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Verifying the accuracy of involute gear measuring machines

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Abstract

This paper describes the most common methods of inspecting gears and the measuring machines used. Methods of verifying the accuracy of gear measuring machines are discussed, with particular reference to BGA codes of practice. Some example results are presented.

1. Background

Gears are important mechanical components found in 90% of mechanical transmissions. They have a complex geometry and transmit high power, often at high speed. They must be made very accurately if their load carrying capacity and noise levels are to be acceptable in service.

Nearly all parallel axis gears are involute spur or helical gears. Involute gears may be inspected by a number of methods, but the most commonly used is to check the individual error parameters. That is lead (tooth alignment) errors, profile (involute profile) errors, and pitch (tooth spacing) errors. It is normal practice to check 4 equally spaced teeth for lead and profile accuracy and check all teeth for pitch accuracy. Gear standards [1] specify the recommended accuracy requirements for these parameters. Table 1 shows the typical accuracy requirements for a gear from an automotive gearbox. These tolerances are tight and demand high standards of metrology. A commonly used rule-of-thumb is that the inspection process should have a measurement uncertainty of approximately 10% of the tolerance being measured. Table 1 shows that these are exceptionally tight limits for a gear inspection machine and in practice, 20% to 30% is the best that may be achieved.

There are many types of machine used to inspect gears these include traditional mechanical machines and CNC machines, examples of which are shown in Fig. 1. CMMs with gear measurement software are available but they are not so commonly used by gear manufacturers because they are generally considered to be too slow. The dedicated gear measuring machines generate the theoretical

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shape of the involute and helix and use a probe to scan the surface of the tooth at a specified measuring position.

Machines will measure a large size range of gears (some up to 2.6m diameter) with different geometries, different weights, at different positions within the measuring volume. Verifying the accuracy of these machines can be a complex, time consuming activity, but obviously very necessary if gear failures caused by measurement errors are to be avoided.

2. Introduction and Methodology

It is not possible to fully 'calibrate' a complex measuring instrument such as a gear measuring machine or a CMM. The best that may be achieved, given reasonable time constraints, is that the function of the machine and its accuracy is verified at a number of settings through its measuring range.

A series of Codes of Practice for traceably verifying the accuracy of a gear measuring machine have been issued by the British Gear Association (BGA). These were prepared by Design Unit, who run the UK National Gear Metrology Laboratory, and members of the BGA Technical Committee. They are not standards as such, but are technical documents which gear manufacturers are able to adopt and follow if they wish. Companies who are ISO 9000 accredited will satisfy the requirement that key measurements are traceably verified to National Standards by following these codes.

The methodology adopted by the codes involves a combination of functional measurements on traceably calibrated artefacts and the direct verification of elements of the machine which are known to be common sources of error and are vulnerable to damage during use. The test results are analysed to determine the measurement uncertainty of the machine within a pre-defined measuring volume. Once this has been established, the operator of the machine must frequently check the performance of the machine by measuring a traceably calibrated gear artefact. This two stage approach minimises the amount of time required to carry out these tests. Once the machine has been verified, the operator is responsible for ensuring that the accuracy of their machine is maintained.

3. Measuring Machine Accuracy Requirements

Table 2 shows the measurement uncertainty (U_{95}) requirements for gear measuring machines. For convenience, machines are divided into 3 accuracy classes, depending on the accuracy grade of the gears being inspected. The uncertainty relates to the accuracy of the machine when measuring a gear artefact or a master gear only.

4. Accuracy Verification Procedure

The procedures for verifying the accuracy of a gear measuring machine are detailed

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in 3 BGA Codes of Practice DUCOP 05/1, 05/2 and 05/3 [2]. It is recommended that these form part of the acceptance tests on the installation of a new machine and then the tests are repeated at the frequency of between 12 to 36 months. The implementation of one or all of the codes depends on the desired size of the verified measuring volume of the machine. Most gear measuring machines check gears up to 600mm in diameter but there are a number of machines in the UK which check gears up to 2.6m diameter. The different requirements of these machines are covered by the three codes.

