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Calibration of Gear Measuring Instruments and Their Application to the Inspection of Product Gears

by: B.L. Cox, Lockheed Martin Energy Systems, Inc.,
and R.E. Smith, R.E. Smith & Co.



TECHNICAL PAPER

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

The condition and alignment of gear measuring instruments can greatly influence the measurement of product gears. This paper provides guidelines for the alignment of instrument elements such as centers, ways, probe systems, etc. The instrument accuracy requirements needed to meet the accuracy of product gears is also discussed. The paper also covers the application of gear artifacts to determine instrument accuracy. This involves the calculation of U_{95} uncertainty at all steps from the artifact to the final product gears.

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1 Scope

This information sheet covers material useful for the calibration of gear measuring instruments and their application to the inspection of product gears. It provides information for determining the condition and alignment of instrument elements such as centers, ways, probe system, etc. It provides guidance for the requirement of instrument accuracy relative to the accuracy of product gears to be inspected.

It also covers the application of gear artifacts to the determination of instrument accuracy. This involves the calculation of U_{95} uncertainty at all steps from the artifact to the final product gears.

2 Normative references

ANSI/AGMA 2114 - A97, *Measuring Instrument Calibration, Pitch and Runout Measurement*

3 Definitions

Abbé offset:

Abbé offset is a linear measuring variation which will be caused by pitch, roll, or yaw variations on a length measuring slide if the axis of measurement (through the probe contact point) is not coincident with the axis of the length measuring scale. The relative offset between these axes is the Abbé offset.

Accuracy verification:

Accuracy verification is the process of verifying that a measuring instrument meets specified accuracy requirements within a defined measuring range. Accuracy verification is appropriate for complex multi-task measuring instruments (such as gear measuring instruments) which it would be impractical to calibrate over the full measuring range. Verification involves comparing a limited number of measured results with corresponding calibration values. The calibration values must be traceable to national standards and the calibration process must include an estimate of the measuring uncertainty of the results obtained.

The verification process must include a sufficient number of tests to ensure that the requirements are met (with 95% confidence) within the defined measuring range.

Calibration:

Calibration is the set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system, and the corresponding standard or known values derived from the standard.

Calibration uncertainty $\pm U_{95 \text{ cal}}$:

Calibration uncertainty is the measuring uncertainty U_{95} associated with a calibration value due to variations in the calibration process. There is a 95% probability that the true value X lies in the range $X_{\text{cal}} \pm U_{95 \text{ cal}}$. The calibration uncertainty must be stated on all calibration certificates.

Cosine variation:

Cosine variation is the variation caused by the angular mis-alignment of the measuring axis and the measuring scale of the instrument. The variation is equal to $X(1-\cos\theta)$ where θ is the alignment variation and X is the length being measured.

Cumulative pitch:

Cumulative pitch is equal to the algebraic difference between the maximum and minimum values obtained from the summation of successive values of pitch variation V_p , and is the same as total index variation.

Datum surfaces:

Datum surfaces are those surfaces used to define the reference axis.

Functional axis:

The functional axis is the axis about which the gear rotates in service. The functional axis is one, which is only meaningful when a complete assembly is being considered.

Functional mounting surfaces:

Functional surfaces are the surfaces, which define the functional axis

Gear Artifact

A gear artifact is a mechanical artifact, which has features that allow it to be measured on a gear measuring instrument. It is not normally a full gear, but may be a cylinder with a series of gashes that will allow the instrument to be tested at a number of different flank geometries. Gear artifacts are usually designed for testing either tooth alignment, profile, or pitch and are very useful for identifying sources of variation in a gear measuring instrument.

Indicated value X_i :

The indicated value is the unmodified (or uncorrected) value of the measured quantity X indicated by an instrument or measuring process as a result of a single measurement.

Lost motion:

Lost motion is the amount of difference the readout displays after the probe has been deflected in one direction and then is reversed to return to the previous position.

Master gear:

A master gear is a standard high quality gear which may be used to test the tooth alignment, profile, or pitch measuring accuracy of a gear measuring instrument at a single specific gear geometry. The master gear should have the appropriate reference surfaces to accurately determine the gear tooth axis.

Measured value X_m :

The measured value is the value of a measured quantity X derived from a single measurement (or the mean of a defined series of measurements). In some cases X_m may be corrected for known systematic variations determined by previous tests on the measuring instrument.

Measurement variation:

Measurement variation is the difference between a measured value and the actual value of an artifact being measured. This value can never be known exactly.

Measurement uncertainty:

Measurement uncertainty is the limits within which a large percentage of measurement variations would be expected to fall if measurement conditions for an artifact remain unchanged. The measurement uncertainty for an artifact can consist of one or more components (sources of variation), each contributing to the total magnitude of the uncertainty. Examples of sources of variation are temperature, coefficient of expansion, position variations, inspectors, etc.

