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Risø-R-1365(EN)

Transition Prediction on the NORDTANK 500/41 Turbine Rotor

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September 2002

Abstract

A new simplified transition model for wind turbine blades is described along with the implementation in the EllipSys3D code. The method is based on a sectional treatment of the turbine blade under the assumption of chordwise flow, and lookup tables of transition point location computed by external 2D programs. The coupling of the 2D transition point location and the 3D sectional flow is performed through the stagnation point location. The method is applied to a single rotor case, the NORDTANK 500/41 rotor with LM19.1 blades. The transitional computations show improved agreement with measurements for wind speeds between 11 and 15 m/s. For higher wind speeds, the validity of the transition location computed by the 2D XFOIL code is questionable, and the results cannot be trusted. Analysis of the results comparing fully turbulent and transitional spanwise distributions of tangential forces, reveal that the decrease in power production when applying the transition model is mainly a consequence of the decrease in driving force on the inboard part of the blade between 5 and 12 meter radius. The results are very encouraging, and further studies of other rotors are needed for further validation.

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Contents

1 Introduction

When predicting wind turbine aerodynamics, both in the case of 2D airfoil flow and for full rotor computations, the issue of transition from laminar to turbulent flow is of great importance. From airfoil flow it is well known, that ignoring the transition process and predicting the flow as fully turbulent over the total airfoil will result in erroneous results. These problems are seen as under prediction of the lift below stall, over prediction of drag in the same region, and failure to predict the correct stall angle. Based on these facts, state of the art 2D Navier-Stokes solvers and airfoil prediction codes as the XFOIL code [1] have the possibility for predicting transitional flows. The models used for this is typically the Michel model [2], the e^n –method [3] and the parameterized e^n –method by Drela and Giles [4].

The laminar/turbulent transition process is closely coupled to the stability of the boundary layer, and therefore methods for transition prediction needs information about several boundary layer parameters. In boundary layer codes as the Xfoil code, this information is readily available. In 2D Navier-Stokes codes, the information can be extracted, but logistics in connection with multi block grids etc. can make the task quite cumbersome. This problem is connected to the fact that one needs to integrate the boundary layer parameters along the flow direction to obtain the needed information.

General implementation of transition models in 3D multi block Navier-Stokes solvers is even more complicated. Here the flow direction, and thereby the integration direction is not know a priori. Another problem is the determination of the location of the stagnation point. All in all the general implementation of a transition model, is a complicated task. Therefore, in the present work another approach was taken. The present model is only intended for rotor blades, and we assume that the flow is chordwise in the laminar region, neglecting any influence of cross flow that may exist. Additionally lookup tables are used to determine the transition location based on the location of the stagnation point.

2 Method

The method used in the present work involves 4 components:

1. A 2D transition prediction method, this may be a 2D Navier-Stokes code, XFOIL or some other 2D tool.
2. A 3D Navier-Stokes solver.
3. A sectional treatment of the rotor blade, to determine the stagnation point location at several radial stations along the blade span.
4. An intermittency model to include the transition information into the flow equations, using an interpolation method to predict the transition location between the selected spanwise sections.

Before the computation is initiated, several stations along the blade span is chosen for sectional transition evaluation, see Figure 1. The number of stations needs to be sufficient to resolve the spanwise variation of the flow. In the present work 5 spanwise stations were used.

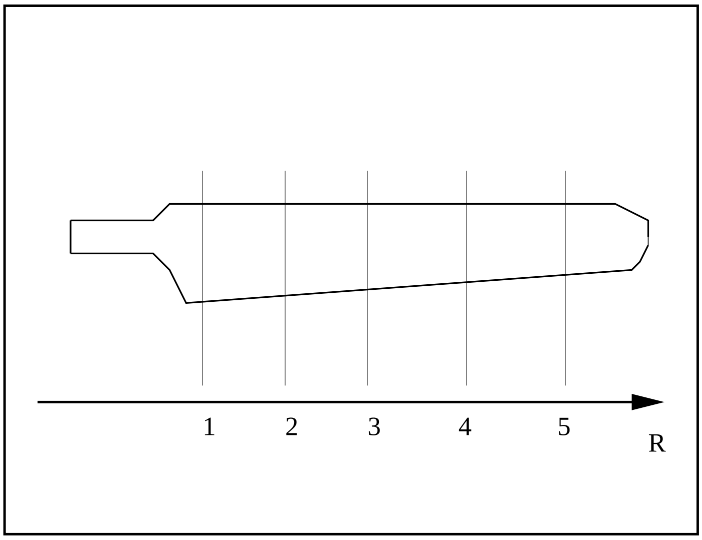

Figure 1. Several sections along the blade span are chosen for evaluation of the transition point location. Positions between these sections the transition locations are determined by interpolation from the nearest neighboring stations.

