Uncertainty and Decision Rules in CMM Calibration

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Abstract

During the past five years there has been significant effort in both American and International standards to develop common practices relative to estimating measurement uncertainty and its application when determining conformance to specifications, *i.e. decision rules*. Of particular interest are the efforts for coordinate measuring machines (CMMs), being that they are complex measuring instruments always calibrated in the field (on-site). At the *2001 NCSL International Workshop and Symposium*, we presented a paper on the efforts of Mitutoyo America to estimate uncertainty for CMM calibration in the field. After five years of using the same basic approach to uncertainty, and having successfully passed a number of ISO 17025 accreditation assessments, we are now beginning to question our uncertainty in light of recent standards. This paper presents some thoughts on these issues with the intention of creating some discussion.

1. Measurement Uncertainty in Dimensional Metrology

Good examples of GUM-complaint [1] measurement uncertainty evaluations in the field of dimensional metrology are so well documented in the literature that a list of references is not going to be included here. This is particularly true for dimensional gages, such as gage blocks and ring gages. What has always been missing in the literature are good techniques and examples of the measurement uncertainty for the calibration of complex measuring instruments, such as CMMs, that are also calibrated on-site in their permanent locations.

The lack of good standardized and accepted measurement uncertainty evaluation techniques is a problem for the CMM industry. Consistency between laboratories seeking accreditation to ISO 17025 [2] is one problem. Another problem is the application of decision rules [3,4]. In 2001, we at Mitutoyo America put forth some suggestions in our NCSLI paper on this topic [5]. Since 2001, some new ideas on CMM uncertainty have been developed and are on the verge of being published as ISO standards [6]. In this paper, we compare our original ideas from 2001 with the new concepts being published.

2. Calibration of CMMs

CMMs are flexible three-dimensional measuring machines. The two powerful capabilities unfortunately complicate their calibration. In this section, we will discuss these issues.

2.1 Infinite Measurands

CMMs are not calibrated in the same manner as many dimensional gages and instruments. Most dimensional calibrations involve measurements that are similar to how the gage or instrument is used. CMMs, however, are capable of an almost limitless variety of dimensional measuring tasks and therefore can never be calibrated for their specific measuring task.

2.2 Performance Standards

CMM performance is specified in accordance to well-documented standards, such as the international standard, ISO 10360-2 [7]. This standard is commonly used in manufacturer's literature, such as the example shown in Figure 1. The purpose of the ISO 10360-2 standard is to provide a common method for comparing and purchasing CMMs. This standard was not written for the purposes of calibration, but it has become the *de facto* industry standard for CMM calibration, and many laboratories are accredited to ISO 17025 for the calibration of CMMs in accordance to ISO 10360-2.

Accuracy ISO10360-2: 2001		MPE_E	MPE_P
Temperature 1 64.4–71.6°F (18 to 22°C)	TP2/20	2.2 + 3L/1000µm	2.2µm
	TP200	1.9 + 3L/1000µm	1.9µm
	MPP100/SP600	1.7 + 3L/1000µm	1.7µm
Temperature 2 60.8–78.8°F (16 to 26°C)	TP2/20	2.2 + 4L/1000µm	2.2µm
	TP200	1.9 + 4L/1000µm	1.9µm
	MPP100/SP600	1.7 + 4L/1000µm	1.7µm

Figure 1. CMM specifications from the literature of a CMM manufacturer.

Figure 2 shows one of the measurements that would be part of a calibration in accordance to the length measuring test in ISO 10360-2. This test involves measuring linear dimensions in various positions on the CMM. This length measuring test is a general system test designed to indirectly control a large number of three-dimensional sources of measurement uncertainty.

2.3 Sampling of Infinite Measuring Lines

As mentioned above, because they are used for an almost infinite number of different measurements, CMMs cannot be calibrated in a manner that is directly the same as the manner in which they are used. The second key difference between how a CMM is calibrated versus other dimensional gages and instruments is that CMMs are three-dimensional measuring machines and have almost an infinite number of potential measuring lines to test. A CMM calibration in accordance to ISO 10360-2 is always an exercise in sampling. The standard requires seven measuring lines with five different measured lengths along each line, which results in a total of

35 measured lengths across the volume of the CMM. Furthermore, the standard recommends some positions, but the user (and often the calibration service provider) is free to choose any positions in the CMM volume.

Example results from one of the seven measurement lines are shown in Figure 3. As can be seen in the figure, each measurement length must be measured three times.

