BACKWARD EXTRAPOLATION OF SHORT-TIME MEASUREMENT DATA FOR A REMAINING SERVICE LIFE ESTIMATION OF WIND TURBINES

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Summary

Wind turbines built in the last decades are commonly designed for a 20 year design lifetime [1]. This is also the typical operational period for which the primary structure, i.e. tower and foundation, is approved by the German building authorities. Due to reserves resulting from design safety factors and lower average wind speeds than expected, turbines are likely to operate beyond their estimated 20 year service life.
The method described in this paper is set out to quantify the remaining service life of any individual wind turbine by means of a short-time load measurement. It additionally uses all available information about the turbine's lifetime, such as wind speed recordings, operational data and recordings of events like standstills or storms. The load measurement will provide information about the correlation between wind loads and stresses in the predamaged tower and foundation. Based on the information about the current condition of the turbine, the acquired data is extrapolated in order to gain the actually endured load spectrum. Thus, a realistic estimation of the existing damage and the resulting remaining service life can be given.
This paper gives an overview of the method and describes the current status of the research project.

1. Introduction

1.1 An underestimated design life

Starting at the beginning of the 1990s, an increasing number of wind turbines has been built. This can be observed all over the world, but especially in Germany, where the first renewable energy law came into effect then. The turbines were then and still are generally designed for a service life of 20 years, in accordance with guidelines like the Germanischer Lloyd's "Guideline for the Certification of Wind Turbines" [1]. Many of these turbines now reach the end of this design lifetime. This means that the approval by the German building authorities is expiring and the turbines would have to be dismantled.
However, many of the turbines in question still structurally qualify for a continued operation. This, on the one hand, is due to the high safety factors used in the design process in the early 1990s. Engineers then lacked the experience they have today with the design of wind turbines. Loads from wind had to be overestimated in order to match the high standards of structural integrity of the German building authorities. Also computational power was much lower and durability calculations had to be simplified with respect to the 10^9 load cycles estimated to occur in the 20 year design lifetime. This led to additional safety factors.
On the other hand, wind speeds especially in the 2000s fell behind expectations, which means that also the loads for these years must have been lower than what was expected during design.
Thus, wind turbines at the end of their design lifetime certainly have reserves in durability. Nevertheless, for a safe continued operation beyond the design life, each individual turbine has to be examined and approved.

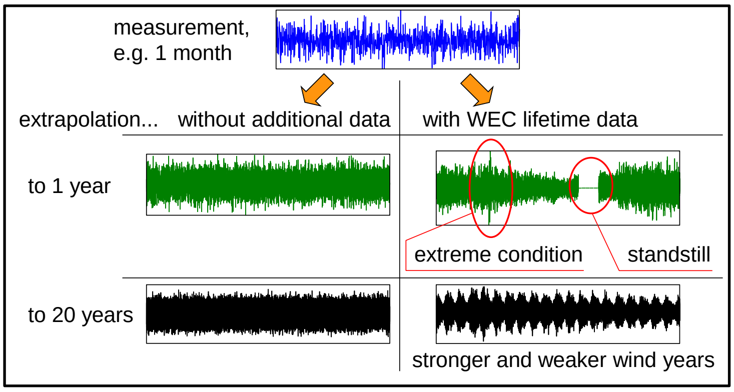

Figure 1: Extrapolation of short-time measurement data using information about the wind turbine's lifetime (right)

1.2 Existing Guidelines

The need for an inspection method examining the lifetime reserves of wind turbines already has been recognised. The Germanischer Lloyd (GL) released its latest edition of the "Guideline for the Continued Operation of Wind Turbines" in 2009 [2]. In Germany, the Deutsches Institut für Bautechnik (DIBt) will refer to the GL in its own guideline for wind turbines, which is to be revised this year [3]. It illustrates a more structural view on the turbine, as for the approval and the structural integrity, the turbine's tower and foundation are the main focus.
According to the GL, the assessment of the remaining service life of a wind turbine can be conducted in three possible ways:

- using an analytical method,
- using a practical method or
- combining those two methods.

The analytical method is essentially a new calculation of the durability of the turbine, based on current norms and guidelines instead of the original ones. Lifetime reserves here stem strictly from changes in the norms and guidelines.