Having determined the sections where transition information will be evaluated, 2D airfoil computations are performed for these stations. The outcome of these computations is two curves connecting the location of the stagnation point and the location of the transition point, for the suction and pressure side respectively. These curves, are computed for angles of attack and a Reynolds number corresponding to the intended rotor operational condition, see Figure 2. The present work used a Reynolds number based on the local airfoil chord, the rotational speed Ω, the local radius of the section r and a wind speed in the mid range of the operational range:

$$\mathrm{Re} = \frac{\rho U C}{\mu} \ , \ U = \sqrt{r^2 \Omega^2 + W^2}$$

For each spanwise section, the outcome of these computations is a curve connecting the location of the stagnation point with the location of the transition points on the suction- and pressure side of the airfoil, as seen in Figure 2.

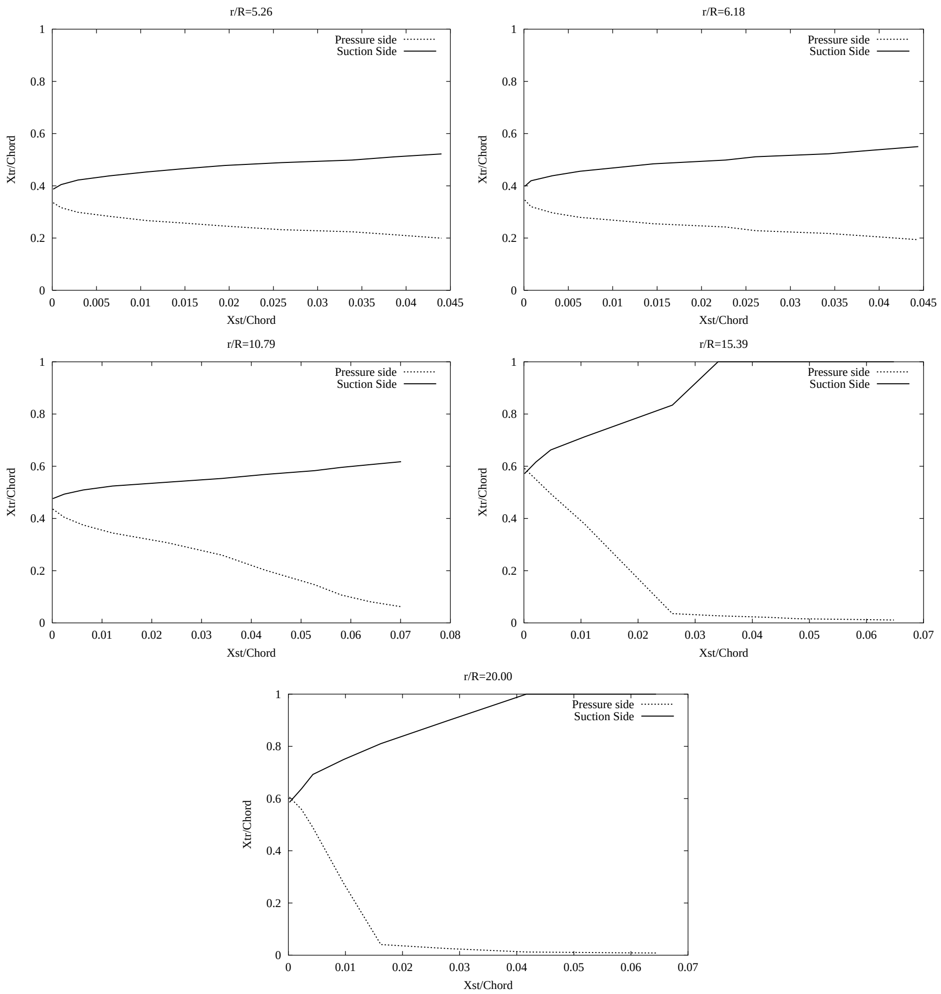

Figure 2. Transition point location on suction and pressure side as function of the location of the stagnation point, for five spanwise stations.

