This is the abstract for a talk given by Ed Morse at the
ASPE Summer Topical Meeting on
Precision Bearings and Spindles, pp. 100-103

Using Alternative Artifacts for Error Motion Analysis

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Abstract

Various methods are used to determine the 'axis of rotation' errors of a machine tool spindle. Many of these techniques use an artifact, or target, mounted to the spindle rotor, with gages monitoring the artifact surface as the spindle rotates. The combined effects of the error motions of the spindle axis, eccentricity of the target, and form errors of the target are seen as variations in the distance from the target surface to the gagehead. The target eccentricity is removed from the data through analysis, while the target form errors are determined using reversal techniques.

In developing a measurement system for spindle (rotor to stator) error analysis that uses a non-standard arrangement of sensors, it became clear that not all sensor setups behave the same way. In addition, the analysis needed to extract the spindle errors from the sensor data will also vary with each sensor configuration. While the analysis for our particular setup is not difficult, we became curious as to the general case of determining the spindle errors from a general set of sensor placements. In this paper we introduce some initial work towards characterizing and analyzing different sensor configurations.

Introduction

A common, commercially available system for determining the error motions of a spindle uses a dual-ball target with five sensors. Synchronous collection of data from the five sensors allows us to reconstruct the error motion (as a function of angular position) in terms of the five degrees of freedom of the axis in space. In order to collect error motion data *while parts are being machined*, we have designed a modified system with a single disk-shaped target and five sensors. As the arrangement of the sensors for this disk is necessarily different than that of the dual-ball system, we must now choose one of two methods to determine the error motions of the spindle axis: (1) modify the measurement data so that the existing algorithms (that use the data from the five sensors on the dual-ball target) can be used to plot and report the data, or (2) develop algorithms dedicated to our particular sensor locations.

Because the exact sensor locations in our system are not known and may change in a later version, we have chosen to address this problem in a more general sense than either of the options listed above. We are attempting to develop a set of generic algorithms for the determination of spindle error motions for *any* sensor configuration. The sensor configuration will be defined by the number of sensors, their location, and their orientation. We assume that the surface of the target is nominally perpendicular to each of the sensor axes at the point of measurement, and develop algorithms for the following tasks:

1. determine if a given sensor placement permits the measurement of all five error motions (two tilt, two radial, and one axial),
2. calculate these error motions as a function of the artifact displacement at each sensor, and
3. determine and map the form error of the target object using reversal methods.

Describing Sensor Placement

We will describe the sensor placement with respect to a non-rotating reference coordinate system whose *z*-axis is coincident with the nominal axis of rotation in question. Because the sensors are measuring a surface that is rotationally symmetric, and the sensor axis should be locally normal to this surface, the sensor axis will either be parallel to the z-axis, or intersect the *z*-axis. The sensor will be located in space by the following 4-tuple: $\{r, \theta, z, \gamma\}$ where (r, θ, z) describe the location and γ describes the angle with the *xy*-plane. These four parameters are shown in Figure 1*a)*.

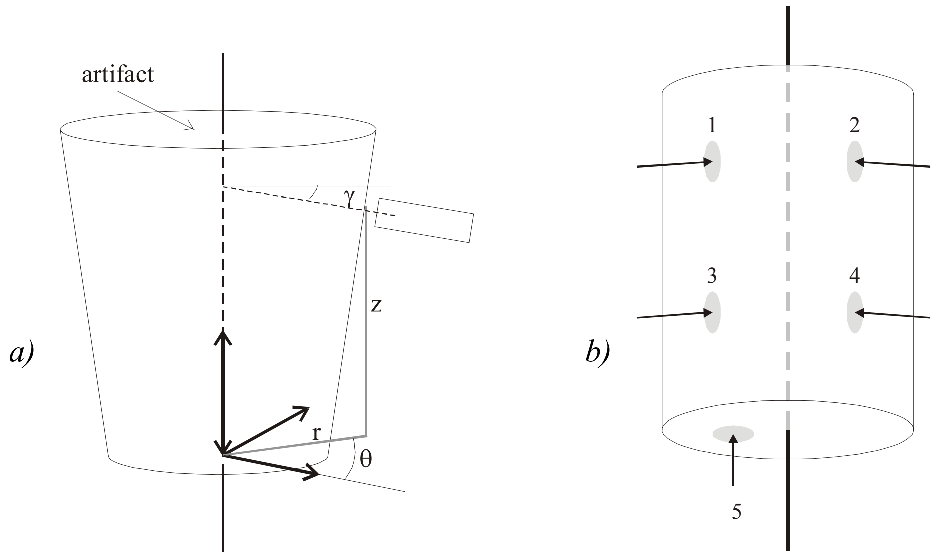

Figure 1: *a)* Parameters describing a single sensor, and *b)* placement of sensors for a cylindrical artifact.

The sensor configuration shown in Figure 1*b)* is one possible arrangement for using a cylindrical artifact. The parameters for this configuration might be as shown in Table 1.

Table 1: Sensor locations for a Cylindrical Artifact.

