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1 Overview

The mechanical components of Wind Energy Systems (WES) are exposed to the highest loads with torques of up to 20 MN·m, wherefore the requirements on these parts are very high. Relating to the geometrical specification this results in very tight manufacturing tolerances whose reliable verification through accurate measurements is a critical part of quality assurance. This project improved industrial measurement capabilities for the mechanical parts of WES following the Manufacturing Metrology Roadmap 2020. The key outputs include the optimised use of optical sensors and scanning measurement methods in coordinate metrology, the development of a digital twin for WES as a forecasting tool and the reliable use of inline measurement and manufacturing methods. The results help to accelerate the energy transition by enhancing the efficiency of WES technology.

2 Need

The 2020 EU climate and energy package (EU 2018/2001) sets the 20-20-20 target rates for the reduction of greenhouse gas emissions, for the share of renewable energy and for the improvement in energy efficiency. These target rates have been increased to 32 % for the share of renewable energy and for the improvement in energy efficiency by 2030.

WES technology has grown considerably in the past three decades. For example, the rotor diameter increased by a factor of more than 8 in the period from 1985 until 2015. This resulted in the growth of the rated output by a factor of 100 in the same time. However, the demands on WES for ever-increasing output and an envisaged working life of 20 years are tremendous. Their efficiency can only be raised by enlarging the hub height and rotor diameter. This leads to higher loads acting on the mechanical parts such as the rotor blades and the drivetrain components. WES breakdowns due to a malfunction of the gearbox lead to downtimes of more than six days on average, while an error with the rotor blades causes a mean downtime of four days. Together both effects account for an annual loss frequency of about 30 %.

Improving the dimensional metrology for WES drivetrain components and rotor blades was an overall objective of the project as prerequisite to enable reliable production processes and to assure that both component life and performance is achieved. The results of the project for a better and more effective metrology contributed to assuring the availability, power density and efficiency of WES, whilst reducing unplanned maintenance costs, noise and waste.

Current trends and challenges in dimensional metrology have been collated in the Manufacturing Metrology Roadmap 2020. This strategic document, published in 2011 by the German VDI/VDE Society for Measurement and Automatic Control (GMA), describes future requirements on precision engineering in modern industry with the keywords fast, accurate, reliable, flexible and holistic.

Specific user needs arose from the lack of validation of optical sensor systems, which are capable of fast and holistic component inspection during production processes. Moreover, reliable in-situ measurements on WES and suitable digital twin (DT) architectures to predict the wear and degradation that causes a loss in efficiency, as well as accurate in-line metrology systems for machine tools were also needed.

To meet these needs, 3D-coordinate metrology needed to be improved. Firstly, traceability for optical and multi-sensor technologies, in terms of measurement uncertainty, needed to be developed (objective 1). The capability of image processing sensors applied on drones for the inspection of rotor blades was investigated to allow reliable measurements even in harsh environments for industrial end-users. Reliable characterisation examinations of the relationship between scanning speed and the loss in harmonic content for large components of WES needed to be carried out and analysed (objective 2). To fully benefit from holistic measurement data, evaluation strategies needed to be developed that considered the complete point cloud and which expressed the results in terms of areal deviation parameters. Moreover, digital twin (DT) technologies of WES turbine blades need to be developed and used to predict the degradation over time of the blade's efficiency (and thereby the loss in annual energy production), which is mainly caused by leading edge roughness (objective 3). Finally, a tighter integration of metrology into production processes, especially by means of machine tool inspection systems, needed to be pursued in order to obtain measurement results faster and to use them more efficiently (objective 4).

3 Objectives

The overall objective of the project was to enhance the reliability and efficiency of WES by ensuring the traceability of the measurements of their mechanical components, thereby improving industrial production processes in order to fulfil the demands of the Manufacturing Metrology Roadmap 2020.

The specific objectives of the project were:

1. To investigate fast optical and multi-sensor measurement methods for roughness, form, and dimensions of mechanical components of WES and to determine the associated uncertainties. This will include coordinate measuring machines with different sensor systems (target uncertainties below 5 µm) as well as image processing sensors applied on drones for wear measurements directly at WES.
2. To develop improved measurement and evaluation methods for the surfaces of industrial and WES drivetrain components, considering material properties, when appropriate. This will include using both tactile and contactless sensors including the comparison of high-speed contact scanning with single-point measurements, taking into account harmonic content, and development of algorithms for characterisation of these components in a shop floor environment.
3. To develop a digital twin (DT) of drivetrain and turbine blades to predict the degradation in the turbine's efficiency based on 2D or 3D images of blade leading edges, wind tunnel experiments and computational fluid dynamics (CFD). This will include a study into the applicability of Model Based Definition (MBD) for measurement script generation.
4. To evaluate and improve the accuracy of machine tool measuring stations for fast and flexible in-line metrology operating in harsh environments. This will include the development of calibration strategies for in-situ machine measuring systems and an assessment of the feasibility of self-calibration methods for rotary axis calibration.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (e.g. ISO TC 213) and end users (large drivetrain component and turbine blade manufacturers).

4 Results

Objective 1

To investigate fast optical and multi-sensor measurement methods for roughness, form, and dimensions of mechanical components of WES and to determine the associated uncertainties. This will include coordinate measuring machines with different sensor systems (target uncertainties below 5 µm) as well as image processing sensors applied on drones for wear measurements directly at WES.

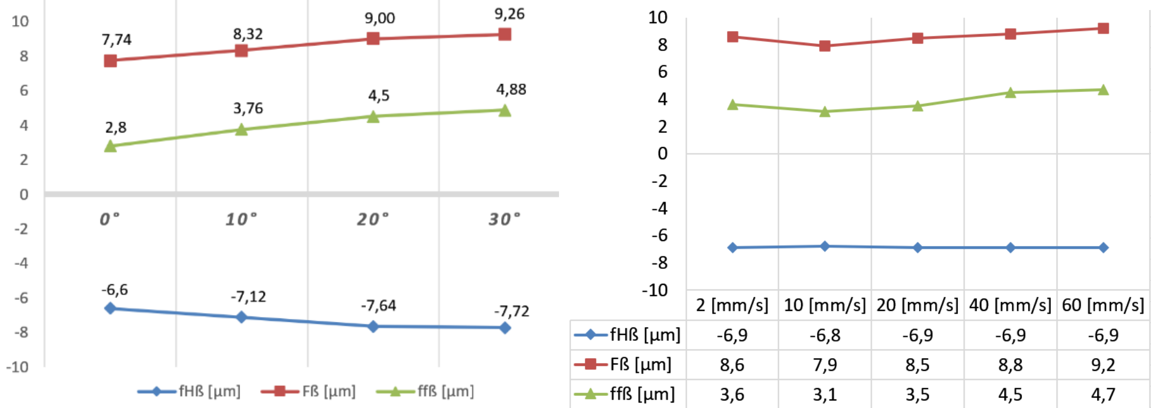
Optical sensors for dimensional measurement on involute gears of WES

PTB defined, in close collaboration with each of both Zeiss and Hexagon, the chances and challenges of the use of optical sensors in coordinate metrology.

To investigate the performance of optical sensors in the dimensional measurement of large WES gears, PTB tested primarily the optical HP-O sensor from Hexagon (Figure 1). For industry, this is a preliminary study of optical measurement methods for WES components. PTB planned a suitability test and a performance test, which were implemented one after the other. The purpose was to test whether the sensor can be used for measuring large gears as well as its measurement performance.

Figure 1: The HP-O sensor

In the performance test, PTB's large gear measurement standard was measured at different speeds and measurement angles using the HP-O sensor. The effect of the measuring angle was noticeable. Although the acceptable measurement angle indicated in the user manual is ± 30° on non-reflective metal surfaces, the results of the angle test showed that there was a difference of more than 1 µm, when comparing measurement deviations at the 0° and 30° measuring angles (Figure 2, left diagram). PTB recommend using smaller measuring angles to ensure accuracy. To investigate the effect of the measuring speed, five scanning speeds (2/10/20/40/60 mm/s) were tested (Figure 2, right diagram and table). A scanning speed up to 20 mm/s is recommended when working with the HP-O sensor. In the 20 repeated measurements of the 6 external gear helices, the average uncertainty of the filtered optical slope deviation measurements lies in the range of 5 µm. In comparison with the uncertainty of the calibration, the maximum difference was 3 µm. As additional research, a Nikon laser scanner, which could be mounted on a CMM (Leitz PMM-G), was tested at PTB. Compared with the HP-O sensor, the measurement uncertainty of this sensor was slightly worse, but it was very efficient for the holistic evaluation of gears.



	2 [mm/s]	10 [mm/s]	20 [mm/s]	40 [mm/s]	60 [mm/s]
fHß [µm]	-6,9	-6,8	-6,9	-6,9	-6,9
Fß [µm]	8,6	7,9	8,5	8,8	9,2
ffß [µm]	3,6	3,1	3,5	4,5	4,7

Figure 2: Effects of measuring angle (left) and scanning speed (right)

Due to very close collaboration with Hexagon, many of their suggestions on the measurement using the optical sensors, and the evaluation of measurement data, could implemented in an optimal way. A highlight for both, PTB and CMI, was the staff exchange between CMI and PTB for two months. The visiting researcher of CMI brought their wind blade artefact to Germany and performed comparison measurements together with PTB.