Now the 3D computation can be performed. Assuming the flow to be chordwise, the location of the stagnation point is straightforward. In each iteration or timestep the stagnation point location; is simply determined as the location of the maximum pressure coefficient, see Figure 3. To obtain a resolution beyond the grid resolution, parabolic variation of the pressure coefficient is assumed between the grid points.

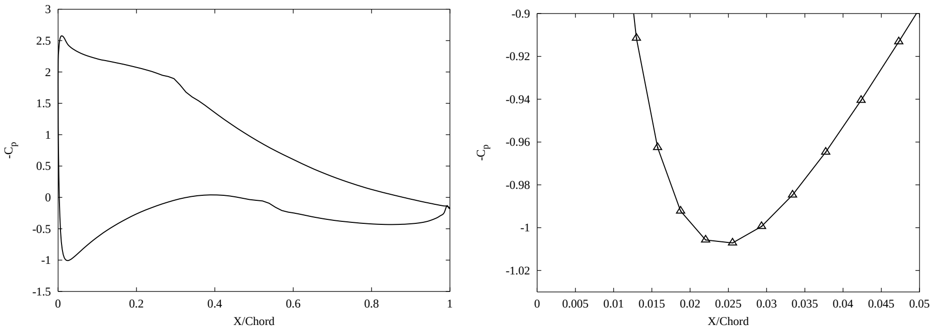

Figure 3. The stagnation point location is determined by the location of the maximum pressure coefficient. To obtain a finer resolution than the grid allows, an assumption of parabolic variation of the pressure between grid points is used.

Having determined the stagnation point locations at the evaluation sections, the transition points can be taken from the lookup tables. What remains now is to transfer the transition information into the flow equations.

The transfer of transition information from the blade surface to the surrounding fluid is done based on the radial position of a given point in 3D space. First we determine based on radius the two evaluation sections between which the point is lying. Now the location of the suction and pressure side transition points are simply determined by radius based interpolation between the nearest neighbouring evaluation sections. Next it is determined whether the point is above or below the extension of the chordline, and the corresponding location of the suction or pressure side transition point is used, see Figure 4.

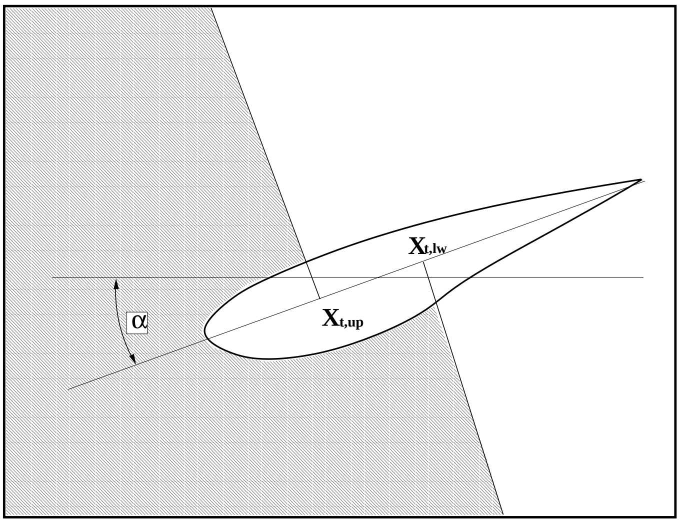

Figure 4. For a given radius the laminar and turbulent regions are determined based on the chordline and the upper and lower transition point locations.

The laminar and turbulent regions are updated in each iteration based on the described method. Computations are continued until a converged solution is obtained.

3 Application of the Method

The following the application of the described transition method to the flow over the rotor of the Nordtank 500/41 turbine rotor is described. The operational conditions for the turbine are given in Table 1. For all computations the EllipSys3D code is used.

Table 1. Parameters for the rotor computations performed in the present study.

Quantity	Value
Rotor diameter	41 meter
RPM	27.1
Rotor blades	LM19.1
Rotor cone angle	0 deg
Blade tip pitch	0 deg
Wind speed	7,10,12,14,15 m/s

3.1 Computational mesh

Using the 120 degrees symmetry of the problem, the grid is only generated around a single blade, the remaining two blades are accounted for through the use of periodic boundary conditions. The mesh consists of two main components see Figure 5. First an inner 5-block O-O-topology is used locally around the blade. Secondly an outer section is wrapped around the inner O-O-section, holding 3 blocks. In total the mesh consists of 8 blocks of 64^3 cells or a total 2.1 10^6 cells.

