SOFT ROTOR DESIGN
FOR FLEXIBLE TURBINES

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Contract JOU3-CT95-0062

PUBLISHABLE FINAL REPORT

01.01.1996 to 30.06.1998

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

Abstract

The project has consisted in development and testing of a two-bladed soft rotor for an existing 15 kW flexible wind turbine. The new concept is characterised as a free yawing down wind turbine with nacelle tilting flexibility and a two-bladed teetering rotor with three-point supported blades with build-in structural couplings. The power and the loads are controlled by active stall and active coning.

The project has constituted a design process, however with the main emphasis on determination of optimal characteristics for the turbine, perceived as a universal concept.

The concept has been developed by extensive application of aeroelastic predictions, numerical optimisation and stability analysis in order to obtain optimal aeroelastic response and minimal loads. The calculations and succeeding model tests have been performed particularly for a 13 m diameter rotor, but all conceptual design principles have been focused on application to large MW turbines. The intention with this has been to make the results generally applicable and not limited to the development of the specific wind turbine.

The flexible blades and the principle of active coning allows the blades to deflect with the wind to such an extent that the loads are much reduced during stand still in extreme winds. Comparisons of predictions for this concept and a similar rigid rotor show that the blade and rotor loads are reduced to between 25 and 50 % during operation as well as during stand still in extreme winds. This, however, is not a universal ratio for the relation between the loads on the two concepts. In particular this relation depends upon the size of the turbine.

The aeroelastic predictions have covered normal operation, stand still in extreme winds and abnormal upwind operation. Corresponding conditions have been investigated with the prototype turbine, and the measurements have to a large extent verified the predicted turbine characteristics. The turbine has been operating perfectly in all conditions, and it has as a result of the experiments and measurements not been necessary to correct one single parameter setting, in order to obtain the estimated optimal characteristics – not even the blade pitch setting.

The work has confirmed that substantial load reductions can be obtained for this concept in comparison to the traditional ones, and that the applied calculation tools are applicable even for such an extreme configuration.

Altogether the experience from conducting the project is that the resulting design represents a frame for a quite universal concept that contains great potentials for future detailed developments and refinements.

Research funded in part by THE EUROPEAN COMMISSION in the framework of the Non Nuclear Energy Programme JOULE 3.EC.

Contract JOR3-CT-0062 "Soft Rotor Design"

Parts of the work performed by Risø has been funded by The Danish Ministry of Energy through the project: "Design af fleksibel rotor til dynamisk aktiv mølle" EFP-95 contract ENS-1363/95-0002

Contents

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1. Objectives

The ultimate objectives of the project are to improve the performance and show the prospects for cost effectiveness of flexible wind turbine designs. This will be achieved by bringing new advanced technological know-how to the design of optimal soft rotors for stall regulated, free yawing, free-tilting, teetered two-bladed wind turbines. The project will result in the design and manufacture of a rotor. A demonstration will be made on an existing flexible wind turbine, developed and erected at Risø. The measurement of its performance and the turbine's overall unsteady behaviour as compared to the use of present "stiff" rotors will show to what extent the set objectives have been attained.

The project aims at initiating entirely new technological advances with potentials for the development of wind turbines of all sizes.

The starting point for the project is the ongoing Risø concept development work, which has resulted in a turbine that is designed to operate super critically with respect to most of the fundamental natural frequencies. The turbine is free yawing, downwind with nacelle tilting flexibility and nearly free teeter. This combination of degrees of freedom is new and the actual turbine has been in continuous operation for almost one year showing excellent stability.

The project consists in a development of this 15 kW turbine from relatively, stiff teetering rotor to a flexible rotor by taking advantage of structural coupling between different component deflections, in order to obtain optimal aerodynamic and dynamic characteristics under load. Even though the resulting turbine design can be used directly for a small scale turbine, all conceptual design principles and calculation methods are focused on application to large turbines.

The work content involves the application of advanced computational tools including optimisation for design of the rotor with respect to aerodynamics (planform, airfoil geometry and tip shape), structural dynamics, and structures. Structural dynamic design comprises comprehensive flutter analysis taking torsional degrees of freedom and dynamic stall models into account. The structural design process includes the possibility to build blades having designed flexible characteristics.

The preconditions for the design of the soft rotor is that it should suit the existing turbine with respect to rotational speed, maximum power and loads and the concept characterised by free yaw, downwind and tilting flexibility. The intention is to reconsider some of the fundamental parameters that are not usually taken into account in the rotor design process and investigate possible potentials by application of new features.

2. Technical description

2.1 Introduction

The main objective of the project has been to demonstrate the potential in flexible wind turbine design, by application of new advanced aeroelastic prediction tools to the design of optimal soft rotors. The project tasks have covered development, design, manufacture and testing of a two-bladed soft rotor for an existing 15 kW flexible wind turbine. The new concept is characterised as a free yawing down wind turbine with nacelle tilting flexibility and a two-bladed teetering rotor with hinged blades that are controlled by active stall and active coning. The “hinging” of the blades is obtained by a three-point support structure with built-in structural couplings.

The work has covered the following work packages:

Aerodynamic design,
Structural dynamic design,
Structural design,
Manufacture,
Testing/measurements and
Evaluation.

The project constitutes a design process, which on the basis of a certain design philosophy represents a chain of well argumented decisions, leading consistently to the final design. However, in this project the emphasis has been on the theoretical investigations that determine the characteristics and the principles and on the verification of this by measurements rather than on the detailed design work.