Measuring variation e :

Measuring variation is the algebraic difference between the indicated value X_i and the true value X during a single measurement.

$$e = X_i - X$$

Parallel Mandrel:

A parallel mandrel is a nominally parallel test bar, which may be supported between centers to test the relative alignment of the centers with the vertical (Z) axis and the straightness of vertical (Z) axis. This should be traceably calibrated using the reversal method.

Pitch variation, V_p :

Pitch variation is the algebraic (+ or -) plus or minus difference in the transverse plane, between the true position pitch, p_m , and an actual pitch measurement. If measured in a plane other than the transverse plane, a correction using the appropriate helix angle must be applied to the measured value.

Position variation:

Position variation is defined as a composite kinematic variation in the relative position of two instrument components (normally the instrument spindle and a linear slide carriage) which move in a manner prescribed by a mechanical linkage or a servo control system.

Random variation:

Random variation is the component of measuring variation which varies at random, with zero mean value, during a large number of repeated measurements of the same quantity X under nominally identical measuring conditions.

Reference axis:

The reference axis is the axis relative to which the gear details, and in particular the pitch, profile, and helix tolerances, are defined.

Reference value X_{ref} (Calibration value X_{cal}):

The reference value is the best available estimate of the true value of X obtained by a traceable calibration process of high accuracy.

Repeatability:

Repeatability is the variation in measurements obtained when one operator uses the same instrument for measuring the identical characteristics on the same part.

Reproducibility:

Reproducibility is the variation in the average of the measurements made by different operators using the same instrument when measuring identical characteristics on the same part.

Resolution:

Resolution is the smallest change in the quantity X_i that may be detected and indicated by the measuring system.

Runout:

Runout is the total range of movement of a probe placed on a rotating spindle measured radially of axially over one complete revolution. Runout variation is normally defined as a total indicated reading (TIR) measured at a specified position on the spindle. Radial runout includes eccentricity and circularity variations.

Scale variation:

Scale variation is the systematic variation caused by manufacturing variations in scales, gratings, etc.

Slide and spindle alignment variations:

Slide alignment variations are the angle between the least squares fit mean line of two nominally parallel axes. When these axes are both axes of rotation the alignment variation is defined as the variation of radial runout with respect to one axis of a component which is concentric with the other. It is defined over a specified axial length (e.g. $\mu\text{m TIR/m}$).

Slide Roll, yaw and pitch variations:

Slide roll variations are undesirable angular motions of a linear slide carriage as it moves a prescribed distance along the slide. Roll variations are rotations about the slide axis; yaw and pitch variations are rotations about two mutually perpendicular transverse axes (e.g. on a horizontal slide, yaw is a rotation about the vertical axis).

Slide straightness variations:

Slide straightness variations are undesirable lateral motions of a point on a linear slide carriage as it moves over a defined length. Straightness variation is defined as the largest deviation from the least squares fit mean line of the slide.

Squareness variations:

Squareness variations are angular variations defined by the least squares fit mean line of two nominally mutually perpendicular axes. Squareness variations are commonly defined in $\mu\text{m}/\text{m}$.

Systematic variation:

Systematic variation is the component of the measuring variation which does not vary in the course of a large number of repeated measurements of the same quantity X under nominally identical measuring conditions.

Tooth Alignment Artifact:

An artifact having a certified helix form.

True position pitch:

The true position pitch is the circumference of the datum circle divided by the number of teeth. This can be determined by the average of all pitch measurements of the entire gear taken on successive pairs of teeth, or between corresponding points of adjacent teeth generated by an angular positioning device.

True value:

The actual value of the quantity X which is to be measured. (This can never be precisely determined in practice.)

Verified measuring volume:

The verified measuring volume is defined by:

(a) Maximum / minimum diameter:

The maximum and minimum diameter is 1.25 times the largest diameter of a gear artifact used for the tests to 0.5 times the smallest artifact diameter used for the tests.

- (b) **Maximum facewidth:**
The maximum facewidth is equal to the length of the calibrated parallel mandrel, which is used for alignment and straightness measurements on the vertical axis.
- (c) **Maximum helix angle:**
The maximum helix angle is the largest helix angle tested on the gear artifacts.
- (d) **Maximum module:**
The maximum module is the largest module tested on the gear artifacts.
- (e) **Maximum weight:**
The maximum weight is 1.5 times the heaviest gear artifact used for the verification tests.

