Implementing ISO 18653—Gears: Evaluation of Instruments for Measurement of Individual Gears

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Management Summary

A trial test of the calibration procedures outlined in *ISO 18653—Gears: Evaluation of Instruments for the Measurement of Individual Gears*, shows that the results are reasonable, but a minor change to the uncertainty formula is recommended. Gear measuring machine calibration methods are reviewed. The benefits of using workpiece-like artifacts are discussed, and a procedure for implementing the standard in the workplace is presented. Problems with applying the standard to large gear measuring machines are considered and some recommendations offered.

Introduction

Cylindrical, involute gears are precision components with a relatively complex geometry that must be made accurately to fulfill their specification in terms of noise, power density and reliability. It is common for gears to specify profile, helix and pitch tolerances in the 5–10 μm region, and many applications demand tighter tolerances. Modern machine tools, operated in a carefully controlled environment and correctly managed, can achieve these tolerances provided there is an appropriate independent method of measuring the geometrical accuracy of the gears and thus control the process.

Figure 1—CMM used for gear measurement.

The traditional Golden Rule for metrology is that the uncertainty of a measurement process should be 10% of the tolerance inspected. Measurement uncertainty is the term used to quantify the unknown random and systematic errors that occur in any measurement process. With tolerances of 5–10 μm, our measurement uncertainty should be 0.5–1.0 μm on the shop floor, which is still too difficult to achieve, and even national measurement institutes (NMIs) around the world can just barely achieve these levels. Thus the shop floor measuring instrument capability is an important consideration when interpreting measurement result conformance with specification.

In recent years, the range of gear measuring equipment available to the gear manufacturer has expanded. There is greater choice of dedicated 4-axis CNC gear measuring machines (GMMs) with three linear axes, a rotary table and tailstock. General purpose coordinate measuring machines (CMMs) are now equipped with gear measurement software where previously only the highest quality machines were considered for gear measurement applications. Recent improvements in error mapping to improve measurement performance and the introduction of scanning probe systems has meant that now even relatively modest-cost CMMs can be considered for gear measurement applications. The gear manufacturer has a wider choice of measurement solutions than ever before, but how should the appropriate solution be selected?

It is surprising therefore, that when ISO published ISO 18653 in 2003, *Gears: Evaluation of Instruments for the Measurement of Individual Gears* and a supporting technical report (guidance document) ISO/TR 10064-5, that the gear industry has not adopted the recommendations and applied the standard more widely.

The proposal to develop the ISO document came from AGMA using ANSI/AGMA 2010-A94, *Measuring Instrument Calibration, Part 1–Involute Measurement*, as the working document. Other documents are also used extensively throughout the gear industry. The VDI/VDE guidelines 2612 and 2613 (Refs. 1–2) propose limits on measurement uncertainty, depending on the DIN 3962 quality grade. They were first published in the 1980s but were revised in 2000. The guidelines also prescribe limits on runout of centers, machine alignment and instrument repeatability and, importantly, the uncertainty of the calibration data artifacts used to prove machine capability. The VDI/VDE measurement uncertainty limits are used to define the measurement capability of the instruments worldwide.

In the U.K. in the early 1990s, there was general acceptance of the philosophy of the VDI/VDE guidelines, but it was considered that more guidance on the procedure to assess measurement uncertainty was required. Also, more guidance on the routine testing of measurement instruments was required. The result of this was a series of codes of practice prepared by the U.K. National Gear Metrology Laboratory (NGML) and published by the British Gear Association (BGA) (Ref. 3).

One of the reasons that the guidance in ISO 18653 is not more widely adopted is that measurement uncertainty is seldom considered unless a dispute occurs, usually between customer and supplier. The supplier's measuring machine shows the gears are within tolerance and customer's machine indicates the gears are outside tolerance and thus rejects them. Sometimes the cause of the disagreement is simply the interpretation of the specification—a gear mounting error or a mistake in the measurement process—but at other times the cause of the differences is subtler. All measurement processes contain error, including NMI and shop floor machines. The only certainty is that the measurement result is wrong.

ISO 18653 addresses traceability; calibration intervals; sources of measurement uncertainty or errors; basic instru-

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Figure 2—Example GMM: the U.K. primary gear measuring machine.

Figure 3—Micrometer and M8-gauge block set used for functional micrometer calibration.

