Kite Square

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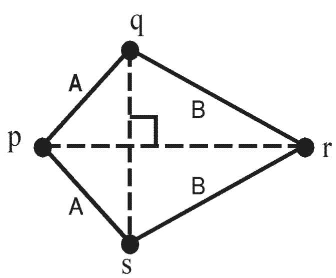
Introduction

Presented is a new technique for independently determining the out-of-squareness of machining centers (MCs) or coordinate measuring machines (CMMs). The method is based upon a self-calibrating scheme and related device. Various embodiments allow for measuring machines with diverse work volume dimensions and also for vision CMMs. The term “Kite Square Technique” is used to refer to the utilization of a “Kite Square” device to obtain the out-of squareness parametric term. Results from measurements taken on a CMM with touch probe, a MC, and also a CMM utilizing a visual probe are given.

The Kite Square Technique

Figure 1. Geometric Kite



A geometric “kite” is a quadrilateral in which each side is adjacent to another side of the same length. In Figure 1, pq and ps have length A whereas qr and rs have length B. An additional advantageous property is that the two line segments between opposing vertices are perpendicular. That is, pr is perpendicular to qs.

Figure 2 shows a conceptualized gage consisting of three artifacts (1), (2), and (3) attached together via a rigid support structure (4). The three artifacts (1), (2) and (3) are at positions (5), (9) and (10), respectively. Allowing the rotation of artifacts (2) and (3) about a line of rotation (6) which passes through the positions (9) and (10) of the artifacts (2) and (3) respectively, artifact (1) thus moves from position (5) to position (7). Since the distances between position (5) and (9), and (7) and (9) are the same along with equal distances between (10) and (5), and (10) and (7), we have generated a kite with vertices at the position of our artifacts. Resultantly, positions (5) and (7) establish a reference line (11) at a right angle with respect to the line of rotation (6). Thus we have a square artifact that is self-calibrated. Rotation about the line through positions (9) and (10) can be effected through the use of kinematically seated precision spheres utilized as artifacts. In three dimensions, artifact (1) rotates in a circular motion within a plane having line (6) as a normal (perpendicular to the plane). This is useful for measuring the out-of-squareness of vertical carriages. By mounting the Kite Square on the table of a machine and subsequently measuring the initial positions of artifacts (1-3) and rotated position of artifact (1) with sensors (not shown) attached to the tool/probe location of a ram, spindle etc. of a machine, the determination of a machine’s ability to move its’ tool or probe in an orthogonal manner across a plane can be determined.

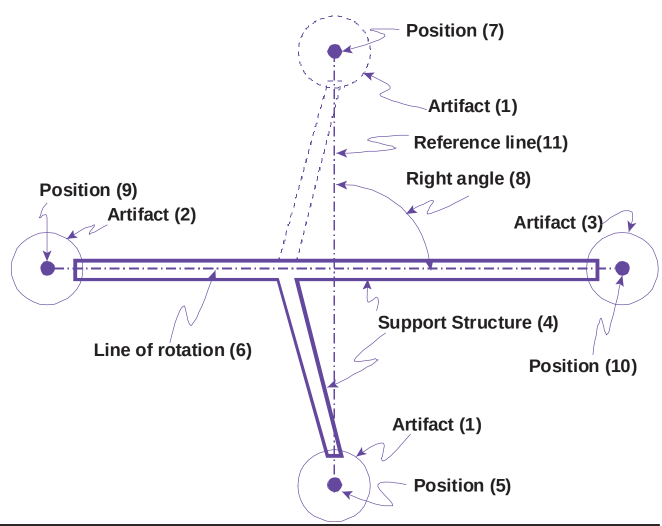


Figure 2. Conceptual Kite Square

A Kite Square

An embodiment of this concept used to measure the out-of squareness of a CMM is shown in Figure 3. The precision spheres used as the kite square artifacts have spherical deviations below one-tenth micrometer. The procedure to get data for one measurement set is simple. The locations of three spheres were measured in one orientation and subsequently in the flipped orientation. Using the X-Y positions of the spheres you can first calculate two lines between the opposite vertices of the kite and then the deviation from square. The actual equations used are given later.