Sensor	***r** (mm)*	*θ (degrees)*	***z** (mm)*	*γ (degrees)*
1	50	0	100	0
2	50	90	100	0
3	50	0	40	0
4	50	90	40	0
5	30	0	0	90

The next step is to calculate the deviation of the artifact surface due to axis of rotation errors. We are only interested in the deviation along the axis of the sensor and we can express this in terms of the sensor location parameters and the axis of rotation errors. The expression for the combined contribution of all of these errors in shown below in Equation (1). Here dS is the deviation seen at the sensor, and dx, dy, dz, $d\alpha$, and $d\beta$ are the error motions of the axis ($d\alpha$ is the rotation about the +x axis, and $d\beta$ is the rotation about the +y-axis).

$$dS = (dx + z\ \tan(d\beta))(\cos\theta\cos\gamma) + (dy - z\ \tan(d\alpha))(\sin\theta\cos\gamma) + (dz - r\ \cos\theta\sin(d\alpha) + r\sin\theta\sin(d\beta))\sin\gamma \tag{1}$$

We may now calculate the deviation at each of the sensors, resulting in the following expression:

$$\begin{pmatrix} dS_1 \\ dS_2 \\ dS_3 \\ dS_4 \\ dS_5 \end{pmatrix} = \begin{pmatrix} \\ \\ SensitivityMatrix \\ \\ \\ \end{pmatrix} \bullet \begin{pmatrix} dx \\ dy \\ dz \\ d\alpha \\ d\beta \end{pmatrix} \tag{2}$$

The calculation of the axis errors can now be calculated using the inverse of Equation (2):

$$\begin{pmatrix} dx \\ dy \\ dz \\ d\alpha \\ d\beta \end{pmatrix} = \begin{pmatrix} \\ \\ SensitivityMatrix \\ \\ \\ \end{pmatrix}^{-\mathbf{1}} \bullet \begin{pmatrix} dS_1 \\ dS_2 \\ dS_3 \\ dS_4 \\ dS_5 \end{pmatrix} \tag{3}$$

The sensitivity matrix will contain trigonometric functions, and the symbolic inversion may be difficult. However, we have had some success with the program Mathematica™ for fairly simple sensor configurations. One example of this is shown in the next section. Important attributes of this matrix are:

1. Rank – If this matrix is not full rank (i.e. two or more of the columns are linearly independent) then we will not gain enough information from the sensor configuration to calculate all of the spindle errors.
2. Condition number – This number captures the relative sensitivity of the different sensors to various errors. When the matrix is singular the condition number goes to infinity because we are no longer able to capture all of the errors.

An Example

We are currently working on a project where we wish to calculate the rotor-to-stator errors while we're cutting the workpiece. Figure 2 shows the CAD model of the tool holder and target disk and a schematic of the sensor placement. Two sensors look at the disk edge and three sensors that look "down" at the disk face. The schematic is inverted to show the reference coordinates in their normal orientation (+*z* is "up").

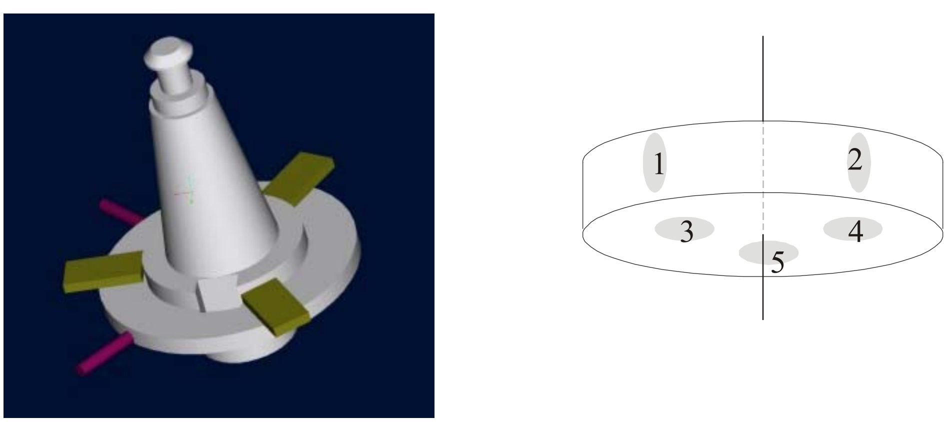

Figure 2: CAD drawing, and sketch of sensor targets for disk-type artifact.

We will present the representation of the sensor configuration and the inversion to obtain the error motions directly from the sensor data. Future work will include a comparison of the condition number for the sensitivity matrix to the matrices obtained for traditional (cylindrical and two-sphere) artifacts.

Sensor	r	θ	z	γ
1	70	0	0	0
2	70	90	0	0
3	40	0	-10	90
4	40	120	-10	90
5	40	240	-10	90

Sensitivity Matrix (simplified w/ small angle approx)

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -40 & 0 \\ 0 & 0 & 1 & 20 & 20\sqrt{3} \\ 0 & 0 & 1 & 20 & -20\sqrt{3} \end{pmatrix}$$

Note: Without the small angle approximations, the entries in column 4 of the matrix will be multiplied by Cos($d\alpha$) and the entries in column 5 by Cos($d\beta$).

When we solve the inversion of the matrix in its full form (no small angle approximations), we obtain the following equations for the error motions:

$$\begin{aligned} dx &= dS_1 \\ dy &= dS_2 \\ dz &= \left(dS_3 + dS_4 + dS_5\right)/3 \\ d\alpha &= ArcSin\left(\left(dS_4 + dS_5 - 2dS_3\right)/120\right) \\ d\beta &= ArcSin\left(\left(\sqrt{3}dS_4 - \sqrt{3}dS_5\right)/120\right) \end{aligned} \quad (3)$$

Acknowledgements

I would like to recognize the original members of B89.3.4 for their clarity and accuracy in producing the 1985 standard, and the current members for their openness and willingness to share their time in explaining the nuances of axis of rotation metrology. This work has been supported in part by the UNCC Center for Precision Metrology Industrial Affiliates.

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