The Application of Geometrical Product Specification (GPS) — Compatible Strategies for Measurement of Involute Gears

R.C. Frazer, G. Koulin, T. Reavie, S.J. Wilson, J. Zhang and B.A. Shaw

Introduction

During the revision of ISO 1328-1:2013 Cylindrical gears — ISO system of flank tolerance classification, ISO Technical Committee TC 60 WG2 delegates discussed proposals that the standard should be modified to ensure that it is compatible with the ISO Geometrical Product Specification (GPS) series of standards (Refs. 1-3). This seems sensible because the gears are geometrical components, but after reviewing the implications, it was rejected because ISO TC 60 WG2 did not think the gear manufacturing industry was ready for such a radical change in measurement strategy. GPS standards are numerous: a search on the British Standards website delivered 203 documents (Ref. 4) and it is probably not surprising that few companies have adopted the guidance within the documents.

An EMRP EURAMET-funded project (ENG56-DriveTrain), which is jointly funded by the EU and participating national states, completed a significant research project to improve the 'Traceable measurement of drivetrain components for renewable energy systems.' Part of this project investigated the feasibility of implementing GPS-compatible measurements to gears. The work concluded that there would be significant benefit in applying GPS strategies to gears, but there are also some significant problems. The need to specify functional, performance-based characterization parameters is very challenging, but the work summarized in this paper provides a framework to develop GPS-compatible measurement strategies for gears.

GPS Methodology

GPS was introduced in 1992 when it was realized that digital definitions of products or workpieces were changing how the design, stress analysis and modeling, as well as CNC machine tool manufacture, and measurement processes were used. There is a need to define inputs mathematically for these tools and to define a structured way of processing the data.

The process assumes that we specify allowable deviations or tolerances to the ideal or theoretically shaped component. We specify functional, performance-based characterization parameters or 'features' for each of these geometry elements. These geometry features have a functional effect on the component performance and require controlling. For example, we specify the effect that eccentricity (μm) will have on out-of-balance forces (*N*) when a shaft is rotating. We calculate these effects reasonably accurately, but the geometry specification parameter may not exactly control or influence the function requirements, so there is residual uncertainty with the specification parameter — although it may be small. For gears, functional performance or key performance indicators (KPIs) may include noise and vibration limits at a range of torque values and operating speeds, contact stress resulting in macro- and micropitting damage, bending fatigue failure and scuffing risk. The correlation between the geometrical component specification and each KPI needs to be quantified to specify tolerance limits. These will be different for each application, but it is likely that common processes and strategies could be adopted. All stages of the process include unavoidable uncertainties, as no process is perfect and these need to be quantified.

The key GPS process stages are:

- A measurement strategy (extraction) is needed to extract points from the selected collection of surfaces on the manufactured workpiece. If we can't measure 100% of the surfaces, there is potential that our measurement data density was not sufficient to capture the manufactured characteristics and uncertainty in characterization of each measured element from the measurement strategy.
- The geometrical extracted feature will include 'noise' from the extraction process (equipment) and include high- or low-frequency workpiece deviations which may not be required for the evaluated functional parameter. Thus, appropriate filters are specified.
- We need to use the extracted data and evaluate functional characterization features. This process is called 'association,' which fits the imperfect extracted feature with an ideal feature (such as a circle or involute profile — both of which are mathematically defined). Each characteristic of the feature is independent of other characteristics (the so-called independency principle).
- Evaluation of the functional characteristics introduces further potential uncertainty.
- The final stage is to establish compliance (or otherwise) with the component's GPS.
- The choice of measuring equipment, environment, calibration strategy and traceability of the evaluated parameters can potentially contribute significant uncertainty to the overall process. For example, if old or poor-performing measuring equipment is used for measuring precise components, such as gears.
- Compliance uncertainty. The uncertainty contributions outlined above will affect the decision process when results are compared to the tolerance limits. To

This paper was first presented at the 2018 Lyon International Gear Conference and is published here with Conference and author permission.

minimize the risk of accepting components outside tolerance or of rejecting components within tolerance, uncertainty of each process should be used to define working tolerance limits that can be used by the shop floor during manufacture.

In summary, we specify functional, performance-based characterization features which are measured, filtered and evaluated with equipment of known measurement uncertainty; this uncertainty is considered when reporting compliance or otherwise with a functional specification.

