ERROR COMPENSATION IN SCEPTRE

There's been much mystery in the metrology industry when it comes to a CMM manufacturer's attempts to perform error compensation. All CMM builders perform some form of error compensation but often they hide behind the "you wouldn't understand it" excuse so they don't have to tell you what they do.

We are all for telling our customers what we do to compensate for the errors in the CMMs we build or upgrade. We incorporate mathematical error compensation in our SCEPTRE System software. At first, I was not convinced it would work, but soon was converted. To our knowledge, no one else is performing this type of error compensation and here I want to contrast the classical way to what we do.

First, let's define "error compensation." You build a CMM and it's not as accurate as hoped. What can you do? Assuming it is repeatable to an acceptable degree, you can identify the errors causing the problems and work to get rid of them either physically or mathematically. The first option is called error reduction, the second is called error compensation.

Prior to computers the only way to get rid of errors was physical; however, now that computers are so fast, it is possible to have real time error compensation as an option to physical work -- but it is still necessary to find the errors!

The classic way to compensate for errors is known as the "21 First Order Error Source" method. This technique is still being used in both modified and unmodified form by various CMM builders. I'll discuss this first, then I'll discuss the much simpler technique used by SCEPTRE. In this way it will become clear that considerable diversity can exist while pursuing the same goals.

21 First Order Error Sources

To describe the possible sources of error of an axis slide, as well as combinations of slides, CMM technicians analyze the error sources individually, as though they really did exist separately. To help them, they make several simplifying assumptions:
The slide is assumed to follow the laws of rigid body mechanics, meaning that an angular measurement made anywhere on the slide is presumed to have the same value as if it had been measured in any other spot.
A "first order" error is a "primary" error. Secondary and tertiary errors are ones which might be caused by a first order error and are ignored when totalling up the primary errors.
Each of these first order error sources is defined as mathematically unique, absolutely separate from all others. They are called "degrees of freedom." All such values must be combined properly to define the total performance of the slide. Any accidental mixing of them due to poor setups when determining their size and location - or for any other reason - can negate the "21" theory completely.
Since repeatability is not a mathematical entity, it is not considered as part of a mathematical analysis, even though it is a practical prerequisite.

Most CMMs have three compounded slides in a variety of configurations, creating 21 first order error sources. This is based upon six per slide added to the three squareness relationships. Suppose you wish to create a system of error compensation, how do you proceed?

First, to remain true to the concept of separate, independent errors, it is necessary to find each of these parameters absolutely isolated from all the others. The yaw of the "Y" axis, for example, cannot contain components of error from any of the other potential sources. If it does, its value will be wrong. This holds true for each and every separate value of the 21.
The setups and instrumentation to obtain all these values thus become critical. There may be numerous ways to obtain them. Factors such as the configuration of the machine can affect the

method used, so it would give a false impression to describe a specific one here. Suffice it to say that the personnel performing this task must be highly skilled and patient. Developing and verifying an algorithm to properly combine all these inputs is a very complex job. This can be done successfully, but it is time consuming. Typically, such work must be done by factory trained personnel.

SCEPTRE System Error Compensation

Whereas the "21 First Order Error Source" method requires the absolute separation of the components of error in a measuring system, the SCEPTRE approach is totally different. It accepts the fact that system errors are inextricably linked together. No attempt is made to separate them.

In deciding how to implement error compensation within SCEPTRE we made several assumptions. Each simplifies the process of compensating our own equipment, with the further belief that the same assumptions will work for other applications. Here they are:
We will not attempt to separate the error sources, but deal with them in combination. All evaluation algorithms will be based upon this decision.
We will use the smallest possible number of artifacts to find the errors.
We will not measure angles, except for the preliminary evaluation of squareness.
The system we develop may be implemented by the User at any time. All required software will be available as part of SCEPTRE.
Because most of our equipment is built using granite and air bearings, we will use the resulting smoothness of movement to our advantage. Due to the way granite is finished, and to the averaging effects of air bearings, we assume there will be no periodic errors in the movements of components relative to each other. Thus, measurements in one inch increments will be proportionally reliable between the inch marks as well.
We assume that if we find all the displacement errors which exist along the perimeters of the measuring volume, we can then capture the totality of the errors inside the volume, in whatever combination they may occur.
The results of our compensation must be at least 90% effective, i.e., an observed error must be decreased by at least that amount upon implementation.
To find part-specific errors at a particular point inside the measuring volume, we will calculate the proportions of machine error existing at that spot in all three directions from the machine origin, where all errors are assumed to be zero.
All such calculations will be transparent to the operator, being fully controlled by SCEPTRE.
All points taken during an inspection process, whether individual or thousands taken during a scan, will be fully corrected.