The concept has been developed by extensive application of aeroelastic predictions, numerical optimisation and stability analysis aiming at obtaining optimal aeroelastic response and minimal loads. The calculations and succeeding model tests have been performed particularly for a 13 m diameter rotor, but all conceptual design principles have been focused on application to large MW turbines. The intention has been to make the results generally applicable in order to establish a general basis for a universal concept, rather than limiting the development to the specific wind turbine.

The idea has been to reconsider some of the fundamental parameters that are not usually taken into account in the rotor design process and to investigate possible potentials by application of new features. Much effort on too deviating and advanced design features could, however, defuse concentration with respect to the main achievements. An identification and quantification of a potential, thus, does not mean that the feature necessarily should be implemented in the prototype design, but could be an opportunity for possible future optimisation of the soft rotor concept.

After the initial calculations, which were based on characteristics corresponding to the original rotor of the Risø experimental turbine, the new LM 6.1 m blade was defined as the state of the art in blade aerodynamic design and chosen as a new starting point for the soft rotor development. All further calculations were performed by parametric variations around the characteristics of this blade.

2.2 Aerodynamic design

Adaptable blade geometry has proven to possess some potentials both with respect to energy production, loads and stability. Adaptable blade geometry could be realised through large deformations with loading or build-in structural couplings between e.g. flapwise bending and blade twist or airfoil shape. These subjects have been further treated in the report, and some features are built into the final design. The potentials with respect to adaptable airfoil shape with loading were not investigated specifically, but the final design is prepared for this feature in that the blade is designed as a pure shell without spars. Furthermore, this is to some extent equivalent to adaptable twist.

An investigation was performed of the potentials for energy output increase by using variable geometry with wind speed by application of numerical optimisation. Realistic blade geometry characteristics were assumed to be variables, in particular the pitch setting and the twist distribution. An optimum collective pitch setting with wind speed resulted in a yearly energy increase of 2.7 %, relative to fixed pitch operation. Assuming an optimum twist distribution for all operational conditions resulted accordingly in a 5.5 % increase.

The resulting optimum twist distribution as a function of radial station and wind speed is illustrated in Figure 1 (Ref.1).

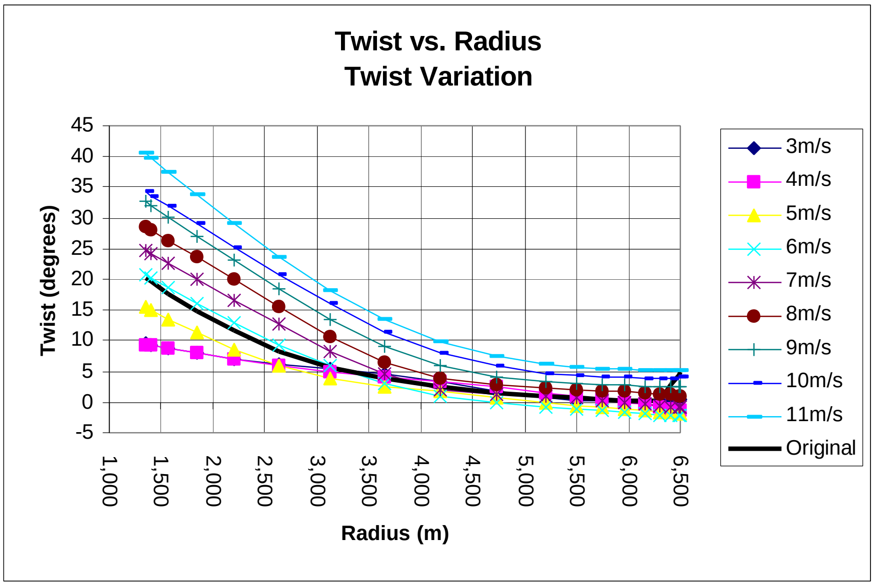

Figure 1. Optimum twist distribution

There is a gradual increase in optimum twist with wind speed, however, only up to 11 m/s, and above this speed the relation is adverse. This behaviour is difficult to obtain by structural coupling without applying advanced active control, so this characteristic is not applied for the prototype concept. However, the final design has semi-pitchable blades as airbrake system and is thus prepared for active stall regulation, which means that the collective pitch setting is very easy to apply, and the optimum twist distribution is then a realistic option for further developments.

The emphasis concerning the blade planform has been on the blade axis shape, which is usually not taken into account as a design parameter. An investigation was performed with different position of the blade axis relative to a line through the rotor centre. The spanwise flow velocities are different in the separated regions for these cases, however, the conclusion is, that the difference is assumed to have minor impact on the pressure distribution and thus lift-coefficient, except very close to the root. Also at the tip there are differences, which are expected to affect the noise emission.

A soft rotor design might give rise to high coning angles and/or large blade deflections. This condition would violate one of the fundamental assumptions in the blade element momentum theory.

An investigation was performed of how the out of plane blade axis shape or swept rotor surface shape affects the rotor efficiency. Four different shapes were investigated using Navier-Stokes simulations of the flow field, with volume forces applied to the rotor surface. The different shapes correspond to a straight rotor, a straight rotor with winglets, a coned rotor and a coned rotor with high tip deflection (flexible rotor) as illustrated in Figure 2. The different rotors were compared on the condition of equal projected swept area and equal thrust coefficient and uniform load distribution in radial direction. The result in the form of axial flow velocities along the radial position for the four rotors is illustrated in Figure 3 (Ref. 2).

The investigation has revealed the important finding that the induced velocities for straight versus coned or flexible rotors are different at the same radial station, and locally the efficiency can exceed the Betz' limit, however, when integrating over the whole rotor projected area, there is no net difference. This means that the total efficiency is equal for all rotors, independent of out of plane shape.