Classical Gear Metrology Methods

Since the development of early gear tolerance specifications (Ref. 5), conventional inspection involved the measurement of individual gear parameters such as single and cumulative pitch, involute profile and helix deviations. Generally, a single profile and helix trace (2-D line) at mid-facewidth or tooth depth on 3 or 4 teeth spaced at 120° or 90° intervals, and single pitch and cumulative pitch on all teeth is measured. 2-D line methods were adopted because they provided information that can be used to modify the machine tool set-up and reduce the deviations. Tolerance values were primarily defined based on machine tool manufacturing capability, rather than gear performance. ISO17485:2003 tolerance grades for bevel gears (Ref. 6) were identical to ISO1328-1995 (Ref. 7) tolerance standard values for cylindrical gears, except that the bevel gear tolerance grades were 1 grade larger to reflect the additional difficulty involved with manufacturing bevel gears.

These measurement methods are sometimes extended to include additional profile and helix 2-D line scans on a single tooth (Fig. 1) to quantify variation in profile and helix deviation caused by the machine tool manufacturing characteristic. Tolerances of evaluated parameters are usually applied uniformly to all profile and helix measurements over the tooth surface.

The helix and profile 2-D line deviations are both evaluated by 3 parameters, which for profile are evaluated between the profile control diameter and tip form diameter, and include the total deviation F_α, the profile slope deviation $f_{H\alpha}$, and profile form deviation $f_{f\alpha}$. The parameters control the manufacturing processes and affect the performance of gears, although the correlation between gear performance and these tolerance values in the ISO 6336 stress analysis standard (Ref. 8) is not so clear. ISO 6336 uses the ISO 1328-1 single-pitch tolerance to contribute to the estimation of the dynamic load modification factor K_v, which estimates the increase in load caused by self-excited dynamic effects. The effect of misalignment caused by manufacturing deviations is also considered, but the implementation is determined by the user.

Another method, commonly known as topography measurement, is illustrated (Fig. 2). Multiple 2-D profile measurements and single-helix line scans fully characterize a single tooth flank surface topography. Such results are usually only examined visually for damage and manufacturing trends, because evaluation parameters have not been developed for this type of measurement.

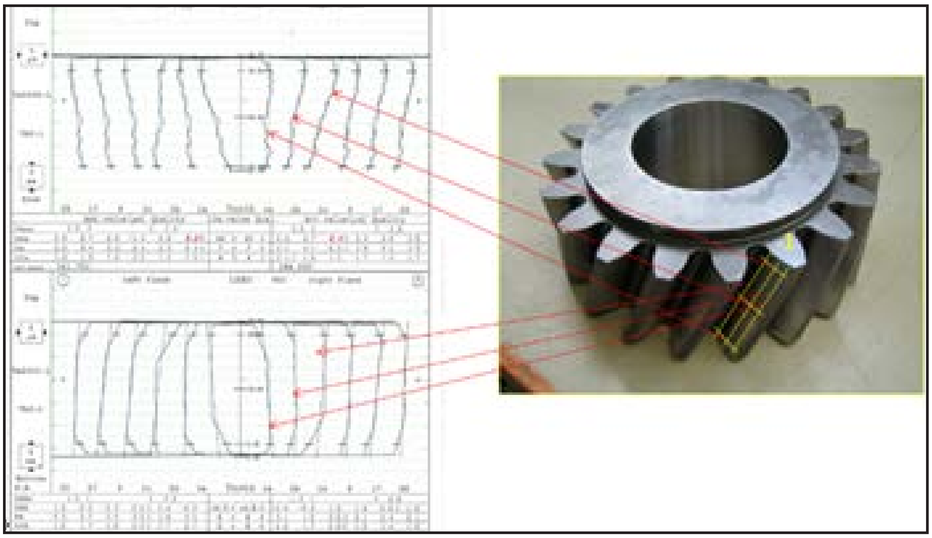

Figure 1 Additional 2-D profile and helix lines commonly referred to as twist measurement to quantify common machine tool manufacturing characteristics.

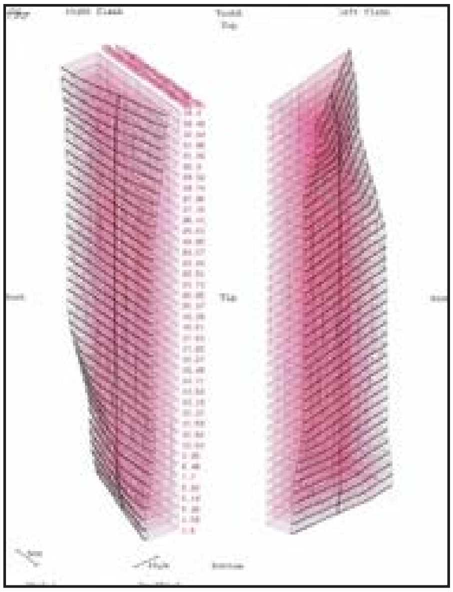

Figure 2 Topography measured on a single tooth combining a single helix 2-D line scan on each flank with multiple profile 2-D line scans.

