Thermal Effects on CMMs

Understanding their causes can improve your precision measurement equipment efficiency.

David Genest

The trend toward moving coordinate measuring machines to the shop floor to become an integral part of the manufacturing operation brings real time process control within the reach of many companies. Putting measuring machines on the shop floor, however, subjects them to harsh environmental conditions. Like any measuring system, CMMs are sensitive to any ambient condition that deviates from the "perfect" conditions of the metrology lab.

Of all the conditions on the shop floor that affect CMM repeatability, temperature has the most dramatic effect. That's because, according to international standards established in 1931, objects only have their correct size at 20°C. This is a matter of politics, not physics, and this standard was chosen by international agreement to ensure that measurements made in one country would agree with those made in another. It stands to reason then that for the highest measurement accuracy, the workpiece and CMM should be at that temperature. At temperatures other than 20°C, thermal expansion of the workpiece and CMM causes errors that can be difficult to correct.

Are there ways to minimize the effects of temperature on measurement? That depends upon a number of factors including workpiece tolerances, degree of acceptable total measurement error and how much of that total can be budgeted for thermal effects, and how much temperature control is necessary to keep thermal effects at an acceptable level. However, by understanding the concepts of *differential* expansion, temperature gradients and temperature variation, the problem and challenge of thermal effects become more manageable.

Differential Expansion

A coordinate measuring machine compares the distance between the locations of probe hits on a workpiece with corresponding distances on scales attached to each axis of the CMM. The corresponding length on the scale is determined by means of an encoder which counts the lines on the scale as the machine moves the probe from one hit position to another.

If the dimensions of a workpiece, or for that matter, the stated accuracy of the CMM, are correct only when they are at 20° C, how is it possible to accurately measure dimensions at any other temperature? The answer is that corrections in the measurement data have to be made that take into account both the effects of the temperature differences between the part and the ideal 20° C environment and between the part and the CMM.

Temperature compensation is a means of correcting measurement errors caused by temperature effects. Compensation can be either manual or automatic, depending on computing power and the software being used. With automatic systems, software-based adjustments are made to measurements according to sensed temperature fluctuations in key locations of the CMM's structure and the air surrounding the machine. Some advanced systems also include probes to detect part temperature variations with an additional compensation value factored into the machine and ambient conditions. With manual compensation, prior to taking measurements, the machine operator takes readings of the temperature of the

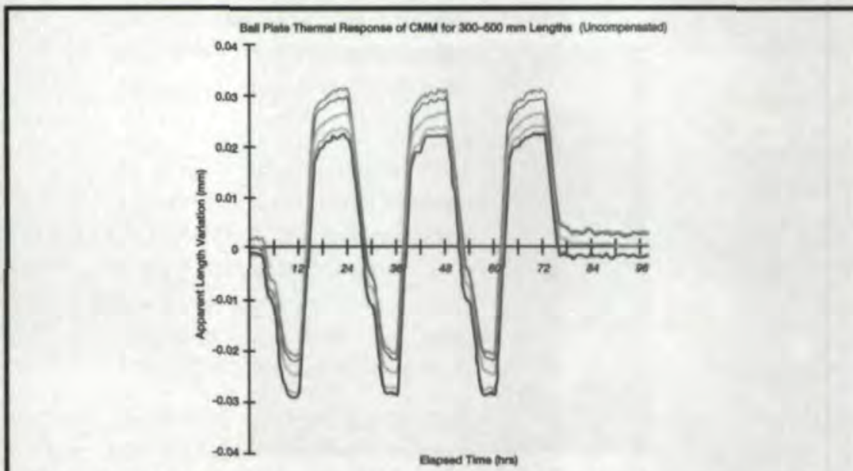

Fig. 1 – Ball plate thermal response of CMM for 300–500 mm lengths (uncompensated).