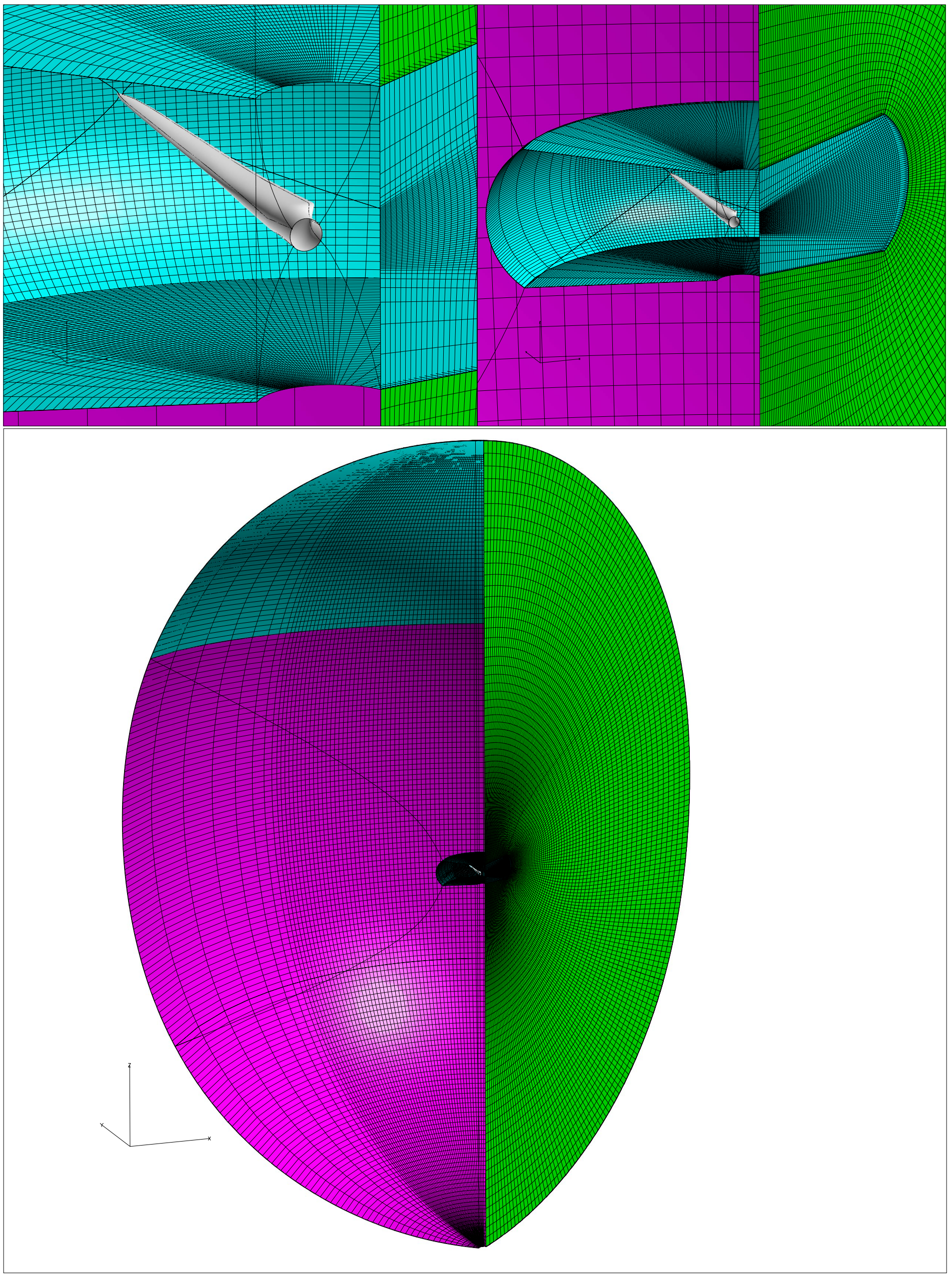

Figure 5. Computational mesh. The upper left figure shows a detail of the block structure around the blade. The upper right figure shows the outer boundary of the inner five-block topology around the blade. Part of the symmetry plane is seen at the right side of the figure. The bottom view shows the total view of the mesh, with the inner five-block topology visible at the center of the picture.

