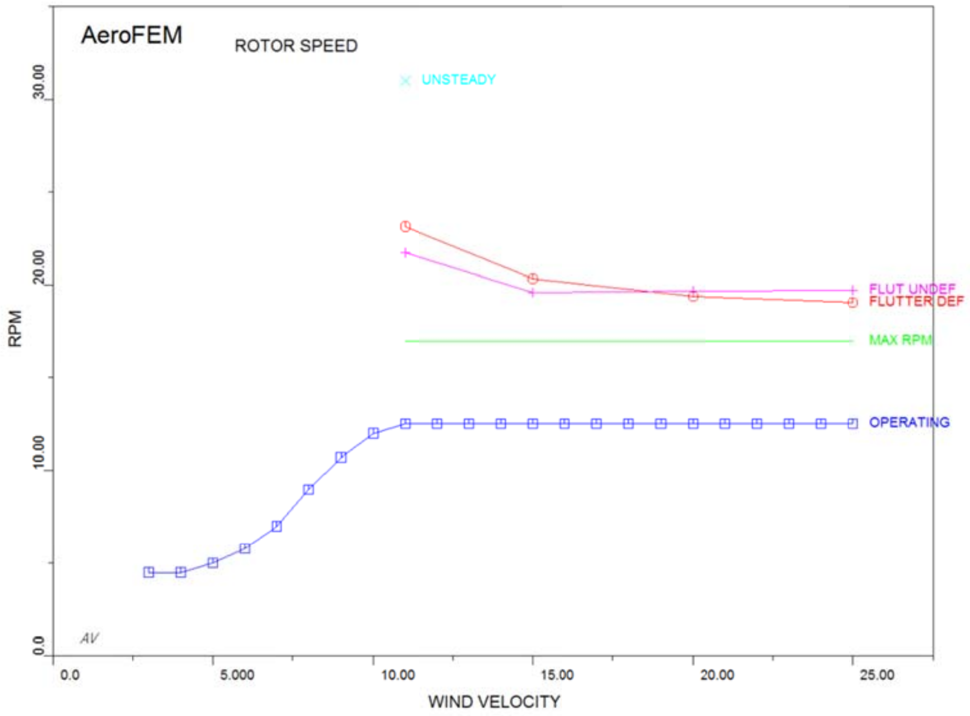
In reality there is a time lag between motion and aerodynamic forces due to the time it takes for the circulation to build up. In the time domain this can be accounted for with the Wagner function operating on the downwash function due to the airfoil motion and with the Küssner function for the forces due to dynamic excitation due to for example a gust. In the frequency domain the Wagner function is transformed to the Theodorsen function which is dependent on the reduced (dimensionless) frequency. The aerodynamic matrices are calculated for a sufficiently high number of reduced frequencies and the solution is found by a PK iteration method similar to the method used for aircraft flutter analysis.



Eigenfrequencies of the undeformed blade with unsteady aerodynamic forces



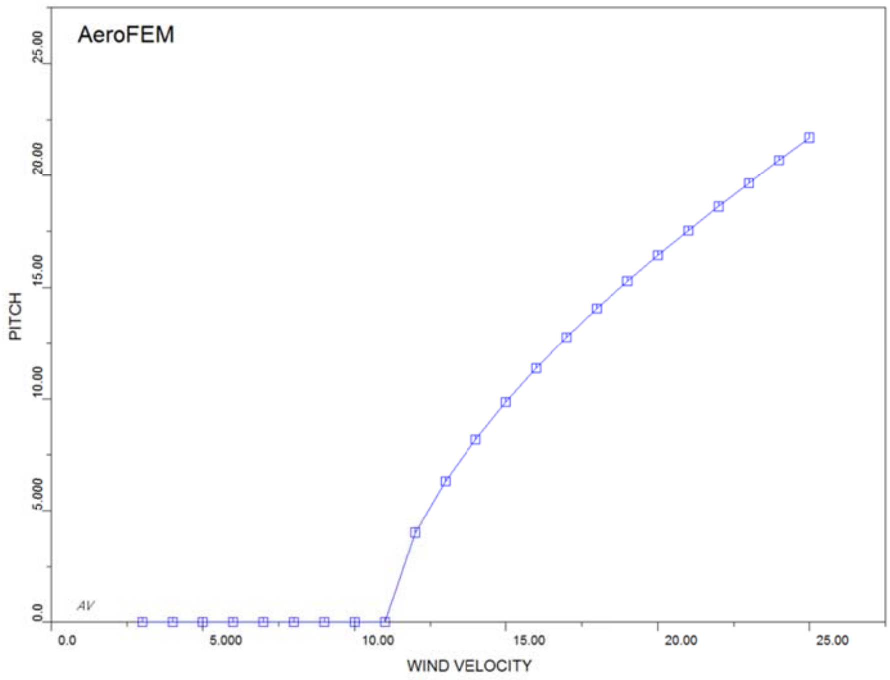
Damping values of the undeformed blade with the unsteady aerodynamic forces are shown. For modes with high frequencies the real part of the aerodynamic forces is reduced and a time lag occurs due to the imaginary part.



