International Master Program in Wind Energy

Analysis on Aerodynamic and Aeroelastic behaviour of a Wind Turbine Rotor During Icing

Giuseppe Soraperra
ACKNOWLEDGMENTS

The present work is the final report of a two-year Master Program in Wind Energy given at the Mechanical Department, Fluid Mechanics Section, at the Technical University of Denmark (DTU).

The Master Program has been attended thanks to an agreement between the Fluid Mechanics Section, at the DTU, the University of Udine, and the Department of Mechanical and Structural Engineering of the University of Trento where the author has been following a three years PhD program in Energetics.

The PhD program has been financed by a private company in the context of a research activity on innovative solutions for wind energy applications in non conventional sites.

Thanks to the unique background given by the Wind Energy Master Program at DTU, the Academic Authority for the PhD Program in Udine (Collegio dei Docenti, Dottorato, Energetica, XVII° Ciclo, Università degli Studi di Udine), authorised including the activity carried out in Denmark in the formative path for the PhD Program.

Since the research activity has involved many subjects, it is worth to remark the fundamental support of all of them.

The author would like to thank:

the Leitner® company for the financial support given to the PhD program;
the Fluid Mechanics Section at the Technical University of Denmark and in particular Prof. Martin O. L. Hansen who supervised the activity, Prof. Jens N. Sørensen, the director of the Wind Energy Master Program, and Stig Øye who has kindly provided the aeroelastic code for the final analysis;
the department of Mechanical and Structural Engineering of the University of Trento and in particular Prof. Ing. Lorenzo Battisti who supervised the activity and the Fluid Machinery Laboratory staff;
the Università degli Studi di Udine who provided the PhD Program itself and in particular the Collegio dei Docenti and all the administrative staff;
the C.I.R.A. (Centro Italiano di Ricerche Aerospaziali) that carried out a series of ice accretion simulations;
all the classmates and the teammates who shared bad and good times during the past months.

Thanks all of you!
SUMMARY

1. INTRODUCTION
   1.1. Motivation and objective of the study. 1.2
   1.2. Survey on standards, regulation and published results. 1.3

2. MODEL OF THE ICED ROTOR
   2.1. Ice Shapes and Ice Accretion. 2.1
   2.2. Model for the Mass Distribution along the Blade. 2.9
   2.3. Model for the Performances of the Iced Airfoils. 2.13

3. AEROELASTIC MODEL OF THE WIND TURBINE
   3.1. The Aeroelastic Code. 3.1
   3.2. The Wind Turbine. 3.2
   Appendix 3.1. Program Listing. 3.8

4. AEROELASTIC SIMULATIONS OF THE TJÆREBORG WIND TURBINE DURING ICING
   4.1. Description of the Input and Output. 4.1
   4.2. Sensitivity Analysis on the Variables. 4.6
   4.3. Effect of Icing on 20-year of Lifetime. 4.14
   4.4. Integration of the aeroelastic analysis in the anti-icing design procedure. 4.20
   4.5. Effect of the Type of Tower 4.24
   Appendix 4.1. Input file for Test 01 (file I_01.pas) 4.27
   Appendix 4.2. Time series for the de-icing simulation, Test 63, wind speed, pitch angle, power output and nacelle loads. 4.29
   Appendix 4.3. Time series for the de-icing simulation, Test 63, blade-1 loads, blade-3 loads and tower loads. 4.30
   Appendix 4.4. FFT of the tower root bending moment in the longitudinal direction considering 5% of operation during icing 4.31

5. CONCLUSIONS AND REMARKS

REFERENCES
1. INTRODUCTION

The need for more installed power together with the fact that many of the conventional sites are already exploited, are leading to the colonisation of non conventional sites. Some of the characteristics of non conventional sites are harsh terrain topographies, high elevations, low air density, low temperature and possible ice accretion on the structures. These characteristics introduce a new class of issues for the Wind Energy Conversion Systems (WECS hereafter) like:

- Conceiving of light and robust structures easily transportable in harsh terrain.
- Conceiving of new, light, electric generators.
- Conceiving of anti-icing/de-icing systems for cold climates.
- Conceiving of new innovative diagnostic systems for WECS operating in non conventional sites, that undergo higher loads.

One of the key issue for WECS to be installed in non conventional sites, is their attitude to work during icing events.

The norms stated for WECS suggest to stop the power production when ice accretion take place. Nevertheless, it is not clear whether this statement has the objective to preserve the structure or else to protect people and goods from the risk of shedding of ice fragment from the WECS.

The anti-icing systems can be convenient for low temperature climates. The power demand of the anti-icing systems depend, among various factors, also on the amount of ice that has been allowed to accrete onto the WECS surfaces. The amount of allowable ice on the structures become a critical value for WECS operating in cold climates.

The study of the aerodynamic and aeroelastic behaviour of the WECS during, and after, ice accretion is a key issue. Ice accretion determines an increment on the load histories of some components that can lower their lifetime below the expected time extent of 20 years. As mentioned, the reduction in lifetime is not the only issue to be taken into account during the design process of the anti-icing/de-icing system. The risk for people and good connected with the shedding of ice fragments from the WECS as well as the drop in power output for operation during icing are some among the many other factors involved in the decisional process. Nevertheless, the integrity of the structure is the very basic requirement for the WECS that operate during ice accretion events.

In case the structure cannot withstand the additional load determined by ice accretion, the anti-icing system has to be taken into account.

The present study developed around the objective of characterising the dynamic behaviour of WECS that operate with a rotor contaminated by ice accretion. The dynamic analysis of WECS requires advanced computational tools like the Aeroelastic codes.
An aeroelastic code is a computer program that carries out dynamic simulations of a system consisting of the wind turbine and the flow field that passes through it for a given extent of time. These aeroelastic codes integrate the calculations of the aerodynamic loads with a structural model, a model for the wake expansion and a dynamic stall model. The dynamic simulations can take into account the stochastic component of the wind field (turbulence) that has typically to be computed before the dynamic simulation itself and stored. The aeroelastic analysis relies on aerodynamic models like the Blade Element-Momentum analysis (BEM hereafter). The BEM analysis consist in dividing the streamtube into a finite number of annular elements; for every element, the momentum theory is coupled with the local velocity triangles taking actually place at the blades. The BEM algorithm represents also one of the simplest tools to predict the power curve of a WECS and has a typical application in preliminary design and for the first estimation of the annual energy output of the WECS. The study of these aerodynamic and aeroelastic analysis tools has been necessary to pursue the final objective and represented a relevant part of the formative path during the entire Master Program.

1.1. Outline of the study.

The present document contains the analysis of the dynamic behaviour of the WECS during icing events. A specific analysis of the ice accretion mechanism and of the modelling of the rotor with ice accretion on the blades has also been carried out. Innovative elements in the research have been achieved both in terms of approach made to the analysis and in terms of results. Although a self-made aeroelastic code has been developed during the research activity, the dynamic analysis of the iced WECS has been carried out with a commercial code named FLEX®. This code has been kindly provided by the Fluid Mechanics Department at the Technical University of Denmark. A typical megawatt-class turbine has been chosen for the analysis.

The path to estimate the effect of icing on a wind turbine rotor consist of the following steps:

- Analyse the mechanism of ice accretion on rotor blades of wind turbine and identify the features that characterise a given icing case.
- Estimate the new aerodynamic performances and the new blade mass distribution for different icing levels.
- Set up an aeroelastic model of the WECS that can take into account the additional mass and the different aerodynamic performances corresponding to the different icing levels.
• Choose a set of load events that could put on evidence the additional loading introduced by the icing. Not only normal operation has to be taken into account: sudden de-icing events have to be considered as well.
• Analysis of the time series. The load cases related to icing at different levels have to be added to the lifetime of the WECS and the fatigue damage distribution has to be determined. A relationship between icing level and reduction in lifetime can be finally established.

All the step outlined above have been analysed in deep and required the development of specific tools (i.e. theoretical and numeric models, etc.). In particular, it is worth to notice that a fully integrated aeroelastic simulation of typical load events that take place on an WECS during icing had not yet been carried out.
Nevertheless, carrying out the calculations straightforward seems not to be enough: what kind of shape has to be chosen to describe the ice mass accreted at the leading edge of the airfoils? How sensitive is the analysis to the models that correct the aerodynamic performances of the iced airfoils and how reliable are these models? How can the icing level that determines a critical load event be chosen? Finally, is the structural integrity the limiting factor that make not possible for WECS to operate during icing?

The study has been conceived in a modular way: at first a simple model that cover all the steps involved is proposed; further improvements are possible for every step and can be linked afterward.

1.2. Survey on standards, regulation and published results

Cold climate and icing affect wind turbines in several ways:
- change in aerodynamic performances of the airfoils with reduction in the efficiency of energy conversion;
- introduction of additional static and dynamic loads on structures;
- possible inhibition of the pitching and yawing mechanism;
- possible inhibition of the power performance measurements;
- risk of shedding away of pieces of ice from rotating part.

The operation of WECS in harsh environments has been analysed in the past by research groups and authorities.
In this section, is reported a brief overview on the issued standards and on the published results of research programs.

Standard
Some of the effect of cold climate and icing are considered in standards, some are not and some are completely ignored.
The main standards concerning operation of wind turbines in cold climates are reported in Table 1.1. In the first column is reported the name of the authority, the number of the norm and the reference. In the second column are summarised the
main features of the norm while in the third column are reported some additional comment.

Table 1.1 Main standards for operation of wind turbines in cold climates.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Features</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC-61400-1 Structural Safety</td>
<td>The standard defines operating conditions as “normal” for temperatures down to –10 °C and “extreme” down to –20 °C.</td>
<td>Special load cases for icing conditions are not yet stated.</td>
</tr>
<tr>
<td></td>
<td>The standard states that all the extraordinary sites, including off-shore and icing conditions belong to the special class “S” in which load cases have to be agreed upon between the customer and manufacturer.</td>
<td></td>
</tr>
<tr>
<td>IEC-61400-12 Power performance measurements [1]</td>
<td>Ice free anemometers for measurements of power performances have to be used when necessary.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Icing of wind turbines determines an additional load during normal operation. Icing together with defective operation is not assumed.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A not-severe icing condition is considered (sites below 400 m a.s.l.).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stand by: is assumed a 30mm thick layer on all exposed sides. The density of ice is 700 kg/m³.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operation: icing is assumed to take place on the leading edge of the profiles. The mass per unit length of ice grows linearly up to 50% of the radius and is constant from 50% of the radius to the tip. The ice thickness can be estimated considering that ice cover 10% of the chord length on both the sides.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The extreme load calculations are made for two cases: 1) all the rotor blade are covered with ice; 2) all the rotor blade except one are covered by ice.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The effects on lifetime are estimated assuming an amount of ice of 50% of that stated above on all the blade except one during seven days per year. During these days the turbine operates at rated speed.</td>
<td></td>
</tr>
<tr>
<td>DIBt Guideline for WECS [2]</td>
<td>Same as DIBt. It contain additional requirements concerning temperature: the turbine have to withstand a temperature range between –20 °C and 50 °C during stand-by and a temperature range between –10 °C and 40 °C during operation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>In case the temperature remains below –20 °C for more than 9 days per year, lower limits must be provided by the manufacturer. In this case, the effect of temperature on air density have to be taken into account.</td>
<td></td>
</tr>
</tbody>
</table>

**Regulations**

In [2] are studied the regulation issued in Austria and Germany concerning the operation of WECS in harsh climate.
The local governments are often the authority that set the rules so that a general guideline is not yet adopted.
In most of the cases the rotor has to be stopped when icing occurs or, in some cases, even during period with temperatures below 0 °C.
A human inspection is required in order to check that all ice has fallen down before starting new operation. Risk analysis about impact of ice fragments with people and object has been required in some cases.

**Studies**

The main analysis on the behaviour of a WECS during icing are reported in Table 1.2. In the first column are reported the names of the authors and the reference. In the second column are summarised the task and the method of the research while in the third column are reported some additional comment. Although icing and cold environments have several effects on WECS, only the studies concerning the aerodynamic of the rotor and the dynamic behaviour of the structure are pointed out herein (i.e. the research on ice accretion, heated anemometers etc. are not analysed).

The main research concerning operation of wind turbines in cold climates was the WECO program (Wind Energy production in Cold climates) which was partially supported by the European Commission DG XII Non Nuclear Energy Programme [3].

<table>
<thead>
<tr>
<th>authors</th>
<th>task and methods</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seifert H., Scholz C. [4]</td>
<td>Task: estimation of the additional load caused by icing on rotor blades during operation. Method: 1) observation of iced turbines, collection of fragments of pieces of ice shaded away from the leading edge of the blade. 2) wind tunnel measurements of $C_l$, $C_d$, and $C_m$ of profile with ice on the leading edge. 3) calculation of the power curve of an iced rotor considering the aerodynamic performances of the iced profiles measured in the wind tunnel; comparison with measured power curves of a given turbine achieved during icing. 4) calculation of static blade root bending moment and blade root torsional moment considering $C_l$, $C_d$ and $C_m$ of profile with ice measured in the wind tunnel. 5) calculation of the influence of ice on the resonance diagram of the rotor. 6) estimation of the dynamic load by comparing measured time histories of a given wind turbine during operation with the clean rotor and with the iced rotor.</td>
<td>It is pointed out how the presence of ice increase the blade root torsional moment so that the pitching system has to be designed to withstand the additional load.</td>
</tr>
</tbody>
</table>
| **Seifert H., Reichert F. [5]** | Task: investigation on the aerodynamics of iced airfoils and their influence on load and power production.  
Method: 1) collection of fragments of pieces of ice shaded away from the leading edge of the blade.  
2) wind tunnel static and dynamic measurements of $C_l$, $C_d$, and $C_m$ of profile with ice on the leading edge; several level of icing were investigated.  
3) exportation of the results achieved in the wind gallery on a generic airfoil.  
4) extrapolation of the profile behaviour in the post stall region.  
5) calculation of the static blade root flap-wise moment by adding an ice mass according to the DIBt standard.  
6) calculation of the annual loss of energy production.  
| **Vølund P., Antikainen P. [6]** | Task: investigation on the load induced by ice on a WECS by measurements and comparison with numeric dynamic models.  
Method: 1) measurements of dynamic behaviour of two given turbines during operation in harsh climates.  
2) analysis of the power spectra diagram with and without icing.  
3) numeric modelling (HawC code) of one of the given turbine.  
4) aeroelastic analysis of the tower of one of the given turbine.  
| **Ganander, H. Ronsten G. [7]** | This study is part of work package 3 (WP3) of EC project NNE5-2001-00259 New Icetools (NICE), aiming at improving recommendations for load and design related to wind turbine ice condition.  
Methods: 1) modeling of an iced WECS rotor by assuming two “ice parameters”: a pitch difference and a mass unbalance. The model describe the dynamic behavior of a given real turbine that has been monitored during operation in harsh climate.  
2) numeric aeroelastic simulation of the iced rotor by assuming different values of the pitch and unbalance mass (sensitivity analysis).  
3) comparing between numeric results and measurements.  
| | The work starts from the achievements of [4].  
A simple method to model the aerodynamic performances of a generic iced airfoil is given.  
| | It seems that the aeroelastic analysis has been carried out to explain the different tower dynamic behaviour only.  
| | The dynamic behavior of an iced rotor is supposed to be reproduced by introducing two simple changes (a pitch difference and a mass unbalance) in the conventional aeroelastic model of the WECS.  
The analysis can be validated and tuned by a comparison with measurements.  

Pag. 1.6
2. MODEL OF THE ICED ROTOR

The aerodynamic and aeroelastic behaviour of the iced rotor is different for the following reasons:

- Change of the mass per unit meter of the blades due to the additional mass of ice (mass distribution along the blade).
- Change of the aerodynamic performances of the airfoils due to the presence of ice that forms typically at the leading edge (lift and drag coefficients versus angle of attack curves of the iced profiles).
- Change of the material mechanical properties with temperature. Icing take place at low temperatures, but also the adoption of a thermal anti-icing/de-icing system can determine a higher temperature in the blade material. The changes in material temperature can turn into a change in the blade stiffness.
- Effect on the control system. The control system is designed to prevent the turbine from working with high yaw angles and, in general, any operational condition that determines high, off-design, loads. The formation of ice can inhibit the sensors and so reduce the efficiency of the control system strategy.

The first two factors have been analysed in detail and implemented in the aeroelastic code. In this chapter the model to estimate the new performances of the airfoils and for the new mass distribution along the blade is described.

2.1. Ice Shapes and Ice Accretion.

The main characteristics of the ice shapes are discussed in this section together with some notes on the ice accretion mechanism.

Ice accretion.

The accretion of ice on to profiles is an extremely complex process that can be predicted only by means of integrated thermo fluid-dynamic models. The ice accretion take basically place when there are supercooled droplets of water in the atmosphere that impinge onto a surface with a temperature below the water freezing point.

The type of ice and shape and its growing rate depend on the climatic conditions (temperature, pressure and velocity) and on the meteorological conditions (liquid water content, mean droplet diameter etc.).

Ice shapes are generally classified as glaze, mixed, and rime accretions. Rime ice is milky white and opaque. Glaze ice is generally clear and is characterised by the presence of larger protuberances, commonly known as glaze horns.

Typically rime ice is formed at lower temperatures, velocities and liquid water content that glaze ice.

Moving into the detail of the icing accretion process, the super-cooled droplets flow trajectories that will cause them either be carried post or impinge upon a body. Upon impact with a clean surface, the droplets coalesce into larger surface drops under the effect of surface tension and flow along the surface. These surface drops will then either freeze on the surface or be shed from the surface because of the aerodynamic forces on the drop.
The ice accretions formed by this initial freezing form rough surface that enhance the convective heat transfer and local collection efficiency of the surface and therefore allows the ice accretion process to continue. The type of ice that will form for a given set of conditions is determined primarily by the rate at which the freezing process occur. If the conditions are such that the droplets freeze rapidly, there is essentially no initial coalescing and flowing of the droplets. Instead, they freeze on impact and form the characteristics rime ice accretions that are white and opaque because of the presence of air bubbles that are trapped in the structure during the rapid freezing process.

As the rate of freezing process decreases, the droplets begin to coalesce and flow on the surface. Upon freezing, these larger surface droplets form surface roughness elements which tend to enhance the convective heat transfer and local collection efficiency which in turn enhance the continuing growth of ice in this region. These local areas of enhanced ice growth are, therefore, the beginners of the characteristics horns found on mixed glaze ice accretion. As the freezing rate decrease further, the drops flow along the surface of the body before freezing, thus moving the regions of enhanced ice growth away from the stagnation point. This in turn, causes the horns of accretion to move further apart and form the familiar glaze accretion.

As the freezing rate decreases, less air is trapped within the ice structure and the ice gradually becomes clearer until it is essentially transparent, as in glaze ice.

Although the development of an accretion model is beyond the scope of the present study, it’s worth to list the typical steps involved in the this analysis:

- Flow field calculation (transition model and roughness model).
- Particle trajectory calculation (collision efficiency).
- Particle impingement calculation (collection efficiency).
- Ice growth calculation (energy and mass balances).
- Modification of the current geometry by adding the ice growth to it.

In the present study it is assumed that a set of ice shapes are known. The ice shapes have to be processed in order to give the mass distribution and the change in aerodynamic performances of the iced airfoils.

**Operative conditions.**

Icing can take place during two main class of operative conditions of the WECS: icing during normal power production operation and icing during standby-idling condition. During power production, the rotor has a relatively high rotational speed that determine relevant peripheral velocities and centrifugal field. The blade are working with an angle of attack different from zero so that relevant aerodynamic forces are generated.

During idling, the WECS is disconnected from the electric grid and has a low rotational speed. The wind velocity is also very low (otherwise, power production mode would take place). On pitch regulated turbine, the angle of attack is set to be as low as possible in order to lower the aerodynamic forces generated by the profiles and so the aerodynamic loads of the blade.
Figure 2.1 illustrates a qualitative scheme of the effect of icing under these two different operation conditions at a particular cross section.

On a pitch controlled turbine also leading edge ice accretion of up to 100 per cent of the local chord has been observed during icing conditions while the turbine was idling. At the same site and the same turbine only up to 40 per cent of the chord leading edge ice accretion have been documented during power production under icing conditions [5].

During power production the relatively high centrifugal forces on the ice at the leading edge and the aerodynamic force acting on the ice itself causes shear forces and bending moments between the ice and the blade, resulting in an early break off of the ice.

During idling no centrifugal loads nor relevant lift forces are acting on the ice growing at the leading edge resulting in a much bigger amount. A similar effect can be observed at slow rotating stall controlled turbines at low wind speeds and under icing conditions.

**Characterisation of the ice shapes.**

The shapes of the ice formation are quite complex due to the stochastic nature of the ice accretion process.