The application of optical sensors for the dimensional measurement of large involute gears was assessed. The tested HP-O sensor performed well. In the measurement of a large gear standard with a large CMM, the measurement accuracy and efficiency of this sensor met project expectations.

NCL and INRiM investigated the feasibility of measuring micropitting on gear surfaces using different optical methods. This is critical for tracking the condition of gear surfaces on wind turbines, which are in service, in order to understand and predict performance and to minimise downtime due to failures.

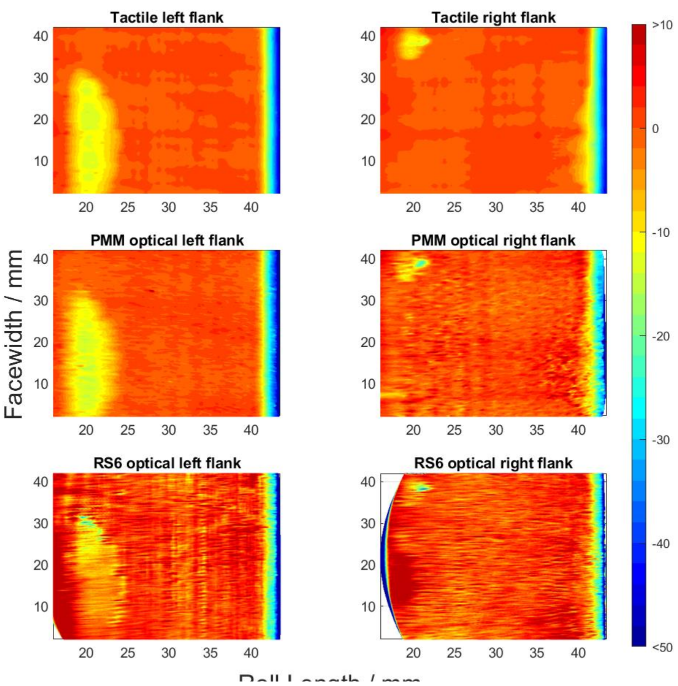


Figure 3: Results in comparison

The damage was initially characterised on smaller contact fatigue test gears from NCL by measuring with tactile methods. In one of the test scenarios Hexagon, UK used their very recently integrated optical measurement and evaluation software with the Nikon LC15Dx laser scanning head to measure the test gear. The damage was measured on both the gear flank surface directly and on soft compound replica of the surface. Example results for the tactile scanning, optical scanning (CMM) and portable optical scanning are shown in Figure 3.

Portable scanning methods, such as the Hexagon Romer arm, have a relatively large stated accuracy of 41 µm for optical scanning compared to the micropitting depth (typically 10 µm to 100 µm).

However, by carefully filtering the data and subsequent analysis, the micropitting damage was characterised within the target limit of ±5 µm. The tests showed that the most reliable method was to take a flexible replica and to measure this in a controlled manner, such as with the laser scanning head on the CMM.

A limitation of measuring gears in service is that there is no guarantee of access to the gear datum axis defined by the bearing journals, particularly when measuring replicas. Therefore, a method of extracting the damage was developed that was independent of the datums but it required the replica to include the tip diameter in order to provide a nominal reference position. The method developed assumed that only the damage relative to the nominal gear surface is of relevance when quantifying damage. The analysis process involved first fitting a polynomial surface to remove the nominal form, then the data was mapped onto a nominal involute co-ordinate system. Following this, another polynomial surface was fitted to remove excessive residual errors from the initial fitting process. Then finally the surface was sectioned, and the damage results were inspected and quantified. This method was proven on the ideal measured data from the CMM optical scanner and then applied to a large gear segment with unknown geometry. The segment was of representative size and manufactured with methods similar to WES gears.

The work showed that optical methods were capable of characterising micropitting damage to the accuracies required to make sensible decisions. The preferred method of taking a soft replica and extracting the damage minimises the equipment needed to be taken onto a wind turbine site and it allows for improved characterisation of the gear working surfaces in-situ.

Devices for measuring the roundness and cylindricity of the shafts and bearings used in WES

Multi-probe roundness measurement methods are based on measuring a nominally round workpiece simultaneously with at least three displacement or angle signals around a workpiece, and then solving a group of equations to separate the signals into centre-point motion (determined by two coordinates for every angular position) and the roundness error for each angular position.

Multi-probe methods can suffer from a phenomenon called harmonic suppression, where certain probe angle combinations cause high condition numbers of the probe equation matrix, which can lead to an amplification of errors when solving the centre-point motion and roundness error for certain harmonics. This positioning of the probes as well as factors related to the construction of the equipment need to be considered when selecting the probe angles for a measurement device.

Figure 4: Left: Measurement of a reference workpiece using the developed ROMES three-probe roundness measurement device. Right: Measurement of a reference workpiece with a Talyrond roundness measurement instrument.

Aalto, with support from VTT and ABB FI, designed and constructed a new three-point roundness measurement device, ROMES, with an adjustable diameter range based on the linear motion of the probes(Figure 4). An aim in the design was to encompass a wider range of harmonics than with previous optimisations. For ROMES, the probe angles were selected by first selecting candidate probe angles based on a performance index calculated with the condition number of the probe equations and a small tolerance to account for misplacement. A simulator was then used to obtain distributions for the errors in the total out-of-roundness values. The new selected probe angles were 0, 49.75 and 88.75 degrees.

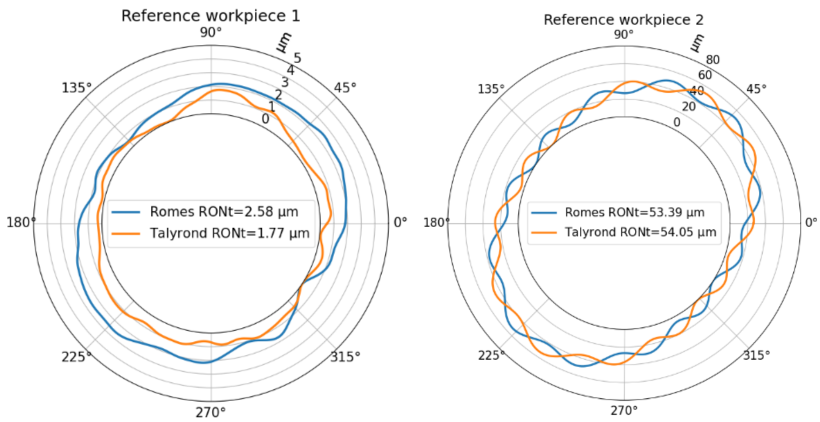


Figure 5: Roundness profiles of two reference workpieces measured with ROMES and the Talyrond 31c. Workpiece 1 is a nominally round workpiece with a very minor roundness error. Workpiece 2 has a roundness error at the 2nd and 12th harmonics.

The device was tested on an electric motor shaft provided by ABB. Furthermore, measurements of two roundness artefacts were performed with the device. A comparison of measurements between ROMES and the measurements with a Taylor Hobson Talyrond 31c roundness measurement instrument was conducted and the results are shown in Figure 5 and Figure 6.

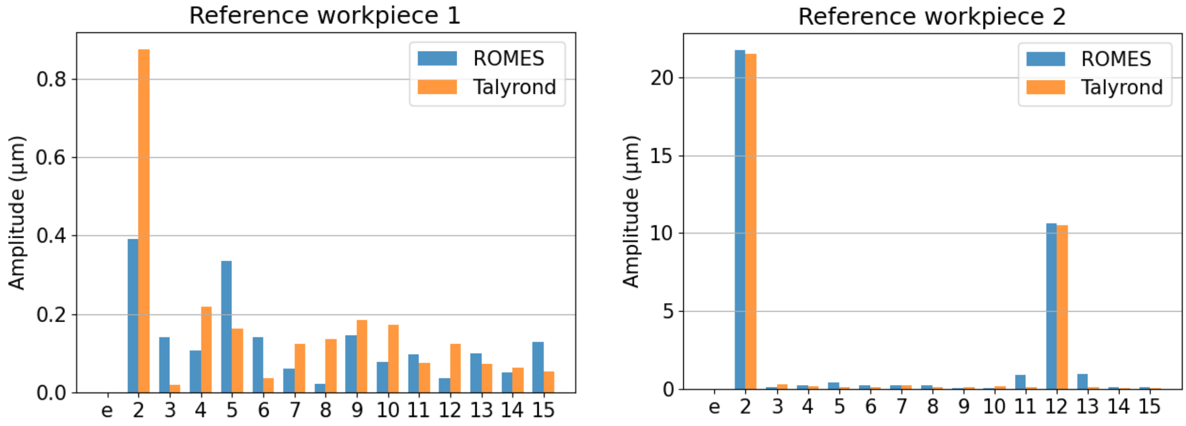


Figure 6: Amplitudes of roundness profile harmonic components for two reference workpieces measured with ROMES and the Talyrond 31c. Left: nominally round reference workpiece. Right: reference workpiece with a roundness error at the 2nd and 12th harmonics. Note the different scales.