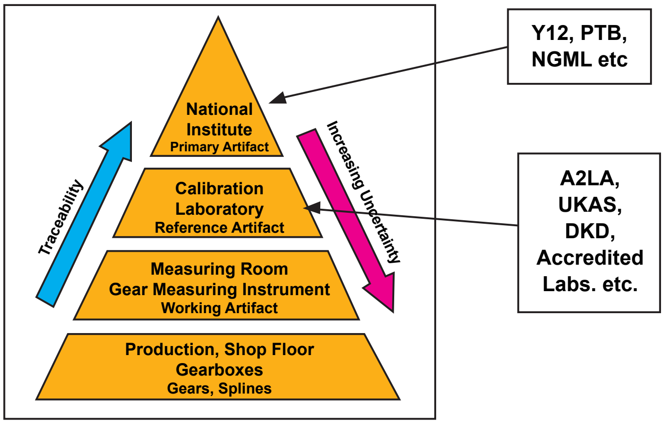

Figure 4—Example of traceability chain for gears using artifacts as transfer standards.

ment checks; environmental conditions; and calibration artifact design. It also provides a method for estimating measurement uncertainty, containing sound guidance on how to estimate gear measurement uncertainty using simple, robust methods. It allows users to assess the differences in measurement instrument capability and thus make informed choices. It minimizes the risk associated with high-accuracy gearing operating in safety-critical situations and allows manufacturers to focus on manufacturing gears rather than measuring them.

Calibration Methods—Micrometer Example

It is the experience of the authors that many gear manufacturers consider that they carefully maintain and calibrate their gear measuring machines. Compared to the care taken to calibrate a simple instrument such as a micrometer, shown in Figure 3, we do very few tests. A typical micrometer calibration procedure is as follows:

- Check that the micrometer spindle is free through its range of operation and the lock functions correctly.
- Verify the fixed anvil is flat within defined limits and free from damage with a calibrated optical flat.
- Verify the moving anvil is free from damage with an optical flat and then verify that the two anvils are parallel within limits with an optical parallel. It is usual to use five optical parallels with different thicknesses arranged to set the spindle at different angles to verify for spindle runout.
- Check that the zero point is within acceptable limits and adjust if necessary.
- Use a range of traceably calibrated gauge blocks to verify the measurement performance through the 25 mm range of operation. It is usual to use 8 gauge blocks (M8) set as a functional verification of the performance of the micrometer.
- If all the results are within acceptable limits, the calibration is complete and the micrometer is returned to the shop for use.

In addition, before use, every competent operator checks the zero point setting and ensures that it is within its calibration interval. We apply these thorough checks to a simple single-axis measuring instrument used to inspect simple lengths with tolerances of 15–100 μm.

Many users of gear measuring instruments do not calibrate them with this rigor. Most rely on the machine service engineer to perform a calibration with the gear artifacts supplied with the machine when it was originally installed. They may use a gear artifact to verify the machine at three- or six-month intervals and then use a mandrel to check alignment, but in general the measurement uncertainty is only considered when there is a problem, flagged by manufacturing machine operators or the customer.

ISO 18653—How it Works

The key concepts in the ISO 18653 standard are summarized below:

- Measurement uncertainty is assessed by performing a series of measurements on a gear or gear artifact that has been calibrated in an accredited calibration laboratory.
- It is a comparison process: the results from the calibration laboratory are compared with the results from a series of measurements on the subject measuring machine.
- All parameters that the machine will measure and evaluate (profile, helix, pitch and tooth thickness parameters) are analyzed.
- The gear or gear artifact should be of similar geometry to product gears inspected by the measuring machine (geometrical similarity implies the same size and weight, module, helix angle, face width and, where possible, the same measurement position and locating arrangement on the measuring machine). Artifact design is discussed in detail in ISO/TR 10064-5.
- It is preferable that data for the series of measurements is gathered over a long period of time so that effects from temperature variation, machine alignment and different operators are taken into account (reproducibility data). The ISO procedure uses the mean and standard deviation from these tests to estimate measurement uncertainty. The minimum number of tests is 10, but 30 is recommended.
- Guidance on other factors that are known to affect measurement results is given, such as temperature and instrument alignment (ISO/TR 10064-5 covers these in detail).
- It recommends minimum recalibration intervals for gear artifacts.
- The methods are consistent with those used for task-specific calibration in general metrology with CMMs.
- If the calibration artifact is significantly different to the product gear geometry, additional time-consuming tests are needed to establish an uncertainty budget for the product gear. This is why the standard recommends that the calibrated gear is similar to the product gears.
- The subject of fitness for purpose of the instrument is complex and is not covered in the standard, but is discussed in detail in ISO/TR 10064-5.
- An accredited calibration laboratory is one that complies with the requirements of ISO 17025, i.e.—laborratories accredited by A2LA, DKD, UKAS, etc. The calibration certificate states how the gear was measured, calibration data and its measurement uncertainty.

