Methods of testing calibration equipment in the UK's National Gear Metrology Laboratory

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Abstract

This paper describes the functions of the U.K.'s National Gear Metrology Laboratory (NGML). The parameters which are measured on gears and the equipment which is used to calibrate these parameters are described. Methods of verifying the accuracy of calibration equipment are discussed, with particular reference to the scanning mode of operation used by the equipment. A comparison of calibration results between the European Primary Calibration facility at PTB, Braunschweig Germany and NGML is presented. The results demonstrate that high accuracy calibration data may be obtained from commercially available inspection equipment, if the correct methods of testing are used.

1. Introduction and Background

The U.K.’s National Gear Metrology Laboratory (NGML) has been run by Design Unit, University of Newcastle upon Tyne for the past nine years. The main function of the Laboratory is to provide a traceable calibration service for the parameters which are measured on gears. These parameters are lead (tooth alignment error), profile (involute shape error), pitch (tooth spacing error) and tooth thickness.

Although NGML is a National Laboratory, it is not the primary calibration facility. Physikalisch Technische Bundesanstalt (PTB) in Germany is the European Primary Gear Calibration Laboratory by the mutual agreement of countries who participate in WECC (Western European Calibration Co-operation) and EAL (European Co-operation for Accreditation of Laboratories). PTB are responsible for the realization of the primary gear standards which are derived from the SI base unit of the metre (Fig. 1)[1].

NGML are accredited by NAMAS (National Accreditation of Measurement and Sampling) which is administered by UKAS (UK Accreditation Service), for the traceable calibration of master gears and gear artefacts. NGML,
as a National Laboratory, can offer the lowest traceable calibration uncertainties of any UK gear calibration laboratory:

- lead ± 1.5µm /100mm
- profile ± 1.5µm
- adjacent pitch ± 1.5µm
- cumulative pitch ± 2.0µm
- radial runout ± 2.5µm
- tooth thickness ± 1.5µm

The secondary functions of the laboratory are to provide:

1) an independent gear inspection service to manufacturers and users of gears.
2) training for industry via short courses and seminars in conjunction with the British Gear Association (BGA).
3) support for gear research in UK Universities.

This paper concentrates on the calibration function of the laboratory, with particular reference to the methods used to verify the accuracy of gear calibration equipment. The methods described in this paper are developed from those which are used on a gear inspection machine in industry and are specified in the BGA Codes of Practice [2, 3].

2. Gear Calibration Equipment

2.1 General Description

NGML use two unmodified and commercially available CNC gear measuring machines to calibrate master gears and gear artefacts. The machines are:

- a Höfler EMZ 632 4-axis CNC gear measuring machine. The software comprises of a Höfler gear software package, Zeiss UMESS software package and the Zeiss GON gear software package. The machine is equipped with a 3-axis scanning probe system (Fig. 2).
- a Gleason GMS 430 4-axis CNC gear measuring machine with Gleason Gear software, with additional gear calibration software written by NGML. The machine has a single axis Tesa GT-31 probe, which is used to scan the tooth surface. The machine slide arrangement is identical to the Höfler.

2.2 Description of Measuring Modes

Both machines measure (calibrate) lead and profile errors by moving a measuring probe across the tooth surface. This involves simultaneously moving one (or more) linear axis with the rotary axis in a synchronous motion under CNC control. Error data is gathered at typically 0.1mm intervals.

The machines measure (calibrate) pitch by indexing the gear, which is mounted on the rotary axis, and directly measuring the angular position error using an optical angular encoder. All the teeth are measured in an incremental manner under CNC control.
2.3 Evaluation of Gear Measurement Results

The tooth shape error parameters which are normally used to assess the accuracy of a gear measuring machine are calculated by constructing a 'least squares fit' mean line through the error curve [3]. This adds further complexity to estimating the accuracy of the calibration process because the calibration data is a calculated value.

2.4 Calibration Strategy

It is not feasible to calibrate a complex gear measuring machine as there are too many sources of error which will combine in a different unique manner for each geometry of gear measured on the machine. The best that may be achieved is that error sources are quantified, and where possible compensated, and their effects considered when estimating the calibration uncertainty budget ($U_{95}$) for the calibration process.

NGML use a combination of parametric calibration and functional tests, which use artefacts, to estimate the calibration uncertainty of the machine. The functional tests are designed, where ever possible, to test the machine in the same manner in which it operates while calibrating gear parameters. The results of this assessment are verified by comparing calibration data with PTB using the UK National Gear Artefacts. Further details of the procedures are given in section 3.