Optimising the multi-probe equipment for a large range of harmonics can be problematic since the overall performance will suffer. Furthermore, the amplitudes of centre-point motion as well as roundness error determine the need and limit for error separation. If there is no centre-point movement, the roundness error can be measured directly. An optimisation such as the one performed in this research is especially beneficial in conditions where there is prior knowledge of the centre-point movement and roundness error.

Optical measurements of WES turbine blades

The aim of these activities was to validate optical systems for use in the measurement of turbine blades directly on the wind energy systems (WES). Blade inspection via drone-based measurements is more efficient than human inspection. WES breakdowns due to malfunction of the gearbox lead and errors with the rotor blades account for an annual loss frequency of about 30 %. For this purpose, CMI, with cooperation with DFM and DTU, designed and manufactured an artefact in the shape of wind turbine blades, which was suitable for tactile and optical measurements (Figure 7). A part was added on the leading edge with artificial erosions representing defects of different sizes occurring on the real turbine blades. The shape of the artefact body was based on two NACA airfoils (National Advisory Committee for Aeronautics). The artefact was manufactured on a 5-axis milling machine from special aluminium alloy and measured on a reference coordinate measuring machine.

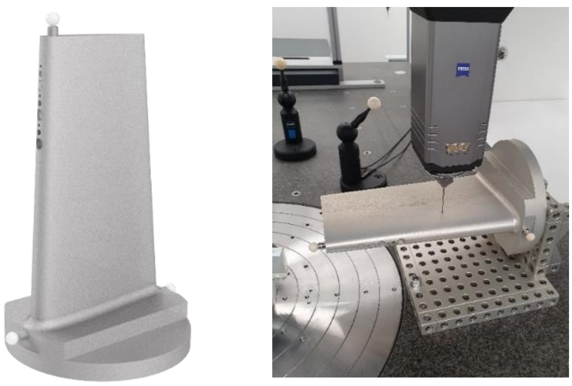


Figure 7: CAD model of the wind turbine blade artefact (left), reference measurement on CMM (right)

CMI with support from DTU used the artefact for testing the ability of 3D optical scanners to perform dimensional measurements of turbine blades in the lab. For this test, three diverse 3D optical scanners with different accuracy were used. The measurement principle was based on triangulation using fringe projection and laser lines. The results were obtained by comparing measured meshes with a point set from the tactile measurement (Figure 8).

DFM have applied and improved a photogrammetric method to reconstruct 3D maps of damage and erosion of the surface of wind turbine blades. The photogrammetric reconstruction was based on multiple photos by analysing the pictures taken from different angles using specialised software. The method developed and

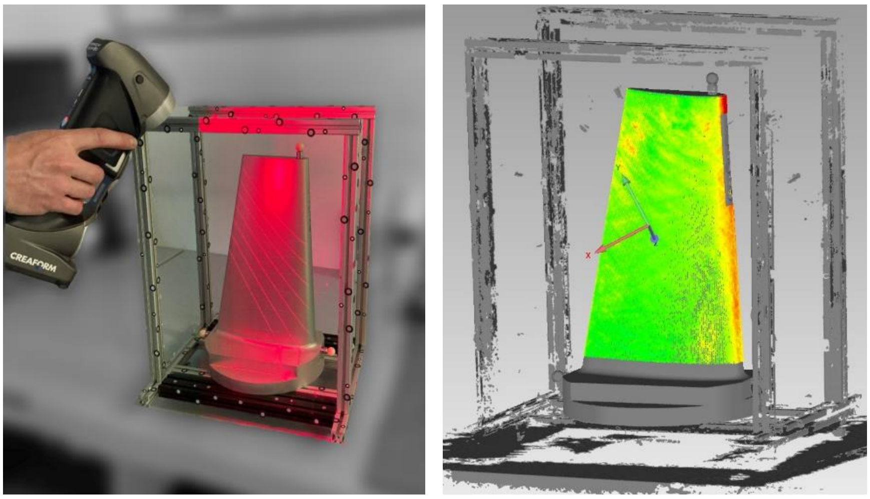


Figure 8: Testing of 3D optical scanners on the wind turbine blade artefact in the lab

assessed focused on measurement conditions equivalent to drone-based observations in terms of e.g., distance to the surface and performance of the measurement system. Based on measurements (by DTU Wind) in a wind tunnel of model wind turbine blades and calculations, the performance of the damaged surface was quantified and compared to the aerodynamic performance of the designed, new and optimal surface. A loss in yearly efficiency can be estimated and this can be used by the WES owners to assess the economically most efficient onset of repair and maintenance. The wind tunnel at DTU Wind is unique in Europe, but the competencies about surface measurements are not present at DTU Wind. The collaboration between DFM and DTU have thus developed new insight and the suggested procedures for investigating wear and tear and the correlation to the significant reduction of efficiency is beyond that achievable by the individual partners and beyond state of the art. The key outputs and conclusions are summarised in the good practice guide on the inspection of WES turbine blades for wear using drone-based imaging.

Summary

The application of optical sensors for the dimensional measurement of involute gears was assessed. This included measurements of the geometry, shape and roughness as well as methods to characterise gear damage. PTB investigated optimal measurement conditions for the implementation of the optical HP-O sensor. Measurement results on a large gear standard with a large CMM showed that the measurement uncertainty and efficiency of this sensor met project expectations. NCL, with support from Hexagon, developed a new method of characterising in-service damage on gears using optical scanners. This method has been successfully extended and applied to soft, flexible replicas from NCL.

The accuracy of optical and multi-sensor systems was improved to measure the shape and surface properties of shafts and bearings. This included research into multi-probe roundness measurement equipment and research into optical sensors that are attached to coordinate measuring machines. Aalto, with support from ABB FI, investigated the feasibility of using optical and multi-sensor measurement methods for measuring the geometry, form and surface texture of large shafts and bearings of wind energy systems.

The optical sensor for measuring turbine blades directly on the WES was validated. This included research into optical scanners for measuring free-form parts and image processing sensors for drones. CMI designed, manufactured and calibrated a 3D wind blade artefact which was suitable for tactile and optical measurement. Combining the research results, DFM submitted a good practice guide to EURAMET, entitled “Good practice guide on the inspection of WES turbine blades for wear using drone-based image processing sensors”.

In summary, all aspects of Objective 1 were achieved.

Objective 2

To develop improved measurement and evaluation methods for the surfaces of industrial and WES drivetrain components, considering material properties, when appropriate. This will include using both tactile and contactless sensors including the comparison of high-speed contact scanning with single-point measurements, taking into account harmonic content, and development of algorithms for characterisation of these components in a shop floor environment.

WES generator rotor and bearing journal measurements

Eddy current sensors are used in vibration measurement-based condition monitoring in WES generator rotors. Vibration measurement is commonly performed by measuring relative displacement changes in the rotating generator shaft during operation. Aalto, with support from ABB FI and VTT, investigated the measurement errors in eddy current displacement measurement. This measurement error is referred to as “electrical runout” in API standards. The electrical runout is caused by variations in material properties and in the surface texture of the moving measurement target.

The main research output was a method which utilises small surface roughness variations to compensate for the electrical runout errors. Surface roughness affects the flow of the induced eddy currents and the associated electric and magnetic fields. Hence, the measurement errors could be mitigated by careful variation of the surface roughness around the WES generator shaft’s circumference. In discussions between Aalto and ABB FI, it was considered that the method could provide high value to WES generator manufacturers.

The measurement error compensation was tested in a lab environment at Aalto. A round test piece was used to simulate a WES generator shaft. The test piece was made of low alloy steel (42CrMo4) and it was confirmed from ABB FI that the material is very common in WES generator shafts. A CNC-lathe was used to rotate the test piece (Figure 9). The runout was measured using an eddy current sensor and small surface roughness variations were created by an abrasive brush mounted on the driven tool of the lathe. The surface was carefully brushed by varying the degree at different locations based on the measurement error in the runout measurement. Figure 9 right side shows the runout measurement before and after the surface roughness variations. The result shows that the eddy current measurement was brought significantly closer to the tactile measurement, which was considered to represent the actual runout of the test piece. This indicates that surface roughness variations can be used to compensate for these measurement errors. The use of this method in practice has been discussed with ABB FI for their WES generator rotors.

