Publishable Summary for 19ENG07 Met4Wind
Metrology for enhanced reliability and efficiency of wind energy systems

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.

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).

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).

Progress beyond the state of the art

Objective 1, Investigate fast optical and multi-sensor measurement methods

The potential for non-contact optical technologies to perform traceable dimensional measurements has to be exploited by providing dense point cloud data for high resolution geometry, form and real surface topography in appropriate measurement times, e.g. < 6-7 hours (this example is the duration for two profiles or helices on a gear measured in tactile mode), which are increasingly being demanded by end users. The project results provide validated non-contact dimensional measurements of mechanical WES components and a reliable assessment in terms of measurement uncertainty of the investigated systems. This will enable faster, more reliable and holistic measurements of these parts.

Within the project the performance of the Precitec and the HP-O sensor of Hexagon was investigated for an optimized application on CMMs for measuring large WES gears. As additional research, a Nikon laser scanner was also included in this study. For industry, this was a preliminary independent study of commercially available optical sensors for the measurement of WES components on CMMs.

A feasibility investigation for measuring micropitting on gear surfaces using portable optical methods was compiled. This is critical to tracking gear surface condition on wind turbines in service to understand and predict performance and to minimise downtime due to failures. 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. Moreover, a method of extracting the damage was developed that was independent of the datums but required the replica to include the tip diameter to provide a nominal reference position.

A new three-point roundness measurement device ROMES with an adjustable diameter range based on linear motion of the probes was designed and constructed. The design of the new device was optimised to encompass a wider range of harmonics than with previous optimisations.

For this purpose, an artefact in the shape of wind turbine blades suitable for tactile and optical measurements was designed and manufactured. On the leading edge a part was added 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 also used for testing a new method to reconstruct 3D maps of damage and erosion of the surface of wind turbine blades on wind WES. The photogrammetry reconstruction was based on multiple photos by analysing the pictures taken from different angles using specialised software. The method developed and assessed focused on equivalent measurement conditions to drone-based observations in terms of e.g., distance to the surface and performance of the measurement system.

Objective 2, Improved measurement and evaluation methods

Tactile measurements and 2D, line based, form and roughness evaluation parameters, which are typically used for the surface measurement and evaluation of WES drivetrain components, have been applied to 3D surface measurement and evaluation strategies.

The project developed a state-of-the-art 3D holistic gear measurement and evaluation process that allowed the separation of tooth helix, profile and pitch deviations. This represented a paradigm change in the evaluation strategy which is Geometric Product Specification compliant and can be applied to point cloud data or classical multiple 2D measurement strategies. The evaluation method can be constrained to provide evaluation results which are consistent with classical gear measurement methods.

Novel harmonic content measurement and analysis, which can have a significant impact on gear and bearing performance, noise and reliable life prediction have been successfully developed.

Bearing journal measurements using a novel multi-probe measurement method suitable for measurement on machine tools and in WES installations in-situ were conducted. The resulting harmonic analysis of the measurement data was performed by using FFT analysis.

The harmonic analysis of gear 3D surface measurement results successfully used Wavelet analysis to identify damage and to characterise the harmonic content from the CNC machine tools that are typically used to manufacture WES gears.

The measurement uncertainty of Eddy current sensors used to measure WES shaft runout by industry to satisfy Standards was quantified for the first time, including the contribution from the electrical runout and other key uncertainty contributions.

Linked to objective 1, novel measurement and evaluation methods for characterising damage on gear teeth have been developed and the measurement uncertainty was assessed to support digital twin and performance models.

The project increased the value of information from workpiece measurements on the WES drivetrain to enable the linking of functional performance to appropriate surface characterisation parameters. This included the reliable assessment of noise-producing structures on component surfaces which was heavily demanded by drivetrain manufacturers and it was needed for large system performance models and Digital Twins.

Objective 3, Develop a digital twin of the drivetrain and the turbine blade

Erosion of the leading edge, which causes leading edge roughness, has a large influence on the efficiency of turbine blades. The visual documentation of the non-uniform surface erosion of the leading edge of the blades by ground based or airborne cameras, serving as a qualitative and empirical decision-making basis was inadequate. Therefore, a digital twin of the turbine blades, focusing on the non-uniform surface erosion of the leading edge as well as on the uniform surface roughness, was based on previous work. This enabled the prediction of erosion and degradation over time which is crucial for end-users like WES operators.

Objective 4, Evaluate and improve the accuracy of machine tool measuring stations

Results related to Objective 4 advanced the state-of-the-art by providing validated and new procedures for evaluating in-situ measuring systems applicable for measuring complex high accuracy WES components in typical harsh environments e.g. directly on the grinding machine.

The experiments made in WP4 yielded new knowledge of modelling and measuring bearing deformations as well as their effects on the dynamics of the complete rotor-bearing assembly. Grinding was verified with dynamic response measurements. Overall, the research provided insights into improving the manufacturing and assembly processes for large rotor-bearing systems.