Care has been taken when preparing the document to make it applicable to dedicated GMMs and CMMs.

Traceability

The requirement that calibration data is supplied by an ISO 17025-accredited laboratory implies measurement traceability. Traceability implies that there is an unbroken chain of calibrations between the subject measurement result and the primary standards (of length, angle and temperature for the dimensional measurement of gears) at the NMI. Traceability is usually established or transferred by calibrated artifact and is illustrated in Figure 4.

Thus data from a properly accredited calibration laboratory is required to establish measurement uncertainty.

Estimating Measurement Uncertainty

It has long been recognized that measurement processes are subject to errors that are not known and therefore cannot be corrected. The results from any measurement process are thus incomplete without the statement of its associated measurement uncertainty. It is common practice to define a measurement uncertainty (U95) with a specific confidence interval of 95%, meaning that there is a 95% chance that the actual result lies within the upper and lower stated limits. There remains, obviously, a 5% chance the actual result is outside the upper and lower limits stated. This is illustrated in Figure 5. The measurement uncertainty statement is a statistical definition of how we quantify measurement uncer-

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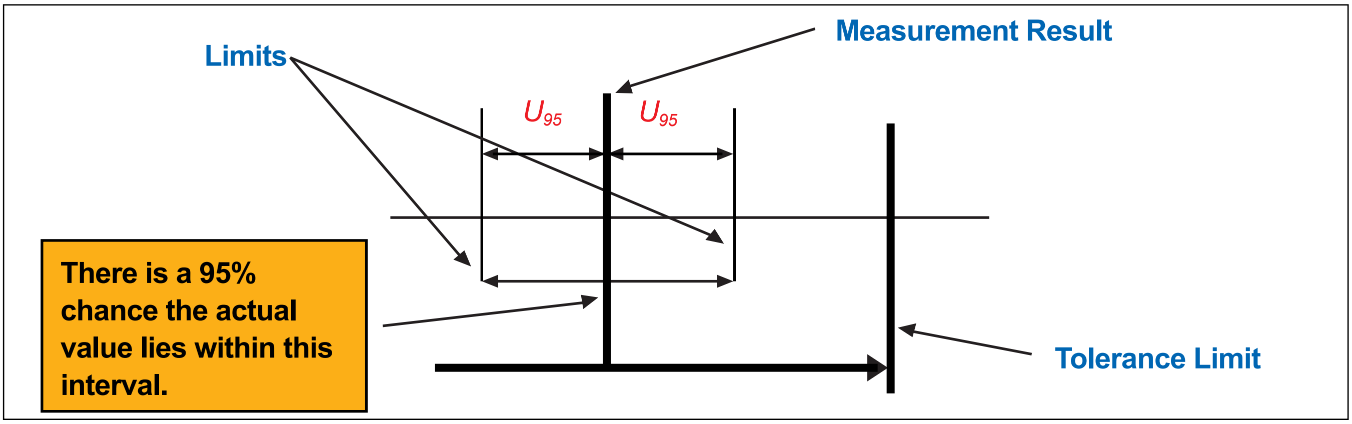

Figure 5—Definition of measurement uncertainty.

Figure 6—Traditional Fellows-type helix (lead) artifact.

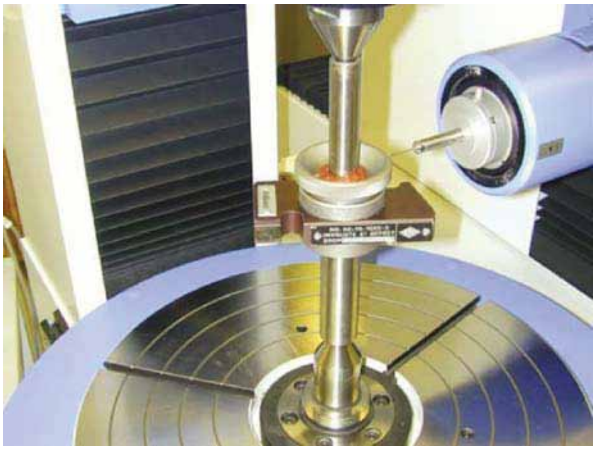

Figure 7—Traditional Fellows involute profile master.

