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TABLE OF CONTENTS

1 Executive Summary

Introduction

Failure of mechanical components in wind energy systems (WES) can lead to downtimes of several days or even weeks resulting in high operation costs and poor reliability. These issues are likely to become worse when offshore installations become more common with the additional access and safety issues associated with an offshore application, therefore more reliable drivetrain components are mandatory. A principal problem is that neither NMIs nor calibration services offered calibrated measuring standards for drivetrain components and even measurement processes for industrial large component measurements were insufficient. This project addressed this problem.

The Problem

According to the roadmap and forecast of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany (BMU), the share of wind power in electricity generation has a goal to achieve 25 % by 2025, based on today's electricity consumption. This step alone would reduce Germany's carbon dioxide emissions by 20 % and therefore provides evidence of the importance of wind energy for climate protection. The directive 2009/28/EC on renewable energy, implemented by EU Member States in December 2010, sets ambitious targets for all EU Member States, such that the EU will reach a 20 % share of energy from renewable sources by 2020. WES are regarded as one of the most promising technologies for the generation of renewable energy to meet these government targets but reliability with the drivetrain components needs to be improved. The high costs associated with the repair of drivetrain components and also lost power generation due to unplanned maintenance is a common problem for renewable energy suppliers

The Solution

This project developed new approaches to deliver measurement standards and procedures for enabling the reliable estimation of a quantitative measurement uncertainty for highly accurate drivetrain components for WES (bearings, shafts and gears) as demanded in international guidelines, and these were optimised for industrial use.

Impact

New measurement standards, procedures and good practice guides have been developed and will now be disseminated to standardisation committees and applied in industry. The key sources for uncertainty for dimensional metrology on large drivetrain components were identified, virtually modelled, quantized and validated in industrial practice.

At INRIM and CMI new gear calibration services have been established.

After having improved the metrology, the manufacturing of drivetrain components can be improved and such the lifetime of renewable energy power generators could be extended, and probably also their failure rate minimised. The best practice guides will allow the consideration of the temperature influence on the measurement uncertainty under harsh environmental conditions and the effects of gravity and clamping effects on large components. Also, the direct application of measurement data within finite element analysis (FEA) packages and design software will allow the prediction of both failure modes and functional performance of drivetrain components.

The outputs from this project may reduce the production costs by 25 % which would lead to WES becoming cheaper and therefore more frequently installed with the same investment. The mandatory installation of traceable measurements into the manufacturing process will lead to increased turnover for measurement equipment and calibration suppliers. As a result, this project indirectly will increase the cost efficiency of the production of renewable energy and such support the EU political goal of reducing CO_2 emissions by 40 % by 2030 at least for power generation.

2 Project context, rationale and objectives

2.1 Project context and rationale

Energy is the lifeblood of industrial processes. It provides prosperity and quality of life especially in industrialised and threshold countries. However, today, electrical energy is mainly generated by fossil resources such as coal, oil, and natural gas, or by nuclear fuel. These energy resources will be exhausted during the next generations. Moreover, their immense usage leads to environmental pollution, e.g. by carbon dioxide emissions, fracking induced chemical soil contamination, and nuclear waste. To overcome the main problems and to guarantee sustainable energy for the future, renewable energy resources are essential.

According to the roadmap and forecast of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany (BMU), the share of wind power in electricity generation have a goal to achieve 25 % by 2025, based on today's electricity consumption. This step alone would reduce Germany's carbon dioxide emissions by 20 % and therefore provides evidence of the importance of wind energy for climate protection. The potential for developing renewable energy is of course available to all EU members.

The directive 2009/28/EC on renewable energy, implemented by EU Member States by December 2010, has set ambitious targets for all EU Member States, such that the EU will reach a 20 % share of energy from renewable sources by 2020.

The control of European energy consumption, the increased use of energy from renewable sources, and improved energy efficiency, constitute important parts of the package of measures needed to reduce greenhouse gas emissions and comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change, and with further Community and international greenhouse gas emission reduction commitments beyond 2012. Those factors also have an important part to play in promoting the security of energy supply, promoting technological development and innovation, and providing opportunities for employment and regional development, especially in rural and isolated areas.

The EC strategy is structured around 5 priorities:

- limiting energy use in Europe
- building a pan-European integrated energy market
- empowering consumers and achieving the highest level of safety and security
- extending Europe's leadership in the development of energy technology and innovation
- strengthening the external dimension of the EU energy market

Besides Europe, strong economic countries, such as China and USA, are investing in renewable energy. North America, for instance, will install several tens of thousands of WES within the next decades along the coast line of North America and in the Great Lakes.

WES is regarded as one of the most promising technologies for renewable energy. Currently, the maximum power provided is 7 MW/WES. In the future, 20 MW/WES seems to be feasible. Two types of WES can be found today: direct drives and gear drives; both comprise technical advantages and disadvantages. Now, it seems likely that a combination of both will be the future solution. However, only very few WES reach the desired lifetime of 20 years without two or more failures of major components. This is very critical as the failure of mechanical components can lead to downtimes of several days or even weeks. In the case of off-shore WES, maintenance effort and even staff working conditions are critical. Therefore, reliable drivetrain components are mandatory.

Today, a principal problem is that neither NMIs nor calibration services offer calibrated measuring standards for large drivetrain components. In the automotive industry, for example, traceable measurements on engine parts are the backbone of economical fabrication processes and quality control. Currently, almost 3×10^9 gears per year are produced. These gears are optimised in weight, surface quality in the range of micrometres, and stability. Large scale drivetrain components of renewable energy systems are a long way from the high performance and low failure rates provided in the automotive industry. This leads to high operation costs, and poor reliability. These issues are likely to worsen when offshore installations become more common, with associated additional access and safety issues.

Neither written nor embodied standards for drivetrain metrology exist. So far, most NMIs have little or no experience in measuring large-size components.

In addition, the manufacturers of drivetrains have had limited possibilities to validate the task specific performance of measurement instruments due to the lack of qualified measurement standards. This lead to potentially high-risk investments in measurement instruments which can cost typically 1 M€. Even more problematic is the broken chain of process control during the manufacturing process.

Waviness and roughness errors have a significant influence on the lifetime of highly stressed parts in drivetrain components because in modern super-clean steels, failures are initiated at the surface. Before the project, qualified measurement techniques and evaluation strategies that would allow a prediction of these influences were missing. However, knowledge was available among the project partners which could be used to transfer their expertise to find solutions for industrial demands.

2.2 Objectives

This project addressed the challenges by focusing on traceable 1D-3D measurements on highly accurate components of drivetrains. These are shafts up to 3 m in length and 1 m in diameter, large bearings up to 3 m, internal and external epicycle gears up to 3 m, and brakes up to 1 m.

This project addressed the following scientific and technical objectives:

Objective 1: To provide solutions for measuring and characterising 2D and 3D size, form, waviness and surface roughness parameters in large drivetrain components, establishing functional characterisation parameters in accordance with the GPS requirements defined in ISO 14253 and ISO/TS 17450.

Six good practice guides for shafts, gears, bearings, and gear measurements were developed and trialled in real industrial applications under harsh environmental conditions. The good practice guides deal with measuring length, surface form (including waviness) and roughness of large drivetrain components. Where guidelines already existed for accredited laboratories, they have been interpreted for industrial use. Recommendations on which properties and parameters to measure for different parts were also made for:

- involute profiles (the profile of the teeth), including superfinished surfaces
- braking systems
- gears, and
- involute helical gears

The good practice guides developed in this objective have established the necessary metrological procedures and recommendations for measuring large drivetrain components, taking into account the effect of temperature, environmental conditions, the effects of gravity and clamping effects. The good practice guides also established functional characterisation parameters in accordance with established written standards e.g. ISO 10825, ISO 5436, ISO 13565, ISO 16610, ISO 12180, ISO 12181, ISO 12780, ISO 14405 (see guides for details).

Objective 2: To research and develop measurement standards and calibration procedures for establishing traceability and estimating measurement uncertainty of drivetrain components

This objective established traceability and uncertainty estimations for large drivetrain components, using the procedures from the first objective. Nine standard artefacts for large gears, bearings, and shafts were designed and manufactured. Novel measurement equipment procedures were then developed by the project to measure and calibrate these standard artefacts as well as other large industrial parts/drivetrain components. These procedures and standard artefacts have been used by industrial manufacturers so that they can calibrate their drivetrain components.

Objective 3: To establish and quantify the key additional sources of uncertainty that influence industrial measurement capability, with particular reference to environmental effects

The project undertook end-user surveys of typical fabrication and processing conditions for large gear and large bearing metrology, as well as typical supports and clamping fixtures for large rings or bearings. The surveys were carried out with four industrial stakeholders who are manufacturers of drivetrain components. Thermalisation experiments, where large parts reach thermal equilibrium, were carried out using a climate chamber. The effect of self-weight deformation of large rings was also investigated, and the results from both have been published in a good practice guide for industrial users on the thermalisation times of large gear and large ring measurement standards. Lastly, the measurement uncertainty due to elastic deformation of components was examined, particularly for the wind power generator tower. Based on the findings of the surveys, and the above experiments in industrial conditions the project has been able to establish and quantify the key additional sources of uncertainty that influence industrial measurement capability. This greater knowledge of the measurement uncertainties allows much better quality control in the production of drivetrain components.

Objective 4: To develop a virtual measuring process to include all the significant uncertainty contributions from the workpiece, environment, measuring strategy and measuring instrument

The project developed computer-aided design (CAD) modules and numerical models, and used these to simulate the significant factors that introduce errors in the measurements of large components. These virtual investigations considered surface characteristics, temperature variations and deformations caused by gravity and clamping. Based on their results it is now possible to minimise these errors in the measurements of large components by using the recommendations resulting from the numerical models/calculations.

Furthermore, recommendations for the selection of scanning parameters for coordinate measurement machines (CMM) from numerical simulations and practical experiments. These recommendations and those from the virtual investigations above are now available for end users as a good practice guide on the minimisation of significant measurement uncertainty contributors such as gravity and clamping. The direct application of these recommendations within finite element analysis packages and design software developed by the project, can be used to predict both failure modes and the functional performance of drivetrain components.

Objective 5: To test the developed measurement standards in industry and critically analyse their performance compared to traditional standards, such as gauge blocks and step gauges

The project’s six good practice guides were found to be easily to use and applicable in practice in an industrial environment. Using the guides the project was able to validate the measurement strategies developed in the previous objectives in an industrial environment. The knowledge gained was also used to analyse the performance of existing fabrication and handling methods including traditional standards, such as gauge blocks and step gauges. From the results, it was possible to establish uncertainties, which were typically within 2 µm to 10 µm.

3 Research results

Wind energy systems size is increasing continuously in order to obtain the maximum possible energy out of the wind. Therefore, metrology methods need to be adapted to this size and characteristics providing traceability. This project focused on traceable 1D to 3D measurements on highly accurate components of drivetrains. These are shafts up to 3 m in length and 1 m in diameter, large bearings up to 3 m, internal and external epicycle gears up to 3 m, and brakes up to 1 m.

3.1 2D and 3D metrology strategies for drivetrain components

One of the main achievement of the project is providing solutions for measuring and characterising 2D and 3D size, form, waviness and surface roughness parameters in large drivetrain components. Functional characterisation parameters have been established in accordance with the GPS requirements defined in ISO 14253 and ISO/TS 17450.

3.1.1 Microprobe

For the determination of microstructures, PTB developed a novel tactile microprobe with 120 µm diameter. The aim of this work was to evaluate the benefits from using microprobes on a gear measuring instrument (GMI) to extend machine versatility and detect key performance characteristics on workpieces up to 3 m diameter.

PTB in cooperation with the Institute of Microtechnology of the Technical University Braunschweig developed this microprobe to be integrated into PTB’s Klingelnberg P40, a conventional GMI. The microprobe (see Figure 1a) is composed out of a tungsten carbide stylus mounted onto a silicon membrane. The stylus has been fabricated with a wire-cutting process, which enables the fabrication of stylus tip diameters from 300 µm down to 50 µm. The silicon membrane has been manufactured with standard photolithography and bulk machining process under clean room conditions. On this silicon membrane, piezo-resistances enable the measurement of the displacement of the stylus tip while probing. These resistances are configured within four Wheatstone-bridges (see Figure 1b) and deliver four voltages.

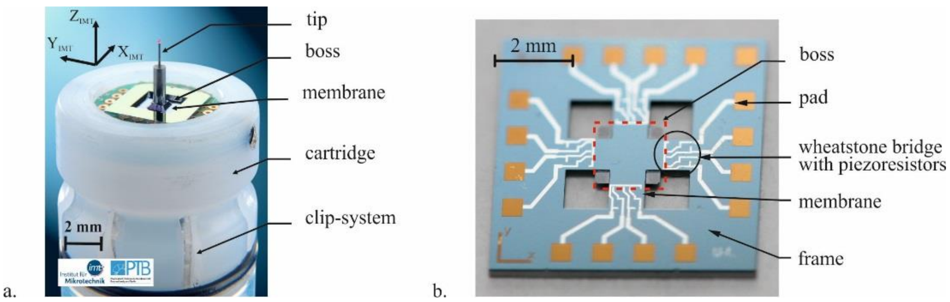


Figure 1*: a. Mounted microprobe in plastic cartridge,*
b. Detail of the silicon membrane and in particular of the piezo-resistances and their electrical connections

For integration into PTB’s GMI a coupling and exchange mechanism has been developed and fabricated. The new adapter design enables also the orientation of the microprobe into two directions: 0° and 90° (see Figure 2 b and c). In this way, the microprobe can be orientated in Y or in Z direction which extends the measuring capabilities of the system.

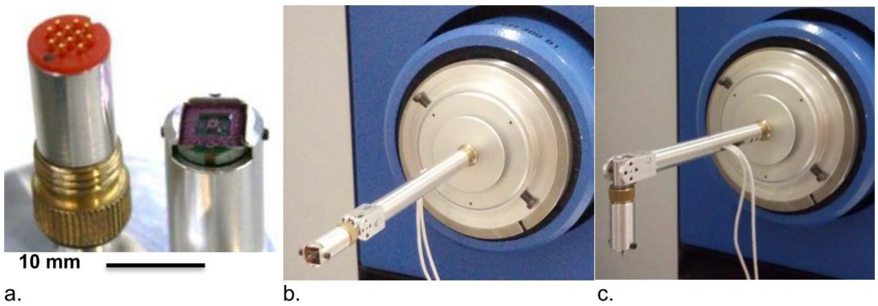


Figure 2*: a. Detail of the spring contacts of the adapter and the new aluminium cartridge with a microprobe without stylus (left)*

b. and c. Mounted adapter on the machine in position 0° (center) and in position 90° (right)

As for verification of the integrated microprobe comparison measurements have been performed on the *involute waviness scanning artefact* (SAFT 2w) against a conventional Klingelnberg probe.