4.1 Verified Measuring Volume

Code DUCOP 05/1 [2] defines the verified measuring volume and other limitations on the definition of uncertainty as follows:

Diameter:	The range of diameters is from 1.25 times the largest gear artefact diameter to 0.5 times the smallest.
Facewidth:	The maximum facewidth is the length of the calibrated parallel mandrel used for alignment or straightness tests.
Helix angle:	The largest helix angle is that which is tested on the gear artefacts.
Module:	The largest module is that tested on the gear artefacts.
Weight:	The maximum weight is 1.5 times the heaviest gear artefact measured.

A specification for the geometry and NAMAS Calibration Uncertainty requirements for general purpose gear artefacts is given in DUCOP.05/1. If the artefacts do not satisfy the size required for the verified measuring volume, the volume may be extended by implementing the additional tests which are specified in DUCOP 05/2 and DUCOP 05/3.

4.2 Procedure

The procedure is outlined below:

- Check that the environmental conditions satisfy the requirements of the codes.
- Verify that the machine is reproducible by examining reproducibility test results for the previous 4 week period (if they exist) to ensure that the machine being assessed is stable.
- Check the alignment and runout of the machine spindles, alignment of tailstock axis, and the main measuring machine vertical axis is aligned to within the recommended limits.
- Check the probe system magnification, discrimination and hysteresis are within the specified limits. Each probe axis which is used to measure gear parameters or define orientation of the gear is checked.
- Check that the temperature of the traceably calibrated artefacts which are to be used stable and within prescribed limits.
- Mount each artefact on the machine and verify the mounting accuracy

before carrying out the measurement tests.

- Measure each calibrated flank on the artefact at 4 different angular positions on the rotary table (i.e. at 0°, 90°, 180° and 270°).
- Calculate the mean ($\bar{x}$) for each calibrated parameter and the standard deviation (S).
- Estimate the random measurement uncertainty at a 95% confidence interval for each calibrated parameter by

$$U_{95R} = K.S \qquad (1)$$

where K is a coverage factor, which in this case is chosen as 2, for the 4 tests.
- Estimate the overall measurement uncertainty for the measurement process for each calibrated parameter using

$$U_{95} = \sqrt{(U_{95R})^2 + (U_{cal})^2 + (\bar{x} - X_{cal})^2} \qquad (2)$$

where U_{cal} is the NAMAS calibration certificate value and ($\bar{x}$ - X_{cal}) is the bias between the two results.
- Verify that the U_{95} value calculated for each parameter satisfies the uncertainty requirements specified in Table 2.
- Use one lead artefact, with a 30° helix angle to check software evaluation accuracy by re-measuring the artefact with different reference data to generate a lead error of approximately 20μm. The difference between the original result and the mean of the measured results should be within the probe system specification.
- If the machine satisfies all the measurement test requirements, for a particular accuracy class, it has satisfied the accuracy requirements in accordance with the Code of Practice.

If the artefacts available do not cover the required verified measuring volume requirements, the measuring volume may be extended by implementing the tests specified in DUCOP 05/2 and DUCOP 05/3. These additional tests are only valid as a continuation of the test programme in DUCOP 05/1.

- Measure the change in alignment of the machine when an additional load is applied to the work table.
- Measure geometrical errors in individual slides (including the spindle) to verify that there is no excessive errors in the slides. The errors which should be checked on a 4-axis gear measuring machine (see Fig. 2) are

Straightness errors	Vertical axis	Δ_{ZY}
	Tangential axis	Δ_{YZ}
Angular errors	Vertical axis	θ_{ZZ} θ_{ZX} θ_{ZY}
	Tangential axis	θ_{YY} θ_{XY}
	Radial axis	θ_{XX}

In addition, position errors should be checked on CNC machines, but on most machines, geometrical errors have a larger contribution to overall slide accuracy than position errors.

The effect of these errors on machine performance will depend on the slide configuration. It is necessary to build a simple mathematical model on most machines to verify that the slides are of suitable accuracy.