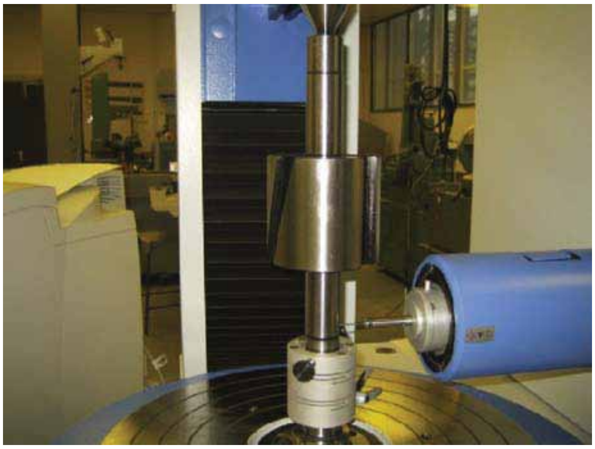

Figure 8—Traditional 100 mm-diameter helix and profile artifact (from Europe).

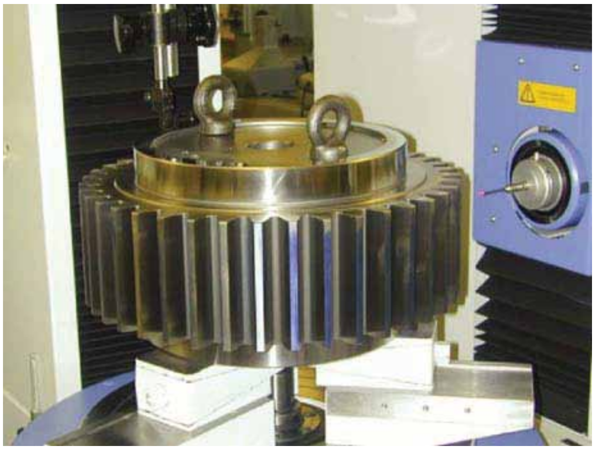

Figure 9—Workpiece-like artifact: master gear to verify a specific geometry.

tainty. The general calculation as defined in ISO 18653 is:

$$U_{95} = k\sqrt{\left(u_m^2 + u_n^2 + u_g^2 + u_w^2\right)} + |E| \quad (1)$$

where :

K = a coverage factor is set to 2 to give an approximate 95% confidence interval, assuming the distribution is a normal distribution.

u_m = standard deviation of the series of reproducibility tests of the subject machine (10–30 test results are required to comply with the standard).

u_n = calibration artifact standard deviation. Assumed to $U_{95}/2$ where U_{95} is calibration certificate measurement uncertainty.

u_g = geometrical similarity uncertainty to account for difference in geometry between the calibrated artifact and the product gears measured.

u_w = workpiece similarity uncertainty, accounting for uncertainty due to the workpiece—e.g., it could be due to excessive workpiece deflection during measurement or poor datum surface quality, etc.

E = bias or difference between the mean measured data (x_{mean}) and the calibration value (x_{cal}).

This relatively simple formula (Ref. 1) is very difficult to apply in practice without suitable experience in modeling measurement uncertainty, but ISO/TR 10064-5 provides information on applying it to common situations.

The easiest situation is to estimate the uncertainty of measurement taken on the calibrated gear artifact used to establish traceability. In this situation, U_g and U_w are zero, because the product gear we are measuring is the calibration artifact (or a near-identical copy of it). Thus the resulting formula is simplified to the standard deviation of the calibration data, standard deviation of the measurements on the subject measuring machine and the bias (difference) between the mean of the measurements and the calibration data values, as:

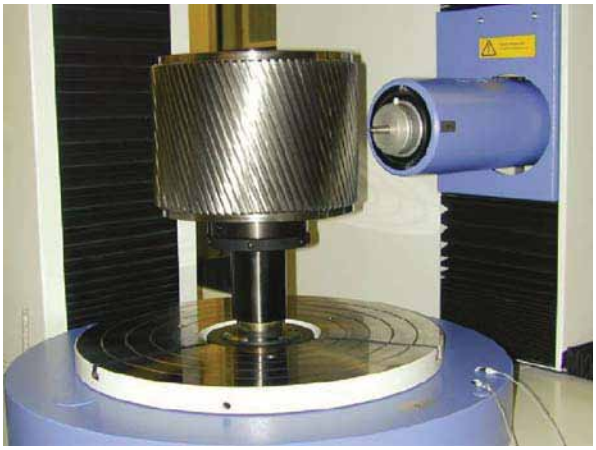

Figure 10—Workpiece-like artifact: 180 mm-face width master involute spline for aerospace applications.

$$U_{95} = k\sqrt{\left(u_m^2 + u_n^2\right)} + |E| \quad (2)$$

The procedures for estimating values of u_g and u_w are more complicated and discussed briefly in ISO/TR 10064-5 but the details, particularly for u_g when there are significant differences in gear geometry between the calibrated artifact, are beyond the scope of that document. Some methods to overcome this are discussed in the following sections, but the recommendation that users obtain workpiece-like artifacts to establish traceability avoids the difficulty of establishing the u_g uncertainty contributions.