Table 1 shows the statistics of the measurements of the external profile with the microprobe only and the probing system MK66.

Table 1: *Gear evaluation results comparison between microprobe only and the probing system MK66*

Gear parameters	Microprobe only	Probing system MK66
F_{α} in µm	24.209 ± 0.128	28.110 ± 0.035
$f_{f\alpha}$ in µm	16.389 ± 0.086	19.136 ± 0.075
$f_{H\alpha}$ in µm	12.120 ± 0.183	14.047 ± 0.015

For the comparison measurement of the microprobe against the standard Klingelnberg system the measurement standard has been removed from the machine and then been centred and clamped again. All measurements results are based on the machine axis of the rotary table. Therefore, the centring of the part has a large influence on the measurement results, especially on slope deviation. This explains the differences between the results in Table 1.

3.1.2 Flank and root form measurements

Flank and root measurements of large gears have been investigated. The aim was to evaluate candidate measurement strategies and performance based characterisation parameters for 2D and 3D flank and root form measurements on large gear elements and small test sample gears. All five activities were successfully completed with good working relationships developed between the partners.

Traditional 2D helix and profile line measurement strategies used to characterise gear flank geometry shown in Figure 3 were investigated by NCL regarding the introduction of data spacing, data density and filter recommendations from the 2013 revision of ISO 1328-1, the gear flank classification standard. A Matlab program was developed to import involute profile measurement data spaced evenly in radial direction (used by many measuring machines) or randomly spaced and project these onto the gear length of roll plane, as required by the new standard. Results quantified the increased uncertainty of evaluated profile slope deviation parameter with different data spacing sampling strategies which increased as tooth form deviations increased. Thus, the specification of profile data spacing was validated.

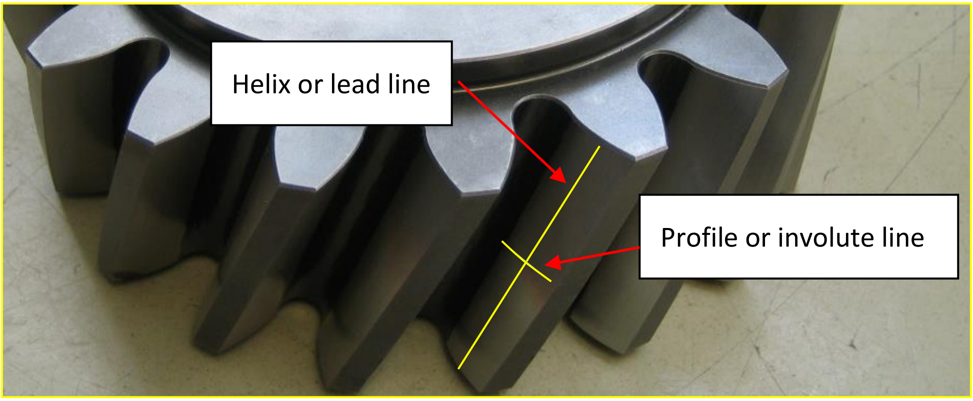


Figure 3*: Gear form 2D measurement lines*

NCL and INRIM analysed the functional requirements of gears and proposed data density requirements based on functional noise and vibration and working contact. The work concluded that the data spacing requirements recommended in ISO 1328-1:2013 of a minimum of 150 points are acceptable for noise and vibration performance prediction. However, contact stress requires a higher data density of 300 points per profile or helix line length which the standard recommended for waviness measurement.

3D gear flank form measurement methods were reviewed and developed during the project by PTB and NCL. Characterising the flank form with two lines, as illustrated in Figure 3, clearly fails to properly characterise the working gear flank geometry. Traditional methods provide acceptable guidance on adjustment of machine tools during manufacture but are not used for gear performance characterisation. Existing 3D methods were evaluated by PTB and found to properly model the tooth surface but without specifying parameters. NCL developed and applied an economic multiple 2D measurement strategy for gear flanks to optimise 3D flank deviation characterisation using a 2-stage interpolation process. The results showed deviations between actual measured profiles and interpolated profiles of < 0.5 µm, when 3 profile deviations and a single helix measurement were interpolated. Test gear measurement results from the new 3D measurement strategy were imported to GATES, a 3D FEA tooth contact analysis (TCA) model, illustrated in Figure 4. This was tested as part the verification of the project and shows TCA models can be used in the future to perform acceptance tests to predict gear performance and thus develop GPS compatible measurement strategies.

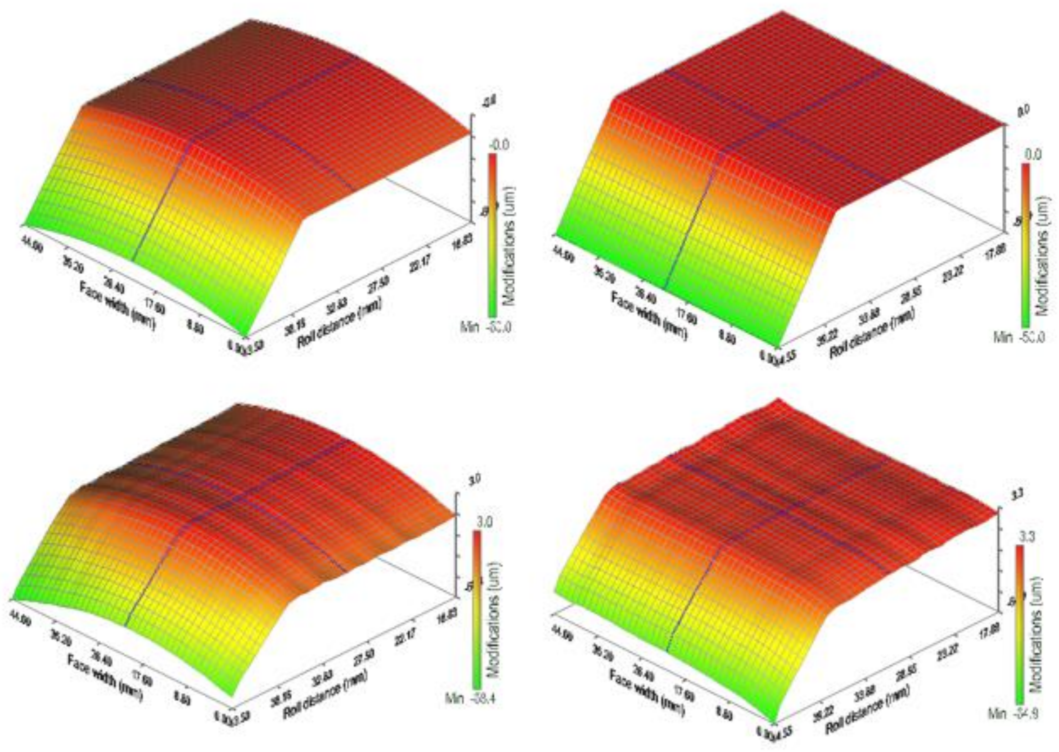


Figure 4*: The difference between theoretical 3D tooth form (top) with actual tooth form (lower) for mating gear teeth from the 3D measurement strategy developed and used to model performance in a gear TCA.*

REG(CARD) used a single profile and helix measurement result from the midface to model the lubrication of the loaded gear tooth pair to predict lubrication film thickness and estimate the cumulative contact fatigue damage caused by the form deviations. The results from this work showed that although differences in performance between different gear conditions were identified, the full 3D tooth shape characterisation is needed to properly model gear performance and this is likely to include surface roughness features. The result shows the limitations of existing 2D measurement and evaluation strategies for predicting gear performance and that further performance based research is needed.

3.1.3 Roughness and waviness measurements

Waviness and roughness errors have a significant influence on the lifetime of highly stressed parts in drivetrain components, because in modern super-clean steels, failures are initiated at the surface. Qualified measurement techniques and evaluation strategies that allow a prediction of these influences were needed.

The aim of this task delivered by NPL, INRIM and NCL was to investigate and specify measurement procedures for the determination and characterisation of roughness and waviness parameters for large gears. Existing measurement and evaluation procedures from surface metrology were analysed and recommendations proposed. Tests on small gear samples with diameters less than 0.3 m, which were manufactured by different methods, were exploited and used for analysing measurement (see Figure 5) and evaluation strategies. The findings were compiled into a good practice guide (GPG).

The investigations into the best strategies for characterising the roughness and waviness revealed the complex nature of gear mesh sliding and rolling contact during operation. Test gears were manufactured by two types of form grinding (a common process used in renewable energy drives) and superfinishing (chemical/mechanical agitation process to improve roughness). The work also investigates the effect from initial running under load, when surface asperities are removed. The surfaces that are subject to sliding and rolling and contact fatigue are thus different from the manufactured surface. The extensive test programme at NCL and measurements performed by INRIM, NPL and NCL resulted in a measurement strategy summarised in NPL's GPG.

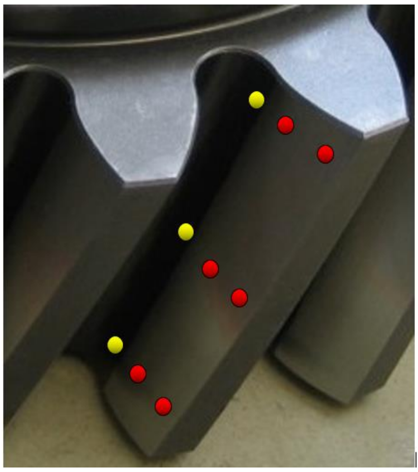


Figure 5*: Recommended measurement position strategy for characterising manufacturing processes*

The investigation showed that the measurement of areal parameters provided little additional characterisation data because of the sliding and rolling direction is defined in the transverse plane. Furthermore, the superfinishing processes leave surface roughness of < 0.1 µm and isotropic in nature, but when these are measured, a measurement strategy that is consistent with the original based on grinding is recommended to quantify the superfinishing process impact on the original surface.

A significant time was spent compiling data sets to continue the research and evaluate proposals from others after the project is completed. In addition to the data sets, replicas were taken from the surfaces to validate any future measurement/evaluation strategies.

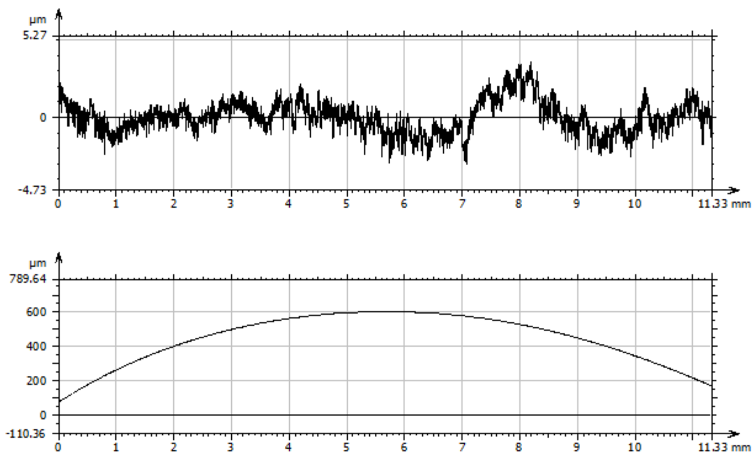


Figure 6: *Form removal using a 5th order polynomial for roughness and waviness evaluation.*

The GPG recommends a measurement strategy, form removal strategy (illustrated in Figure 6) and the filter length for both the active flank region and root fillet region of gear teeth. The guide includes a discussion of characterisation parameters including those that are mandatory for the needs of other ISO standards (ISO 6336-2 & ISO 6336-3 for contact and bending fatigue, ISO TR 13989-1 & ISO TR 13989-2 for scuffing resistance and ISO TR15144-1 for micro-pitting resistance) and recommends some candidate parameters that can be considered for future research and validation.

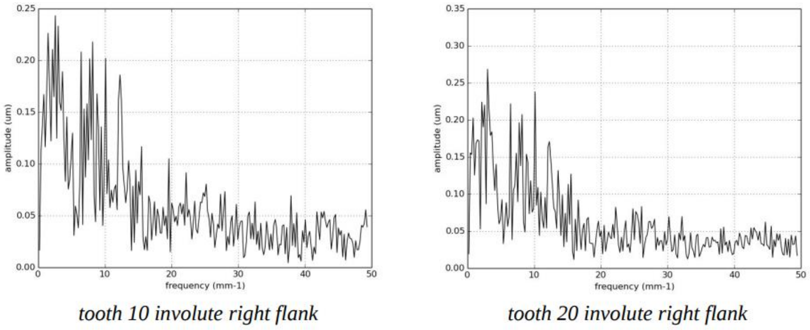


Figure 7: *Harmonic analysis of an involute gear tooth roughness profile*

INRIM applied a harmonic analysis (see Figure 7) method to evaluate involute profile roughness and helix measurement which provides an alternative robust method of characterising gear tooth roughness. The method may be used for involute measurement relating to micro-pitting contact fatigue initiation features, and is worthy of further research and development outside this project using the data sets available to partners.

3.1.4 Metrology strategies for large bearing elements

Metrology strategies for large bearing elements have been developed. The aim was to research and develop suitable measurement strategies to characterise the size and form of bearing elements with diameters of more than 1 m used in renewable energy applications.

To assess the current challenges in dimensional, form, waviness, and roughness metrology for large bearing elements under the aspect of economical relevance INRIM, supported from NPL and PTB, arranged a successful workshop in Torino in 2015. The scope of the workshop was to arrange a technical meeting with delegates from industry and National Metrology Institutes (NMIs) within stimulating the exchange of information between metrologists in science and industry and manufacturers as planned by the project.

The industrial workshop moreover provided information about existing applications used in the field of cylindrical ring measurement detailing the critical dimensional, form, waviness and roughness parameters for bearings. The report entitled: *The metrological parameters for critical dimensional, form, waviness, and roughness parameters for bearing rings* has been compiled by PTB, with support from INRIM and NPL, and it describes the typical measurands, measurement procedures and their parameterization for bearing rings, mainly based on existing standards and guidelines (see Figure 8).