4.3 Estimation of Measurement Uncertainty

The functional tests on measurement performance define the uncertainty of the machine. The other tests are used to verify that the results are valid and identify the sources of systematic errors which are measured. The method of estimating U_{95} from (2) has 3 separate elements. The combination of these 3 elements in equation (2) cannot be justified statistically. In a calibration laboratory, the systematic error (bias) would be corrected, leaving the residual systematic and random uncertainty to define the overall uncertainty. Also the use of a coverage factor of K = 2 not K = 3.18, for 4 samples from Students' distribution, is unusual practice. This is used because the measurement positions (0°, 90°, 180°, and 270°) are not random samples, but positions chosen to maximise differences in measurement results.

This unusual approach, has been validated by analysing the results from calibration records from over 50 different gear measuring machines, the results from which are retained by the National Gear Metrology Laboratory. An examination of these results shows that the U_{95} estimated is reasonable because very few of the differences between calibration values and the individual measured values (x_i) were outside combined uncertainty shown below:

$$X_i - X_{cal} \leq \sqrt{(U_{cal})^2 + (U_{95})^2} \qquad \textbf{(3)}$$

4.4 Equipment

The tests require a range of traceably calibrated equipment.

a) Traceably calibrated gear artefacts to satisfy the requirements for the verified measuring volume.
b) Parallel mandrels are used to verify slide alignment and straightness measurements.
c) Differential levels, with digital display are used for verifying the accuracy of some slide angular errors.
d) Calibrated indicators, 0.5µm discrimination are used for runout and alignment checks.
e) A traceably calibrated laser interferometer system and environmental compensation unit is used for position accuracy verification. Geometrical errors may also be measured by using the appropriate optics and software.

4.5 Error Compensation

Very few gear measuring machines use error compensation software for systematic slide error compensation. The approach adopted if compensation is applied is that the tests on individual slide errors should be carried out but the test results should only be treated as errors if

(a) the error correction method and data are disclosed by the machine manufacturer, and is considered to be valid by the calibration engineer OR
(b) the accuracy of the error compensation method can be verified by independent measurement tests which are agreed between the client and the calibration engineer.

4.6 Example Measurement Results

Fig. 3 shows some typical measurement results on a profile artefact indicating that the uncertainty is within class A requirements. Fig. 4 shows a slide accuracy test result with a significant angular yaw error. This could introduce an Abbé error of approximately 0.8μm / 30mm of profile measured.

5. Reproducibility Tests

Once the accuracy of a measuring machine has been verified, the machine operator is responsible for ensuring that accuracy is maintained. DUCOP. 04 [3] recommends tests to verify that on a day-to-day basis, the measurement results from the machine are reproducible. The routine checks include:

- a visual check of the condition of the machine, probe system, stylus and environmental conditions.
- a measurement (functional test) on a traceably calibrated master gear or lead, profile and pitch artefact.
- A record of the runout reference bands, machine centres and between-centres axis alignment.
- verification that the difference between the gear parameter measured and the NAMAS calibration certificate value is within the combined measurement uncertainty U_{95}, given below

$$U_{95} = \sqrt{U_{cal}^2 + U_{M/C}^2} \tag{4}$$

where U_{cal} - NAMAS certificate U_{95} and $U_{M/C}$ - measuring machine U_{95}

- verification that the difference between two consecutive reproducibility tests are within the $U_{M/C}$ value (i.e. if $U_{M/C} = \pm 2.2\mu m$, difference between results is less than 2.2μm). If the accuracy requirements are not satisfied, the machine may not be used for traceable gear measurement until the causes of the excessive errors are investigated and rectified.

The frequency for reproducibility testing is specified in Table 3.

6. Discussion

The procedures which have been described for verifying the accuracy of gear measuring machines are primarily based on functional measurements, as well as tests on elements of the machine which are known to cause common measurement errors. However, they also acknowledge that it is not possible to use artefacts to cover all verification requirements, particularly on the larger machines. The assessment of individual slide errors must be included as well.