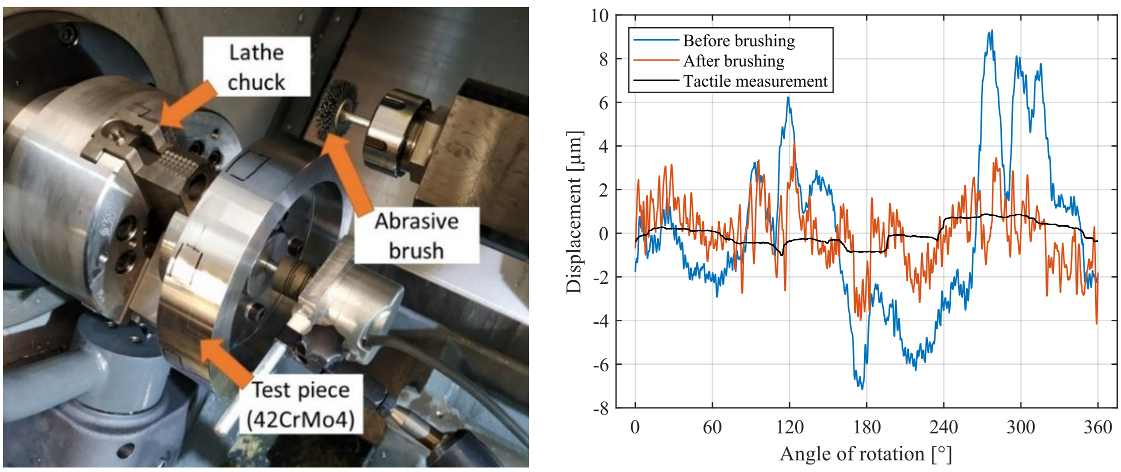


Figure 9: Left side: brushing setup in a lathe. Right side: runout measured before and after careful brushing of the test piece.

The key output resulting from this work was a method for electrical runout reduction based on surface roughness variations. The main goal of the activity was to investigate the electrical runout phenomenon and the performance of the eddy current sensors. Surface roughness was identified as a cause for electrical runout during the research and this knowledge was applied to develop the method for electrical runout compensation. The objective of this activity was successfully achieved. The performance of the eddy current sensors has been significantly improved as the electrical runout errors can be potentially mitigated by using the developed compensation method.

The measurement uncertainty of Eddy current sensors has been quantified by VTT, in collaboration with Aalto and ABB, as part of the work programme. The error of the indication E_x of the Eddy current measurement is given by:

$$E_x = l_{ec} - l_{hh} - \sigma_l$$

Where:

l_{hh} the standard uncertainty for profile measured with a Heidenhain MT12 tactile system was previously estimated to be 2.3 µm.

l_{ec} the profile measured with the Eddy current has an error estimated to be ± 6 µm, and the based workpiece measurements have a corresponding standard uncertainty of ± 3.5 µm.

σ_l other corrections due to vibrations and changes in temperature are estimated to contribute to a standard uncertainty of 1 µm.

The expanded uncertainty for the roundness profile, measured by the Eddy-Current system, was evaluated to be 8.6 µm as illustrated in Table 1. The uncertainty is rather high but it can be reduced by filtering out short wavelengths.

Table 1: Uncertainty budget for Eddy Current sensors

Quantity	Standard uncertainty / µm	Propability distribution	Sensitivity coefficient	Uncertainty contribution / µm	
l_{hh}	2.3	normal	1	2.3	
l_{ec}	3.5	rectangular	1	3.5	
σl	1	normal	1	1	
E_x			Combined standard uncertainty	4.3	
			Expanded uncertainty (*k*=2)	8.6	µm

In metrology, systematic errors can be used as correction but in this case more test data is required as there are many error sources. This would be possible in the laboratory, but it is probably not practical in industrial applications.

The work has shown that the uncompensated uncertainty from Eddy current sensors can be significant when compared to the rotor runout tolerance specified in WES components. This means there may be a significant risk from accepting measurements which are outside specification or rejecting measurement results which are acceptable.

The WES drivetrain component measurement and evaluation methods were reviewed by AU and considered to provide useful data for updating WES digital twin models with in-situ measurement data.

WES gear measurement

Classical gear measurement methods measure single helix traces at mid gear tooth depth or profile traces at mid face width with additional optional 2D line measurements being used to verify the ends of the tooth contact regions on the operating tooth flank surface. The method has allowed for the successful manufacture of precision gears for WES applications, but it is limited. The method is not Geometrical Product Specification compliant; it may miss gear flank errors which affect gear performance, and it is not suitable for use with optical measurement methods where most of the point cloud measurement data on the gear surface is ignored.

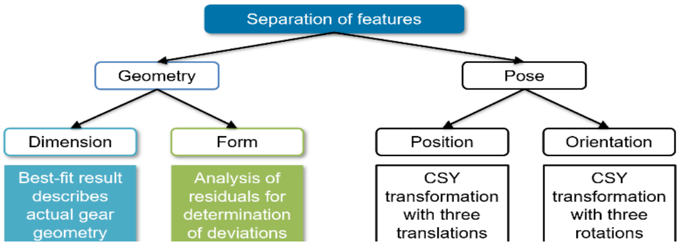


Figure 10: Summary of the feature separation strategy

Initial work to establish the optimum parameters for high-speed tactile scanning, compared to static single point measurement, was carried out by PTB in a controlled series of experiments and a range of CMMs commonly used by the WES gear, gearbox, and drivetrain manufacturers. This work underpins the 3D scanning work which was needed to develop the holistic point cloud inversion method described below.

PTB and NCL investigated algorithms to analyse 3D gear measurement data. This is a departure from traditional 2D measurement methods which only give information to a small portion of a gear flank. The prevalence of increasingly large and precise gearing exhibit different manufacturing trends that conventional measurement knowledge is based on. Therefore, PTB's method of feature separation, summarised in Figure 10, and NCL's harmonic content methods, can provide greater insight for the Wind Energy Sector and beyond.

The holistic feature separation algorithm has no limitations regarding data density, data distribution, regular profile and helix data or randomly scattered point clouds. This makes the algorithm measurement machine agnostic and it allows for the use of both tactile and optical data. The algorithm fits parameterised involute surfaces to the measured data of each flank rather than the traditional evaluation from nominal data for the whole gear. Separation of dimension, form and pose is a common approach in coordinate metrology, but it not yet established in gear metrology.

The methods were proven first on synthesised data with known errors (dimension, form, and pose parameters were fitted to nanometre accuracy). Then in close collaboration with Hexagon and Zeiss, the method was tested on a physical gear standard with microgeometry corrections at PTB (Figure 11). Figure 12 compares the measured deviations with the traditional method applied (left) and the next holistic method (right). It was shown that the holistic method can be used to evaluate arbitrary point clouds and that it is particularly well suited for the identification of microgeometry corrections.

The advantage of the holistic evaluation approach, which is fitting all relevant gear geometry parameters at once, has been demonstrated by evaluating a tactile measurement of the flanks of a standard with microgeometry corrections (Figure 11). Figure 12 shows the 3D residuals, which are the remaining differences between measured datapoints (11 helix lines and profile lines per flank) and the fitted form element of an involute gear. Both evaluations include all measured lines, but the left figure shows the result for one fixed geometry parameter, which is the base radius. The left plot shows significant deviations with respect to the radius of the gear, whereas the right plot reveals the expected microgeometry corrections. Obviously, these can only be identified if all geometry parameters are fitted simultaneously.

Figure 11: Standard with microgeometry corrections

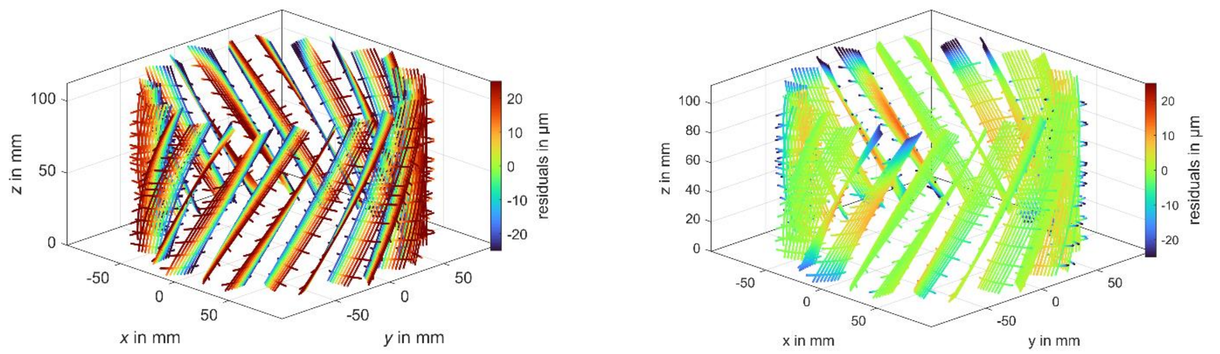


Figure 12: 3D surface deviations of all measured gear flanks. Left: Fixed conventional result in 3D. Right: Holistic evaluation result.

The point cloud inversion method applied to 3D gear surface measurement represents a paradigm change in measurement strategy which will be developed into a VDI/VDE guideline document in Germany. This is a prerequisite to the method becoming accepted worldwide.

The partnership between PTB and NCL was enhanced by the visit to NCL from PTB's expert in 3D modelling which was facilitated by the Researcher Mobility Grant (RMG) during the summer of 2022. This allowed NCL to better understand the practical challenges that PTB had to overcome to develop and apply the point cloud inversion method. This improved NCL's knowledge and increased confidence to apply this strategy to industrial applications.