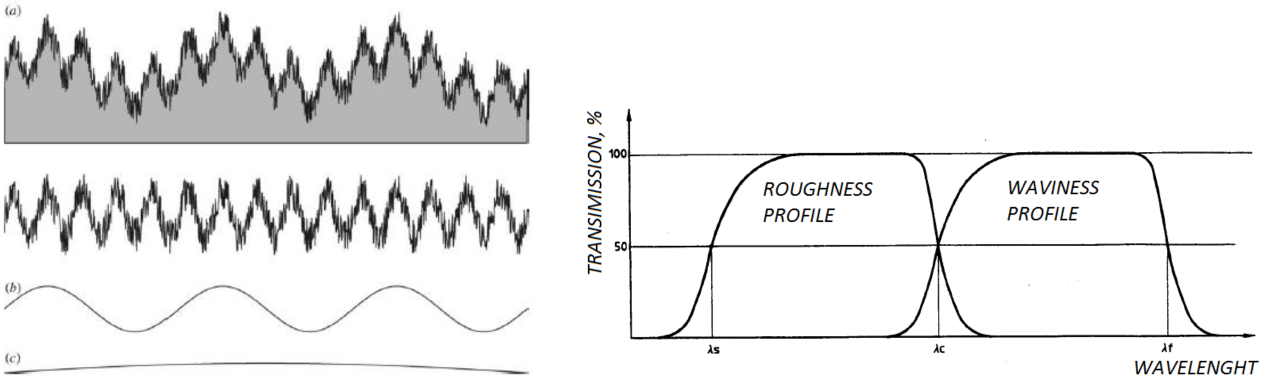
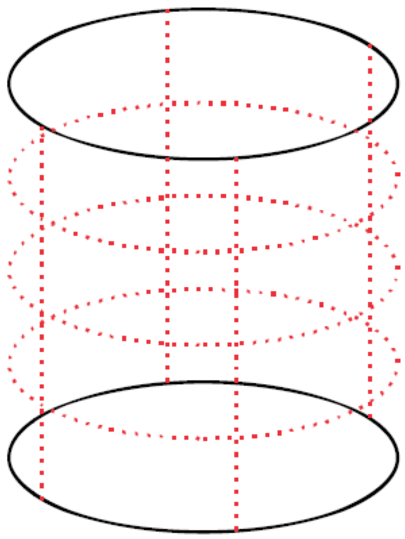


Figure 8*: Geometric components of a surface profile: (a) roughness, (b) waviness, and (c) form (left); Transmission characteristics of roughness and waviness profiles (ISO 4287: 1997) (right).*

This report has been preparatory for a detailed analysis of a measurement strategy such as sampling density distributions, filter types and filter settings for the measurement of rings up to 3 m in diameter and of a measurement strategy such as the definition of region of interest to identify meaningful roughness parameters considering economical and technical aspects. These studies contributed producing the basis for writing of two GPGs on measurement strategies.



First preliminary GPG has been written by PTB, with support from INRIM and VTT, and deals with surface parameter measurement strategies for form and diameter measurements on large bearings (formed as large bearing up to 3 m). The parameters considered as measurands by the guide are: roundness, straightness and cylindricity as indicators for global form deviation, waviness as indicator for local form deviation, and diameter. Waviness has been considered part of the form deviation according to definition of international standards for form. This GPG has been organized in two topics: *measurement strategy* description and *measurement uncertainty* evaluation. The first topic took into account the typical dedicate instruments and the most used measurement strategies (an example is shown in Figure 9). About measurement uncertainties, the guide cited published procedures for the uncertainty evaluation of form measurement and suggested the use of virtual coordinate measurement machine (VCMM) and empirical data as strategy to evaluate the measurement uncertainty. This GPG gives recommendations, which can be used for industrial measurements.

Figure 9*: Minimum proposed measurement positions for form measurements of a cylindrical body (red dotted lines).*

Second report has been written by NPL and deals with surface parameter measurement strategies and roughness measurements on large bearings up to 3 m in diameter. This preliminary GPG is quite detailed and has been dividend in two main sections: First section focuses on the *bearing lubrication and friction* (shown in Figure 10) and on the *influence of surface roughness,* whereas the second section is entirely dedicated to *stylus measurements of bearing surface roughness.* It describes the surface roughness measurement parameters that have to be considered as well as the parameters that the user should select appropriately for the workpiece investigation. Further it contains all the considerations that should be taken in account when measuring the surface roughness of bearings, a step-by-step procedure for measuring bearing surface roughness and finally how to evaluate the obtained data.

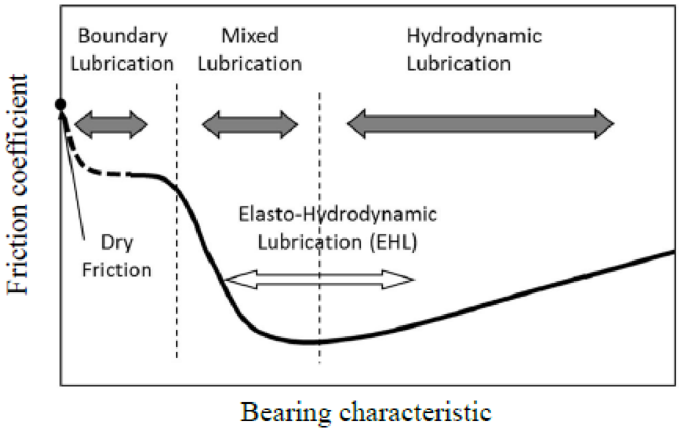


Figure 10*: Schematic of the Stribeck curve, the friction coefficient as a function of the bearing characteristic.*

Finally, in order to complete this topic on bearing measurement strategies, the probing system dynamics have been considered and analysed because of their importance for coordinate measurement machine (CMM) performance, particularly when probing in scanning mode. For this purpose, INRIM wrote a report entitled *Dynamics modelling of CMM probing system*. This work presents a modelling of a contouring probe and a method to select the right scanning speed versus the waviness of the workpiece, taking into account both the probe dynamics and the CMM global dynamics. The model is based on the characteristics of real probes; more specifically, continuous passive systems are considered, resulting essentially in second order 3D systems. The theoretical model is validated experimentally by scanning suitable surfaces exhibiting a range of slopes. The separation between static and dynamic effects is achieved by repeating the experiments at varying scanning speed, so that the same geometrical slope results in different temporal slopes - which the probing system dynamics is sensitive to. The model is oriented to define a good trade-off between the scanning speed and the measurement uncertainty (see Figure 11).

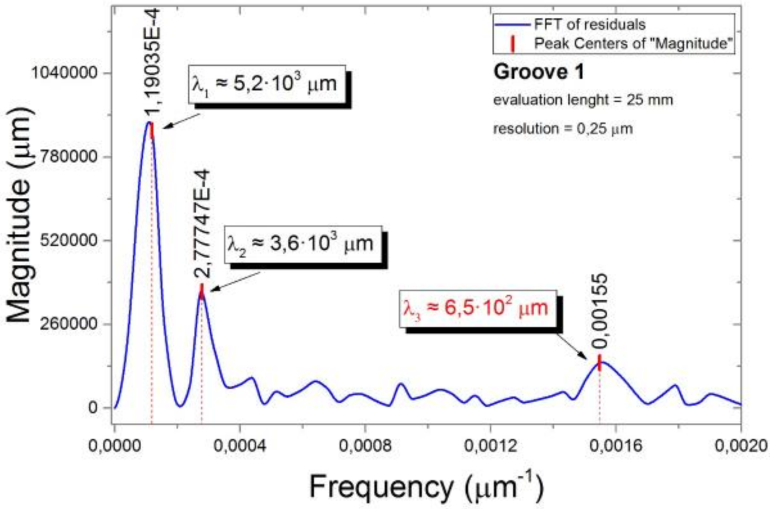


Figure 11*: FFT study of roughness measured on the ring segment along path "groove 1". Lower peaks are artefacts generated by fitting algorithm, while the λ3 peak is the real waviness of the measured surface.*

3.1.5 Metrology strategies for large shaft elements

The aim of the following work was to survey the current situation in large shaft metrology, develop measurement strategies and summarise findings for future techniques.

Based on a survey with companies (ABB, Hollming, Moventas and Sandvik) the geometrical requirements and existing measurement and evaluation strategies for drivetrain components have been investigated by VTT. A report describes typical requirements and measurement strategies. During visits to companies the roles of designer, manufacturing and verification measurements were discussed together with the effects of sub-contracting. These discussions gave a valuable understanding of the situation of manufacturing industries to researchers, both economical and technically.

For example, form errors on the workpiece contribute to uncertainty and are discussed in the GPG, which was verified and finalised within this project.

3.1.6 Geometrical product specification conforming measurement strategies

Geometrical product specification (GPS) conforming measurement strategies have been provided. The aim was to research and develop a strategy for applying the GPS philosophy defined in ISO/TS 17450 and ISO 14253 to large gear, bearing and shaft elements. The majority of the work was completed by REG(Aalto), VTT, PTB and NCL but we relied on unfunded partner MDM who represent both the gear measurement GPS ISO Technical Committee TC213 and TC60 WGs to initiate the GPS gear work. GPS is conceptually very simple but the application is complicated because it involves design, specification, manufacture, measurement and acceptance stages of product development and manufacture.

VTT, REG(Aalto) and PTB reviewed the existing standards that were relevant to shafts and large bearings. They concluded that large bearings were effectively covered by existing GPS standard documents. VTT reviewed GPS standards relating to shafts in wind turbine gearboxes and noted that currently the influence of form deviations on shaft runout and resulting vibration that can excite is not considered (see Figure 12). Other aspects are covered adequately in existing GPS standards.

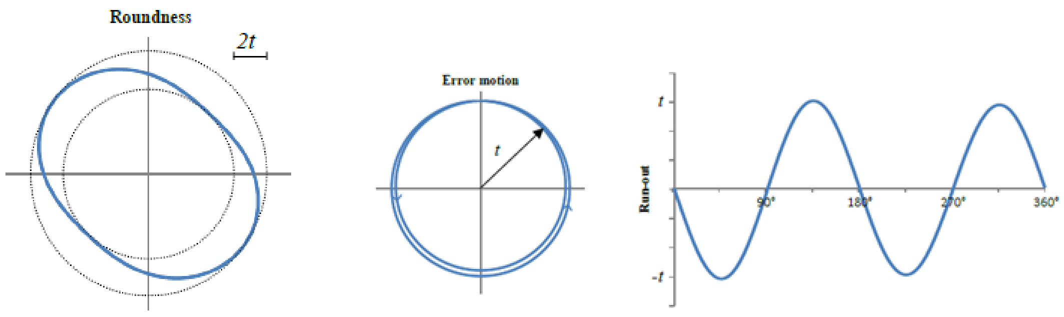


Figure 12: *Roundness deviations can cause vibration and runout and should be added to existing GPS standards.*

Gears have yet to be included in the GPS series of standards. When ISO TC60 WG2 revised ISO 1328-1: 2013 unfunded partner MDM introduced the GPS strategies to the working group but although they acknowledged that there was much merit, the gear industry and experience of most of the members meant that it was not practical to revise ISO 1328-1 to be compatible with GPS requirements. This situation has not changed. NCL, who are also members of ISO TC60 WG2 lead the review of the feasibility of applying GPS strategies to gears. NCL concluded that gear measurement and tolerance classification standards should be a machine element standard and other ISO documents could be adopted as GPS documents provided current GPS document requirements were modified.

ISO 199:2014 Rolling Bearings- Thrust bearings- Geometrical product specification (GPS) and tolerance values was used as a benchmark for a gap analysis for ISO 1328-:2013. The key findings from this work were a series of recommendations that included:

- References to GPS documents should be normative within the standard.
- The option to apply tolerances without reducing the limits to account for measurement uncertainty is of primary importance to get the GPS revisions accepted by industry.
- The use of existing functional based tolerance features, retaining ISO symbols and a gear specification and tolerance data table as part of the drawing specification is also a key requirement if GPS principles are to be applied to gears. Without this the standard will be ignored by industry.
- ISO 1328-1. Tolerance values are required for user guidance. The compliance/non-compliance with tolerance in accordance with ISO 14253-1 should be optional. This is a big issue for gear makers who argue (correctly) that measurement uncertainty is not new and is already therefore part of the standard which relates to functional gear performance.
- ISO 1328-1. A mandatory statement about the strategy on measurement uncertainty is required as part of the tolerance class specification.
- ISO 18653. Requires revision of uncertainty calculation to more accurately account for uncorrected bias from the comparator method of estimating measurement uncertainty.
- ISO 18653. References to ISO 10360, ISO 14253 (all parts), ISO 15530 (all parts) should be strengthened.
- ISO TR 10064-5. Update this by removing all but the ISO 14253-1 method of defining limits and add the (trivial) example where uncertainty is simply stated when reporting results.
- ISO TR 10064-5. Update and align with the latest revisions to ISO 1328-1.
- It is expected this process will take 10-15 years to implement.

3.1.7 Braking systems

The metrological needs for structural and functional components of the wind energy systems have been identified. The problematic of noise and heat generation in the brakes is also an important issue. Hypothesis on form and dimension effects on noise of yaw drive brakes and heat concerns of gearbox brakes are drawn from automotive brake literature and from metrological and tribological research on wind turbine brakes. The following relevant points have been identified:

- Wind turbines have different brakes with different functions, working principles and configurations, depending on wind-turbine design. Brake failure may have serious safety consequences as well as maintenance and shut-down costs. Brake performance, reliability and duration are therefore of most importance.
- Noise is a complex, fugitive and still open problem investigated along the last 70 years in the automotive industry. In wind turbines, it affects especially the yaw-drive brake.
- Heat affects high-speed gearbox brakes (temperatures reaching 600°C) and pitch brakes (155°C) and is considered tied cyclic thermo-elastic instabilities induced by friction surface form and to heat dissipation capacity.
- Part of the wind-turbine brake components have dimension or weight that require large-object metrology strategies and equipment, in particular large brake discs and yaw drive flange.

DTU conducted an experimental investigation of the characterization of heat and noise generation problems related to wear in the braking pads. Surface characterization is a crucial step since current surface characterization techniques are not able to identify the cause of noise and heat generation problems. Yaw drive brake friction pad surfaces have been used to define and identify plateaus, which are the features generated in the braking process and linked therefore with noise and heat generation problems. A focus variation microscope and a 3D image metrology software, SPIP, have been used in the characterization process. The traceability of the measurements has been one of the main focus since it is essential to any metrological measurement and it has not been guaranteed in this kind of surface measurements. Confocal microscope, scanning electron microscope and stylus measurements, allowed comparing the surfaces. The characterisation model plateaus as those surfaces that are higher than certain height threshold, smoother than certain roughness threshold and larger than the dimension of debris. This type of analysis is novel to wind turbines and appears bringing a higher level of formalization of friction pad surface interpretation. In this qualitative stage of investigation, within project resources, it was possible proposing a model to map plateaus.

3.1.8 Achievements beyond the state of the art

A specific algorithm which allows the unification of profile measurements on gears considering different data spacing strategies was developed. This is a progress beyond the state of the art, because user software of different instrument manufacturers have varying data spacing strategies resulting in deviating values for required parameters.

3.2 Novel measurement standards and calibration procedures for drivetrain components

Drivetrain components for wind energy systems have to be manufactured precisely to ensure that they reach the desired lifetime of 20 years. Longevity of these components reduces costs of renewable energy and increases the reliability and efficiency of wind energy systems. Industry needs calibrated measurement standards to be able to ensure a quality management and achieve the demanded accuracies. Therefore, one aim of this project was to research and develop mandatory measurement standards and calibration procedures for establishing traceability and estimating measurement uncertainty of large drivetrain components. The standards developed are suitable for use in industrial settings.