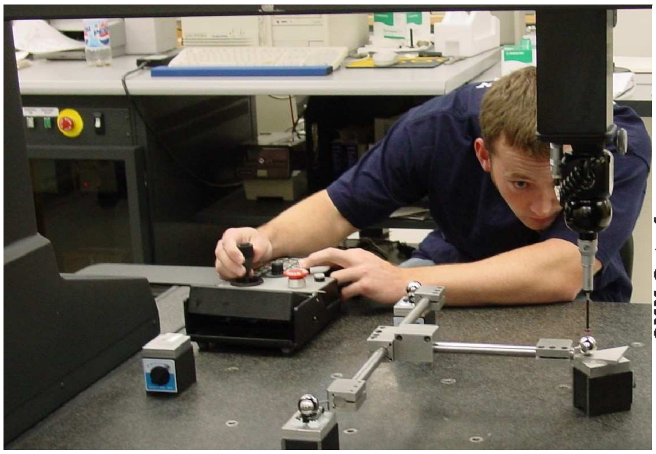


Figure 3. Kite square in use on CMM

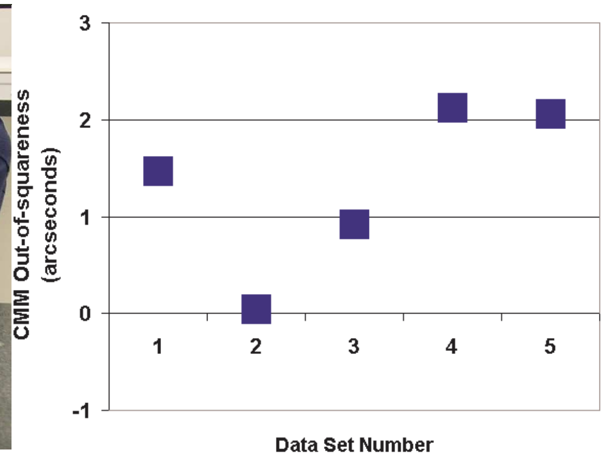


Figure 4. Out-of Squareness for CMM.

The out-of-squareness calculated from five data sets are shown in Figure 4. The average is 1.3 arcseconds. Two possible sources of variation in data are probe repeatability and kinematic seating repeatability. A source of measurement bias is deviations in position due to the beam bending of the fixture. The beam may stretch along the direction of the axis of rotation in one orientation and shrink in the other orientation if the rods connecting the two balls are bent differently depending on the orientation. This can be seen in the data. Correcting the calculations for this lowers the squareness values by 1 arcsecond. Shortening the connecting rods may eliminate this effect.

This kite square was also used to measure the out-of squareness of a machining center as shown in Figure 5. Instead of touch probe measurement as for the CMM, a capacitance sensor[1] was used to first set up the gage and then measurements. Setup was accomplished by first measuring the X,Z machine coordinates for obtaining a maximum reading against the ball that was constrained in three linear degrees of freedom, then moving the machine (Y) so that the capacitance sensor gave a nearly zero nominal displacement reading. The sensor was then moved to make measurements on the second ball constrained in two linear degrees of freedom. After finding the appropriate X-Z position and keeping the Y position as for the previous ball, the kinematic mount was tapped with a rawhide hammer to obtain a sensor scale reading near that of the

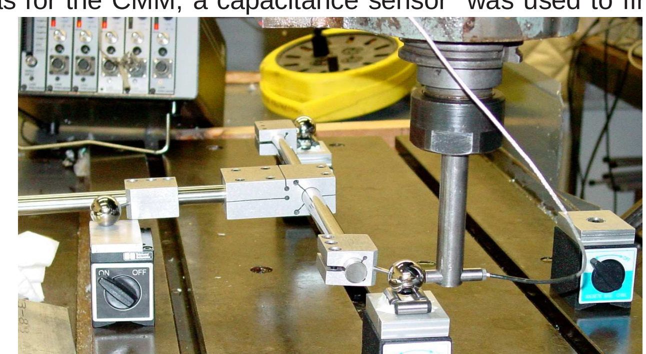


Figure 5. Setup on Vertical Machining Center

[1] Manufactured by Lion Precision, Inc.