As mentioned, the presence of ice on the rotor change the mass distribution and the aerodynamic performances of the blade. The first change can be straightforward related to the mass of ice. The second change depend on the shape of the ice accretion. In case a quasi-2D flow were assumed, the aerodynamic performances of the iced airfoil would depend on the shape of the ice accretion cross section.
Any generic ice shape can be described by means of a set of polynomial functions with order $n$:

$$y_{up}(x) = a_0 + a_1 \cdot x + a_2 \cdot x^2 + \ldots + a_n \cdot x^n$$

$$y_{down}(x) = a_0 + a_1 \cdot x + a_2 \cdot x^2 + \ldots + a_n \cdot x^n$$

The higher is the order $n$ of the polynomial functions, the better is the accuracy of the description of the ice shape.

Once that the contour of the ice accretion is well defined, the mass per unit meter result equal to the area of the ice accretion cross section times the ice density. To describe the ice accretion cross section with a high order polynomial function is not always possible.

In general it is necessary to characterise the shape of the ice accretion cross section with very few simple geometric parameters as the maximum ice thickness and the extension of profile covered by ice around the leading edge. These geometric quantities make also possible to relate the size of the ice accretion with the change in the aerodynamic performances. It is worth to notice that there can be different ice shapes that have the same mass per unit meter.

Several standards can be defined to describe the ice cross section in terms of two or three basic geometric parameters as for example in [10].

An example of simplified characterisation of the shape is proposed hereafter. The ice accretion cross section can be described by means of a pseudo-rectangular shape. Two lines parallel to the chord line are drawn from the ice limits and two lines perpendicular to the chord line direction are drawn tangent to the leading point and the back point of the ice accretion. The curvature of the profile is subtracted from two sides. The maximum ice thickness is then defined as the distance from the leading edge of the profile to the leading point of the ice accretion. In Figure 2.2 is shown a qualitative scheme for this approach.

![Figure 2.2 Characterisation of the ice shapes.](image-url)
**Impingement limits.**
The ice accretion take place only where supercooled droplets impinge onto the surface. The trajectories of the supercooled droplets around the airfoils can intersect or not the contour of the airfoil. The two limiting points where such trajectories intersect the airfoils are said impingement limits.

The impingement limits can be detected experimentally or they can be estimated by means of numeric simulations. In any case, the dynamic modification of the airfoil geometry determine a dynamic change in the streamlines that make difficult a simple estimation of the impingement limits.

The impingement limits represent the basic points to estimate the extension of the ice accretion. Runback of water downstream respect to the impingement limits, and his subsequent freezing, determines the maximum extension of the ice accretion.

A good example of complex ice accretion is reported in Figure 2.3 below; the results of Figure 2.3 have been achieved both experimentally (dotted line) than numerically (dashed line) [10]. The tested profile was a NACA0012 and the declared test conditions were a velocity of 102.8 m/s, an angle of attack of 4°, a temperature of 262 K, a LWC=1.30 g/m³, a MVD=30 µm for a spraying time of 6 minutes. This test condition are representative for aeronautical application.

![Figure 2.3 Example of ice accretion on a NACA0012 (numeric vs. experimental).](image)

Pag. 2.5
**Ice accretion simulations.**

A series of numeric tests of ice accretion has been performed for the turbine to be modelled in the dynamic simulation, that will be presented in the next sections of this paper. This set of simulations aims to give a database of significant cases for wind energy application.

The ice accretion simulations have been carried out by the C.I.R.A. (Centro Italiano di Ricerche Aerospaziali).

The simulations have been carried out for power production operation at the rated speed. The rotor taken into account is that to be used for the dynamic simulation.

The angles of attack and the relative velocities given as an input to the ice accretion simulations have been computed with a BEM model in order to take the induced velocity into account.

In Table 2.1 are reported the global input of the simulations that have been divided into two groups: the wind turbine/operative input (rotor diameter, number of blade, the undisturbed wind speed, the global pitch angle and the rotational speed) and the meteorological conditions (mean droplet diameter, liquid water content, air temperature, time of accretion and air pressure).

This case represents an example of light icing event concerning wind energy application where an exposure to icing environment of 45 minutes represent a short icing event duration.

In Table 2.2 are reported the main input (Name of section, radius, type of profile, chord size, angle of attack, relative velocity) and the impingement limits achieved at every section. The impingement limit are reported in terms of distance from the leading edge normalised respect to the chord size.

It is worth to remark that the given input determined a moderate ice accretion that is almost negligible for the stations from 6 to 9. Moreover, stations 4 and 5 did not give any accretion at all.

In Figure 2.4 are depicted the ice accretions for the sections from 9 to 14 where the ice where visible.

Prediction and correction shapes are reported on top of the airfoil silhouette. Sections 12 and 13 show for large part of the lower impingement area a small ice accretion compared to the horn that form close to the leading edge.
### Table 2.1 Input for the ice accretion simulations.

<table>
<thead>
<tr>
<th>Wind Turbine/Operative Input</th>
<th>Meteorological Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>MVD</td>
</tr>
<tr>
<td>Nblade</td>
<td>LWC</td>
</tr>
<tr>
<td>V_0</td>
<td>T</td>
</tr>
<tr>
<td>(\theta_{\text{pitch}})</td>
<td>t_icing</td>
</tr>
<tr>
<td>(\omega_{\text{rated}})</td>
<td>P</td>
</tr>
</tbody>
</table>

### Table 2.2 Impingement limits for every station of the rotor blade.

<table>
<thead>
<tr>
<th>Sec.</th>
<th>r [m]</th>
<th>Profile Type</th>
<th>(C) [m]</th>
<th>(\alpha_{\text{attack}}) [°]</th>
<th>(V_{\text{ref}}) [m/s]</th>
<th>Upper Limit/C [-]</th>
<th>Lower Limit/C [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.46</td>
<td>Circular</td>
<td>3.3</td>
<td>30.16</td>
<td>19.35</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>2.75</td>
<td>Circular</td>
<td>3</td>
<td>21.23</td>
<td>25.32</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>2.96</td>
<td>Circular</td>
<td>2.7</td>
<td>15.41</td>
<td>31.66</td>
<td>5.94%</td>
<td>7.27%</td>
</tr>
<tr>
<td>4</td>
<td>6.46</td>
<td>NACA 4430</td>
<td>2.4</td>
<td>12.32</td>
<td>38.19</td>
<td>3.84%</td>
<td>4.87%</td>
</tr>
<tr>
<td>5</td>
<td>9.46</td>
<td>NACA 4424</td>
<td>2.1</td>
<td>11.03</td>
<td>44.8</td>
<td>2.45%</td>
<td>4.30%</td>
</tr>
<tr>
<td>6</td>
<td>12.46</td>
<td>NACA 4421</td>
<td>1.8</td>
<td>10.4</td>
<td>51.5</td>
<td>1.01%</td>
<td>4.69%</td>
</tr>
<tr>
<td>7</td>
<td>15.46</td>
<td>NACA 4418</td>
<td>2.1</td>
<td>10.12</td>
<td>58.25</td>
<td>0.46%</td>
<td>6.98%</td>
</tr>
<tr>
<td>8</td>
<td>18.46</td>
<td>NACA 4416</td>
<td>1.5</td>
<td>9.87</td>
<td>65.04</td>
<td>0.23%</td>
<td>9.76%</td>
</tr>
<tr>
<td>9</td>
<td>21.46</td>
<td>NACA 4415</td>
<td>1.2</td>
<td>9.45</td>
<td>68.43</td>
<td>0.07%</td>
<td>12.24%</td>
</tr>
<tr>
<td>10</td>
<td>24.46</td>
<td>NACA 4414</td>
<td>1.05</td>
<td>8.62</td>
<td>70.45</td>
<td>0.02%</td>
<td>12.24%</td>
</tr>
<tr>
<td>11</td>
<td>27.46</td>
<td>NACA 4413</td>
<td>0.96</td>
<td>5.07</td>
<td>71.92</td>
<td>-0.22%</td>
<td>7.69%</td>
</tr>
<tr>
<td>12</td>
<td>28.96</td>
<td>NACA 4412</td>
<td>0.94</td>
<td>5.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>29.86</td>
<td>NACA 4412</td>
<td>0.94</td>
<td>5.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>30.5</td>
<td>NACA 4412</td>
<td>0.94</td>
<td>5.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 2.4 Ice accretion on the wind turbine rotor blade achieved numerically for sections 9 to 14
MVD=20 μm, LWC=0.1 g/m³, T=270.15 K, t_{icing}=45 minutes, P=100000 Pa.
2.2. Model for the Mass Distribution along the Blade.

The mass distribution depend on the ice accretion mechanism and on the shedding mechanism.

**The Germanisher Lloyd approach.**

The Germanisher Lloyd (GL hereafter) proposes a standard for the estimation of the ice distribution and the load induced by ice (Germanisher Lloyd GL Wind 2003 4.2.4.2.3, [2]):

- Icing of wind turbines determines an additional load during normal operation. Icing together with defective operation is not assumed.
- A not-severe icing condition is considered (for example sites below 400 m a.s.l.).
- Stand by: is assumed a 30mm thick layer on all exposed sides.
- The density of ice is 700 kg/m$^3$.
- Operation: icing is assumed to take place on the leading edge of the profiles. The mass per unit length of ice grows linearly up to 50% of the radius and is constant from 50% of the radius to the tip. The ice thickness can be estimated considering that ice cover 10% of the chord length on both the sides.
- The extreme load calculations are made for two cases: 1) all the rotor blade are covered with ice; 2) all the rotor blade except one are covered by ice.

The mass per unit length of ice at the leading edge of the rotor blade at half the rotor radius, $m_{E}$, can be estimated with the following set of equations:

\[
\begin{align*}
\rho_{\text{ice}} & \cdot C_{\text{min}} \left(C_{\text{min}} + C_{\text{max}}\right) \\
\rho_{\text{ice}} & \cdot C_{\text{min}} \left(C_{\text{min}} + C_{\text{max}}\right) \\
k & = 0.00675 + 0.3 \cdot \exp\left(-0.32 \cdot \frac{R_{\text{tip}}}{R_{0}}\right)
\end{align*}
\]

(eq. 2.1)

where $\rho_{\text{ice}}$ is the ice density, $C_{\text{min}/\text{max}}$ are the minimum/maximum chord size, $R_{\text{tip}}$ is the rotor radius and $R_{0}=1$m.

The GL standard states a method to estimate the mass distribution of ice but are not very helpful concerning the ice shape to be assumed.

As mentioned, the characterisation of the ice shape is necessary to estimate the change in the aerodynamic performances. At least, it has to be known the maximum thickness of the ice accretion.

A simplified approach to estimate the ice thickness is proposed in [2] where the authors assume that the ice covers about 10 per cent of the chord length on both the sides and that the thickness is about constant over this area.

Once that the extensions of the area covered by ice is known, the thickness of the ice can be calculated as follow:

\[
t_{\text{ice}}(r) = \frac{m_{\text{ice}}(r)}{\rho_{\text{ice}} \cdot \text{Ext}(r) \cdot C(r)}
\]

(eq. 2.2)

where $r$ is the radius, $t_{\text{ice}}(r)$ is the thickness of the ice layer at a given value $r$, $m_{\text{ice}}(r)$ is the ice mass distribution according with GL norms, Ext($r$) is the extension of the area covered by ice in percentage of the chord size at a given $r$, $C(r)$ is the chord size at a given $r$ and $\rho_{\text{ice}}$ is the ice density.
A qualitative scheme of this approach is depicted in Figure 2.5 below. As noticeable, it is assumed that the ice has a volume defined by the ice thickness and the area covered by ice projected onto a line tangent to the leading edge.

\[ \text{Ice Volume per unit meter} = \frac{m_{\text{ice}}}{\rho_{\text{ice}}} \]

Figure 2.5 Simplified scheme for the estimation of the ice thickness.

**The mass distribution model.**

The standard suggested by the GL has been the base for the mass distribution model used in this study that is described below:

- The mass per unit meter has been assumed to follow the trapezoidal shape of the GL (mass per unit meter growing linearly until 50% of the radius and constant from there to the tip).
- The mass per unit length of ice at the leading edge of the rotor blade at half the rotor radius, \( m_E \), has been calculated through Equation 2.1. \( m_E \) can then be scaled arbitrarily in order to carry out a sensitivity analysis on the ice mass.
- The extension of profile covered by ice around the leading edge has been estimated by analysing the impingement limits obtained from the ice accretion simulation (see Table 2.2). The results of the simulations have been analysed in the light of on-filed observations, as the picture aside.

By observing the picture, it is noticeable that the ice thickness is growing linearly up to a given point and than is about constant. This ice thickness profile along the blade, that is the result of both the ice accretion and the ice break off, follows pretty much the mass
distribution model suggested by the GL norms. Since the ice thickness and the ice mass change in the same fashion along the blade, the product Ext(r)·C(r) to be used in Equation 2.2 has to be about constant. The product Ext(r)·C(r) has been calculated from the impingement limits and the chord lengths of Table 2.2. The extension of profile covered by ice around the leading edge has then been calculated by taking the average value of the product Ext(r)·C(r) for stations from 9 to 14 (where the icing was visible) and resulted to be about 0.1 m.

- The ice thickness has then been calculated through Equation 2.2 assuming a constant value for Ext(r)·C(r)= 0.1 m (see Figure 2.5).

In Table 2.3 is reported one example of ice mass distribution achieved assuming a mass per unit length of ice at the leading edge of the rotor blade at half the rotor radius, \( m_{E,i} = 18.89 \) and an ice density \( \rho_{\text{ice}} = 700 \text{ kg/m}^3 \). The first value resulted through Equation 2.1 with the values of \( R_{\text{tip}} \), \( C_{\text{min}} \) and \( C_{\text{max}} \) of Table 2.1 and Table 2.2.

The first five columns contain the data of the clean blade for every section (name of section, radius, type of profile, chord size, angle mass per unit length). The last five columns contain the ice extension, the ice extension normalised respect to the chord length, the mass of ice, the maximum ice thickness and the maximum ice thickness normalised respect to the chord length for every section.

<table>
<thead>
<tr>
<th>Sec.</th>
<th>( r ) [m]</th>
<th>Profile Type</th>
<th>( C ) [m]</th>
<th>( m_{\text{blade}} ) [kg/m]</th>
<th>Ext [m]</th>
<th>Ext/C [-]</th>
<th>( m_{\text{ice}} ) [kg/m]</th>
<th>( t_{\text{ice}} ) [m]</th>
<th>( t_{\text{ice}}/C ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.46</td>
<td>Circular</td>
<td>1.80</td>
<td>3460</td>
<td></td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.75</td>
<td>Circular</td>
<td>1.80</td>
<td>443</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.96</td>
<td>Circular</td>
<td>1.80</td>
<td>436</td>
<td>3.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6.46</td>
<td>NACA 4430</td>
<td>3.30</td>
<td>337</td>
<td>0.10</td>
<td>3.02%</td>
<td></td>
<td>8.0</td>
<td>0.115</td>
</tr>
<tr>
<td>5</td>
<td>9.46</td>
<td>NACA 4424</td>
<td>3.00</td>
<td>276</td>
<td>0.10</td>
<td>3.32%</td>
<td></td>
<td>11.7</td>
<td>0.168</td>
</tr>
<tr>
<td>6</td>
<td>12.46</td>
<td>NACA 4421</td>
<td>2.70</td>
<td>229</td>
<td>0.10</td>
<td>3.69%</td>
<td></td>
<td>15.4</td>
<td>0.221</td>
</tr>
<tr>
<td>7</td>
<td>15.46</td>
<td>NACA 4418</td>
<td>2.40</td>
<td>191</td>
<td>0.10</td>
<td>4.15%</td>
<td></td>
<td>18.9</td>
<td>0.271</td>
</tr>
<tr>
<td>8</td>
<td>18.46</td>
<td>NACA 4416</td>
<td>2.10</td>
<td>167</td>
<td>0.10</td>
<td>4.74%</td>
<td></td>
<td>18.9</td>
<td>0.271</td>
</tr>
<tr>
<td>9</td>
<td>21.46</td>
<td>NACA 4415</td>
<td>1.80</td>
<td>159</td>
<td>0.10</td>
<td>5.54%</td>
<td></td>
<td>18.9</td>
<td>0.271</td>
</tr>
<tr>
<td>10</td>
<td>24.46</td>
<td>NACA 4414</td>
<td>1.50</td>
<td>85</td>
<td>0.10</td>
<td>6.64%</td>
<td></td>
<td>18.9</td>
<td>0.271</td>
</tr>
<tr>
<td>11</td>
<td>27.46</td>
<td>NACA 4413</td>
<td>1.20</td>
<td>48</td>
<td>0.10</td>
<td>8.30%</td>
<td></td>
<td>18.9</td>
<td>0.271</td>
</tr>
<tr>
<td>12</td>
<td>28.96</td>
<td>NACA 4412</td>
<td>1.05</td>
<td>33</td>
<td>0.10</td>
<td>9.49%</td>
<td></td>
<td>18.9</td>
<td>0.271</td>
</tr>
<tr>
<td>13</td>
<td>29.86</td>
<td>NACA 4412</td>
<td>0.96</td>
<td>25</td>
<td>0.10</td>
<td>10.38%</td>
<td></td>
<td>18.9</td>
<td>0.271</td>
</tr>
<tr>
<td>14</td>
<td>30.5</td>
<td>NACA 4412</td>
<td>0.94</td>
<td>20</td>
<td>0.10</td>
<td>10.60%</td>
<td></td>
<td>18.9</td>
<td>0.271</td>
</tr>
</tbody>
</table>

The mass distribution of the iced blade \( m_{\text{tot}}(r) \) is the sum of the blade mass distribution \( m_{\text{blade}}(r) \) (fifth column in Table 2.3) and the ice mass distribution \( m_{\text{ice}}(r) \) (eighth column in Table 2.3).

Nevertheless, the aeroelastic code Flex\textsuperscript® to be adopted for the dynamic analysis cannot accept a generic mass. The reason for such a limitation depend on the choice of
using the modal approach to model the wind turbine and so, the mass distribution of
the iced rotor blades have to restrain the same eigenmodes of the clean rotor blades.
The only way the aeroelastic code can accept any change in the blade mass
distribution, without changing the eigenmodes of the system, is by a magnification
factor to be multiplied to the clean blade mass distribution.
The magnification factor represents a degree of freedom that can be tuned to
reproduce only one of the mass properties of the iced blade.
The possible iced blade mass properties to be reproduced are:

1. The first flapwise eigenfrequency.
2. The following integral: \( M = \int m_{tot}(r) \cdot r \cdot dr \) corresponding to the blade root
   bending moment as well as the blade root centrifugal force
   \( F_{cent} = \omega^2 \cdot \int m_{tot}(r) \cdot r \cdot dr \).
3. The overall blade mass.

The magnification factor \( K_1 \) to reproduce the first eigenfrequency of the iced blade
has been calculated as follow:
- The first eigenfrequency of the clean blade has been calculated.
- The first eigenfrequency of the iced blade has been calculated.
- The first eigenfrequency of the clean blade with a tentative magnification factor
  \( K_1 \) has been calculated.
- By means of an iterative calculation, the magnification factor \( K_1 \) has been tuned
to obtain the same value of the iced blade case.

An example of calculation for \( m_E = 18.89 \) and an ice density \( \rho_{ice} = 700 \text{ kg/m}^3 \), as
recommended by the G.L. norms, gave the following results:

Eigenfrequencies of the Clean Blade [Hz]: 1F= 1.1895  1E= 2.3421  2F= 3.4343
Eigenfrequencies of the Iced Blade [Hz]: 1F= 1.0321  1E= 2.0801  2F= 2.9972
Magnification factor to restrain 1F-eigenmode = 1.3283  (19 iterations performed)
Eigenfrequencies of the New Blade [Hz]: 1F= 1.0321  1E= 2.0321  2F= 2.9798

The magnification factor \( K_2 \) to reproduce the integral \( M \) of the iced blade is simply
the ratio between the value of \( M \) of the iced blade and that of the clean blade. An
example of calculation for \( m_E = 18.89 \) and an ice density \( \rho_{ice} = 700 \text{ kg/m}^3 \) gave the
following results:

\[
\text{INT}(m*r*dr) \text{ of the Clean Blade [NM]}: 69497.4343 \\
\text{INT}(m*r*dr) \text{ of the Iced Blade [NM]}: 77572.6097 \\
\text{Magnification factor to restrain INT}(m*r*dr) = 1.1162
\]

The magnification factor \( K_3 \) to reproduce the same overall mass of the iced blade is
simply the ratio between the overall mass of the iced blade and that of the clean
blade. An example of calculation for \( m_E = 18.89 \) and an ice density \( \rho_{ice} = 700 \text{ kg/m}^3 \)
gave the following results:

Total M of the Clean Blade [NM]: 7962.23
Total M of the Iced Blade [NM]: 8392.7105
Magnification factor to restrain the Total M = 1.0541
2.3. Model for the Performances of the Iced Airfoils.

