DE-COUPLING OF AN OPTICAL GRATING BASED MEASUREMENT NORMAL FROM THE MACHINE TOOL STRUCTURE

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Introduction

Precision machine tools use optical encoders for accurate position feedback [1,2]. A novel encoder based on three cross grid gratings mounted on a thin wall beam and a sensor head consisting of six optical sensing elements was developed to calibrate the linear machine tool axis in six Degrees of Freedom (Figure 1). The feasibility of this device has been tested and verified under laboratory conditions [3]. However, in order to use the device under varying environmental conditions it has to be guaranteed that the measurement normal is decoupled from the mounting surface in order to prevent induced forces to distort its shape. Therefore this paper describes the design procedure for such de-coupling mounts based on slip stick free flexures.

![Figure 1. Encoder Prototype (1m long)](image)

Principle

During calibration the encoder base is mounted on the table of a machining center and the bracket that holds the sensing heads is attached to the machine spindle. The three optical glass gratings on the stainless steel thin wall beam act as measurement normal. Therefore a mounting scheme which de-couples the measurement normal from the machine structure itself is necessary. For in-process calibration the de-coupling unit has to be slip stick free. To de-couple the measurement normal from the mounting surface, 2-Degrees of Freedom (DOF) must be provided at the side with the thermal reference, whereas the other end should provide only support in horizontal and lateral direction (Figure 2). As far as the basic motion range requirements are concerned a maximum thermal change of 15 Kelvin is assumed. Giving this particular steel beam of one-meter length an expansion of approximately 200µm. The mounting beam has a weight of about 10kg. We also assume an offset of 100µm between the two ends of the beam due to mounting misalignment and due to the deformation of the mounting surface on the machine table. This would cause the beam to bend about 100µrad over 1m.
To provide the necessary DOF while maintaining a slip stick free setup the use of flexures is proposed. In order to provide the desired degrees of freedom, while maintaining rigidity and providing a defined thermal and geometrical reference the mounting flexures have to be properly dimensioned [4]. The 2-DOF mount consists of a toroidal two-axis flexure (Figure 3), and it allows small bending deflections about a point located at the thinnest point with the thickness t. In order to size the mount, the axial, torsion, and bending stiffness must be calculated. Goal is to keep the torsional and axial stiffness high while maintaining a low bending stiffness to prevent deformation of the measurement normal due to bending. The equations for the bending stiffness $k_b$ can be approximated from Paros and Weissbord [5]

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E t^{3/2} \over 20 R^{1/2}
$$

The parameter G is the shear modulus, T is the applied moment and $I_{px}$ the polar moment of inertia that varies over the length L. With the mathematical descriptions, one can create graphs for each bending, torsion, and axial stiffness depending on the individual geometric variables such as length, diameter, and thickness (Figure 4).

Analogous the same can be done for the torsional stiffness.
The 4-DOF flexure consists of a cruciform type of flexure for torsional motions and a disk type flexure for translational motion as well as bending.

![Cruciform Flexure](image1)

**Cruciform Flexure**

Torsion, bending, axial stiffness

\[ k_i = \left( \frac{d}{l} - 0.373 \right) \frac{2Gi^4}{3L} \]

\[ k_a = \frac{L}{EA} \]

**Figure 4. Three Degree of freedom mount**

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**Evaluation**

The axial, torsion, and bending behavior of these structures has to be evaluated simultaneously in order to validate the functionality of the proposed mounts. From the previously derived figures, the individual geometry can be selected to achieve the desired deflections. The general requirements for the flexure designs are:

1. Nearly all axial deformation should be provided by the disk flexure.
2. All torsion deformation due to movement of the mounting base has to be provided by the cruciform flexure.
3. Axial deflection should not lead to a substantial in- or decrease of the bending deflection of the measurement normal.

The evaluation of the axial deformations is simple because the elongation of each individual element adds. Knowing the individual stiffness, one can calculate the total Force \( F_{axial} \) that correlates to the axial elongation:

\[ F_{axial} = \delta_{tot} \sum_{i=1}^{4} k_i \]

\[ \delta_{Ax} = \frac{F}{k_i}, i=1..4 \]  \hspace{1cm} (1)

The plot of the axial force versus a total deflection of 0 to 200\( \mu \)m, which corresponds to an approximate thermal elongation caused by a change of temperature of about 15K is shown in Figure 5. The individual deflections are then determined for each flexure as well as the beam. This allows the evaluation of the functionality of the flexure mechanism. Plotting the individual deflections for a total deflection of 200 \( \mu \)m shows that nearly all-axial deformation (more than a factor 100) is provided by the disk flexure.

![Figure 5. Axial deflection of the disk flexure, Axial deflection of the beam, the toroidal and the cruciform flexure](image2)
The effect of torsion and bending can be analyzed analogous to axial deformations. The flexures and the beam act as torsion springs, which are connected in series. As noted, the cruciform flexure is the most elastic torsion element provides nearly all flexibility in torsion. Figure 6 shows the cruciform flexure’s angular displacement if a total torsion deflection of up to 0.8mrad is induced into the structure. Compared to the disk, the bending, the beam and the toroidal flexure its angle of twist $\phi$ is almost 1000 fold larger (Figure 6). This verifies its functionality as a decoupling element.

In order to evaluate the thermal behavior of the measurement device it was mounted on the granite base of a CMM. Than the measurement beam was fitted with two fluid fittings on both sides. Water at various temperatures was run through the beam to simulate a thermal expansion similar to that of a machine tool. While the water was running, the average temperature of the beam was closely monitored. An increase in temperature led to an elongation of the beam, whereas the mounts stayed at a steady position due to the minimal expansion of the granite surface. Therefore, the elongation must be compensated by the disk flexure. In order to insure that the elongation doesn’t lead to a distortion of the beam, a touch probe measured its shape. The test showed promising results and ongoing tests are carried out to investigate the behavior over time.

**Conclusion**

A procedure for the design of flexure mounts for a volumetric encoder was proposed. The mounts enable the de-coupling of a measurement body from the mounting forces induced during mounting on the machine table.

**References**