A self-calibration method for the error mapping of a 2D precision sensor

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Abstract

In this paper two calibration techniques for the error mapping of a 2D sensor – a cross grid encoder – are presented: a mathematical correction to assess the squareness errors and a self-calibration of the cross grid encoder itself. The calibration setup includes a metrology frame made of Zerodur®, a very low thermal expansion coefficient material in order to reduce thermal errors. Additionally, an analysis by means of a finite element analysis software has been carried out for an adequate design of the setup. Finally, uncertainty values for the 2D cross-grid encoder system are estimated.

1 Introduction

2D cross-grid encoders are very suitable to be used not only in the machine tool area but also in metrology precision applications, such as, coordinate measuring machines characterization and 2D optoelectronic sensors calibration. However, the calibration of a 2D cross grid encoder is done by the manufacturer just in their main two axes separately, which can be an accuracy limitation in some high precision applications. To calibrate the whole area of the grid a calibration technique was proposed in a previous work where the grid was used as a squareness reference [1]. But if this cross-grid encoder is not perpendicular enough this error can also be a source of influence in the final uncertainty of its calibration. To solve these calibration problems, two different techniques are proposed in this work. The first one involves a correction in the mathematical model presented in [1] to assess the squareness error of the 2D cross-grid encoder. The second one is the application of a self-calibration technique that includes the lack of squareness of the 2D cross-grid encoder. Besides, in order to meet nanometer accuracy in this procedure, the use of very low thermal
expansion materials together with a controlled environment (temperature, humidity and pressure) are necessary.

2  **Zerodur metrology frame design**

The metrology frame used in this work is made of Zerodur® due to its very low coefficient of thermal expansion in addition to its light weight which is necessary for the assembly. This frame consists of two parts, a base and a top. Since Zerodur is a brittle material, it has to be assembled without any direct contact with some metals or any sharp material that can cause a micro fissure in the Zerodur. Different preliminary tests involving a first design of a piece of aluminium (instead of Zerodur), one or three screws with plastic or rubber washers to fix the parts and two capacitive sensors were used to measure the stability of the system, as shown in Figure 1 (a). After analysing the results it was decided that the best option to our application consisted of using three screws and plastic washers. Once the couple of Zerodur top plate was disposed, an optimum Zerodur plate form was designed and analysed using Ansys Workbench software, taking into account that the top plate is exposed to compression and tensile stresses as detailed in Figure 1 (b). The results show that Zerodur top plate geometry is adequate to withstand tension and compression stresses.

![Figure 1: a) Stability test setup; b) Tension and compression stress acting on Zerodur](image)

3  **Cross-grid encoder calibration methods**

The proposed setup shown in Figure 2 is mounted on a 2D moving table and it includes the metrology frame described above, the 2D sensor to be calibrated (a Heidenhain grid encoder KGM 181 with nanometer resolution, comprising a grid plate with waffle type graduation and a scanning head) and a 2D laser encoder system
as a reference instrument (a Renishaw laser encoder RLE dual axis system with nanometer resolution that includes RCU environmental compensation units).

Figure 2: a) proposed setup; b) angular misalignments of KGM.

As mentioned before, a mathematical model to calibrate the KGM was proposed in a previous work [1], where a perfect perpendicularity in the cross-grid encoder was assumed. Nevertheless, the grid encoder could have squareness errors that can influence the final uncertainty of its calibration. One way to approach this problem comes by assuming that all X lines and Y lines in the KGM grid are parallel but not perpendicular between them, as shown in Figure 2b. If this squareness error is included in the mathematical model presented in [1], then the new mathematical model that relates the cross-grid encoder and the laser read-outs is as follows:

\[
\begin{pmatrix}
\cos \rho_x \cos(\alpha X - \alpha X) & \cos \rho_y \sin(\alpha X - \alpha X) \\
\cos \rho_x \sin(\alpha Y - \alpha Y) & \cos \rho_y \cos(\alpha Y - \alpha Y)
\end{pmatrix}
\begin{pmatrix}
\Delta X_{KGM} \\
\Delta Y_{KGM}
\end{pmatrix}
= 
\begin{pmatrix}
\Delta X_L \cos \alpha X / \cos \beta_X \\
\Delta Y_L \cos \alpha Y / \cos \beta_Y
\end{pmatrix}
\tag{1}
\]

Another proposed way to fully calibrate the KGM would include the use of the self-calibration method presented in [2]. The KGM error map is taken out from three different views of the KGM, a normal view (view 0), another one rotated 180° with respect to view 1 (view 1) and a translated view in the positive X axis direction (view 2). In each view the measurement deviation from X and Y KGM position and the nominal position of laser system are denoted as:

\[
\begin{align*}
V_{0,x,m,n} &= G_{x,m,n} + L_{x,m,n} + E_{0,x,m,n} \\
V_{0,y,m,n} &= G_{y,m,n} + L_{y,m,n} + E_{0,x,m,n} \\
V_{1,x,m,n} &= -G_{x,m,n} + L_{x,m,n} + E_{1,x,m,n} \\
V_{1,y,m,n} &= -G_{y,m,n} + L_{y,m,n} + E_{1,x,m,n} \\
V_{2,x,m,n} &= G_{x,m,n} + L_{x,m+1,n} + E_{2,x,m,n} \\
V_{2,y,m,n} &= G_{y,m,n} + L_{y,m+1,n} + E_{2,x,m,n}
\end{align*}
\tag{2-4}
\]

where \( m = n = -(N-1)/2 \ldots (N-1)/2 \). Go and Gy are the KGM error function in the Cartesian space grid of 13 x 13 points (N x N) in an area of 60 mm x 60 mm (L x L).
around the centre of the KGM. Lₓ and Lᵧ are the measurement deviation of the grid of the laser from the initial Cartesian space grid. Eₓ and Eᵧ are the misalignment errors between KGM and Laser axes.

4 Uncertainty analysis

Once the error maps of the grid encoder are calculated, an uncertainty analysis of this 2D sensor is carried out, as follows:

\[ U(k = 2) = k \sqrt{u_{Laser}^2 + \frac{S_{Cal.KGM}^2}{n_{Cal.KGM}} + u_{Error.Residual}^2 + u_T^2 + u_{Resolution.KGM}^2} \]  \hspace{1cm} (5)

where \( u_{Laser} \) is the reference 2D laser uncertainty, \( S_{Cal.KGM} \) is the standard deviation of the KGM calibration, \( n_{Cal.KGM} \) is the number of data in calibration procedure, \( u_{Error.Residual} \) is the final error after alignment uncertainty, \( u_T \) is the uncertainty of expansion/contraction of KGM due to small changes in temperature at test with constant temperature and \( u_{Resolution.KGM} \) is the KGM resolution uncertainty. The values obtained are between 300 and 400 nm both for X and Y axes.

5 Conclusion

In this work, two different calibration techniques for a 2D cross grid encoder are presented using the same thermally stable setup and a 2D laser system as a reference system. Finally, an uncertainty analysis of this 2D encoder is described.

Acknowledgements

This project was funded by Spanish government project DPI2010-21629 “NanoPla”. Appreciation to DGEST which sponsored the first author.

References:
