Target Block Alignment Error in XY Stage Metrology

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Abstract

This paper discusses a fundamental question in the characterization of XY stages: Is the orthogonality error of the stage distinguishable from a target block alignment error without explicitly measuring the target block misalignment? The conclusion reached here is that, for parallel kinematic stages this is not possible using any metrology setup or any number of measurements.

Keywords: XY Stage, Metrology Errors, Target Block Alignment

1. Introduction

In the error mapping of an XY stage, one of the primary objectives is to measure the cross-axis and yaw motion errors [1]. Several deviations from ideal behavior can occur in this characterization. Some of these are attributed to the stage itself while others arise from the metrology setup. It is important to design a metrology setup and scheme that explicitly determine the former, and are capable of discarding the latter.

2. XY Stage Errors

We first proceed to define the various errors that may be associated with a serial XY stage. In Fig. 1, X and Y are the stage reference axes for manufacturing and assembly, and for mounting sensors and actuators. These are referred to as the ideal Cartesian axes along which stage motion is expected in response to X or Y actuation, if the manufacturing, assembly, and the linear bearing-ways are flawless. X' and Y' axes are the linear fits of the motion trajectories along which stage motion actually occurs in response to X and Y actuation, respectively. For most serial stages, these X' and Y' motion axes simply correspond to the physical axes of the constituent linear bearing-ways. In these cases, either X and X', or Y and Y', can be chosen to be coincident. Errors resulting from imperfect behavior of the stage are traditionally classified as follows:

1) *Orthogonality or Squareness Error:* The true motion axes of the stage, X′ and Y′, may not be perfectly orthogonal. In Fig. 1, since the ideal Cartesian axis X and stage motion axis X' are chosen to be coincident, this

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orthogonality error is quantified by the angle α_y between the Y and Y' axes. For serial stages, this error typically arises due to an improper mounting and assembly of the linear bearing-ways. The orthogonality error results in a cosine error along the Y axis measurement and a sine error along the X axis measurement, in response to motion along the Y' axis.

2) *Straightness Error:* Straightness error shows up as a non-linear variation in the X axis measurement during a motion along Y′, and results due to imperfections in the Y axis bearing-way in a serial stage. Since this error is not linear, it cannot be expressed in terms of an angle, and is therefore not shown in Fig.1.

3) *Yaw Error:* Yaw error is the actual yaw, θ, of the motion stage as it moves within its range of motion

Although the above classification remains the same for a parallel stage, the orthogonality and straightness errors assume a slightly different interpretation. In a parallel stage, these two errors are not independent entities since they both arise from the kinematics and mechanics of the stage. The overall cross-axis error can have a linear component, which corresponds to the orthogonality error, and a non-linear component, which corresponds to the straightness error. Error motions of a parallel stage are shown in Fig. 2. As earlier, X and Y constitute the ideal Cartesian axes along which the motion would occur given ideal manufacturing, assembly and stage characteristics. X' and Y' represent the linear components of the stage motion in response to X and Y actuation, respectively. However, in this case, there are no physical bearing-way axes to which the X' and Y' motion axes correspond. For this reason, it is not possible to choose an ideal Cartesian axis such that it coincides with a true motion axis of the stage. The true motion axes X' and Y' are fundamentally unknown. This results in an independent orthogonality error associated with each axis, which is indicated by angles α_x and α_y in Fig. 2. In general, these two angles may be unequal.

3. Metrology Errors

The metrology set-up invariably includes a set of sensors, such as C_1, C_2, and C_3 shown in Figures 1 and 2, which are fixed to ground and aligned with respect to the ideal Cartesian axes. It also includes a true-square artefact attached to the motion stage that acts as the target block for contactless sensors, such as capacitance gauges and laser inteferometers. Irrespective of whether the stage is serial or parallel, the errors associated with the metrology remain the same. These are:

1) *Artefact Geometry Error:* The artefact is usually such that it provides two flat faces that are closely perpendicular. The lack of orthogonality between the artefact faces is captured by the angle γ. It may be recalled that producing a high degree of orthogonality between two surfaces is significantly more difficult than producing flat surfaces.

2) *Artefact Alignment Error:* This represents the misalignment between the artefact axes and the ideal Cartesian axes, for example, the angle β shown between axis X and the artefact face. Precisely ground pins pressed into precisely drilled holes, referenced with respect to X and Y axes, are typically employed to minimize this misalignment. This misalignment results in a sine error in the X axis measurement when the stage moves along the Y′ axis.

3) *Artefact Straightness Error:* This represents the lack of flatness of the artefact faces, and is not shown in the figures. Typically, artefact straightness is several orders of magnitude smaller than the stage straightness errors and is therefore not an important contributor. As indicated earlier, it is relatively easy to grind and polish surfaces to a great degree of flatness.

4) *Sensor Alignment Error:* This is the angle, ξ, that the sensor line of measurement makes with the ideal Cartesian axes. It results in the typical cosine error and can be minimized by careful alignment of the sensor axes.