3.2.1 Measurement standards to quantify the influence of probe measuring systems

Measurement standards to quantify the influence of probe measuring systems for drivetrain elements have been developed. The aim was to extend gear calibration capability with the partners and investigate the metrological differences between tactile and optical or scanning and single point probing. This task involved CMI and INRIM, who were establishing a gear calibration capability and PTB, NPL and NCL who provided supporting gear calibration and scanning measurement experience to complete the activities.

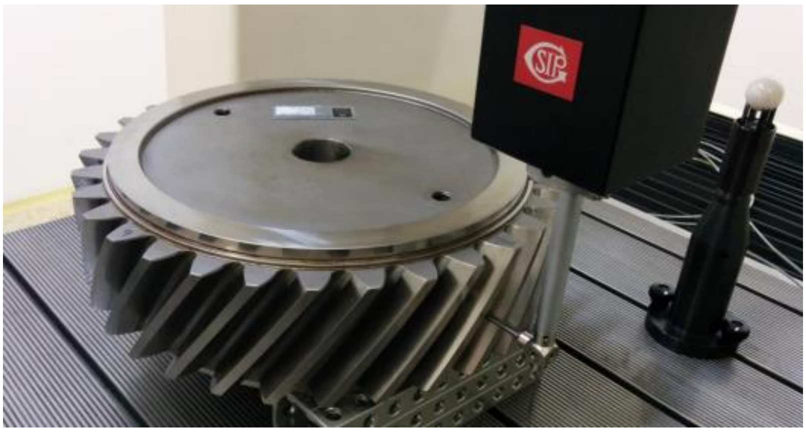


Figure 13: *Validation work for gear calibration at CMI using a SIP CMM.*

The new calibration facilities were validated by measurements on both existing and new gear measurement standards that enabled CMI to validate measurement uncertainty using a comparator method using a SIP CMM (see Figure 13). INRIM also extended their calibration capability to include the measurement of helical gears considering the most important measurands for profile, helix and pitch according the ISO 1328 series using a Leitz CMM (see Figure 14). Both laboratories successfully measured gears using a CMM. The work significantly extends the European gear calibration capability from 2 to 4 NMIs and DIs.

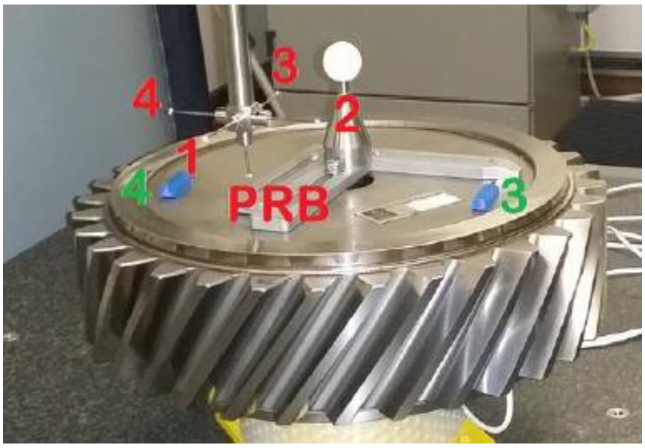


Figure 14: *Validation work for gear calibration at INRIM using a Leitz CMM.*

Many measuring machines use scanning probes for measuring large drivetrain components which vary between 60 and 650 mm in length. Industry commonly use probe diameters of 2 to 10 mm and we found that scanning speeds were typically between 1 and 30 mm/sec. The dynamic response of the probe systems is unknown and thus valuable and functionally important higher frequency deviations may not be properly measured with these arrangements. PTB used these specifications to develop involute based scanning measurement standards with specified undulations to quantify the measurement capability.

Two identical looking measurement standards were manufactured as illustrated in Figure 15. One standard has a nominally perfect involute curve and provided a reference geometry for the measuring machine performance and the second one has undulations with 3 different amplitudes and frequencies. Both were measured and analysed with a Fast Fourier Transformation (FFT) to extract the amplitude of the undulations and compare the results to reference values. The standards were used on several machines at a range of scanning speeds to quantify potential probe uncertainty contributions. The waviness standard can be used on both CMMs and GMIs with and without a rotary table.

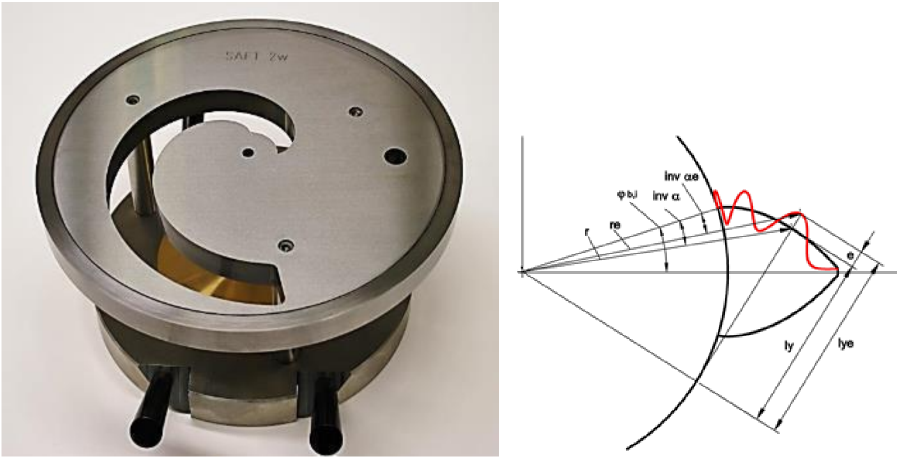


Figure 15: a. *Waviness measurement standard (left);*
b. sketch of the geometry which is used to quantify uncertainty contributions (right).

Further NPL developed and calibrated a gear root fillet measurement standard with support from NCL. The root fillet region of a gear tooth does not contact the mating gear during operation but the shape of the root can have a significant effect on the stress in the root region during operation, and thus the life of the gear. Root fillets are commonly of trochoidal form, and thus the radius around the partial arc varies. A novel root fillet standard was developed that provided both a single radius root fillet and a trochoidal root fillet form to assist with the assessment of GMI and CMM measurement capability (see Figure 16). It was designed to be measured on both CMMs and GMIs and also on general form measurement (optical and stylus) instruments for comparison purposes.

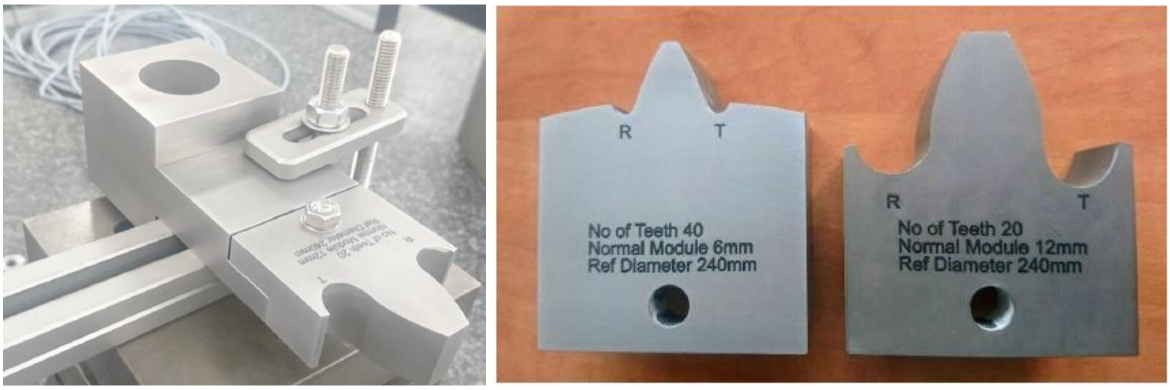


Figure 16: a. *Clamped example of root fillet radius measurement standard (left);*
b. Measurement standards for CMM and GMI validation with 6 mm or 12 mm normal module

A comparison of results with NCL shows good compatibility with the reference results provided by NPL and it is expected that this standard will be used for verifying industrial measurement capability as part of NCLs UKAS scope of accreditation.

3.2.2 Measurement standards to quantify the influence of the environmental conditions on measuring instruments and workpieces

The aim of this task was to investigate temperature distributions in a workpiece, dependent on the acclimatisation time. This was necessary because existing written standards consider only homogeneous temperature distributions.

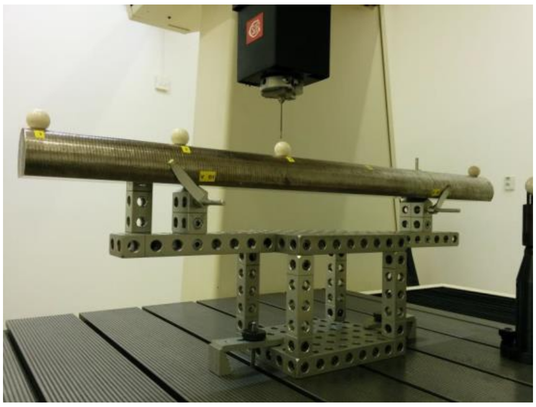
PTB with support from REG(RWTH) designed a large ring measurement standard (see Figure 17) which was provided by Schaeffler Technologies. It has an outer diameter of about 800 mm, an inner diameter of 600 mm and a height of 200 mm. It includes 12 bores at the outer side for Pt100 temperature sensors for information about temperature distributions inside the workpiece and further bores for ring bolts and feet upside and below.

Figure 17: *Large ring measurement standard*

PTB provided a calibration report about the measurement strategy for standard. The measurements were carried out at the industrial partner HexMet, due to capacities in instruments and time. The large ring has been measured with tactile probing inside the inner cylinder for the roundness at three axial positions, for the straightness at four generatrices and for the diameter at the central axial position.

The form deviation of the roundness was measured in a scanning modulus with ten repetitions for the three different heights. The diameter was also measured with ten repetitions via scanning as well as straightness and parallelism by single point probing. The achieved measurement uncertainty was maximal 3.0 µm for the mentioned parameters of this large measurement standard.

PTB provided a ball bar measurement standard made of Invar which will be used to quantify the performance of measurement instruments under harsh environmental shopfloor conditions. It has a length of about 780 mm and four ceramic balls at different positions (see Figure 18 left). The ceramic balls have a diameter of 22.0 mm. The yellow numbers enumerate the ball positions. The lower marks point the two Bessel points (the “V” is meant as an arrow) to have two supporting points for mounting the bar while measuring on a CMM.



CMI calibrated the ball bar and produced a calibration certificate. The clamping of the measurement standard is shown in Figure 18 right. The ball bar was clamped in marked Bessel points. Each ball was measured in five levels per five points and on the top, overall 26 measuring points. Then the least square sphere was calculated. Finally, the distances were evaluated.

Figure 18*:Clamping of the ball bar measurement standard*

3.2.3 Measurements standards to quantify the influence of the workpiece surface

Measurement standards have been developed to quantify the influence of the workpiece surface. The aim was to investigate the feasibility of using a ring segment for establishing the traceability of large diameter workpieces. INRIM designed the ring segment to be representative of bearing rings with a diameter > 1 m and with the ring segment size not exceeding the measurement volumes of the various measurement systems available at the JRP-Partners. This enabled the calibration of the ring segment at the NMI’s facilities. The design has been first submitted for review to NPL, then presented and agreed at a JRP meeting (Prague, 2015). The overall design including CAD files, has then been submitted to the manufacturer MG Marposs from Italy. Due to feasible shape of the grinding tool the inner groove has been made with a circular (not aspherical) shape (see Figure 19). After some measurements by the manufacturer the ring segment has been delivered first to NPL for the optical calibration and then to INRIM for the tactile calibration.

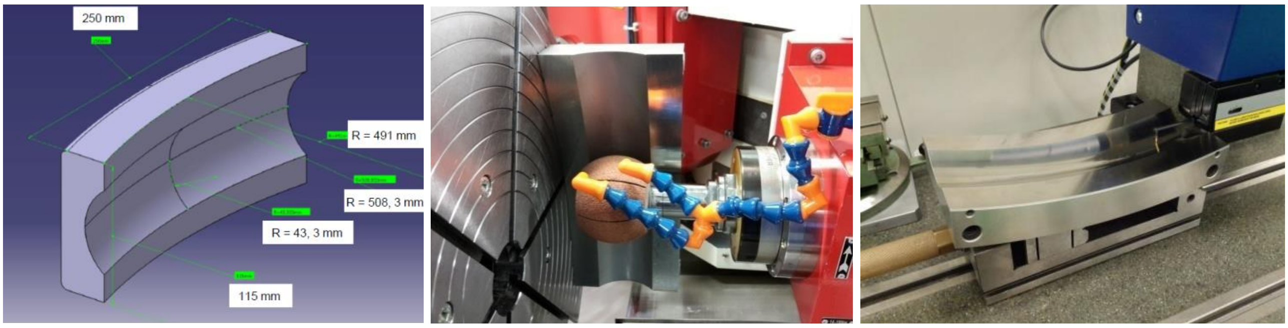


Figure 19*: a. Workpiece design (left); b. manufacturing - finishing grinding (centre); c. characterisation - surface texture by a stylus profilometer (right)*

The ring segment embodies two nominally coaxial features: A cylinder and a torus. Both the cylinder and the torus are highly partial features. The torus is partial along its ring and its tube, and the cylinder has an aperture of roughly 30° for a diameter of about 1 m.

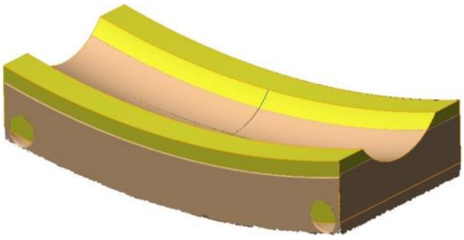


Figure 20*: CAD model and 3D optical scan of the ring segment overlaid on top of one another*

The ring segment has been calibrated with optical and tactile measurements at NPL and INRIM:

The optical measurements of the ring segment form show large differences from the nominal CAD model (see Figure 20). These are caused by the CAD model and the manufactured ring segment being physically different. Differences of approximately 8 mm are observed along the raceway edges. Along the central raceway, deviations of up to +250 µm are observed. Differences from the CAD model of measured cylinder features fitted to the two outer edges of the raceway are likely to be caused by the optical scanner measurement or the presence of the applied diffuse coating. Comparison of ball-bar measurements between the CMM and the 3D optical scanner, suggest an uncertainty of ±76 µm associated with the optical measurements. These measurements highlight that more work is required in 3D optical scanning metrology for the technique to become suitable for the form measurement of high precision artefacts, such as bearing components. In particular, greater understanding of the uncertainty components associated with 3D optical scanner measurements is required.
The tactile calibration has been performed with a CMM, with the ring segment mounted on the workpiece table and a configuration of the probing system with two styli. Calibration parameters were the form deviation of the inner cylinder, the coaxiality by torus and cylinder and the angles by the axes of torus and cylinder in the radial and tangential planes, according to the model for geometrical specification and verification (EN ISO 17450-1). Traceability of CMM along tangential direction and along radial direction have been obtained by means of two gauge blocks, whereas a straightness standard is used to correct the straightness error of the relevant portion of the CMM axis the ring sector is aligned to.