Figure 2. Testing length measuring accuracy on a CMM.

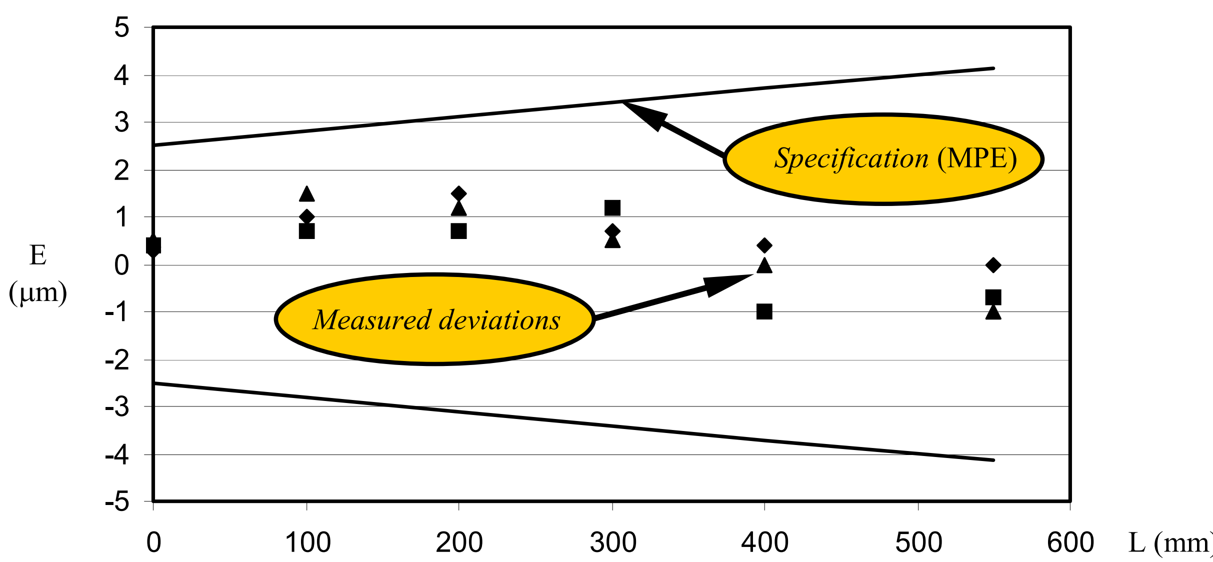

Figure 3. Example results of one of seven measurement lines following ISO 10360-2.

2.4 Interpretation of CMM Calibration

When a gage block is calibrated, we are told exactly where the measurement point in located. When a caliper is calibrated, we are told the various measurement points that were calibrated. When a CMM is calibrated, all we know is that five different lengths were measured along seven different lines. We may know the approximate location of the measurement lines, for example, parallel to the X-axis, but it is rare, and not required by the ISO standard, to report the exact location.

The experts who wrote the ISO standard determined this amount of data was enough information to determine the overall performance of the CMM. This type of sampling exercise calibration, however, is very different than most dimensional calibrations. Because of the sampling, all we can really claim is that the CMM is either in or out of tolerance. Doing anything else with the data, such as how one might use the calibrated value of a gage block, is not possible. This can also create some very interesting situations with proficiency testing of CMM calibration.

3 CMM Test Uncertainty

Based on the discussion above, a CMM calibration in accordance to ISO 10360-2 is a type of indirect verification test of the overall CMM performance. The big question is how to evaluate the uncertainty of this type of test. We at Mitutoyo America put forth some ideas on this topic in our paper presented at the *2001 NCSL International Workshop and Symposium* [5]. Table 1 from that paper is reproduced in this paper again as Table 1. The uncertainty budget shown in Table 1 is for the measurement of a one meter length, in a defined environment, and for a CMM equipped with sensors for temperature compensation. As can be seen in the table, most of the typical sources of uncertainty in dimensional measurement can be found, such as the calibration uncertainty of the master gage, repeatability, and various thermal effects.

3.1 ISO/TS 23165

In the past few years, the ISO CMM standards writing body, ISO TC213 WG10, has been developing some very solid ideas of the concept of the CMM test uncertainty. The resulting standard, ISO/TS 23165 [6], is a guide to the evaluation of uncertainty for ISO 10360-2. The key concept of that standard is that the ISO 10360-2 test is designed to measure CMM errors, and therefore the measurand is an error. Following that thought, any variations in the measurement results associated with the CMM are part of the measurement results, and not part of the uncertainty of the measurement. If the CMM results do not repeat, or if the environment changes the CMM results, then that is part of the measured error, and not part of the uncertainty of the test.

