Filtering effects on involute gear form measurement

OPEN ACCESS
IOP Publishing

Measurement Science and Technology

Meas. Sci. Technol. 34 (2023) 045006 (10pp)

https://doi.org/10.1088/1361-6501/acadf8

Filtering effects on involute gear form measurement

Tom Reavie*, **R C Frazer and Brian Shaw**

National Gear Metrology Laboratory, Newcastle University, Newcastle upon Tyne, United Kingdom

E-mail: tom.reavie@ncl.ac.uk

Received 25 August 2022, revised 7 December 2022
Accepted for publication 22 December 2022
Published 9 January 2023

Abstract

Traditional gear measurement results are used to classify a gear tolerance grade in accordance with ISO 1328-1:2013 but as more stringent requirements are placed on gear performance it is important to also characterise performance related features properly on the gear flank surface. However, the measurement uncertainty of the measurement machines is not improving at the same rate as the tolerance requirements, and it is not uncommon to have less than 10 µm tolerances to be measured with a 1–3 µm measurement uncertainty capability. This breaks the 'rule of thumb' that the uncertainty should be smaller than one tenth of the value you are trying to measure. It is therefore important to review the measurement and evaluation process to identify if there are any areas for improvement within our current methods. Additionally, the measurements are being used to refine gear tooth contact analysis performance models and the development of optical and high speed tactile scanning measurement methods is allowing the full 3D gear flank surface measurement a feasible option on the shop floor. Greater understanding of the involute flank beyond the standard evaluation limits is thus required. These additional requirements have prompted this review of the effect that the Gaussian filters specified in ISO 1328-1:2013 have and that their characteristics are fully understood by those who must perform and interpret the measurement results. This paper examines the effect that these filters have on measurements where micro geometry corrections, such as tip relief, or tooth tip and end face chamfers are present. Methods of minimising these effects are reviewed with specific reference to strategies defined in ISO 16610-28:2016. Recommendations are offered to minimise the effects when evaluating the gear tolerance class and quantifying gear flank micro geometry.

Keywords: involute gear metrology, filtering end effects, surface characterisation, digital twin, analysis of filter standards

(Some figures may appear in colour only in the online journal)

1. Introduction

Gears and gearbox products demand increased power density [1, 2] and require smaller geometry tolerances to reduce costs and minimise noise and vibration during operation. To ensure that gears are fit for purpose they are commonly measured and evaluated in accordance with the gear geometry tolerance classification standard, ISO 1328-1:2013 [3]. When ISO 1328-1 was revised the standard included filter recommendations were not specified previously in any gear tolerance standard.

Filtering of the measured data is an important part of the metrology evaluation process to assure that only the required characteristics are evaluated. In many gear measuring machines, this is typically applied by a default filter during the measurement process without considering the potential effects

* Author to whom any correspondence should be addressed.

on the measurement evaluated results. However, as the performance requirements of gears are increased in terms of scuffing risk, efficiency, micro-pitting risk, contact stress and noise, it is required that we understand more about the gear flank surface in terms of how it performs and how we model this performance [4–7]. In particular, micropitting and scuffing are difficult to model and there is much on-going research in this area [8–11] supported by international standards [12–16]. Some of these failure modes are sensitive to regions where the geometry changes suddenly, such as initial contact at the tip or edges of the gear face width where the lubrication regime changes are difficult to simulate [17–19]. It is desirable to measure and characterise these edges correctly so they can be considered in analysis models.

The standard Gaussian filter discards data at the edges but we cannot simply measure further along the gear surface, as no more metal exists. We are forced to apply edge effect strategies that artificially extend the trace or modify the filter to minimise the impact from the filter characteristic on the measured surface.

ISO 16610-28:2016, part 28 of the filter standards, defines methods to address this issue including [20]:

- Zero padding (which has a different effect depending on where the zero datum is defined).
- Linear extrapolation.
- Line symmetrical reflection (LSR).
- Point symmetrical reflection (PSR).
- Moment retainment criterion (MRC).

In addition,

- End padding—which is a modification of zero padding method used by the author, but not included in the standard.

All these methods are relatively simple to understand and implement for the standard metrologist except for the MRC method.

Understanding filtering characteristics is important in defining what information can be usefully extracted from the gear flank measurement, especially considering relatively large measurement uncertainties compared to the parameter tolerances [21]. It is thus necessary if the measurement results are to be used to:

- Classify the gear tolerance class in accordance with ISO 1328-1:2013.
- Model tooth contact analysis (TCA) to simulate and predict functional performance.
- Create digital twins, a requisite for Industry 4.0.
- Understand and quantify the effect of new and improved manufacturing and finishing methods.

2. State of the art

The standard which dictates edge extension methods, ISO 16610-28, was published in 2016. Thus, there is only a small body of research applying the methods in the ISO 16610 series and highlighting the strengths and deficiencies of the methods.

Wiśniewska and Żebrowska-Łucyk acknowledge surface texture measurement and analysis as one of the most important current fields in metrology and reviews the recent ISO 16610 series standards. They state that the standard Gaussian filter remains the one and only filter used by most professionals despite the plethora of new filters devised and published. Although little mention is made to the ISO 16610-28 end extension methods in the main text it importantly discusses the non-uniformity of the layout of the standards, and some errors—notably a spline filter which cannot be solved—which may contribute to lack of understanding and reticence to apply these standards [22].

Seewig *et al* discuss the filtering methods in ISO 16610-21 and the limitations of the standard for analysing closed profiles. The process of analysing the closed profile as an open profile and, using ISO 16610-28, replicate the profile at either end. They state that the standard does not suggest how far to replicate (as it can be infinitely done) and instead present a periodic weighting function [23, 24].