In summary, the parameters evaluated in both previous and current versions of the ISO 1328-1 tolerance standard are at best weakly correlated to gear performance, and the link to KPIs such as contact stress, scuffing risk and noise are not properly established. Deviations in involute gear flank form from design intent contributes to a number of potential failure mechanisms which can be considered as KPIs for gears. These include:

Peak load intensity increase leading to premature gear failure by tooth root bending fatigue, flank contact fatigue by macropitting or micropitting, and scuffing failure.

Excessive noise and vibration resulting from high dynamic loads (potentially causing premature fatigue failure of the gears).

Reduced reliability, efficiency and variability in product performance.

It can be imagined that the classical 3-form characterization parameters, which include microgeometry corrections such as tip relief and helix crowning, applied to a tooth surface that is misaligned and deflects elastically when loaded, is unlikely to fully characterize gear performance.

GPS-Compatible Revisions to ISO 1328-1:2013

General. Although GPS strategies were not adopted during the revision, a number of changes were introduced that are compatible with GPS:

- Involute profile measurement requires a minimum of 150 points equally spaced along the profile length of roll.
- Helix measurement requires a minimum of 150 points (expressed as $5.b/\lambda_\beta$).
- If waviness is to be checked, a minimum of 300 points or 5/mm is required.
- A profile filter cut-off is defined as $\lambda_\alpha = L_\alpha/30$, where L_α is the profile length of roll [mm] and the helix filter cut-off is $\lambda_\beta = b/30$ where b is the face width [mm].
- The filter is a Gaussian 50%, defined in accordance with ISO/TS 16610-1 and ISO 16610-21 — both of which are GPS standards.
- Evaluation methods to assess deliberate microgeometry corrections to improve functional gear performance.

These changes minimize the measurement uncertainty caused by different sampling strategies, which is particularly sensitive where larger deviations from involute form exist (Refs. 8-9). The results in Figure 3 with significant deviations resulted in $f_{H\alpha}$ values of 14.0 µm and 16.2 µm for length of roll and radially spaced data; deviation in form parameters $f_{f\alpha}$ varies between 20.4 to 19.7 µm, and total form F_α of 27.1 and 27.0 µm. These are significant differences in values compared to the tolerance.

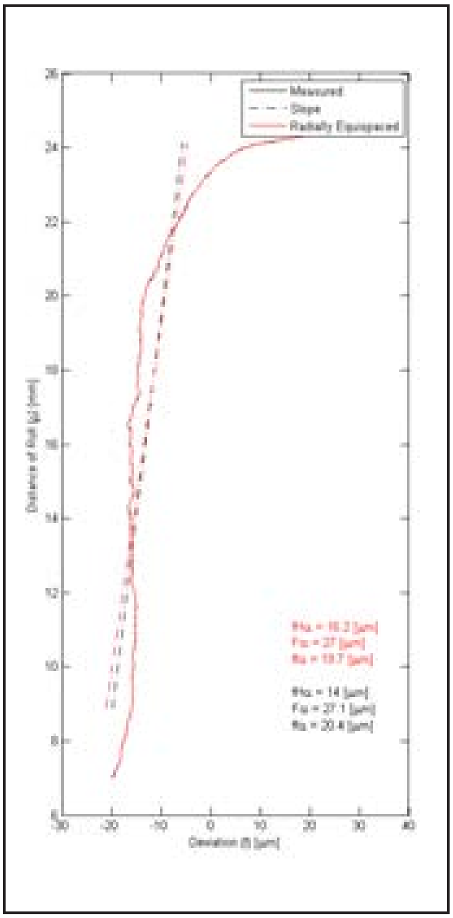

Figure 3 **Change in profile parameters with data spacing strategy for large deviations with 480 data points.**

A comparison of 2-D profile data requirements for wind turbine gears. The EMRP ENG56 project considered the requirements of wind turbine gearboxes and reviewed the ISO 1328-1:2013 recommendations for filter and data spacing, compared to the functional impact on gear noise/vibration and contact fatigue. Large wind turbine gearbox drives commonly have 3 stages, i.e. — low-speed 1st and 2nd stage are often epicyclic gear arrangements and the 3rd high-speed stage is a parallel axis gear pair. The typical gear size (module) depends on the detailed design, but it is common to use around 18 mm, 16 mm and 8 mm module gears for 1st, 2nd and 3rd stages, respectively. The length of path of contact (L_α) — that defines the length of profile measurement for each of these stages — again varies, but is usually around 80 mm for the 1st and 2nd stages, and 45 mm for the 3rd stage. Face widths are usually around 400 mm (1st and 2nd stage) and 200 mm (3rd stage) gears.