3. Machine Calibration and Verification Methods

3.1 Datum Axis and Linear Axis Alignment

The rotary table axis is defined as the datum axis (Fig. 3). Alignment of the linear axes is carried out using a parallel 500mm long ($\varnothing$50mm) mandrel. The mandrel straightness is within $0.4\mu m \pm 0.2\mu m / 500mm$ and is traceably calibrated by the reversal technique at NGML.

The mandrel is mounted on the rotary table (Fig.4). Radial and tangential axis alignment is calculated by the slope of the 'least squares fit' mean line using straightness data gathered at 2.0mm intervals on the mandrel. Mandrel mounting (swash) errors are eliminated by rotating the table through 180°, repeating the straightness measurement and averaging the results. Squareness of the radial and tangential slides is calculated from straightness data after using the rotary table to index the mandrel through 90° intervals. The effect of rotary table indexing errors is reduced by averaging 4 pairs of straightness errors with the mandrel mounted at different angular positions on the rotary table.

The vertical axis alignment on the Höfler is more accurately assessed by using Zeiss UMESS cone software. The mandrel is mounted vertically on the rotary table and measured as a cone by scanning vertical lines and gathering data.
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at 0.1mm intervals. The table is rotated through 180° and the mandrel is re-measured. The average of the cone axis alignments defines the angular alignment of the vertical axis with respect to the rotary table axis. Errors in this axis alignment will directly affect the accuracy of calibration data.

Angular roll errors ($\theta_{xy}$) of the radial (X) slide are also important, as they change the alignment of the vertical measuring slide with the datum axis (Fig.4). They are checked using Zeiss differential, electronic levels. The accuracy of the levels in differential mode is traceably verified by NGML using a small angle generator over 10 $\mu$m/m range. The calibration uncertainty of the levels is $\pm 0.5 \mu$m/m over this range.

The results from these tests show that the axes of the Höfler are aligned within $3 \mu$m/m. Calibration data is corrected for the residual alignment error.

3.2 Straightness Measurement

Vertical (Z) and tangential (Y) axis straightness errors ($\Delta_x$, $\Delta_z$) are measured using a Renishaw Laser Interferometer with straightness optics and software. This measurement method is preferred because the dynamic data capture software allows data to be gathered dynamically, at 0.1mm intervals, at normal calibration scanning speeds of 1 and 2 mm/sec. Angular errors ($\theta_{xy}$, $\theta_{xz}$, $\theta_{yz}$) are checked, using angular optics and software, to identify the causes of the straightness errors, but in most cases, the Abbe offset of the probe is constant so this information is not used for calibration data correction.

The laser Interferometer is traceably calibrated by the National Physical Laboratory (NPL). Straightness and angular optics and software are traceably verified at NGML. The measurement system errors are within $\pm 0.3 \mu$m for straightness errors (over a 5 $\mu$m range) and $\pm 0.6 \mu$m/m for angular errors (over a 10 $\mu$m/m range), with 700 mm axis travel and in the laboratory environment.

Fig 5 shows an example of a static, vertical axis straightness result from the Höfler EMZ 632 over 700 mm of axis travel. The bi-directional straightness error is less than 1.2 $\mu$m.

3.3 Probe System Verification

Each probe axis which is used to calibrate gears is verified separately using artefact based tests. The magnification and discrimination is verified by calibrated gauge blocks and bi-directional repeatability is verified using calibrated ring gauges. Artefacts are used to check the dynamic performance of the probe and the data gathering system. The test methods include:

- A ‘bent’ mandrel (2.3 $\mu$m TIR) which is rotated under the probe. As the mandrel is rotated the probe readings are taken and compared to static calibration data. (The mandrel is traceably calibrated using Zeiss UMESS software by the reversal technique). The Höfler x-axis probe normally indicates 2.0 to 2.2 $\mu$m TIR.
- A ‘rough’ mandrel which has a thread of 0.6 mm pitch and a mean 16 $\mu$m height,
has been traceably calibrated by Teeside Metrology Centre, and is used to assess the probe dynamic performance at normal calibration speeds. The mandrel is measured as a gear, which also checks data acquisition. The results in Fig. 6 show that at a 2mm/sec scanning speed, the differences between the static calibration results are less than 0.5μm at any specific calibration point. This calibration technique is still being developed because variations in form error on the mandrel can still cause comparison problems.

