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Measurement uncertainty in the performance verification of indicating measuring instruments

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ABSTRACT

This paper is concerned with measurement uncertainty in the performance verification of the metrological characteristics of indicating measuring instruments to specified tolerances, often called maximum permissible errors (MPE). Performance verification differs from other types of calibrations in that the measurement does not necessarily result in an assigned quantity value. When a measurement involves assigning a quantity value, as is typical with the calibration of material measures or inspection of features on commercial workpieces, the measurand is different than in performance verification. The research literature and published standards and practice for measurement uncertainty typically only address the measurement uncertainty associated with assigned quantity values. When these general approaches to measurement uncertainty are applied to performance verification as well, the measurement uncertainty is not properly estimated and therefore incorrect practice is wide spread in the calibration industry. The purpose of this paper is to clarify the measurand in performance verification and to develop an associated general measurement uncertainty model. Examples are presented that highlight some cases where a measurand associated with performance verification results in a very different measurement uncertainty than when the measurand is associated with the assignment of a quantity value. Some issues for future work are also identified, particularly for consideration in the standardization of specifications for indicating measuring instruments.

1. Introduction

The formalization and broad recognition of measurement uncertainty that is in place today started with the publication of the ISO "Guide to the Expression of Uncertainty in Measurement," cited hereafter as the GUM [1]. The GUM was quickly adopted as a national standard in many countries [2] and implemented at National Metrology Institutes [3]. Calibration and testing laboratories accredited to ISO/IEC 17025 [4] were also quick to apply the GUM, as its use became a requirement of accreditation bodies worldwide [5]. Many industrial metrology standards include so-called "GUM compliant" measurement uncertainty examples; [6–10] contain examples from the dimensional metrology field.

1.1. Performance verification

The GUM applies to any and all types of measurements. The first step in applying the GUM to estimate the measurement uncertainty of a particular measurement is to have a well-defined measurand. One general type of measurement is the calibration of measuring instruments, or more specifically, the calibration of the important *metrological characteristics* [11] of measuring instruments. Following the definition of *measuring instrument* in the International Vocabulary of Metrology (VIM) [12], there are two types of measuring instruments – *indicating measuring instruments*, such as voltmeters or micrometers, and *material measures*, such as gage blocks or standard weights.

While the VIM is quite clear in defining when a measurement is a calibration, there are three general types of measurements often associated with the overall calibration process [13]:

1. Assignment of values, for example as correction factors.
2. Measurements used for adjustments, such as in service and repair.
3. Verifications to defined tolerance(s).

A further refinement to the broad category of verification can be made for indicating measurement instruments, where the term *performance verification* is used to clarify that the measuring accuracy, or performance, of the metrological characteristics of the indicating measuring instrument are being tested and

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Table 1
The different types of measurements associated with the calibration of measuring instruments.

Device calibrated	Type of calibration measurement	Examples
Material measure	Assigned quantity value	Central length of a gage block
	Verification	Roundness measurements on a master sphere to verify a spherical form tolerance
Indicating measuring instrument	Adjustments (service, repair)	Squareness error between two axes on a coordinate measuring machine (CMM)
	Performance verification	Conformance of micrometer length measuring error to the manufacturer's specifications
	Assigned quantity value	Magnification error in an optical comparator at a specific location and under specific conditions

verified against some specified tolerance(s). The term performance verification is not in the VIM, but it is used here as it is a descriptive term that is found in some literature and in metrology practice [14–17]. The concept of performance verification of indicating measuring instruments, not specifically the metrological characteristics, is also seen in practice. This usage is not precise or complete, as performance verification always applies to specific metrological characteristics of indicating measuring instrument; however, for simplicity, this usage often appears where it is understood that the performance verification applies to specific metrological characteristics. Table 1 summarizes the different types of measurements associated with the general calibration function.

It has been argued, for example in [18,19] for the coordinate measuring machine (CMM), that performance verification is not a type of calibration. There have also been attempts to differentiate between performance verification and calibration [14,15]. It is not within the scope of this paper to debate this terminology issue; however, it is noted that the concept of performance verification does not conflict with the VIM definition of calibration. In addition, it could be argued that performance verifications are widely used as calibrations in practice.