Noise and Vibration Frequencies and Measurement Data Requirements

Noise and vibration caused by gears during operation is at tooth passing frequency and its higher harmonics. 10× tooth passing frequency ($f_{max} = \times 10$) are not likely to cause significant problems, and generally ×5 or ×6 tooth passing frequency are common limits. Thus we need to properly capture flank features that cause deviations at or below these frequencies. Assuming a minimum of 5 (*n*) data points to model each harmonic of tooth passing frequency (for an FFT analysis for example) the minimum data spacing requirements in the transverse profile are given in Equation 1.

$$\text{data spacing [mm]} = \frac{L_\alpha}{f_{max} \cdot n \cdot \varepsilon_\alpha} \tag{1}$$

Where:

L_α profile length of roll [mm]

f_{max} tooth passing harmonic (relative frequency)

n number of data points per frequency

ε_α gear transverse contact ratio

The required number of data points in Table 1 for the wind turbine gears is significantly less than the minimum of 150 specified by ISO 1328-1:2013. The data density for 2-D helix measurement on helical gears is not so critical for noise and vibration because the line of contact is inclined at an angle over the face width.

Contact Stress Modeling and Measurement Data Requirements

The data spacing requirements for contact stress can be estimated from the Hertzian contact half-width (*a*). Under normal nominal load conditions in wind turbine gears, the Hertzian contact half-width (*a*) varies between 0.35 mm and 0.7 mm — assuming aligned and perfect surfaces. Geometry features with a wavelength of around the Hertzian contact length will have a significant effect on the actual contact stress.

Assuming the same minimum of 5 data points are required for modeling involute profile shape over the Hertzian contact length, the data density and number of measurement point requirements are summarized (Table 2). The results suggest we need approximately twice the minimum requirement of 150 specified

Table 1 **Profile data density requirements for noise and vibration**

Stage	Module mn [mm]	Profile length L_α [mm]	Transverse contact ratio ξ_α	Data spacing [mm]	Points per profile length
1st (epicyclic)	18	85	1.6	1.06	80
2nd (epicyclic)	16	80	1.6	1.00	80
3rd (gear pair)	8	45	1.8	0.50	90

Table 2 **Data spacing and number of points based on contact stress modeling**

Stage	Module m_n [mm]	Profile length L_α [mm]	Hertzian length [mm]	Data spacing [mm]	Points per profile length
1st (epicyclic)	18	85	0.7×2	0.28	304
2nd (epicyclic)	16	80	0.7×2	0.28	285
3rd (gear pair)	8	45	0.35×2	0.14	321

in ISO 1328-1:2013. This is consistent with the recommendations for waviness measurement where a minimum of 300 points is recommended by ISO 1328-1.

Local contact stress is significantly affected by smaller deviations at the surface roughness and waviness level. It could be argued that the profile form measurement does not need to measure features around the Hertzian contact length, and that waviness and roughness measurement methods using small 2 or 5 µm radius stylus or optical methods are more appropriate. This depends on the CMM and GMM probe system performance, which is generally not verified by CMM or GMM users. If CMMs and GMMs can detect waviness parameters which will characterize features that affect micro-pitting, macro-pitting and scuffing performance acceptably, then waviness can be measured independently of roughness.

2-D Helix Line Data Density

The inclined line of contact at the base helix angle on helical gears is influenced by both profile and helix form deviations. ISO 1328-1:2013 recommends a minimum of 150 points for helix measurement and a minimum 300 points or 5 points/mm of facewidth, if waviness is required. Table 3 shows that meeting the minimum number of points for waviness measurement requires significantly more than 300 points. The helix data density at 5 points/mm gives a similar density to the requirements for involute profile measurement, and this is appropriate for contact stress analysis with CAD models. The data density resulting from the 150 minimum points provides sufficient information to define load distribution for bending stress analysis with CAD models.

ISO 1328-1 Filter Specification

The cut-off lengths for involute profile and helix measurement, λ_α and λ_β, respectively, are low-pass cut-offs that exclude high-frequency deviations. The cut-off lengths are specified as $L_\alpha/30$ and $b/30$ and examples for typical wind turbine gear applications are illustrated (Table 4).

Other Considerations

A line of contact on a helical gear is inclined at the base helix angle (β_b) and thus the effect of the attenuation of measured features used to model a tooth surface is influenced by both profile and helix deviations.

If the base helix angle (β_b) is greater than the $\mathrm{Tan}^{-1}(\lambda_\alpha/\lambda_\beta)$ from Table 4, the highest frequency that influences geometry modeling is limited by the profile filter selection; conversely, if it is smaller, the helix filter limits the geometry frequency.