The practical method uses an inspection of the entire turbine as means of determining the remaining service life. The inspection is to be conducted by a technical expert. It assesses the very current state of the turbine. This means that cracks will be detected if they are observable, at which point a continued operation might be impossible. Any estimation on the remaining service life depends on the experience of the technical expert and have to be backed up by periodic monitoring, resulting in additional standstill times.
Regardless of whether any individual method or a combination of the two is used, the actually endured loads over the lifetime of an examined turbine are not quantified. This means that the analytical method might over- or underestimate the actual remaining service life, whereas the practical method can only detect damages that might already disqualify the turbine for a continued operation.

1.3 Uses of Remaining Service Life Assessment

The assessment of the remaining service life primarily is a tool for the certification of a wind turbine for a continued operation. It can also aid in determining the residual value of a turbine for an insurance company or in cases of change of ownership.
The continued operation is very likely to be worthwhile for an operator. The earnings from wind energy already are profitable. Nevertheless, for the first ten years, an operator might have to pay back loans and only then can they profit entirely from a project. During the continued operation of an acquitted turbine, the profits don't have to be reduced by loans and go to the operator in full amount. As no new turbine has to be built and no changes are to be made, the energy balance is also improved beyond its initial positive state.

1.4 Differentiation vs. Repowering and Condition Monitoring

An alternative to the dismantling of a wind turbine after the end of its design life is the process of repowering. The old turbines in a wind park are replaced by fewer, but new and bigger turbines that will altogether produce a higher amount of energy. While a good solution for the continuation of a wind park project, this is not always possible. Restrictions regarding the maximum height of structures exist that are supposed to prevent a visual obstruction of the landscape. In coastal regions in Germany, these height restrictions can go below 100 m, which might make the construction of a new and big turbine at such a site difficult or impossible. The continued operation of the existing turbine is an excellent solution that allows going on to produce renewable energy at an existing site.
Condition monitoring systems are generally installed – permanently or temporarily – at the drive train or at the main bearing. The tower and the foundation are not monitored. Therefore, continuous data about the endured loads and the structural integrity are not available.

2. Methodology

2.1 Introduction

In order to address the issues mentioned, an innovative method is being investigated that incorporates the actual condition of a turbine's tower and foundation in the estimation of the remaining service life. The method consists of a load measurement campaign at the wind turbine and an extrapolation algorithm that integrates information about the turbine's lifetime and wind speed recordings of the examined site.

2.2 Measurement Setup

The measurement system, assembled by engineering firm BerlinWind, uses strain gauges at the tower and acceleration sensors in the nacelle. The strain gauges are placed at the tower base, where the highest loads are expected, and the tower head under the nacelle to give a distribution of the strain over the height. Both head and base position are equipped with two sensors each, shifted by 90° (Figure 2) in order to acquire signals in *x* and *y* directions. The strain gauges will provide information about the stresses induced by the wind loads, calculated from the lengthening ε and Young's modulus E according to the basic formula $\sigma = \varepsilon \cdot E$. Acceleration sensors placed in the interior of the nacelle will register forces induced from wind loading.

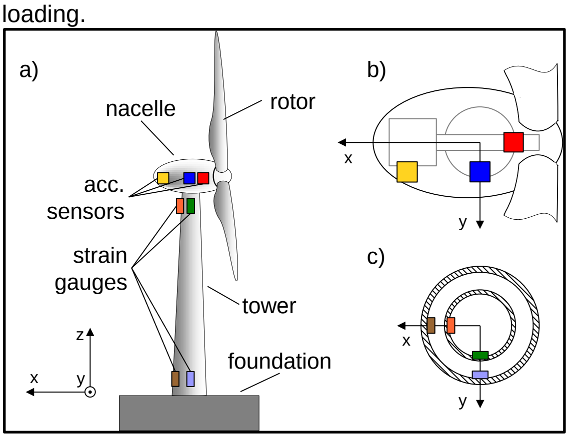

Figure 2: Measurement system for the assessment of the remaining service life a) as installed on the turbine, b) acceleration sensors in the nacelle, c) strain gauges at the tower base and head

Additionally, weather data is to be recorded such as wind speed, wind direction temperature and air pressure. The turbine itself will deliver operational data such as rotor speed, power, blade pitch angle and also weather data. In total, the system supports up to 17 measurement channels.
In combination, acceleration sensors and strain gauges will show a correlation between loads and stresses in the predamaged structure of the wind turbine over the measurement period. Using the information about the wind speeds, an assertion about the behaviour of the predamaged turbine is to be given.