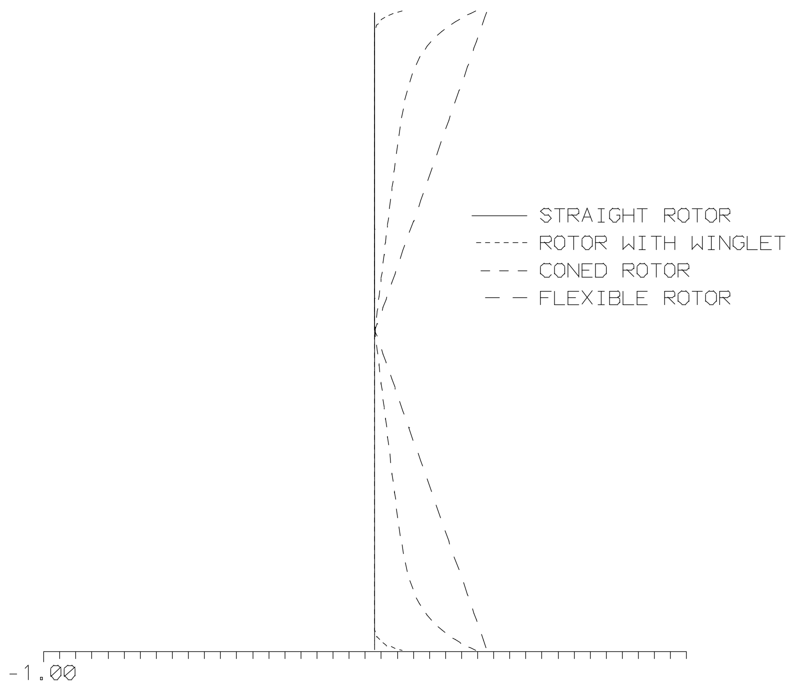

Figure 2. Different rotor configurations

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plot.eps
Oprettet af:
gnuplot 3.5 (pre 3.6) patchlevel beta 340
Eksempel:
EPS-billedet blev ikke gemt
med et eksempel.
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EPS-billedet kan udskrives på en
PostScript printer, men ikke på
andre printere.

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Figure 3. Axial flow velocities for different rotor configurations

A soft rotor that is suited for operation at high coning angles should be designed e.g. with respect to twist distribution by correction for the lower induced velocities at the inboard blade sections.

The blade tip shape has been subject to some considerations concerning noise and aerodynamic damping. The roll-up of the tip vortex on the blade surface is important for the aerodynamic noise, and the development and extent of separation at the tip determines the aerodynamic damping, which at the tip is of particular importance in order to avoid stall-induced vibrations. This problem was solved by application of flap/edge blade coupling at the blade hinge. As there was no aerodynamic advantage by application of a soft tip, it was decided to use the existing tip shape of the LM 6.1 m blade, which meant that it is not necessary to modify the mould at the tip end.

The conclusion from the detailed aerodynamic investigations was that, altogether there are no very important arguments for modifying the aerodynamic characteristics of the LM 6.1 m blade in order to fulfil the objectives and demonstrate the feasibility of soft rotor design. This means that the modifications could be limited to the structural dynamic characteristics and structural design.

2.3 Structural dynamic design

An important objective of the project has been to show which potentially favourable degrees of freedom can be accounted for in the design phase in order to obtain a light weight, simple and stable turbine. The emphasis has been on subjects that are beyond the usual wind turbine design considerations.

The basis for the structural dynamic design has been aeroelastic modelling of the turbine in different configurations [4], [5]. All calculations were performed by parametric variations around the characteristics of the LM 6.1 m blade, and numerical optimisation was applied in order to estimate the optimum combination of some of the characteristics.

Six different concepts were defined by combination of the existing turbine and the LM 6.1 m blade in a 13 m diameter rotor configuration with assumed different structural properties. This represents concepts from rigid hub rotor with distributed flexibility, over hinged rotor to hinged blades with different flap/pitch couplings.

An extensive parametric study was conducted by setting parameters corresponding to the above defined configurations and running aeroelastic predictions at three different wind speeds. The wind speeds correspond to operation before stall, in stall and beyond stall, respectively. One test case was defined as a step change in wind direction, from which the total turbine dynamics is reflected and can be compared between the various configurations. The conclusion from the evaluation of the overall advantage of the different configurations was that a certain combination of flexibility in both teeter hinge and blade root is most optimal. This means that the concept had converged towards one with all characteristics integrated: the teetering rotor with blade root flexure and any favourable structural coupling.

The parametric study thus led to the selection of five main characteristics to be used as optimisation variables : the teeter and flex-beam stiffnesses, the amount of $\delta 3$ coupling on the teeter and on the flex-beam and finally the radial position of the hinge simulating the flex-beam. Some side constraints were set on the optimisation variables, Usually corresponding to certain minimum and maximum values, in order to allow for a realistic dimensioning of the turbine.

The optimisation was carried out at different wind speeds. Each solution was then recalculated at the other wind speeds in order to see whether the optimum found at one speed also yielded gain under different wind conditions.

Figure 4 presents the values of the optimisation variables for different weighting functions for the unsteady flap moment (F) and the torque fluctuation (T) for the optimum designs. One can see that both the flex-beam stiffness and $\delta 3$ coupling present some variation with wind speed as well as with the weighting function. A positive $\delta 3$ coupling value on the teeter hinge means that when the blade at the top position is deflected downwind, the angle of attack is increased on this blade. A negative $\delta 3$ coupling value of the flex-beam means that when the blade is deflected downwind, its angle of attack is decreased.

This procedure led to the choice of the best solution, being in fact a compromise between the various gains obtained at different wind speeds. The selected design was then calculated over a wide range of wind speeds, ranging from 5 m/s to 25 m/s. This was done to check whether the optimum significantly improved the overall aeroelastic behaviour of the turbine and to assure that the optimum was not only local.