Artifacts and Master Gears

ISO 18653 provides examples of different artifact designs, and ISO/TR 10064-5 provides further information on the design and specification of artifacts. Users should ensure they have artifacts that cover all the features that are measured on the measuring machine, including profile, helix, pitch, tooth thickness and other features such as datum axis runout correction.

Traditional artifacts are illustrated in Figures 6–8. These were originally developed to prove the performance of manual gear measuring machines, where base discs were used with a mechanical sine bar to set the base helix angle. In these cases, the range of helix angles was necessary to ensure that the sine bar was correctly set and no excessive play affected results when measuring left- or right-helix angles. The benefit of this artifact style is that a single artifact can test a range of geometries, and the source of any bias due to a machine setting can be established. As such, they are very useful for investigative work in calibration laboratories (Refs. 4–5). The disadvantage is that they often do not use the same software as standard gear measurement processes, and require manual intervention to measure them correctly. A further disadvantage is that many measuring machine suppliers use identical artifacts, calibrated by NMIs to error map the machine and, thus, when the user tests the machine with the same geometry artifact, the measurement results can give an overly optimistic assessment of measurement uncertainty.

Although the older style of gear artifacts is acceptable, ISO 18653 recommends that full workpiece-like artifacts or product gears are used for establishing industrial traceability of gears to perform a functional test on the machine performance. Matching the artifact geometry to the customer's product gears eliminates the complexity associated with the uncertainty due to geometrical differences u_g and thus minimizes the costs and additional costs with establishing the uncertainty associated with u_g. Examples of workpiece-like artifacts are illustrated in Figures 9–11.

Figure 9 shows a spur gear that was identical to a workpiece that had particularly stringent accuracy requirements, compared to the available measurement capability. Routine calibration with an identical artifact avoided measurement problems. Figure 10 is a helical involute spline used in an aerospace application. Its geometry is totally different from "standard" artifacts that would traditionally be used to prove instrument measurement performance, and is a functional test of machine performance. Figure 11 shows a large face width, left-hand helical master gear used to calibrate measuring machines for the wind turbine industry. The disadvantage with a full gear is that only a single helix is tested, so a right-hand helix master gear was also manufactured. Helix, profile and pitch errors, radial runout of tooth space, tip and root diameters and tooth thickness parameters are calibrated to meet a customer's requirements. The customer also defined the mounting arrangement and the datum surfaces.

Workpiece-like artifacts are more challenging to calibrate because of larger flank and datum surface geometry form errors. But the potential problems caused by this are avoided if the procedure used on the shop floor measuring instrument is identical to the procedure used by the calibration laboratory.

ISO 18653 Survey Results

The NGML carried out a survey of gear measurement uncertainty (capability) using the 5 mm module, 30º-helix angle artifact illustrated in Figure 12 to test the procedures in ISO 18653. The gear was measured over 10 times on each measuring machine. The master gear was measured using standard procedures: 4 teeth at 90º intervals were measured on both left and right flank, and pitch errors measured on all teeth, left and right flanks. Radial runout of the tooth space was calculated from the pitch results. Although 4 teeth were measured, only the first tooth was evaluated to minimize the risk of problems caused by instruments selecting different teeth to measure around the gear. Operators from each participating company performed the tests. Seven machines were tested, including manual gear testers, CNC GMMs and CMMs with gear software that were located in a shop floor environment or inspection rooms located on the shop floor.

The calculated measurement uncertainty results are summarized in Table 1 for profile error slope ($f_{H\alpha}$), total profile error (F_α), profile form error ($f_{f\alpha}$), helix slope error ($f_{H\beta}$), total helix error (F_β) helix form error ($f_{f\beta}$), tooth-to-tooth pitch error (f_p), cumulative pitch error (F_p) and radial runout (F_r) parameters, defined in accordance with ISO 1328, parts 1 and 2.

Table 1 shows most instruments operated in a shop floor environment are capable of 2–3 µm measurement uncertainty with a 95% confidence interval, which seems to be reasonable when compared to NMI capability of 0.7 to 1.5 µm (Refs. 6–7). The results for cumulative pitch (F_p) and radial runout (F_r) are generally higher due to the excessive runout of the centers on most of these machines. It appears that the importance of basic instrument alignment and runout of mounting centers is still not fully appreciated by users of measuring instruments. The ISO 18653 procedures quantify the importance of this, thus encouraging companies to invest in proper servicing and maintenance procedures.

The results show that, in general terms, the procedures for evaluating measurement uncertainty appear realistic. Examining individual measurement results revealed none in excess of the 95% confidence limits, and although it is

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Figure 11—Workpiece-like artifact: 350 mm-face helical gear for the wind turbine industry.