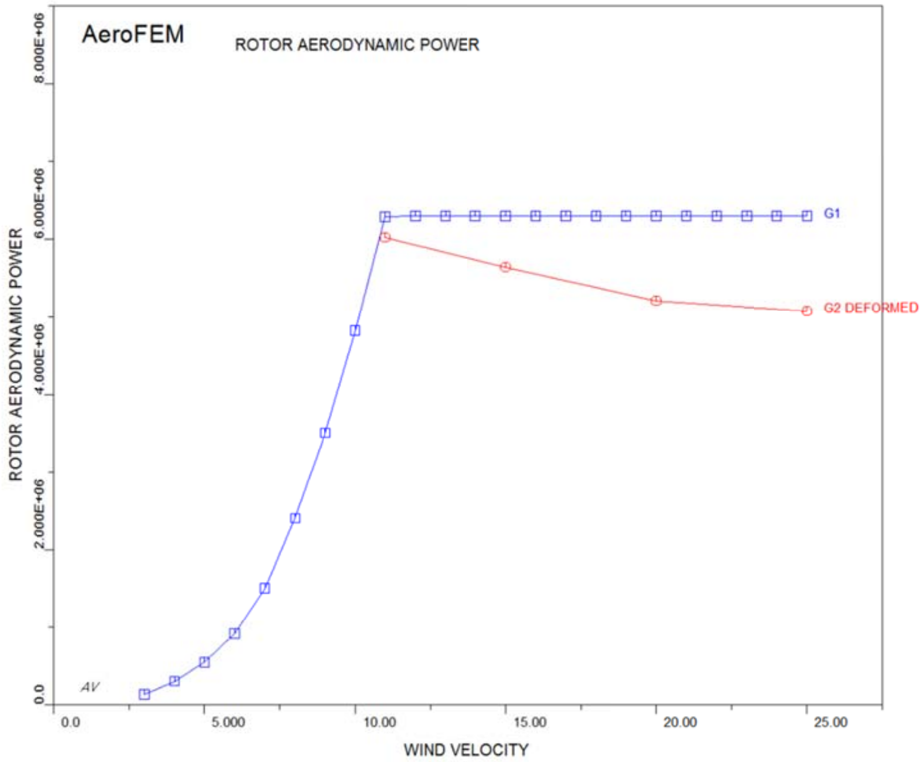
The flutter analysis must be done for different operating conditions. The plot shows decreasing flutter margin for higher wind speeds. In this case the margin is very low. The flutter margin is substantially improved when the true unsteady aerodynamic forces are used.