Example: ISO 1328-1: Filter Test Results and Analysis

The sample measurement results are from a ground gear artifact with geometry summarized in Table 5; a 5 mm-diameter probe was used for these tests. Each profile and helix evaluation used 480 data points, which is greater than the minimum of 150 points specified in ISO 1328-1 and consistent with the requirements for the measurement of features that will influence noise, vibration and contact stress. Selected flanks were measured on a Klingelnberg P65 at the UK's National Gear Metrology Laboratory. Three conditions were tested:

- No filter, except a morphological filter (5 mm probe diameter) and mechanical filtering from the P65 probe system (unquantified).
- ISO 1328-1:2013 Gaussian filter defined in accordance with ISO/TS 16610-1 and ISO 16610-21.
- A Klingelnberg 2CR filter. This is the standard filter offered by Klingelnberg — with a cut-off wavelength λ_α of $L_\alpha/15$ and λ_β of $L_\beta/15$ — and thus removes higher frequencies than the ISO filter. It provides an example of an existing filter and illustrates the

Table 5 Test gear geometry

Module m_n	8 mm
Profile length L_α	32.33 mm
Helix β_b	0°
Face with (b)	155 mm
Involute profile λ_α	1.077 mm
Helix λ_β	5.166 mm
Profile data (n)	480
Helix data (n)	480
$\mathrm{Tan}^{-1}(\lambda_\alpha/\lambda_\beta)$	11.78°

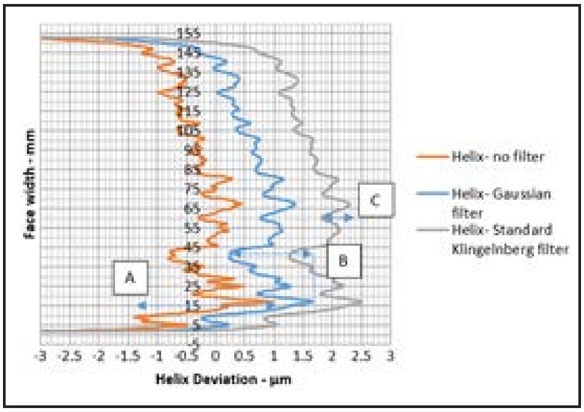

Figure 4 Helix results with different filters (Sample 1).

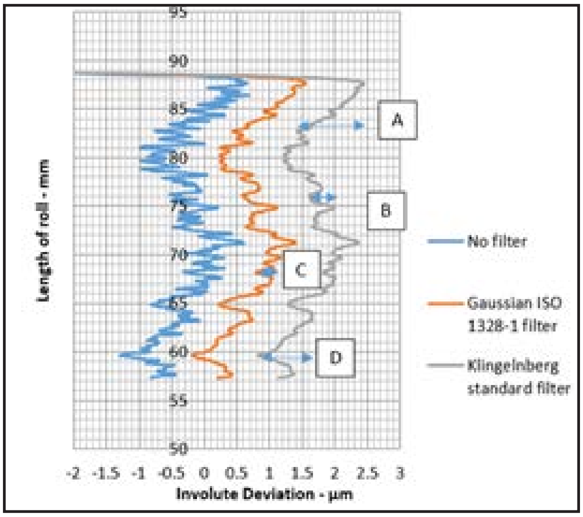

Figure 5 Profile results with different filters (Sample 1).

Table 3 Data sampling requirements for helix measurement

Stage	Module m_n [mm]	Face width (b) [mm]	ISO max data spacing for 150 points [mm]	ISO number of points at (5/mm)
1st (epicyclic)	18	400	2.67	2000
2nd (epicyclic)	16	260	1.73	1300
3rd (gear pair)	8	300	2.00	1500

Table 4 ISO 1328-1:2013 filter cut-off length

Stage	Module m_n [mm]	Profile length L_α [mm]	Face (b) [mm]	Involute profile λ_α [mm]	Helix λ_β [mm]	$\mathrm{Tan}^{-1}(\lambda_\alpha/\lambda_\beta)$
1st (epicyclic)	18	85	400	2.83	13.33	11.98°
2nd (epicyclic)	16	80	260	2.67	8.66	17.14°
3rd (gear pair)	8	45	300	1.50	10.00	8.53°

expected differences with the ISO filter.

2-D helix and profile measurement results are illustrated (Figs. 4 and 5, respectively); a visual examination of the results shows clearly the attenuation in high-frequency content. The influence on the helix and profile slope deviation, form deviation and total deviation was < 0.5 µm.

Some individual characterizing features in the results have also been examined, and the findings summarized in Table 6. The results show that typically 10% greater attenuation of feature transmission with the traditional 2CR filter compared to the ISO Gaussian filter. It also shows that as λ/λ_β or λ/λ_α reduces, the effect of the filter and feature amplitude increases — as expected.