A similar article from Tomov *et al* showcases the ISO 16610-28 end effect methods and the effect on roughness parameter calculations, in particular zero-padding, LSR and point symmetric reflection. The authors again highlight the standard's lack of support for choosing which edge method is appropriate for periodic or non-periodic profiles and specifically investigate when the cut off wavelength is equal to one profile length. They conclude that caution is needed when applying the standard to these methods and the calculated roughness parameters can differ significantly when high waviness occurs [25].

Letocha and Miller investigates the Gaussian filter methods and briefly mentions the end extension methods. The paper stresses that improper choice of Gaussian filter parameters can occlude important information and the most useful method for understanding this is inspection of the filtered profile graphs [26].

Kondo *et al* draw attention to ISO 16610-30 and ISO 16610-31 and describe that none of the filters stated can perform robustly to the three examples given in the standard. The effects are similar to the problems encountered by the ISO 16610-28 methods described in this paper—blunting of corners and steps. A new filter is suggested which performs well in all suggested conditions due to an iterative approach. The authors highlight the long processing time required for 1000–100 000 iterations [27–29].

These reviews highlight that the ISO 16610 series standards require accompanying research into how to apply the methods properly and that any deficiencies in the standards should be highlighted. With a prescriptive gear filtering standard, ISO 1328-1:2013, the only parameters than can be varied within ISO 16610 is the edge extension methods described in part 28. It is deemed most constructive to the gear industry to describe how to best apply these methods within the standards than to provide another alternative filter method.

Additionally, the papers that cover ISO 16610-28 only discuss the zero-padding, line symmetric reflection and point symmetric reflection. It is not mentioned why they restricted themselves to these methods, perhaps due to the availability of the methods coded into software, but all these methods should be investigated.

3. Methodology

The effect of application of the end extension methods described in ISO 16610-28 are analysed by posing the following questions:

- What does the result of the edge extension methods and subsequent filtered data look like?
- Does the filter introduce errors for ideal profile and helix data?
- Does edge chamfering and the tip diameter affect the filtered results and what is the interaction with the default evaluation parameters?

The process of applying the filtering method is:

- Extend data at both edges using the defined method.
- Filter data.
- Discard edges of data not covered by filter to return to original data length.

3.1. Geometry

The profile and helix geometry were defined from the gear geometry in table 1, selected because it has been used in prior papers [30, 31]. The symbols used are the same as in the cylindrical gear geometry standard, ISO 21771 [32] and the gear measurement evaluation standard ISO 1328-1:2013. A gear tooth with the profile, helix and location of important parameters are highlighted in figure 1, also an image of the measured gear. The position and data spacing was defined by measured data.

3.2. Review of the evaluated zones in ISO 1328-1:2013

ISO 1328-1:2013 defines three parameters to be evaluated for profile and helix traces; slope deviation, form deviation, and total deviation. It is assumed that there is no affect from the extension methods on the evaluated parameters when the standard evaluation limits are applied. This is because the measured zone is larger than the evaluated zone by at least one cut-off wavelength. However, we need to consider the effects when chamfers or other surface discontinuities are present. A chamfer or tooth break is typically applied to deburr and protect the edges during the manufacturing process. When applied, the chamfer start position will vary between the profile tip and root diameter of the tooth due to the difficulty in applying the process on a production machine, particularly for involute helicoid geometry.

To understand whether the results will be affected by a chamfer, the cut-off wavelength, λ, needs to be compared to the non-evaluated portion of the measurement, b_{end} and the chamfer magnitude, c. The default cut off wavelength is one thirtieth of the evaluation zone. See the calculation below:

Table 1. Nominal geometry parameter table.

Parameter	ISO symbol	Value
Number of teeth	z	23
Face width	b	44 mm
Normal module	m_n	6 mm
Base diameter	d_b	144.614 mm
Tip diameter	d_a	168.764 mm
Tip relief	C_α	Linear 50 µm
Start of tip relief diameter	$d_{C\alpha}$	166.070 mm
Profile control diameter	d_{Cf}	148.481 mm
Profile form diameter	d	Tip diameter
Helix crowning	C_β	Parabolic 15 µm
Profile evaluation length	L_α	26.66 mm
Profile filter cut off wavelength	λ_α	0.889
Helix evaluation length	L_β	39.6 mm
Helix filter cut off wavelength	λ_β	1.32 mm

$$b_{\text{end}} - \lambda \leqslant c$$

$$\lambda = \frac{b - 2 \cdot b_{\text{end}}}{30}$$

where b_{end} is defined by ISO 1328-1 and is the minimum of normal module and 5% of facewidth; $\min(m_n, 0.05 \cdot b)$. The case where 5% of facewidth is smaller than the normal module follows:

$$\lambda = \frac{b - 2 \cdot 0.05 \cdot b}{30} = 0.03 \cdot b$$

$$0.05 \cdot b - 0.03 \cdot b = c$$

$$\frac{b}{50} \leqslant c. \tag{1}$$

When the module is smaller than 5% of facewidth the calculation follows:

$$\lambda = \frac{b - 2 \cdot m_n}{30}$$

$$m_n - \frac{b - 2 \cdot m_n}{30} \leqslant c$$

$$\frac{32 \cdot m_n - b}{30} \leqslant c. \tag{2}$$

This shows that the limit of facewidth before artefacts are introduced into the evaluation region, with a chamfer size of 0 mm, is 32 times module. The combined effect of these equations is shown graphically in figure 2, where the default evaluation lengths and cut off wavelengths specified by ISO