4 Operating Conditions

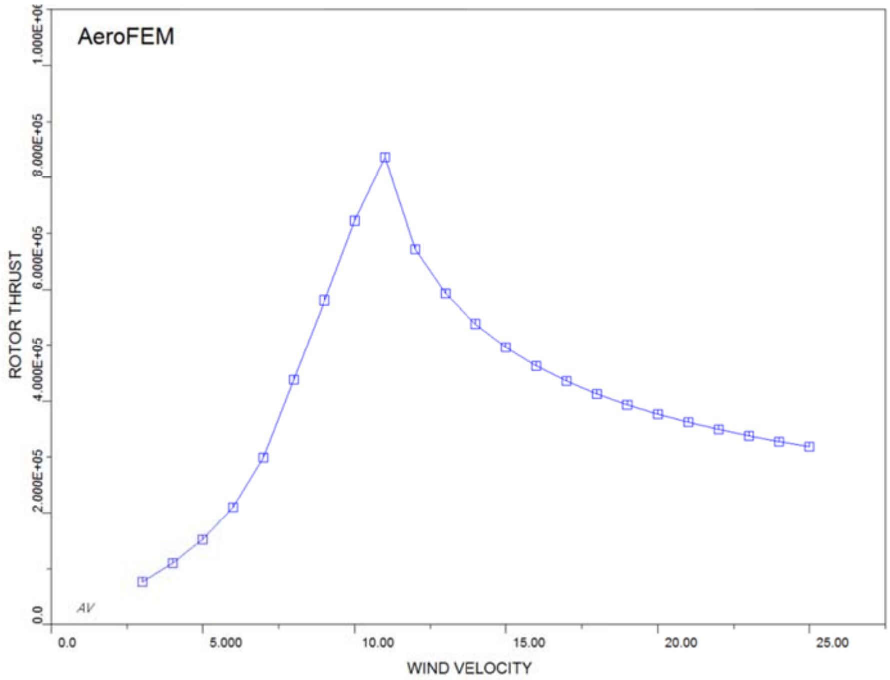
It is useful to calculate rotor thrust and power in order to check the aerodynamic model. These global values can be compared to the results of other programs.



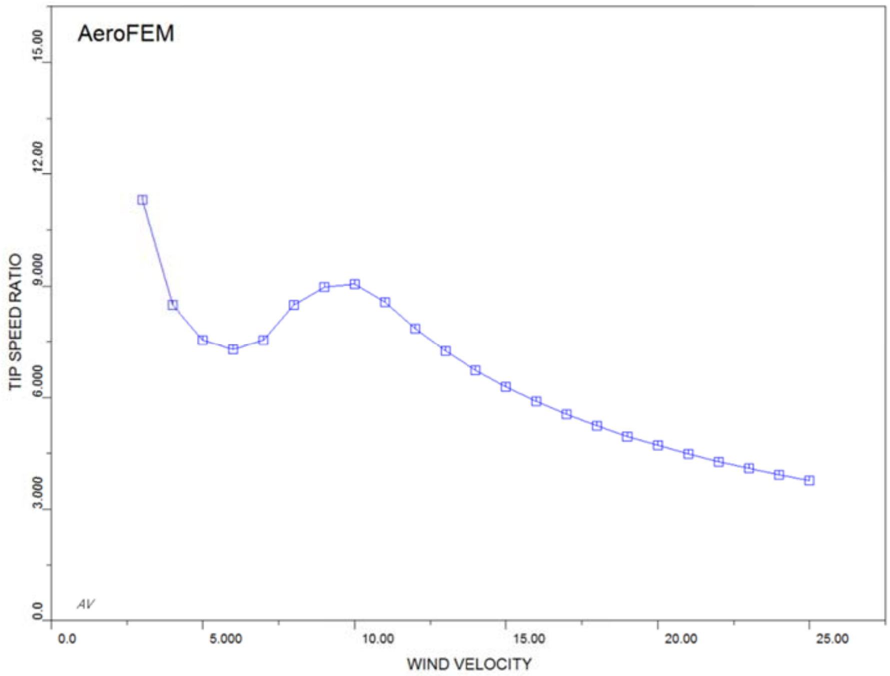
Pitch angle as function of wind velocity



Rotor aerodynamic power shown as function of wind velocity for rigid and elastic blades. Influence of the blade torsional deformation on the power curve is shown as a red line. This loss of power can be compensated for by reducing the pitch angle.