Table 1 Alphabetical table of symbols with terms, by terms

Symbol	Terms
D	Measurement diameter
F	Facewidth
Ψ	Helix angle
L	Length between datum surfaces
V_{pA}	Pitch variation, allowable
V_{ap}	Pitch, cumulative
V_{rT}	Radial runout tolerance
$V_{\psi T}$	Tooth alignment tolerance
p_m	True position pitch
$V_{\phi T}$	Profile tolerance

4 Instrument condition

The calibration engineer and the client should agree on the accuracy requirements, verified measuring volume size, and parameters that are to be tested before starting the verification work. Much of the general information in this information sheet comes from the British Gear Association codes of practice DUCOP.03, "Involute Gear Measurement"¹, DUCOP.04, "Checking the Reproducibility of Gear Measuring Machines"², DUCOP.05/1, "Verifying the Accuracy of Gear Measuring Machines: Part 1"³, and DUCOP.05/2, "Verifying the Accuracy of Gear Measuring Machines: Part 2"⁴.

4.1 Instrument checking procedure

- (a) Carry out a brief, preliminary visual inspection of the instrument, verifying that the centers, drivers, and stylus are in good condition. Check that the environmental conditions meet the requirements in section 6.2.
- (b) Mount each traceably calibrated tooth alignment, profile, and pitch artifact between centers and measure and record the runout of the reference bands and of the instrument centers. Verify that these runout values are within the limits specified in Table 5.
- (c) For instruments checking ANSI/AGMA-2000-A88 accuracy grade Q13 and higher only: Measure and record the alignment variation on the top center relative to the bottom spindle axis. This should be checked as shown in Figures 1-3. Measure the alignment variation by probing the master or the spindle with the indicator and rotating the whole assembly. Record the total runout (TIR) over one revolution. Verify that the results are within the limits specified in Table 2, column 3.
- (d) Instruments with tooth alignment masters, which are less than 100 mm facewidth, should be checked for alignment with a parallel mandrel. Permissible variations are specified in Table 5.

- (e) Measure each gear artifact for a sufficient time period (4 weeks) to verify that the measured variation is within statistical control (see Appendix A). The results must satisfy the requirements in Table 4. If they do not, further testing is pointless. Investigate the cause of any variations, which are outside these limits before the instrument is used for measuring gears.
- (f) Determine the measurement uncertainty of each gear artifact as specified in section 6. If the measurement uncertainty of the instrument exceeds the values in Table 4, conduct further checks outlined in this section.
- (g) Once the measurement uncertainty of the instrument is determined, periodic tests of the gear artifacts should be conducted to verify that the instrument uncertainty has not changed.

Table 2 Permissible variations when checking instrument alignment
[values in μm]

Accuracy Grade to be Tested [ANSI/AGMA 2000-A88]	Runout of Spindle Top Center & Base Disc (TIR)	Z-axis Alignment and Straightness with a Parallel Mandrel over 200 mm		Alignment of Top Center with the Spindle Axis (TIR)
		A	B	
Q15	1.5	2.0	2.5	2 μm /150 mm

Note: A - in the measuring (base tangent) plane
B - perpendicular to the measuring plane

The variation values in Table 2 can be adjusted by a factor of $\sqrt{2}$ for each successive change in accuracy grade.

