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Effect of environmental compensation errors on measurement accuracy

Overview

The accuracy of measurements taken with a laser interferometer system depends upon the environmental and machine conditions of the system under test. This application note describes the operation of compensating for these conditions and the effects of incorrect compensation.

Air refractive index

The accuracy of linear positional measurements depends on the accuracy to which the wavelength of the laser beam is known. This is determined not only by the quality of the laser stabilisation, but also by ambient environmental parameters. In particular, the values of air temperature, air pressure and relative humidity will affect the wavelength (in air) of the laser beam. These errors can be reduced by using a Renishaw XC or EC compensation system.

If the variation in wavelength is not compensated for, then linear laser measurement errors can reach 50 ppm. Even in a temperature-controlled room the variation in day-to-day atmospheric pressure can cause wavelength changes of over 20 ppm. As a guide, the error incurred for each of the following changes in the environmental conditions from nominal values of 20 °C, 1013.25 mbar and 50 %RH is:

≈ +0.96 ppm / °C
≈ -0.27 ppm / mbar
≈ +0.0084 ppm / %RH

A Renishaw compensator measures the air temperature, pressure and humidity, then calculates the air's refractive index (and hence the laser wavelength) using the modified Edlen equation as recognised by NIST. The laser read-out is then automatically adjusted to compensate for any variations in the laser's wavelength away from the nominal values. The advantage of an automatic system is that no user intervention is required and that compensation is updated regularly.

Wavelength compensation only applies to linear interferometric measurements. For other measurements (angle, flatness, straightness etc), environmental influences are far less significant, as environmental changes affect both the measurement and the reference beams to a similar degree.

Although the effect on the laser wavelength is small, if high accuracies are required, then air refraction compensation should be performed on the laser reading.

The approximate 'measurement error' resulting from an 'environmental compensation error' can be calculated using the guide values (shown above) as follows:

Examples:

Air Temperature

Measurement error (µm) ≈ +0.96 x Measured distance (m) x Temperature Error (°C)

Distance	-0.3 °C	-0.2 °C	-0.1 °C	+0.1 °C	+0.2 °C	-0.3 °C
1.0m	-0.29 µm	-0.19 µm	-0.10 µm	+0.10 µm	+0.19 µm	-0.29 µm
10.0m	-2.88 µm	-1.92 µm	-0.96 µm	+0.96 µm	+1.92 µm	-2.88 µm

Air Pressure

Measurement error (µm) ≈ -0.27 x Measured distance (m) x Air Pressure Error (mbar)

Distance	-0.3 mbar	-0.2 mbar	-0.1 mbar	+0.1 mbar	+0.2 mbar	+0.3 mbar
1.0m	+0.08 µm	+0.05 µm	+0.03 µm	-0.03 µm	-0.05 µm	-0.08 µm
10.0m	+0.81 µm	+0.54 µm	+0.27 µm	-0.27 µm	-0.54 µm	-0.81 µm

Relative Humidity

Measurement error (µm) ≈ +0.0084 x Measured distance (m) x Relative Humidity Error (%RH)

Distance	-6.0 %RH	-4.0 %RH	-2.0 %RH	+2.0 %RH	+4.0 %RH	+6.0 %RH
1.0m	-0.05 µm	-0.03 µm	-0.02 µm	+0.02 µm	+0.03 µm	+0.05 µm
10.0m	-0.50 µm	-0.33 µm	-0.17 µm	+0.17 µm	+0.33 µm	+0.50 µm

Material thermal expansion compensation

The international reference temperature used by the calibration community is 20 °C and CMMs and machine tools are normally calibrated with reference to this temperature. In a normal factory environment where precise temperature control is often not available, the machine will not be at this temperature. Because most machines expand or contract with temperature, this can cause an error in the calibration.

To avoid this calibration error, the linear measurement software incorporates a mathematical correction called thermal expansion compensation or 'normalisation' which is applied to the linear laser readings. The software normalises measurements using the coefficient of expansion of the machine, which must be entered manually, and a mean machine temperature measured using the XC compensator and material temperature sensor. The objective of this correction is to estimate the laser calibration results that would have been obtained if the machine calibration had been performed at 20 °C.

The thermal expansion coefficient of a machine is specified in parts per million per degree C (ppm/°C). These coefficients specify the amount that the material will expand or contract for every degree rise or fall in material temperature. For example, suppose the coefficient of thermal expansion is +11 ppm/°C. This means that for every 1 °C rise in material temperature, there will be a material expansion of 11 ppm, which is equivalent to 11 µm/m of material.

Incorrect compensation for material thermal expansion is one of the primary sources of error in laser linear distance measurements in non-temperature controlled environments. This is because the expansion coefficients of common engineering materials are relatively large compared to the coefficients associated with wavelength compensation errors and laser beam alignment errors.

The normalised measurement will have an error relating to the measurement accuracy of the material temperature sensor. The size of this error depends on the coefficient of thermal expansion (CTE) of the machine under test.

Examples:

Assuming C_{TE} = 11.7 ppm / °C

Measurement error (µm) = C_{TE} x Measured distance (m) x Temperature Error (°C)

Distance	-0.3 °C	-0.2 °C	-0.1 °C	+0.1 °C	+0.2 °C	-0.3 °C
1.0m	-3.51 µm	-2.34 µm	-1.17 µm	+1.17 µm	+2.34 µm	+3.51 µm
10.0m	-35.1 µm	-23.4 µm	-11.7 µm	+11.7 µm	+23.4 µm	+35.1 µm

This is in addition to the laser system measurement accuracy when using an environmental compensation unit. However, since the two errors are uncorrelated, their combined effect is the square root of the sum of their squares and not their arithmetic sum.

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