Figure 12—M5 master trial gear.

acknowledged that few tests were taken, it suggests that the procedure is somewhat in question.

Implementing ISO 18653 in the Workplace

Implementing the ISO 18653 standard in the workplace is relatively easy to accomplish in a 5-stage process:

1. Select two or three good-quality, representative, hardened workpieces with tooth numbers etched on them, and set them aside for measurement purposes. Once a week, measure these using standard measurement procedures and record the results in a table by hand or preferably in a spreadsheet (because it makes the sums easier, updating easier and the results can be plotted to identify trends). An example of this is in Figure 13. Experience at NGML is that once established, it takes only 30 minutes a week to complete, but this will depend on the manufacturing environment and artifact size.
2. For each parameter, estimate the mean and standard deviation with a minimum of 10 sets of results. This defines the reproducibility of the measurement process. Reproducibility is defined as the long-term repeatability of the measurement process.
3. Carefully record the measurement process, includng: geometry, axis correction method (if used), evaluation ranges, tooth numbers and flanks measured, probe size and how the axial position of the gear is defined. Send the gear to an accredited calibration laboratory and calibrate each parameter used for defining gear quality. The calibration interval will be less than for proper master gears, but because they represent typical workpieces, the value of the calibration data is enhanced.
4. Use the calibration data and the measured data on the subject gears to evaluate measurement uncertainty using Equation 2.
5. Tests on runout of centers and alignment with a mandrel should be made at between 1- to 4-week intervals, in accordance with the guidelines in ISO/TR 10064-5.

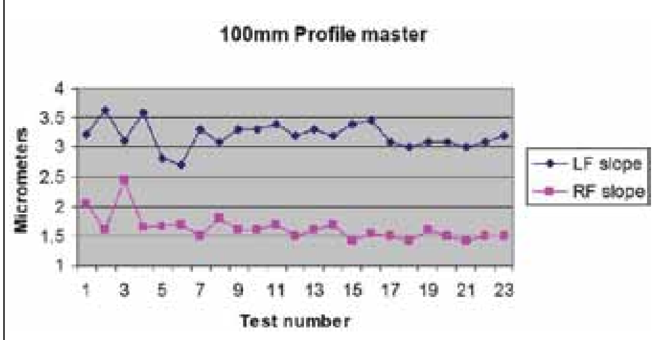

Figure 13—Example plot of reproducibility for profile measurement from weekly measurements.

These simple procedures will provide sufficient information to evaluate measurement uncertainty using the comparator procedure, to identify drift and trends with the measurement processes and to provide greater confidence in results obtained from the machine.

Problems arise if workpieces are larger than existing

Table 1—Summary of measurement uncertainty values calculated using the ISO 18653:2003 procedure.

Flank/ parameter	Measurement uncertainty (U_{95})							
	A	B	C	D	E	F	G	Mean U_{95}
1LF $f_{H\alpha}$	1.89	3.07	2.31	1.90	2.01	2.58	3.93	2.53
1LF F_{α}	4.01	2.22	2.29	2.23	2.47	3.08	3.47	2.82
1LF $f_{f\alpha}$	5.35	2.63	2.21	2.07	2.06	2.62	2.43	2.77
1RF $v_{H\alpha}$	2.88	4.39	1.73	2.55	2.05	3.26	2.66	2.79
1RF F_{α}	7.15	3.85	2.47	2.64	2.44	2.80	2.24	3.37
1RF $f_{f\alpha}$	5.06	2.03	3.11	2.15	2.03	2.31	3.09	2.82
1LF $f_{H\beta}$	2.10	3.00	3.77	2.46	2.51	2.10	1.98	2.56
1LF F_{β}	4.92	2.98	2.20	2.80	2.90	3.32	2.21	3.05
1LF $f_{f\beta}$	5.41	2.26	2.81	2.18	2.00	3.17	2.47	2.90
1RF $f_{H\beta}$	2.70	2.64	2.89	2.00	1.73	2.87	2.25	2.44
1RF F_{β}	5.75	2.47	2.81	2.47	2.05	4.06	2.17	3.11
1RF $f_{f\beta}$	5.08	2.40	2.99	2.27	2.06	3.53	2.28	2.95
LF f_p	1.60	2.48	1.63	1.96	1.64	2.90	1.91	2.02
RF f_p	2.06	3.17	2.17	1.68	1.97	2.50	1.89	2.21
LF F_p	2.48	14.41	4.15	5.17	3.37	4.79	2.28	5.24
RF F_p	2.38	14.99	4.79	5.77	2.67	3.44	3.11	5.31
F_r	3.01	9.59	3.75	4.31	3.63	3.60	2.96	4.41