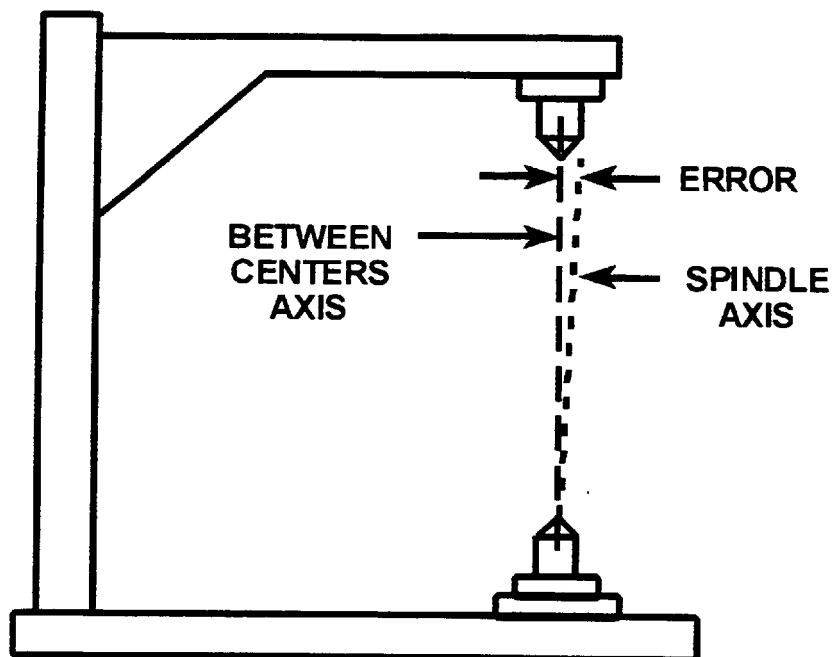


Figure 1 Alignment variation of the spindle axis and the between-centers axis

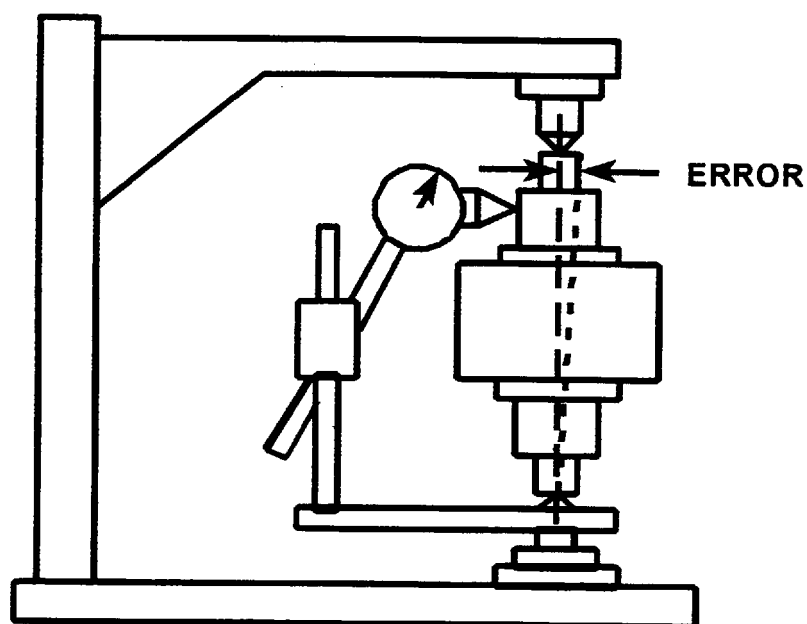


Figure 2 Measurement method

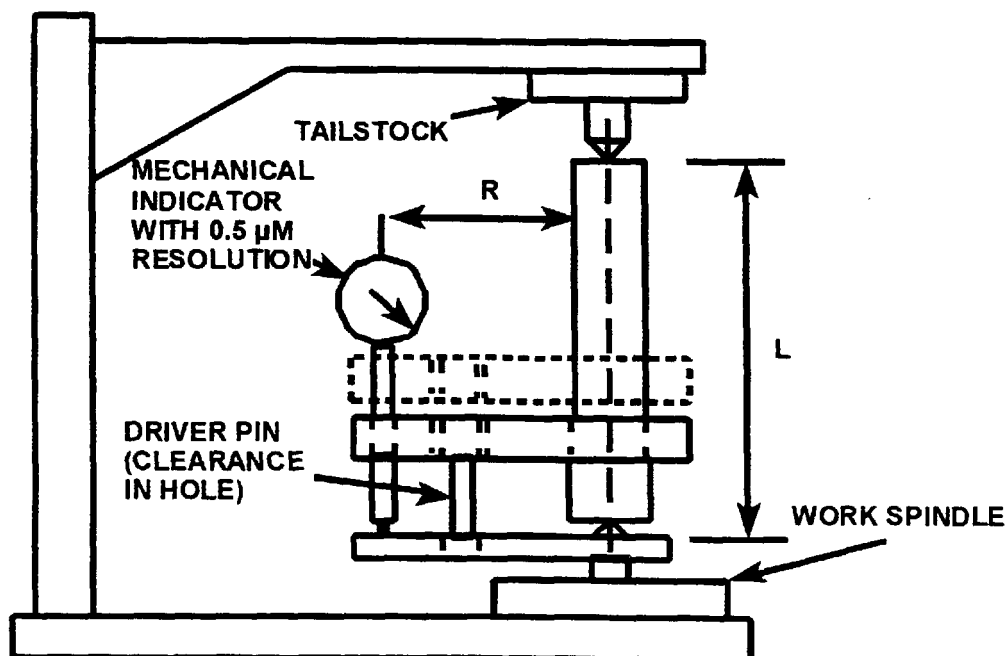


Figure 3 Tailstock center alignment fixture for horizontal or vertical work spindles

4.2 Probe system

Check the condition of the stylus that is to be used to measure the artifacts and record its size and geometry. Verify the position of the probe on the instrument by re-datuming (re-qualifying) or use the manufacturer's setting fixture. For each probe axis that is used to measure gear variations, use a traceably calibrated probe tester to carry out the following tests:

- (a) Check the magnification of the probe system over a $\pm 50 \mu\text{m}$ range and verify that it satisfies the requirements specified in Table 3.
- (b) Check the resolution and lost motion of the probe system at 3 positions in the probe range and verify that it satisfies the requirements in Table 3.