The size of the inner O-O section is difficult to see in Figure 5. The up and downstream faces are place approximately 1 meter away from the rotor plane. The grid has 64 cells in the direction normal to the surface, 256 cells around the airfoils, and 64 cells in the spanwise direction. To facilitate the modeling of the blade tip a 64x64 block is placed at the tip. The total number of cells for the 5 block inner O-O-section is 1.3 10^6 cells. In order to resolve the boundary layer the y^+ values at the wall is kept below 2 everywhere on the blade surface. No mesh independency test was performed, as this is very expensive in 3D. Instead experience from previous 2D airfoil computations and 3D rotor computations regarding the necessary number of mesh points was used when designing the 3D mesh.

3.2 3D Flow solver

The in-house flow solver EllipSys3D is used in all. The code is developed in co-operation between the Department of Mechanical Engineering at DTU and The Department of Wind Energy at Risø National Laboratory, see [5], [6] and [7].

The EllipSys3D code is a multiblock finite volume discretization of the incompressible Reynolds Averaged Navier-Stokes (RANS) equations in general curvilinear coordinates. The code uses a collocated variable arrangement, and Rhie/Chow interpolation [8] is used to avoid odd/even pressure decoupling. As the code solves the incompressible flow equations, no equation of state exists for the pressure, and the SIMPLE algorithm of [9] is used to enforce the pressure/velocity coupling. The EllipSys3D code is parallelized with MPI for executions on distributed memory machines, using a non-overlapping domain decomposition technique. For rotor computations, a moving frame attached to the rotor blades is used, and the necessary fictitious forces are added to the governing equations. Polar velocities (v_r, v_θ, v_z) are used in order to allow simple treatment of periodic boundary conditions in the azimuth direction, [10] and [11].

The solution is advanced in time using a 2nd order iterative time-stepping (or dual time-stepping) method. In each global time-step the equations are solved in an iterative manner, using underrelaxation. First, the momentum equations are used as a predictor to advance the solution in time. At this point in the computation the flowfield will not fulfill the continuity equation. The rewritten continuity equation (the so called pressure correction equation) is used as a corrector making the predicted flowfield satisfy the continuity constraint. This two step procedure corresponds to a single sub-iteration, and the process is repeated until a convergent solution is obtained for the timestep. When a convergent solution is obtained, the variables are updated, and we continue with the next timestep.

For steady state computations, the global time-step is set to infinity and dual time stepping is not used, this corresponds to the use of local time stepping. In order to accelerate the overall algorithm, a three level grid sequence is used in the steady state computations. The convective terms are discretized using a second order upwind scheme, implemented using the deferred correction approach first suggested in [12]. Central differences are used for the viscous terms. In each sub-iteration only the normal terms are treated fully implicit, while the terms from non-orthogonality and the variable viscosity terms are treated explicitly. Thus, when the sub-iteration process is finished all terms are evaluated at the new time level.

In the present work the turbulence in the boundary layer is modeled by the k-ω SST eddy viscosity model [13]. The details of the model will not be given here, we will only state that the model is chosen because of the very promising results for 2D separated flows, [14], [15]. The equations for the turbulence model are solved after the momentum and pressure correction equations in every sub-iteration/pseudo time step.

The three momentum equations are solved decoupled using a red/black Gauss-Seidel point solver. The solution of the Poisson system arising from the pressure correction equation is accelerated using a multigrid method.

3.3 Transition evaluation

Five radial stations were chosen for sectional transition evaluation, as shown in Table 2. The radii's given refer to the actual rotor radius of 20.5 meters. The 2D transition predictions were performed with the XFOIL analysis program, using a Reynolds number of 1.2 million for all sections and an N_{crit} factor equal to 9 for the onset of transition.

Table 2. The five sections where the transition location are evaluated.

Section	Radius [m]
1	5.26
2	6.18
3	10.79
4	15.39
5	20.00

The computed transition point location curves used as look up tables in the 3D computations are shown in Figure 2.

3.4 3D rotor computations

Two series of rotor computations are performed one series of fully turbulent computations for reference purpose, and one series of transitional computations. The investigated wind speeds are given in Table 1. In Figure 6 and Figure 7 the resulting transition line locations are shown for the five computed wind speeds. Figure 8 shows the computed mechanical power for the two series of computations and measurement are shown. The previous reported over prediction, [16], of the power by the fully turbulent predictions is clearly seen. The over prediction is around 40 percent at a wind speed of 18 m/s. For the transitional computation, an improved agreement is observed for wind speeds between 11 and 18 m/s. For wind speeds above 15 m/s, the transitional predictions under predict the power in contrast to the over prediction of the fully turbulent computations.