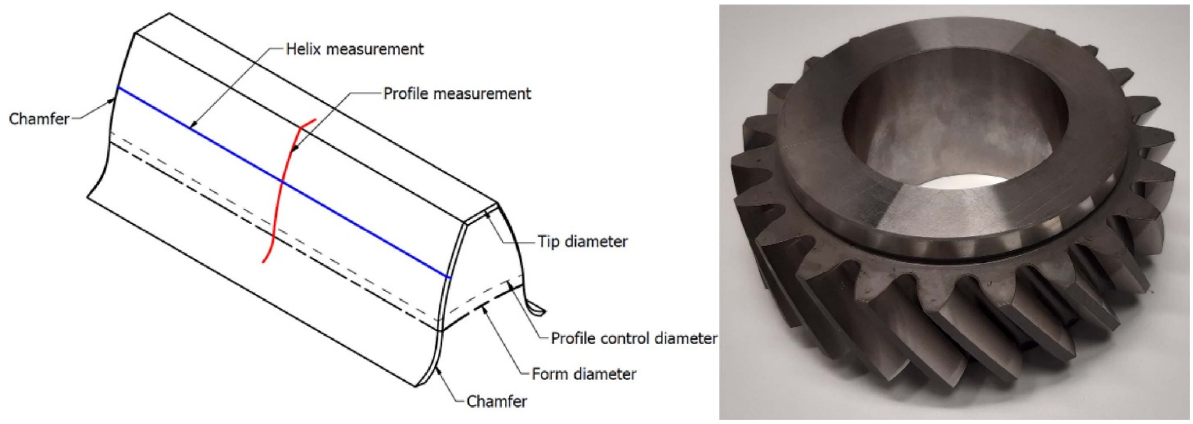

Figure 1. Gear tooth with profile and helix measurement (left), image of measured gear (right).

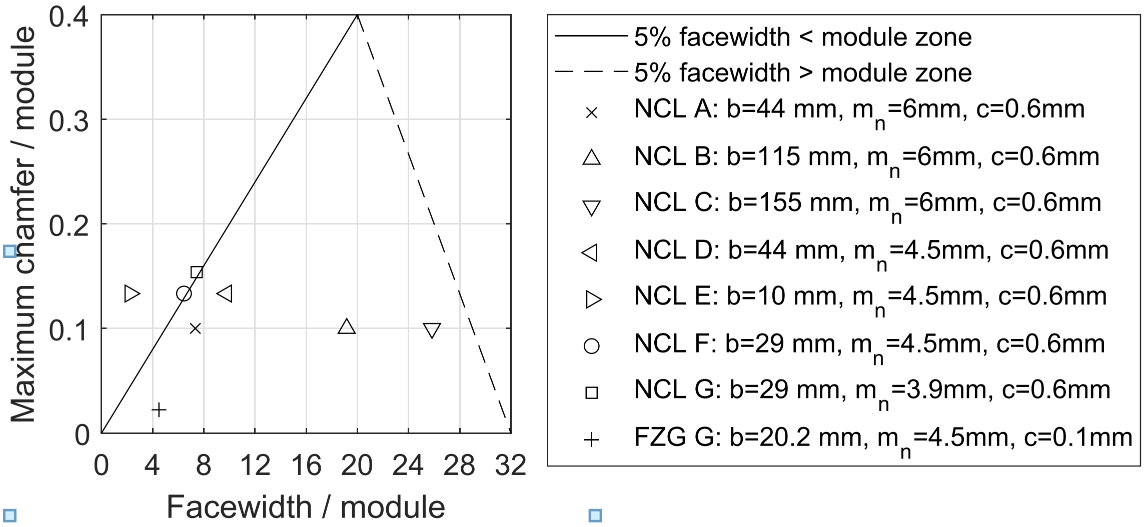

Figure 2. Maximum chamfer per module allowed before filtering artefacts occur when default evaluation zone and cut off wavelengths specified by ISO 1328-1:2013 are used. Gear geometries used at Newcastle University (NCL) with maximum chamfer tolerance (0.6 mm) and in FZG geometry ISO 14635-1:2000 with an assumed chamfer of 0.1 mm. In legend b is face width, m_n is normal module, c is chamfer magnitude.

1328-1:2013 are used. Also shown are the locations of various gear geometries used at Newcastle University to evaluate contact fatigue, micropitting and scuffing performance and the FZG scuffing load capacity of oils test geometry defined in ISO 14635-1:2000.

3.3. Defining filtering regions

This section describes the reasons for proper preparation of data before filtering. In the circumstances when the surface beyond the evaluation range is important the effect of the filter is significant. As the cut off wavelength increases, the effect from the chamfer extends across a greater evaluation length and the sharp discontinuity at the end of the facewidth is rounded. This may be significant when used in a TCA model, or as part of a digital twin, where the rounding effect may produce significantly different stresses, contact loads and contact conditions that are hidden by the filter. A similar rounding effect occurs at the interface between the end of profile and the tip land. When contacting over the tip with the probe rounding of the profile occurs and the tip appears to extend further than it should, as illustrated in figure 3. This is a mechanical morphological closing filter caused by the probe radius. As the probe traverses beyond the tip the probe will fall off dramatically and this may be captured by the measuring machine in the measurement data. When filtering a profile with this apparent tip extension—and 'fall off' in the resultant trace—will show additional minus metal at the end of tip relief. If this is used to evaluate the magnitude of tip relief, the tip relief amount will appear to be larger than the actual amount applied. This may result in not putting sufficient tip relief on the gear which may cause higher noise and vibration, increased friction losses, contact stresses and scuffing risk.