3.2.4 Measurement standards for performance analysis in industry

Further measurement standards have been developed for performance analysis in industry.

PTB provided and calibrated a large ring gear measurement standard with an outer diameter of about 2 m (see Figure 21 a). It embodies three different internal and external gears each one with helix angles of 0°, 10° and 20°. A matching large external planet gear measurement standard was manufactured (see Figure 21 b). Both have a facewidth of about 420 mm.

Figure 21: *a. large internal gear measurement standard (left);*
b. the external planet gear measurement standard (right)

Further relevant for the calibration of measurement standards are gauge blocks. They are mandatory for many dimensional measurement tasks, but each time a specific length is necessary. Therefore, the availability as well as costs are a problem. Because of those reasons an interferometric step gauge (ISG) for CMM verification was developed by VTT. The scheme and its implementation of the ISG are shown in Figure 22 a and b.

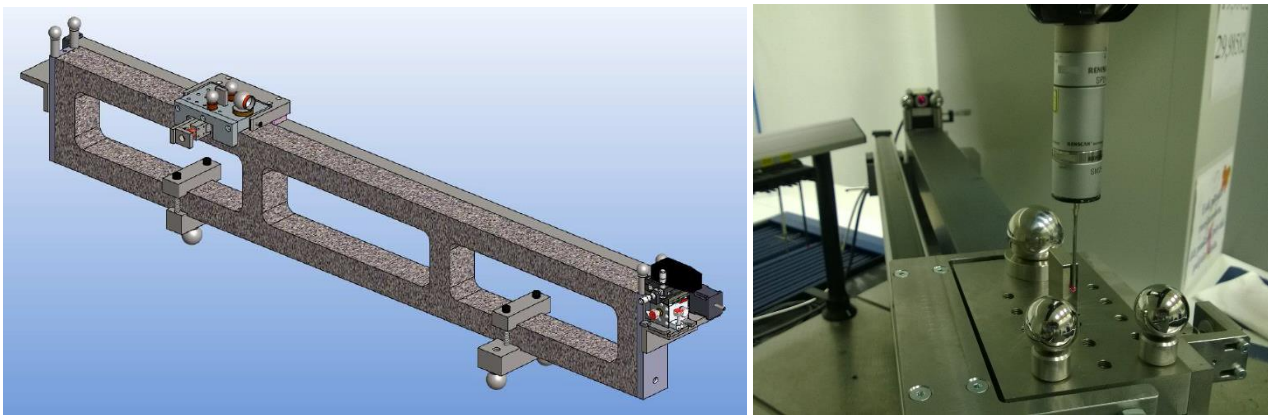


Figure 22: *a. Schematic drawing of the developed ISG (left);*
b. Implementation of the ISG inside a measurement volume (right).

The idea was to have a moving carriage with surfaces for tactile probing connected to an interferometric reference. The main surface to probe is a gauge block. The coordinate system of the CMM is aligned along the laser beam before measurements are taken. From the deviation between results of CMM and ISG the errors of the CMM can be concluded at an uncertainty of 0.5 µm, which is a satisfying uncertainty for performance testing in industry. The developed interferometric step gauge has the functionality of a traditional step gauge but also the ability for arbitrary steps. Tests in laboratories have shown the possibility for verification of length measurements on a CMM with an accuracy comparable to the traditional step gauge. Tests in an industrial environment show the usability as a transportable and universal reference for length measurements.

3.2.5 Achievements beyond the state of the art

The project went beyond the state of the art by providing the first calibrated measurement standards for drivetrain components. The measurement standards are based on industrial demands and are developed for bearings, and gears. They can be used to address the most important measurands for size, form, waviness and roughness. All developed standards are available for hire by industry from the NMIs. Further a portable ISG can be used for universal length measurements in industrial manufacturing places.

3.3 Measurement uncertainty under typical conditions in industry

High costs associated with the repair of drivetrain components and also lost power generation due to unplanned maintenance is a common problem for renewable energy suppliers. To improve the reliability of drivetrain components, besides having calibrated measurement standards, it is also necessary to have measurement procedures and to determine the measurement uncertainty. The aim was to establish and quantify the key additional sources of uncertainty that influence industrial measurement capability, with particular reference to environmental effects. A GPG for industry was provided.

3.3.1 Effect of temperature variation

The aim was to develop a reliable strategy for quantifying the influence of workpiece temperature variation in large diameter workpieces and to provide recommendations for industry.

The shop floor and laboratory conditions may vary under environmental influences, as for example the surrounding temperature, which in bad cases can vary up to 15 – 17 K. This kind of temperature variation causes stress on workpieces as the temperature inside will assimilate in a slow and irregulate way. When exact geometrical parameters, such as the size, form or roughness are a matter of interest, one has to know when the workpieces are acclimatised completely. Measurements during an inhomogeneous temperature distribution will neither be corrected nor reproducible. Especially in the industry, the acclimatisation time for temperature homogeneity should be optimized to enable a reduction of the fabrication and control time, which means a gain of productivity.

First, recommendations for thermalisation times for workpieces such as involute gear components, bearings, shafts and brakes typically encountered in industry have been made. Complex geometries have been simplified to simple geometries, so it is easier to compute temperature distributions and geometry changes over time. Measurement conditions and temperature measurement procedures have been researched. It was decided to measure the temperature inside of a workpiece over a couple of days every two minutes. The measurements should take place in a climate chamber and a temperature range of 15 – 30 °C should be applied. This research also included a list of questions to be considered for the placement of temperature sensors on large workpieces such as use of a rotary table, clamping and kinematic of the CMM. These points have to be considered anew in each situation.

Test conditions have been specified by PTB and REG(RWTH) and a test matrix has been designed to investigate the thermalisation process for the ring measurement standard and a large involute gear measurement standard (see Figure 23) provided by PTB. The test investigates the geometrical deformation of the measurements standards under thermal load. The standards will be placed on a CMM which stays in the climate chamber at REG(RWTH). This was the only available facility to have control about the environmental temperature. At the beginning of the test, the measurement standards will start at a constant and homogeneous temperature of approximately 20 °C to have a reference measurement. The further thermalisation starts at 15 °C and will rise up to 30 °C in steps of each 2.5 K, 5 K and 10 K upwards and downwards. After every temperature load and a sufficient time interval (of about twelve hours or more), the geometrical deformation will be measured on the coordinate measurement machine. Measurement parameters are slope deviations for profile and helix measurements on gears, diameter and form for ring measurements. The temperature will be recorded every 2 - 5 minutes.

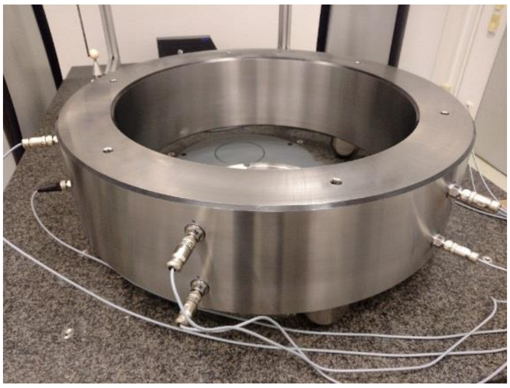



Figure 23*: a. Ring measurement standard (left); b. large involute gear measurement standard (right)*

All form and diameter parameters were influenced by temperature changes of 2.5 K or more. The trend of the gear parameters at temperature changes followed the theoretical considerations. Mainly the slope helix deviation was influenced by temperature changes of 5 K or 10 K. The measurement uncertainty increased in both cases with increasing temperature difference to 20 °C which is the reference temperature.

Guidance for industry has been prepared. Suggestions for thermalisation times of large gear and large ring measurement standards based on the measurements in the climate chamber described above have been made and summarised in a GPG. Accredited laboratories and other laboratories with the demand of high accuracy are respect the reference temperature of 20°C. Due to requirements of accurate measurements and small measurement uncertainties, not only the environmental temperature is important, but also the temperature of the measurement standard. Therefore, a homogeneous temperature distribution inside of a large workpiece is important. The thermalisation process is more time-consuming than the process of small workpieces due to its material volume. A large workpiece is not easily stored inside the laboratory without huge effort due to its weight and disadvantages as storage space. The adjustment of temperature is a time-consuming factor. A pre-thermalisation-period within controlled climate conditions (close to the conditions of the laboratory environment, if possible) is recommendable. A temperature monitoring of the measurements volume and the workpiece surface are mandatory. Further control of the inner workpiece temperature is preferable, if possible. The sensors have to be calibrated and their position must be equally distributed. For the monitoring of the laboratory and measurement volume environment at least eight sensors should be positioned. The workpiece should be equipped with at least eight inner and four outer sensors. In the described test measurements, the time-period for the simultaneous adjustment of environment and workpiece temperatures is necessary for at least 30 hours inside the measurement volume, if the temperature difference of the workpiece temperature and the environmental temperature is up to 10 K. In contrast to the test measurements a pre-thermalised workpiece has a slightly (smaller than 10 K) different temperature than the environment of the laboratory. Therefore, a comparison to the test measurements is difficult. Experiences due to a national intercomparison of a large ring gear measurement standard (2 m in diameter and 0.2 m thickness of material) show a storage of 24 hours inside the measurement volume is acceptable to reach a homogeneous temperature distribution. Further this value is close to theoretical considerations.

3.3.2 Effect of other significant measurement uncertainty contributors

Significant contributors to the measurement uncertainty of large workpieces are especially influences of the gravity, which have a different effect depending on the clamping situation. Therefore, one aim of the project was the investigation of typical clamping situations and their effect on the measurements. For this purpose, VTT in cooperation with Moventas investigated endplates, the largest part of planetary gearboxes.

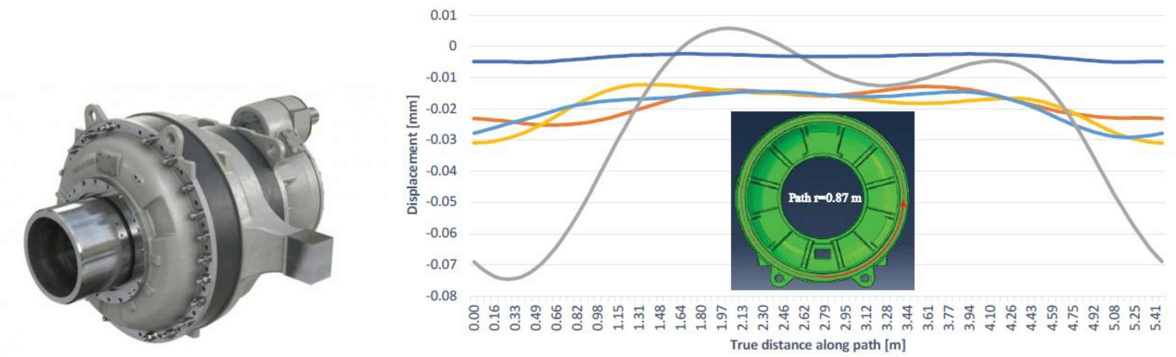


Figure 24: *a. Endplate as largest component of gearbox (left);*
b. Results for simulated flatness error of endplate (curves represent different clamping situations; right).

The endplate, considered for test measurements, has a diameter of about two meters and a weight of 700 kg. Different clamping situations were discussed with Moventas, who have the facilities, but not the required environment and time for such measurements. Therefore, it was decided to analyse selected endplates with FE-method. The FE analysis done by Aalto showed that the worst case for support would result in a flatness error of 89 µm. If supports are placed with 120° spacing, the maximum error is between 10 µm – 20 µm. If more than three supports are used the combined gravity and support effects results in considerable deformations. Actually, it is possible to reach any form as the height of the supports vary.

Although the measurement result for flatness is very sensitive to changes for the supports it is still a functioning test for an acceptable flatness of the endplate before assembly. It can be concluded that gravity effects for endplates are large compared to typical geometrical requirements of drivetrain components. This result was expected as it was already expressed during discussions with industry. However, this study gives further understanding of these effects.

Further drivetrain components are effected by gravity due to its large dimensions. One aim was to quantify these significant sources of uncertainty in large workpiece measurements and propose guidelines for good measurement practice. Work involved the close collaboration of VTT, PTB, DTU, INRIM, REG(Aalto), HexMet, MDM, Moventas, Zeiss and other industrial partners to establish how workpieces are mounted on machine tools and measurement platforms and how they are located when installed for service.

The results from FEA modelling carried out by VTT, INRIM and CMI of typical workpieces from large renewable drivetrains showed that deflections caused by clamping or gravity can vary between 0.1 µm and 90 µm, depending on the workpiece geometry (both size and symmetry) and the location strategy (number of support features) and clamping effects. Furthermore, the effect on measurement uncertainty depends on both the influence of the workpiece datum axes definition and its effects on the measurand. Feedback from industry suggested that clamping effects were considered and minimised but gravity effects were not quantified.

Modelling deflections using FEA is not easy and the results from any model require validation by measurement. General deflection models using FEA can be arranged to define the deflections and direction cosines of datum surfaces and measured surfaces but this is very time consuming and difficult to implement. A GPG on minimising the effects from gravity and clamping was prepared based on FEA modelling with an analytical method described to estimate workpiece deflection effects on the measurands (see Figure 25).

The GPG

- Discusses location fixtures and FEA modelling of deflections
- Discusses how the measurement strategy influences the effect of deflection due to gravity
- Discusses how FEA deflection data from simple features (circles and planes) can be extracted for analysis
- Recommends how to use these deflection values to estimate the deflected shape of the measurand
- Shows simple methods to estimate measurement uncertainty
- Provides a worked example application for gear helix measurement which estimates an increase in measurement uncertainty from ±1.9 µm to ±2.8 µm when gravity effects are considered.