It is always desirable to design a metrology setup and scheme that are capable of characterizing the true stage performance regardless of the metrology setup errors. By making multiple measurements and employing principles of reversal and symmetry, one can cleverly discard some metrology related errors.

4. XY Stage Characterization

For the purpose of the present discussion pertaining to both serial and parallel stages, only the linear component of cross-axis error is considered because it can be represented by a small angle. From either Fig.1 or Fig.2, one can determine that

$$C_1 \cos\xi_1 = x_1 = -y'\sin\alpha_y - y'\sin(\beta+\gamma) - R_1\sin\theta \tag{1}$$

where x_1 is the displacement along the X axis at location C_1, measured positive when the target surface moves away from the sensor, in response to displacement y' along the Y' axis. The angles in expression (1) are typically of the order of 10ppm, which justifies the use of small angle approximation. Thus,

$$\begin{aligned} C_1 \cos\xi_1 = x_1 &= -y'\alpha_y - y'(\beta+\gamma) - R_1\theta \\ &= -y'(\alpha_y+\beta) - y'\gamma - R_1\theta \end{aligned} \tag{2}$$

Similarly, $C_2 \cos\xi_2 = x_2 = -y'(\alpha_y+\beta) - y'\gamma - R_2\theta$ (3)

These expressions show that if ξ_1 and ξ_2 are small, one can accurately estimate the stage yaw error θ using the difference between the measurements C_1 and C_2, irrespective of what the other stage and metrology errors are. Furthermore, γ can be eliminated by employing a well-known angle closure technique [2]. This involves making four C_1 measurements, using each face of the artefact as a target surface so that each time a different corner angle γ is involved.

$$\begin{aligned} &C_{1k}\cos\xi_1 = x_{1k} = -y'_k(\alpha_y+\beta) - y'_k\gamma_k - R_1\theta_k \qquad \forall\ k = 1 \text{ to } 4 \\ &\Rightarrow \sum_{k=1}^{4}\frac{C_{1k}\cos\xi_1}{y'_k} = -4(\alpha_y+\beta) - R_1\sum_{k=1}^{4}\frac{\theta_k}{y'_k} - \sum_{k=1}^{4}\gamma_k \end{aligned} \tag{4}$$

The last term in the above expression drops out because of the angle closure constraint $\sum_{k=1}^{4}\gamma_k = 0$. This procedure makes the reasonable assumption that β remains the same over the four measurements.

Other metrology arrangements can also be considered, such as rotating the target block by 90 degrees and recording a measurement from sensor C_4, shown in Fig. 1, in response to displacement y' along the Y′ axis. This yields,

$$C_4 \cos \xi_4 = x_4 = y'(\alpha_y + \beta) - y'\gamma + R_4\theta \tag{5}$$

Comparing expressions (3) and(5), it can be noticed that the sign of the γ term reverses with respect to the other terms. Subtracting the two expressions offers another method of eliminating the γ term. However, in all the measurements so far, the target block alignment error and the stage orthogonality error always occur in the same additive combination: $(\alpha_y+\beta)$. It may be further verified that no matter what configuration of sensors is used, α_y and β always manifest themselves in this combination, and therefore are indistinguishable.

It is important to note that in several practical applications, the above-described problem may not pose a significant challenge. For example, in a serial stage where the X' and Y' motion axes are indeed the physical axes of the linear bearing-ways, X' and Y' are known *apriori* without any measurements. A known X' axis may then be used as a reference and made to coincide with the ideal Cartesian axis X, as in Fig. 1. In this particular case, a sensor C_3 may be used to measure the target block alignment error as follows.

$$C_3 \cos \xi_3 = y_3 = x'\beta + R_3\theta \tag{6}$$

However, in general, for a parallel stage, or for a serial stage where the true motions axes do not coincide with the physical bearing-way axes, the true motion axes X' and Y' are fundamentally unknown, and the situation is as depicted in Fig.2. A C_3 measurement in this case will yield

$$C_3 \cos \xi_3 = y_3 = x'\left(\alpha_x + \beta\right) + R_3\theta \tag{7}$$

Thus, yet again, the orthogonality error associated with the X axis and the target block alignment error show up as a specific summation.

5. Conclusion

This brings us to what appears to be a classic problem in metrology: in the error characterization of a parallel kinematic XY stage, how does one differentiate between two key errors – the orthogonality error of the stage and the alignment error of the sensor target block? Based on the above arguments and a thorough literature search, we conclude that these two errors remain indistinguishable irrespective of the number and arrangement of sensors used. Apart from the mathematical treatment presented here, this observation also has a physical basis. Once a target block is attached to the motion stage, it becomes integral to the stage. Therefore, in general, an external sensing arrangement can only measure the characteristics of this assembly, which is a combination of the stage error and target block error, and not the individual components. For this reason, a relatively large target block misalignment may be easily mistaken as an orthogonality error, thus giving an incorrect assessment of the cross-axis error characteristics of an XY stage. To truly characterize the XY stage, this problem may be resolved by separately and explicitly measuring the misalignment between the stage Cartesian axes and the target block using a Coordinate

Measuring Machine, for example. All subsequent measurements should then be corrected based on this initial measurement.