2.3 Short-Time Measurement and Extrapolation

The measurement campaign is based on the norm for measurement of mechanical loads on wind turbines IEC 61400-13 [4]. Hence, a classing of the measurement data in a capture matrix is being carried out so as to determine if a sufficient amount of measurement data has been recorded. However, the campaign is supposed to last for only several weeks for a relatively quick assertion of the condition of the turbine.

Once the data has been recorded, the measured stresses are rainflow-counted according to ASTM E1049-85 [5]. Thus, a load spectrum for the measurement period can be compiled. As the damage derived from this spectrum comes only from the loads endured during the measurement campaign, an extrapolation has to take place. This extrapolation or reconstruction of the endured strain uses all data available, such as:

- wind speed recordings from the site,
- wind speed recordings from sites/weather stations nearby,
- information about the turbine's lifetime,
- statistical distributions.

Information about the wind turbine's lifetime can be:

- standstill durations (due to maintenance, low wind speeds, …),
- special incidents (storms, lighting strikes, emergency stops, grid loss, …),
- weather conditions (wind speed and direction, air pressure, temperature, …),
- exchange of components,
- the design load spectrum.

For example, the loads during standstill are lower than during operation, which adds to the lifetime reserves. In contrast, extreme conditions of a storm will decrease the reserves.

The use of the design load spectrum, if available, can help as a comparison against the actually endured load spectrum and thus as a mean to estimate the lifetime reserves.

3. Current Status and Results

3.1 Challenges

The main challenge being the reconstruction of the endured loads, other aspects have to be considered. As the whole assessment is based on measurements, the reliability of the sensors has to be ensured. The main loads result from the wind whose speed is measured by the anemometer, generally on top of the nacelle. If the anemometer is changed during the 20 years of operation, or if it is not calibrated to begin with, the measured speeds may not be reliable. A simple solution here is to quantify wind speeds by more reliable values such as rotational speed or generated power, which are proportional to the wind speed.

The calibration, i.e. the establishment of a correlation between a measured, electrical signal and a physical value, is also important for the sensors used temporarily in the measurement campaign. The acceleration sensors can be attached magnetically and can easily be calibrated, unlike the strain gauges. The difficulty here lies in the application of the sensors: they are glued on the measuring point and covered in a protective silicone layer. This is done so that the sensors are as close to the measured object – the tower – as possible and actually register the strain on the surface of the material. For the purpose of calibrating the strain gauges, they have to be in an applied state, which makes the procedure difficult to execute in a laboratory environment before the actual measurement.

3.2 Video-based strain gauge calibration

In the course of the project, a video-based calibration method has been investigated for feasibility. The strain gauges are applied at the tower and a video camera is used to capture the horizontal displacement of the nacelle (Figure 3). Such displacement may be induced by a stopping manoeuvre or even by the loads during normal operation. The video recording is evaluated by a software-based tracking of a user-defined object in the frames. Using a mechanical model of the turbine's tower (see also section 3.3), the displacement w can be converted to a stress σ.

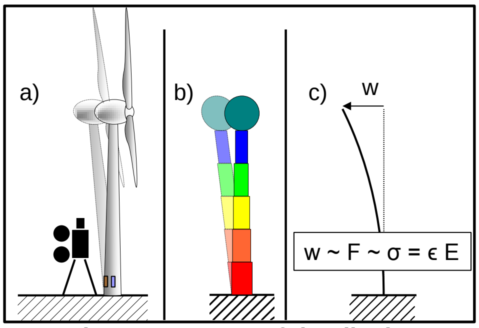

Figure 3: a) Measurement of the displacement of the nacelle by video camera, b) modelling of the tower and c) calculation of the corresponding stresses

This calibration method has been tested on a small vertical wind turbine and on a test stand (see section 3.4) with positive results. A challenge in the application in the measurement campaign will be the modelling of the big turbine.