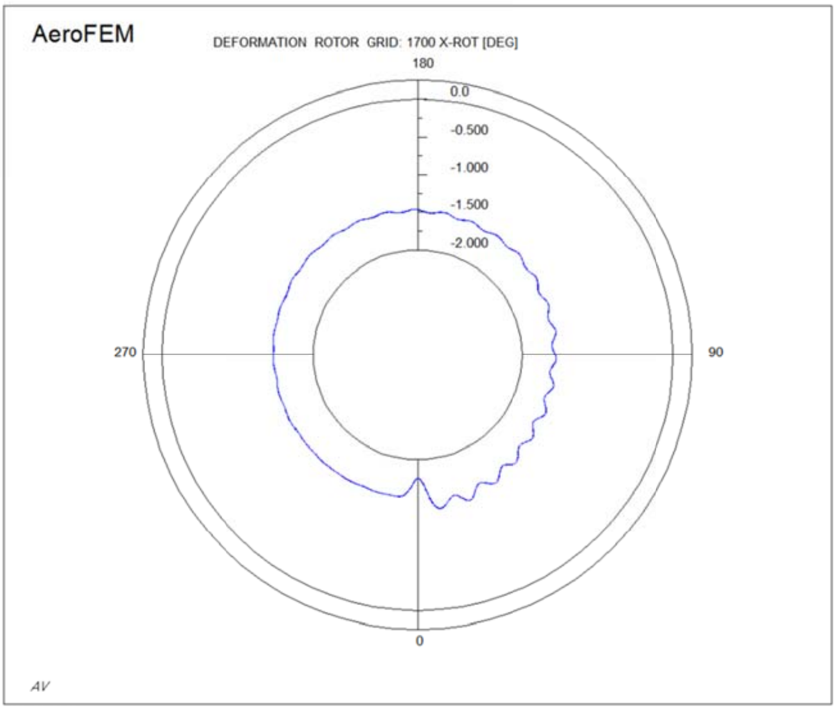
Rotor thrust. Maximum is obtained at the point where the blades start to be pitched. At this point the static deformation of the blades will be large.



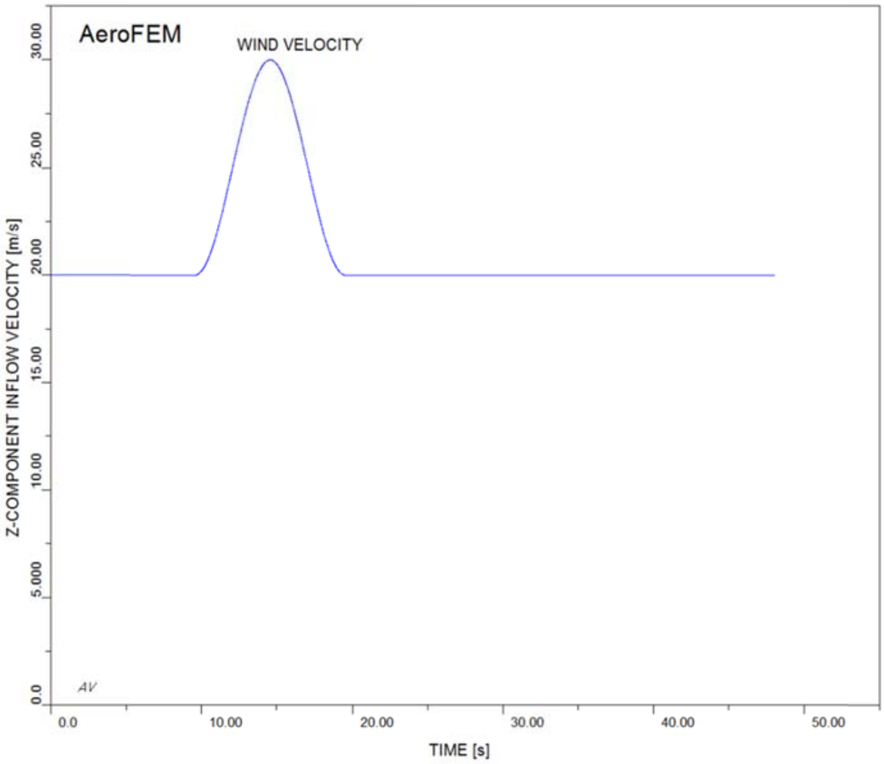
Tip speed ratio as function of the wind velocity.