Note: Most probe systems are bi-directional (so that they can measure left and right flanks of teeth). It is important that the probe is tested in both directions. Also note that the dynamic characteristics are not verified with this test procedure.

Table 3 Probe accuracy and measuring system requirements

Accuracy Grade to be Tested [ANSI/AGMA 2000-A88]	Probe Magnification Deviation (E_m) (% of Measured Variation)	Resolution [μm]	Lost Motion [μm]
Q15	$\pm 2\%$	0.2	0.3

The variation values in Table 3 can be adjusted by a factor of $\sqrt{2}$ for each successive change in accuracy grade.

To enable the static tests of the probe to be carried out, a traceably calibrated probe test system with the following characteristics is required:

Range	$\pm 50 \mu\text{m}$
Resolution	$0.1 \mu\text{m}$ over $\pm 10 \mu\text{m}$
Resolution	$0.3 \mu\text{m}$ over $\pm 50 \mu\text{m}$
Measurement uncertainty (U_{95})	range $\pm 10 \mu\text{m}$ $U_{95} = \pm 0.3 \mu\text{m}$ range $\pm 50 \mu\text{m}$ $U_{95} = \pm 0.8 \mu\text{m}$

The test system must be capable of being mounted on the instrument and aligned parallel to the probe axis being tested.

4.2.1 Readout condition

This section provides an explanation and general guidelines for determining critical probe measurement errors, including the calibration of the readout electronics.

4.2.1.1 Gain

Evaluation of a gaging system gain involves comparing the actual probe deflection to the amount of deflection indicated by the final output device (see Figure 4). Gain accuracy is dependent upon the performance of the Linear Variable Differential Transformer (LVDT) measuring probe, and the supporting electronics which convert an analog signal representing probe deflection into a numerical value or travel of the strip chart pen. Gain can be tested either by using gage blocks or a pin master. A pin master is preferred since it produces two reversals when checked as an involute profile.

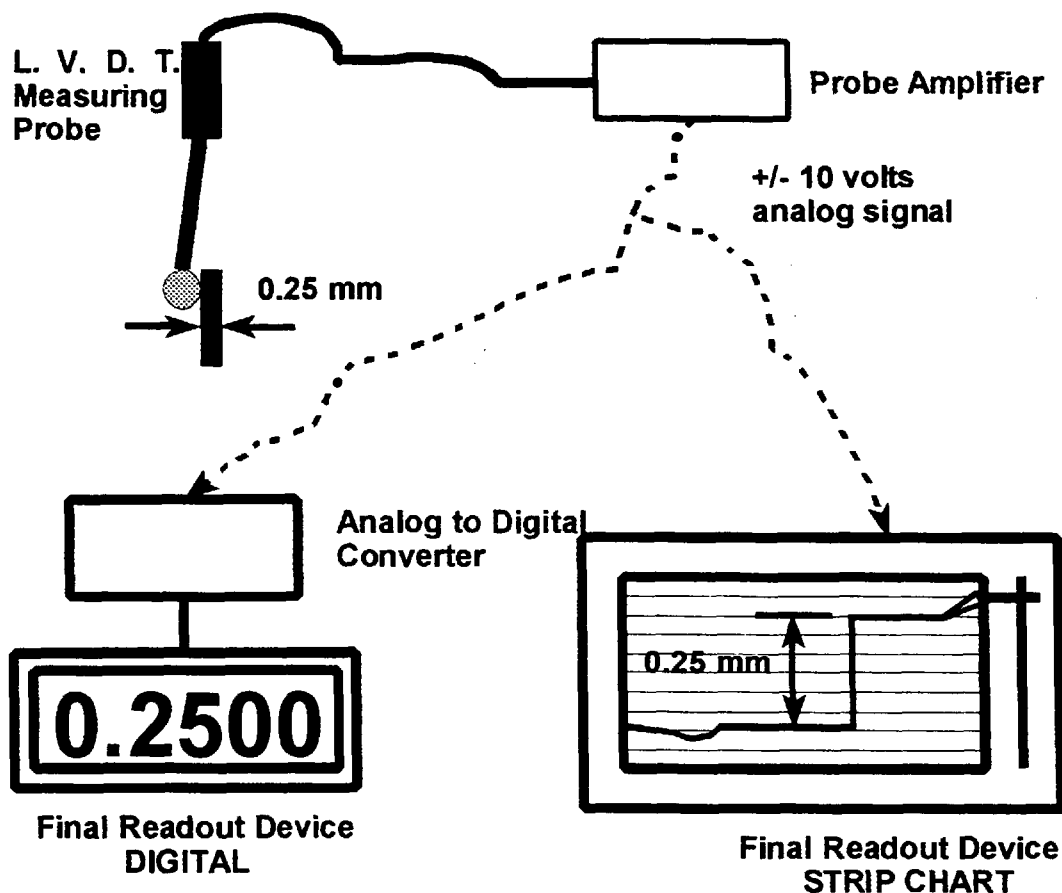


Figure 4 Gaging system gain

4.2.1.2 Linearity

Gaging system linearity can be evaluated observing the pattern of a change in the error in magnification as the actual deflection of the probe varies along its measurement range. A typical LVDT accuracy characteristic shown in Figure 5 demonstrates the increase in measurement error as the probe deflection increases significantly plus or minus from electrical zero.