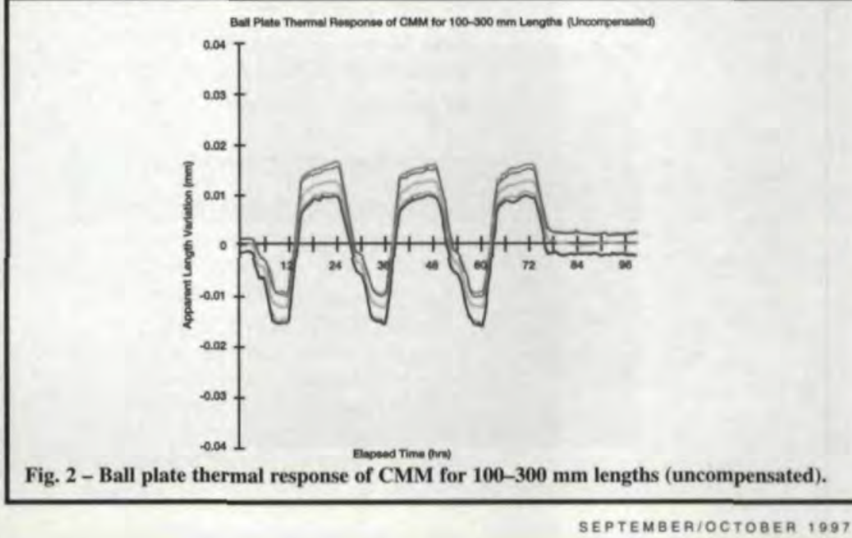

Fig. 2 – Ball plate thermal response of CMM for 100–300 mm lengths (uncompensated).

CMM's axes, the workpiece and the surrounding air and enters them into the software program for compensation.

Compensation does not allow the same degree of accuracy as in a controlled environment. The uncertainty of measurement increases as the temperature deviates from 20° C.

Nearly all materials expand when their temperatures increase. The amount of expansion, called the coefficient of thermal expansion, varies for each material, but tends to be the same for similar families of materials. This is called Nominal Differential Expansion (NDE). For example, in the case of a coordinate measuring machine, if the workpiece is steel and the scale is steel, they theoretically expand at the same rate, canceling out any measuring error. If the workpiece is aluminum, however, it expands faster than the steel scale. This uncertainty between the CMM scale and the workpiece is called Uncertainty of Nominal Differential Expansion (UNDE).

Differential expansion can be somewhat compensated for by subtracting scale expansion from workpiece expansion to determine the magnitude of the error. In effect, this is what temperature compensation software routines do. However, values for the coefficients of expansion are general, not exact. Actual rates of expansion that occur in practice and the value found in textbooks can vary as much as ± 10%. These variations are caused by workpiece geometry, exposed surface area, cross sectional area and variations in the microstructure as a result of processing.

The best current method for assessing the influence of the thermal environment on dimensional measurement is specified by ANSI/ASME Standard B89.6.2, "Temperature and Humidity Environments for Dimensional Inspection." It combines the calculation of the NDE of the CMM and the workpiece with the consequence of the UNDE and an observed temperature variation error (TVE). TVE is determined through a "drift test" where the measurement of a single object is repeated over an extended period with the center of the object plotted with respect to time.

Thermal Gradients

Other causes of measurement uncertainty are the effects of thermal gradients. Any change of temperature in the room where the CMM is located changes the dimensions of the machine structure. The same happens with the workpiece. Changes in temperature immediately surrounding the machine are called thermal gradients, and they cause different expansions in different parts of the machine and the workpiece.

Rapid temperature changes in the same direction for a long period of time cause the most errors. Large, rapid changes often occur on a shop floor because of ambient temperature differences between morning and afternoon. These large, rapid changes cause thin sections of the machine or workpiece to change temperature more quickly than thick parts, creating bending.

If air temperature cycles rapidly, due to air conditioning, for example, there is less time for heat to flow into the machine or workpiece before it has to flow out again. Gradients are close to the surface, and machine bending is minimized.

The goal in any CMM operation is to eliminate the effect of thermal gradients

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The "Stimulated Response" Test For Measurement Uncertainty

The conflict resulting from the movement of coordinate measuring machines to the shop floor and thermally induced measurement errors has led to a variety of claimed solutions using mathematical compensation techniques, thermally insensitive machine components and localized temperature control methods. The best current method for assessing the influence of temperature on dimensional measurement is specified by the ANSI/ASME Standard B89.6.2.