The results of these tests yield a probe $U_{95}$ of ±0.3μm over a 10μm measuring range when measuring gears with waviness errors of less than 2μm.

### 3.4 Linear Axes Position Errors

Linear axis position errors are measured dynamically using a Renishaw laser Interferometer ($U_{95} \pm 1.1\mu m/m$) with quadrature signal output. Position data is gathered using a Klingelnberg PEW-02 Transmission Error Measuring System which compares the position of the laser with the linear encoder position and calculates the difference. Data is normally gathered at 0.1mm intervals along each linear axis with the laser mounted in the probe stylus plane. Fig. 7 shows the results from the Gleason GMS 430 CNC gear measuring machine. The cyclic error and general form errors were found to be caused by problems with the ball screw drive and Abbé errors.

### 3.5 Rotary Table Tests

The rotary axis roundness accuracy and runout is verified by measuring a traceably calibrated roundness standard using the measuring machine probe. Axial runout is verified by checking the runout of the table over 3 revolutions. The indexing or position accuracy is verified by comparing the spindle encoder output (Quadrature signal) with a second encoder (Heidenhain ROD800) using the Klingelnberg PEW-02. The differences between encoder positions at typically 1800 positions over 360° is checked and plotted (Fig. 8). The second encoder is indexed by 90° and the process repeated. The average combined error for both encoders is calculated and verified that it be less than the combined uncertainty claimed by the encoder manufacturers (the ROD 800 and spindle encoder $U_{95}$ are each ± 1.0 arc sec). The 0.36 arc sec. steps shown in Fig. 8 are caused by the resolution of the ROD800 encoder.

### 3.6 CNC Servo Control Errors

The servo control errors are not verified. Work is currently being carried out on applying the Klingelnberg PEW-02 encoder checking technique to this problem.
3.7 Software

Two methods are used to verify the analysis software:
• Three software packages are available in the laboratory and direct comparisons between packages is carried out by calibrating artefacts. Differences between packages indicate errors less than 0.6\(\mu\)m/\(100\)mm are caused by differences in evaluation and data gathering methods.
• The evaluation of calibration data from artefacts which have the nominal geometry changed to create differences in measured errors. Differences between a predicted 20\(\mu\)m change in calibration data were within 0.3\(\mu\)m.

4. Uncertainty Budgets

The individual sources of error are used to estimate the uncertainty budget for the calibrated gear parameters. Uncertainty budgets are estimated in accordance with NAMAS directives [4].

5. Comparison with PTB Calibration Data using Artefacts

NGML maintain a range of artefacts which are frequently calibrated by PTB. Comparisons between PTB and NGML calibration data are carried out before calibration of a client’s gear artefact. Typical results are shown in table 1 to 3 for the 200mm diameter lead artefact with 0° and 30° helix angles, profile artefact and pitch artefact. The differences in results are within the PTB calibration uncertainty. (Important systematic errors which are measured using the techniques in section 3 are corrected before comparing calibration values. Data correction is carried out independently from the measuring software using simple mathematical models).

6. Conclusions

The methods use a combination of artefact and laser based calibration techniques to efficiently verify the accuracy of gear calibration machines. The results from the tests demonstrate that using standard, commercially available, gear measuring machines in a calibration environment can give accurate calibration results.

Acknowledgement

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References


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Table 1. Comparison of PTB and NGML Lead Calibration Data (μm)

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Table 2. Comparison of PTB and NGML Profile Calibration Data (μm)

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Table 3. Comparison of PTB and NGML Cumulative Pitch Calibration Data (μm)
Fig. 1 Traceable Calibration Chain for Involute Gears

Fig. 2 Höfler EMZ 632 Gear Measuring Machine.

Fig. 3 Measuring Machine Axis Definition.
Fig. 4 Measurement of Axis Alignment with a Parallel Mandrel.

Bidir. Straightness

Fig. 5 Höfler Z axis straightness Measurement results (µm).

Fig. 6 Dynamic Probe Performance Evaluation.
Fig. 7 Linear Axis Position Errors Tested With a Klingelnberg PEW-02
Composite Transmission Errors [arcsec] / right flank

Fig. 8 Rotary Table Encoder Errors Measured With A Klingelnberg PEW-02