This can easily be evaluated by calibrating the magnification at varying probe deflections. It is recommended to evaluate probe linearity within the range of deviations that exists in the production gears being measured on the instrument. Some modern CNC measuring instruments may provide software corrections for LVDT non-linearity.

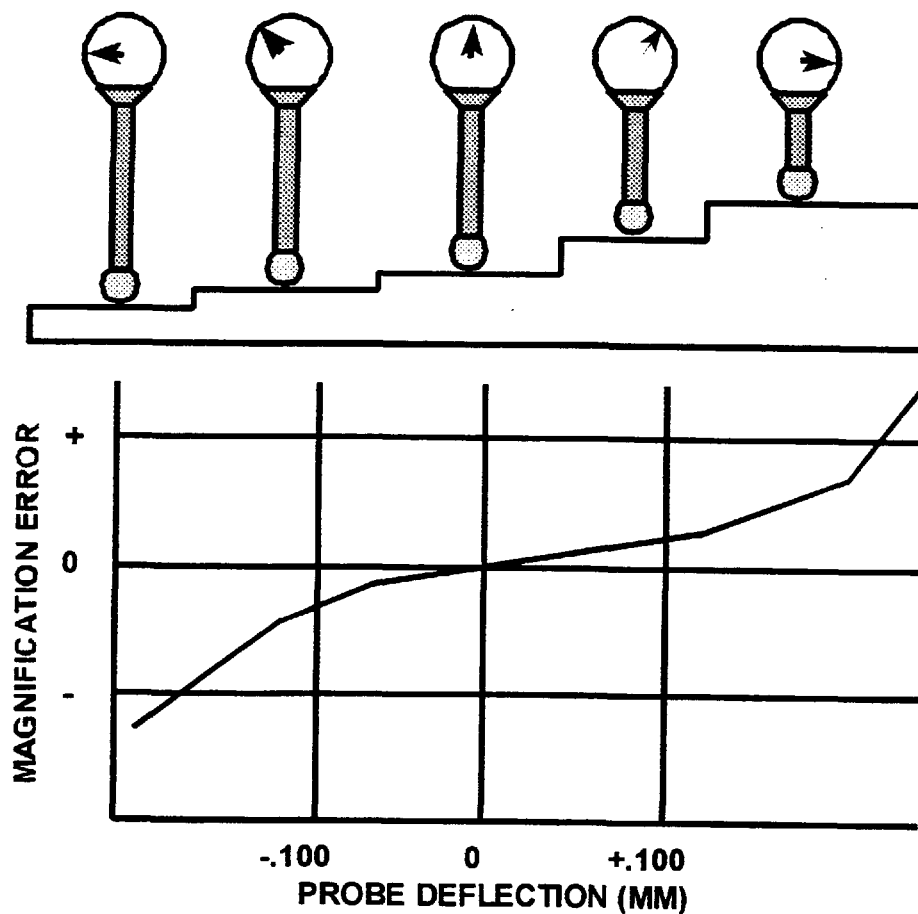


Figure 5 Gaging system linearity

4.2.1.3 Lost motion

Lost motion is the amount of difference the readout displays after the probe has been deflected in one direction and then is reversed to return to the previous position (see Figure 6). Lost motion can be checked by tracing along a calibrated drop in an involute profile or a lead surface, by measuring a flank master, or by measuring a pin master.

4.2.2 Filtering

There are two types of filtering related to the probing system, mechanical and electronic. Mechanical filtering occurs by nature of the probe tip diameter used in the gear measuring instrument. Spherical probe tips also have an averaging effect by not allowing the probe tip to fall into the small valleys on the surface.

Since the lower frequency surface irregularities, i. e. waviness and form error, may be of greater importance to the part function than the higher frequency irregularities, an electrical signal filter is commonly used for the suppression of the representation of high frequency deviations. This tends to smooth the data and eliminate the surface texture effects. It is important to know the type of filtering used and if possible to be able to view the data with different filters or no filter applied.