These optimisations led to the optimal characteristics for the rotor, which was then the precondition for the design and construction work.

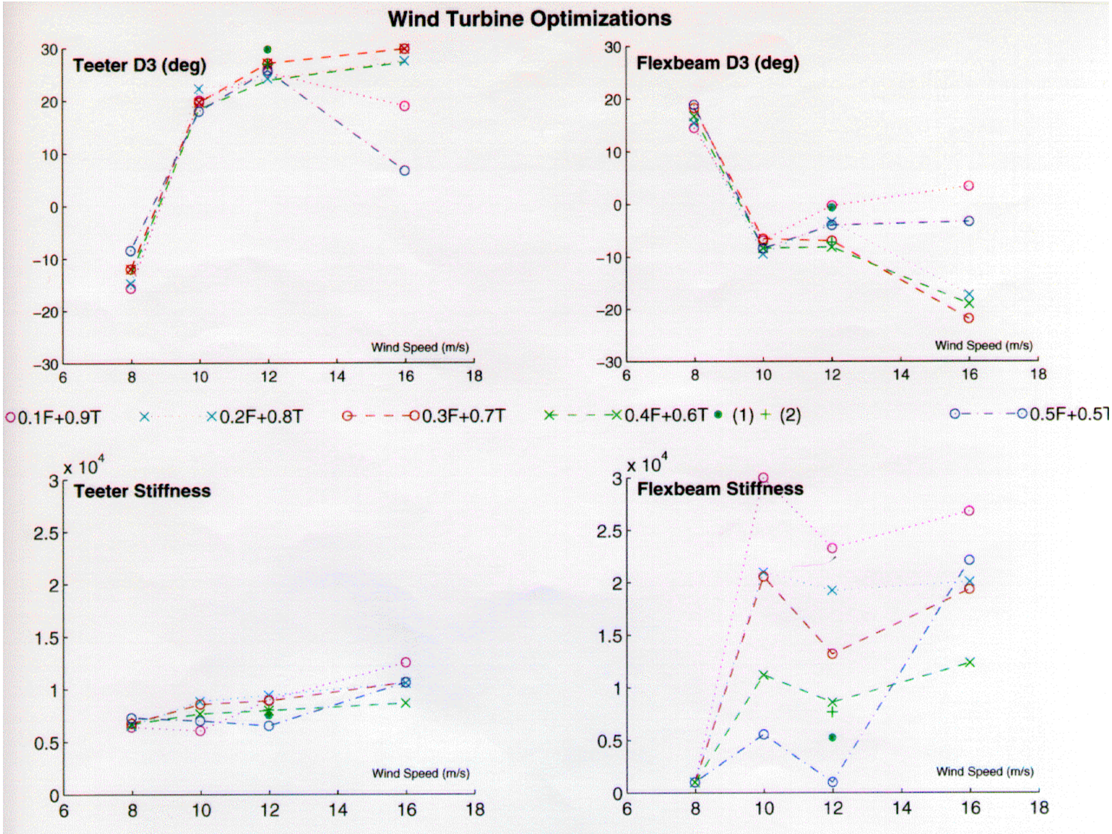

Figure 4. Values of the optimisation variable

2.4 Design of the soft rotor

In order to arrive at a realistic (or universal) solution, it was decided to consider the airbrake as a requirement for the soft rotor design. Numerous considerations lead to the decision of using the blade pitch function as a basis for the design of the air brake system. This furthermore gives the opportunity for the concept in the future to include the principle of active stall, which will be advantageous for large turbines.

The design considerations for the blade led to a solution, where the blade practically only consists of the shell, which constitutes the aerodynamic shape, and a flex-beam that is designed to give the optimum blade flapwise stiffness and damping characteristics. This means that the blade has no spar or webs and thus has potentials for very light weight and future application of adaptable airfoil geometry.

The flex-beam is a sandwich construction in glass-fibre and rubber, which gives favourable damping characteristics [3] with respect to stall-induced vibrations and yaw-stability.

Alternatively to the traditional blade root flange, the new concept applies a three-point support of the blades that in principle is applicable independent of wind turbine size. Two of the points constitute flap hinges at the leading and trailing edges. The third point transfers the flapwise bending moment through a flex-beam of well-defined stiffness – the value of which depends highly on the size of the wind turbine. This is due to the fact that the centrifugal stiffening, by up-scaling with similarity, will decrease relative to the aerodynamic forces. The principle offers the possibility to cone the blades 90° so that they are aligned with the wind in order to reduce blade and tower loads at stand still in extreme winds.

The airbrake function is obtained by pitching of the blades approximately 15^o negative, which further offers the possibility for adjustable pitch angle and thus active stall-regulation.

For the actual manufactured turbine, the two control possibilities are only obtained by manual adjustment. A picture of the final turbine is given in Figure 5.

In summary the final concept is characterised by:

Two-bladed teetering rotor.
Hinged blades with flap/edge-coupling that is controlled by both active stall and active coning.
Free-yawing downwind turbine.
Nacelle tilt flexibility.

Figure 5. The flexible turbine during the measurement campaign

During the design phase compromises were made with respect to some of the less important optimal characteristics, in order to facilitate manufacture and testing. Comprehensive calculations were performed once more with parameter values corresponding to those obtained for the finally manufactured turbine. In some cases comparisons were made to calculations for a corresponding teetering rotor turbine with rigid blades. This comparison is illustrated in Figure 6 and 7 for the flapwise blade bending moment and the axial thrust, respectively. It is revealed that these loads are much reduced for the soft rotor design compared to the teetering rotor.