first ball. Also, the adjustable mount of the swinging ball was moved along the mounting rod to get it within the working range of the machine. Then the nominal X,Y,Z locations for the swinging ball in both orientations were determined using the previous methods. A machine program was written to step between the two locations of the swinging ball keeping the X coordinate the same and reading the capacitance sensor displacement at each location. The readings for one data set varied by about 2 micrometers due to the servo action of the machine. Whenever the kite square was flipped, the fixture was tapped by a rawhide hammer to get a repeatable seating in the kinematic mount. Ten sets of data were obtained and the repeatability of the swinging ball location data taken from the capacitance sensors is shown in Figure 6. Position C and D are the two positions of the swinging ball. Using the average values we obtained an out-of-squareness value of 4 arcseconds for the machine. This data is in line with out-of squareness values obtained with laser diagonals measurements and other techniques. A one-to-one correspondence to other data is not expected due to the model of squareness used (discussed later) and a knowledge that this machines' out-of-squareness has been previously determined to change a few arcseconds with the ambient temperature. During these measurements the temperature was kept near 20^o C.

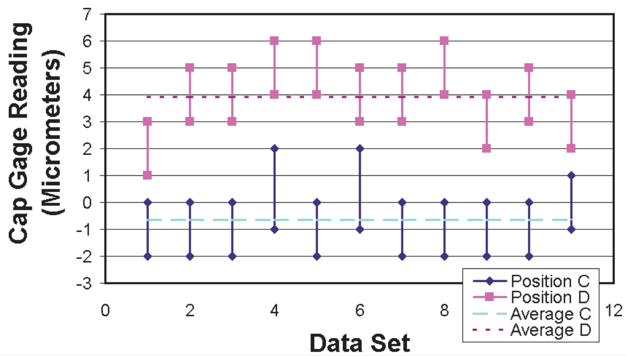


Figure 6. Repeatability of Measurements

In order to use the Kite Square Technology on a vision based CMM, a change in design was necessary since a sphere is a poor reference artifact for determining location visually. Figure 7 shows the resulting design and embodiment incorporating sphere and kinematic mounting for rotation but includes separate artifacts that can be measured using the camera and light sources of the machine. Figure 7(A) shows an isometric view taken from the drawings showing the placement of the artifacts. These recessed artifacts, produced by electro-discharge machining, each have a diameter less than 500 micrometers. Figure 7(B) shows the actual device on a visual CMM. Figure 7(C) is the visual image of one of the artifacts as viewed by the visual CMM. Notice that there is a pair of balls for allowing the swinging artifact to rotate in order to keep it viewable at all positions. This design enables the measurement of vertical as well as horizontal squareness. Actual use of the visual CMM Kite Square revealed a few flaws in the design. First, placement of one of the hole artifacts prohibited the use of backlighting to get the position in one critical orientation. Second, the artifact placement was not sufficiently near the axis of rotation resulting in a rather large uncertainty. For these reasons the resulting calculations are not given at this time.