Table 6 shows that, based on the typical noise requirements and most contact stress needs, the ISO 1328-1:2013 filter requirements are reasonable and provide a good platform to develop GPS measurement strategies.

3-D Gear Flank Reconstruction and Evaluating Parameters

Part of the EMRP ENG56 project was to establish how many measurement scans on a conventional GMM were needed to characterize the 3-D surface geometry. A 2-stage Gaussian interpolation method was developed (Ref. 8), which shows that a gear tooth surface could be accurately generated from as few as 3 profile and 1 helix scans. The optimum number of profile scans required depends on the manufacturing process characteristic. The method involves 5 steps:

- Select the number of profile measurements to model the tooth surface (5 are selected in the example in Fig. 6).
- Fit a surface polynomial to the selected profile and helix data (Fig. 6), and then subtract the surface polynomial surface to create 5 residual deviation profile scans.
- Use these to synthesize the high-frequency surface deviations using Gaussian interpolation (Fig. 7).
- Add the surface polynomial back to the synthesized surface from the previous step to reconstruct the tooth surface (Fig. 7).
- Test the sampling strategy by comparing the reconstructed surface to the high-density measured surface and quantify the deviations (deviations in Fig. 7 are ×10 magnification).

This process allows for the accurate modeling of gear teeth surfaces and the

Table 6 Sample 1 feature attenuation

Profile/helix	Feature	Feature λ [mm]	λ/λ_β or λ/λ_α	Amplitude [µm]		
				No filter	Gaussian filter	2RC filter
Helix $\lambda_\beta = 5.16$ mm	A	10.68	2.06	2.33	1.90 (82%)	1.65 (71%)
	B	21.68	4.20	1.71	1.38 (81%)	1.21 (71%)
	C	7.12	1.38	0.67	0.56 (84%)	0.44 (66%)
Profile $\lambda_\alpha = .08$ mm	A	7.37	6.82	1.64	1.27 (77%)	1.17 (71%)
	B	0.47	0.44	0.72	0.38 (53%)	0.35 (47%)
	C	0.67	0.62	0.58	0.21 (40%)	0.15 (26%)
	D	4.52	4.19	1.18	0.91 (77%)	0.83 (70%)

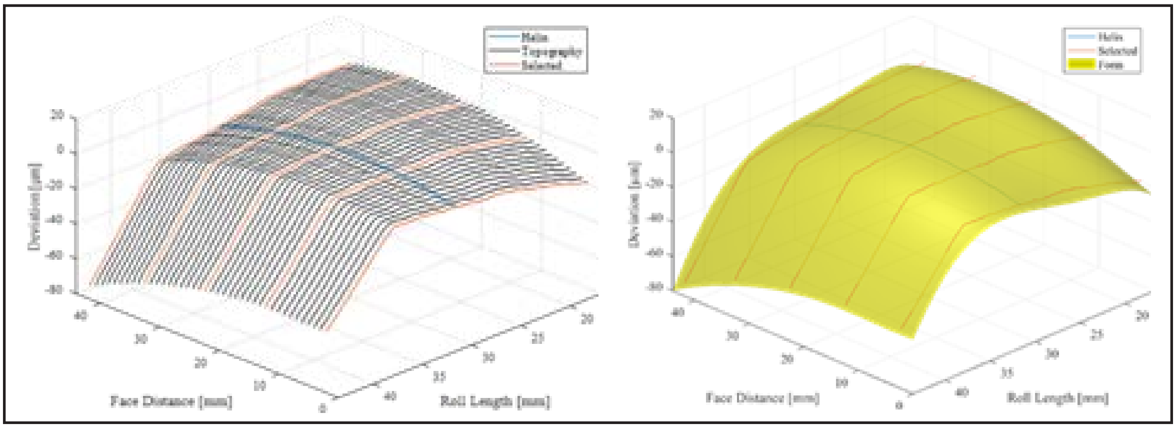

Figure 6 Selected 2-D profile scans (left) for surface polynomial fitting (right).