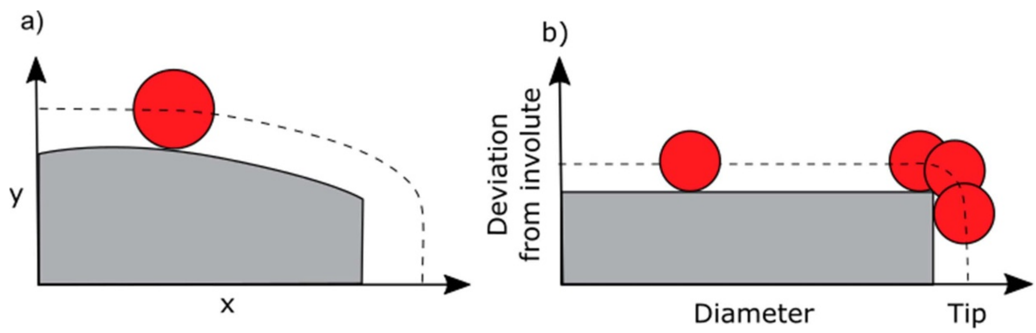

Figure 3. (a) Illustration of probe measurement of an involute gear tooth in Cartesian co-ordinate system. (b) Deviation map of measurement with various probe positions. Flat line represents no deviation from involute, tip land is at a constant radius and will be an almost vertical line on deviation plot. Path traced by centre of probe shown as dashed line. Assuming no probe radius compensation, gear tooth will appear to extend further than the tip diameter with a rounded shape rather than the sharp discontinuity of the tip region.

A simple method of addressing both the chamfer and tip extension problem is to treat the data before filtering by dividing the trace length into separate filtering zones—removing the data where we know no more material exists:

- At the chamfer location.
- At the tip diameter (nominal or measured separately).

Combined with the edge extension methods this removes the effect of large non-contacting features on the filtered data.

4. Results

4.1. Synthetic profile and helix data

4.1.1. Visual inspection of extension methods. Synthetic profile and helix data was created following the geometry in table 1 and the end extension methods from ISO 16610-28 were applied. An exaggerated filter response is shown in figure 4. It can be seen from inspecting the end extension methods that:

- Zero padding causes a large discontinuity after tip relief and crowning and is thus not recommended when microgeometry is applied.
- End padding (author modification of zero padding) extends the first and last data points mitigates the problems with zero padding somewhat but does not eliminate them.
- Linear extrapolation is well suited for both profile and helix traces, even though it cannot replicate the parabolic shape of crowning microgeometry corrections.
- LSR works well whenever the trace form is flat, such as the start of profile.
- PSR continues the trace trend well provided there is no local large error (such as waviness) which would cause a large change in the resulting mean line.

The MRC is a complicated method that can be adjusted based on the order of the nominal trace characteristic but does

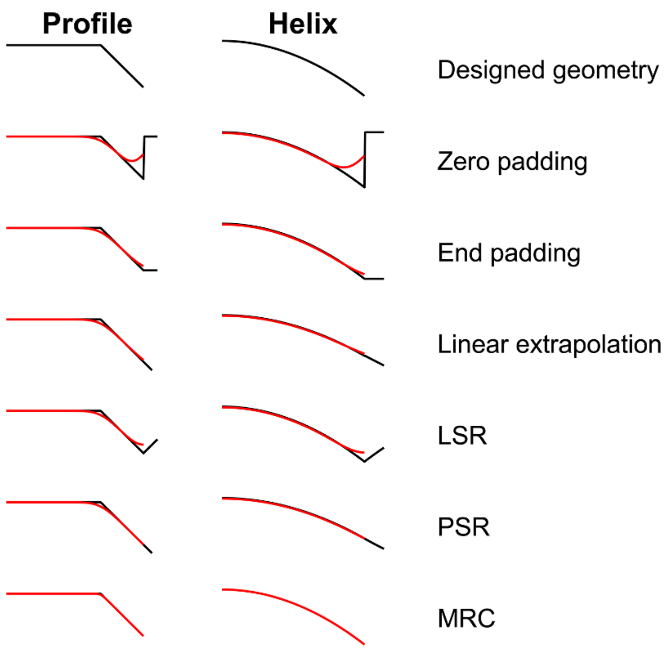

Figure 4. Comparison of filter methods for profile (left column) and helix (right column) showing the extended trace (black) and an exaggerated result from the filter (red).

not require extension of the trace at all. It calculates statistical parameters of the trace and then weights the Gaussian curves (truncated at the edges) to maintain the 0th–2nd derivatives—simplified as mean, slope, curve. It requires several looped operations and is significantly more complicated computationally than the other methods. It is far more difficult to understand what the filtered trace may look like before filtering. ISO 16610-28 gives the mathematical definition of the filter but successfully implementing this was onerous. The authors could not find an example implementation of this filter but checked the filter implementation against ideal data for a zero trace, line, and parabola with relative differences less than 1 nm.

The pseudocode for the MRC is provided at the end to aid implementation.