The WECO approach.
The behaviour of iced airfoils has been mainly studied during the WECO research program and some results are reported in [4] and [5]. One of the goals of the WECO project has been to evaluate experimentally the effect of simulated ice accretion on the aerodynamic performance of a modified airfoil. The study consisted on the following steps:

- A full-size 100 kW wind turbine operating in an sub-arctic site has been monitored. Pieces of rime ice from the leading edge with typical cross sections as it is shown in Figure 2.6 were collected from various rotor blades under various icing conditions, preserved and catalogued.

![Figure 2.6 Example of ice accretion cross sections documented from on-field observations.](image)

- The ice shapes have been put into a basket with model-plaster that after hardening has left a negative mould. This have been cast out with epoxy and filling material. The reproduced artificial shapes have been joined to the leading edge of a test profile (Fig. 2.7 right).

![Figure 2.7 Test open-jet wind tunnel & example of artificial iced airfoil.](image)

- The modified airfoils have been tested in an open jet wind gallery for a range of angles of attack (Fig. 2.7 left). Instationary measurements have also been performed for the iced and non-iced cross section in order to investigate the influence of icing on the dynamic stall behaviour. A NACA 4415 profile have been chosen for the tests since it was the same profile of the real monitored turbine.

- Several curves for the lift, drag and moment coefficients as a function of the angle of attack of clean and iced profiles have been finally obtained. These curves have been used as input for aerodynamic load calculations. The $C_l(\alpha)$ and $C_d(\alpha)$ curves are one of the main input for the present study and will be commented in detail afterward.
The power curves for clean and iced rotor have been calculated from the achieved \( C_l(\alpha) \) and \( C_d(\alpha) \) curves and compared with measurements from the real turbine.

**Model for the aerodynamic performances of the iced blades.**

The results from the experiments of the WECO program have been the basis for the aerodynamic model of the iced rotor and is also used in this paper.

In Figure 2.8 are reported the original plots from [5] for the \( C_l(\alpha) \) and \( C_m(\alpha) \) curves (right side) and \( C_l(\alpha) \) vs. \( C_d(\alpha) \) curves for four icing conditions. The icing conditions are named according to the maximum extension of the ice expressed in terms of percentage of the chord size (for example 22%-type means an ice shape that has a maximum extension of 22% of the chord of the profile).

There is a remarkable difference between the 44%-type curves and the 22%-type curves. The first has an higher maximum lift coefficient and a lower minimum drag coefficient compared to the second one. This behaviour goes against the intuitive idea that the lift get worse and worse with the extension of the ice.

It is worth to remark that the \( C_l \) and \( C_d \) coefficients have been defined according to the clean chord size. In principle, the lift coefficient of the iced airfoil, based on the clean chord size, can be higher than that of the clean one: as long as the ice accretion grows, the aerodynamic efficiency of the modified profile get worse but on the other hand the actual chord size get higher!

![Figure 2.8 Experimental aerodynamic performances of a NACA4415 with different icing levels.](image-url)
The original publications do not report any data table that had to be created as follows: the original plot has been included as background into a Excel® plot and four sets of points have been created to fit reasonably the points in the plots. The achieved data table of the four series are reported in Table 2.4.

<table>
<thead>
<tr>
<th>NACA 4415 - Clean</th>
<th>NACA 4415 - A 02%</th>
<th>NACA 4415 - B 22%</th>
<th>NACA 4415 - C 44%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{\text{attack}}$ [deg]</td>
<td>$C_l$ [-]</td>
<td>$C_d$ [-]</td>
<td>$\alpha_{\text{attack}}$ [deg]</td>
</tr>
<tr>
<td>-8.8</td>
<td>-0.340</td>
<td>0.034</td>
<td>-5</td>
</tr>
<tr>
<td>-4.5</td>
<td>0.000</td>
<td>0.020</td>
<td>-1.15</td>
</tr>
<tr>
<td>1.5</td>
<td>0.500</td>
<td>0.015</td>
<td>2.7</td>
</tr>
<tr>
<td>4.3</td>
<td>0.750</td>
<td>0.019</td>
<td>6.55</td>
</tr>
<tr>
<td>8</td>
<td>1.000</td>
<td>0.030</td>
<td>10.45</td>
</tr>
<tr>
<td>10</td>
<td>1.100</td>
<td>0.039</td>
<td>14.3</td>
</tr>
<tr>
<td>13</td>
<td>1.170</td>
<td>0.057</td>
<td>18.35</td>
</tr>
<tr>
<td>16.5</td>
<td>1.240</td>
<td>0.085</td>
<td>22.4</td>
</tr>
<tr>
<td>17.9</td>
<td>1.285</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>19.3</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.6</td>
<td>0.720</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td>0.770</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.800</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Figure 2.9 and 2.10 the $C_l(\alpha)$ and $C_d(\alpha)$ curves for the NACA 4415 profile achieved from different sources are compared. The curves achieved from the measurements in [5] are reported in green crosses while the measurements achieved by Abbott & Von Doenhoff [8] are reported as a background. The rhombs, squares and circles correspond respectively to a Reynolds number of $3.0 \cdot 10^6$, $6.0 \cdot 10^6$ and $9.0 \cdot 10^6$.

There is a remarkable difference between the behaviour of the lift coefficient curves achieved in [5] and [8] both in terms of slope of the curves for moderate angles of attack and in terms of maximum lift coefficient. Also in the drag coefficient is slightly different in the two cases. The Reynolds number is the key parameter to interpret the behaviours depicted in Figures 2.9. Re=$6.3 \cdot 10^5$ is declared in [5] while Re ranges between $3.0 \cdot 10^6$ and $9.0 \cdot 10^6$ in [8]. The blade-chord based Reynolds number for the turbine to be modelled in the dynamic simulation has also been estimated at the rated speed and resulted to range between $4.4 \cdot 10^6$ and $6.5 \cdot 10^6$. For low Reynolds number two effects are typically shown by the lift coefficient of airfoils: the maximum value tends to be lower and the slope of the curves for moderate angles of attack tends also to be lower. This behaviour is also recognisable from the Abbott & Von Doenhoff measurements depicted in the background.
The $C_l$ and $C_d$ curves have to be extended to at least in the range of angles of attack form $-10^\circ$ to $+90^\circ$ in order to be used in the aeroelastic code. 

The range of the curves have been extended using the following set of equations (Viterna’s equations) proposed in [5] for the post-stall region:

\[ C_{d,\text{max}} = C_{d,\text{plate},\alpha=90^\circ} \cdot \left( 1 + \frac{t_{\text{ice}}}{t} \right) \]  
\[ (\text{eq. 2.3}) \]

\[ C_d(\alpha) = C_{d,\text{max}} \cdot \sin^2 \alpha + B_2 \cdot \cos \alpha \quad \text{with} \quad B_2 = \frac{C_{d,\text{ref}} - C_{d,\text{max}} \cdot \sin^2 \alpha_{\text{ref}}}{\cos \alpha_{\text{ref}}} \]  
\[ (\text{eq. 2.4}) \]
where $t$ is the chord size, $t_{\text{ice}}$ is the extension of the ice at the leading edge $\alpha$ is any generic value of the angle of attack in the post-stall region, $C_{d,\text{plate},\alpha=90^\circ}$ is the drag coefficient of a flat plate for $\alpha=90^\circ$, $\alpha_{\text{ref}}$, $C_{d,\text{ref}}$ and $C_{l,\text{ref}}$ are respectively the angle of attack, the drag coefficient and the lift coefficient of the point where the Viterna’s equations starts taking place (see also Fig. 2.11).

A linear extrapolation down to $\alpha=-10^\circ$ has also been carried out taking into account the slope of the two first points.

![Figure 2.11 Original iced profile and model of flat plate with “ice” extension.](image)

Equations 2.3 to 2.5 have then be corrected taking into account the following set of empirical rules based on physical observations [11]:

I. $C_l = C_l \cdot \sin \alpha - C_d \cdot \cos \alpha > 0 \text{ for } -90^\circ < \alpha < 90^\circ$

II. $C_a = C_l \cdot \cos \alpha + C_d \cdot \sin \alpha \equiv \text{const. for } 45^\circ < \alpha < 90^\circ$

III. $C_i \approx 0$ and $C_d \approx 1.3$ for $\alpha = 90^\circ$

IV. $C_d \approx 0.2$ for $\alpha = 20^\circ$

no sharp drop in post-stall for $C_l$ (3-D effect)

The previous constrains should be considered as an aid to tune any method, numerical or empirical, to extend the lift and drag curves to a broader range of angles of attack.

The main parameter that has been tuned to meet the constrains was the drag coefficient of a flat plate for $\alpha=90^\circ$ $C_{d,\text{plate},\alpha=90^\circ}$. In [5] it is recommended the value for $C_{d,\text{plate},\alpha=90^\circ}=2$ that would not respect the third empirical rule.

By using straightforward $C_{d,\text{plate},\alpha=90^\circ}=1.3$ the $C_d(\alpha)$, $C_l(\alpha)$, $C_n(\alpha)$ and $C_t(\alpha)$ curves have a reasonable agreement with the second, third and fourth constrains.

The first constrain is violated in all the cases for $\alpha=0^\circ$; in particular a relevant violation is shown by the 22%-type.
Nevertheless, the points for $\alpha=0^\circ$ have been measured and so this violation does not depend on the extrapolation method. The final curves are shown in Figures 2.12-2.15 respectively for the clean profile, 2%-type, 22%-type and 44%-type.

Figure 2.12 $C_d(\alpha)$, $C_l(\alpha)$, $C_n(\alpha)$ and $C_t(\alpha)$ curves for the clean profile.

Figure 2.13 $C_d(\alpha)$, $C_l(\alpha)$, $C_n(\alpha)$ and $C_t(\alpha)$ curves for the 2%-type.
The curves achieved represent a database of aerodynamic performances for the NACA 4415 airfoils with different icing levels to be used in the model of the iced rotor. The tests have been carried out for one thickness to chord ratio only. In the next sections, will be pointed out how to model the full rotor blade.
3. AEROELASTIC MODEL OF THE WIND TURBINE


The dynamic behaviour and the loads of the iced wind turbine have been studied through a campaign of numeric simulations carried out with a aeroelastic code. In this section will be briefly presented the characteristics of the code employed for the simulations.

An aeroelastic code is a computer program that carries out dynamic simulations of a system consisting of the wind turbine and the flow field that pass through it for a given extent of time. The aeroelastic code integrates the calculations of the aerodynamic loads (as for example with the BEM method) with a structural model, a model for the wake expansion and a dynamic stall model [12]. The dynamic simulations can take into account the stochastic component of the wind field (turbulence) that has typically to be computed before the dynamic simulation itself and stored. The code used for the simulations is named FLEX® and has been developed at the Fluid Mechanics Department at the Technical University of Denmark. The code has the following main characteristics:

• It simulates the operation of horizontal axis wind turbines with one to three blades, fixed or variable speed, pitch or stall controlled.
• It runs in the time domains producing outputs files that are directly comparable with measurements.
• It is based on a structural model with relatively few, but important degrees of freedom to describe the rigid body motions and elastic deformations of the turbine.
• Simulates transients like starts and stops by pitching or breaking. This characteristics are believed to be close to the optimum regarding the trade-offs between computational efficiency and accuracy. Further details are available in [13], [14], and [15].

The code is widely used by wind turbine manufacturers and wind turbine installers to predict the loads during design, test the control systems and accomplish the verification calculations according with the norms. A long experience of measurements obtained over the years has been used to evolve the code that is now at the second issue named FLEX5®.

The simulation campaign carried out in the present paper is quite peculiar because the ice accretion can be in general different on the three blade due to the shedding of ice. Moreover, it was intended to check the case where the shedding was taking place suddenly during the time series.
A special version of FLEX5® with few minor changes have been developed by the Fluid Mechanics Department at the Technical University of Denmark in order to simulate the behaviour of an uneven iced rotor and of a sudden shedding of the ice from some of the blades. The first and more important change involved the way to give the airfoil performances database, that can have a different set of data for every blade. The second change involved the way of storing the generalised co-ordinates at the final instant of the time series into a file that now contains also the pitch angle and the derivative of the pitch angle (pitching velocity). This file can be given as initial condition to a subsequent time series making the second one to be practically a continuation of the first one. The second time series can be carried out changing the airfoil performances database of one or more rotor blades in a way to simulate the sudden shedding of the ice.

The simulations will be further discussed in the next sections.

3.2. The Wind Turbine.

The original wind turbine.

An example of megawatt-class wind turbine have been chosen and modelled taking into account the effect of the icing events on the rotor. The wind turbine that has been modelled was pretty much derived from an existing one build up in the late eighties for research purposes.

The original wind turbine, named Tjæreborg Turbine from the name of his location, was an horizontal axis, three blade, upwind, pitch regulated wind turbine. It was equipped with a 4-poles, asynchronous generator and it had a reinforced concrete tower.

The Tjæreborg Turbine was erected in the context of the WEGA development program, an international research study, within the European Union, commissioned in order to keep European technology leadership in the wind energy field. The main objective of its construction was to analyse and solve the specific problem of the huge megawatt-class wind turbine, that were still forthcoming at that time.

The wind turbine was erected in 1988 and operated, in the next ten years, for 38161 hours producing altogether 27130 GWh.

The main characteristics of the original Tjæreborg Turbine are listed in Table 3.1. Among the several details on this wind turbine, the most important one is the airfoil sections adopted that belong to the NACA 44xx family with a thickness to chord ratio that range from 12 per cent to 30 per cent.

Such a family of airfoil is the same of the profile tested by Seifert [5] with different icing levels, as described in the previous sections.

This particular characteristics of the Tjæreborg Turbine make easier to implement the model for the iced rotor proposed in Section 2.2 of this paper. Further details on the Tjæreborg Turbine are available in [16] and [17].
Modification of some input for the aeroelastic code.
The model of a given wind turbine into the FLEX® code are defined by the set of input files. Some of these input have been modified in order to model a wind turbine more suitable to put on evidence the effect of ice on the rotor. The characteristics that have been modified are the overall mass of the nacelle and the characteristics of the tower. By reducing the weight of the nacelle, the behaviour of the new turbine is believed to be more similar to that of a contemporary, lighter megawatt-class wind turbine. The tower has also been changed from a reinforced concrete tower to a steel tower. In Table 3.2 the blade mass, the hub mass, the nacelle mass and the tower mass of the original Tjæreborg Turbine has been compared with those of three modern wind turbine with a similar design concept: the G58 and the G80 of Gamesa Eolica® [18] and the V66 of Vestas® [19].
The characteristics of the new, lighter Tjæreborg Turbine are reported in Table 3.3 and compared with that of the original, heavier one and with that of the Vestas® V66.

The blade mass have not been changed and so also the weight of the hub. The nacelle has been reduced to about the half of the original weight. The tower have been changed into a steel tower with finer, but stiffer walls.

The first eigenfrequencies of the tower of the Tjæreborg Turbine have been calculated with FLEX® and reported in the last row.

The first eigenfrequency for the tower of the Vestas® V66 turbine has been estimated to be about 0.59 Hz considering for the system a virtual spring constant of about $1.1 \cdot 10^6$ Nm [20].

<table>
<thead>
<tr>
<th>Wind turbine</th>
<th>Light Tjæreborg</th>
<th>Original Tjæreborg</th>
<th>Vestas V66</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade mass [kg]</td>
<td>7963</td>
<td>7963</td>
<td>3592</td>
</tr>
<tr>
<td>Rotor mass [kg] (blades included)</td>
<td>42500</td>
<td>42500</td>
<td>23000</td>
</tr>
<tr>
<td>Nacelle mass [kg] (rotor included)</td>
<td>80000</td>
<td>154000</td>
<td>80000</td>
</tr>
<tr>
<td>Tower wall thickness [mm]</td>
<td>12</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>Tower material Young modulus [Pa]</td>
<td>$2.1 \cdot 10^{11}$</td>
<td>$4.0 \cdot 10^{10}$</td>
<td>-</td>
</tr>
<tr>
<td>Tower material density [kg/m$^3$]</td>
<td>7850</td>
<td>2600</td>
<td>-</td>
</tr>
<tr>
<td>Tower mass [kg] (57m height)</td>
<td>86200</td>
<td>550000</td>
<td>-</td>
</tr>
<tr>
<td>First tower eigenfrequency [Hz]</td>
<td>0.60</td>
<td>0.81</td>
<td>0.59</td>
</tr>
</tbody>
</table>

**Implementation of the iced rotor model in the aeroelastic code.**

The way of implementing the iced rotor model on the aeroelastic model of the Tjæreborg Turbine is presented in this section.

In order to understand the model of the iced rotor, it is worth to introduce the concept of “Contamination Level” that will be also discussed afterwards. A Contamination Level is a consistent set of data that model a given shape of ice on the blade.

The basic data necessary to characterize the ice on the blade are the mass distribution $m(r)$, and the performances of the airfoils $C_l(\alpha)$, $C_d(\alpha)$ and $C_m(\alpha)$ for every station.

As mentioned, the ice accretion is a complex stochastic process that depend on meteorological and operative conditions; on top of it, the ice can shed off from the blade due to centrifugal and aerodynamic forces.
Although the definition of the actual ice shape is quite complex, a simplified approach is that of defining some arbitrarily, but reasonable, Contamination Levels and check the damage level determined on the machine by such an ice accretion. The meteorological characteristics of the site where the turbine is going to be installed can, afterward, identify the more consistent Contamination Level for that machine in that site.

All the procedural aspects will be discussed in deep afterward in a specific section.

What it has to be explained extensively in this section is how to use the database and the equations developed in Section 2 to build up a given Contamination Level. A Contamination Level is determined carrying out the following steps:

- The first parameter to be chosen is the mass per unit length of ice at the leading edge of the rotor blade at half the rotor radius, \( m_E \).
- In Equation 2.1 such a quantity is calculated according to the Germanisher Lloyd specifications.
- It is worth to remind that this specifications state one specific icing level that is believed to be a relevant case for most of the conditions. It is always possible assume lower icing level.
- Higher values of \( m_E \) can also be assumed considering that Equation 2.1 refers to a not-severe icing condition according to [2]. Moreover, according to [5] the ice accretion can reach up to 100 per cent of the chord length during idling operation and up to 40 per cent during power production operation.

- Once that \( m_E \) has been chosen, the ice mass distribution \( m(r) \) is calculated assuming a linear growth from the hub to 50 per cent of the rotor diameter where it reach \( m_E \). From there to the tip \( m(r)=m_E \).
- By assuming \( \text{Ext}(r)\cdot C(r)= 0.1 \text{ m} \) and using Equation 2.2, it is possible to achieve the maximum ice thickness \( t_{\text{ice}}(r) \) along the blade.
- An example of mass distribution achieved in such a way is reported in Table 2.3
- The mass distribution has then to be processed in order to achieve the three blade mass magnification factors \( K_1, K_2, \) and \( K_3 \) to be given as input to the FLEX® code. \( K_1, K_2, \) and \( K_3 \) give to the original Tjæreborg Turbine blade respectively the same first flapwise eigenfrequency, the same blade root bending moment and the same overall mass as the iced blade (see Section 2.2).
- A Matlab® code has been developed to carry out this operation and is reported in Appendix 3.1 (M_eq.m and subroutine eigenvalues.m).
- The next step is the implementation of the airfoils performances of the iced rotor. The plots of Figures 2.8 and Table 2.4 have been measured for a NACA 4415 at \( \text{Re}=6.3\cdot10^5 \). The real blade has, along the spanwise direction, a thickness to chord ratio that ranges from 12 per cent to 30 per cent and a Reynolds number for the rated speed that ranges between \( 4.4\cdot10^6 \) and \( 6.5\cdot10^6 \).

Nevertheless, it is believed that the performances measured by Seifert in [5] could be used as performances database for the iced blades of the Tjæreborg Turbine.

The reason is that the ice is a rough protuberance that is promoting the flow transition from laminar to turbulent close to the leading edge making the iced
profile less sensitive to the effect of Reynolds Number and also to the effect of the thickness to chord ratio.

The airfoil performances database of Figures 2.12-15 have been used for any station and at any operative conditions when ice was supposed to be accreted on the leading edge of the blades. The performances of Figures 2.12, that were relative to a clean airfoil, have not been employed because in that case the effect of Reynolds number has to be taken into account.

The standard airfoil database of the Tjæreborg Turbine has been used for any station and any operative condition when no ice was supposed to be accreted on the leading edge of the blades. In this case, the effect of the thickness to ratio has been taken into account giving a different performances at every station.

- The airfoil performances database to be used depend on the ratio between the maximum ice thickness and chord length $t_{\text{ice}}/C$.

The available experimental data are for three value of the $t_{\text{ice}}/C$ value only: 02%-type, 22%-type and 44%-type (see Section 2.3).

Once that $m_e$ has been chosen, $m(r)$ and then $t_{\text{ice}}(r)/C$ can be calculated as for shown in the last column of Table 2.3. These estimated icing level can have any generic value of $t_{\text{ice}}/C$ that in general is different from that of the three icing levels tested experimentally.