The straightness errors of the stage and the target block share the same fate. Depending on the straightness characteristics of the stage and the flatness of the target block faces, this may or may not be a concern in a given application. Furthermore, while a two-dimensional geometry is employed in this paper to highlight the importance of target block alignment inplane, the problem of distinguishability extends to the third dimension as well. Target block misalignments about the X and Y axes similarly contribute to the error motion measurements in the Z direction.

Finally, this discussion also reasserts the importance of sensor alignment in eliminating cosine errors, which typically may not be discarded by means of geometric principles. Alignment methods to minimize cosine errors in plane mirror interferometry have been detailed in the literature [3].

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Figures

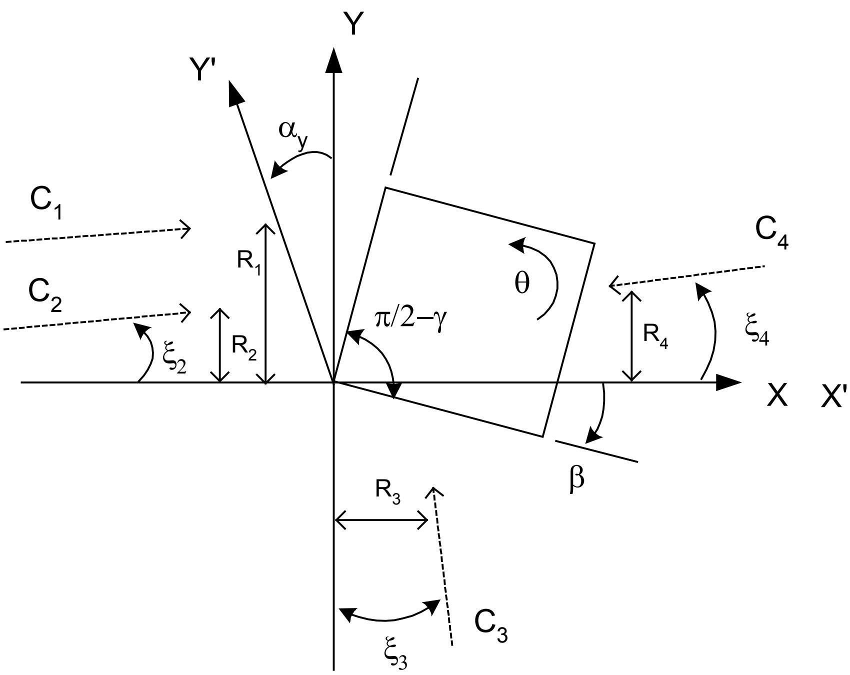

Fig.1 Errors and Misalignments in Serial XY Stage Metrology

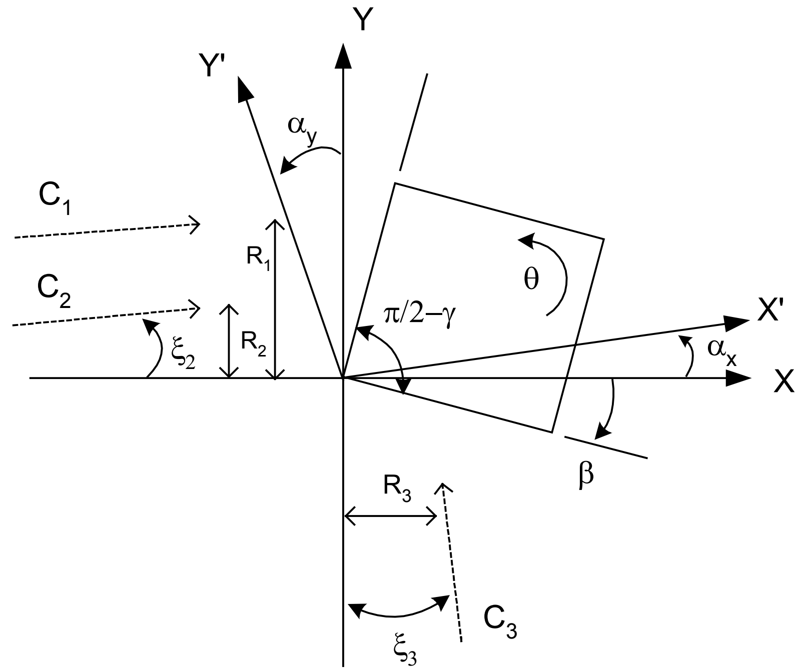

Fig.2 Errors and Misalignments in Parallel XY Stage Metrology

Figure Legends

Fig.1 Errors and Misalignments in Serial XY Stage Metrology

Fig.2 Errors and Misalignments in Parallel XY Stage Metrology