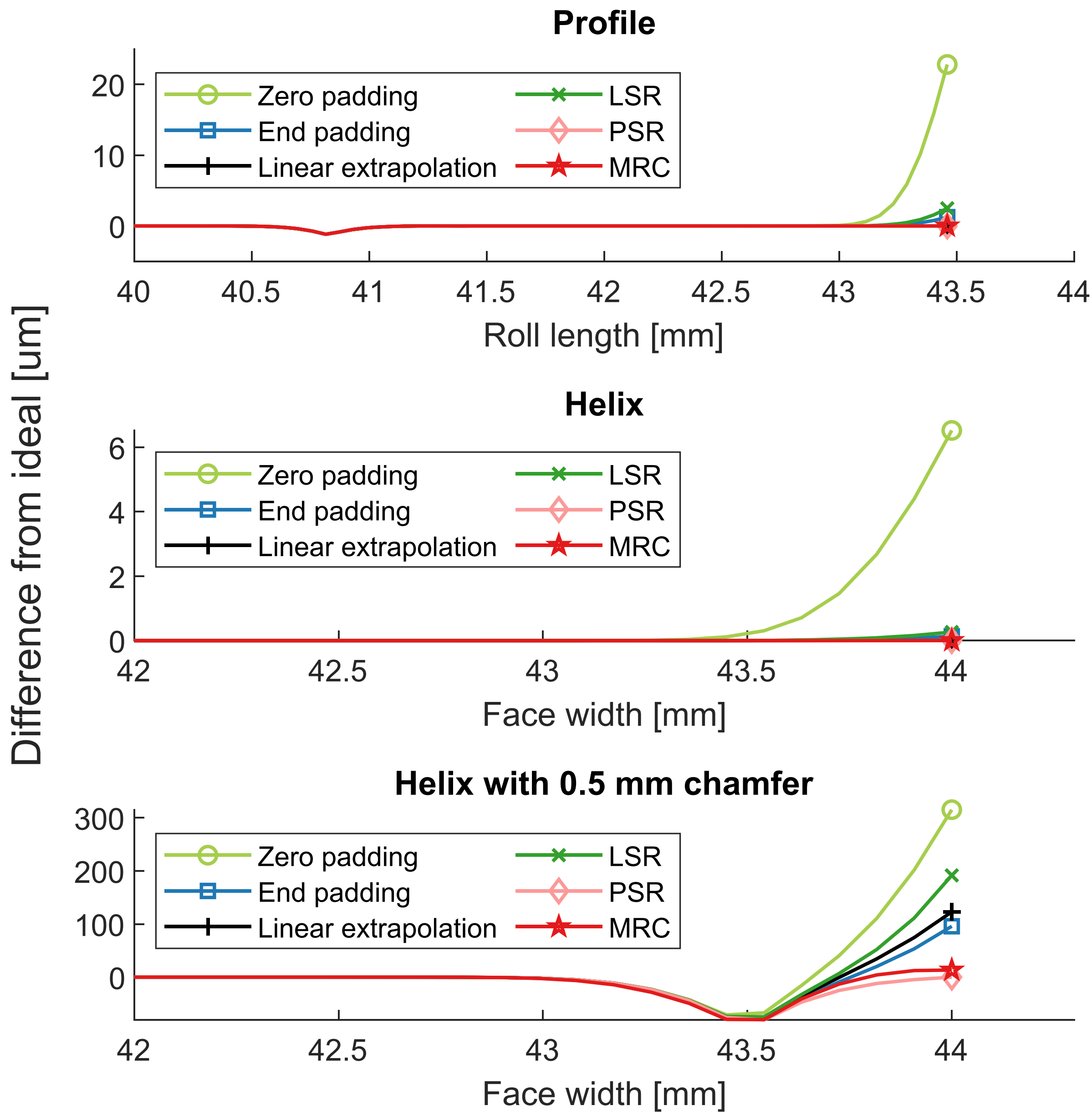

Figure 5. Difference from filtered traces and ideal traces for the various end effect methods for ideal profile (top), ideal helix (middle), ideal helix with 0.5 mm chamfer (bottom).

Table 2. Difference between filtered traces and ideal traces at the end point.

	Difference at end point (rounded to nearest 0.1 µm)		
End effect method	Profile	Helix	Helix with chamfer
Zero padding	22.8	6.5	315.2
End padding	1.3	0.1	95.8
Linear extrapolation	0.0	0.0	122.9
Line symmetrical reflection (LSR)	2.5	0.3	191.6
Point symmetrical reflection (PSR)	0.0	0.0	0.0
Moment retainment criterion (MRC)	0.0	0.0	13.4

4.1.2. Analysis of errors caused by extension methods. The difference between the methods and ideal traces have been plotted in figure 5 and end point difference recorded in table 2. Linear extrapolation, PSR and MRC show the closest results to ideal. It is the authors opinion that the extra precision of the MRC method does not outweigh the extra computational complexity and technical understanding required. To implement the method metrologist discretion should be used, and the most suitable method considered before each application. These extension methods can be applied to any application of surface texture analysis but considering the specific application for gears we can assume that when microgeometry is present the suitable methods reduce to:

- Linear extrapolation.
- PSR.
- MRC.

By adding 0.5 mm × 45° chamfers to the ideal helix data, we can observe the errors induced by this surface discontinuity. The bottom plot in figure 5 shows that data around the start of chamfer (43.5 mm) is pulled down significantly. The magnitude of error is ∼70 µm, however this is underestimated due to the data point spacing which does not occur exactly on the start of chamfer location. The chamfer has not affected the trace within the evaluation limits for this geometry, but the extents are greatly affected.

Using equation (2) for the geometry modelled, $b/50$ is 0.88 mm which is greater than the chamfer of 0.5 mm. If the chamfer was 1 mm there would be an artefact on the measured results at the evaluation limits, however, this effect is still limited to errors in nanometres as it is at the tail end of the Gaussian filter, thus is not a significant issue. The chamfer would need to be increased to 1.64 mm to see an error greater than 1 µm at the evaluation range. This would then start to significantly affect the evaluated parameters in ISO 1328-1, particularly form and total deviation.