6 Response analysis

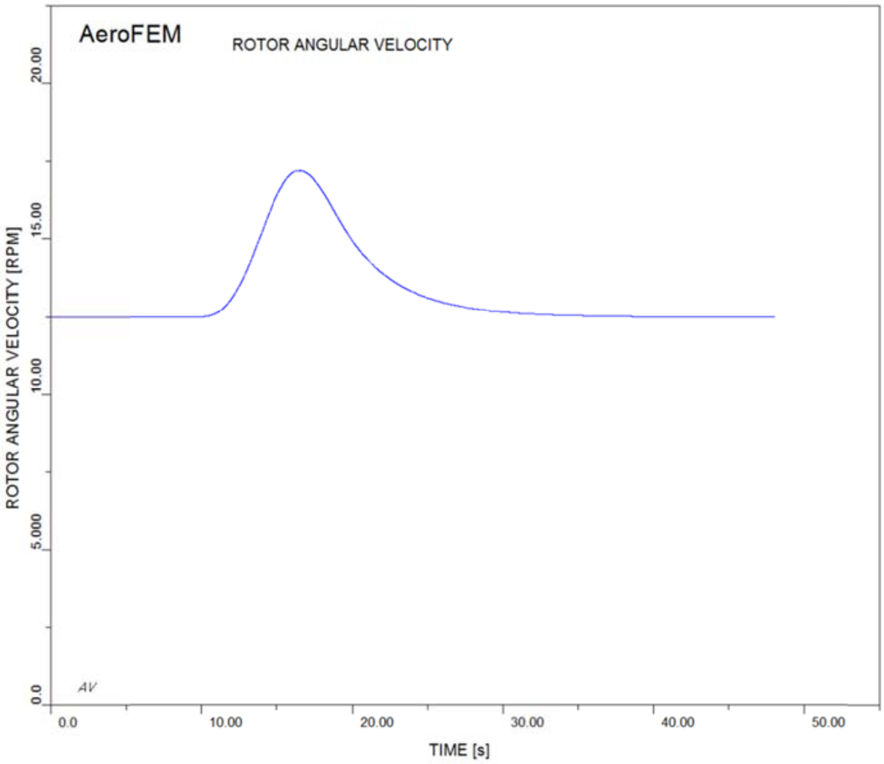
Response analysis can be done for different operating conditions and dynamic loads.



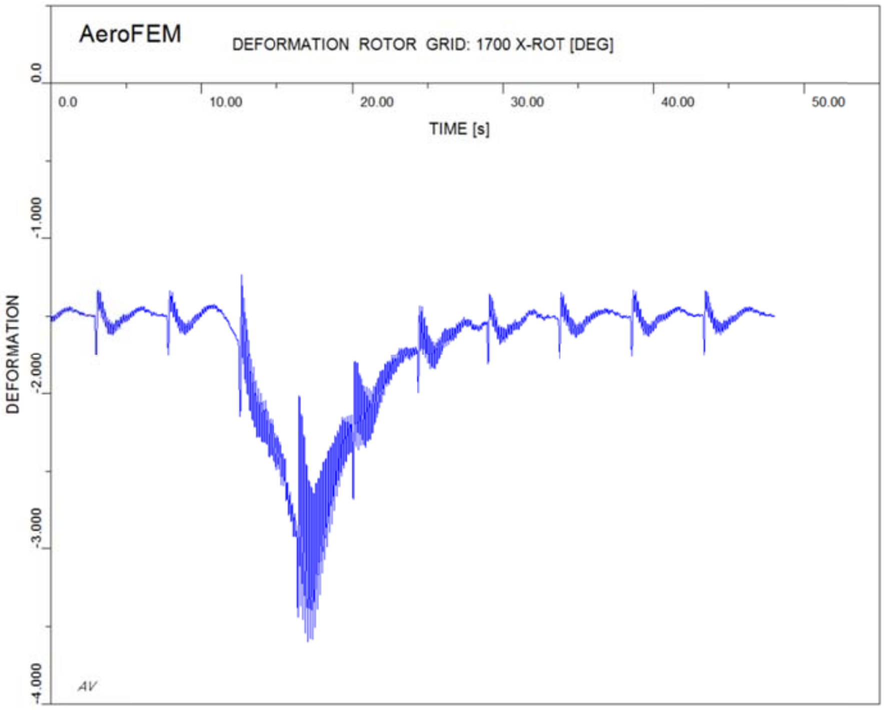
Blade tip torsion due to tower influence for a steady state simulation



A Gust of 10 m/s is added to the steady wind velocity of 20 m/s for a duration of 10 seconds



The rotor speed is increased to 17 RPM due to the gust. Here no pitching of the blades was accounted for.



The plot shows the torsion deflection of the blade during a gust. At the maximum speed the rotor is close to the torsion instability and the damping is low. Therefore the amplitudes are strongly increasing when the rotor speed is high. Here tower influence and gradient were accounted for.