However, extensive laboratory testing at Brown & Sharpe and shop floor experience with customers indicates that this method can be enhanced to provide more realistic estimates of shop floor accuracy degradation that results from thermal influences. First, the drift test evaluates the response of a CMM to its current environment, but does not provide a sensible way to make quantitative predictions about instrument behavior in an unknown, loosely specified environment like that found in most shops. Also, during an actual drift test, a real environment is unlikely to exhibit the full range of thermal behavior allowed by a specification, only the overall temperature range and a few rates of change. It is not easy for the ultimate user of the CMM to verify how well the machine will perform under a specified range of thermal conditions. Second, the thermal response of a CMM measuring a workpiece is highly dependent on both the workpiece thermal characteristics and the specific geometric quantity being measured.

To better address these concerns, Brown & Sharpe is proposing a new testing method call the "stimulated response" test. To stimulate thermal effects in the CMM and workpiece, the test uses a specific environmental temperature profile as a function of time to get typical shop floor results. By standardizing this profile, it is possible to compare the results from many different machines using different compensation techniques to handle temperature effects. The second feature of the test is the use of a simple artifact as a substitute workpiece, and to specify the measurement sequence to be used. This eliminates the ambiguity of the results from real workpieces and allows sensible comparative studies. The third feature is a single method of analyzing and presenting measurement data that graphically gives a realistic estimate of dimensional measurement uncertainty due to poor thermal environment.

A common test methodology like this provides a means for quantitative comparison of new technical approaches to control thermal effects, including studies into new structural materials, use of self-compensating structures and composites and thermal compensation mathematics. A well-designed, easily understood test will reduce confusion among CMM users and can serve as a vehicle to clarify the practical consequences of thermal effects. ○

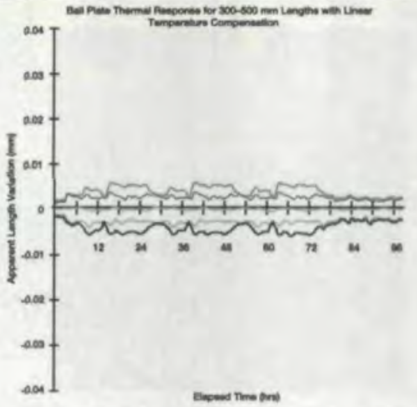

Fig. 3 – Ball plate thermal response for 300–500 mm lengths with linear temperature compensation.

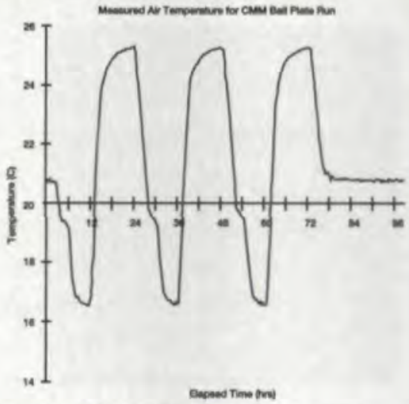

Fig. 4 – Measured air temperature for CMM ball plate run.

on measuring performance. One way to accomplish this is to provide constant air turnover in the room housing the CMM. The effect of thermal gradients can be virtually eliminated in rooms where the air flow rate completely changes the room air every minute. Another good idea is to allow the part to "soak" at the machine's ambient temperature so that its temperature is close to that of the machine. Both of these techniques help minimize UNDE and improve measurement accuracy.

Temperature Compensation

The uncertainties of thermal effects make complete, accurate compensation virtually impossible. Coordinate measuring machine manufacturers conduct tests that show how well a particular machine can compensate for changes in ambient temperature. However, due to there being an infinite variety of thermal conditions that can be encountered on the shop floor, not all types of tests give a complete picture of the true effects of temperature changes. Brown & Sharpe has undertaken the development of a standard thermal effects test that should prove to be an accurate and easily comparable method that can show how coordinate measuring machines respond to changes in workplace temperature. (See sidebar.)

The effects of temperature will always have a role in metrology. Although there are ways to control those effects, whether by special temperature compensation methods or enclosures that reduce temperature gradients, there is currently no way to avoid them completely. Understanding how temperature-induced errors are caused, however, can help minimize their influence on precision measurement. ○

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