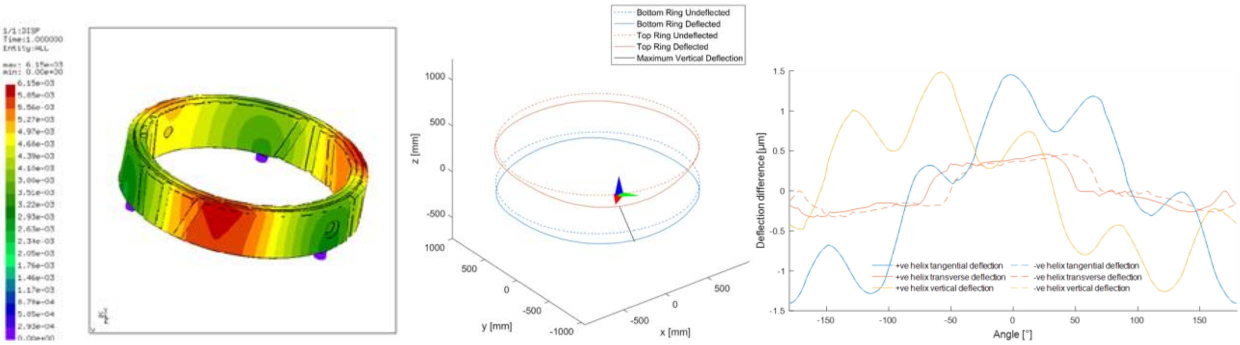


Figure 25: *FEA model, extracted feature deflections converted to measurand deviations on a helical gear*

<u>3.3.3 Achievements beyond the state of the art</u>

Experimental measurements were carried out to determine the measurement uncertainty contribution of temperature variation inside workpieces. The tests were conducted in a special setup of a CMM in a climate chamber. Due to this controlled and changeable environment, it was possible to investigate the influence of the contribution. A GPG on thermalisation times for large workpieces has been provided for industry. A further GPG discusses gravity and clamping influences to broaden the knowledge of these effects.

3.4 Virtual measuring process for traceably measuring large drivetrain components

One aim of the project was the determination of measurement uncertainty for measurements of large workpieces considering the challenges due to the large dimension and the respective influences like the weight, clamping, temperature effects and thermalisation times. Within the determination of the measurement uncertainty the parameter becomes reliable. This is an important fact for the quality management including reference measurements, verification measurements and production with less failure rates. Within the project, first steps were conducted to develop traceability routes for measuring large drivetrain components (diameter > 1.0 m) following the GUM simulation directives to establish a virtual measuring process (VMP) method for large CMMs in the future. The aim was to develop a VMP including all significant uncertainty contributors from the workpiece, environment, measuring strategy and measuring instrument.

Application of VMP for traceable measurement of drivetrain components is considered to be an important project goal. Virtual approach offers a possibility to simulate the influence of errors caused by temperature and gravity on the measurement uncertainty contributions. It is possible to estimate an influence of temperature or gravity and separate it from the measurement results when measuring large drivetrain components.

The problem of non-homogenously distributed temperatures inside the workpiece material is well-known in engineering sciences. A solution getting along without any powerful and cost-intensive finite element analysis (FEA) might be helpful. Therefore, an interpolation method named Kriging was expanded by PTB to a three-dimensional calculation, investigated, tested and compared to FEA as well as conducted measurements. One advantage of Kriging method is the generation of information about variance values to each of the calculated interpolated temperature values. The software tool (see Figure 26) needs dimensional data for an option of workpiece geometry (cuboid, cylinder or cylinder segment) and point-wise temperature information from the workpiece surface and the inner material temperature values. Inside the mathematical progress of the software one best-fit algorithm is chosen and extensive temperature distribution is calculated due to a specified grid. Afterwards a graphical representation of the distribution is possible regarding various vertical and horizontal or further chosen intersections. Test parameters were tested and real measurement results were evaluated (see Figure 26). Therefore two measurement standards with large dimensions (bearing ring with a diameter of 600 mm and a large gear segment with a radius of 500 mm) were used.

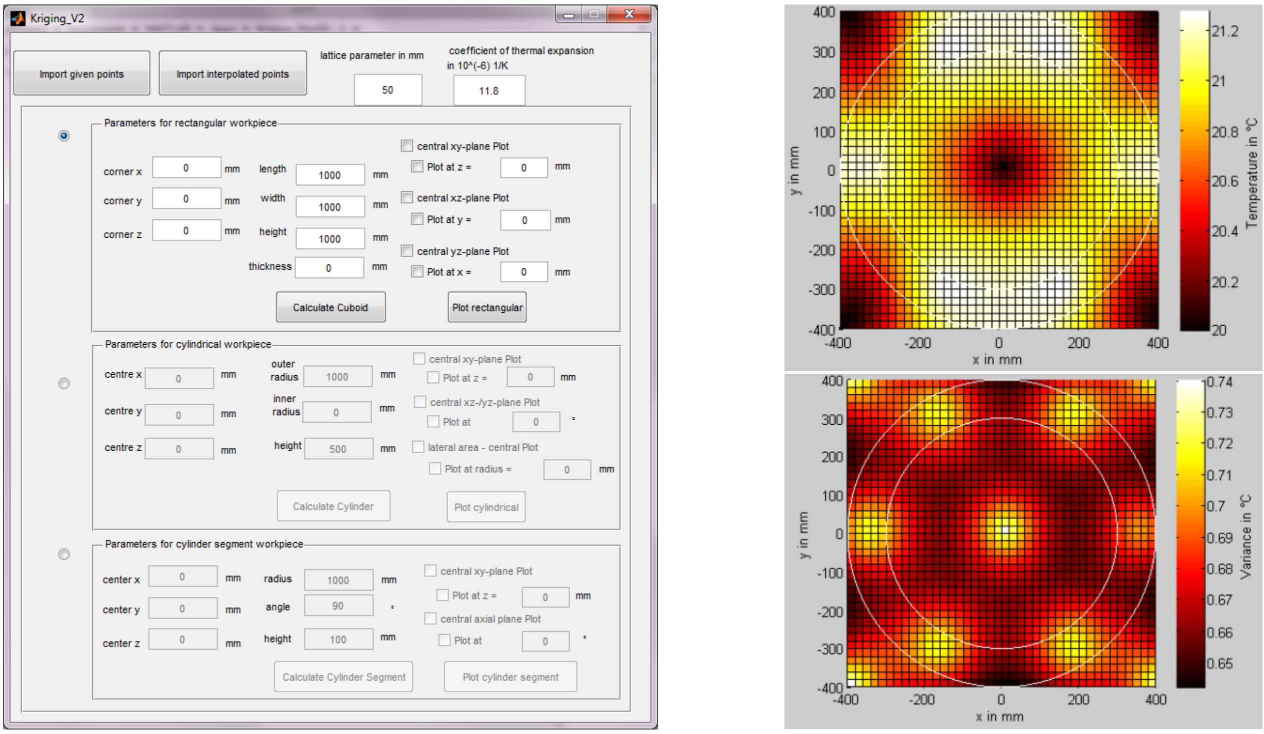


Figure 26: *a. Graphical user interface of Kriging interpolation tool (left);*
b. Diagram showing interpolation results on temperature and variance values (right)

As a result of the tests, one optimization was considered and applied by PTB. However, the evaluation shows that the software works without problems. Comparing the results with measurement results or FEA, the accuracy of the results seems to be less than expected. This occurs probably due to the simple mathematic, which is used. Further due to the fact, that the amount of temperature sensors, which are distributed inside the workpiece is small and its distribution is very symmetrically, which has consequences on the algebraic calculations. In terms of temperature distributions, the software offers a low-cost, fast and simple way to get a graphic response. In the case of further evaluations with specific values or an accurate point-wise temperature value, the powerful FEA is probably still preferable.

Further the influence on the measurement uncertainty of surface form and roughness characteristics is important. Large components are often measured with a CMM, instead of specific instruments for form or roughness measurements. Due to the larger probing tips or balls and the smaller sampling rates the respective uncertainty influences increase. The impact of these two influences were investigated based on profile and helix measurement data of gears of varying roughness characteristics due to different manufacturing processes by Monte-Carlo simulations. The results were shown graphically (see Figure 27) and numerically. Furthermore, a comparison with conducted measurements on the large ring measurement standard was done.

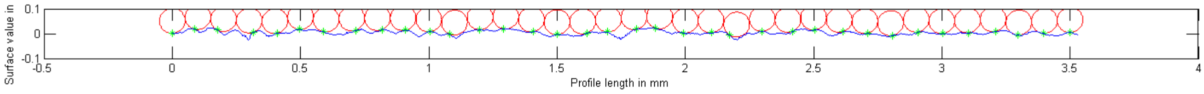


Figure 27: *Graphical example for tactile probing on a profile measurement data set*

Different mathematical approaches have been applied during the development, application and validation of VMP, especially the development of mathematical model of the measured component as an application of FEA.

Firstly, CMI described necessary input parameters to apply VMP by means of FEA simulation. Secondly, 3D geometry, boundary conditions, mechanical and material properties for selected drivetrain measurement standards have been defined. Finally, FEA model for simulation of temperature and gravity influence when measuring not only the concrete geometry but also any similar component has been accomplished.

Application of FEA for VMP and simulation of temperature and gravity influence for measurement of large ring measurement standard has been successfully performed. Individual contributions to the measurement uncertainty have been evaluated from the datasets obtained by simulation. Example of the deviations of the inner diameter 600 mm in dependence on increasing temperature is given in Table 2.

Table 2: *Temperature dependence of inner diameter deviation*

Temperature in °C	22.5	25.0	27.5	30.0
Diameter deviation in µm	17	35	52	70

Example of measurement task for simulation of gravity influence is depicted in left. Measurement results in form of colour map of deviations are shown in Figure 28 right. This output is intended for estimation of error caused by gravity and for localization of maximal displacements of nodes. It is possible to determine the value and position of nodal maximum displacement after simulation with respect to the reference ones given by theoretical CAD model.

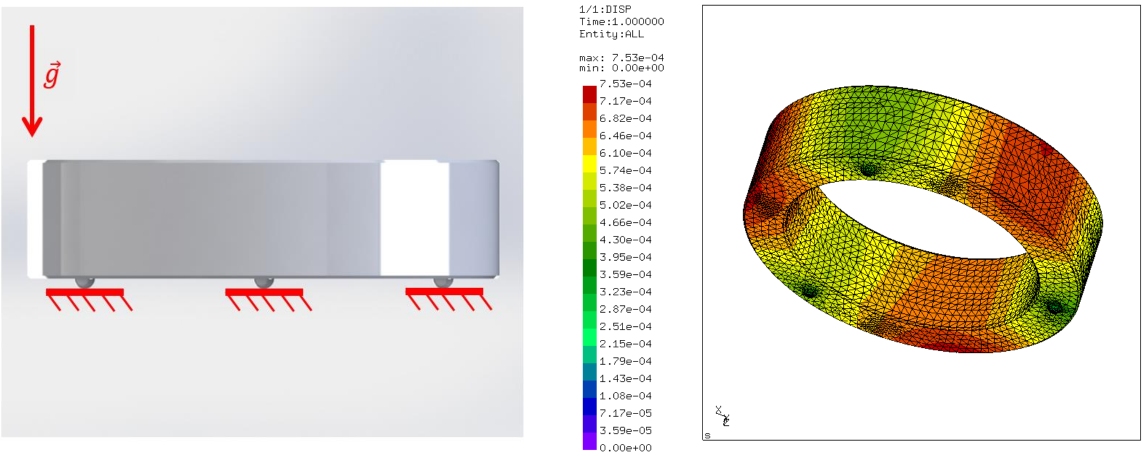


Figure 28: a. *Large ring measurement standard standing on three supports (left);*
b. Nodal displacements of large ring measurement standard due to gravity (right)

The work has resulted in a huge number of outputs in form of datasets. These datasets have been evaluated numerically or graphically. The simulation of temperature and gravity influence on large ring has been successfully performed. The obtained results can be applied in virtual measurement of component surface geometry with respect to the reference CAD model. The developed method can be extended to other large drivetrain components.

The results obtained by FEA simulation has been validated to obtain feedback and propose corresponding possible improvement of VMP. The necessary feedback has been realized in cooperation with project partners. The resulting datasets obtained by simulations have been compared and validated with the real measurement. The accuracy of errors estimation reached by simulation has been determined.

Three models have been developed within the project: CFD model for acclimatisation time estimation, FEA model for virtual measurement of geometrical deformation due to gravity, FEA model for virtual measurement of geometrical deformation due to temperature. The method VMP developed in CMI has been successfully validated.

VTT discussed thermal and elastic geometrical deformation of gearbox parts together with the industrial collaborator Moventas and Aalto. As a result of the discussions a large end-plate of a planetary gearbox was selected for FE-analysis of thermal distributions. The CAD model of the end-plate was kindly given to Aalto from Moventas. VTT supported the FEA of thermal analysis and geometric deformation FEA done at Aalto. The FE-model and its input parameters and results were validated by REG(Aalto) and VTT.

The work and results served as input for the VMP model developed at VTT. This model was written using Matlab script language. The work also served as input for an Excel template and Android App for uncertainty evaluation for diameter measurements created later in the project.

<u>3.4.1 Achievements beyond the state of the art</u>

On the basis of CAD modules and developed numerical models, it was possible to simulate the significant error influences for measurements of large components. These investigations consider surface characteristics, temperature variations and deformations caused by gravity and clamping.

3.5 Validation of measurement strategies and determination of achievable measurement uncertainty in industrial environment

The developed measurement standards were tested in industrial environment and the performance was critically analysed compared to traditional standards, such as gauge blocks and step gauges for example. The JRP partners Zeiss, HexMet, Mitutoyo, and stakeholders Moventas and ThyssenKrupp tested the standards due to their possibility to use measurement facilities. Further measurements were conducted at INRIM, VTT and CMI. This validation includes measurement strategies for shafts, bearings and gears from drivetrain components in an industrial environment and the achievable measurement uncertainty, which was determined.

This led to the production of a comparison protocol, a report on the use of 3D form evaluation methods for gears, a report on the use of 3D surface measurement data in gear Tooth Contact Analysis, a comparison of a new bearing thickness measuring machine with a CMM and four Measurement GPG to disseminate the expertise developed within the project. These outputs are summarized below.

An inter-laboratory comparison of measurements of the large internal gear measurement standard and the external planet gear measurement standard was conducted (see Figure 21). CMI, with support of PTB, prepared a technical protocol including descriptions of the standards (containing the type of gear teeth), the required mounting technique, the measurands (gear parameters), the measurement strategy and alignment techniques (including the minimum number of measurement points, filtering techniques and the probe diameter), measurement conditions and an example of how to report the results.

The measurement uncertainty results achieved during gear pair comparison by industrial JRP-Partners and NMIs have been reported by CMI. Measurement have been done according to the technical protocol provided. Gear profile and helix parameters were measured and evaluated from three different types of gaps each of them with left and right flanks. All parameters were measured on the large internal gear measurement standard and external planet gear measurement standard provided by PTB. Example of graphical profile comparison is given in Figure 29.