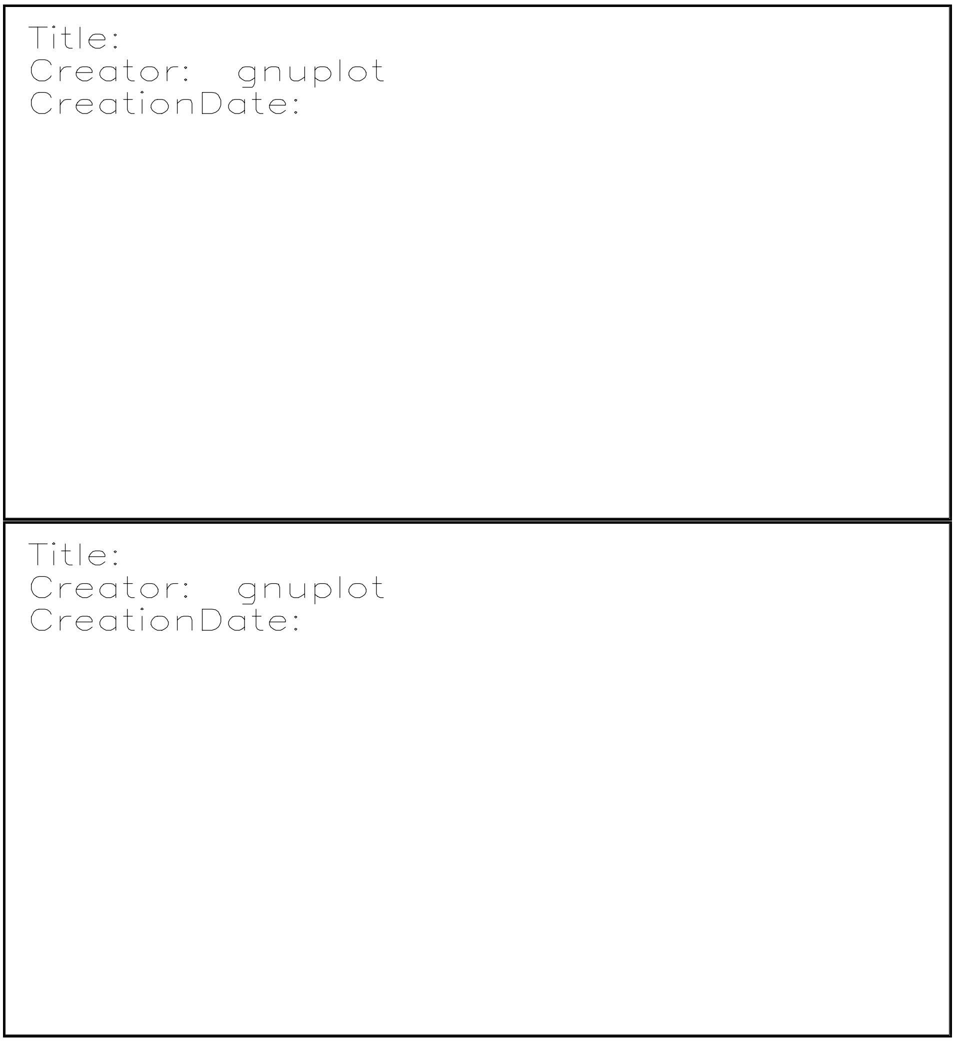

Figure 6. Statistics of flap moment in operation for a teetering rotor with soft and rigid blades, respectively.

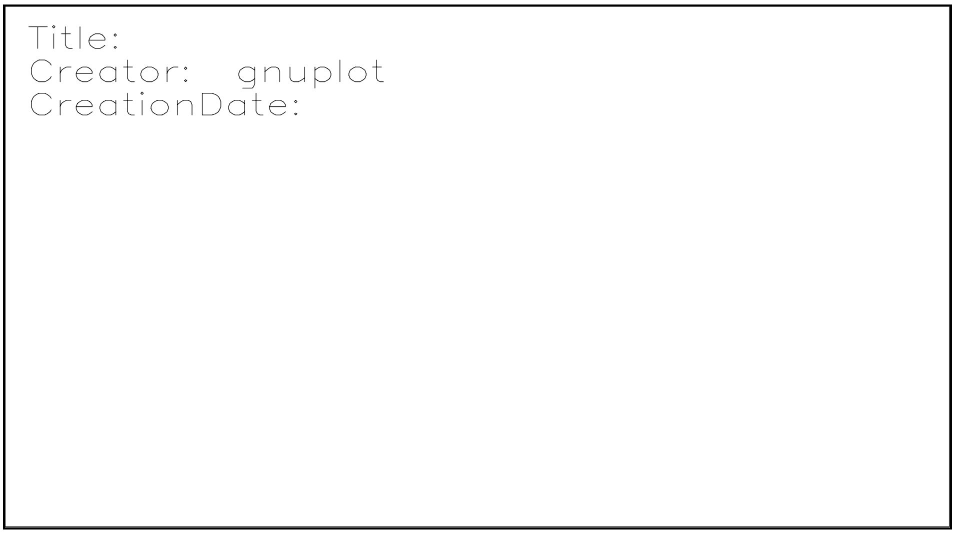

Figure 7. Statistics of thrust for a teetering rotor with soft and rigid blades, respectively.

One of the imaginable problems with the free yawing soft rotor design is the possibility for the downwind rotor to yaw 180 degrees into upwind position, as a response to an unusual turbulence- or gust input. This is particularly critical if the turbine is stable in yaw in upwind operation. The prediction of the yaw behaviour revealed that the turbine in upwind operation is unstable in yaw at wind speeds below 8 m/s and above 12 m/s, however, in the range 8-12 m/s, there is a risk that it is stable in the unwanted position.