Where: LF = left flank and RF = right flank facilities at NMIs. An alternative strategy is required, which addresses three key areas:

1. ***The effect of temperature is potentially far greater because thermal stabilization times are high.*** The only reliable solution to this is to leave gears to stabilize and complete a simple test to verify drift in measurement results against time to establish a suitable interval. Provided the stabilizing times are adhered to, this will not be a significant source of measurement uncertainty.
2. ***Measurement of elastic deflection of the measuring machine with workpiece load***. Large gears are heavy and they can cause significant deflections of the measuring machine. This can be addressed by measuring the deflection of the machine using precision electronic levels or laser interferometer methods to detect the movement of the machine when the gear is loaded. Not all deflections will have a first-order effect on measurement results, depending on instrument measurement strategy. This should be assessed on each specific machine, but guidance is provided in the BGA Code of Practice DUCOP 05/2 (Ref. 3).
3. ***The final additional source of uncertainty that should be assessed is*** u_g ***— the uncertainty from the difference between workpiece geometry and calibrated artifact geometry***. This is necessary because large gears use different parts of the instrument slides and are thus susceptible to different slide errors. Methods of measuring these errors are the subject of research by PTB and NPL (Ref. 8), although the results are not published. The solution has two elements: 1.) the measurement of geometry errors using laser systems or artifact-based systems such as ball/hole plates, and the use of a virtual CMM to simulate the effect that the errors have on measuring gears of a defined geometry using a Monte Carlo Simulation.

Until research is completed, NGML recommends (similar to the ISO procedure itself) the following strategy:

1. Select two or three good quality representative, hardened workpieces with tooth numbers etched on them and set

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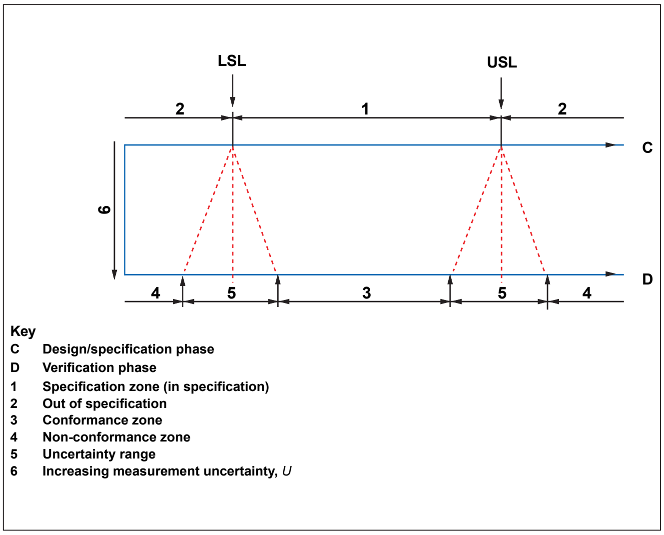

Figure 14—Extract from ISO/TS 14253-1:1995: the GPS method.

Table 2—Example of Measurement Uncertainty Budget.

Uncertainty Source	Units	Value	Dist	Divisor	Ci	n	Ui
Calibrated Artifact Uncertainties							
1 Artifact	mu	1.2	n	2	1.0	1	0.6
Repeatability of artifact measurement	mu	0.5	n	1	1.0	5	0.2
Uncorrected differences between data	mu	1	r	1.732	1.0	1	0.6
Drift of the reference artifact	mu	0.5	n	1.732	1.0	1	0.3
Difference in artifact temp. and 20°C	deg C	1	r	1.732	2.0	1	1.2
Uncertainty in artifact CTE	na	1.16E-06	r	1.732	173205.1	1	0.1
Workpiece Uncertainties							
2 Temperature affects	deg C	0.3	r	1.732	2.0	1	0.3
Reproducibility of workpiece measurement	mu	1.5	n	1	1.0	1	1.5
Instrument Geometry Uncertainties							
3 X-axis combined uncorrected slide errors		0.5		1	1.0	1	0.5
X-axis uncertainty		0		1	1.0	1	0.0
Y-axis combined uncorrected slide errors	mu/m	0.5	r	1.732	0.0	1	0.0
Y-axis uncertainty	mu/m	0	n	2	0.0	1	0.0
Z-axis combined uncorrected slide errors	mu	1.5	r	1.732	1.0	1	0.9
Z-axis uncertainty	mu	0.5	n	2	1.0	1	0.3

them aside for measurement purposes. Once a week measure them with the standard measurement procedures and record the results in a spreadsheet. It is important that if the standard measurement process involves transferring gears from the shop floor to the inspection room and stabilizing, this is reflected in the test practice.