A reduced three-rosette method for determination of rotary table errors was trialled, requiring either reduced measurement positions of the CMM or reduced required numbers of balls for a much more economical applicability in industry than the complete three-rosette method.

Results

Objective 1, Investigate fast optical and multi-sensor measurement methods

Using the tactile measurement results as a reference, PTB tested the measurement performance of an interferometric point sensor on PTB’s large gear measurement standard for comparison. To further decrease the measurement uncertainty, a special probe head has been installed allowing for probing in different angular directions. This made the measurements easier and faster. In the measurements of the three external gears of PTB’s large gear measurement standard, the measurement uncertainty of the HP-O sensor was higher than that of the tactile probe, the average uncertainty of the filtered optical slope deviation measurements was 4 µm and the maximum uncertainty was in the range of 5 µm. As additional research, a Nikon laser scanner that could be mounted on a CMM (Leitz PMM-G) was provided by Hexagon and tested at PTB. Point cloud data collected by the scanner on gear flanks can be meshed in the software 3DReshaper from Hexagon and then virtually measured in Quindos. Compared with the HP-O sensor, the measurement accuracy of this sensor was slightly worse, but it was very efficient for the holistic evaluation of gears.

With support from the other partners, NCL investigated 3 measurement strategies to characterise in-service damage on gears in a WES gearbox. Based on direct comparison with tactile measurements, optical evaluations of damaged gear teeth were feasible to within 5 µm of the defined constraints. The evaluation process has been extended and proven on a small demonstrator gear and on a 520 mm facewidth large gear segment. Measurements were made directly on the flank and on soft replicas of the damaged regions.

Optical texture measurements of a gear tooth were preliminarily tested by INRIM, with a confocal microscope and an interferometric sensor with a focusing head. The confocal point sensor was characterised thoroughly. Moreover, optical measurements of the surface texture of a segment of a large bearing, diameter 1 m, were performed by using an optical profiler in confocal mode. Preliminary results of the texture parameters from the tactile and optical measurements showed some deviations between the tactile and optical measurements.

Aalto constructed and tested a new variable diameter multi-probe roundness measurement instrument on reference workpieces and a rotor provided by ABB FI. Reference measurements were made with a Talyrond TR31c roundness tester. The measurement data for the reference measurements has been published in Zenodo as an open dataset. A good correspondence with uncertainties below 5 µm was observed between the new device and reference measurements. Furthermore, the evaluation of uncertainty in roundness measurement was discussed. VTT performed optical measurements on a shaft provided by Moventas FI.

CMI, with support from DFM and DTU, designed and manufactured a 3D freeform artefact, which represents the curvatures present on WES blades as well as artificial surface erosion on the leading edge. They have also made progress in preparing the artefact for calibration. DFM has reconstructed roughness and surface form in the millimetre to centimetre scale of an artefact from camera images resembling the possible quality of drone images of leading-edge roughness. Results were compared to accurate CMM measurements and standard uncertainties in the range from 0.5 mm to 5 mm were verified.

All tasks in objective 1 were achieved.

Objective 2, Improved measurement and evaluation methods

Aalto investigated the performance of the eddy current sensors that are used by industry for rotor runout measurement with ABB FI who provided a large electrical machine rotor for testing. Aalto used the newly built variable diameter roundness multi-sensor measurement device as well as surface roughness measurements with micro probes provided in cooperation with VTT.

Eddy current sensors have been tested to quantify the effects of surface roughness, residual magnetism and residual stress on the measured runout and thus quantify the contribution to the measurement uncertainty. Data acquisition hardware, which gathered data on the electrical runout was developed and used on a larger number of rotors at ABB FI. The results show that the measurement uncertainty can be large with respect to the tolerance specification.

The influence of different scanning speeds with tactile scanning was quantified with PTB's 600 mm bearing standard. With the first CMM, an increasing number of outliers in the form measurement were examined, which led to larger deviations at speeds > 5 mm/s, compared to single point measurements. The bearing standard was also measured with a second CMM. Due to pre-filtering, the measurement curve becomes smoother as the scanning speed increases, Helix and profile lines were measured on a large gear standard with spur and helical gears. When filtering the helix line, unwanted filter effects occurred because the measurement and evaluation range were too close to each other. According to the ISO 1328-1:2013 standard, filtering must be used for scanning measurements. Therefore, the evaluation range was reduced to solve the problem.

An algorithm for the 3D holistic evaluation of the involute spur and helical gears used in a WES has been implemented in MATLAB. The algorithm inverts three-dimensional point clouds by fitting the position and geometry parameter of the parameterised gear shape. The evaluation method was also applied to multiple 2D classical measurements such as those used on conventional gear measurement machines in industry. The method is robust and can be implemented on any number of teeth in the gear. This new method is compatible to Geometrical Product Specification (GPS) measurement and evaluation methods (unlike classical gear measurement methods) and represents a paradigm change in the measurement strategy for gears. The method was tested on both synthesised data and real measured data from a PTB gear artefact. The methodology and results have been published and discussed with gear manufacturers at a number of conferences and a VDI/VDE guideline has been planned to cover 3D gear surface measurement and evaluation methods.