4.1.3. Effect of trimming data before filtering. The effect of trimming data beyond the tip diameter before filtering is investigated for the MRC method. Data beyond the tip has a large impact when the deviations are relatively large compared to the profile. The analysed data is illustrated in figure 6 and it can be seen that an error of −13 µm occurs approaching the tip diameter then increasing sharply to +18 µm error just beyond the tip diameter.

Figure 7 shows the results when the data beyond the tip diameter is removed before filtering, and the effect is completely removed. Additionally, a rounding of the profile at the start of tip relief occurs for both results, which could be controlled by the same method—dividing into a pre and post tip relief filter regions which are filtered independently. The effect for this geometry is minimal and in reality, the transition to tip relief is not infinitely sharp. This is therefore an application specific metrology decision to be made.

Controlling helix data for chamfer transitions will be simpler as the magnitude of deviation changes are in orders of millimetres. It should be noted that some measurement software has chamfer detection built into the analysis and will automatically define a filter region to be within the chamfers detected.

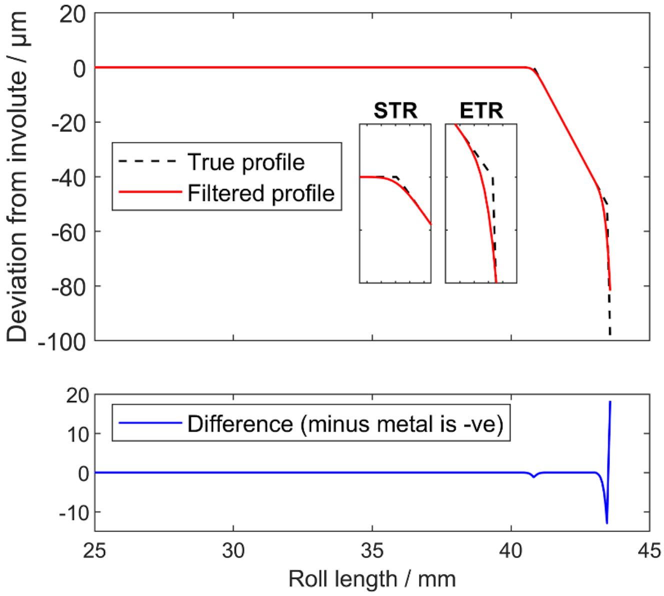

Figure 6. Filtered profile (MRC method) including tip land, moment retained $n = 1$. Start of tip relief (STR) and end of tip relief (ETR) regions highlighted.

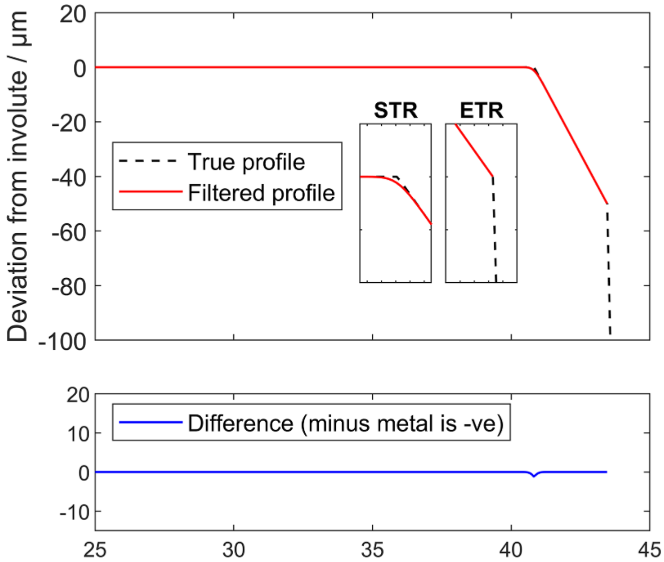

Figure 7. Filtered profile (MRC method) after excluding tip land, moment retained $n = 1$. Start of tip relief (STR) and end of tip relief (ETR) regions highlighted.

4.2. Measured results

A single profile and helix were measured on the gear with the geometry defined in table 1 of the gear shown in figure 3(b). The data was filtered using the PSR edge extension method and the results compared with and without trimming data beyond the tip and chamfers before filtering. The plotted traces can be seen in figure 8 and the improvement of trimming data can be seen visually as it closely follows the unfiltered data as