(Note: at the time of this writing, it was expected that ISO/TS 23165 would be available, but it has been delayed at the printing phase at ISO. This was unexpected and unfortunate, however, the focus of this paper is on the concept and not the specific details of that pending standard.)

Table 1. Uncertainty for 1 meter length measurement in 20±1°C environment.

Symbol	Uncertainty Source	Type	Limit Value	Units	Distribution	Divisor	Sensitivity Coefficient	Standard Uncertainty
Um	Step gage	B	1.50	μm	Normal	2.00	1.00	0.75
Ur	Repeatability	B	0.50	μm	Normal	1.00	1.00	0.50
Uts	Measurement of CMM scale temperature	B	0.20	°C	Normal	2.00	8.00	0.80
Utm	Measurement of step gage temperature	B	0.15	°C	Normal	2.00	10.00	0.75
Uas	CTE of CMM scale	B	0.40	μm/m°C	Rectangular	1.73	1.00	0.23
Uam	CTE of step gage	B	0.50	μm/m°C	Rectangular	1.73	1.00	0.29
Uc	Combined standard uncertainty (in μm)							1.5
U	Expanded uncertainty using coverage factor k = 2 (in μm)							3.0

3.2 Uncertainty Comparison

The concepts of ISO/TS 23165 have been applied to the same measuring example shown in Table 1. The results are shown in Table 2. Any sources of uncertainty due to the CMM have been highlighted in gray and removed from the calculations of the uncertainty. The resulting uncertainty is reduced to almost 50% of the uncertainty shown in Table 1.

The only remaining sources of uncertainty are those due to the step gage that is used in the measurement. As seen in the table, the only two sources of uncertainty are the calibration uncertainty of the step gage and the uncertainty due to the lack of knowledge of its coefficient of thermal expansion (CTE) at the temperature used.

Repeatability drops from the uncertainty since repeatability is part of the measurement errors of the CMM, *i.e. the measurand*. In this case, the CMM is equipped with a temperature compensation system, and therefore the measurement of temperature is also part of the CMM, and any uncertainty introduced is part of the measurement, and not the uncertainty. In a similar manner, the uncertainty due to the CTE of the CMM scales drops out, as that is part of the CMM.

Table 2. Application of ISO/TS 23165 to the same measurement shown in Table 1. Gray fields are those from Table 1 that no longer apply when using ISO/TS 23165.

Symbol	Uncertainty Source	Type	Limit Value	Units	Distribution	Divisor	Sensitivity Coefficient	Standard Uncertainty
Um	Step gage	B	1.50	μm	Normal	2.00	1.00	0.75
Ur	Repeatability	B	0.50	μm	Normal	1.00	1.00	0.50
Uts	Measurement of CMM scale temperature	B	0.20	°C	Normal	2.00	8.00	0.80
Utm	Measurement of step gage temperature	B	0.15	°C	Normal	2.00	10.00	0.75
Uas	CTE of CMM scale	B	0.40	μm/m°C	Rectangular	1.73	1.00	0.23
Uam	CTE of step gage	B	0.50	μm/m°C	Rectangular	1.73	1.00	0.29
Uc	Combined standard uncertainty (in μm)							0.8
U	Expanded uncertainty using coverage factor k = 2 (in μm)							1.6

4 Decision Rules

Recent standards have brought much clarification to decision rules [3,4]. The latest 2001 update of ISO 10360-2 specifically mentions the use of ISO 14253-1. It was this inclusion that lead to the need for improved clarification of the uncertainty, which resulted in ISO/TS 23165. What is not clear in ISO 10360-2 is whether the default rule of ISO 14253-1 is required. The default rule is the 100% guard banding of the expanded uncertainty, called *stringent acceptance* in ASME B89.7.3.1 [4]. The positive news is that terminology now exists for communicating the decision rule that applies in manufacturer specifications and in calibration reports.

5 Summary and Conclusions

Five years ago we at Mitutoyo America thought we were the experts in measurement uncertainty for calibration of CMMs. In recent years, more and new concepts have been developed in this area. In this paper, we update our work presented at the *2001 NCSL International Workshop and Symposium*. Our goal is to create some discussion with a broader audience as these issues impact many people.

References

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7. ISO 10360-2:2001, Acceptance and reverification tests for coordinate measuring machines.