In comes out that is necessary to carry out an interpolations between the experimental data respect to the current icing level characterised by a value of $t_{\text{ice}}/C$ in percentage.

Assuming, for instance that a generic icing level $X%$-type were between the 02%-type and the 22%-type, his $C_{l,X%}$ and $C_{d,X%}$ would be:

$$C_{l,X%} = C_{l,02%} + \left( \frac{C_{l,22%} - C_{l,02%}}{22% - 02\%} \right) \cdot (X\% - 02\%) \quad \text{(eq. 3.1)}$$

$$C_{d,X%} = C_{d,02%} + \left( \frac{C_{d,22%} - C_{d,02%}}{22% - 02\%} \right) \cdot (X\% - 02\%) \quad \text{(eq. 3.2)}$$

These equations have to be solved for every value of the angle of attack of the database.

The FLEX® code has been set up to have three airfoil performances database for three stations along the spanwise direction.

The first database refers to station 4, that is the first airfoil encountered starting from the hub. The second database has been assigned to station 7 where the radius is the half of the rotor radius and so where the maximum ice thickness stops growing linearly and starts being constant. The third database has been assigned to station 14 at the tip.

Once that these three database are assigned at the three stations, the FLEX® code interpolate linearly among them in a similar manner as for Equations 3.1 and 3.2.

Concerning the clean rotor blade, the FLEX® code has been set up to have five airfoil performances database for five stations along the spanwise direction, as in the standard model of the Tjæreborg Turbine.
A special discussion is required about the moment coefficient $C_m$.
It Figure 2.8 is also depicted the behaviour of $C_m(\alpha)$ for the three icing levels measured by Seifert [5].
Due to the growth of chord length at the leading edge the pitch moment increases dramatically [21]. This fact is very important for the design of the pitch control mechanism.
Since this study deals mainly with the overall load of the structure, the change in the pitching moment has been disregarded and the $C_m(\alpha)$ column in the airfoil performances database has been set to be zero whenever the ice accretion was present.
The consequence of such a choice is a small underestimation of the overall pitching moment acting on the blade whose main component is due to the gravity of the blade itself.

Three contamination Levels have been chosen for the numeric simulations and have been defined according with the procedure stated above.
The main data of the Contamination Levels are reported below in Table 3.4.

<table>
<thead>
<tr>
<th>Contamination Level</th>
<th>CL-1</th>
<th>CL-2</th>
<th>CL-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_E$ [kg/m]</td>
<td>9.44</td>
<td>18.89</td>
<td>37.76</td>
</tr>
<tr>
<td>$K_1$ [-]</td>
<td>1.1624</td>
<td>1.3283</td>
<td>1.6616</td>
</tr>
<tr>
<td>$K_2$ [-]</td>
<td>1.0578</td>
<td>1.1162</td>
<td>1.2324</td>
</tr>
<tr>
<td>$K_3$ [-]</td>
<td>1.0269</td>
<td>1.0541</td>
<td>1.1081</td>
</tr>
<tr>
<td>$t_{ice, hub}/C$ [-]</td>
<td>1.7%</td>
<td>3.5%</td>
<td>7.0%</td>
</tr>
<tr>
<td>$t_{ice, mid}/C$ [-]</td>
<td>5.6%</td>
<td>11.3%</td>
<td>22.6%</td>
</tr>
<tr>
<td>$t_{ice, tip}/C$ [-]</td>
<td>14.4%</td>
<td>28.8%</td>
<td>57.6%</td>
</tr>
</tbody>
</table>

The tip icing level of CL-3 is 57.6 per cent that is above the higher experimentally measured icing level of 44%.
For this Contamination Level, it has been set up a four-station airfoil performances database along the spanwise direction.
From the fourth station to the tip, the icing level is supposed to be constant en equal to 44%-type.

It is worth to notice that the input furnished to the FLEX® code to model the Tjæreborg Turbine are very many and not all of them have been modified.
The original input of the Tjæreborg Turbine have been restrained except for: the airfoil database in case the rotor is iced, the magnification factor for the blade mass distribution, the mass of the nacelle and the data of the tower.
Appendix 3.1. Program Listing.

*M_eq.m*

```matlab
% §§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§
% §§§§§§§§§§                        M_eq                     §§§§§§§§§§§§§§
% §§§§§§§§§§     Calculation of the Magnification Factor     §§§§§§§§§§§§§§
% §§§§§§§§§§    to be used in Flex in order to reproduce    §§§§§§§§§§§§§§
% §§§§§§§§§§     one of the characteristics of the blade     §§§§§§§§§§§§§§
% §§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§§

% --> preliminary
clc
close all
clear all

load Geom_TJ.mat
doplot=0;       % --> doplot=1 shows the eigemnodes
dotest=0;       % --> dotest=1 shows the tip displacement that should be 1

% --> copy and paste the mass of ice
M_ice=[
3.6
6.8
7.3
16.0
23.4
30.9
37.8
37.8
37.8
37.8
37.8
37.8
37.8
37.8
37.8
37.8
]

disp(' ')
disp(' §§§§§§§§§§§§§§ Magnification factor to restrain 1F-eigenmode §§§§§§§§§§§§§§')
disp(' ')

% --> eigenfrequencies of the clean blade
[omegasq_clean] = eigenvalues(radius,twist,M,EI1,EI2,doplot,dotest);
disp(['Eigenfrequencies of the Clean Blade [Hz]: 1F= ' num2str(sqrt(omegasq_clean(1))/(2*pi)) '   1E= ' num2str(sqrt(omegasq_clean(2))/(2*pi)) ' 2F= ' num2str(sqrt(omegasq_clean(3))/(2*pi))])
```

Pag. 3.8
% --> eigenfrequencies of the iced blade
[omegasq_iced] = eigenvalues(radius,twist,M+M_ice,El1,El2,doplot,dotest);
disp(['Eigenfrequencies of the Iced Blade [Hz]: 1F= ' num2str(sqrt(omegasq_iced(1))/(2*pi)) ' 1E= ' num2str(sqrt(omegasq_iced(2))/(2*pi)) ' 2F= ' num2str(sqrt(omegasq_iced(3))/(2*pi)))])

% --> searching for the magnification factor
k_up=10;
k_down=1;
omegasq_med(1)=0;
n=0;
while (abs(omegasq_med(1)-omegasq_iced(1))>10^-4&n<100)
    n=n+1;
k_med=0.5*(k_up+k_down);
[omegasq_up] = eigenvalues(radius,twist,k_up*M,El1,El2,0,0);
[omegasq_med] = eigenvalues(radius,twist,k_med*M,El1,El2,0,0);
[omegasq_down] = eigenvalues(radius,twist,k_down*M,El1,El2,0,0);
    if omegasq_med(1)>=omegasq_iced(1)
k_down=k_med;
else
    k_up=k_med;
end
if mod(n,5) == 1
    disp([' --> Residual= '  num2str(abs(omegasq_med(1)-omegasq_iced(1))/(2*pi)) ' ' num2str(n) ' iterations performed']);
end
end

[omegasq_k] = eigenvalues(radius,twist,M*k_med,El1,El2,0,dotest);
disp(['Maginification factor to restrain 1F-eigenmode = ' num2str(k_med) ' (' num2str(n) ' iterations performed')])
disp(['Eigenfrequencies of the New Blade [Hz]: 1F= ' num2str(sqrt(omegasq_k(1))/(2*pi)) ' 1E= ' num2str(sqrt(omegasq_k(2))/(2*pi)) ' 2F= ' num2str(sqrt(omegasq_k(3))/(2*pi)))])
disp('')
disp('$$$$$$$$$$$$$$$$ Magnification factor to restrain INT(m*r*dr) $$$$$$$$$$$$$$$$$$')
disp('')

% --> mr_dr of the clean blade
Mom_clean = trapz(radius,radius.*M);
disp(['INT(m*r*dr) of the Clean Blade [NM]: ' num2str(Mom_clean)])

% --> mr_dr of the iced blade
Mom_iced = trapz(radius,radius.*(M+M_ice));
disp(['\text{INT}(m\cdot r\cdot dr) \text{ of the Iced Blade [NM]}: ' num2str(Mom_iced) '])

k=Mom_iced/Mom_clean;
% Mom_k = trapz(radius,radius.*(M*k));
disp(['\text{Magnification factor to restrain } \text{INT}(m\cdot r\cdot dr) = ' num2str(k) '])
% disp(['\text{INT}(m\cdot r\cdot dr) \text{ of the New Blade [Nm]}: ' num2str(Mom_k) '])

disp('
% --> total mass of the clean blade
Mom_clean = trapz(radius,M);
disp(['\text{Total M of the Clean Blade [NM]}: ' num2str(Mom_clean) '])

% --> total mass of the iced blade
Mom_iced = trapz(radius,(M+M_ice));
disp(['\text{Total M of the Iced Blade [NM]}: ' num2str(Mom_iced) '])

k=Mom_iced/Mom_clean;
% Mom_k = trapz(radius,radius.*(M*k));
disp(['\text{Magnification factor to restrain the Total M} = ' num2str(k) '])
% disp(['\text{INT}(m\cdot r\cdot dr) \text{ of the New Blade [Nm]}: ' num2str(Mom_k) '])

eigenvalues.m

function [omegasq] = eigenvalues(radius,twist,M,EI1,EI2,doplot,dotest)

%-------------------------------------------------
%%%% Initializing the values %%%%%%%%%%%%%%%%%%%%
%-------------------------------------------------

% Initializing the values %%%%%%%%%%%%%%%%%%%%

%-----

% changing twist to radians
R=33;
m = M;
N = length(radius);
x = radius;
p_z = ones(N,1)*1;
p_y = ones(N,1)*1;
T_y = zeros(N,1);
T_z = zeros(N,1);
M_y = zeros(N,1);
M_z = zeros(N,1);
theta_y = zeros(N,1);
theta_z = zeros(N,1);
u_y = zeros(N,1);
\( u_z = \text{zeros}(N,1); \)
\( \omega_{\text{new}} = 1; \)
\( \omega_{\text{sq}} = 0; \)

\[ \text{while abs}(\omega_{\text{new}}-\omega_{\text{sq}}) > 0.0001 \]
\[ \omega_{\text{new}} = \omega_{\text{sq}}; \]
\[ \text{for } i = N:-1:2 \]
\[ \quad \text{\%--> Shear strength} \]
\[ \quad T_y(i-1)=T_y(i)+0.5*(p_y(i-1)+p_y(i))*(x(i-1)-x(i)); \]
\[ \quad T_z(i-1)=T_z(i)+0.5*(p_z(i-1)+p_z(i))*(x(i-1)-x(i)); \]
\[ \quad \text{\%--> Bending Moment} \]
\[ \quad M_y(i-1)=M_y(i)+T_z(i)*(x(i-1)-x(i))+(1/6*p_z(i-1)+1/3*p_z(i))*(x(i-1)-x(i))^2; \]
\[ \quad M_z(i-1)=M_z(i)+T_y(i)*(x(i-1)-x(i))+(1/6*p_y(i-1)+1/3*p_y(i))*(x(i-1)-x(i))^2; \]
\[ \text{\%--> translate moments in Principal Inertia Axis} \]
\[ M_1 = M_y.*\cos(\text{twist})-M_z.*\sin(\text{twist}); \]
\[ M_2 = M_y.*\sin(\text{twist})+M_z.*\cos(\text{twist}); \]
\[ \text{\%--> curvatures around the principal axis} \]
\[ \kappa_1 = M_1./EI1; \]
\[ \kappa_2 = M_2./EI2; \]
\[ \text{\%--> curvatures around the z and y-axis} \]
\[ \kappa_z = -\kappa_1.*\sin(\text{twist})+\kappa_2.*\cos(\text{twist}); \]
\[ \kappa_y = \kappa_1.*\cos(\text{twist})+\kappa_2.*\sin(\text{twist}); \]
\[ \text{for } i = 1:N-1 \]
\[ \quad \text{\%--> slope} \]
\[ \theta_y(i+1)=\theta_y(i)+0.5*(\kappa_y(i+1)+\kappa_y(i))*(x(i+1)-x(i)); \]
theta_z(i+1)=theta_z(i)+0.5*(kappa_z(i+1)+kappa_z(i))*(x(i+1)-x(i));

%--> deflection
u_y(i+1) = u_y(i)+theta_z(i)*(x(i+1)-x(i))+(1/6*kappa_z(i+1)+1/3*kappa_z(i))*(x(i+1)-x(i))^2;
u_z(i+1) = u_z(i)+theta_y(i)*(x(i+1)-x(i))+(1/6*kappa_y(i+1)+1/3*kappa_y(i))*(x(i+1)-x(i))^2;

end

omega_sq = p_z(N)/(u_z(N)*M(N));
p_z = omega_sq.*M.*u_z/(sqrt(u_z(N)^2+u_y(N)^2));
p_y = omega_sq.*M.*u_y/(sqrt(u_z(N)^2+u_y(N)^2));
end

% updating all deflection, slope, curvature ,eigenfrequency-1
u_z_1f = u_z;
u_y_1f = u_y;
theta_z_1f = theta_z;
theta_y_1f = theta_y;
kappa_z_1f = kappa_z;
kappa_y_1f = kappa_y;
omegasq_1f = omega_sq;

%%%%%%% Calculation of 1. edgewise mode %%%%%%%
%%%%%%% initialization of loads and eigenfrequencies
omega_new = 1;
omega_sq = 0;
p_z = ones(N,1)*-1;
p_y = ones(N,1)*-1;
while abs(omega_new-omega_sq) > 0.0001
omega_new = omega_sq;

for i = N:-1:2
    \%--> Shear strength
    T_y(i-1)=T_y(i)+0.5*(p_y(i-1)+p_y(i))*(x(i-1)-x(i));
    T_z(i-1)=T_z(i)+0.5*(p_z(i-1)+p_z(i))*(x(i-1)-x(i));

    \%--> Bending Moment
    M_y(i-1)=M_y(i)+T_z(i)*(x(i-1)-x(i))+(1/6*p_z(i-1)+1/3*p_z(i))*(x(i-1)-x(i))^2;
    M_z(i-1)=M_z(i)+T_y(i)*(x(i-1)-x(i))+(1/6*p_y(i-1)+1/3*p_y(i))*(x(i-1)-x(i))^2;
end

\%--> translate moments in Principal Inertia Axis

M_1 = M_y.*cos(twist)-M_z.*sin(twist); 
M_2 = M_y.*sin(twist)+M_z.*cos(twist);

\%--> curvatures aroung the principal axis

kappa_1 = M_1./EI1;
kappa_2 = M_2./EI2;

\%--> curvatures aroung the z and y-axis

kappa_z = -kappa_1.*sin(twist)+kappa_2.*cos(twist);
kappa_y = kappa_1.*cos(twist)+kappa_2.*sin(twist);

for i = 1:N-1
    \%--> slope
    theta_y(i+1)=theta_y(i)+0.5*(kappa_y(i+1)+kappa_y(i))*(x(i+1)-x(i));
    theta_z(i+1)=theta_z(i)+0.5*(kappa_z(i+1)+kappa_z(i))*(x(i+1)-x(i));

    \%--> deflection
    u_y(i+1) = u_y(i)+theta_z(i)*(x(i+1)-x(i))+(1/6*kappa_z(i+1)+1/3*kappa_z(i))*(x(i+1)-x(i))^2;
    u_z(i+1) = u_z(i)+theta_y(i)*(x(i+1)-x(i))+(1/6*kappa_y(i+1)+1/3*kappa_y(i))*(x(i+1)-x(i))^2;
end

\%\%\% --> Constant for the 1. edgewise mode

Pag. 3.13
\[ C_{le} = \frac{\text{trapz}(x, u_{z_{1f}} \cdot M \cdot u_{z}) + \text{trapz}(x, u_{y_{1f}} \cdot M \cdot u_{y})}{\text{trapz}(x, u_{z_{1f}} \cdot M \cdot u_{z_{1f}}) + \text{trapz}(x, u_{y_{1f}} \cdot M \cdot u_{y_{1f}})}; \]

%--> actualization of the edgewise values

\[ u_{z_{1e}} = u_{z} - C_{le} u_{z_{1f}}; \]
\[ u_{y_{1e}} = u_{y} - C_{le} u_{y_{1f}}; \]

\[ \omega_{sq} = p_{z}(N)/(u_{z_{1e}}(N) \cdot M(N)); \]

\[ p_{z} = \omega_{sq} \cdot M \cdot u_{z_{1e}}/(\sqrt{u_{z_{1e}}(N)^2 + u_{y_{1e}}(N)^2}); \]
\[ p_{y} = \omega_{sq} \cdot M \cdot u_{y_{1e}}/(\sqrt{u_{z_{1e}}(N)^2 + u_{y_{1e}}(N)^2}); \]

end

% updating all deflection, slope, curvature, eigenfrequencies

\[ \theta_{z_{1e}} = \theta_{z}; \]
\[ \theta_{y_{1e}} = \theta_{y}; \]

\[ \kappa_{z_{1e}} = \kappa_{z}; \]
\[ \kappa_{y_{1e}} = \kappa_{y}; \]

\[ \omega_{sq_{1e}} = \omega_{sq}; \]

% Calculation of 2. flapwise mode

%--> initialization of loads and eigenfrequencies

\[ \omega_{new} = 1; \]
\[ \omega_{sq} = 0; \]
\[ p_{z} = \text{ones}(N,1) \cdot 1; \]
\[ p_{y} = \text{ones}(N,1) \cdot 1; \]

while abs(\(\omega_{new} - \omega_{sq}\)) > 0.0001

\[ \omega_{new} = \omega_{sq}; \]

for i = N:-1:2

%--> Shear strength
\[ T_{y(i-1)} = T_{y(i)} + 0.5 \cdot (p_{y(i-1)} + p_{y(i)}) \cdot (x(i-1) - x(i)); \]
\[ T_{z(i-1)} = T_{z(i)} + 0.5 \cdot (p_{z(i-1)} + p_{z(i)}) \cdot (x(i-1) - x(i)); \]
%--> Bending Moment
M_y(i-1)=M_y(i)+T_z(i)*(x(i-1)-x(i))+(1/6*p_z(i-1)+1/3*p_z(i))*(x(i-1)-x(i))^2;
M_z(i-1)=M_z(i)+T_y(i)*(x(i-1)-x(i))+(1/6*p_y(i-1)+1/3*p_y(i))*(x(i-1)-x(i))^2;
end

%--> translate moments in Principal Inertia Axis
M_1 = M_y.*cos(twist)-M_z.*sin(twist);
M_2 = M_y.*sin(twist)+M_z.*cos(twist);

%--> curvatures aroung the principal axis
kappa_1 = M_1./EI1;
kappa_2 = M_2./EI2;

%--> curvatures aroung the z and y-axis
kappa_z = -kappa_1.*sin(twist)+kappa_2.*cos(twist);
kappa_y = kappa_1.*cos(twist)+kappa_2.*sin(twist);

for i = 1:N-1
%--> slope
theta_y(i+1)=theta_y(i)+0.5*(kappa_y(i+1)+kappa_y(i))*(x(i+1)-x(i));
theta_z(i+1)=theta_z(i)+0.5*(kappa_z(i+1)+kappa_z(i))*(x(i+1)-x(i));

%--> deflection
u_y(i+1) = u_y(i)+theta_z(i)*(x(i+1)-x(i))+(1/6*kappa_z(i+1)+1/3*kappa_z(i))*(x(i+1)-x(i))^2;
u_z(i+1) = u_z(i)+theta_y(i)*(x(i+1)-x(i))+(1/6*kappa_y(i+1)+1/3*kappa_y(i))*(x(i+1)-x(i))^2;
end

%%% --> Constant for the 1. edgewise mode
C_1e= (trapz( x , u_z_1f.* M .* u_z ) + trapz( x , u_y_1f.* M .* u_y )) / (trapz( x , u_z_1f.* M .* u_z_1f ) + trapz( x , u_y_1f.* M .* u_y_1f ));

u_z = u_z - C_1e*u_z_1f;
u_y = u_y - C_1e*u_y_1f;

%%% --> Constant for the 2. flapwise mode
\( C_{2f} = \frac{\text{trpz}(x, u_{z_1} \cdot M \cdot u_z) + \text{trpz}(x, u_{y_1} \cdot M \cdot u_y)}{\text{trpz}(x, u_{z_1} \cdot M \cdot u_z) + \text{trpz}(x, u_{y_1} \cdot M \cdot u_y)} \);

\( u_{z_{2f}} = u_z - C_{2f} u_{z_1} \);
\( u_{y_{2f}} = u_y - C_{2f} u_{y_1} \);