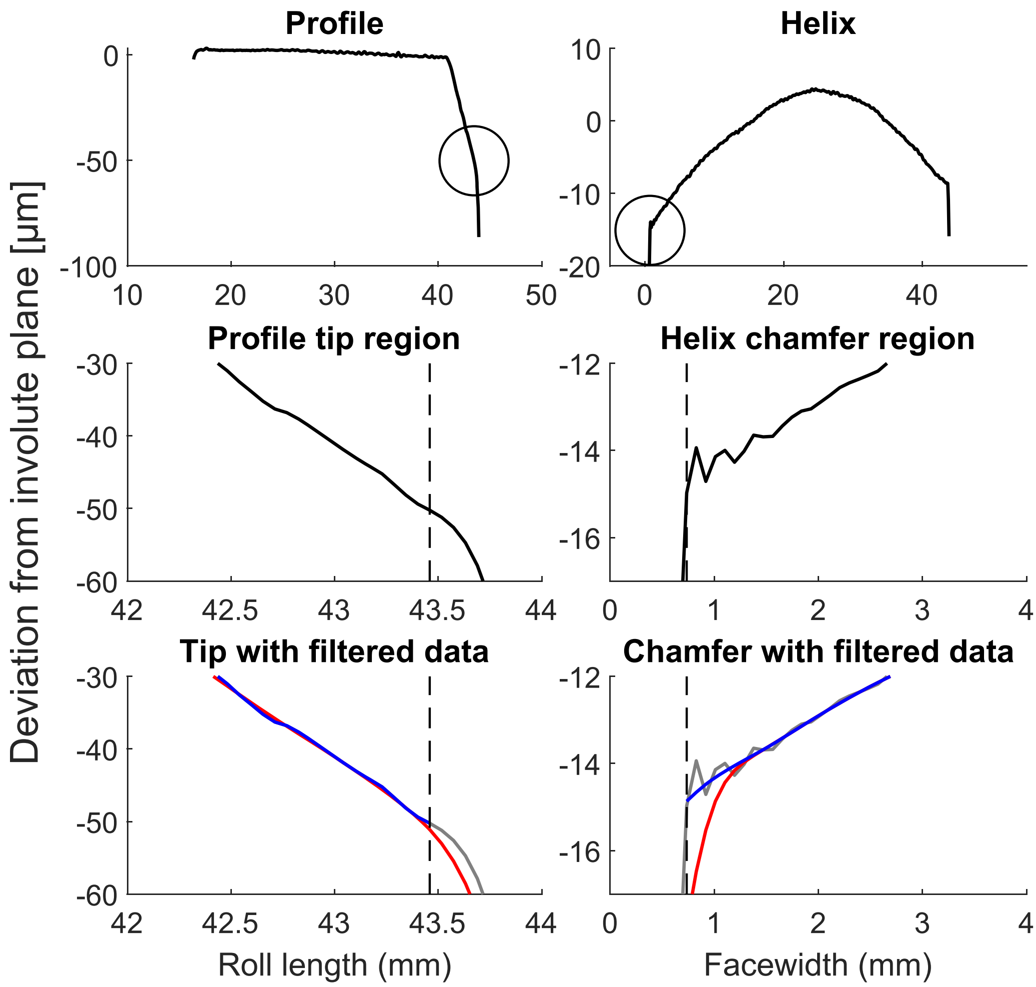

Figure 8. Measured profile (left) and helix (right) data, top row shows full trace, middle row shows zoomed tip and chamfer region with dashed limits, bottom row shows zoomed regions with un-cut filtered data (red), cut filtered data (blue) and original profile (grey). Y-axis is deviation from involute in microns for all plots. PSR end effect method used in filtering.

Table 3. Error from filtering without trimming versus with trimming data.

Position	Error (μm)
Profile tip	0.9
Helix chamfer (left)	2.9
Helix chamfer (right)	3.5

we expect. Table 3 compares the magnitude of error between the methods.

5. Conclusions and recommendations

The effect of the extension methods and filtering in ISO 16610-28 combined with the gear evaluation standard ISO 1328-1 has been reviewed for synthetic data and measured data. The following conclusions and recommendations are presented:

- Data within the evaluation zone close to discontinuities, such as chamfers, end relief and tip relief can be affected by the filter.
- These effects can be eliminated by:
  - Defining the evaluation limits that are greater than one cut-off wavelength away from any discontinuities—which may be different than the standard evaluation limits defining in ISO 1328-1:2013.
  - Defining the face width chamfer/end relief position and magnitude so that it is greater than one cut-off wavelength away from the evaluation limits.
- Where the edge data is important to characterise the end effect, methods in ISO 16610-28 should be applying by either:
  - Choosing the start of measurement positions that exclude any discontinuities.
  - Defining filtering regions that reduce or eliminate the effect of discontinuities.
  - Note that the 'correct' end effect method is application specific and will be based on the metrologists discretion—however, the author's recommendation is the point symmetric reflection method based on the analysis in this paper.

These are essentially the same strategy but implemented either before or after measurement by the metrologist or by software. The measurement position method will be gear or even tooth specific as tip diameters and chamfer positions vary. The filter region method can be applied automatically and is already implemented in some measurement software for helix measurement in the form of chamfer detection. A metrologist should be aware of these issues and understand how this may affect their data and interpreting the measurement results.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This work was funded by the UK Government's Department for Business, Energy & Industrial Strategy, National Measurement System for the National Gear Metrology Laboratory at the University of Newcastle upon Tyne.

MRC psuedocode

Pseudocode provided to aid understanding and implementation of the MRC filter method described in ISO 16610-28.

Data: Trace, cut off wavelength, number of retained moments
Result: Filtered trace using the MRC
One cut off wavelength at either end defines edges of data
For all positions in Trace
    Read current position in Trace
    While at edges of data
        For one to number of retained moments
            Numerically integrate moment function centred on current position
            Save result into a Hankel matrix
        End
        Solve matrix to get weight values for moment functions
        Sum weighted moment functions to get modified filter curve
        Numerically integrate the elementwise product of Trace and modified filter curve to get filtered point
    Else
        Use standard Gaussian filter to get filtered point
    End
    Save filtered point
End

ORCID iDs

Tom Reavie https://orcid.org/0000-0003-3981-6077
Brian Shaw https://orcid.org/0000-0002-5778-9917