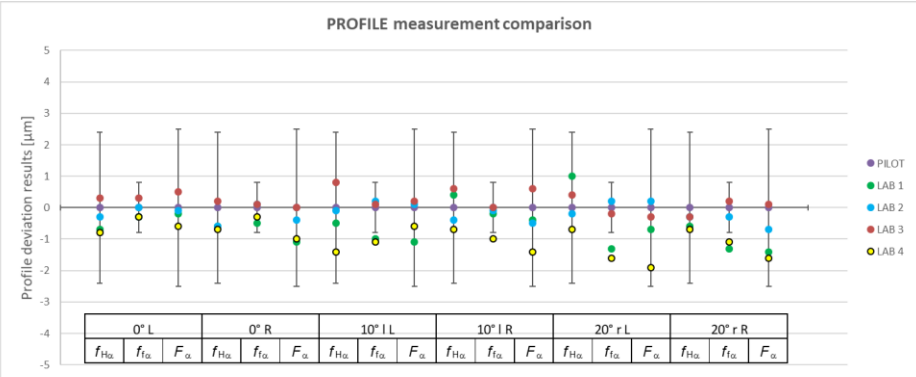


Figure 29: *Profile measurement comparison*

Consequently, achieved measurement uncertainty has been evaluated. Results of measurement uncertainty have been presented in the form of graphs and tables.

PTB, in cooperation with NCL, developed and investigated 3D evaluation methods to see how they differ in comparison to established 2D evaluation strategies. Measurements of left and right flanks of two different involute gear standards, with varying helix angles, have been evaluated using both established strategies and the new 3D strategy. For 3D evaluation, a large amount of measurement points across each flank surface are necessary. The points were recorded using multiple 2D profile scans. For the first of two strategies, profiles at three axial positions (mid-facewidth and at the start and end of the helix evaluation length) and one helix at the V-cylinder have been measured. For the second strategy 40 profile measurements at different heights equally spaced along the facewidth were performed, with the first and last profile at start and end of the helix evaluation length. One helix at the V-cylinder has been measured.

The 2D and 3D evaluations of both datasets (from three industrial partners) have been compared for the two measuring strategies by evaluating the differences between the calculated parameters. The maximum differences in profile parameters between 2D and 3D were much higher using 3 profile measurements for evaluation than using 40 profile measurements in most cases. For helix parameters, no trend between the two strategies could be observed. Possible explanations for this might be that there was only one helix measurement to compare, but there were several profile measurements, or that the workpiece manufacturing method generates consistent characteristic helix deviations.

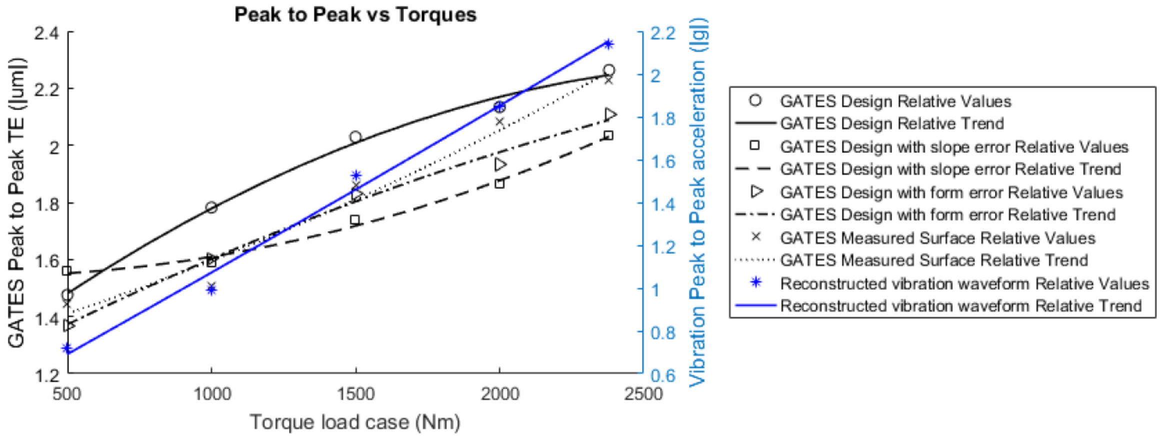


Figure 30: *Vibration data and transmission error predictions for a range of torques in the test gearbox*

3D measurement and evaluation methods provide more characterisation data on the actual gear surface but how do you use it? In this project, NCL investigated the feasibility of using measured 3D surface data in a Tooth Contact Analysis (TCA) software used by designers to optimise the macro and micro geometry of gears. An optimised measurement strategy was developed based on functional performance characteristics of noise and vibration was developed using only 3 profiles and 3 helix measurements for each of the mating gears. A two-stage form removal and interpolation method, which was developed in this project, was applied to simulate the tooth surface of a sample test gear pair. The result demonstrated the feasibility of using measured data to simulate GPS compatible measurement procedures linking measurement evaluation to gear performance.

The results were confirmed by measuring the vibration levels of a test gearbox at a range of torque levels to correlate the TCA transmission error (TE) prediction with measured data. Figure 30 shows that the linear relationship of the measured vibration levels was only predicted using measured surface data in the TCA.

Large bearings are important elements in industrial machines, especially in the field of power generation where they are used extensively. One of the factors which affects the quality of a bearing is the thickness deviation of the inner and outer rings, because these elements are comparatively thin compared with the housing and shaft that they are mounted with. This difference in thickness means that the rings will conform to the shape of the adjacent parts. Thickness measurements of rings has been performed by VTT and REG(Aalto) using both the LSBET device (see Figure 31) evaluated in this project and a CMM. The comparison showed that the agreement between the two devices is better than 0.2 µm for filtered data.

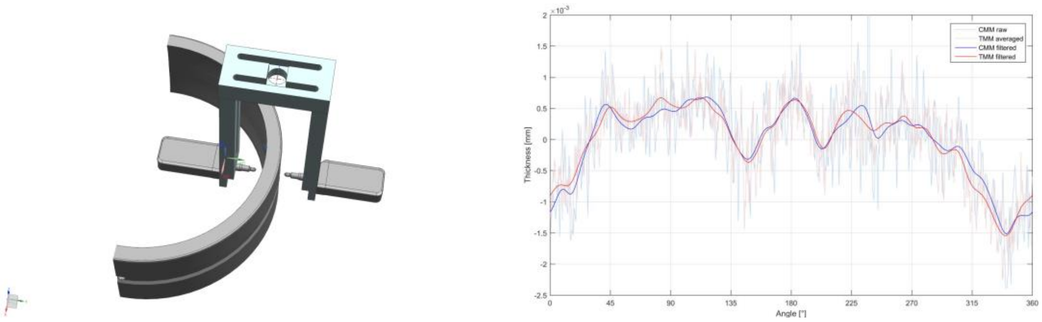


Figure 31: *a. Model of LSBET device (left);*
b. Comparison of raw and filtered data of bearing thickness measured with LSBET (TMM) and CMM (right)

The influence of data spacing on involute profile evaluation was investigated by PTB and NCL. Two types of data spacing have been applied: Roll length equidistant data spacing (see Figure 32) and radius equidistant data spacing (see Figure 33). An involute gear measurement standard with certain profile modifications provided by PTB was used for the measurements. The measurements have been carried out by three industrial partners and the datasets have been evaluated with software developed in this project by NCL. According to different setting options of the CMM controller it was not always possible for the partners to measure both required strategies. In these cases, the sets of radially equidistant data were resampled to maintain roll length equidistant spacing or vice versa.

The results were analysed for each partner separately. The datasets have been evaluated with and without including modifications. In summary, small differences of < 1 µm for the total profile deviation and up to 9.1 µm for the form deviation have been observed. The largest effect of up to 19.0 µm was on the slope deviation. This is significant, since the slope deviation is a functional parameter which effects noise and vibration amongst other operating conditions.

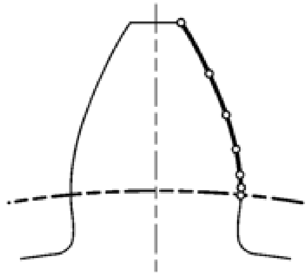


Figure 32*: Roll length equidistant*

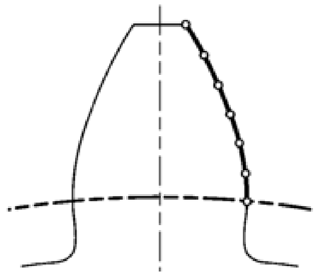


Figure 33*: Radius equidistant*

A model for estimating the measurement uncertainty contribution caused by different scanning parameters when measuring profile characteristics of involute gear by freeform scanning technology has been developed by CMI. The influence of different scanning parameters (5 different scanning speeds within the range of the machine specification, 3 different workpiece orientations inside the measurement volume and 3 different stylus lengths) has been investigated. The measurement has been carried out on a SIP CMM5 by using the PTB internal involute scanning measurement standard (see Figure 34 left). Mathematical model for estimation of contribution to the measurement uncertainty caused by different scanning parameters has been developed and applied on measurement results. The mathematical model is described by function of two variables (see Figure 34 right). Based on this mathematical model, it is possible to determine recommended scanning ranges, i.e. position of the measured workpiece, scanning speed and stylus length.

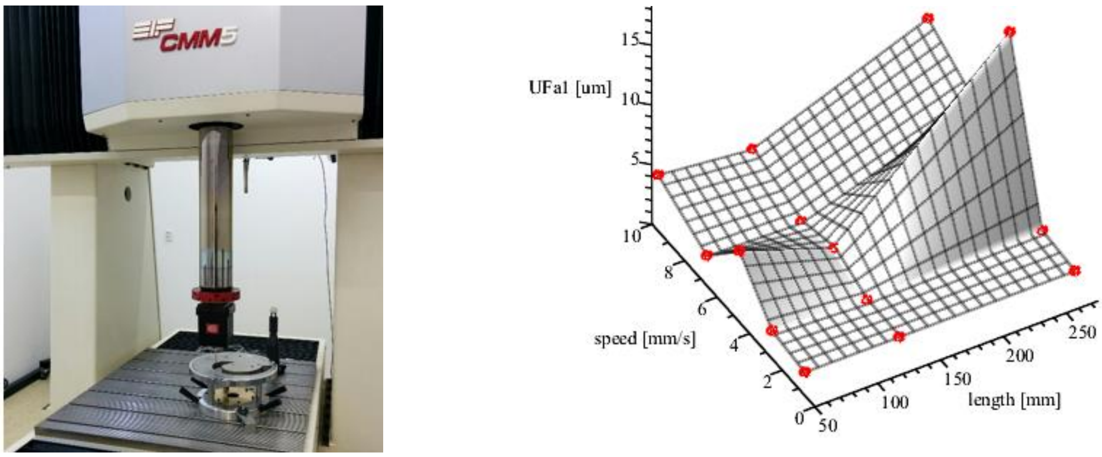


Figure 34: a. *Measurement of standard (left);*
b. mathematical model of contribution to the measurement uncertainty $U_{F\alpha}$ *for external profile (right)*

Freeform scanning on an internal involute profile measurement standard designed and manufactured by PTB has been conducted by INRIM. First evaluations on measurement data evidenced the presence of unsuspected effects as a possible eccentricity and some possible thermal effects not deeply investigated, yet. Results after eccentricity reduction, suggest a not very significant trend of the profile slope deviation $f_{H\alpha}$ as a function of scanning speed or stylus length; variation of $f_{H\alpha}$ values at different orientations seems to suggest a not adequate evaluation of secondary effect rather than a real effect of orientation on measurement result. About profile total $\boldsymbol{F}_{\alpha}$, and form deviations $\boldsymbol{f}_{f\alpha}$ it is not possible to infer a significant trend as function of scanning speed, orientation or stylus length; limited differences seem to suggest a modest worsening of performances but magnitudes of these differences do not allow to define a clear trend. On the contrary, spectral analysis of data, suggest high and stable performances of the machine. Results show that evaluations of wavelength and amplitude are very repeatable and that they are not influenced by workpiece orientation, scanning speed or stylus length. In particular, negligible variations in evaluation of wavelength and amplitude as function of orientations and stylus length could mean respectively an adequate compensation of machine geometrical error and a valid probing system qualification, whereas the analysis in term of scanning speed, in the range considered with respect to the waviness investigated, allows to confirm the maintenance of these high performances also at the most critical measuring conditions. A first evaluation of uncertainty sources and of their influence on the overall uncertainty value has been implemented. Result of this analysis evidenced the presence of a significant influence of the algorithm of analysis that, theoretically, should be a negligible source; this result is due to the empirical evaluation model of eccentricity effect that should had not to be present according to the initial design of the standard.

For the measurements of large gears under shop floor conditions, the influence of the temperature is mainly important for the profile and helix slope deviation. Those parameters are directly influenced due to the extension of the workpiece comparing its form at the reference temperature of 20 °C. The temperature distribution inside the workpiece is mandatory information for the investigation of the parameters characteristic regarding the temperature.

Therefore, simulations using the developed FE-analysis dataset and the Kriging interpolation method are used to interpolate a spatial distribution of the temperature derived from punctual measured data. On the basis of a temperature dataset close to shop floor conditions of 23 °C with nearly homogeneous values, which was measured in the climate chamber only available at REG(RWTH), the distribution and its influence on the workpiece extension was calculated by PTB. Due to theoretical investigation of this influence the slope deviation value as well as the measurement uncertainty estimation were determined. The results are in the same dimension as the results of real measurements at temperature test settings.

The achievable measurement uncertainty for shafts under shop floor conditions was investigated by VTT. The main property of a shaft is diameter. Variations of diameter are related to run-out, roundness and cylindricity. There are also other geometric properties for shafts but as shafts usually rotate are these radial measurements the most critical. The task specific uncertainties depend on instrument, part to be measured and the conditions. Uncertainties in the range of 5 µm to 50 µm are typical in shop floor conditions, but both smaller or much higher uncertainties are possible depending on instrument, part and environment. The following numbers and data are based on visits and discussions at the collaborator Moventas. Using a CMM an expanded uncertainty of 7.8 µm is achievable when measuring a diameter of 1000 mm and for a diameter of 500 mm an uncertainty of 7.7 µm has been evaluated at shop floor measurements.

As a part of the work both an Excel template and an Android Application for tablets were developed by VTT for two point measurements using micrometres. The Excel template and App consider the temperatures of the object, measuring instrument, and used reference either by temperature measurements or by measuring their magnitude based on experience. In addition, thermal factors and uncertainties of the measuring instrument and zeroing normal are known or evaluated.

Four GPGs (NPL, PTB and VTT) were produced, wherein each method was tested extensively, often with support from industrial or other JRP partners. All of the guides are available on the ENG56 website (https://www.ptb.de/emrp/eng56-impact.html) and cover:

- Surface texture measurements of gear surfaces using stylus instruments.
- Surface parameter measurement strategies for form and diameter measurements for large bearings.
- Measurement of the surface texture of large roller bearings.
- Form and diameter measurements for large shafts.