In the calibration of material measures, it is common practice to measure and report an assigned quantity value, e.g. the calibrated central length of a gage block. In these cases, the assigned value is the error, or value, under specific conditions. These conditions should be consistent with the definition of the measurand, and if not, then additional measurement uncertainty must be considered. In [20], Phillips et al. introduce the concept of *validity conditions* for a calibration; they also show how *extended validity conditions* can be developed, along with the associated impact on the estimated measurement uncertainty.

Unlike the calibration of a material measure, the performance verification of an indicating measuring instrument does not typically result in an assigned quantity value. In a performance verification test, the measured value is an error, or set of errors, observed under any set of conditions allowed by the definition of the metrological characteristic and its associated specification. These errors are often called *errors of indication* [11] and the associated specification, tolerance, or limit value is often called the *maximum permissible error* (MPE) [11,12].

1.2. Measurement uncertainty literature

In surveying the measurement uncertainty literature – particularly in the field of dimensional metrology, which is the focus of the examples in this paper – it is possible to find detailed treatment of measurement uncertainty examples for the calibration of material measures. In one instance, Decker et al. present a thorough and complete consideration of the measurement uncertainty for the calibration of the length of gage blocks [21]. As the metrology experts at National Metrology Institutes are often concerned with the calibration of material measures, it is not surprising to see this focus in their published work; other examples include [22] and [23]. In contrast to the measurement uncertainty literature for material measures, the treatment of measurement uncertainty for the performance verification of indicating measuring instruments is usually only included as a brief example in documents focused on broader topics, for example [5–9]. Issues such as the definition of the measurand and the general measurement uncertainty model for the calibration or verification of indicating measuring instruments have therefore not been formally and thoroughly explored in the literature.

The first document to give detailed treatment to measurement uncertainty for performance verification of indicating measuring instruments is ISO/TS 23165 [10]. This document, written only for coordinate measuring machine (CMM) use, introduces the concept of *test uncertainty*, which is defined as the uncertainty associated solely with the test equipment and its use in the test. The term *test* is used in ISO/TS 23165 in the sense where the test is a verification of a specific metrological characteristic of the CMM to a defined MPE, i.e. performance verification as defined in this paper. The concepts of ISO/TS 23165 were also applied by Savio to another related CMM test in [17].

The publication of ISO/TS 23165 was motivated by the need to account for measurement uncertainty in conformance decisions when testing CMMs to ISO 10360-2 [24]. A number of standards on risk analysis and conformance or acceptance decision rules have been published in various industries [25–29], and national and international metrology standards have begun to explicitly require these decision rules. It has therefore become critical for there to be a common understanding for the estimation of the measurement uncertainty in the performance verification of indicating measuring instruments. Because of the lack of a common approach in industry, ISO/TS 23165 was written to address measurement uncertainty when testing CMMs to ISO 10360-2, and it is the goal of this paper to refine and expand some of those fundamental concepts, building off prior work in [30–33], to develop a generalized measurement uncertainty model that can be applied in the performance verification of any indicating measuring instrument.

The scope of this paper is restricted to estimating the measurement uncertainty in the performance verification of indicating measuring instruments. The measurement uncertainty associated with other types of calibrations, such as the measurement uncertainty of an assigned quantity value, is specifically not addressed here. In addition, the measurement uncertainty associated with using an indicating measuring instrument for measurement tasks, such as measuring features on an industrial workpiece, is also outside the scope of this paper (for related work, see for example [34–36]). The measurement model and the associated measurement uncertainty model developed in this paper only applies to the specific case of the performance verification of metrological characteristics of indicating measuring instruments.

2. Measurement model

For an indicating measuring instrument, an error of indication is determined by measuring a reference measurement standard, whether the reference standard is a material measure or another indicating measuring instrument. The error of indication, E, is defined as the difference between the measured indication, I, and