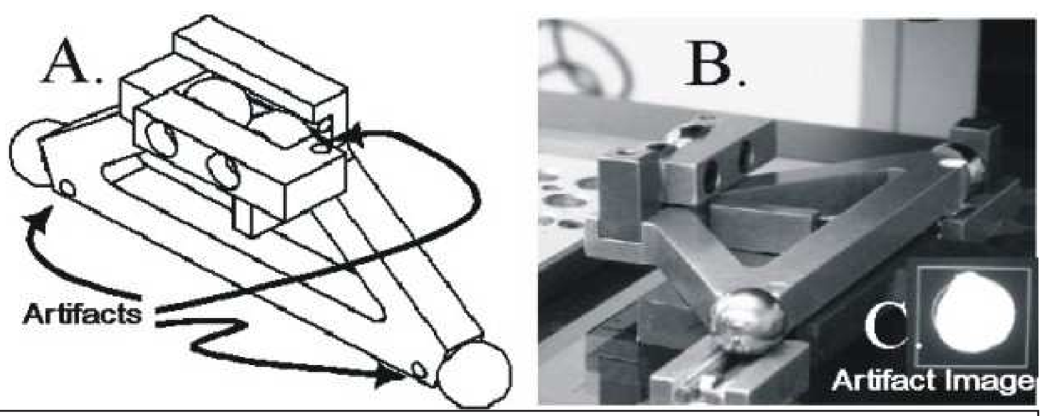


Figure 7. (A) Drawing showing artifacts, (B) on visual CMM, and (C) image of artifact on this Kite Square design.

General Mathematics:

These mathematics assume a kinematic rotation of the device while allowing, in general, artifact positions (2) and (3) to not necessarily lie along the line of rotation (6). For clarity, assume a two dimensional case. Let subscript B denote the measured position of the artifact before rotation and subscript A denote a position measured after rotation along line (6). Let $P_{1B} = (X_{1B}, Y_{1B})$, $P_{2B} = (X_{2B}, Y_{2B})$ and $P_{3B} = (X_{3B}, Y_{3B})$ etc. The squareness value α (radians) is related by the following equation:

$$\tan(\alpha) = \frac{X_{1A} - X_{1B}}{Y_{1A} - Y_{1B}} - \frac{\frac{1}{2}(Y_{3B} + Y_{3A}) - \frac{1}{2}(Y_{2B} + Y_{2A})}{\frac{1}{2}(X_{3B} + X_{3A}) - \frac{1}{2}(X_{2B} + X_{2A})} = \frac{X_{1A} - X_{1B}}{Y_{1A} - Y_{1B}} - \frac{Y_{3B} + Y_{3A} - Y_{2B} - Y_{2A}}{X_{3B} + X_{3A} - X_{2B} - X_{2A}}.$$

If the line of rotation (6) passes through positions P_{2B}, P_{2A}, P_{3B} , and P_{3A} , so that, $P_{2B}=P_{2A} =P_2$ and $P_{3B}=P_{3A} =P_3$ then $\tan(\alpha) = \frac{X_{1A} - X_{1B}}{Y_{1A} - Y_{1B}} - \frac{Y_3 - Y_2}{X_3 - X_2}$ or for small angled squareness values where α is approximately equal to the sine of α, we have $\alpha = \frac{X_{1A} - X_{1B}}{Y_{1A} - Y_{1B}} - \frac{Y_3 - Y_2}{X_3 - X_2}$.

For non-kinematic rotation, more sophisticated mathematics are required.

Machine Modeling in Light of the Kite Square

There are at least two different mathematical approaches to volumetrically model the errors of a machine. One is frame-based and the other is table-based (part-based). In the frame-based approach, the mathematics corresponds to the errors (straightness, linear positioning, angular) of each carriage being referenced to a coordinate system associated with the stationary frame or base of the carriage. In the table-based approach, the errors of a tool or probe are referenced to a coordinate system that is associated with the component of the machine on which a part or workpiece is mounted. National industrial standards for performance evaluation typically (but not consistently) follow a table-based approach to measuring the parametric errors of machine tools and CMMs with measurement lines midway in the work volume. If we use a modeling approach that is table-based and we measure errors along or near the axes of the modeling coordinate system, then the angular errors do not influence the displacement measurements. The straightness errors can be defined to be zero at two fixed points along each modeling coordinate system axis leaving the remaining lateral displacement error to be defined as squareness. This is possible because the errors due to squareness complement the straightness errors and any slope removed from the straightness finds its way in the squareness term. For example, we can choose a 10%-90% rule to define the straightness to be zero at 10% and 90% of the range of motion for each carriage.

Conclusions

We have disclosed and demonstrated novel metrology tools dubbed Kite Square for measuring the out-of-squareness of manufacturing and measuring machines having orthogonal axes. Their versatility and simplicity should enable it to replace more expensive and weightier devices in current use.

Acknowledgement:

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