\( \omega_{sq} = p_z(N)/(u_{z_2f}(N) \cdot M(N)) \);
\( p_z = \omega_{sq} \cdot M \cdot u_{z_2f}/(\sqrt{u_{z_2f}(N)^2 + u_{y_2f}(N)^2}) \);
\( p_y = \omega_{sq} \cdot M \cdot u_{y_2f}/(\sqrt{u_{z_2f}(N)^2 + u_{y_2f}(N)^2}) \);

end

% updating all deflection, slope, curvature, eigenfrequencies

\( \theta_{z_{2f}} = \theta_z \);
\( \theta_{y_{2f}} = \theta_y \);
\( \kappa_{z_{2f}} = \kappa_z \);
\( \kappa_{y_{2f}} = \kappa_y \);
\( \omega_{sq_{2f}} = \omega_{sq} \);

if doplot
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% plot of the 1st flapwise eigenmode
    plot(x/R, u_{z_{1f}},'b')
    hold on
    plot(x/R, u_{y_{1f}},'r')
    title('1^{st} Flapwise')
    xlabel('radius [per unit]')
    ylabel('Deflection [per unit]')
    legend('u^{1f}_z','u^{1f}_y',2)
    grid

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% plot of the 1st edgewise eigenmode
    figure
    plot(x/R, u_{z_{1e}},'b')
    hold on
    plot(x/R, u_{y_{1e}},'r')
    title('1^{st} Edgewise')
    xlabel('radius [per unit]')
    ylabel('Deflection [per unit]')

else
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% plot of the 1st flapwise eigenmode
    plot(x/R, u_{z_{1f}},'b')
    hold on
    plot(x/R, u_{y_{1f}},'r')
    title('1^{st} Flapwise')
    xlabel('radius [per unit]')
    ylabel('Deflection [per unit]')
    legend('u^{1f}_z','u^{1f}_y',2)
    grid

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% plot of the 1st edgewise eigenmode
    figure
    plot(x/R, u_{z_{1e}},'b')
    hold on
    plot(x/R, u_{y_{1e}},'r')
    title('1^{st} Edgewise')
    xlabel('radius [per unit]')
    ylabel('Deflection [per unit]')
legend('u^{1e}_z','u^{1e}_y',2)
grid

%% plot of the 2nd flapwise eigenmode
figure
plot(x/R,u_z_2f,'b')
hold on
plot(x/R,u_y_2f,'r')
title('2^{nd} Flapwise')
xlabel('radius [per unit]')
ylabel('Deflection [per unit]')
legend('u^{2f}_z','u^{2f}_y',2)
grid
end

%% Test for the normalization of the displacements
if dotest
disp_f1=u_z_1f(N)^2 + u_y_1f(N)^2;
disp_e1=u_z_1e(N)^2 + u_y_1e(N)^2;
disp_f2=u_z_2f(N)^2 + u_y_2f(N)^2;
disp(['Tip displacements: 1F= ' num2str(disp_f1) '   1E= ' num2str(disp_e1) '   2F= '
num2str(disp_f2)])
end

u_z=zeros(3,length(radius));
u_y=zeros(3,length(radius));

u_z(1,:)=u_z_1f';
u_z(2,:)=u_z_1e';
u_z(3,:)=u_z_2f';

u_y(1,:)=u_y_1f';
u_y(2,:)=u_y_1e';
u_y(3,:)=u_y_2f';

omegasq=[omegasq_1f omegasq_1e omegasq_2f];
theta_y_all=[theta_y_1f theta_y_1e theta_y_2f];
theta_z_all=[theta_z_1f theta_z_1e theta_z_2f];
kappa_y_all=[kappa_y_1f kappa_y_1e kappa_y_2f];
kappa_z_all=[kappa_z_1f kappa_z_1e kappa_z_2f];
4. AEROELASTIC SIMULATIONS OF THE WIND TURBINE

Once that the Tjæreborg Turbine has been modelled, FLEX® can simulate his behaviour for various operative conditions producing time series. The series can then be processed to achieve a great variety of statistic values thanks to a set of post-processing tools [22].

The time series produce the value of a given set of quantities, said “sensors” for every time step of the series. Many of these quantities are the loads of a given component; in these cases the time series represent load histories of the component.

The main task of the simulation campaign is that of putting on evidence the increase in these loads due to icing accretion on the rotor blades. The tests presented in this section have been conceived to accomplish this task.

4.1. Description of the Input and Output.

The input for an aeroelastic calculation are very many, as mentioned in the previous section. A complete set of input for the Tjæreborg Turbine were available because that machine have been extensively analysed in the past. Since the original set of input for the model of the Tjæreborg Turbine were known, they have been restrained as much as possible in these numerical simulation campaign.

The modified data were the airfoil database in case the rotor is iced, the magnification factor for the blade mass distribution, the mass of the nacelle and the data of the tower as described in the previous section.

The main input file for a specific simulation named Test 1, that will be used as reference case, is reported in Appendix 4.1. All the other simulations have a limited number of input different from those of Test 1; if not declared differently, any input have the same value of those listed in Appendix 4.1.

The description of all the singles quantities contained in the main input file (default name: Infile.pas) has been omitted for aim of brevity; further details are contained in [14]. The main input file contain the name of many other files to be called by the aeroelastic code; the file used as input and the description of their content is reported in Table 4.1.

Three turbulence files have been produced for every value of the mean wind speed at the hub height; the XX notation in Table 4.1 represents the value of the mean wind speed in meter for second.

Many other additional files can be used to model the generator, the braking system, the pitching system, the yawing system, the control system and the average wind speed changes (gusts, etc.). In the file of Appendix 4.1 these additional data were listed straightforward in the main input file.
A special discussion is necessary for the *.inx file (last raw in Table 4.1) that contains the initial condition for a simulation, in case they have to be specified. The *.inx file contains a vector with the values of all the generalised coordinate, a vector with the first derivative of all the generalised coordinate, a value for the pitch angle and for the pitching velocity. This file has been used during the simulations of sudden deicing events where two time series with different input have to be carried out and joined. The *.inf file contains in this case the values stored at the last time step of the first time series that become the values of the first step of the second time series. In case the *.inf file is not specified, FLEX® calculate the equilibrium positions for the system at the first time step before starting the time marching procedure. The whole input files have not been included into this document for aim of brevity.

Two main output files are produced by the FLEX® code: a text file (default name: Outfile.pas) that replicate all the input and few generic quantities that characterise the output and a binary file that contain the time series itself (default name: x.res). A further output (default name: Outfile.pas) contains a vector with the generalised coordinate, a vector with the first derivative for the generalised coordinate, a value for the pitch angle and for the pitching velocity that can be used as initial conditions for a subsequent time series, as explained above. The time series contains the value of 94 virtual sensors for every time step of the series. Example of sensors are the wind speed at the hub height, the pitch angle, the rotational speed, the power output, the generalised coordinates and the deflections at some points. Forces, moments and loads represents another group of the sensors. Not all the sensors are relevant for all the kind of analysis, so not all of them have been monitored in this study.
The sensors that have been selected to be analysed are listed below together with the respective FLEX® short denomination in squares brackets:

- Flapwise blade root bending moment of Blade 1 [-My1 Flap mom, R=1.46 m, bl. 1].
- Edgewise blade root bending moment of Blade 1 [-My1 Edge mom, R=1.46 m, bl. 1].
- Flapwise blade root bending moment of Blade 3 [-My1 Flap mom, R=1.46 m, bl. 3].
- Edgewise blade root bending moment of Blade 3 [-My1 Edge mom, R=1.46 m, bl. 3].
- Yaw shaft bending moment [MxN Shaft (N-sys), Yaw].
- Tilt shaft bending moment [MyN Shaft (N-sys), Tilt].
- Shaft torque [MzN Shaft (N-sys), Torque].
- Yaw nacelle bending moment [MxK1 Nacelle (K1-sys), Yaw].
- Tilt nacelle bending moment [MyK1 Nacelle (K1-sys), Tilt].
- Nacelle bending moment along the wind turbine axis direction [MzK1 Nacelle (K1-sys)].
- Tower root bending moment due to longitudinal load (along the wind direction) [Myh0 Tower bending, h=0 m, L].
- Tower root bending moment due to transverse load (normal to the wind direction) [Mzh0 Tower bending, h=0 m, T].

The FLEX® short denomination refers to a set of points, and to their relative reference frame, that are defined in the input main file [14].

Two main post-processing operations can be carried out on the time series: the Fast Fourier Transformations (FFT hereafter) and the Rainflow Count (RFC hereafter). The FFC produces a frequency spectra of a given time series; several options for the realisation of this operation and the representation of the results are possible. The frequency spectra show some peaks that help in putting on evidence the eigenfrequency and the exciting frequency of the system. The RFC is a procedure to estimate the fatigue damage produced by a load history and consist in the following steps:

- transforming the load-time history into a peak/through sequence of events characterised by a cycle-range and a cycle-average value;
- defining a set of bins of cycle-range and cycle-average value;
- recording a Markov-Matrix in which the elements are the number of events within two cycle-range levels and two cycle-average value levels.

The Rainflow count procedure is quite complex and his description is well above the scope of the present study; further details are available in [23].

The load spectra can be compared with the Wöhler curves of the material in order to achieve the safety coefficients of the component respect to the fatigue damage. The load spectra of a Markov-Matrix can be further processed to calculate the “Equivalent Load” of the time history respect to a given reference frequency. If a given component were cyclically loaded with the equivalent load at the reference frequency during all the time series, the damage produced would be the same as for the original load spectra.
The equivalent load can be calculated only by assuming a given fatigue behaviour of the material (damage-rate-exponent of the Wöhler curve). The FLEX code give the equivalent load for six damage-rate-exponents from a value of 3 to a value of 12. The equivalent load have been recorded for one value of the damage-rate-exponent only.

Concerning the blade root bending moments, it has been recorded the value corresponding to a damage-rate-exponent of 10 that is representative for a fibre-glass component.

Concerning all the other load histories, it has been recorded the value corresponding to a damage-rate-exponent of 4 that is representative for steel component.

Calculating how many times a given time series take place in the expected lifetime of the machine (that is typically 20 years), it is also possible to calculate the overall fatigue load of a given component of the machine.

The equivalent load of the monitored load histories have been used as key value for the comparisons among the cases.

A fundamental input for the aeroelastic simulation is the turbulence intensity level. As mentioned, the FLEX® code has a pre-processing tool for the generation of the stochastic components of the wind that are stored in a file (*.int files in Table 4.1). These stochastic component are added to the deterministic components of the wind according to the turbulent intensity levels defined in the main input file.

A complete and coherent model of the turbulence of the wind is quite complex [24]; nevertheless for the aim of this study it is sufficient to estimate the turbulence intensity level to be given as an input for the simulations.

The following simple correlation taken from the Danish standards DS 472 for loads and safety for wind turbine constructions has been adopted:

\[
I = \frac{\sigma}{V_{10\text{min}}} = \frac{1}{\ln(h/z_0)}
\]  

(eq. 4.1)

where \(\sigma\) is the standard deviation of the wind speed, \(V_{10\text{min}}\) is the 10-minute average wind speed, \(h\) the height above the terrain and \(z_0\) the roughness length.

The roughness length is a quantity that is used in the logarithmic model of the wind shear to define the height where the wind speed is virtually nil.

The logarithmic model of the wind shear gives the wind velocity at a given height \(V(h)\) as follows:

\[
V(h) = V_0 \cdot \frac{\ln(h/z_0)}{\ln(h_0/z_0)}
\]  

(eq. 4.2)

where \(h_0\) is a reference height above the terrain, \(V_0\) is the wind speed at the reference height and \(z_0\) is once again the roughness length.

Several classes of roughness have been defined in wind turbine applications according to the value of \(Z_0\).

In Table 4.2 are reported the main roughness classes used in wind energy application together with the roughness length and the turbulence intensity level calculated with Equation 4.1.

Table 4.2 contains also a quantity named “Wind Gradient Exponent” that refers to the following model for the wind shear:
\[ V(h) = V_0 \left( \frac{h}{h_0} \right)^n \]  \hspace{1cm} (eq. 4.3)

where \( h_0 \) is a reference height above the terrain, \( V_0 \) is the wind speed at the reference height and \( n \) is the wind gradient exponent.

This power law produces a wind shear behaviour that is pretty much similar to that of Equation 4.2 around the reference height, provide that the coefficient \( n \) is tuned properly.

The values listed in the fourth column of Table 4.2 have been achieved by plotting the power law curve on top of the logarithmic curve and by tuning the parameter \( n \) in such a way to have a good agreement between the two curves. A reference height of 61 m, corresponding to the actual hub height of the Tjæreborg Turbine, has been assumed in both the cases.

It is worth to point out that the wind gradient exponent \( n \) has to be calculated because it’s the input required by the FLEX® code.

**Table 4.2 Roughness classes and characteristics turbulence intensity levels.**

<table>
<thead>
<tr>
<th>Roughness Class</th>
<th>Terrain Characteristics</th>
<th>Roughness Length [m]</th>
<th>Wind Gradient Exponent [-]</th>
<th>Turbulence Intensity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Water surface</td>
<td>0.0002</td>
<td>0.09</td>
<td>7.9%</td>
</tr>
<tr>
<td>0.5</td>
<td>Completely open terrain</td>
<td>0.0024</td>
<td>0.11</td>
<td>9.9%</td>
</tr>
<tr>
<td>1</td>
<td>Open agricultural area</td>
<td>0.030</td>
<td>0.14</td>
<td>13.2%</td>
</tr>
<tr>
<td>1.5</td>
<td>Agricultural land with some houses 8m tall sheltering hedgerows with a distance of approx. 1250m</td>
<td>0.055</td>
<td>0.16</td>
<td>14.3%</td>
</tr>
<tr>
<td>2</td>
<td>Agricultural land with some houses 8m tall sheltering hedgerows with a distance of approx. 500m</td>
<td>0.1</td>
<td>0.18</td>
<td>15.6%</td>
</tr>
<tr>
<td>2.5</td>
<td>Agricultural land with many houses</td>
<td>0.2</td>
<td>0.20</td>
<td>17.5%</td>
</tr>
<tr>
<td>3</td>
<td>Village, small towns</td>
<td>0.4</td>
<td>0.22</td>
<td>20.0%</td>
</tr>
<tr>
<td>4</td>
<td>Very large cities with tall buildings and skyscrapers</td>
<td>1.6</td>
<td>0.30</td>
<td>27.6%</td>
</tr>
</tbody>
</table>

The values listed in Table 4.2 are valid for a single value of the wind speed only; a recommendation about how to model the effect of wind speed on the turbulence intensity is reported in the standard IEC 61400-1, section 6.3.1.3 “Normal turbulence model (NTM)”.

According to the standard, the characteristic value of the standard deviation \( \sigma \) of the longitudinal wind velocity component shall be given by the following:

\[ \sigma = I_{15} \frac{(15 \text{ m/s} + a \cdot V_0)}{a + 1} \]  \hspace{1cm} (eq. 4.4)

where \( I_{15} \) is the turbulence intensity level at a wind speed of 15 m/s, \( V_0 \) is the wind speed at the hub height and \( a \) is a constant that for low turbulence cases is 3.

The values of \( I_{15} \) and \( a \) are tabulated in the IEC 61400-1 for four standard wind turbine classes and two level of turbulence; an extra class is conceived for specific tasks.
The turbulence intensity level at any generic value of the wind speed is simply the ratio between $\sigma$ and $V_0$.

The dependence of the turbulent intensity level from the wind speed is particularly relevant for low values of the wind speed. An example of $I(V_0)$ for $I_{15} = 13\%$ and $a=3$ is depicted in Figure 4.1 below; the solid line represents $I(V_0)$ calculated by means of Equation 4.4 while the dashed line represents $I_{15}$.

Following this discussion, it has been assumed the simplified hypothesis that the turbulence intensity level is about constant respect to the wind speed.

![Figure 4.1 I(V₀) for I₁₅ = 13% and a=3 according with IEC 61400-1 standard.](image)

### 4.2. Sensitivity Analysis on the Variables.

A first campaign of simulations has been carried out in order to put on evidence the influence of the input, and so the influence of the choices in the physical model, on the equivalent loads of a given set of sensors.

The chosen operative condition to perform such an analysis consisted on power production with a constant wind on a low roughness terrain. The stochastic component of the wind has been taken into account for some simulations only.

The chosen wind speed at the hub height were 15 m/s that is just above the rated speed of the Tjæreborg Turbine (see Table 3.1); this operative point produces the highest aerodynamic forces on the blades for a pitch regulated machine during cases with constant mean wind speed.

The chosen values for the wind gradient exponent and for the turbulence intensity level are respectively 0.14 and 13\% that correspond to the Roughness Class 1 (see Table 4.1).

This set of conditions with high aerodynamic forces on the blade, low wind gradient and low, if any, turbulence can emphasise the effect of icing on the equivalent loads of the monitored sensors.

The extent of the time series has been chosen to be 300 s in case the turbulence were taken into account and 150 s otherwise.

The others variables considered for the analysis were:

- two types of tower;
- icing on zero, two or three blades;
• three different airfoil databases for the iced blades plus the clean blade case;
• three magnification constants for the blade mass distributions plus the clean blade case.

Twenty time series have been carried out and have been named according to the chronological sequence of realisation.

The time series for the pitch angle and the power output have been processed to calculate the average value and the standard deviation.

The time histories have been processed to achieve the equivalent loads respect to a frequency of 1 Hz. The bin width on the load histories has been chosen in such a way to achieve at least 20 bins.

A damage-rate-exponent of 10 that is has been assumed for the blade root bending moment and a damage-rate-exponent of 4 for all the other load histories.

**Effect of the tower type.**

The effect of the tower type has been analysed through Tests 01, 02, 03 and 20 that are reported in Table 4.3.

**Table 4.3 Tests 01 and 02 vs. Tests 03 and 20.**

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Unit</th>
<th>Equivalent Load Ranges (1 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T_01</td>
</tr>
<tr>
<td>Turbine Type</td>
<td>-</td>
<td>Light</td>
</tr>
<tr>
<td>Number of Iced Blades</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Contamination Level of Iced Blades</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turbulence intensity (v component)</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>Blade Mass Magnification Constant</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>[s]</td>
<td>150</td>
</tr>
<tr>
<td>Wind Speed at Hub Height</td>
<td>[m/s]</td>
<td>15</td>
</tr>
<tr>
<td>Mean Pitch Angle</td>
<td>[deg]</td>
<td>3.42</td>
</tr>
<tr>
<td>Sigma Pitch Angle</td>
<td>[deg]</td>
<td>0.02</td>
</tr>
<tr>
<td>Sigma Power Output</td>
<td>[kW]</td>
<td>24</td>
</tr>
</tbody>
</table>

-**My1** Flap mom, R=1.46 m, bl. 1          | [kNm]| 262   | 263  | 779  | 790  |
-**Mz1** Edge mom, R=1.46 m, bl. 1          | [kNm]| 1167  | 1167 | 1308 | 1306 |
-**My3** Flap mom, R=1.46 m, bl. 3          | [kNm]| 263   | 263  | 764  | 764  |
-**Mz3** Edge mom, R=1.46 m, bl. 3          | [kNm]| 1164  | 1164 | 1301 | 1306 |
-**MxN** Shaft (N-sys), Yaw                 | [kNm]| 153   | 156  | 587  | 601  |
-**MyN** Shaft (N-sys), Tilt                | [kNm]| 146   | 146  | 596  | 599  |
-**MzN** Shaft (N-sys), Torque              | [kNm]| 30    | 30   | 175  | 175  |
-**MxK1** Nacelle (K1-sys), Yaw            | [kNm]| 165   | 175  | 665  | 723  |
-**MyK1** Nacelle (K1-sys), Tilt            | [kNm]| 165   | 164  | 736  | 744  |
-**MzK1** Nacelle (K1-sys)                  | [kNm]| 28    | 28   | 178  | 179  |
-**Myh0** Tower bending, h=0 m, L           | [kNm]| 210   | 539  | 2876 | 5620 |
-**Mzh0** Tower bending, h=0 m, T            | [kNm]| 226   | 456  | 929  | 2137 |
Tests 3 and 20, with turbulence, show higher loads compared to, respectively Tests 1 and 3; such an effect will be further discussed sequentially. These tests confirm that the choice of a light turbine together with a low turbulence level help producing a low standard load and so it help putting on evidence the additional load induced by ice accretion.

**Effect of the change in airfoil database only.**
The effect of icing on the blade has been modelled in Tests 4 and 5 by changing the airfoil database type only; Tests 1, 3, 4 and 5 are reported in Table 4.4.