Harmonic content analysis of gear surfaces is beginning to be used in the industry, but standardised methods are not yet developed, and interpreting results can be difficult. NCL led an investigation supported by CMI and INRIM into harmonic evaluation before focussing on the methods detailed in Table 2.

Table 2 - Harmonic analysis methods

The Fourier transform	Decomposes a signal into sine and cosine waves, relaying information about frequency
The Wavelet transform	Decomposes a signal into wavelets, relaying information about frequency and position
The Cosine transform	Decomposes a signal into cosine waves only, a common compression method used in image storage
Bayesian spectral analysis	Considers the Fourier transform from a Bayesian perspective and provides information about the most probable frequencies present
Overlapping profile analysis	A method developed by Günther Gravel and implemented by Klingelnberg, it overlays all profiles along the length of a roll including pitch errors and it fits sines to the data

After reviewing the benefits and limitation of each method, the Fourier transform and the wavelet transform methods were selected for their ability to capture information related to noise and surface durability and they were applied to both traditional line traces and surface measurements.

The results were proven in tandem to the holistic method, utilising the residuals as the input for the harmonic analysis. Additionally, a harmonic content artefact was defined, manufactured by methods representative of the wind energy sector, and measured by both NCL and PTB with support from Hexagon and Zeiss, then the algorithms were applied and evaluated. Example images of the artefact, a measurement result, and a 2D FFT analysis can be seen in Figure 13.

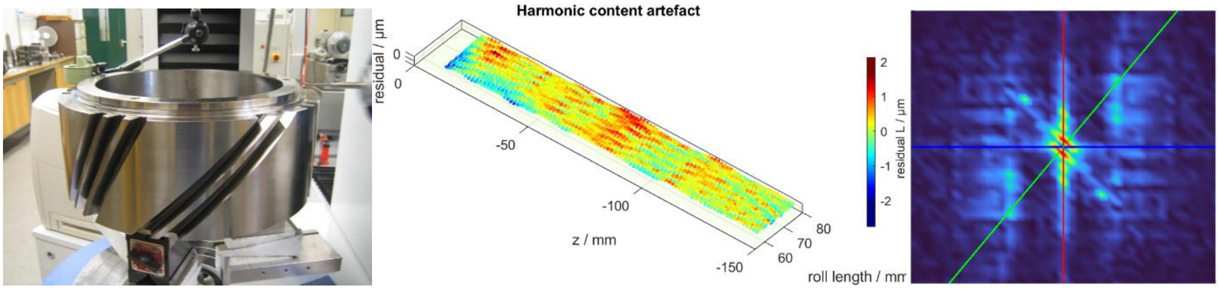


Figure 13: Harmonic analysis. Left – harmonic content artefact, middle - unwrapped deviations, right - example 2D FFT analysis.

The visit by PTBs expert facilitated by the RMG to NCL was of great benefit to PTB. NCL were able to transfer their WES gear application knowledge to PTB to ensure that the benefits from using the Point Cloud Inversion residual deviations in a harmonic analysis were understood and the challenges around minimising noise and contact stress were understood.

Commercial software packages are now available that provide options to import gear measurement data to enhance the validity of the results. The 2D and 3D measurement and evaluation strategies developed in this project can be applied to the measurement data that is used for Tooth Contact Analysis (TCA) models to predict gear performance in terms of gear stress, friction and lubrication, efficiency, vibration and Transmission Error characteristics. Furthermore, improved Digital Twin models of WES drivetrains, which were refined by AU during this project, can be used to assist with more reliable maintenance planning and for improving drivetrain reliability and availability.

Summary

Objective 2 requirements have been fully achieved in accordance with the project plan by close collaboration of the partners, unfunded partners, and project collaborators. The key outputs from the work include:

- Improvement in the performance of the Eddy Current sensors used by WES drivetrain manufacturers to satisfy the specifications required by standards by accounting for changes in electrical characteristics, surface roughness and residual stress.
- Characterisation of Eddy Current sensor performance with a validated measurement uncertainty budget.
- A systematic study of the performance of the high-speed tactile scanning sensors used in the CMMs that are used by WES manufacturers.
- The development and validation of a 3D holistic gear measurement strategy applying a Point Cloud Inversion method to gears which has resulted in a GPS compatible, gear measurement and evaluation strategy. The method will be adopted in a VDI/VDE standard guideline in Germany.
- Harmonic analysis methods based on 2D and 3D surface measurements of gears has been successfully developed using Fast Fourier Transform and Wavelet Transform analysis to identify characteristics that cause noise and vibration during service and affect gear failure modes. The wavelet transforms can also be used to characterise the surface deviations when using measured surfaces in predictive performance models and Digital Twin models.
- Results from the research and development work were validated with tests on workpiece-like-artefacts.

Objective 3

To develop a digital twin (DT) of drivetrain and turbine blades to predict the degradation in the turbine's efficiency based on 2D or 3D images of blade leading edges, wind tunnel experiments and computational fluid dynamics (CFD). This will include a study into the applicability of Model Based Definition (MBD) for measurement script generation.

Objective 3 has two main components. The investigation and generation of simulation models of the Wind Energy Systems (WES), in particular gearbox, shafts, gears and bearings for the estimation of performance and expected lifetime. Furthermore, new work was undertaken towards the end of the project to go beyond the state of the art by investigating bedframe flexibility under operational loads to shed light on the effects of support flexure on load sharing. Secondly, work on defining a Neural Network based DT for the fast monitoring of changes in system states in the context of condition monitoring was performed. The methods and progress of the work were shaped and discussed in project meetings with representatives from PTB, DFM, NCL, Aalto, DTU, CMI, INRIM, VTT, ABB, Moventas, SKF and Vestas. In depth discussions were held with Vestas on key driving factors for bottom line value generation. NCL participated in design and model generation of gear modifications for documentation of improved lifetime estimations through simulation models. DTU and DFM participated in the generation of degradation models of leading edge erosion of turbine blades. Aalto provided insight into the DT monitoring using machine learning.

The WES digital twin (DT) is intended to assess the impact of enhanced measurement systems on the drivetrain's performance, to assist in their design, to detect faults and to predict the remaining useful life of the drivetrain's mechanical components. The intrinsic difficulties of monitoring internal components of the drivetrain can be overcome by physics-based DT. Moreover, for this application, the DT should be able to account for micro-geometry measurements. To reach a compromise between efficiency and accuracy the DT was built using a multi-resolution strategy. The DT distinguishes between three levels of resolution, low, medium and high.

The implemented low-resolution DT is responsible for the calculation of the external loads of the drivetrain and blades under different environmental conditions and leading-edge erosion levels. To meet this goal aeroelastic and hydrodynamic models are used to account for the blade-wind and platform-water interactions, respectively. The low-resolution DT also allows us to find correlations between different measurable parameters and the drivetrain's loads. These correlations will be exploited by artificial intelligence algorithms for the estimation of real loading conditions. The WES implemented in the low-resolution level corresponds to an offshore 10-MW system working under the environmental conditions of the North Sea.

The medium and high-resolution levels concern the geared drivetrain. The publicly available information on 10-MW geared drivetrains was not sufficient to develop a detailed model. Therefore, it has been necessary to enrich previous studies to define a drivetrain suitable for our goals. This task has involved the design of planetary carriers, housing, the definition of lubricants, and the selection of bearings, among others. The optimum gear micro-geometry has been defined using genetic algorithms to compensate for gear misalignments and to achieve a homogeneous distribution of the load along the gear tooth flanks.

The medium-resolution DT represents the whole drivetrain accounting realistically for the different mechanical components (gears, bearings, planetary carriers, shafts). This enables the internal load distribution patterns to be estimated. The medium-resolution level can account for the micro-geometry by using pre-calculated data, which makes it perform fast. This is useful to set the micro-geometry according to the nominal design or as initially measured. However, if micro-geometry deviations or different sorts of defects need to be studied it becomes inefficient.

In this regard, the high-resolution level is more flexible. It can easily account for a wide range of micro-geometry deviations or measured profiles at the cost of reducing computational efficiency. Therefore, this feature enables the DT to estimate the drivetrain's behaviour with some specific components whose micro-geometry is deviating from the nominal design.

By using medium and high-resolution levels, the damage to mechanical components caused by different environmental conditions has been estimated. This will allow the monitoring of the remaining useful life of the drivetrain.

The influence of dynamic simulations of the previously derived and presented quasi-static simulation model of the WES was implemented. The results of this effort showed that adding dynamics to the simulation to account for inertia forces during fluctuating wind loads did not appear to degrade the estimated lifetime of the gear mesh. In fact, longer estimated lifetimes were found. While these simulations require a longer simulation time and analysis efforts, representing several orders of magnitude, and that their results showed less damage, a complete study of the effects of dynamics is needed. Within the timeframe and computing power available within this project it is not fully conclusive whether the added efforts of including dynamics in high fidelity models is needed, and if the return on investment of doing so is significant. However, it is comforting that the quasi-static methods were conservative for the particular turbine of interest. AU, NCL together with the Hexagon Romax software team were able to generate lifetime estimations of multi-megawatt WES.