4.3 Mechanical elements

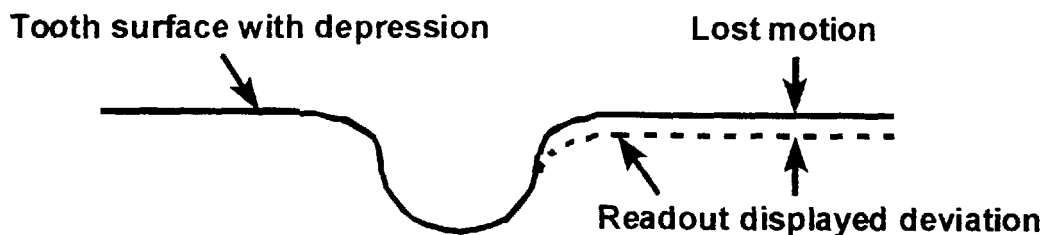


Figure 6 Gaging system lost motion

All equipment used for gear measuring instrument uncertainty tests should be traceably calibrated to national standards. The function of all equipment should be verified before use on site.

Laser interferometer equipment used for straightness variation, angular variation, and length measurement should be re-calibrated within every 18 months period.

Precision levels should be re-calibrated within every 12 month period.

The accuracy requirements for straightness measurement are as follows:

$U_{95} = \pm 0.6 \mu\text{m}$ on slides up to 300mm over $\pm 10 \mu\text{m}$ range

$U_{95} = \pm 0.8 \mu\text{m}$ on slides over 300mm over $\pm 10 \mu\text{m}$ range

The accuracy requirement for angular measurement is as follows:

$U_{95} = \pm 1.0 \mu\text{m/m}$ for all slides over $\pm 20 \mu\text{m/m}$ range

The accuracy requirement for length measurement is as follows:

$U_{95} = \pm 1.0 \mu\text{m/m}$ over any specified slide length

4.3.1 Spindle runout

Check that the center is free from damage and corrosion. Measure runout over several revolutions on the center and verify that it meets the requirements in Table 2.

Mechanical or electronic indicators are used to measure runout and alignment during tests. They require the following characteristics:

Measurement uncertainty (U_{95})	$\pm 25 \mu\text{m}$ range $U_{95} = \pm 1.0 \mu\text{m}$ $\pm 5 \mu\text{m}$ range $U_{95} = \pm 0.5 \mu\text{m}$
Resolution	$0.5 \mu\text{m}$

The function of the indicator should be tested before use and the indicator should be traceably calibrated.

4.3.2 Centers

Check that the center is free from damage and corrosion. If the instrument has a live center, measure runout over several revolutions of the center while the center is supporting a mandrel and verify that it meets the requirements in Table 2. Check the alignment of the axis between centers with the spindle axis by measuring runout of the tailstock center relative to the spindle axis (see Figure 2) with a mandrel between centers. Verify it meets the requirements specified in Table 2 at 3 different heights over 80% of the tailstock range. Check the alignment of the axis between centers with the main vertical (Z) axis and verify that the mean alignment and straightness variations of the vertical axis meet the requirements specified in Table 2.

A parallel mandrel which will normally be mounted between centers should be calibrated for straightness using the reversal method. The calibrated length of the mandrel should be over 250 mm long. The mandrel should be straight within 1.0 $\mu\text{m}/100\text{mm}$ length with a calibrated uncertainty of $\pm 1.0 \mu\text{m}$.

4.3.3 Ways, slides, columns

Some CMMs and gear measuring instruments use variation correction software which should compensate for systematic variations in slides of the instrument. This may mean that variations measured when testing the individual slides may be correctly compensated by the instrument software.

In these cases the tests on the individual slide variations should be carried out but the test results should not be treated as variations if:

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

Slides less than 300mm long should be tested for geometrical variations with measurements taken at 20mm intervals. Slides greater than 300mm long should be tested with measurements taken at 50mm intervals. A minimum of 3 bi-directional repeat tests must be carried out on each parameter being tested.

The measurement of slide squareness variations is not normally required provided that the measurement results on the gear artifacts are satisfactory, but the calibration engineer may include them if it is considered necessary to do so.

Tests on short wave components of geometrical slide variation are not necessary if the measurement results on the gear artifacts are satisfactory, but may be carried out if the calibration engineer considers it necessary to do so.

It is recommended that the complete slide length is tested irrespective of the size of the verified measuring volume although the accuracy requirements are applied to that part of the slide used for the required measuring volume.