**Table 4.4 Tests 01 and 03 vs. Tests 04 and 05.**

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Unit</th>
<th>Equivalent Load Ranges (1 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T_01</td>
</tr>
<tr>
<td>Turbine Type</td>
<td>-</td>
<td>Light</td>
</tr>
<tr>
<td>Number of Iced Blades</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Contamination Level of Iced Blades</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turbulence intensity (v component)</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>Blade Mass Magnification Constant</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>[s]</td>
<td>150</td>
</tr>
<tr>
<td>Wind Speed at Hub Height</td>
<td>[m/s]</td>
<td>15</td>
</tr>
<tr>
<td>Mean Pitch Angle</td>
<td>[deg]</td>
<td>3.42</td>
</tr>
<tr>
<td>Sigma Pitch Angle</td>
<td>[deg]</td>
<td>0.02</td>
</tr>
<tr>
<td>Mean Power Output</td>
<td>[kW]</td>
<td>2000</td>
</tr>
<tr>
<td>Sigma Power Output</td>
<td>[kW]</td>
<td>24</td>
</tr>
<tr>
<td>-My1 Flap mom, R=1.46 m, bl. 1</td>
<td>[kNm]</td>
<td>262</td>
</tr>
<tr>
<td>Mz1 Edge mom, R=1.46 m, bl. 1</td>
<td>[kNm]</td>
<td>1167</td>
</tr>
<tr>
<td>-My3 Flap mom, R=1.46 m, bl. 3</td>
<td>[kNm]</td>
<td>263</td>
</tr>
<tr>
<td>Mz3 Edge mom, R=1.46 m, bl. 3</td>
<td>[kNm]</td>
<td>1164</td>
</tr>
<tr>
<td>MxN Shaft (N-sys), Yaw</td>
<td>[kNm]</td>
<td>153</td>
</tr>
<tr>
<td>MyN Shaft (N-sys), Tilt</td>
<td>[kNm]</td>
<td>146</td>
</tr>
<tr>
<td>MzN Shaft (N-sys), Torque</td>
<td>[kNm]</td>
<td>30</td>
</tr>
<tr>
<td>MxK1 Nacelle (K1-sys), Yaw</td>
<td>[kNm]</td>
<td>165</td>
</tr>
<tr>
<td>MyK1 Nacelle (K1-sys), Tilt</td>
<td>[kNm]</td>
<td>165</td>
</tr>
<tr>
<td>MzK1 Nacelle (K1-sys)</td>
<td>[kNm]</td>
<td>28</td>
</tr>
<tr>
<td>Myh0 Tower bending, h=0 m, L</td>
<td>[kNm]</td>
<td>210</td>
</tr>
<tr>
<td>Mzh0 Tower bending, h=0 m, T</td>
<td>[kNm]</td>
<td>226</td>
</tr>
</tbody>
</table>
Test 3 is reported to give a comparison between the changes in load due to the different airfoil performances and the changes in load due to turbulence.

The effect of an evenly iced rotor can be understood by comparing Tests 1 and 4. The change in the aerodynamic performances of iced airfoils reduces the aerodynamic load on the blades and this is recognisable by the relevant reduction in power output and in the reduction of the flapwise equivalent load range.

The most of the equivalent loads ranges are slightly reduced; the shaft torque, nacelle in z-direction (that is aligned with the shaft) and the tower bending moments are somewhat higher. Nevertheless, these increases are believed to be due to an initial unstable transitory in the first 20 seconds by the time series.

The effect of icing on two blade only can be understood by comparing Tests 1 and 5; blade 1 is the one free from ice accretion.

The drop in mean value of power output is lower but the standard deviation of power output is higher.

The loads on blade 1 in Test 5, that is free from ice, is similar to that of Test 1 while the loads on blade 3 in Test 5, that is iced, is similar to that of Test 4.

All the other loads are increased and this is due to the uneven aerodynamic loads on the blades that reflects also on the increase on the standard deviation on power output.

By comparing Tests 4 and 5 with Test 3 it can be seen that the increase in equivalent load due by the change in aerodynamic performances of iced airfoils is lower than that due to turbulence.

The effect of icing on two blade only can be understood by comparing Tests 1 and 5; blade 1 is the one free from ice accretion.

The drop in mean value of power output is lower but the standard deviation of power output is higher.

The loads on blade 1 in Test 5, that is free from ice, is similar to that of Test 1 while the loads on blade 3 in Test 5, that is iced, is similar to that of Test 4.

All the other loads are increased and this is due to the uneven aerodynamic loads on the blades that reflects also on the increase on the standard deviation on power output.

By comparing Tests 4 and 5 with Test 3 it can be seen that the increase in equivalent load due by the change in aerodynamic performances of iced airfoils is lower than that due to turbulence.

The drop of power output is probably the most relevant effect of the change in aerodynamic performances of iced airfoils; nevertheless, some effect on equivalent loads is recognisable.

**Effect of the change in blade mass distribution only.**

The effect of icing on the blade has been modelled in Tests 12, 13, 14, 15, 16 and 17 by changing the blade mass distribution type only; Tests 1, 3, 12, 13, 14, 15, 16 and 17 are reported in Table 4.5.

The three magnification factors used to reproduce respectively the first flapwise eigenfrequency, the blade root bending moment and the overall mass of the iced blade, have been adopted for this simulations and have been reported in the sixth row of Table 4.5.

In Tests 12, 14 and 16 all the three blades are iced, in Tests 13, 15 and 17 two blades only are iced.

Test 3 is reported to give a comparison between the changes in load due to the different blade mass distributions and the changes in load due to turbulence.

Flapwise blade root bending moments are not very much affected by the change in blade mass distribution while the edgewise blade root bending moments increase.

All the other quantities show a significant change only in the case with two blades iced.

The mean value of the power output is not affected by the change in the blade mass distribution while the standard deviation of power output grow pretty much in case two blades are iced.
The loads of shaft, nacelle and tower also grow with an unevenly iced rotor; the increment shown by this quantities is some cases higher to that induced by turbulence. In particular, the tower root bending moment in the z-direction shows a dramatic change of the equivalent load with uneven icing. Since the z-direction is aligned with the wind direction, this load is due to the lateral forces induced on the tower by the unbalanced rotor.

All the shown changes depends pretty much on the chosen magnification factor. The time history for power output is very important because it influence the behaviour of the control system and in general the operative condition of the machine.

The power output of the wind turbine changes along with the azimuthal position of the rotor because of the uneven blade bending moments due to gravity.

Since it is very important to reproduce the time history for power output during dynamic simulations, it necessary to use the $K_2$ magnification factors that reproduce the blade root bending moment.

Table 4.5 Tests 01 and 03 vs. Tests 12, 13, 14, 15, 16 and 17.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Unit</th>
<th>T_01</th>
<th>T_03</th>
<th>T_12</th>
<th>T_13</th>
<th>T_14</th>
<th>T_15</th>
<th>T_16</th>
<th>T_17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Type</td>
<td>-</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
</tr>
<tr>
<td>Number of Iced Blades</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Contamination Level of Iced Blades</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turbulence intensity (v component)</td>
<td>-</td>
<td>0%</td>
<td>13%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Blade Mass Magnification Constant</td>
<td>-</td>
<td>-</td>
<td>1.33</td>
<td>1.33</td>
<td>1.12</td>
<td>1.12</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>[s]</td>
<td>150</td>
<td>300</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Wind Speed at Hub Height</td>
<td>[m/s]</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Mean Pitch Angle</td>
<td>[deg]</td>
<td>3.42</td>
<td>4.49</td>
<td>3.43</td>
<td>4.64</td>
<td>3.42</td>
<td>3.49</td>
<td>3.42</td>
<td>3.39</td>
</tr>
<tr>
<td>Sigma Pitch Angle</td>
<td>[deg]</td>
<td>0.02</td>
<td>3.37</td>
<td>0.01</td>
<td>1.72</td>
<td>0.02</td>
<td>1.51</td>
<td>0.02</td>
<td>0.88</td>
</tr>
<tr>
<td>Sigma Power Output</td>
<td>[kW]</td>
<td>24</td>
<td>201</td>
<td>15</td>
<td>759</td>
<td>20</td>
<td>372</td>
<td>22</td>
<td>195</td>
</tr>
<tr>
<td>-My1 Flap mom, R=1.46 m, bl. 1</td>
<td>[kNm]</td>
<td>262</td>
<td>779</td>
<td>282</td>
<td>387</td>
<td>268</td>
<td>333</td>
<td>264</td>
<td>254</td>
</tr>
<tr>
<td>Mz1 Edge mom, R=1.46 m, bl. 1</td>
<td>[kNm]</td>
<td>1167</td>
<td>1308</td>
<td>1551</td>
<td>1098</td>
<td>1299</td>
<td>1076</td>
<td>1228</td>
<td>1109</td>
</tr>
<tr>
<td>-My3 Flap mom, R=1.46 m, bl. 3</td>
<td>[kNm]</td>
<td>263</td>
<td>764</td>
<td>282</td>
<td>743</td>
<td>268</td>
<td>638</td>
<td>264</td>
<td>475</td>
</tr>
<tr>
<td>Mz3 Edge mom, R=1.46 m, bl. 3</td>
<td>[kNm]</td>
<td>1164</td>
<td>1301</td>
<td>1546</td>
<td>1750</td>
<td>1546</td>
<td>1457</td>
<td>1225</td>
<td>1292</td>
</tr>
<tr>
<td>MxN Shaft (N-sys), Yaw</td>
<td>[kNm]</td>
<td>153</td>
<td>587</td>
<td>156</td>
<td>686</td>
<td>155</td>
<td>281</td>
<td>154</td>
<td>192</td>
</tr>
<tr>
<td>MyN Shaft (N-sys), Tilt</td>
<td>[kNm]</td>
<td>146</td>
<td>596</td>
<td>147</td>
<td>604</td>
<td>143</td>
<td>293</td>
<td>144</td>
<td>194</td>
</tr>
<tr>
<td>MzN Shaft (N-sys), Torque</td>
<td>[kNm]</td>
<td>30</td>
<td>175</td>
<td>20</td>
<td>767</td>
<td>26</td>
<td>387</td>
<td>28</td>
<td>214</td>
</tr>
<tr>
<td>MxK1 Nacelle (K1-sys), Yaw</td>
<td>[kNm]</td>
<td>165</td>
<td>665</td>
<td>169</td>
<td>1870</td>
<td>167</td>
<td>635</td>
<td>166</td>
<td>314</td>
</tr>
<tr>
<td>MyK1 Nacelle (K1-sys), Tilt</td>
<td>[kNm]</td>
<td>165</td>
<td>736</td>
<td>178</td>
<td>1563</td>
<td>164</td>
<td>663</td>
<td>164</td>
<td>363</td>
</tr>
<tr>
<td>MzK1 Nacelle (K1-sys)</td>
<td>[kNm]</td>
<td>28</td>
<td>178</td>
<td>20</td>
<td>857</td>
<td>24</td>
<td>421</td>
<td>26</td>
<td>229</td>
</tr>
<tr>
<td>Myh0 Tower bending, h=0 m, L</td>
<td>[kNm]</td>
<td>210</td>
<td>2876</td>
<td>290</td>
<td>8088</td>
<td>233</td>
<td>5720</td>
<td>221</td>
<td>3272</td>
</tr>
<tr>
<td>Mzh0 Tower bending, h=0 m, T</td>
<td>[kNm]</td>
<td>226</td>
<td>929</td>
<td>299</td>
<td>24840</td>
<td>251</td>
<td>8834</td>
<td>237</td>
<td>4131</td>
</tr>
</tbody>
</table>
Effect of icing, not-turbulent simulations.

The effect of icing on the blade has been modelled in Tests 6, 7, 8, 9, 10 and 11 by changing the airfoil database type and the blade mass distribution; Tests 1, 3, 6, 7, 8, 9, 10 and 11 are reported in Table 4.6.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Unit</th>
<th>T_01</th>
<th>T_03</th>
<th>T_06</th>
<th>T_07</th>
<th>T_08</th>
<th>T_09</th>
<th>T_10</th>
<th>T_11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Type</td>
<td>- Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
</tr>
<tr>
<td>Number of Iced Blades</td>
<td>- 0 0 3 2 3 2 3 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contamination Level of Iced Blades</td>
<td>- - - CL-2 CL-2 CL-2 CL-2 CL-2 CL-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbulence intensity (v component)</td>
<td>- 0% 13% 0% 0% 0% 0% 0% 0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade Mass Magnification Constant</td>
<td>- - - 133% 133% 112% 112% 105% 105%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulation Time</td>
<td>[s]</td>
<td>150</td>
<td>300</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Mean Pitch Angle</td>
<td>[deg]</td>
<td>3.42</td>
<td>4.49</td>
<td>1.01</td>
<td>1.24</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>Sigma Pitch Angle</td>
<td>[deg]</td>
<td>0.02</td>
<td>3.37</td>
<td>0.14</td>
<td>0.35</td>
<td>0.14</td>
<td>0.15</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td>Mean Power Output</td>
<td>[kW]</td>
<td>2000</td>
<td>1917</td>
<td>1032</td>
<td>1421</td>
<td>1031</td>
<td>1428</td>
<td>1031</td>
<td>1429</td>
</tr>
<tr>
<td>Sigma Power Output</td>
<td>[kW]</td>
<td>24</td>
<td>201</td>
<td>39</td>
<td>550</td>
<td>38</td>
<td>189</td>
<td>38</td>
<td>93</td>
</tr>
<tr>
<td>Mx1 Flap mom, R=1.46 m, bl. 1</td>
<td>[kNm]</td>
<td>262</td>
<td>779</td>
<td>188</td>
<td>208</td>
<td>177</td>
<td>238</td>
<td>173</td>
<td>242</td>
</tr>
<tr>
<td>Mz1 Edge mom, R=1.46 m, bl. 1</td>
<td>[kNm]</td>
<td>1167</td>
<td>1308</td>
<td>1542</td>
<td>1236</td>
<td>1291</td>
<td>1188</td>
<td>1217</td>
<td>1186</td>
</tr>
<tr>
<td>Mx3 Flap mom, R=1.46 m, bl. 3</td>
<td>[kNm]</td>
<td>263</td>
<td>764</td>
<td>190</td>
<td>252</td>
<td>181</td>
<td>192</td>
<td>177</td>
<td>183</td>
</tr>
<tr>
<td>Mz3 Edge mom, R=1.46 m, bl. 3</td>
<td>[kNm]</td>
<td>1164</td>
<td>1301</td>
<td>1537</td>
<td>1652</td>
<td>1287</td>
<td>1316</td>
<td>1214</td>
<td>1226</td>
</tr>
<tr>
<td>MxN Shaft (N-sys), Yaw</td>
<td>[kNm]</td>
<td>153</td>
<td>587</td>
<td>113</td>
<td>206</td>
<td>119</td>
<td>485</td>
<td>119</td>
<td>614</td>
</tr>
<tr>
<td>MyN Shaft (N-sys), Tilt</td>
<td>[kNm]</td>
<td>146</td>
<td>596</td>
<td>87</td>
<td>184</td>
<td>80</td>
<td>467</td>
<td>80</td>
<td>562</td>
</tr>
<tr>
<td>MzN Shaft (N-sys), Torque</td>
<td>[kNm]</td>
<td>30</td>
<td>175</td>
<td>82</td>
<td>559</td>
<td>82</td>
<td>198</td>
<td>82</td>
<td>99</td>
</tr>
<tr>
<td>MxK1 Nacelle (K1-sys), Yaw</td>
<td>[kNm]</td>
<td>165</td>
<td>665</td>
<td>134</td>
<td>1219</td>
<td>135</td>
<td>240</td>
<td>133</td>
<td>444</td>
</tr>
<tr>
<td>MyK1 Nacelle (K1-sys), Tilt</td>
<td>[kNm]</td>
<td>165</td>
<td>736</td>
<td>113</td>
<td>951</td>
<td>102</td>
<td>252</td>
<td>99</td>
<td>469</td>
</tr>
<tr>
<td>MzK1 Nacelle (K1-sys)</td>
<td>[kNm]</td>
<td>28</td>
<td>178</td>
<td>81</td>
<td>623</td>
<td>80</td>
<td>207</td>
<td>80</td>
<td>94</td>
</tr>
<tr>
<td>Myh0 Tower bending, h=0 m, L</td>
<td>[kNm]</td>
<td>210</td>
<td>2876</td>
<td>723</td>
<td>4162</td>
<td>689</td>
<td>692</td>
<td>683</td>
<td>1089</td>
</tr>
<tr>
<td>Mzh0 Tower bending, h=0 m, T</td>
<td>[kNm]</td>
<td>226</td>
<td>929</td>
<td>501</td>
<td>23940</td>
<td>442</td>
<td>8351</td>
<td>426</td>
<td>4072</td>
</tr>
</tbody>
</table>

In Tests 6, 8 and 10 all the three blades are iced, in Tests 7, 9 and 11 two blades only are iced.

The effect of change in airfoil performances database and the effect of change in blade mass distributions produce a non-linear superposition.

Icing on two blades produces in general a higher value of the mean power output and also an higher equivalent loads, respect to the case with three blades iced.

The effect of the value of the magnification factor is different on every sensor: some quantities grow with the value of K, some other decrease, some show a minimum for $K_2$ respect to $K_1$ and $K_3$.

In some cases, the equivalent load achieved by changing the airfoils performances and the mass distribution are lower compared to the case where only one of these two issues were taken into account (see Tables 4.4 and 4.5).
Although a full comprehension of such a behaviour is not possible by looking at the equivalent loads only, a possible interpretation of it is given below.

In Figure 4.2 is reported a qualitative scheme of the rotor with two blades iced seen from upwind; the rotor has been divided into two halves: the left one with the two iced blades and the right one with the clean one.

**Figure 4.2 Overload of iced rotor for two different models.**

In case the effect of icing on the blade were modelled by changing the airfoil performances database only (Case A in Figure 4.1), the right side would have the additional load respect to the left side because the iced blade have in general a lower lift coefficient respect to the clean one.

In case the effect of icing on the blade were modelled by changing the blade mass distribution only (Case B in Figure 4.1), the left side would have the additional load respect to the right side because the iced blade are heavier.

From this argumentation, it can be understood how the superposition of the two effects can be partially cancelled out.
**Effect of icing, turbulent simulations.**

The effect of icing on the blade has been modelled in Tests 18 and 19 by changing the airfoil database type and the blade mass distribution; the stochastic component of the wind has been taken into account in these simulations. Tests 1, 3, 8, 9, 18 and 19 are reported in Table 4.7.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Unit</th>
<th>Equivalent Load Ranges (1 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T_01</td>
</tr>
<tr>
<td>Turbine Type</td>
<td>-</td>
<td>Light</td>
</tr>
<tr>
<td>Number of Iced Blades</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Contamination Level of Iced Blades</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turbulence intensity (v component)</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>Blade Mass Magnification Constant</td>
<td>[s]</td>
<td>150</td>
</tr>
<tr>
<td>Simulation Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Speed at Hub Height</td>
<td>[m/s]</td>
<td>15</td>
</tr>
<tr>
<td>Mean Pitch Angle</td>
<td>[deg]</td>
<td>3.42</td>
</tr>
<tr>
<td>Sigma Pitch Angle</td>
<td>[deg]</td>
<td>0.02</td>
</tr>
<tr>
<td>Mean Power Output</td>
<td>[kW]</td>
<td>2000</td>
</tr>
<tr>
<td>Sigma Power Output</td>
<td>[kW]</td>
<td>24</td>
</tr>
<tr>
<td>-My1 Flap mom, R=1.46 m, bl. 1</td>
<td>[kNm]</td>
<td>262</td>
</tr>
<tr>
<td>Mz1 Edge mom, R=1.46 m, bl. 1</td>
<td>[kNm]</td>
<td>1167</td>
</tr>
<tr>
<td>-My3 Flap mom, R=1.46 m, bl. 3</td>
<td>[kNm]</td>
<td>263</td>
</tr>
<tr>
<td>Mz3 Edge mom, R=1.46 m, bl. 3</td>
<td>[kNm]</td>
<td>1164</td>
</tr>
<tr>
<td>MxN Shaft (N-sys), Yaw</td>
<td>[kNm]</td>
<td>153</td>
</tr>
<tr>
<td>MyN Shaft (N-sys), Tilt</td>
<td>[kNm]</td>
<td>146</td>
</tr>
<tr>
<td>MzN Shaft (N-sys), Torque</td>
<td>[kNm]</td>
<td>30</td>
</tr>
<tr>
<td>MxK1 Nacelle (K1-sys), Yaw</td>
<td>[kNm]</td>
<td>165</td>
</tr>
<tr>
<td>MyK1 Nacelle (K1-sys), Tilt</td>
<td>[kNm]</td>
<td>165</td>
</tr>
<tr>
<td>MzK1 Nacelle (K1-sys)</td>
<td>[kNm]</td>
<td>28</td>
</tr>
<tr>
<td>Myh0 Tower bending, h=0 m, L</td>
<td>[kNm]</td>
<td>210</td>
</tr>
<tr>
<td>Mzh0 Tower bending, h=0 m, T</td>
<td>[kNm]</td>
<td>226</td>
</tr>
</tbody>
</table>

Tests 18 and 19 have been compared to the turbulent case with clean rotor (Test 3) and with three not-turbulent simulations: Test 1, 8 and 9.

All the loads of the evenly iced rotor case (Test 18) show a lower value than that of the clean rotor case (Test 3) except for the edgewise bending moment that shows a small increment.

Some relevant increments on the equivalent load are shown by the shaft loads and tower root bending load, in case two blade are iced (Test 19); a smaller increment is also shown by the edgewise blade root bending moment.