A software manual was generated by AU for multiresolution DT architecture. It explains and exemplifies the process for generating operating loads from low fidelity models in operational scenarios. These loads are used in high fidelity gear and bearing simulations for WES lifetime estimation with respect to these components. The effects of micro geometry were demonstrated and key findings in the form of reduced gear dimensions or longer lifetime were shown. Furthermore, the tool chain of the software also showed how gears - as measured during or after production - can be imported to estimate the "as-built" lifetime – a key output for the DT and the entire project.

An effort to include a flexible bedframe in the simulations to illustrate the importance of differentiated load sharing and its influence on component lifetime were demonstrated and reported in a separate report. Finally, work performed at AU, with inputs from DTU, DFM and Alto, showed the generation of a fast executing DT for leading edge degradation detection. This work also showed the process for determining easy measurable states with the highest detective capability for the faults of interest. This was an important finding as many direct measures for fault detection could be located inside the gearbox or other hard to measure locations. Being able to trace these faults to more manageable measuring points was key. A report was submitted on this work. In most of the above work, there was a lack of real WES design and measurements as these data are confidential. Therefore, a DTU theoretical 10 MW reference WES model was chosen as other researchers have used the same reference turbine for comparative studies.

Summary

- A multi-resolution modelling approach was developed for connecting low fidelity models for rotor loads in WES operational scenarios to high fidelity gear and bearing simulations for accurate loads estimations.
- Utilising the above approach, the influence of micro geometry on estimated fatigue life were demonstrated. The importance of including micro geometry, and how to use this modification in the design process for lowering the gear dimension and thereby the cost of energy was demonstrated. Furthermore, it was investigated weather dynamic effects were critical. Simulations indicated that quasi-static simulations were significantly faster and generated results that are more conservative. It is inconclusive if the added effort in terms of computational time versus the improved accuracy of the results are worth the cost with the computational resources available.

- Adding component flexibility to the design of a bedframe and showing how the design and dimensioning can affect load sharing enabled this effect to be taken advantage of for improved load levelling in the structure.
- A complete example of how to generate a DT for leading edge degradation, using results generated in the project by DTU, DFM and AU, was presented. Selection of the modelling states that were most sensitive to the detection of leading edge degradation was presented with the idea of favouring states that are already available or easy to instrument for measuring.
- Using the approach for generating high fidelity models, together with the inclusion of virtual faults, is beyond the state of the art for simulation based fault indicators and it should be used as a starting point before historic fault data are available.

In conclusion, two main points should be made:

1. Collaboration between partners was key in generating the designs of multi-megawatt turbines. Experience and knowledge shared among partners enabled results that were not achievable from individual partners alone.

2. To carry the work forward, it is detrimental that data from actually produced WES are included. Knowledge of actual challenges, faults in mechanical components and the history leading up to the failure, accurate dimensions and tolerances and as-built measurements are key factors that can carry this work even further beyond state of the art. The lack of WES data due to confidentiality is understandable and a premise in an Open Access framework.

In summary Objective 3 was achieved to full extent possible with the data available in the areas of impact of gear modification and its use in model prediction of expected lifetime of gears and bearings. Furthermore, beyond the original stated objective it was explored how the impact of nacelle bedframe flexibility has a significant impact on load path and thereby load sharing between main shaft bearings. The objective of including wind tunnel data and CFD simulations for the degradation of relevant wind turbine blades was achieved by wind tunnel experiment of surfaces with different artifacts for imitation of leading-edge erosion. The objective of linking 2D and 3D images of the eroded blades to wind tunnel data was only partially achieved through the blade synthetic modification with artifacts. The objective of generating scripts for MBDs of measurements was achieved through test of gear flank measurements in microgeometry modification. The extent of this achievement was limited to simulation as no real gear for the modelled gearbox existed. However, the process for doing so once available is in place.

<u>Objective 4</u>

To evaluate and improve the accuracy of machine tool measuring stations for fast and flexible in-line metrology operating in harsh environments. This will include the development of calibration strategies for in-situ machine measuring systems and an assessment of the feasibility of self-calibration methods for rotary axis calibration.

Research related to objective 4 provided validated and new procedures for evaluating the in-situ measuring systems that are applicable for measuring complex high accuracy WES components in typical harsh environments e.g. directly on the grinding machine. The conducted research included modelling, measurement and compensation of bearing deformations, and error separation of a 5-axis machine tool rotary table

Measurement and optimisation of the bearing assembly geometry using metrology data as feedback for the compensation grinding for fast and flexible in-line metrology operating in harsh environments

Aalto, in collaboration with SKF, ABB FI and Moventas, and in consultation with Vestas, conducted studies focused on understanding the impact of the total effect of the shaft roundness error and thickness variations in bearing components on the performance of the complete rotor-bearing assembly. VTT confirmed the traceability of the method to the SI.

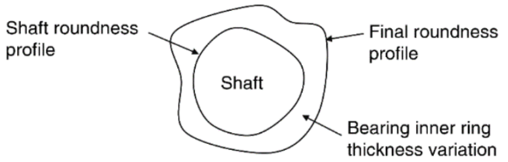


Figure 14: Scheme of the final roundness profile of the inner ring raceway due to the stacking of the shaft roundness deviation and the inner ring thickness variation.

An experiment was conducted to validate a stacking error hypothesis that predicts the final roundness profile of an assembled bearing inner ring. This simplified assumption (schematic shown in Figure 14) is that the total out-of-roundness can be modelled. This study was different from previous studies as it was done on a conically tapered fitting that is used to mount the bearing directly on the shaft. Both simulation and empirical measurements were conducted, and the performance of the final assembly was verified on a large scale rotor test bench with conically ground compensative geometry tapered shafts where the bearings were mounted.

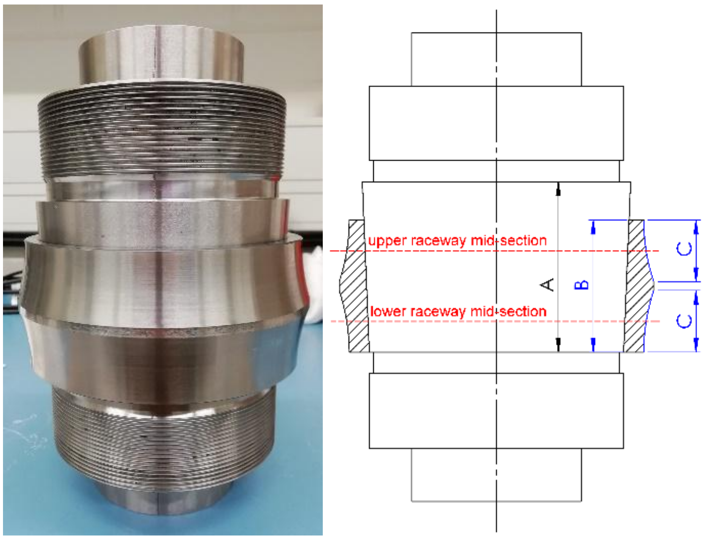


Figure 15 Investigated bearing inner ring and shaft assembly.

Various orientations between the shaft and the inner ring, as well as different mounting conditions, were examined (bearing shown in Figure 15 and the stacked error process model and correspondence with measurements in different orientations is shown in Figure 16).

After these tabletop-scale studies, the findings were further applied to explore the potential for reducing subharmonic vibrations using a 3D grinding technique on a paper machine roll (shown in Figure 17). The results show that the use of the conical installation site on the shaft, without the need of an adapter sleeve, can efficiently reduce the roundness error of the bearing's inner ring when paired with the compensative grinding methodology. The reduction of the roundness error in the drive side was substantially larger, but the final roundness error on both ends appears in the same range (5.0 µm in the tending end, 3.2 µm in the drive end).

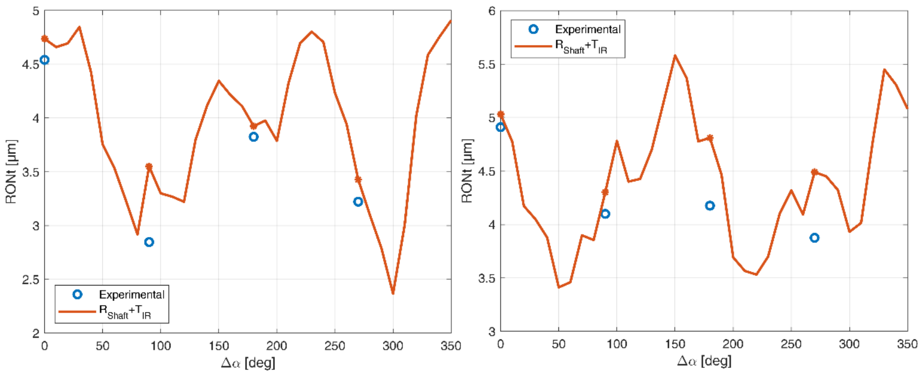


Figure 16: Variation of the summed (stacked error process) roundness RONt (red) as a function of the relative orientation Δα of the components, for the upper (left) and lower (right) raceway mid-sections measuring locations. In blue, the RONt of the experimentally measured raceway profiles in mounted condition.