References

[1] Tom L, Khowja M, Vakil G and Gerada C 2021 Commercial aircraft electrification—current state and future scope *Energies* **14** 8381
[2] Köller S and Schmitz V 2022 Systematic synthesis and multi-criteria evaluation of transmission topologies for electric vehicles *Automot. Eng. Technol.* **7** 65–79
[3] BS ISO 1328-1:2013 2013 *Cylindrical Gears-ISO System of Flank Tolerance Classification* (British Standards Institution)
[4] Shah R, Woydt M, Tung S and Rosenkranz A 2022 Grease *Lubricants* **10** 45
[5] Zhang J, Dong M and Hu Y 2022 Influence of coating material on elastohydrodynamic lubrication between gear meshing interfaces based on direct coupling solution *Adv. Compos. Hybrid Mater.* **5** 3117–36
[6] Artoni A 2018 A methodology for simulation-based, multiobjective gear design optimization *Mech. Mach. Theory* **133** 95–111
[7] Wang S, Zhou Y, Tang J, Tang K and Li Z L 2022 Digital tooth contact analysis of face gear drives with an accurate measurement model of face gear tooth surface inspected by CMMs *Mech. Mach. Theory* **167** 104498
[8] Morales-Espejel G, Rycerz P and Kadiric A 2018 Prediction of micropitting damage in gear teeth contacts considering the concurrent effects of surface fatigue and mild wear *Wear* **398–399** 99–115
[9] Castro J and Seabra J 2018 Influence of mass temperature on gear scuffing *Tribol. Int.* **119** 27–37
[10] Peng B, Spikes H and Kadiric A 2019 The development and application of a scuffing test based on contra-rotation *Tribol. Lett.* **67** 1–25
[11] Lin J, Bergstedt E, Lindholm P, Shi Z and Olofsoon U 2019 *In situ* measurement of gear tooth profile during FZG gear *Surf. Topogr.: Metrol. Prop.* 7
[12] BS ISO 14635-1:2000 2000 *Gears—FZG Test Procedures* (British Standards Institution)
[13] PD ISO/TS 6336-20:2017 2017 *Calculation of Load Capacity of Spur and Helical Gears. Calculation of Scuffing Load Capacity (Also Applicable to Bevel and Hypoid Gears)—Flash Temperature Method* (British Standards Institution)
[14] PD ISO/TS 6336-21:2017 2017 *Calculation of Load Capacity of Spur and Helical Gears. Calculation of Scuffing Load Capacity (Also Applicable to Bevel and Hypoid Gears). Integral Temperature Method* (British Standards Institution)
[15] PD ISO/TS 6336-22:2018 2018 *Calculation of Load Capacity of Spur and Helical Gears. Calculation of Micropitting Load Capacity* (British Standards Institution)
[16] Amendola J, Amendola J and Errichello R 2019 Calculated scuffing risk: correlating AGMA 925-A03, AGMA 6011-J14 and original MAAG gear predictions *2019 Fall Technical Meeting* (American Gear Manufacturers Association)
[17] Kamycki W and Noga S 2020 Application of the thin slice model for determination of face load distribution along the line of contact and the relative load distribution measured along gear root *Strojniški vestnik—J. Mech. Eng.* **66** 300–10
[18] Hutt S, Clarke A, Pullinand R and Evans H 2019 The acoustic emission from asperity interactions in mixed lubrication *Proc. R. Soc.* **475** 20180900
[19] Prajapati D K 2021 Prediction of coefficient of friction for different surface topography in mixed-EHL regime *Surf. Topogr.: Metrol. Prop.* **9** 015008
[20] BS EN ISO 16610-28:2016 2016 *Geometrical Product Specifications (GPS)—Filtration, Part 28: Profile Filters: End Effects* (British Standards Institution)

[21] VDI/VDE 2612 2000 *Profile and Helix Checking of Involute Cylindrical Gears* (VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik)

[22] Wisnewska M and Zeobrowska-Lucyk S 2014 Toward improved performance in separation of roughness, waviness and form: ISO 16610 series *IMEKO TC10 Workshop on Technical Diagnostics* (Warsaw)

[23] Seewig J and Eifler M 2013 Periodic Gaussian filter according to ISO 16610-21 for closed profiles *Precis. Eng.* **38** 439–42

[24] BS EN ISO 16610-21 2012 *Geometrical Product Specifications (GPS)—Filtration Part 21: Linear Profile Filters: Gaussian Filters* (British Standards)

[25] Tomov M, Kuzinovski M, Trajcevski N, Cichosz P and Skowronek H 2014 Influence of the end effects on roughness parameters for short non-periodic profiles *Mechanik* **9** 323–7

[26] Letocha A and Miller T 2015 The essence of proper selection of Gaussian filtration parameters (Mechanik) 2

[27] Kondo Y, Numada M, Yoshida I, Yamaguch Y and Machida H 2021 L1-norm Gaussian filter satisfying all three robust examples in ISO16610-30 *Measurement* **181** 109622

[28] BS EN ISO 16610-30:2015 2015 *Geometrical Product Specifications (GPS)—Filtration—Part 30: Robust Profile Filters: Basic Concepts* (British Standards)

[29] BS EN ISO 16610-31:2016 2016 *Geometrical Product Specifications (GPS)—Filtration Part 31: Robust Profile Filters: Gaussian Regression Filters* (British Standards)

[30] Koulin G, Reavie T, Frazer R and Shaw B 2018 Economic method for helical gear flank surface characterisation *Surf. Topogr.: Metrol. Prop.* **6** 015001

[31] Reavie T, Koulin G, Frazer R, Wilson S and Shaw B 2019 A method to quantify waviness measurement capability of a gear measurement machine *Surf. Topogr.: Metrol. Prop.* **7** 015002

[32] BS ISO 21771:2007 *Gears—Cylindrical Involute Gears and Gear Pairs—Concepts and Geometry* (British Standards)