The nacelle loads in Test 19 are a little bit lower respect to Test 3, except for the z-axis moment that follows pretty much the behaviour of the shaft torque moment.
At the end of these first campaign of simulations, it is worth to state the main achievement of the analysis:

- It is necessary to take into account the effect of icing on the airfoils performances mainly because it determines a drop in the mean power output but also because it has some effect on loads.
- It is necessary to model the mass distribution of the blades by adopting the magnification factor $K_2$ that restrains the blade root bending moment of the iced case because it is the only one that make possible to reproduce correctly the power output fluctuation during the dynamic simulation of the iced rotor.
- The load of nacelle with iced rotor is, in many cases, lower than that with the clean one; the sensors concerning these loads have not been monitored in the next simulations.
- The main increment on the loads is determined on the tower root bending moment in the z-direction due to the lateral forces induced by the unbalanced rotor.

### 4.3. Effect of Icing on 20-year of Lifetime.

The effect of icing on a specific operative condition has been analysed in the previous section; the effect of icing is especially relevant when the ice accretes unevenly on the rotor blades.

To estimate the effective incidence of operation during icing events on the lifetime of the machine, it is necessary to perform a different type of calculation where all the operative conditions (or at least a reasonable range of them) are taken into account. The approach consisted in the following steps:

- choose a wind speed distribution and calculate the number of hours of operation for every wind speed bin;
- choose a reasonable number of hours of operation with iced rotor for every wind speed bin;
- perform dynamic simulation for every wind speed bin considering both the case of iced rotor and of clean rotor;
- calculate the overall equivalent loads weighing the results of every time series respect to the number of hours for every wind speed bin. This last operation can be performed through a specific post-processing tool given together with FLEX®.

**Wind speed distribution and number of hours of operation during icing.**

A Weibull distribution has been calculated assuming a size parameter of 8 m/s and a shape parameter of 1.9.

The operative range of the Tjæreborg Turbine ($V_{in}=5$ m/s, $V_{off}=25$ m/s; see Table 3.1) has been divided into ten bins of 2 m/s of width. For every bin, the number of hours of operation in 20 years has been calculated by means of a pre-processing tool given together with FLEX® and reported in the second column of Table 4.8.
The number of hours of operation for every wind speed bin during icing at three Contamination Level has also been estimated and listed in Table 4.8. The number of hours of icing correspond to the 20 per cent of the total number of hour for a given wind speed bin \( N_{\text{tot}} \); these have been subtracted from the total number of hour to give the number of hours of operation with the clean rotor \( N_{\text{clean}} \). The number of hours of operation during icing for every wind speed bin have been further subdivided into the three contamination levels in such a way that the number of hours at CL-2 plus the number of hours at CL-3 are the 20 per cent of the sum of the hours at CL-1, CL-2 and CL-3. Again, the number of hours at CL-3 is the 20 per cent of the sum of the hours at CL-2, CL-3.

Icing is supposed to take place only in the wind speed bins from wind speed of 7 m/s to a wind speed of 17 m/s. Sudden de-icing events have been taken into account and calculated as follow: the number of 10-minute events between 13 m/s and 15 m/s have been calculated; then it has been assumed that a 10 per cent of them determines a de-icing event. Finally the number of hours of operation with sudden de-icing have been calculated taking into account that the duration of the time series for these cases is 60 s. The sudden de-icing events have been calculated for one wind speed condition only because it is assumed that this event take place only when the highest aerodynamic load take place. The sudden de-icing has been associated to the extreme coherent gust shown below in Figure 4.3.

The sudden de-icing take place on top of the gust for \( t=30 \) s when the wind speed reach the maximum local pike. Three simulations have been performed for the three contamination levels joining two subsequent time series according with the following steps:

- a first time series has been carried out from \( t=0 \) s to \( t=30 \) s assuming that the rotor is evenly iced;
- the file containing a vector with the values of all the generalised coordinate, a vector with the first derivative of all the generalised coordinate, a value for the pitch angle and one or the pitching velocity have been stored in the Outfile.pas file;
• the Outfile.pas file has been renamed into the Part1_to_part2.inx file so that the values stored at the last time step of the first time series become the values of the first time step of the second time series;
• a second time series has been carried out from t=30 s to t=60 s assuming that the rotor has one blade iced and two blades clean;
• the two time series have been joined into a final one that has been processed to achieve the equivalent loads.

![Extreme coherent gust (20 s < t < 40 s).](image)

Sudden de-icing is expected to determine a severe dynamic transitory of the wind turbine.
In real applications, there are sensors (inertial sensors etc.) that stops the machine whenever excessive vibrations are taking place.
Such a possibility of the control system has not been considered in the model of the wind turbine developed for this study.
The reason is that the task of this analysis is to check the additional load level induced by power production operation with an iced rotor independently from the strategy to be adopted to protect the machine from excessive damaging.
It is worth to remark that the strategies of the control system should be developed together with that of the anti-icing/de-icing system in order to maximise the power production and minimising the load, during icing events.
Estimation of the 20-year lifetime

A set of 43 time series have been realised with FLEX named Test 21 to 63. All the simulations except those for sudden de-icing have a constant wind speed, a wind gradient exponent of 0.14 and a turbulence intensity level that has been assumed to be 13 per cent for every value of the wind speed.

The simulations for sudden de-icing follow the man wind speed plotted in Figure 4.3 and have no turbulence.

The number of iced blades, the type of contamination level and the mean wind speed can be deduced from Table 4.9 where the names of the tests have been listed and classified; in case of sudden de-icing, the mean wind speed correspond to the background value during the gust.

The \( K_2 \) magnification factor (see Table 3.4 fourth row) have been adopted in all the cases where the blades were iced.

<table>
<thead>
<tr>
<th>( V_0 ) [m/s]</th>
<th>Clean</th>
<th>CL-1 3-bl. 2-bl. De-icing</th>
<th>CL-2 3-bl. 2-bl. De-icing</th>
<th>CL-3 3-bl. 2-bl. De-icing</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>T_21</td>
<td>T_22 T_31 T_36</td>
<td>T_41 T_46</td>
<td>T_51 T_56</td>
</tr>
<tr>
<td>8</td>
<td>T_22</td>
<td>T_32 T_37</td>
<td>T_42 T_47</td>
<td>T_52 T_57</td>
</tr>
<tr>
<td>10</td>
<td>T_23</td>
<td>T_33 T_38</td>
<td>T_43 T_48</td>
<td>T_53 T_58</td>
</tr>
<tr>
<td>12</td>
<td>T_24</td>
<td>T_34 T_39 T_61</td>
<td>T_44 T_49 T_62</td>
<td>T_54 T_59 T_63</td>
</tr>
<tr>
<td>14</td>
<td>T_25</td>
<td>T_35 T_40</td>
<td>T_45 T_50</td>
<td>T_55 T_60</td>
</tr>
<tr>
<td>16</td>
<td>T_26</td>
<td>T_27 T_28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>T_27</td>
<td>T_29 T_30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>T_28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Once that the time series have been carried out, they have been processed taking into account the wind speed distribution of Table 4.8.

Test 30 showed values of the rotational speed well above those expected at the rated condition together with no power output. The reason might be in the setting of the model of the electric generator. Since the operative conditions of Test 30 are supposed to take place 74 hours in 20 years only, this simulation has not been processed.

Four type of computations have been carried out:
- **Clean**: no icing is assumed to take place at any time; in this case, the number of hours of operation for every wind speed are those in the second column of Table 4.8.
- **Balanced Icing**: three blade icing only is assumed to take place.
  In this case, the number of hours of operation with the clean rotor for every wind speed are those in the third column of Table 4.8 while the number of hours of operation during icing for every wind speed are those in columns 4, 6 and to 8 of Table 4.8.
- **Unbalanced Icing**: three blade icing and two blade icing are assumed to take place.
In this case, the number of hours of operation with the clean rotor for every wind speed are those in the third column of Table 4.8 and the number of hours of operation during icing for every wind speed are those in columns 4, 6 and to 8 of Table 4.8. It is supposed that during half of the time of operation under icing condition, two blades are iced (50% 3-blades icing, 50% 2-blades icing).

- Unbalanced Icing with De-icing events: three blade icing, two blade icing and sudden de-icing events are assumed to take place.

Also in this case, the number of hours of operation with the clean rotor for every wind speed are those in the third column of Table 4.8 and the number of hours of operation during icing for every wind speed are those in columns 4, 6 and to 8 of Table 4.8. It is supposed that during half of the time of operation under icing condition, two blades are iced (50% 3-blades icing, 50% 2-blades icing).

The sudden de-icing events in terms of hours, listed in column 5, 7 and 9 of Table 4.8, have been added to the time series distribution.

The plots achieved for the de-icing event of Test 63 are also shown in Appendixes 4.2 and 4.3 in attachment to this chapter.

The 20-year equivalent loads achieved for the blade root bending moments, shaft bending moments and tower root bending moments have been calculated for the four hypothesis listed above; the results are reported in Table 4.10.

A damage-rate-exponent of 10 that has been assumed for the blade root bending moment and a damage-rate-exponent of 4 for all the other load histories.

The case without icing has been used as reference to calculate the relative increment in the loads where icing was taken into account.

In case Balanced Icing only were assumed, the equivalent loads resulted lower than the reference case except for the edgewise blade root bending moments that shows a negligible increment and the z-direction tower root bending moment that shows an increment of about 18 per cent.

In case Unbalanced Icing was taken into account, the equivalent loads showed different behaviours.

The flapwise bending moments are slightly reduced while the edgewise bending moments show negligible increments.

It is worth to remark that this calculation assumes for all the simulations with two blades iced that blade-1 is clean, that is unphysical. The effective changes in equivalent loads for the flapwise and edgewise blade root bending moment should be somewhere in between the value listed in Table 4.10.

From the results achieved, it seems that the blades are not much affected by icing and so the question is no longer relevant.

The equivalent loads for the shaft moments were increased of about 3 per cent that has some relevance although it is the author opinion that this value could be lower than the uncertainty to be assumed for the estimation of the loads and so could not require a re-design of the component.

The tower root bending moment along the y-direction is slightly lower than the reference one.
The most relevant change in the equivalent load is shown by the tower root bending moment along the z-direction that is more than four times bigger than the reference case.
This increase, if confirmed by further analysis, could require a re-design of the component for sites where frequent icing accretion take place.
In case Unbalanced Icing and sudden De-Icing were taken into account, the equivalent loads showed a negligible difference respect to those achieved in the previous case. Apparently, for the frequency considered in this study, the sudden de-icing does not play a relevant rule over 20-year of lifetime.
It is worth to remark that all this results are conditioned to the number of hours, or the number of events, for which a given situation is assumed to take place.
This numbers have to be identified by analysing the meteorological characteristics of a given site in order to achieve a reasonable estimation of the additional loads induced by icing.

Table 4.10 20-year equivalent loads (reference frequency 1 Hz).

<table>
<thead>
<tr>
<th>Wind Speed at Hub Height</th>
<th>Clean [kNm]</th>
<th>Balanced Icing [kNm]</th>
<th>Unb. Icing [kNm]</th>
<th>Icing + Deicing [kNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-My1 Flap mom, R=1.46 m, bl. 1</td>
<td>744.36</td>
<td>741.47 (-0.4%)</td>
<td>741.85 (-0.3%)</td>
<td>741.85 (-0.3%)</td>
</tr>
<tr>
<td>Mz1 Edge mom, R=1.46 m, bl. 1</td>
<td>1204.42</td>
<td>1212.00 (0.6%)</td>
<td>1208.60 (0.3%)</td>
<td>1208.60 (0.3%)</td>
</tr>
<tr>
<td>-My3 Flap mom, R=1.46 m, bl. 3</td>
<td>758.00</td>
<td>755.39 (-0.3%)</td>
<td>755.41 (-0.3%)</td>
<td>755.40 (-0.3%)</td>
</tr>
<tr>
<td>Mz3 Edge mom, R=1.46 m, bl. 3</td>
<td>1198.51</td>
<td>1207.33 (0.7%)</td>
<td>1210.89 (1.0%)</td>
<td>1210.89 (1.0%)</td>
</tr>
<tr>
<td>MxN Shaft (N-sys), Yaw [kNm]</td>
<td>423.51</td>
<td>410.85 (-3.0%)</td>
<td>437.58 (3.3%)</td>
<td>437.58 (3.3%)</td>
</tr>
<tr>
<td>MyN Shaft (N-sys), Tilt [kNm]</td>
<td>429.98</td>
<td>417.04 (-3.0%)</td>
<td>441.76 (2.7%)</td>
<td>441.77 (2.7%)</td>
</tr>
<tr>
<td>MzN Shaft (N-sys), Torque [kNm]</td>
<td>155.77</td>
<td>153.46 (-1.5%)</td>
<td>160.70 (3.2%)</td>
<td>160.74 (3.2%)</td>
</tr>
<tr>
<td>Myh0 Tower bending, h=0 m, L [kNm]</td>
<td>2101.78</td>
<td>2049.02 (-2.5%)</td>
<td>2074.01 (-1.3%)</td>
<td>2077.06 (-1.2%)</td>
</tr>
<tr>
<td>Mzh0 Tower bending, h=0 m, T [kNm]</td>
<td>734.26</td>
<td>865.78 (17.9%)</td>
<td>3931.93 (435%)</td>
<td>3932.97 (436%)</td>
</tr>
</tbody>
</table>
4.4. Integration of the aeroelastic analysis in the anti-icing design procedure

Ice accretion on the rotor blades reduces the power output and increases the load on the structures of a WECS. Anti-icing/de-icing systems for WECS have the task to improve the capability of the machine to convert wind energy in harsh environments where ice accretion can take place. The design of the anti-icing/de-icing system is quite complex and his exhaustive discussion is beyond the scope of the present study. The design of the Anti-icing/de-icing system has two main targets: the first is that of optimising the system from the economic point of view, the second is that of preserving the machine from excessive loads. In order to preserve the machine from excessive loads, it is necessary to identify the amount of allowable icing time and shape of the ice on the rotor. The allowable ice accretion on the rotor depends mainly on the increase in the damage of some component due to the additional load determined by ice accretion. The amount of allowable icing time and shape of the ice on the rotor are some of the input for determining the power demand of the anti-icing/de-icing system. A tentative procedure to integrate the aeroelastic analysis into the de-icing design procedure has been set up in this study and is presented below.

The proposed procedure consist on the following steps:

- A set of arbitrary “Contamination Level” (CL) and “Events Frequency Levels” (EFL) have to be chosen and implemented in the aeroelastic model of the wind turbine. A Contamination Level is a consistent set of data that model a given shape of ice on the blade. The data necessary to characterise the ice on the blade are the mass distribution \( m(r) \), and the performances of the airfoils \( C_l(\alpha) \), \( C_d(\alpha) \) and \( C_m(\alpha) \) for every station. An “Event Frequency Level” is a set of temporal quantities that characterise the persistence of the icing on a given site. The temporal quantities can be, for example, the number of hours of operation with ice on 1, 2 and 3 blades and number of sudden shedding events from 1 or 2 blades. A reference wind speed distribution has to be associated to the set of temporal quantities.

- The Contamination Levels and the Events Frequency Level determine a matrix of arbitrarily cases where the additional damage induced by icing to the wind turbine can be determined by means of the aeroelastic analysis. This map, named “Damage Level Matrix”, is valid for a given turbine. The Damage Level for every CL-EFL couple can be defined as the maximum increase in the 20-year equivalent load of a given set of monitored components.

- Any given site can then be fitted into one of the CL-EFL case based on his meteorological characteristics. In case the Damage Level exceeded a critical value \( D_{critical} \), the turbine has to be equipped with the de-icing system and the data from
the Contamination Level and the Event Frequency Level are fed as input to the De-icing Design Procedure.

The previous procedure relies on the basic hypothesis that there are sufficient information about temporal and physical characteristics of icing of a given site macro/micro area. They can be originated from direct measurements or meteorological extrapolations. In Figure 4.4 is represented a scheme about the Damage Level Matrix.

![Damage Level Matrix](image)

Figure 4.4 Scheme of a Damage levels matrix.

The proposed procedure has been carried out for the Tjæreborg Turbine with the time series achieved previously in Tests 21-63 (see Table 4.9). In Table 4.11 are shown the arbitrary Event Frequency Levels (EFL hereafter) chosen to carry out the integrated procedure. These EFLs correspond to a percentage of operative time during icing of, respectively 3 per cent, 9 per cent and 27 per cent. Three blade icing, two blade icing and sudden de-icing events are assumed to take place. The number of hours of operation with the clean rotor for every wind speed are those in columns 2, 5 and 8 of Table 4.11, the number of hours of operation during icing for every wind speed are those in columns 3, 6 and to 9 of Table 4.11. It is supposed that during half of the time of operation under icing condition, two blades are iced (50% 3-blades icing, 50% 2-blades icing).
The sudden de-icing events in terms of hours, listed in column 4, 7 and 10 of Table 4.11, have been added to the wind speed distribution.

For every EFL, the calculations have been carried out with every CL. The edgewise blade root bending moment, the yaw shaft bending moment and the tower root bending moment along the z-direction have been monitored, although it was expected that the last one should have the highest Damage Level.

### Table 4.11 Event Frequency Levels.

<table>
<thead>
<tr>
<th>(V_0) Range</th>
<th>EFL-1 (3% icing time)</th>
<th>EFL-2 (10% icing time)</th>
<th>EFL-3 (30% icing time)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(N_{\text{clean}})</td>
<td>(N_{\text{CL-1}})</td>
<td>(N_{\text{Deicing}})</td>
</tr>
<tr>
<td>[m/s]</td>
<td>[-]</td>
<td>[-]</td>
<td>[-]</td>
</tr>
<tr>
<td>5 - 7</td>
<td>35697</td>
<td>35697</td>
<td>35697</td>
</tr>
<tr>
<td>7 - 9</td>
<td>29571</td>
<td>915</td>
<td>2744</td>
</tr>
<tr>
<td>9 - 11</td>
<td>21426</td>
<td>663</td>
<td>1988</td>
</tr>
<tr>
<td>11 - 13</td>
<td>13489</td>
<td>417</td>
<td>1252</td>
</tr>
<tr>
<td>13 - 15</td>
<td>7477</td>
<td>231</td>
<td>694</td>
</tr>
<tr>
<td>15 - 17</td>
<td>3679</td>
<td>114</td>
<td>341</td>
</tr>
<tr>
<td>17 - 19</td>
<td>1667</td>
<td></td>
<td>1667</td>
</tr>
<tr>
<td>19 - 21</td>
<td>657</td>
<td></td>
<td>657</td>
</tr>
<tr>
<td>21 - 23</td>
<td>233</td>
<td></td>
<td>233</td>
</tr>
<tr>
<td>23 - 25</td>
<td>74</td>
<td></td>
<td>74</td>
</tr>
</tbody>
</table>

In Table 4.12 are shown the Damage Mass Matrixes; the Damage Level for every entry of the matrixes are defined as follows:

\[
\text{Damage Level} = \frac{L_{\text{CL,EFL}} - L_{\text{Standard}}}{L_{\text{Standard}}}
\]

(eq. 4.5)

where \(L_{\text{CL,EFL}}\) are the 20-year equivalent loads achieved for every couple CL,EFL and \(L_{\text{Standard}}\) are the 20-year equivalent loads achieved in case no icing event are taking place (second column of Table 4.8).

The \(L_{\text{CL,EFL}}\) achieved for the tower root bending moment in the z-direction have also been normalised respect to the \(L_{\text{Standard}}\) of the tower root bending moment along the y-direction (values between brackets in Table 4.12).

For the standard case, the tower root bending moment along the y-direction is higher, respect to that in the z-direction (respectively 2102 kNm vs. 734 kNm).

It is worth to remind that the wind comes from different directions during the year and so, the y-direction and the z-direction in the tower reference frame changes.

The Damage Level for the tower root bending moment and for the edgewise blade root bending moment grows according with the amount of ice on the blades and with the frequency of the icing events.

The Damage Level for the yaw shaft bending moment grow with the frequency of the icing events but shows a minimum for CL-2 respect to CL-1 and CL-3.

The Damage Level shows an non-linear behaviour respect to the Contamination Level that means that doubling the amount of ice on the blades does not determines a double increase in the Damage Level.
The Damage Level for the edgewise blade root bending moment ranges from less than 0.1% and almost 9%. The Damage Level for the yaw shaft bending moment ranges from less than 0.1% and about 5.5%. Although some of these Damage Levels have some relevance, it is the author's opinion that these values could be lower than the uncertainty to be assumed for the estimation of the loads and so could not require a re-design of these two components. The Damage Level for the tower root bending moment ranges from less than 81% and 1100% (63% and 419%, by normalising respect to the tower root bending moment in the y-direction). These Damage Levels, if confirmed by further analysis, could require the adoption of the anti-icing system and/or the re-design of the component, for sites where frequent icing accretion take place. The proposed integrated procedure make possible to identify the cases where the anti-icing system have to be adopted.