The risk for upwind operation was taken into account in the design phase by applying increased blade hinge stiffness for negative deflection of the blades, and by application of sufficient blade tower distance.

2.5 Test and evaluation

The measurements on the turbine were performed with the primary objective to verify that the concept resulting from the design process has the desired characteristics on a more general level. The objectives of the measurements have thus been to verify the characteristics of the new concept, rather than to verify the aeroelastic code in detail. The design and instrumentation of the turbine has not in all cases allowed a “clean” measurement of corresponding predicted parameters, however, the ambition has been to design a prototype rather than a test turbine.

The flexible blades and the principle of active coning allows the blades to deflect with the wind to such an extent that the loads are much reduced during stand still in extreme winds. Comparisons of predictions for this concept and a similar rigid rotor shows that the blade and rotor loads are reduced to between 25 and 50 % during operation as well as during stand still in extreme winds. This, however, is not a universal ratio for the relation between the loads on the two concepts. In particular this relation depends on the size of the turbine.

In order to illustrate the reduced loads for the soft rotor, the statistics for the measured flapwise blade bending moment is illustrated in Figure 8.

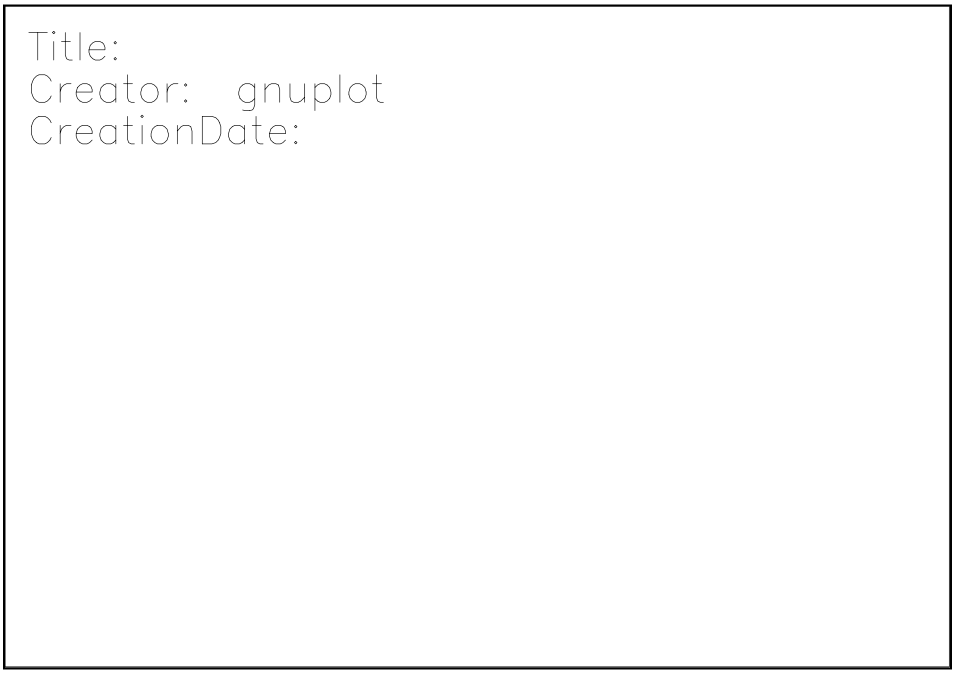

Figure 8 Statistics for the flap moment in operation.

The yaw stability reflects the important characteristics for the turbine, as it is determined as the resulting response of the sum of the main forces on the turbine. The mean yaw angle is predicted to be very close to zero degrees, except for very low wind speeds, where there is a tendency for positive yawing, as reflected in Figure 9. This was also the case for the measurements that are presented in Figure 10.

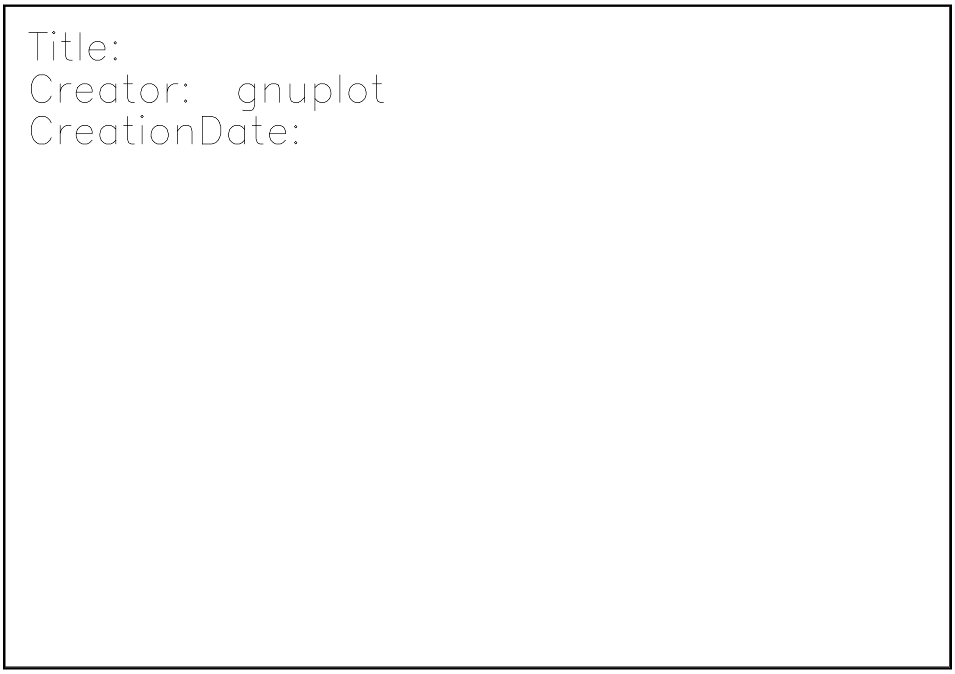

Figure 9 Statistics of predicted yaw angle in operation.