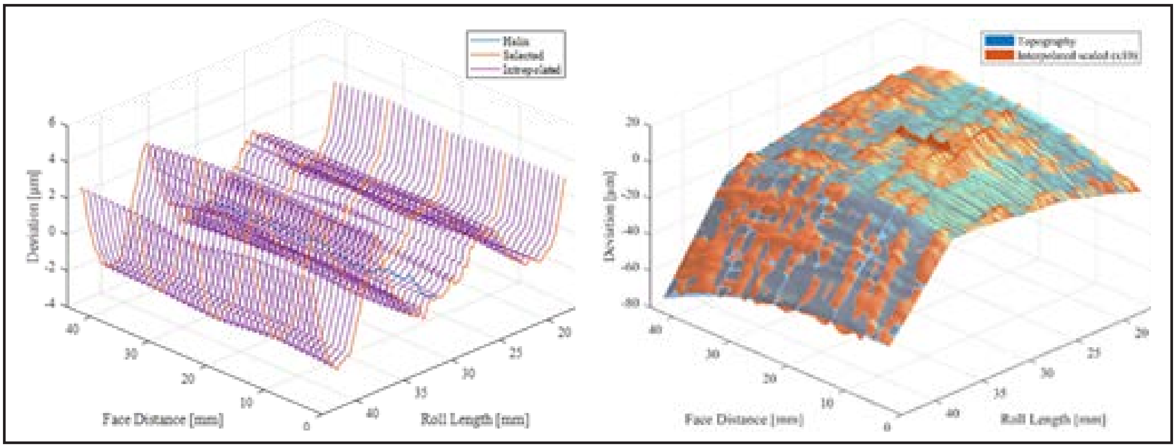

Figure 7 Residual form deviation after extraction of the surface polynomial and a comparison of the synthesized surface with the measured surface.

development of efficient GPS-compatible measurement and evaluation strategies based on functional KPIs required for the gear application. The KPIs should consider the gear geometry deviations, microgeometry corrections, elastic deflections and the sliding and rolling speeds at the mesh, among other requirements. This is only practical if the actual measured gear geometry is used in a TCA model to predict performance and the TCA is validated by testing. This approach has already been developed for gear tribology modeling, and researching the initiation and progression of micropitting (Refs. 12–13).

GPS Implementation Recommendations — General

Gear geometry measurement standards should be part of the GPS matrix of standards. ISO TC60 WG2 should retain the technical responsibility for standard development, with appropriate support from ISO Technical Committee TC213 delegates. It is expected this process will take 10–15 years to implement. Specific comments on the key ISO documents follow.

ISO 1328 -1: 'ISO system of flank tolerance classification.' Tolerance standards are required for user guidance. The compliance/non-compliance with tolerance in accordance with ISO 14253-1 should be optional. Measurement uncertainty statements should accompany all measurement results. Tolerance values should remain unchanged. References to measurement methods and minimum strategies should remain with the GPS document and not in a separate document. In addition, datum surfaces should make reference to ISO 5459.

ISO 18653: 'Evaluation of instruments for the measurement of individual gears.' ISO 18653 requires revision of measurement uncertainty calculations to more accurately account for uncorrected bias from the comparator method. References to ISO 10360, ISO 14253 (all parts), ISO 15530 (all parts) should be strengthened. A review of artifact requirements for the assessment of measurement uncertainty and a strategy for using a combination of uncalibrated and calibrated workpieces is recommended.

ISO TR 10064. ISO TR 10064-3: Review and revise the TR for compatibility with ISO 5459 datum surfaces and datum systems; provide new examples.

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; update and align with ISO 1328-1. Removal of limits on alignment, runout and probe gain where machine manufacturer's recommendations take precedence.

Conclusions

The feasibility of the implementation of gears into the GPS matrix of standards has been carried out and the results conclude that this is practical, provided some key issues related to measurement uncertainty and establishing appropriate KPIs are addressed. A review of the revisions to ISO 1328-1:2013 concludes that they are compatible with GPS strategies. Also, the filter and data density requirements for profile and helix measurement are suitable for characterizing noise KPIs and some contact stress KPIs. A method to efficiently characterize the 3-D tooth surface form has been developed, with the specific intention of using the data in gear TCA models.

The development of a holistic approach to gear specification, measurement, modeling of gear performance, and validation by testing is a necessary requirement for implementing GPS measurement strategies.

Acknowledgement. *The authors acknowledge the European Metrology Research Program (EMRP). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union. This work was completed as part of EMRP collaborative project ENG56.*

For more information. Questions or comments regarding this paper? Contact Robert Frazier at *robert.frazer@newcastle.ac.uk*.