2. From a minimum of 10 sets of results for each parameter, estimate the mean and standard deviation for each parameter to define the reproducibility of the measurement process.

3. Measure the elastic deflection of the machine with electronic differential levels in the appropriate planes that effect measurement results.

4. Use precision differential levels and laser-based systems to quantify systematic errors in guideways.

5. Construct an uncertainty budget similar to the simplified example in Table 2 (Ref. 9).

The uncertainty budget in Table 3 lists uncertainty sources, the units, the value of the uncertainty and defines the distribution as either normal- or rectangular-type (see ISO/TR 10064-5) and defines the sensitivity coefficient C_i, to calculate the effect the uncertainty source has on the measured result. In accordance with standard evaluation procedures, the overall standard uncertainty (1 standard deviation) is calculated by $\sqrt{\sum u_i^2}$ multiplied by a coverage factor of 2. For the example budget, this yields a measurement uncertainty of ± 4.7 µm for a 95% confidence interval.

It is acknowledged that this is a complex process, which requires specialist measurement skills, but giving due consideration to the value of large gears and costs incurred if mistakes are made, it is worth the effort.

Limitations with the Standard

The results from testing the procedures in ISO 18653 show no significant issues with using the standard method, but a small revision to the formula is proposed as follows:

$$U_{95} = k\sqrt{u_m^2 + u_n^2 + u_g^2 + u_w^2 + \left(\frac{E}{\sqrt{3}}\right)^2} \qquad (3)$$

The effect of this change is that bias is not added linearly—which, in the opinion of the authors—overestimates measurement uncertainty when the bias value is significant. The reason behind this proposal is that the bias E will vary from test to test, and is thus only a single example of the bias on the machine.

Conformance with Specification

Measurement uncertainty, once established, should be applied. ISO 18653, unlike the VDI/VDE guidelines (Ref. 2) and BGA codes of practice (Ref. 3), does not specify allowable limits for measurement uncertainty. This is addressed in ISO/TR 10064-5, where three methods are described:

1. ***GPS (ISO/TS 14253-1) tolerance reduction method***. This is the preferred method, unless there is prior agreement between supplier and customer. In this method the specified tolerance from the accuracy specification is reduced by the measurement uncertainty to define smaller limits. This is illustrated in Figure 14 and shows that if measurement uncertainty is small, the allowable manufacturing limits are large while, conversely, if measurement uncertainty is large, the manufacturing limits are small. This will reduce the chances that poor-quality gears are accepted and good-quality gears rejected.
2. ***Tolerance ratio method.*** This method defines that the measurement uncertainty should be a maximum of 30% of the specified tolerance. It has the benefit that it is simple to apply, but may result in a larger or smaller uncertainty than the application requires.
3. ***Instrument uncertainty guidelines***. These define maximum recommended uncertainties for a group of ISO 1328 accuracy grades. It is easy to apply, but gears of 10 mm diameter, say, require the same measurement uncertainty as gears of 2 m diameter, and thus is not very flexible. An extract is given in Table 3 for an ISO 1328 grade 8 gear.

The GPS method is the only method that realistically describes how we should consider measurement uncertainty when interpreting results. However, in the opinion of the authors, simply estimating measurement uncertainty using the procedures in ISO 18653 and stating it on the measurement report would be a far more simple way of applying the measurement uncertainty estimate.

Discussion/Conclusion

- Introducing ISO 18653 procedures into the work place is straightforward and requires minimum time and investment to implement, provided artifacts are suitable for existing calibration facilities. A simple procedure has been recommended.
- The benefits from using workpiece-like artifacts rather than the traditional artifact designs have been demonstrated.
- The ISO 18653 uncertainty values have been tested and found to be acceptable, but a small modification to the formula is recommended in future revisions.

Table 3—Example Maximum Process Measurement Uncertainty (ISO/TR10064--5).

ISO 1328 Grade	Maximum process measurement uncertainty (µm)				
	Single pitch	Cumulative pitch	Runout	Helix	Profile
8	±5	±6	± 6	± 5	± 5

- The requirements for calibration of large gears can still be achieved by applying the procedure in ISO18653, but the additional work requires suitable expertise and guidance from metrology institutions. The costs of this are small compared to potential benefit-and-risk reduction that results from this work.
- The strategies for applying measurement uncertainty when interpreting results were discussed. Until the revision to the ISO 1328 accuracy standard is completed, it is recommended that measurement uncertainty simply be accompanied by measurement results so informed decisions can be made.

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