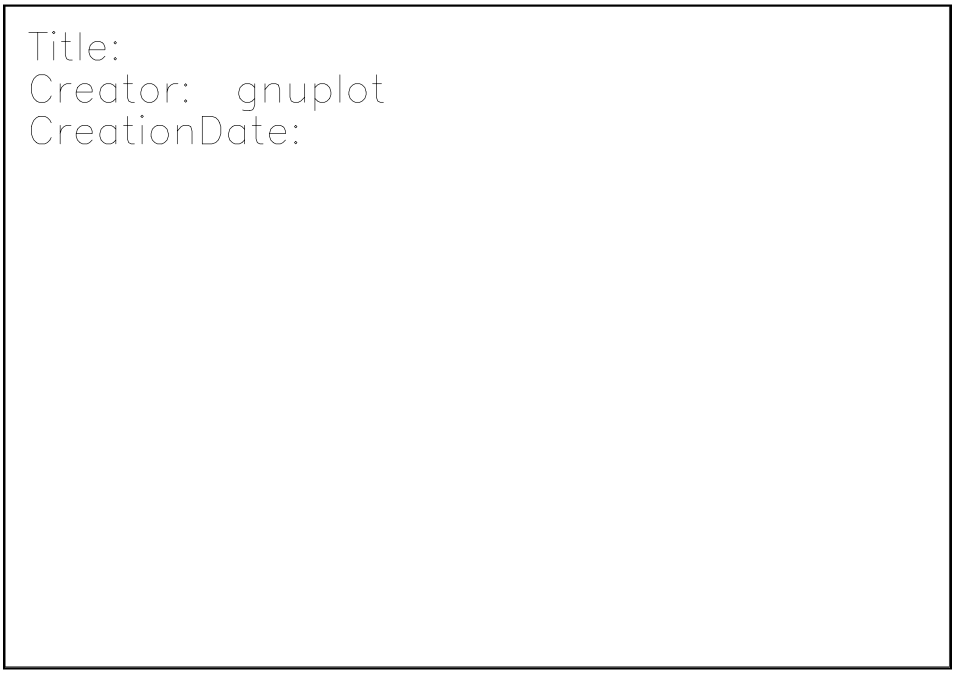

Figure 10. 30 seconds mean values of measured yaw error.

Teeter instability could be a serious problem, but no such phenomenon has been encountered for the turbine. The statistics for the predicted and measured teeter angle is given in Figure 11 and 12, respectively. Both graphs demonstrate that the teeter angles will be limited to +/- 8^o in normal operation.

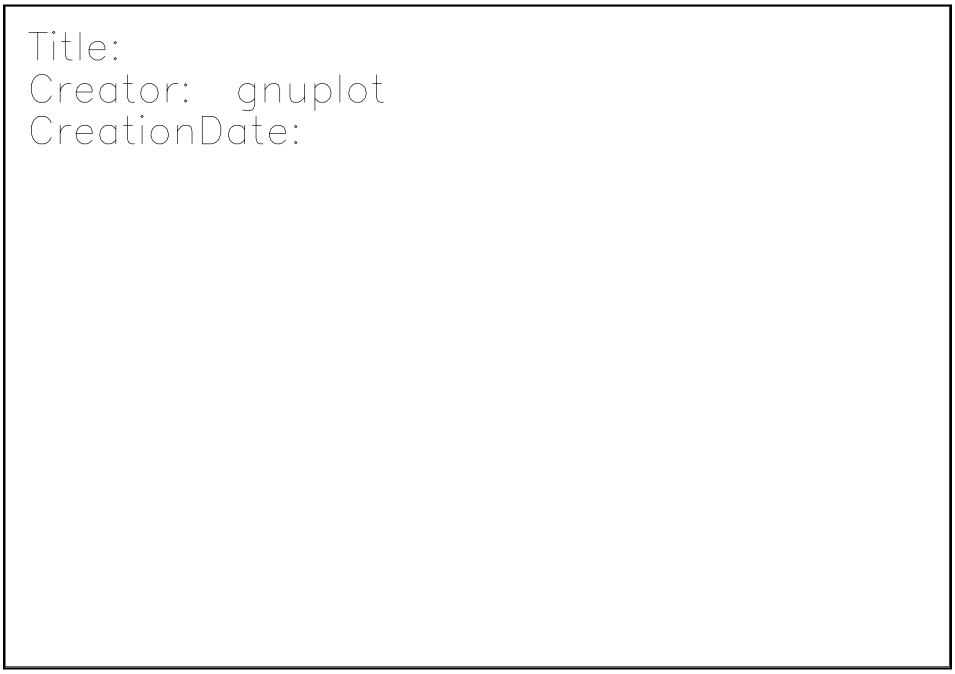

Figure 11. Statistics of predicted teeter angle in operation.