The codes of practice will be revised within the next 18 months based on the experience gained since their introduction.

7. Acknowledgements

Design Unit gratefully acknowledge the support and help from the BGA technical committee in preparing these codes of practice and DTI 'Programme for Length' funding the work.

References

1. ISO 1328-1. Cylindrical Gears - ISO System of Accuracy.
2. Codes of Practice for Verifying the Accuracy of a Gear Measuring Machine, parts 1, 2 and 3. DUCOP 05/1, 05/2, 05/3, British Gear Association, 1994.
3. Code of Practice for Verifying the Reproduceability of a Gear Measuring Machine, DUCOP.04, British Gear Association, 1994.

Parameter	Adjacent pitch	Cumulative pitch	Profile	Alignment
Tolerance	9	27	11	11
Measuring Machine Uncertainty 10% of tolerance	0.9	2.7	1.1	1.1

Table 1. Typical gear tolerances for lead, profile and pitch parameters [μm].

Class of M/C	Grade	Maximum Allowable Measurement Uncertainty (U_{95}) [μm] When Measuring Gear Artefacts			
	ISO 1328 Part 1	Adjacent Pitch Error [f_p]	Cumulative Pitch Error [F_p]	Alignment $f_{H\beta}$/100mm	Profile $f_{H\alpha}$/40 mm
A	3 4 5	±1.8	±2.5	±2.2 ($\beta = 0°$) ±3.0 ($\beta < 45°$)	±1.8
B	6 7 8 9	±2.5	±3.5	±2.5 ($\beta = 0°$) ±4.0 ($\beta < 45°$)	±2.5
C	10 11 12	±3.5	±5.0	±4.0 ($\beta = 0°$) ±6.0($\beta < 45°$)	±4.0

Table 2. Accuracy requirements of gear measuring machines

Class	Lead and Profile Reproduceability	Pitch Reproducibility
A	Before each series of tests	1 week
B	Every 24 hours	1 week
C	1 week	1 month

Table 3. Frequency of reproduceability tests.

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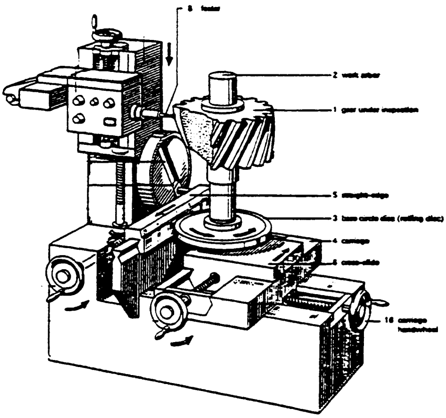