3.3 Tower Modelling

Initial, simple models were based on the Euler-Bernoulli beam theory (1st order) and on the transfer matrix method and implemented in a spreadsheet program and in MathWorks' Matlab. Although they were adequate for the purpose of the initial feasibility investigation, the tower models are to be optimised. New models are built using the finite element software Ansys. After validation by measurement data (see section 3.4), the models are used to calculate strain from the measured displacement of the tower head during calibration. Also, simulations will be run to investigate lifetime reserves of the predamaged towers. The goal is to attain tower models that are simple enough to execute fast calculations during evaluation of the measurement data, but also detailed enough for a low uncertainty in the final lifetime estimation.

3.4 Test Stand and Test Measurements

A test stand has been built for the purpose of testing the measurement system, the software, the strain gauge calibration method and for generating data. The test stand operates outside of any wind tunnel, instead the theoretical tower bending moment from thrust is induced by the weight of an axially positionable servo motor (see Figure 4). Two other motors allow for an azimuth and rotor rotation. The test stand is controlled by a software that generates the commands for user-defined load distributions automatically.

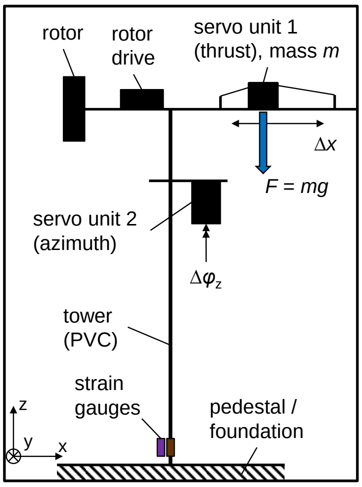

Figure 4: Scheme of the test stand: the weight force F induces a bending moment in the tower base comparable to that induced by thrust on the rotor

First successful measurements with the measurement system have been carried out at the test stand and at a small vertical axis wind turbine. The measurement software has proved effective as well as the video-based calibration method. A first unattended measurement over several days is successfully running and will lead to insight in possible optimisations of the measurement system, software and method.

3.5 Evaluation Software

The actual calculation of the remaining service life of the measured wind turbine will take place in the evaluation software. It provides the following features:

- import of measurement files, saved in portions of fixed size or duration,
- viewing and editing of measurement data (smoothing, frequency analysis),
- classing of the data according to IEC 61400-13,
- rainflow counting of the measured loads according to ASTM E1049-85,
- generating load spectra and calculating damage according to Palmgren-Miner linear damage hypothesis.

4. Conclusion and Outlook

The assessment of the remaining service life of wind turbines is a very current matter, as many of the early turbines are now reaching the end of their 20 year design lifetime. The ongoing research project described in this paper aims at developing and investigating a method that assesses the actually endured damage of the tower and the foundation by means of a short-time load measurement campaign. Using additional information about the turbine's lifetime, the measurement data is extrapolated to give a realistic estimation of the remaining service life.
The use of strain gauges for the acquisition of stresses in the tower leads to the need of a calibration. A new method has been successfully developed that uses video recordings of the displacement of the nacelle. For the calculation of the corresponding value of strain, various mechanical tower models are used. First test measurements have been conducted on a small vertical axis wind turbine, additional measurements are following and are supposed to validate the mechanical models.
For the evaluation of the measurement data and the calculation of the endured damage, an evaluation software has been programmed.
As the project progresses, the inclusion of the data about the turbine's lifetime and the extrapolation of the loads in the software has to be programmed. Also, an assertion about the strain in the foundation has yet to be made based on the measurement at the tower base. All findings will then be validated by measurements on wind turbines.
As the extent of the available information about an examined wind turbine's lifetime is uncertain, a sensitivity analysis is to be conducted regarding the importance of specific information. The global uncertainty of the method is then to be quantified.
A long-term goal is also the investigation of the transferability of the method from the primary structure to the drive train. A model of a simple drive train has been created using a multibody system that is to be expanded in the future.

Acknowledgements

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