The spanwise force distributions for several wind speeds are shown in

Figure *9* and Figure 10. From these figures it is evident that the changes to the driving forces are mainly observed at the inboard part of the rotor, for the higher wind speeds the main changes are seen between the 4- and 12-meter spanwise positions.

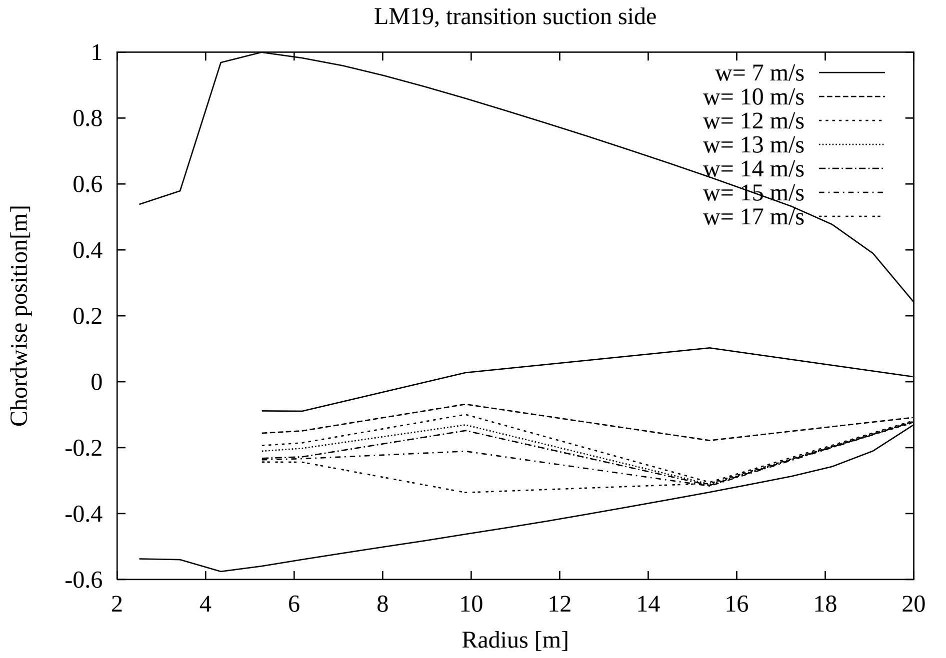

Figure 6. Transition lines on the pressure side of the blade for a series of wind speeds.

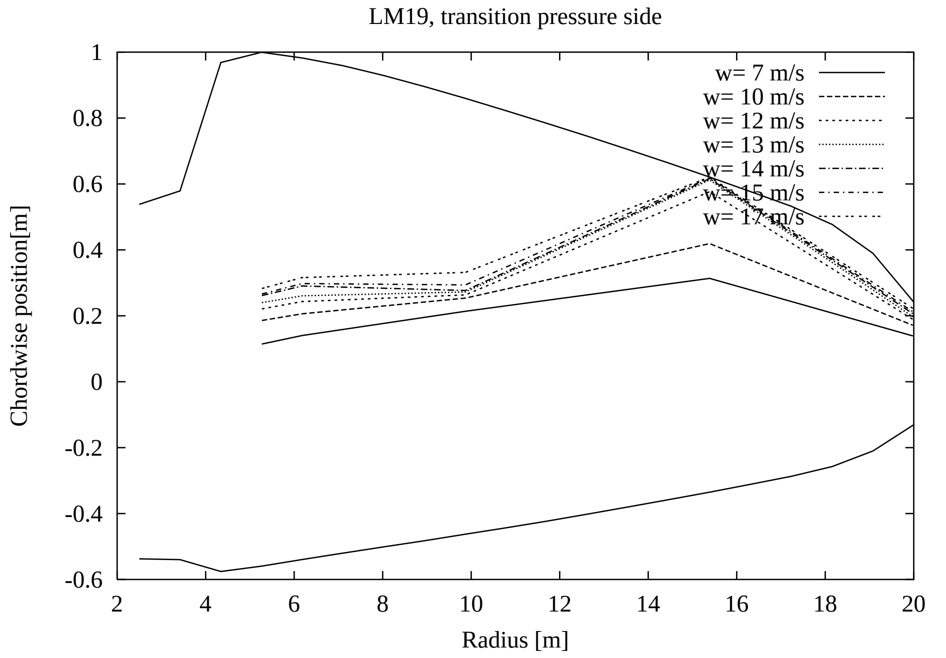

Figure 7. Transition lines on the suction side of the blade for a series of wind speeds.