References

1. Deni, M. "Considerations on the Geometrical Characterization of Tooth Form," ISO TC60 WG2 N525, November 2008.
2. Deni, M. "Considerations on the Geometrical Characterization of Tooth Form," ISO TC60 WG2 N568, September 2010.
3. Deni, M. "Issues to be Considered on Filtration Operators," ISO TC60 WG2 N618, October 2012.
4. *https://bsol.bsigroup.com/Search,* Geometrical Product Specification, accessed 19/4/2018.
5. BS 436: 1940. Specification of Machine Cut Gears, British Standards, 1940.
6. ISO 17485:2006. Bevel Gears — ISO System of Accuracy.
7. ISO 1328-1:1995. Cylindrical Gears — ISO System of Accuracy.
8. Koulin, G., J. Zhang, R.C. Frazer, B.A. Shaw and I. Sewell. "A New Profile Roughness Measurement Approach for Involute Helical Gears," *Meas. Sci. Technol.* 28 (2017) 055004 (16pp) March 2017.
9. Koulin, G., M. Stein and R.C. Frazer. "EMRP ENG56 Deliverable Report: D1.2.1 Evaluated Algorithm for Unifying Gear Profile," March 2015.
10. Koulin, G., T. Reavie, R.C. Frazer and B.A. Shaw. "Economic Method for Helical Gear Flank Surface Characterization," STMP-100357.
11. Frazer, R.C. EMRP ENG56 Deliverable Report D1.6.1 and D1.6.2: Report on the Integration of Gears into the GPS Matrix, August 2017.
12. Sharif, K.J., A. Clarke, H.P. Evans, R. C. Frazer and B.A. Shaw. "Effects of Micro-Gometry Features and Profile Error on Elastohydrodynamic Lubrication of Helical Gears," *STLE Society of Tribologists and Lubrications Engineers, 71st Annual Meeting*, May 2016.
13. Clarke, A., H. Jamali, K. Sharif, P. Evans, R. C. Frazer and B. Shaw. "Effects of Profile Errors on Lubrication Performance of Helical Gears," *43rd Leeds-Lyon Symposium on Tribology*, Sept. 2016.

Rob Frazer received a BSc in Mechanical Engineering and Ph.D. from Newcastle University. He is a senior engineer with the Design Unit at Newcastle University and has spent the last 35 years working with gears. Rob leads gear measurement research at the UK's National Gear Metrology Laboratory (NGML), is chair of BSI's gear committee MCE-5, and is a member of the ISO gear accuracy committee (ISO TC60 WG2). Frazer provides technical support to the British Gear Association's research committee, helps deliver its KT program and teaches Newcastle University's MSc and MEng Mechanical Power Transmissions Modules.

Giorge Koulin received in 2013 a BEng degree in mechanical engineering with a specialization in mechatronics from Newcastle University, UK. Since graduation he worked as a researcher in the Design Unit, Newcastle University focusing on developing metrology techniques to allow simulation of real, as-manufactured versus as-designed ideal mechanical power transmissions meshing elements. In 2018 Koulin moved to the field of software engineering and currently works for Pulsic, developing the new-generation, smart placement tool for analogue integrated circuits, Pulsic Animate Ltd.

Tom Reavie received his Masters in Mechanical Engineering from Newcastle University in 2016. He has since been working as a research engineer at Newcastle University's Design Unit, specializing in gear design and analysis. Recently, Reavie joined the National Gear Metrology Laboratory team and has begun a Ph.D. in 3-D gear form measurement and geometric product specification (GPS) for gears.

Stephen Wilson received a Bachelor of Engineering in Mechanical Engineering from Northumbria University in 2000, after working in the manufacturing industry for several years. He has been working for the Design Unit at Newcastle for over 20 years in the manufacturing, gear testing and gear metrology fields. Wilson is the Technical Manager of the UK National Gear Metrology Laboratory and is an active member of national standardization body BSI – Gear Accuracy MCE/005/05-02, which is responsible for the UK input into the work of the ISO Technical Committee 60 Working Group 2 Accuracy of Gears.

Jishan Zhang received his bachelor degree in mechanical engineering from Hunan University (China) in 1988. After graduation, he worked in production engineering in the Dongfanghong Tractor Plant (China) for 4 years. He received his master degree in mechanical engineering from Zhengzhou Research Institute of Mechanical Engineering (China) in 1995, and started studying and testing gears, firstly as a research engineer and then as a senior research engineer up to 2000. He obtained his Ph.D. degree in mechanical engineering from Newcastle University (UK) in 2005 and has since worked in the Design Unit as a research associate, and was appointed senior test engineer by Newcastle University in 2016. Dr Zhang's current research interests include the scuffing, micro-pitting, macro-pitting and efficiency of case hardened involute gears

Brian Shaw received a BEng in Materials Engineering from Sheffield University and his Ph.D. from Newcastle University. He is Professor of Transmission Materials Engineering, the Director of the Design Unit and Director of Business and Engagement at the School of Engineering. Since 1993 he has worked within the field of gear metallurgy, carrying out research into micro-structural aspects of the fatigue strength of gear materials, and in particular the crack initiation and propagation in pitting and bending fatigue. Shaw's research includes the investigation of the influence of heat and surface treatments on the bending and contact fatigue strength of carburized, nitrided and induction hardened gears, the effect of residual stress, surface texture and lubricant additives on pitting in gears.