Initial work to review harmonic evaluation methods for gear flank line surface measurements including FFT, Discrete Wavelet Analysis, Discrete Cosine transform, and Bayesian spectral analysis has been completed by NCL using MATLAB. Methods were evaluated with synthesised data that includes typical micro geometry corrections which are used in WES gears. The synthesised data included multiple frequency content and local damage regions which occur on gears that have been used in service. The ability of each method to compress data was also evaluated for data transfer for DT and advanced CAD gear modelling. FFT and Wavelet transforms have been further developed and successfully applied to larger artefacts. A comparison between a CMM and GMM at PTB and NCL, respectively used a 400 mm diameter gear artefact. A measurement uncertainty strategy has been developed and results from this initial test showed acceptable compatibility between results and identified future research areas that need to be investigated. The methods have been presented at a number of gear industry conferences and meetings during the last 12 months. Objective 2 requirements have been fully achieved in accordance with the project plan by close collaboration of the partners, unfunded partners, and project collaborators.

Objective 3, Develop a digital twin of the drivetrain and the turbine blade

During the last reporting period, 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 was not fully conclusive weather 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 we have shown 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.

In summary the following key conclusion were generated in the project period:

- Adding component flexibility to a design of a bedframe and showing how the design and dimensioning can affect load sharing and thereby take advantage of this effect for improved levelling of loads 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 most sensitive modelling states 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 inclusion of virtual faults was beyond state of the art for simulation-based fault indicators as a starting point before historic fault data are available.

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

In summary, Objective 3 was achieved to the 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.

Objective 4, Evaluate and improve the accuracy of machine tool measuring stations

During the project, an inner multi-probe roundness measurement device was developed at Aalto and tested on a bearing outer ring provided by SKF. The performance of the device was verified with reference measurements by VTT. Experiments related to compensating the roundness error of a conically fitted bearing by altering the geometry of the mounting taper has been performed successfully, and further studies on the measurement and compensation possibilities are underway. A simulation and verification experiment on the effects of the bearing inner ring orientation on the total out-of-roundness of a rotor-bearing assembly was conducted and a report summarising the findings was prepared and submitted to EURAMET accordingly. Simulations of the feasibility of compensation geometry for mechanical loads on a hydrostatic bearing were made with Moventas.

A software tool for the evaluation of the geometric errors of the rotary table was written in MATLAB by PTB. The tool allows the evaluation of measurements of a ball disk according to the reduced three-rosette method. The reduction can either take place in the measurement positions of the CMM or in the balls of the used ball disk, or in both rosettes. Moreover, a new ball plate for the measurements of rotary table error motions in steps of 5° using the reduced three-rosette method was designed and manufactured at PTB. Measurements with several rotary tables at PTB have been performed and evaluated. The results show good agreement between the complete and reduced method. Moreover, ZEISS performed measurements with the reduced three rosette method and achieved results in good agreement with the results from their own method using a spindle analyser. A patent application is pending for this method. This knowledge was transferred by NCL and NCL collaborated with PTB by applying methods derived by PTB using the full rosette and reduced methods. To validate and apply the method a machine tool with a high accuracy touch trigger probe was used to measure a full rosette and reduced method ball plates at NCL.

NCL devised a strategy to assess the in-situ gear measurement capability on a 5-axis machine tool. The investigated method was to use a calibrated "workpiece like'" artefact and analyse the measurements taken from the machine tool. CMI with support from VTT developed a CAD model based on non-uniform B-spline representation (NURBS) of nominal geometries of the workpieces selected to enable CAD-based measurement on a CMM. This objective was clearly achieved.

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.

List of publications

1. 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
2. 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
3. S. Pedersen et al., Multibody models for tower vibrations with unbalanced rotor, Proceedings ASME 2021, https://doi.org/10.1115/DETC2021-72182
4. A. Przyklenk et al., Holistic evaluation of involute gears, Proceedings AGMA FTM 2021, https://eprints.ncl.ac.uk/281861
5. 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
6. 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
7. 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
8. 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
9. 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/

Project start date and duration:		September 2020, 36 months
Coordinator: Karin Kniel, PTB Tel: +49 531 592 5300 E-mail: Karin.kniel@ptb.de Project website address: https://www.ptb.de/empir2020/met4wind/home/		
Internal Funded Partners: 1. PTB, Germany 2. CMI, Czechia 3. DFM, Denmark 4. INRIM, Italy 5. NCL, United Kingdom 6. VTT, Finland	External Funded Partners: 7. Aalto, Finland 8. AU, Denmark 9. DTU, Denmark	Unfunded Partners: 10. ABB FI, Finland 11. Hexagon, Germany 12. Moventas, Finland 13. NCMT, United Kingdom 14. SKF, Finland 15. Vestas, Denmark 16. Zeiss, Germany
RMG1: PTB, Germany (Employing organisation); NCL, UK (Guestworking organisation)		