Figure 17: Compensative 3D grinding of the bearing installation tapered site. The tapered section was ground to the profile which minimised the roundness error of the assembled bearing inner ring raceways.

A reduced error separation method to determine rotary table errors in six DoF

Coordinate measuring machines (CMMs) or machine tools (MTs) are often equipped with rotary tables which expand the machine's kinematics to include a fourth or fifth axis. This is beneficial for the production and measurement of rotationally symmetric workpieces. However, the additional axis introduces further sources of errors that must be investigated before a numerical correction or proper uncertainty analysis can be carried out.

For the determination of machine errors, self-calibration strategies based on error separation are favourable, as no externally calibrated measurement standard is needed. The method developed and investigated in this project builds on an error separation method combined with a reduced measurement effort and a novel circular ball plate with a sophisticated design. The mathematical evaluation necessary for the reduced method was developed by PTB in consultation with Hexagon and Zeiss. The method is based on a Least Squares best-fit of the error model to the measurement data.

Figure 18: The new circular ball plate mounted on a rotary table. It can be seen that the spheres do not have uniform angular spacing.

For the application of the method, a new ball plate with 12 balls was manufactured at PTB, which is suitable for the measurement of rotary table deviations in 5° steps (Figure 18). The balls are arranged at irregular intervals on a 5° angular grid, the positions having been optimised with regard to the measurement uncertainty to be expected. 10 of the 12 balls are located on a 10° angular grid, so that the ball plate can also be used for measuring deviations in 10° increments.

The method was successfully tested by PTB and Zeiss on the rotary tables of several CMMs. Measurements were carried out and evaluated with the new type of ball plate in 5° and in 10° steps. To verify the reduced method, the results were compared with the measurements of the complete method using the conventional ball plate at the common 30° angular grid points. Very good agreements were found overall, in the range of no more than 0.2 µm for the position deviations and no more than 0.5 µrad for the rotational deviations. The results are depicted in Figure 19.

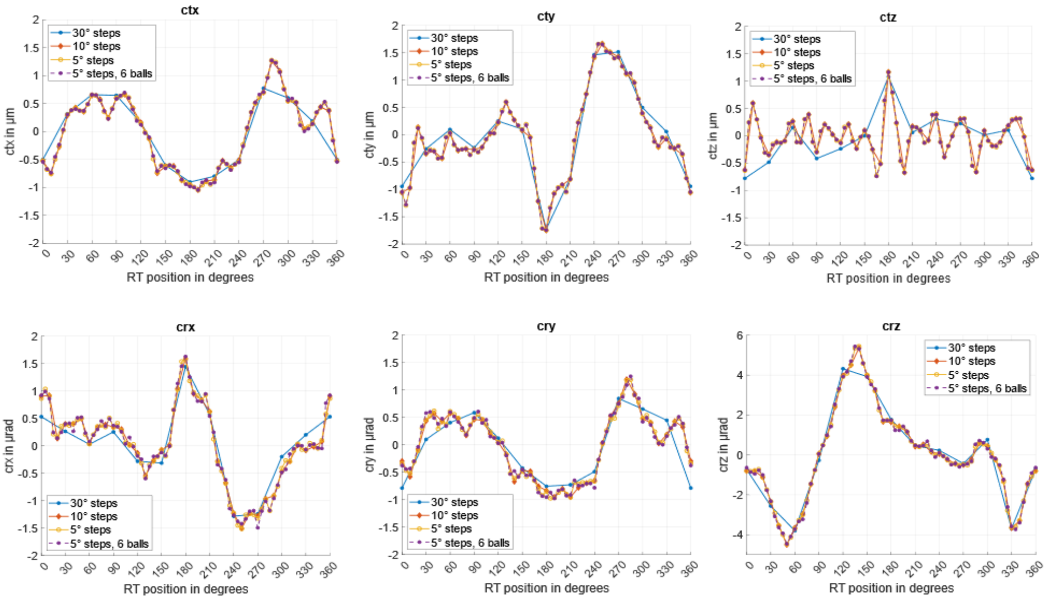


Figure 19 Rotary table deviations. The blue lines (solid line with dots) show results of measurements with a ball plate with 12 equidistant balls. The lines with the markers show the results with the new ball plate, measured in 5° steps. The lines with the marker show the same measurement with the new ball plate but evaluated in 10° steps. The dashed lines again show the same measurement with the new ball plate, but now only using the results of six balls for the evaluation.

Applying error separation methods to a 5-axis machine tool rotary table

NCL collaborated with PTB by applying methods derived by PTB. Using the full rosette and reduced methods it should be possible to routinely check the condition of the MT rotary table using an uncalibrated artefact. Initial validation tests were performed with NCMT but due to software limitations the method was applied to a machine tool at NCL with a high accuracy touch trigger probe (see Figure 20) was used to measure a full rosette and reduced method ball plates. The full rosette method measures 12 balls at 30° rotational positions around the rotary table. The reduced method measures either 6, 8 or 12 balls at 5° rotational positions around the rotary table. It has been shown by PTB theoretically and by measurement on a CMM rotary table that measuring a reduced number of balls combined with smaller rotational increments (5°) gives comparable results and that rotational errors missed by the full rosette method could be determined. This work showed that the complete rosette and reduced method have been implemented on to a machine tool rotary axis. Although the measurement results show variance between the two methods, especially for the translational errors, the positioning deviation crz gives reasonable results. With further work it should be possible to resolve the discrepancies and achieve better results across all six DOF errors.

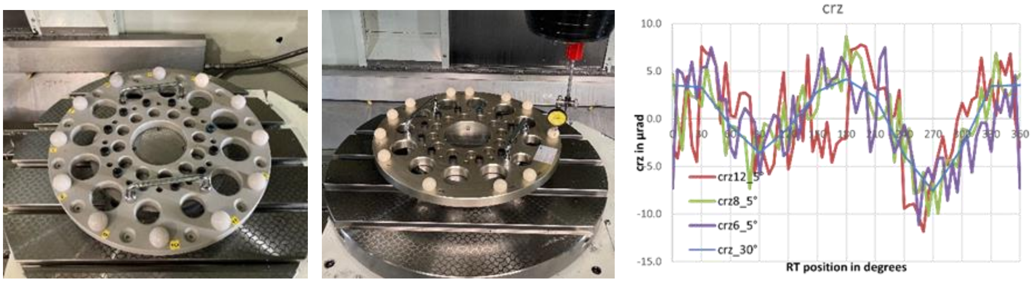


Figure 20: Full rosette ball plate on the left and reduced ball plate in the middle on the MT rotary table. The blue line shows the complete rosette method with 12 equidistant balls measured at 30°intervals. The red, green and purple lines show results from the reduced method ball plate with 12 non-equidistant balls measured at 5° intervals. The red line is the result of measuring 12 balls, the green line 8 balls and the purple line 6 balls. crz is the rotational position of the rotary table about the z-axis.

Investigating improvements in machine tool gear measurement using calibrated gear workpieces

The ability to measure in situ on machine tools allows greater throughput as potential machining errors can be rectified more easily as costly re-setting times are reduced. This also means that machine set ups do not have to be broken down so that components can be measured in a lab or shop floor off the machine tool. Onboard measurement has its greatest benefit during the set-up / first off operations where periodic component measurements can show potential problems. Changes to machining programs can be made and the re-machined surfaces can then be checked again in situ. On board measurement does not constitute the final pass off criteria in most cases as that function will still be carried out in a metrology lab environment. To have confidence in the on-board measurements the capability of the measuring systems must be known. NCL with support from NCMT and advice from CMI investigated the use of a calibrated 'workpiece like' artefact and analysed the measurements taken from a machine tool at NCL (see Figure 21). It has been shown that by using a calibrated gear artefact that improvements can be made on a machine tool regarding measurement capability and an estimate of measurement uncertainty for individual gear parameters can also be made. It must be noted that the influence of measurement filter, measurement data density, and measuring speeds were not investigated during this exercise but have the potential to affect measurement results. However, guidance can be found in ISO1328-1:2013.