Table 4.12 Damage Level Matrix for the Tjæreborg Turbine.

<table>
<thead>
<tr>
<th></th>
<th>Mz3</th>
<th>CL-1</th>
<th>CL-2</th>
<th>CL-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFL-3</td>
<td>0.602%</td>
<td>2.423%</td>
<td>8.849%</td>
<td></td>
</tr>
<tr>
<td>EFL-2</td>
<td>0.204%</td>
<td>0.867%</td>
<td>3.751%</td>
<td></td>
</tr>
<tr>
<td>EFL-1</td>
<td>0.068%</td>
<td>0.296%</td>
<td>1.393%</td>
<td></td>
</tr>
</tbody>
</table>

standard case Mz3=1199 kNm

<table>
<thead>
<tr>
<th></th>
<th>MxN</th>
<th>CL-1</th>
<th>CL-2</th>
<th>CL-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFL-3</td>
<td>5.353%</td>
<td>0.222%</td>
<td>0.914%</td>
<td></td>
</tr>
<tr>
<td>EFL-2</td>
<td>1.880%</td>
<td>0.076%</td>
<td>0.307%</td>
<td></td>
</tr>
<tr>
<td>EFL-1</td>
<td>0.640%</td>
<td>0.026%</td>
<td>0.104%</td>
<td></td>
</tr>
</tbody>
</table>

standard case MxN=424 kNm

<table>
<thead>
<tr>
<th></th>
<th>Mzh0</th>
<th>CL-1</th>
<th>CL-2</th>
<th>CL-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFL-3</td>
<td>207%</td>
<td>501%</td>
<td>1100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(107%)</td>
<td>(210%)</td>
<td>(419%)</td>
<td></td>
</tr>
<tr>
<td>EFL-2</td>
<td>135%</td>
<td>357%</td>
<td>812%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(82%)</td>
<td>160%</td>
<td>(319%)</td>
<td></td>
</tr>
<tr>
<td>EFL-1</td>
<td>81%</td>
<td>247%</td>
<td>593%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(63%)</td>
<td>(121%)</td>
<td>(242%)</td>
<td></td>
</tr>
</tbody>
</table>

standard case Mzh0=734 kNm

(standard case Myh0=2102 kNm)
4.5. Effect of the Type of Tower.

In tables 4.10, last row, and 4.12, third block, can be noticed how the tower root bending moment along the z-direction has a relevant increase of the equivalent load. It has been identified that this increase is mainly due to the uneven mass distribution of the rotor (see Table 4.5, last row, two-blade iced rotor cases).

From Table 3.3, last row, it is also noticeable that the type of tower changes the value of the first tower eigenmodes.

The three statements listed above suggests that the load of the unbalanced iced rotor can has a resonance interaction with the steel tower due to his low value of the first tower eigenmode.

A sensitivity analysis on the type of tower is discussed in this section of the study.

In Table 13, last row, are shown the values achieved for first tower eigenmode by changing the weight of the nacelle only, by changing the weight of the nacelle together with the type of tower and that of the original Tjæreborg Turbine.

The first case has the higher value of the first eigenfrequency, while the second case has the lowest value of the first tower eigenfrequency.

Table 4.13 Effect of the type of tower on the first tower-eigenmode.

<table>
<thead>
<tr>
<th>Wind turbine</th>
<th>Light Tjæreborg (concrete tower)</th>
<th>Light Tjæreborg (steel tower)</th>
<th>Original Tjæreborg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nacelle mass [kg] (rotor included)</td>
<td>80000</td>
<td>80000</td>
<td>154000</td>
</tr>
<tr>
<td>Tower wall thickness [mm]</td>
<td>250</td>
<td>12</td>
<td>250</td>
</tr>
<tr>
<td>Tower material Young modulus [Pa]</td>
<td>4.0·10^10</td>
<td>2.1·10^11</td>
<td>4.0·10^10</td>
</tr>
<tr>
<td>Tower material density [kg/m^3]</td>
<td>2600</td>
<td>7850</td>
<td>2600</td>
</tr>
<tr>
<td>Tower mass [kg] (57m height)</td>
<td>550000</td>
<td>86200</td>
<td>550000</td>
</tr>
<tr>
<td>First tower eigenfrequency [Hz]</td>
<td>0.93</td>
<td>0.60</td>
<td>0.81</td>
</tr>
</tbody>
</table>

In order to put on evidence the effect of the type of tower on the load, it has been carried out a new set of simulations adopting the light nacelle and the concrete tower.

A simplified 20-year operation history has been conceived with a reduced number of wind speed bins and a unique Contamination Level.

All the simulations have a constant mean wind speed $V_0$, a wind gradient exponent of 0.14 and a turbulence intensity level of 13 per cent.

Wind speed bins from $V_0=7$ m/s to a $V_0=17$ m/s only have been considered for this specific analysis.

CL-2 on two blades has been adopted in all the case where icing was present (unbalanced rotor); no sudden de-icing events have been considered for this specific analysis.

The number of hours of operation during icing event corresponds to five per cent of the total number of hour $N_{tot}$ for every wind speed bin (see Table 4.14).
Table 4.14 Event Frequency Level for 5% of operation during icing.

<table>
<thead>
<tr>
<th>$V_0$-Range [m/s]</th>
<th>$N_{tot}$ [-]</th>
<th>EFL = 5% icing time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{clean}$ [-]</td>
<td>$N_{CL-2}$ [-]</td>
</tr>
<tr>
<td>7 - 9</td>
<td>30486</td>
<td>28962</td>
</tr>
<tr>
<td>9 - 11</td>
<td>22089</td>
<td>20985</td>
</tr>
<tr>
<td>11 - 13</td>
<td>13906</td>
<td>13211</td>
</tr>
<tr>
<td>13 - 15</td>
<td>7708</td>
<td>7323</td>
</tr>
<tr>
<td>15 - 17</td>
<td>3793</td>
<td>3603</td>
</tr>
</tbody>
</table>

The new time series of the turbine with concrete tower and light nacelle have been named Tests 64 to 73. Tests 22-26 and Tests 46-50, that had been achieved previously with a similar set of input, have been used to build up a reference case. Tests 22-26, Tests 46-50 and Tests 64-73 are listed in Table 4.15 according with their value of the mean wind speed and their contamination level.

Table 4.15 Tests 22-26 and 46-50 vs. Tests 64-73.

<table>
<thead>
<tr>
<th>$V_0$ [m/s]</th>
<th>Steel Tower</th>
<th>Concrete Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clean</td>
<td>CL-2</td>
</tr>
<tr>
<td>8</td>
<td>T_22</td>
<td>T_46</td>
</tr>
<tr>
<td>10</td>
<td>T_23</td>
<td>T_47</td>
</tr>
<tr>
<td>12</td>
<td>T_24</td>
<td>T_48</td>
</tr>
<tr>
<td>14</td>
<td>T_25</td>
<td>T_49</td>
</tr>
<tr>
<td>16</td>
<td>T_26</td>
<td>T_50</td>
</tr>
</tbody>
</table>

This EFL of 5% of Table 4.14 and the time series listed in Table 4.15 have then been used to calculate the equivalent loads for the tower root bending moments during 20-year of operation. In Table 4.16 are reported the 20-year equivalent loads achieved for the tower root bending moment along the y-direction and z-direction that are the only sensors taken into account for this specific analysis. The data are grouped in two blocks referring, respectively, to the case with steel tower and that with concrete tower. For both the cases, and both the sensors, the equivalent load has been calculated for two 20-year lifetime: the first named Clean Rotor does not take into account operation during icing events (see second column in Table 4.14) and the second named Iced Rotor takes into account for 5% of operation with two blades iced (see third and fourth columns in Table 4.14). The difference between the equivalent loads achieved in the two cases has been defined as follow:
\[ \Delta_{\text{Iced-Clean}} = L_{\text{Iced Rotor}} - L_{\text{Clean Rotor}} \]
\[ \Delta_{\text{Norm}} = \frac{L_{\text{Iced Rotor}} - L_{\text{Clean Rotor}}}{L_{\text{Clean Rotor}}} \]  
(eq. 4.6)

Table 4.16 Equivalent loads for tower root bending moments of the Tjæreborg Turbine with steel tower and concrete tower.

<table>
<thead>
<tr>
<th></th>
<th>Myh0 Tower bending, h=0 m, Longitudinal [kNm]</th>
<th>Mzh0 Tower bending, h=0 m, Transverse [kNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Tower</td>
<td>Clean Rotor 2092</td>
<td>583</td>
</tr>
<tr>
<td></td>
<td>Iced Rotor 2086</td>
<td>3801</td>
</tr>
<tr>
<td></td>
<td>( \Delta_{\text{Iced-Clean}} ) -6</td>
<td>3218</td>
</tr>
<tr>
<td></td>
<td>( \Delta_{\text{Norm}} ) -0.3%</td>
<td>552%</td>
</tr>
<tr>
<td>Concrete Tower</td>
<td>Clean Rotor 6519</td>
<td>2475</td>
</tr>
<tr>
<td></td>
<td>Iced Rotor 6496</td>
<td>3202</td>
</tr>
<tr>
<td></td>
<td>( \Delta_{\text{Iced-Clean}} ) -23</td>
<td>727</td>
</tr>
<tr>
<td></td>
<td>( \Delta_{\text{Norm}} ) -0.4%</td>
<td>29.4%</td>
</tr>
</tbody>
</table>

The equivalent loads of the concrete tower case are higher than those of the steel case tower due to his higher rigidity. The \( \Delta_{\text{Iced-Clean}} \) of the steel tower case is higher than that of the concrete tower case and this fact could be due to a resonance interaction with the load of the unbalanced iced rotor.

The FFT plots for the tower root bending moment along the z-direction of Test 50 and Test 73 have been realized in order to check the difference in the spectra of the two cases; the plots are reported in Appendix 4.4. The chosen cases are those with the highest mean wind speed and two blades iced. The time series were processed in such a way to have 2 sub-series of 4096 observations. The Welch weight function with 50 per cent of overlapping was chosen. Logarithmic vs. linear plots have been chosen with a frequency range between 0 Hz and 2 Hz.

The mean rotational speed during the time series has been achieved and resulted to be 2.331 rad/s in both Test 50 and Test 73; the corresponding exciting frequencies below 2 Hz resulted: 1P=0.371 Hz, 2P=0.742 Hz, 3P=1.113 Hz, 4P=1.484 Hz, and 5P=1.855 Hz.

The steel tower case has a first eigenfrequency of about 0.60 Hz that can not be clearly distinguished from the 2P exciting frequency. On the other hand, the Concrete Tower has a first eigenfrequency of about 0.93 Hz that is above the 2P exciting value. This behaviors support the hypothesis of a possible resonance phenomenon in case the steel tower were adopted.
Appendix 4.1. Input file for Test 01 (file I_01.pas)

Test 01

**** Blade data ****
Tjb_blad.vda    Blade data filename, '-'= data below

**** Rotor + Nacelle ****
3                  B  (number of blades)
N44re6.pro       airfoil data filename, blade 1
N44re6.pro       airfoil data filename, blade 2
N44re6.pro       airfoil data filename, blade 3
1.0 1.0 1.0 1.0 1.0 1.0  K_flap_fak  K_kant_fak, pairs, blade 1..3
1   1            M_fak, blade 1..3
0.0 0.0 0.0       Pitch offset blade 1..B (deg)
0.0              X_rod (offset blade data x) (m)
0 3.0            coning tilt (deg, deg)
6.81 2.44        Znav Zrn   (rotor overhang + pos. of shaft bend)
42500 -0.54      Mnav Zgnav
7E4 7E4 6E4      Ixnav Iynav Iznv
1E9 1E9 1.1E8    Kgax Kgay Ktors  (shaft stiffness, DOF 14,15,28)
170 68.4         Iggenerator Ngear
80000 0.58 3.61  Mkab Zgkab XKK2
1.4E6 1.4E6 3E5  Ixkab Iykab Izkab
1E10 1E10        Ktx KKy   (yaw- and tilt stiffness)
0.0 0.0 0.0       CdARz CdARxy ZlatR  aero drag of hub
0.0 0.0 0.0       CdAKz CdAKxy ZlatK  aero drag of nacelle
0.03 .03 .03 .03 .1 Damp. DOF 11,12 + 14,15 + shaft tors. (log.decr.)

****  tower data ****
Steel_Tower_TWR.tda    Tower data filename, '-'= data below

****  foundation data ****
Fund_dat.v02    Foundation data filename, '-'= data below

**** operational data ****
1.225 9.81 Ro g
2.342 3.4 1 Omega Tetap Generator (1 = o n, 0 = off)
15 0.14 0 0 Vnav Vexp Vdir Vslope
0.0 0.8 0.5 Turb.intens (u), Rel.ti. (v) og (w)
..\Wind\vs30152.int 0 Turbulence-filename  T-offset (u)
..\Wind\vs30153v.int 0 Turbulence-filename  T-offset (v)
..\Wind\vs30154w.int 0 Turbulence-filename  T-offset (w)

**** data for simulation ****
1 1 1 0     Blade-dof: 1F 2F 1K 2K, 1 = active, 0=stiff
0 0 1 1 1 1  DOF 11..15 + 28 (shafttors) 1=active, 0=stiff, DOF11=yaw
1 0 1 0  DOF 7..10 (twr: L1, L2, T1, T2) L = long., T=transv.
0 0 0 0 0 0  DOF 1..6 (foundat: Tx, Tz,Ry, Ty,Rz, Rx) (T=transl,R=rot)
0 0.025 150  Tstart dt Tmax
0 200 2 2  Printop Nprint Filop Nfil

Pag. 4.27
Tjareborg, nonlinear slip,

1  number of generators

2000 1500 2.00 2.60 0.05  Pref (kW), RPMsync, slip (%), tangentslip, tau (s)
20 40 80  P_loss_el (kW) at 0%, 50%, 100% Pref
40 60 100  P_loss_mech (kW) at 0%, 50%, 100% Pref
40 1500  P_loss_mech Nref (mech. loss (kW) at RPM, gen. off)

Tjareborg

15.0  Dynamic brake moment on generator shaft (kNm)
18.0  Static brake moment (kNm)
0.05  tau (s)
0.1  T-delay (s)
0.2 0.25 0.05  V (deg), R/V, K0/Ktors (mainshaft play)

Tjareborg

5.0  0.8  OMres (rad/s) Ksi-rel (< 1)

Tjareborg

0.5  0  Yaw-rate (deg/s) Yaw-tau (s)

Tjareborg

2000 0.02 4.6  Pref KI KK (kW, deg/s/kW, deg)
90 1 5  Tetamax Tetamin Pitchratemax (deg,deg,deg/s)
-1 1 15  TEPstart TEPstop TEPsstop (deg/s)
0.10  Tsamp (sec)

Tjareborg test

2  N number of lines in interpolation table below
20 10 0  T Vhub Vdir (s, m/s, deg)
22 15 0
Appendix 4.2. Time series for the de-icing simulation, Test 63, wind speed, pitch angle, power output and nacelle loads.
Appendix 4.3. Time series for the de-icing simulation, Test 63, blade-1 loads, blade-3 loads and tower loads.
Appendix 4.4. FFT of the tower root bending moment in the longitudinal direction considering 5% of operation during icing.

Steel Tower case.

Test 50 DEMO
Sensor no. = 79  No. of obs. = 6001
Tmin = 0.000  Tmax = 299.964  dT = 0.0500
No. of subseries = 2 of length 4096, dF = 0.0049 Hz
Weight function: Welch (parabola), 50% overlap.
Power spectrum, f*S(f) ;  \text{rms} = 3.777E+03

Concrete Tower case.

Test 73 DEMO
Sensor no. = 78  No. of obs. = 6001
Tmin = 0.000  Tmax = 299.964  dT = 0.0500
No. of subseries = 2 of length 4096, dF = 0.0049 Hz
Weight function: Welch (parabola), 50% overlap.
Power spectrum, f*S(f) ;  \text{rms} = 2.765E+03
5. CONCLUSIONS AND REMARKS

**Summary.**
The aeroelastic behaviour of a MW-class horizontal axis wind turbine operating during icing events has been analysed by means of a numeric code and a semi-empirical physical model.
The aerodynamic and aeroelastic behaviour of the iced rotor is different due to the change of the mass distribution along the blades and to the change of the aerodynamic performances of the airfoils.
The mass distribution has been deduced following the norms concerning operation of wind turbine and by analysing on-field observations.
The database of the iced airfoils performances have been achieved by processing the results of experimental tests in wind tunnel on reproductions of iced airfoils.
The dynamic behaviour of the wind turbine with the rotor contaminated by ice has been simulated with the FLEX® aeroelastic code. Power production operation with ice and non-standard operation like sudden shedding of ice from the blades have been taken into account.
The achieved time series have been post-processed with a rainflow-count algorithm in order to determine the equivalent load induced on a chosen set of monitored components.
The 20-year lifetime of the monitored components has been calculated for a typical wind speed probability distribution and for different temporal frequencies of the icing events.
The damage increase on the monitored components has been related to environmental and operational conditions characterised by a contamination level and a set of temporal quantities of the icing events.
The identification of critical operational conditions can be used to design the control systems in order to prevent the turbine from dangerous load evens or to select a proper anti-icing/de-icing system.

**Power Output.**
The ice accretion on the leading edge of the airfoils determines, in general, a drop of the lift coefficient and an increase of the drag coefficient for range of angles of attack that take place during power production operation.
An increase of the maximum lift coefficient can eventually take place in case of very large ice formation that have, on the other hand, a high probability of break down and shed off from the blade.
Generally speaking, it can be stated that the ice accretion determines a drop in the power output of the wind turbine.
This drop in the power output represents the most evident effect of ice formation and also the most relevant one from the economical point of view.
In Figure 5.1 is reported the power curve of the Tjæreborg Turbine as achieved by interpolating the mean value of the power output of Tests 21-29. On top of this power curve obtained with the clean rotor, there are four series of points that represent the mean value of the power output of Tests 31-50 achieved with CL-1 and CL-2, in both the cases with three blades iced or two blades iced.
Figure 5.1 Power curves resulting by interpolating the average value of power output.

The drop in power output is about 50 per cent for the case where three blades were iced and about 25% in case only two blades were iced. The difference between contamination levels is relatively small. It is sufficient a moderate icing to determine a relevant drop in power output.

**Loads.**

Although the drop in power output has a radical impact on the economics of the wind turbine, the fundamental requirement for the turbine is that of surviving to the icing events.

The loads of some key components have been analysed during a wide range of operative conditions and the results have been discussed in the previous sections.

The analysis on the load represents the core of the present study; the followings can be stated:

- The main increases in load are due to operation during power production with two blades iced on the rotor. It is worth to remark that it has been considered that the control system let the machine operate during these events.
- The main increase on the loads is determined on the tower root bending moment due to the transverse forces induced by the unbalanced rotor. The tower root bending moment equivalent load of wind turbines operating with heavily iced rotors can be up to four times respect to that of the standard case.
- From the results achieved, it seems that the loads on the blades are not much affected by icing.
- The equivalent loads for the shaft moments were increased of only 3 per cent.
- The sudden de-icing does not play a relevant rule over a 20-year lifetime for the frequency of the event considered during the analysis.
**Resonance.**
The huge increase in the tower root transverse bending moment induced by the uneven mass distribution of the iced rotor suggested a further analysis on the role of the characteristics of the tower.
The steel tower has lower equivalent loads respect to the concrete one but it also has a lower value of the first tower eigenmodes.
The additional load showed by the Tjæreborg Turbine with light nacelle and concrete tower is on the order of 30 per cent respect to more than 500 per cent of the case with steel tower (see Table 4.16).
This facts together with the analysis of the FFT frequency spectra achieved for two time series, suggests that the additional load of to the unbalanced iced rotor can have a resonance interaction with the steel tower.

**Role of the Control System.**
The role of the control system in a key issue!
In the present study it has been assumed that the machine was working under any load level; it is worth to remark that this is an arbitrary assumption. In real applications, there are sensors (inertial sensors etc.) that stop the machine whenever excessive vibrations are taking place.
The tuning of these sensors is very important for exploitation of wind energy in environments where ice accretion can take place.
An excessive sensitivity of these sensors can determine a relevant loss of power production by stopping the machine too often. Whereas, this study shows that power production with the iced rotor is possible in a certain extent.
It is the author’s opinion that the study of the dynamic behaviour of the machine during icing event is a useful analysis instrument for wind energy application in harsh environment.

**Future Work.**
The definition of the EFL and CL has been done taking into account some realistic figures, nevertheless this numbers have to be improved for design purposes.
The wind turbine considered in this study allows a limited change in the rotational speed. In case a full-variable speed machine was adopted the results could be different: the ice accretions lower the power output determining a further reduction of the rotor rotational speed. This behaviour of the full variable turbine can enhance the value of the cut-in speed of the machine and should be further analysed.
REFERENCES (in order of appearance in the text)


ADDITIONAL REFERENCE MATERIAL (in alphabetic order)