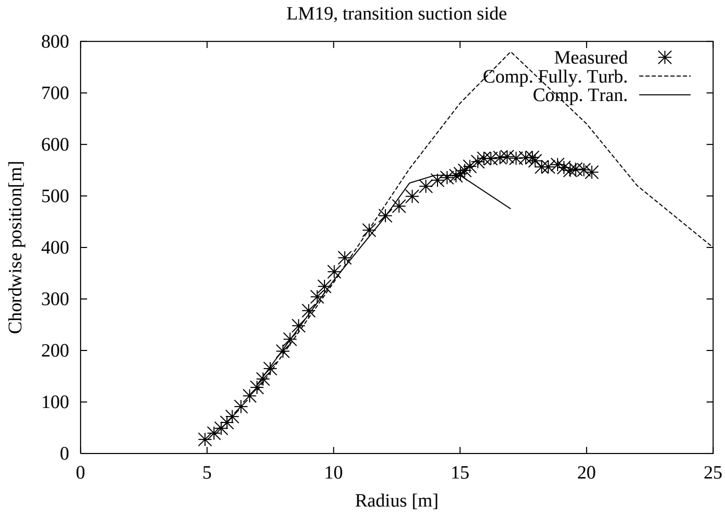

Figure 8. Comparison of computed mechanical power with measurements for the LM19.1 blade, both fully turbulent and transitional computations are shown.

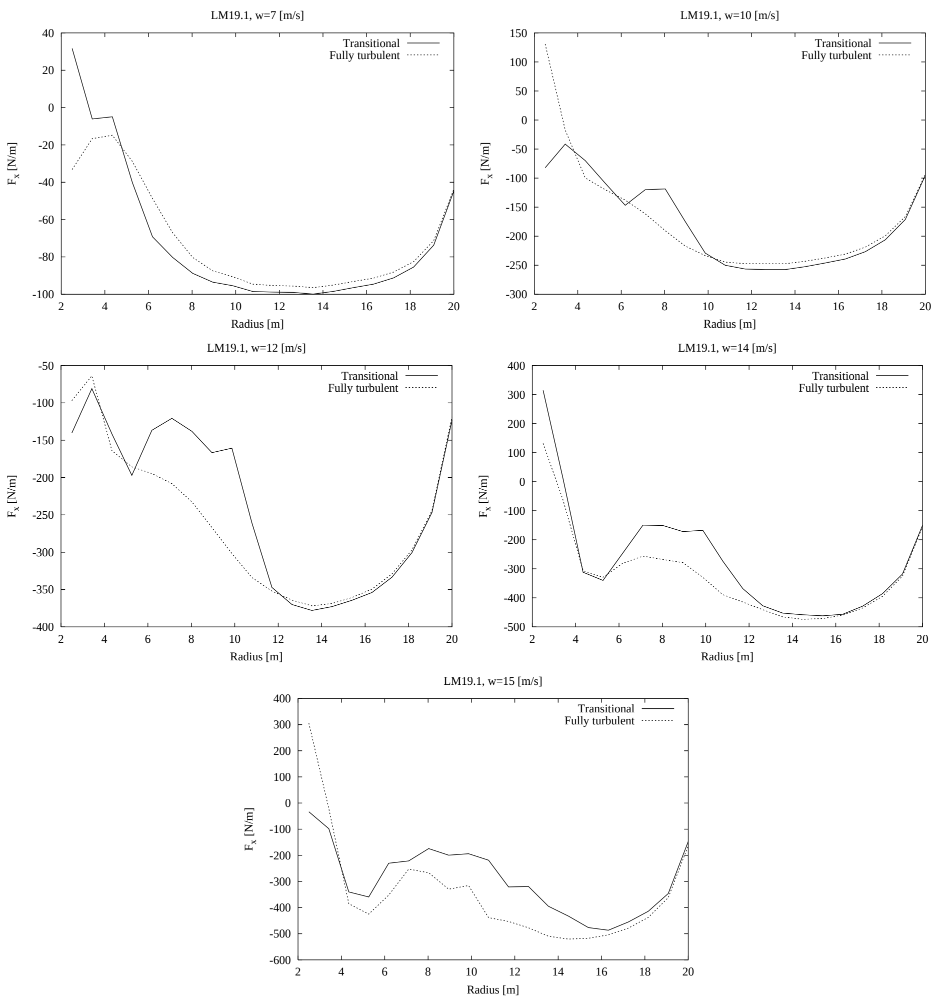

Figure 9. Comparison of the fully turbulent and transitional spanwise variation of the tangential force per length.