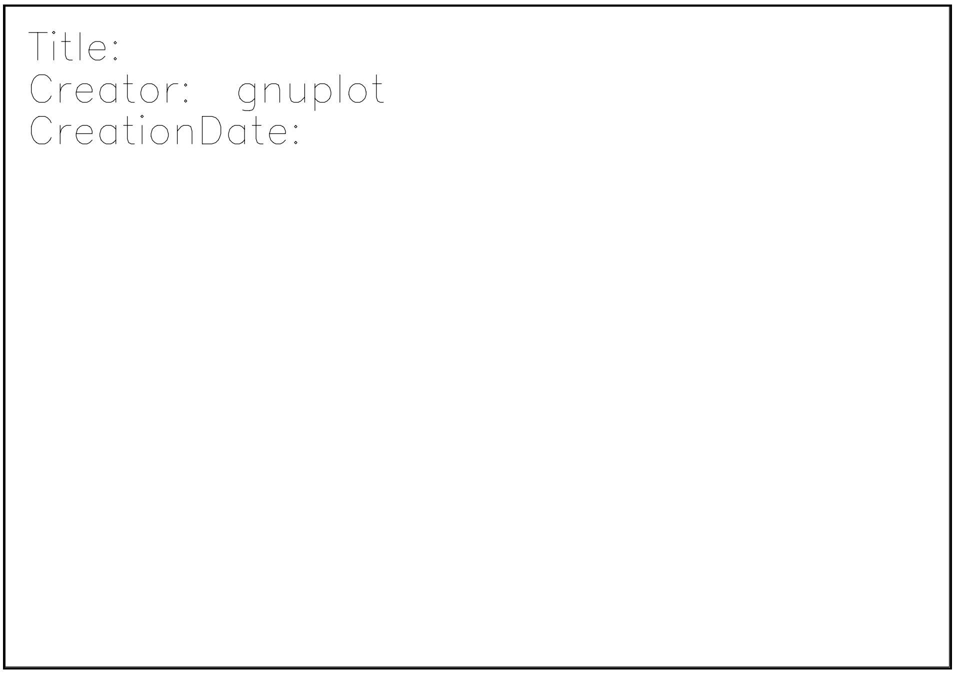

Figure 12. Statistics for measured 30 sec. time series of teeter angle.

The flap moment is higher at stand still in extreme wind than in operation up to 25 m/s. This situation is remedied by coning the blades fully downwind in parked horizontal position. In this condition the blade- and tower loads are much reduced, as the measurements on this configuration has verified. A picture of the turbine in the parked and fully coned condition is presented in Figure 13.

Figure 13. The turbine with the blades at 80 ° coning.

3. Results and conclusions

Advanced aeroelastic predictions in combination with numerical optimisation and stability analysis have been developed and applied in the design process of a 13 m diameter soft rotor, aiming at establishment of a verified design tool for soft rotors in order to obtain optimal aeroelastic response and minimal loads.

The design process has covered development, design, manufacture and testing of a two-bladed soft rotor for an existing 15 kW flexible turbine. The new concept is characterised as a free yawing down wind turbine with nacelle tilting flexibility and a two-bladed teetering rotor with hinged blades that are controlled by active stall and active coning. The blades have built-in structural coupling. The aeroelastic optimisations have been performed particularly for the 13 m diameter rotor, but all conceptual design principles have been focused on application to large MW turbines.

The aeroelastic predictions have covered normal operation, stand still in extreme winds and abnormal upwind operation. Corresponding conditions have been investigated with the manufactured prototype turbine, and the measurements have to a large extent verified the estimated turbine characteristics and thus the design tools.

The flexible blades and the principle of active coning allows the blades to deflect with the wind in order to reduce the loads. The loads are reduced to between 25 and 50 % during operation as well as during stand still in extreme winds for this concept in comparison with a similar one with a rigid teetering rotor. The work has thus confirmed that substantial load reductions can be obtained for this concept in comparison to the traditional ones, and that the applied calculation tools are applicable even for such an extreme configuration.

The turbine has been operating perfectly in all conditions, and it has as a result of the experiments and measurements not been necessary to correct one single parameter setting, in order to obtain the estimated optimal characteristics – not even the blade pitch setting.

Altogether the experience from conducting the project is that the resulting design represents a general basis for a quite universal concept that contains great potentials for future detailed developments and refinements.

4. Exploitation plans and anticipated benefits

The manufactured and tested soft rotor turbine is a scale model prototype for demonstration of the design tools. The real application is intended to be the design of a large MW turbine of the soft rotor concept. This requires the cooperation with a manufacturer of large wind turbines. While the conducted project also included the development of the concept, the exploitation of the result is limited to be focused on up-scaling. The aeroelastic predictions and optimisations can be done with the existing tools, however, a substantial investment in technology transfer, further development, detailed design, manufacture and testing of a MW-size prototype turbine is foreseen.

All together the innovative features of the result are new ways to limit steady and unsteady loads on wind turbines, which has a high commercial potential, however, it requires much know-how on wind turbine technology and high investments.

5. References

[1] Bak, Christian; *Aerodynamic optimisation of a two-bladed wind turbine*. Risø-I-1343(DA), Risø National Laboratory, November 1998.

[2] Madsen, Helge Aagaard; Rasmussen, Flemming; Fact-sheet AED-RB-5 "*Flexible blades and coning changes the efficiency locally*", Risø National Laboratory, July 1998.

[3] Mortensen, Peter R., *"Dæmpning for Flexbeam til tobladet vindmølle"*, d 94 22 32, Technical University of Denmark, October 1998.

[4] Petersen, J.T.; *The Aeroelastic Code HawC – Model and Comparisons"*. In proceedings of "State of the Art of Aeroelastic Codes for Wind Turbine Calculations". 28th Meeting of Experts, International Energy Agency, Annex XI. Technical University of Denmark, Lyngby, Denmark. April 1996, pp. 129-135.

[5] Leconte, P.; Szechenyi, E.; "Aeroelastic Tailoring of Blades: Prospects for Reducing Unsteady Loads and Enhancing Performance", EUWEC '96, Göteborg.