The following parameters should be tested:

- (a) 4-axis gear measuring instruments (see Figure 7)
 - Straightness variations
 - vertical axis Δ_{ZY}
 - tangential axis Δ_{YZ}
 - Angular axis
 - vertical axis $\theta_{ZZ}, \theta_{ZX}, \theta_{ZY}$
 - tangential axis θ_{YY}, θ_{YZ}
 - radial axis θ_{XX}
- (b) 3-axis gear measuring instruments
 - Straightness variations
 - vertical axis Δ_{ZY}, Δ_{ZX}
 - radial axis Δ_{XY}, Δ_{XZ}
 - Angular axis
 - vertical axis $\theta_{ZZ}, \theta_{ZX}, \theta_{ZY}$
 - radial axis $\theta_{XX}, \theta_{XY}, \theta_{YZ}$
- (c) 3/4-axis CMM
 - Straightness variations
 - $\Delta_{XY}, \Delta_{XZ}, \Delta_{YX}, \Delta_{YZ}, \Delta_{ZX}, \Delta_{ZY}$
 - Angular axis
 - $\theta_{XX}, \theta_{XY}, \theta_{XZ}, \theta_{YX}, \theta_{YY}, \theta_{YZ}, \theta_{ZX}, \theta_{ZY}, \theta_{ZZ}$
 - Position variations (T.E.)
 - $\Delta_{XX}, \Delta_{YY}, \Delta_{ZZ}$

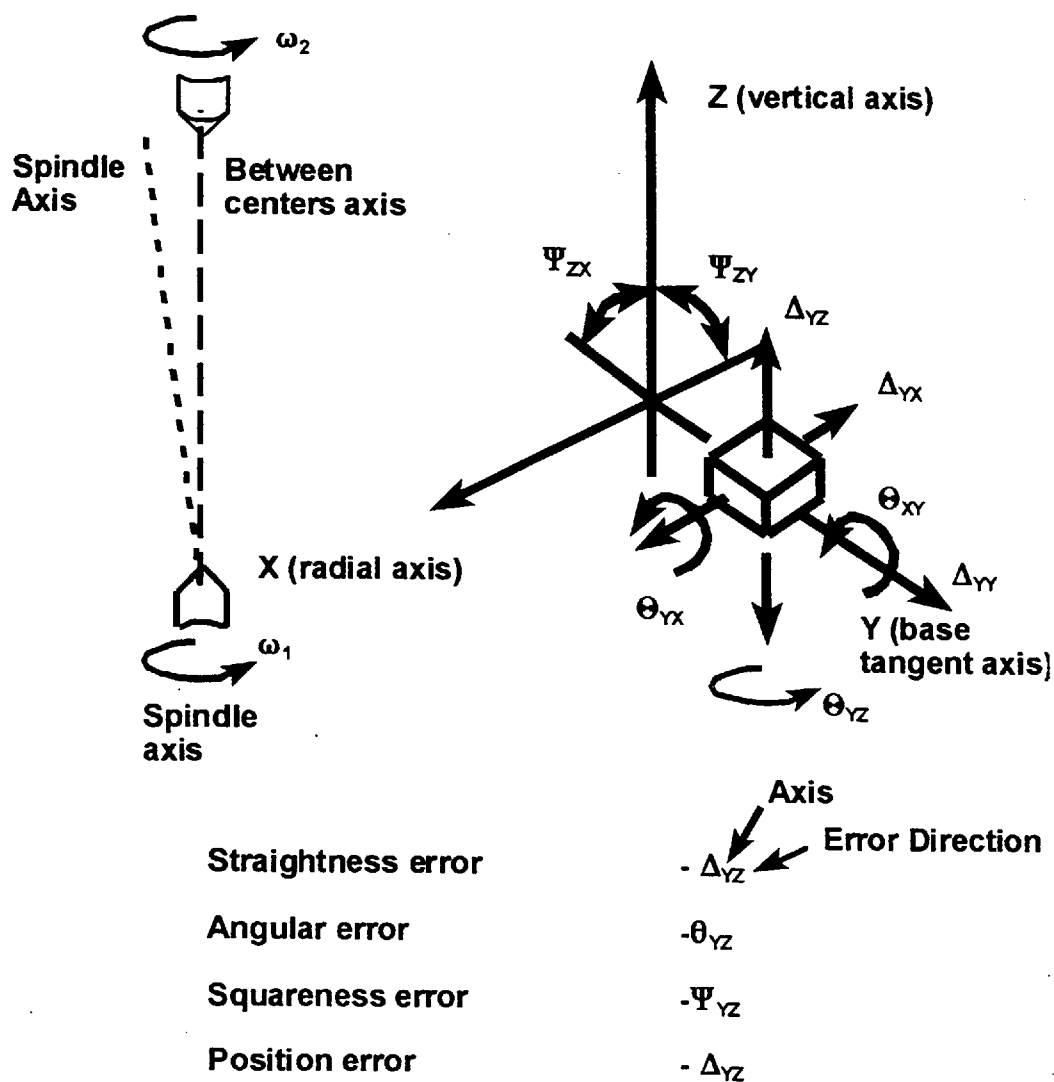


Figure 7 Definitions of axes on a 4-axis gear measuring instrument and slide errors