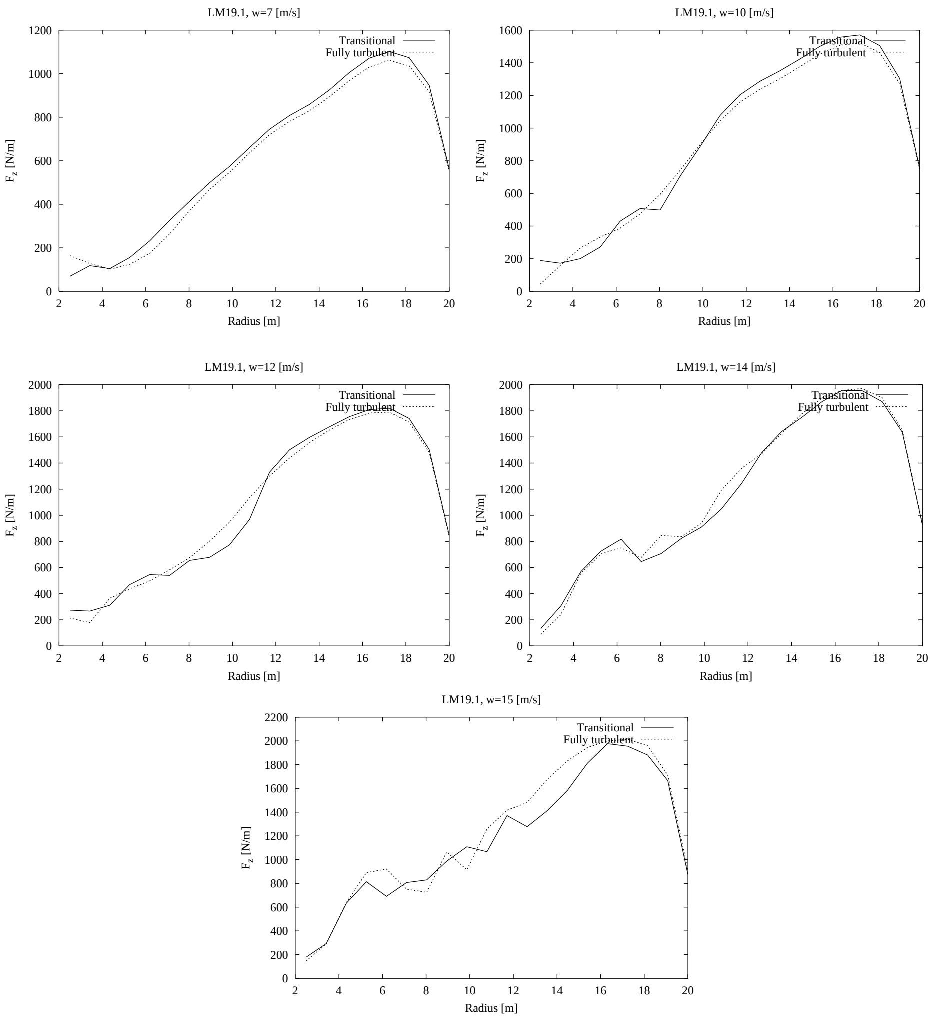

Figure 10. Comparison of the fully turbulent and transitional spanwise variation of the normal force per length.

4 Conclusion

A new simplified transition model for wind turbine blades is described along with the implementation in the EllipSys3D code. The method is based on a sectional treatment of the turbine blade under the assumption of chordwise flow. A series of lookup tables of transition point locations computed by external 2D programs. The coupling of the 2D transition point location and the 3D sectional flow is performed through the stagnation point location. The method is applied to a single rotor case, the NORDTANK 500/41 rotor equipped with LM19.1 blades. The transitional computations show improved agreement for wind speeds between 11 and 15 m/s. For higher wind speeds, the validity of the transition location computed by the 2D XFOIL code is questionable, and the results cannot be trusted. Analysis of the results comparing fully turbulent and transitional spanwise distributions of tangential forces, reveal that the decrease in power production is mainly a consequence of the decrease in driving force on the inboard part of the blade between 5 and 12 meter radius. The results are very encouraging, and further studies of other rotors are needed for further validation.

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Descriptors INIS/EDB

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