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Monte-Carlo simulation and experimental validation of the self-calibration of a linear encoder

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Abstract
This paper proposes a self-calibration method to determine the non-linear length deviation of a linear encoder, which makes use of two reading heads. First, both reading heads are scanned over the scale, after which one of the heads is displaced. The scale is then scanned again and from the obtained data, the deviation is calculated by a least-squares estimation. A Monte-Carlo simulation of this procedure indicates that for an optimal displacement of the second head, 2.6 nm calibration uncertainty is within reach. The procedure is then experimentally verified, which shows that the estimated uncertainty is in good agreement with the real uncertainty value.

Keywords: Linear encoders, self-calibration, metrology

1. Introduction

To measure linear motion in high-accuracy machine tools, CMMs and other inspection machines, linear encoders and laser interferometers are mostly employed. Linear encoders, however, are the preferred choice because of their lower cost and easier integration with respect to laser interferometers, while at the same time having a lower sensitivity to environmental changes. Nevertheless, to reach sub-micrometre or even nanometre accuracies, calibration of the linear encoders is indispensable. Calibration is mostly done by comparison with a laser interferometer [1], but if one is only interested in the non-linear length deviation of the scale instead of the absolute length deviation, self-calibration might be an easier and more cost-effective approach.

This paper proposes a method to perform self-calibration of a linear encoder to determine the deviations from linearity by using two reading heads. The calibration concept is explained and a numerical simulation is carried out, which gives more insight in the calibration uncertainty. Experiments on a 170-mm Heidenhain LIP281 encoder are conducted, which show the reproducibility of the proposed method.

2. Calibration concept

The deviation of the measured value of the encoder from the true value is constituted by a linear deviation from the true value, called the 'scale error', and the deviation from linearity, as depicted in Figure 1. The calibration method that is discussed in this paper focusses on the calibration of the non-linearity.

The calibration is performed as follows. First, two reading heads that are located a distance D_{12} apart are scanned over the scale's measurement length by either translating the scale or the reading heads in the measurement direction (Figure 2). The measurement of each reading head can be expressed as:

$$x_{1,1} = x_{true,1} - e(x_{true,1})$$
$$x_{2,1} = x_{true,1} - e(x_{true,1} + D_{12}) + D_{12}$$

in which $x_{1,1}$ *and* $x_{2,1}$ are the measured positions of the two reading heads and *e(x)* is the deviation from the true position in function of the position *x* on the scale. If the scale is calibrated for *N* index positions, each a distance Δx apart, these expressions lead to $2\cdot(N\text{-}D_{12}/\Delta x)$ equations. Next, one of the two reading heads is displaced a distance d_{23} and the measurement is repeated, giving the following expressions:

$$x_{1,2} = x_{true,2} - e(x_{true,2})$$
$$x_{2,2} = x_{true,2} - e(x_{true,2} + D_{12} + D_{23}) + D_{12} + D_{23}$$

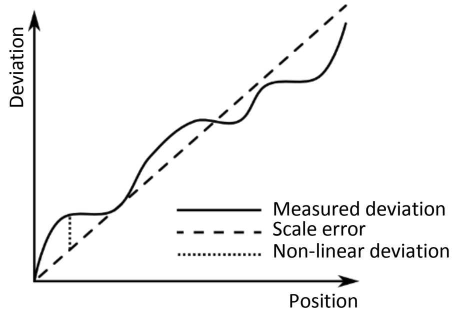

Figure 1. Definition of the length deviations of a linear encoder with respect to position.

This results in $2\cdot(N\text{-}(D_{12}+D_{23})/\Delta x)$ additional equations. From these equations, $x_{true,1}$ and $x_{true,2}$ can be eliminated. The remaining equations can be translated to a linear least-squares formulation and solved for e(x). In order to only solve for the non-linear deviation, the equations are also solved for D_{12} and D_{23} and a constraint demanding no correlation of the deviation with position is added. To make sure this system of equations has a solution, D_{12} and D_{23} should be chosen such that the greatest common divisor of $D_{12}/\Delta x$ and $(D_{12}+D_{23})/\Delta x$ is equal to 1.

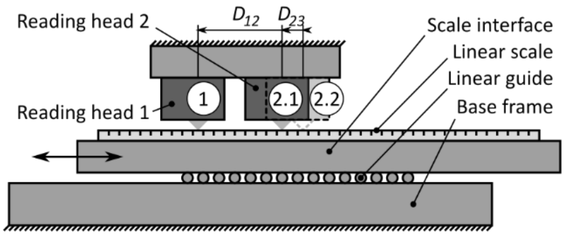

Figure 2. Self-calibration concept. The reading heads or the scale are translated over the scale's measurement stroke. Next, Reading head 2 is displaced a distance D_{23} and the scale is scanned again.