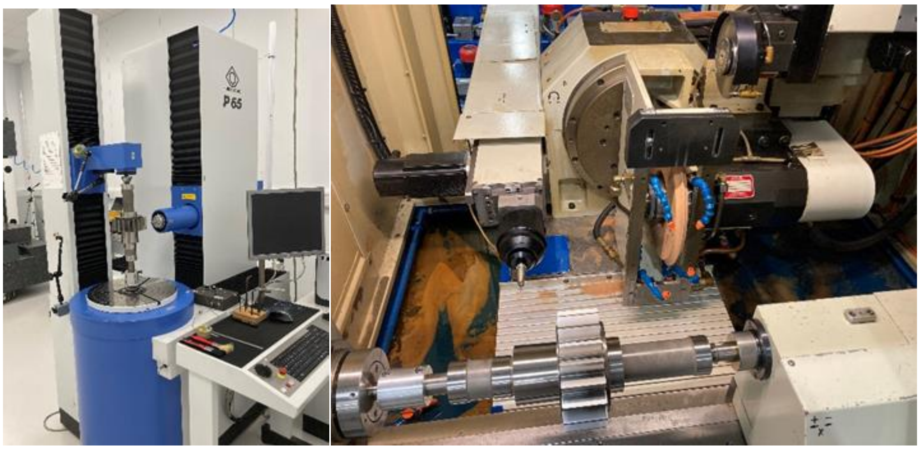


Figure 21: The left image shows the workpiece like artefact being calibrated at the UK National Gear Metrology Laboratory (NCL). The right image shows the same artefact mounted on a gear grinder ready for measurement.

Strategies for measuring WES parts using CMMs utilising model-based definition and digital twins.

The aim of this task was to provide generic traceability support for geometry measurement of WES drivetrain components. The benefits and drawbacks of measurement scripts generated form CAD model were investigated.

Two artefacts were designed and manufactured by CMI and VTT, with the support of PTB – first with the simple geometry, second with the complex freeform geometry. Both were measured on CMMs using tactile probes. To measure pieces for NURBS based digital twin generation, CMI and VTT with support from INRIM, utilised CAD models containing MBD data to generate measurement scripts for CMMs. Verification measurements were generated in the same way, reducing the required time to make measurement scripts of freeform- and complex-shapes. Two types of metrological software – ZEISS Calypso freeform and MiCAT planner, were used for generating measurement strategy.

These measurements were used for the development of calibrated (corrected) CAD models, also known as freeform digital twins. In this step, based on a mathematical-geometrical approach new bicubic interpolation B-spline surfaces were created. These surfaces reflect the real shape of the artefacts and present continuous reference for other measurement principles, e.g. optical.

CAD-based measurements provide a user-friendly approach to the generated measurement strategies. In addition to saving programming time, the suitable strategy can be defined more easily and also ahead of the measurement itself. A big role in this type of measurement is the way how the CAD model was created and how it is defined, i.e. directions of u and v parameters and so on.

Summary

The conducted research contributed towards objective 4 of the project, by testing, developing and verifying in-line measurement and manufacturing methods. The key outputs include a validated stacking error hypothesis for bearing assembly roundness, the application of a compensative 3D grinding technique to minimise errors in rotor-bearing assemblies, and the implementation and verification of a reduced self-calibration method for rotary axis calibration. The objective was clearly achieved.

5 Impact

To promote the uptake of project results and to share insights generated throughout the project, results were shared broadly with scientific and industrial end-users. Nine papers reporting project results have been published in peer-reviewed international journals and proceedings, one has been accepted and is awaiting publication, two additional articles have been submitted and five have been drafted. Three Master thesis have also been completed. Sixteen presentations have been given at conferences and two more are planned for 2024. In addition, presentations have been made at four seminars. The Met4Wind project has hosted nine trainings and workshops and has been presented at national and international standardisation committees. Project newsletters were published in February 2022, December 2022 and August 2023.

The project developed a range of new measurement capabilities for mechanical WES components at the NMIs as well as directly in industry. As described above the project's results meet industrial requirements for increasingly fast, *accurate, reliable, flexible and holistic measurements.*

Impact on industrial and other user communities

To facilitate the early uptake of project outputs the project engaged with industrial stakeholders including manufacturers of coordinate measuring machines as well as WES component manufacturers and calibration laboratories. Industrial partners and stakeholders attended project meetings to interact with the project and ensure that industrial impact was generated.

The project was represented at the international trade fairs WindEnergy Hamburg in September 2022 and CONTROL in May 2023.

Project newsletters shared project outputs and engaged with the target user communities to encourage early uptake among manufacturers of coordinate measuring machines and drivetrain components. These were distributed in February and December 2022 as well as in August 2023.

The following good practice guide and reports were produced to enable quick and effective dissemination and uptake of newly developed measurement strategies and methods.

- Good practice guide on the inspection of WES turbine blades for wear using drone-based image processing sensors
- Report on in-situ machine tool rotary axis calibration in six DoF using self-calibration methods
- Report on CAD-based measurements in WES

In addition, several measurement standards and procedures have resulted from the project and are available on the project website such as a ball plate and reduced three-rosette method for in-situ rotary table calibrations, freeform wind blade artefact, surface roughness-based measurement error reduction for eddy current displacement measurement, wind tunnel tests of airfoils with systematic damage, shaft artefact, and a variable diameter multi-probe roundness measurement device.

Impact on the metrology and scientific communities

To support the rapid development of science and technology, papers reporting project results have been published in nine peer-reviewed international journals and proceedings, one has been accepted and is awaiting publication, two additional articles have been submitted and five have been drafted. Presentations have been given at 16 international conferences and the project was also presented at seminars in Finland, Germany, and the United Kingdom.

The Met4Wind project has hosted several training events and workshops:

- A tutorial was held at the euspen Special Interest Meeting Precision Engineering for Sustainable Energy Systems on October 13, 2021. The tutorial showed attendees how gears are currently measured, discussed the limitations of these processes and introduced participants to some of the strategies that are being researched.
- Together with the British Gear Association BGA the project hosted a workshop on April 28, 2022. It was aimed at industrial stakeholders, the workshop provided information on project progress, showed how project results will benefit industry and informed participants about how to get involved. 46 persons from industry, academia and National Metrology Institutes attended.
- The project was represented at the international exhibition and conference WindEnergy Hamburg in September 2022. See the presentation about the project, large gear measurement standards, gear calibration services offered by PTB, research on rotary axis characterisation and an animation on large coordinate measuring machines.
- The online course "Optical measurements and measurement systems for gears and rotary axes" was held on March 1, 2023. This training course described the capabilities of various optical measurement systems as well as calibration strategies of rotary axes with a focus on optical measurements of WES components, however, these procedures may also be transferred to other industrial parts.
- A training course on electrical runout and digital twins was hosted by ABB Helsinki on June 6, 2023 with presentations by Aalto University and ABB.

- The final stakeholder workshop took place at PTB, Germany and online on June 28, 2023.

Impact on relevant standards

The project participated in 78 national and international standardisation committees. It was presented to two working groups of ISO TC 60 Gears, ISO/TC39/SC2, the gear committee BSI MCE/5, DIN NA 060-34-11 AA Zylinderräder - Terminologie und Toleranzen and at VDI/VDE FA 3.61 Verzahnungsmesstechnik. Several working groups of ISO/TC213 have been updated on project results. PTB has provided input to a new normative document at the VDI/VDE FA 3.61 Verzahnungsmesstechnik committee.

Longer-term economic, social and environmental impacts

The developed measurement procedures and uncertainty estimations are also transferable to other production processes. Optical sensors, holistic evaluation strategies, the metrological use of DTs and in-line metrology are important subjects for a broad variety of engineering industries that will also benefit from the project's findings in the long term.

The deployment of wind energy in Europe is a remarkable industrial success. The outcome of this project will help to foster Europe's position among other countries regarding the growth of renewable energy systems.

This project improved metrology for mechanical WES components and enhanced industrial production processes. This will lead to better products and increase the availability and energy efficiency of wind power plants. Finally, it will help to accelerate the energy transition and thereby reduce environmental pollution. In addition, more effective, safer and quieter WES will raise the population's acceptance of this technology and thereby facilitate its further expansion.

6 List of publications

T. Tianen et al., Analysis of total rotor runout components with multi-probe roundness measurement method, Measurement, Vol. 179, 2021, 109422. https://doi.org/10.1016/j.measurement.2021.109422

M. Stein, et al., A Unified Theory for 3D Gear and Thread Metrology, Appl. Sci 2021, 11(16), 7611. https://doi.org/10.3390/app11167611

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A. Przyklenk et al., Holistic evaluation of involute gears, Proceedings AGMA FTM 2021, https://eprints.ncl.ac.uk/281861

T. Tianen, et al., Multi-probe roundness measurement and harmonic content of Reuleaux polygons, Proceedings euspen 2022, https://www.euspen.eu/knowledge-base/ICE22283.pdf

C. Jensen et al., On the Combination of Geometrically Nonlinear Models and Substructuring for Multibody Simulation of Wind Turbine Blades, Proceedings ASME 2021, https://doi.org/10.1115/DETC2022-90948

F. Keller et al., A reduced self-calibrating method for rotary table error motions, Meas. Sci. Technol. 34 065015, 2023, https://doi.org/10.1088/1361-6501/acc265

B. Blanco et al., On the definition and effect of optimum gear micro-geometry modifications for the gearbox of an offshore 10-MW wind turbine, Wind Energy 26 (7), 2023, https://doi.org/10.1002/we.2825

K. Kinnunen et al., The effect of surface roughness variations to eddy current displacement measurement, Proceedings I2MTC 2023, (2023), https://doi.org/10.1109/I2MTC53148.2023.10175923

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

7 Contact details

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