Fig. 1a **Traditional Mechanical Gear Inspection Machine**

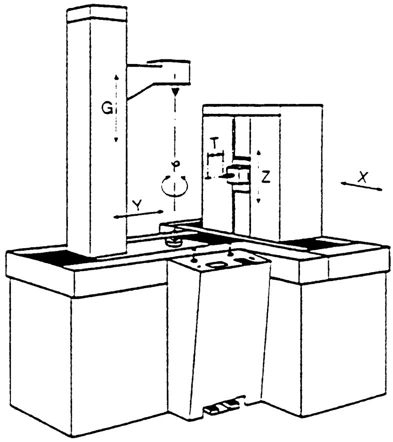

Fig. 1b **CNC Gear Inspection Machine**

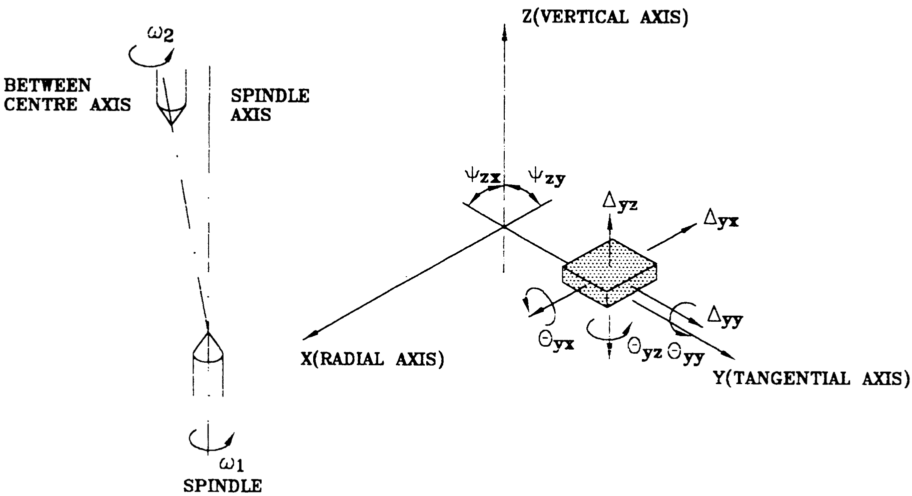

Fig.2 **Definition of axes**

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Flank	PTB Cal. Data	Repeat Tests	$\bar{x}$	S	U_{95}
Left	-1.1 ± 1.0	-1.4, -0.7, -1.4, -1.3	-1.2	0.3	1.2
Right	+0.3 ± 1.0	+0.2, 0.0, +0.1, +0.4	+0.2	0.2	1.1

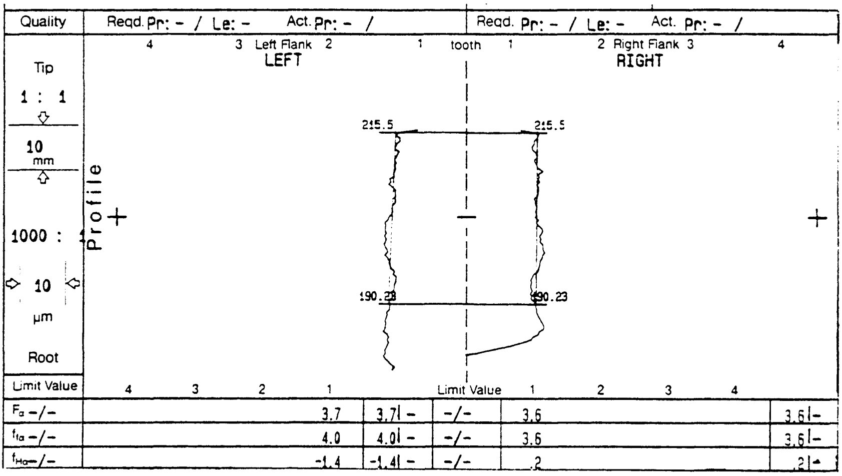

Fig. 3 Profile artefact - profile measurement results and comparison with calibration certificate value

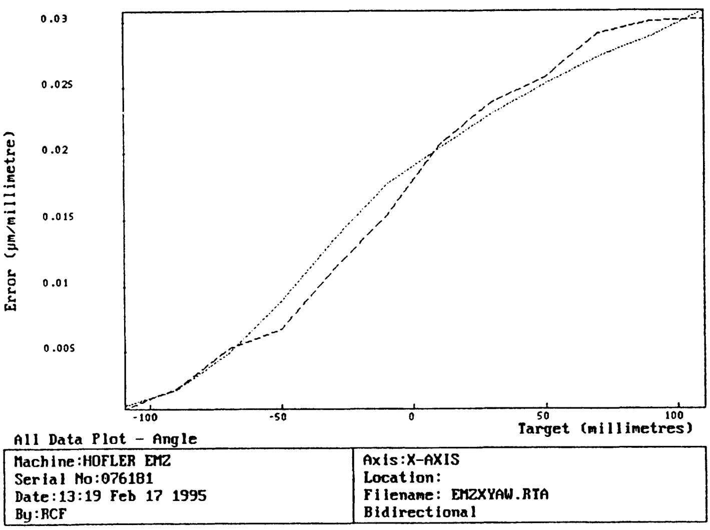

Fig. 4 Typical Side Yaw Error (µm/m) Result from a Renishaw Laser Interferometer