3. Numerical simulation

A numerical simulation has been carried out to determine the calibration uncertainty of the proposed method. The calibration chart of the scale, supplied by the manufacturer, was used to obtain typical values and profiles of the length deviation. The simulation has been set up as a Monte Carlo simulation, in which a virtual measurement of the displacement has been conducted, while for every measurement the following errors were randomly added to the data: Abbe error, sensor noise, position deviation of D_{12} (55 mm) and D_{23} (0.3 mm) and thermal drift of the reading heads. The errors that were incorporated in the simulation correspond to those of the setup that will be described in the next section. The simulation has been repeated 100 times and the error w.r.t. the true deviation has been determined for every calculated deviation. Figure 3 gives the calculated and true deviation, while Figure 4 displays the error. The calibration uncertainty has been derived by calculating the standard deviation of the 100 repetitions, which amounted to 18 nm (95% confidence level). This uncertainty can be reduced by increasing D_{23}, as this decreases the sensitivity to thermal errors. The latter has also been verified using the Monte Carlo simulations. The uncertainty can be lowered to 2.6 nm for a displacement D_{23} of 3.3 mm.

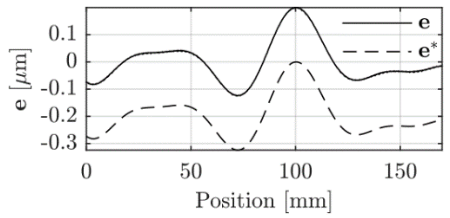

Figure 3. Calculated (**e**) and true (**e***) length deviation of one experiment of the Monte Carlo simulation of the self-calibration procedure for a 170-mm scale. **e*** is shifted by -0.2 µm for clarity.

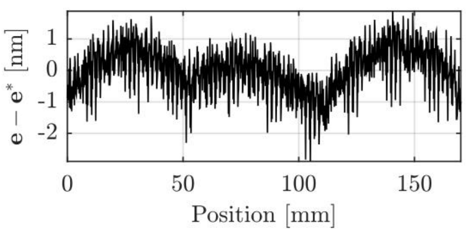

Figure 4. Calibration error of one experiment of the Monte Carlo simulation of the self-calibration procedure for a 170-mm scale.

4. Experiments

The calibration method has been experimentally verified on a Heidenhain LIP 281 linear encoder with a measurement length of 170 mm that is contained in a setup that was previously used for determining the reproducibility of an Abbe-compliant linear encoder-based measurement system [2]. On this setup, one of the mounts for the reading heads was replaced by a mount on which the reading head can be displaced by set screw, while the motion is guided by two parallel leaf springs. The maximum allowable stress in the leaf springs limits the maximum displacement of the reading head to 0.3 mm, which puts a limit on the attainable calibration uncertainty.

The calibration procedure has been carried out 8 times on this setup over a length of 146 mm and the resulting calculated deviations $\mathbf{e}_i$ are depicted in Figure 5 together with their mean value $\bar{\mathbf{e}}$. The difference with respect to this mean value is shown in Figure 6. The periodicity can be ascribed to the amplification of certain spatial frequency errors by the least-squares estimation. From the difference in calculated length deviations, the reproducibility of the calibration procedure is estimated at 15 nm (95%). The reproducibility incorporates all previously simulated errors, except for the repeatable Abbe errors. If we assume a maximum Abbe-offset of 100 µm and we calculate the sensitivity to Abbe-offsets for this setup by Monte Carlo simulations, which equals 2.9 nm/(100 µm), the total uncertainty, calculated by root-sum-square, equals 16 nm.

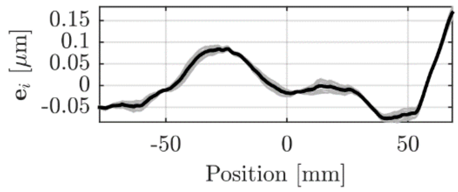

Figure 5. Length deviation $\mathbf{e}_i$ for 8 self-calibration experiments (grey) conducted on a Heidenhain LIP 281 scale over a measurement length of 146 mm and mean length deviation.

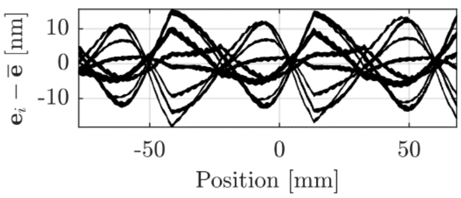

Figure 6. Difference of the length deviation $\mathbf{e}_i$ with the mean length deviation $\bar{\mathbf{e}}$.

5. Conclusion

This paper presented a method for the self-calibration of the non-linear length deviation of linear encoders by using two reading heads. The method allows calibration of a scale while it is mounted on the machine by adding a second reading head which can be translated over a small distance. Simulations and experiments have shown that the calibration uncertainty decreases with increasing displacement. For a displacement of 0.3 mm, it has been calculated that the calibration uncertainty (95%) for a 170-mm scale was 18 nm, while experimental results have verified that the numerical simulation of the procedure gives a good indication of the calibration uncertainty.

References

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