And here is how we proceed to compensate one of our CMMs, the LEGEND:
After a LEGEND is fully assembled the travel of all three axes must be made as straight as possible. We will use the finished side of a NIST certified Moore lug bar, straight to within 10µ" TIR as our reference. The straightness of each axis must be measured, full travel, in both transverse directions. This is done by analog scanning, using the full SCEPTRE system. Enough runs are taken to ensure a good set of averages (at least three). For each axis the runs are made in the center of the measuring volume. We ignore the errors in the Moore bar. They are very small, and they can easily be ascribed to observational error. Thus, in determining the straightness of the LEGEND's movements, we compare them to a "perfect" straightedge.
After having a reliable average, the SCEPTRE software will automatically apply mathematical correction values, both in size and location, to eliminate straightness errors. These corrections are easily checked by rerunning the straightedge. The errors will have disappeared, within the repeatability of the machine. Just don't forget that the physical error is still there, but no longer a factor in measuring accuracy!
Having achieved straightness all around, we now set squareness more precisely. We use the Moore bar, this time measuring distances, proceeding as follows:

Place the Moore bar at approximately 45° to an axis, in the center of the measuring volume, and measure the distance between the furthest lugs which can be reached with the probehead. Repeat at least three times to establish a reliable average.

Reposition the bar to the other 45° position and remeasure between the same two lugs. When the readings are the same, the two axes can be said to be square to an accuracy better that can be achieved by any other method.

Repeat this process between all the axes. When finished, enter all the deviations into SCEPTRE. Corrections for squareness will be calculated, and will be applied in all subsequent measurement tasks, in real time, as though all axes were actually this square to one another.

The final step in our compensation method is to measure the displacement errors found on each of the 12 edges of the "box" which define the limits of the measuring volume. There will be four positions at right angles to one another at the level of the worktable, four similar positions 12" above the table, and four vertical positions connecting their corners. Using SCEPTRE, determine the distances between all the lugs in each setup. Once again use at least three runs to establish an average.
SCEPTRE requires that you tell it the correction values found when the Moore bar was certified. These are automatically removed from the observed errors found during the compensation procedure.

So far we have collected data in one inch increments, all the way around the measuring volume, in the cardinal directions. This allows for the creation of a grid of data points, each of which has had the Moore bar errors removed.
From now on everything is mathematical.

We select the three displacement data sets which intersect at the corner defined as the machine zero. They act as references for all the others. For example, let's consider the data collected in the "X" axis. Since it has all been corrected at this location, no errors exist within its 12 inch measured length. Now let's move over to the other side of the cube, and look at the results of our measurement there, in the same "X" direction. There will undoubtedly be differences between the two. The differences will represent the totality of errors in "X" caused by whatever geometric anomalies exist within the system. We neither know nor care exactly what the source of the errors is. It is their aggregate amount we are interested in.

We assume that all errors in "X" are proportional to their distance between the two sets of readings, but to measure something we need the "Y" axis data to define a coordinate location of the workpiece, in order to know what portion of the total "X" error to assign to it. So we do the same thing in the "Y" direction as we did in "X".
Once having completed this procedure in "Y" there now exists a grid of data, on nominal one inch centers, at table level. Now the portion of errors from one side to the other in both the "X" and "Y" directions can be determined. Everything is linearly proportioned. By continuing this process upward in the "Z" direction we will obtain a three dimensional grid of points, and the assignment of errors in three dimensions can be made. All corrected readings are from the reference corner, and are proportional to their position within the measuring volume.
This method works. Measuring the Moore bar in random positions without corrections being applied shows errors in varying amounts. Upon use of the compensation we have experienced somewhere between 90 -95% reduction in those errors. Furthermore, the same approach has been successfully used on larger machines by "stacking" the bar. Customers have made use of the technique themselves, so that it is not necessary for a "factory" man to be present. Considering these and other factors we are convinced that dealing with errors 'en masse', rather than as isolated happenings, is completely viable.

-- Russ Shelton