3.5.1 Achievements beyond the state of the art

After validation measurements, the GPGs containing measurement strategies for gears, bearings and shafts were finalised and are available for industry. This information will be used for establishing new calibration services for gears. A novel thickness measurement device was validated in comparison to a common CMM. The results are comparable and the new device has the advantage of portability.

3.6 Summary

This project went beyond the state of the art by developing new approaches delivering measurement standards and procedures for providing traceability to the SI by enabling the reliable estimation of a quantitative measurement uncertainty as demanded in international guidelines. The outcome delivered robust measurement standards optimised for industrial use.

New measurement capabilities:

- Extension of machine versatility by novel tactile microprobe with 120 µm diameter successfully integrated into a commercial GMI
- TCA models to perform acceptance tests to predict gear performance and develop GPS compatible measurement strategies
- Significant extension of the European gear calibration capability from 2 to 4 NMIs and DIs
- Excel template and Android Application for tablets developed for two point measurements using micrometres providing the possibility for calculating measurement uncertainties

New reference materials, reference methods and procedures developed:

- Development and calibration of several new measurement standards for large rings (optical and tactile) and large gears for task-specific investigations that are available for hire by industry
- Six GPGs for gears, bearings and shafts regarding surface characteristics, form measurements and thermalisation times available for free to support the calibration sector and industry
- Transportable ISG for universal length measurement tasks for industry after request
- Software tool for a graphical representation of temperature distribution inside a workpiece available after request

Important new knowledge developed in the project:

- Influence of temperature variation on measurement uncertainty for gear and bearing parameters
- Experimental investigation of heat and noise generation problems related to wear in the braking pads
- Broadened knowledge of significant influences of measurement uncertainties by using the developed VMP-models
- Algorithm unifying data spacing strategies conforming to standards

4 Actual and potential impact

4.1 Metrology achievements

Traceability of large drivetrain component measurements for renewable energy systems remains a highly challenging field. This project developed measurement standards and strategies for traceable measurements of large drivetrain components. Quantification of measurement uncertainties were successfully met by the project, including temperature measurement uncertainties for large measurement standards. Many of these outputs are already available to end users to improve traceability in drivetrain component and measurement instrument production.

Concerning the improvement of reliability with the large drivetrain components calibrated measurement standards are needed as reference values. Manufacturers of drivetrain components have the possibility to validate the task specific performance of measurement instruments with these qualified measurement standards as a reference. The following standards for distances, gear parameter, form and diameter and shaft measurements have been manufactured and calibrated during the project:

- Ball bar standard
- Internal involute scanning standard
- Internal involute waviness scanning standard
- Large external planet gear standard
- Large ring standard
- Large ring segment standard
- Shaft standard

In the field of the mandatory measurement strategies for the respective corresponding calibration process, the following good practice guides for an optimized measurement process of newly large-dimensional measurements have been written:

- Good practice guide on the thermalisation times of large gear and large ring measurement standards
- Good practice guidance for minimisation of significant measurement uncertainty contributors such as gravity and clamping
- Good practice guide for surface parameter detection on gears
- Good practice guide for surface parameter measurement strategies for form and diameter measurements for large bearings
- Good practice guide for surface parameter measurement strategies for waviness and roughness measurements for large bearings
- Good practice guide for surface parameter measurement strategies for form and diameter measurements for large shafts

The good practice guides were written in a pre-version in the first step. Measurements by industrial partners have been conducted to see their potential. After their feedback, improved versions were finalized and are now publicly available for free downloads from the project webpage under.

https://www.ptb.de/emrp/2757.html

4.2 Dissemination activities

4.2.1 Scientific publication

The project has planned and/or generated 17 publications so far, predominantly in high impact peer-reviewed journals such as Precision Engineering and Measurement Science and Technology. Eight additional papers have been published in the proceedings of international conferences. These incorporate the significant scientific outputs of the project. A list is provided in section 6.

4.2.2 Conferences and relevant fora

The project consortium was very well represented at conferences. In total, 24 oral presentations as well as eight poster presentations have been given by the partners during the life time of the project. Industry was addressed by contributions to the FVA GETPRO conference 2015, in Germany, and the GETPRO 2017 in Germany, and the scientific community by contributions to the ASPE, American Society Precision Engineering, 2014 in the United States, and the EUSPEN 2017, in Germany, for example. Positive reactions were received to all these contributions, attracting discussions and comments.

4.2.3 Stakeholder Engagement and Standards

The DriveTrain Consortium made every effort to engage with wind turbine manufacturers and operators to strengthen the exchange of needs and approaches for problem solving. A list of over 50 German wind turbine manufacturers and operators has been compiled and provided with information and a flyer regarding PTB's wind energy activities including the ENG56 project. As a result, Windwärts Energie GmbH, part of the MVV Energy Group, offered their WES for testing purposes and a collection of test results for future projects. The Verband Deutscher Maschinen und Anlagenbau e. V. (VDMA) was contacted and confirmed their support of the project in connecting the consortium with wind turbine operators and manufacturers. Further VDMA passed project information on to their technical committee members. CMI informed the Czech Wind Energy Association, a member of the European Wind Energy Association, about the project. The Czech Wind Energy Association provided the information to end-users in the Czech Republic. PTB made contact with CWD, Center for Wind and Power Drives, to obtain data sources quantitatively describing the reasons for WES failure. CWD is building a test gondola which will be used to investigate the causes and effects of gear damage in WES. Extensive discussion regarding the latest publications about possible WES failure sources was carried out. CWD provided PTB three reports with detailed information regarding WES failure sources, so that the ENG56 project consortium became aware of the specific problems.

To support the presentation of project results to the industrial community three newsletters or flyers and two articles in trade and daily press have been published. Such activities are essential for realising immediate impact with the stakeholder community, with whom engagement is better through newsletters, flyers and technical trade articles rather than scientific journal articles. PTB visited the Wind Energy trade fair in Hamburg. Flyers were distributed and contact made with several WES operators and manufacturers. An email was sent to all contacts regarding project progress and to encourage collaboration. Additionally, the project was presented at “Control” trade fair (May 2017) in Stuttgart, Germany, which is the leading international trade fair for quality assurance.

Several other activities were executed during the project to facilitate further dissemination of impact and output, including presentations at seminars, articles on partners' websites and company visits. Such visits were essential for partners to learn about stakeholders' technical needs, ensuring that the impact of involvement in the project was high. For example, VTT and REG(Aalto) visited Katsa Gears Oy, a wind turbine gear and gear box manufacturer, to present the project and discuss challenges in gearbox manufacturing. MDM met with two Italian WES manufacturers to inform them about the ENG56 project. As a result, Bonfigliolo Riduttori S.P.A., producer of 35% of the global epicycloidal reducers market including electric motors for WES yaw and pitch drives, became a project stakeholder. In addition, Brevini Power Transmission S.P.A., producers of yaw and pitch drives for WES, also became a stakeholder NPL visited Osborne Engineering Ltd. to discuss surface texture measurement of bearings.

During the project, the consortium had considerable interaction with standardisation and regulatory bodies. Members of the JRP-Consortium regularly attended meetings and used their existing links to several standardisation bodies to ensure that the outcomes of the project are absorbed in ISO and other standardisation bodies, professional metrology institutions, calibration services and laboratories. The consortium participated in ten different committees over the past three years, attending 32 different meetings.

The consortium discussed its outcomes with a number of major standardisation bodies in dimensional metrology, including the international standards development organisation ISO TC213 "Dimensional and geometrical product specifications and verification" and the German national standards development organisation DKD Technical committee "Length".

The project has also been presented to the German national standards development organisation VDI/VDE-GMA "Fachausschuss 3.34 Large Volume Metrology" in June 2016. Input regarding thermalisation times of large workpieces has been used to draft a German documentary standard.

NCL attended the ISO TC60 WG2 meeting on gears in July 2017 and provided a short update on the project status to delegates. A discussion document delivered by the project was circulated regarding the impact of GPS compatible measurement strategies on gears. Some comments were offered and it was acknowledged that this work would continue after the project was completed.

4.2.4 Workshops

Two workshops have been organised during the project. The first concentrated on the topic of gear measurements regarding large dimensions and was held in Italy in October 2015 in conjunction with the periodic project meeting. About 25 participants attended the workshop. It was a mixed audience from NMIs, DIs and industry.

The second workshop, entitled "Workshop on Dimensional Metrology for Large Drivetrain Components" was held in Braunschweig in August 2017, to summarize the new state of the art in large-scaled metrology for drivetrain components at the end of the project. About 40 participants from a mixed audience, especially from industry such as drivetrain producers and measurement instrument manufacturers as well as researchers met to exchange on the needs of large-scaled dimensional metrology. During this one-day workshop highlights and outcome of the project as well as the established procedures and its challenges from the industrial point of view were presented in detail. Four members of industrial partners (from unfunded partners as well as collaborators) presented their handling of metrology on large components from the industrial sight. It expressed the importance of the developments and progress of the project as well as the experiences the industry collected according to tasks of the project. Furthermore, the interest in future work and its need was discussed.

For both workshops, the delegates showed very positive interest about the outputs of the project, in particular emphasising the role of the NMIs in the development of metrological standards, needed to ensure the comparability of the field measurement results.

Further INRIM presented the project at the workshop *1° Take away dell'Innovazione – Tecnologie per le misure dimensionali di component meccanici* (www.mesap.it/take-away-dellinnovazione) on March 6, 2017, to an audience of approximately 30 people (mostly from the technical side) from various industries.

Throughout the project 17 additional training activities have been completed, including training courses for an external audience and one-to-one training for the consortium. For gear comparison measurements and validation, NCL provided VTT with training, advice and a gear.

4.3 Effective cooperation between JRP-Partners

The European Metrology Research Programme (EMRP) is a metrology-focused European programme of coordinated research and development aimed at facilitating closer integration of national research programmes and ensuring collaboration between National Measurement Institutes, reducing duplication and increasing impact.

This project has been a good example of the implementation of this programme, gathering seven NMIs/DIs and three academic partners (all Research Excellent Grants) from six European countries with four unfunded industrial partners and 16 collaborators concerning metrology for wind energy systems like ThyssenKrupp and Moventas. Some NMIs from countries which are smaller contributors to the EMRP are also involved in the project.

The project brings together expertise in coordinate metrology, a large number of different measurement systems, several simulation techniques and knowledge about industrial needs.

The participation of a large number of research groups from several countries shows the general interest of the topic and represents the first valuable impact created by the project.

Many exchanges between the partners have taken place. This is also shown in the frame of a "Research Mobility Grant". One researcher from MER (Ministry of Economy, Montenegro) has spent four months at REG(RWTH) (University of Aachen, Germany) on the experimental and model-based examination of the thermal-elastic behaviour of drivetrain components and measurement systems during geometric inspection.

Several tasks have benefited from the collaboration between the partners, as demonstrated by the several joint publications and presentations (see below). Furthermore, different measurement methods have been validated through measurements of partners in a joint cooperation. Here also some industrial collaborators contributed actively to the project by taking over verification measurements and giving advice to the measurements and the treatment of the measurement standards. The close cooperation between the partners was helpful for strengthening the knowledge exchange during the numerous validation measurements for good practice guides, measurement strategies and measurement standards. After the end of the project, these standards are still available for all interested parties.

Last but not least, due to the common activities of several partners, most of them having their expertise in a different subject, a valuable gain in knowledge could be achieved. This opens new perspectives and ideas for future common projects. Cooperation between partners, abroad the current project, became much easier. This is also true for the interaction with industrial partners. More sincere discussions were possible, which showed current limitations and needs of the industry as well as research institutions.

4.4 Examples of early impact

User uptake

CMI and INRIM conducted a first gear calibration in their laboratories. As a result of the close collaboration the process could be achieved. Furthermore, the measurement uncertainty estimation was performed, so that a calibration certificate can be issued. In the end, a new calibration service for gears has been established, which is of great importance for the NMIs and the associated national industries.

VTT developed and manufactured an instrument for evaluating the accuracy of distance measurements on a coordinate measuring machine. This so-called step gauge measures precisely with an interferometer and can be used for diameter measurements on shafts. It is portable and so it was already used in shop floor conditions by the industrial partner Moventas. It is now available for further usage.

Further an e-learning course on the traceable measurement of drivetrain components for renewable energy systems is available free of charge on the NPL website (http://bit.ly/2gwFqcQ). It can be used by research institutes and industry interested in metrology for optimizing measurements of large drivetrain components for wind energy systems. The course introduces the current state of the wind energy industry, the basics of wind turbine and drivetrain structure, an overview of common mechanical problems that occur with each of these components and measurement strategies for key drivetrain components. The course also introduces metrology terms and practices in relation to wind energy systems, and outlines measurement considerations for components within the drivetrain to support longevity and performance of the wind turbine.

VTT developed an application for Android devices to evaluate measurement uncertainty of two-point length measurements in industrial conditions. It can be downloaded from "Google Play" under the name "Uncertainty Calculator for Diameter Measurements". The App is presented on the VTT-MIKES Facebook page (www.facebook.com/MIKES.fi).

PTB designed a fast software tool, which can be operated easily, to represent the distribution of temperatures inside a workpiece. It was tested and can be used for further projects, which need simulations for a virtual process of the task-specific measurements to enable the possibility of an accurate measurement uncertainty estimation of complex processes. This is gaining importance due to increasing digitalisation.

NCL discussed GPS compatible gear measurement strategies with a delegation from Honda Automotive, Japan, because of the known links between Honda and JIS standard development who wish to encourage GPS measurement strategies for all drivetrain components.

4.5 Potential future impact

The projects outcome will support European manufacturers of drivetrain components and measurement instruments to face the challenges of traceable measurements of large drivetrain components for wind energy systems. Drivetrain components will become increasingly accurate and therefore more reliable, thus ensuring the unfailing operation of renewable energy systems, increasing efficiency and reducing the costs of green energy generation. This will strengthen the position of European manufacturers on the global market.

New measurement and calibration services at NMIs disseminating traceability, e. g. to commercial measurement service providers, will emerge based on the outcomes of the project.

The project will further contribute to the knowledge transfer on the topic of measuring drivetrain components by establishing a network between research institutions and industry and allowing easier collaboration between the participants in the future.

The outcome of this project will not only provide technological benefits to European industries, it will also potentially facilitate strong economic and social development. The JRP is a cornerstone for the European political goal of reducing the CO_2 emissions by 40 % until 2030 at least for power generation and could help in accelerating the realisation.

The new approach of characterising the surface roughness in braking systems will provide tools and knowledge to reduce the braking effects on heat and noise generation.

5 Website address and contact details

A public website is available at: http://www.ptb.de/emrp/drivetrain.html

The contact person for general questions about the project is Karin Kniel. (karin.kniel@ptb.de).

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6 List of publications

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