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Calibration and verification of areal surface texture measuring instruments

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ABSTRACT

In this paper, the calibration and verification infrastructure to support areal surface texture measurement and characterisation will be reviewed. A short historical overview of the subject will be given, along with a discussion of the most common instruments and directions of current international standards. Traceability and uncertainty will be discussed, followed by a presentation of the latest developments in software and material measurement standards. The concept and current infrastructure for determining the metrological characteristics of instruments will be highlighted and future research requirements will be presented.

1. Introduction

The understanding and measurement of three-dimensional (areal) surface topography is of critical importance in many disciplines, including modern advanced manufacturing. Conventional manufacturing processes produce stochastic surfaces resulting from the need to achieve the nominal geometry of a part. The micro- and nano-scale features of the topography are a by-product of the processing technique and little or no attempt is made to manipulate them to benefit the surface function. More recently, surfaces are increasingly structured, where processing imparts predetermined functional properties [38,98]. With the increasing development of advanced components, surfaces and their associated properties are recognised as the critical factor dominating function [31,174]. Consequently, to maximise the component functionality there has been a large focus on the component surfaces and designing the surface structures to optimise a particular surface-related function [16,23,99,125,125]. To support manufacturing of such surfaces, a measurement traceability and calibration infrastructure is essential to ensure product quality.

1.1. History

The history of surface texture measurement can be found elsewhere [11,71,118,145,189,193] and this section will highlight some of the important developments, specifically in calibration and performance verification. One of the earliest attempts at controlling surface texture was made in the USA by a company that mounted samples of textures produced by different methods in cases [157] which were given to the machinist, who was expected to obtain a texture on his or her workpiece as near to that specified as possible. This was a suitable method for controlling the appearance of the workpiece but did not in any way indicate the magnitude of the surface texture. Around 1947, Rolt (at the National Physical Laboratory, UK) was pressing for surface texture measurement to produce a single number that would define a surface and enable comparisons to be made. The first parameter in use was Rq, but it was soon replaced in popularity by the number most easily obtainable from a profile graph, the *Ra* parameter, obtained using a planimeter.

Calibration and performance verification of stylus instruments from the 1940s onwards was carried out using various techniques, which included (list adapted from [164]):

- Checking the condition and tip radius of the diamond stylus using: metallurgical optical or stereoscan microscopes, and specially shaped (usually triangular) calibration artefacts with a *Ra* value that reduces as the stylus wears [203] or by tracing slowly over a sharp edge, such as a razor blade [169].
- Determining the linearity of the input (pick-up) and output (electronic meter and/or recorder) of the instrument, usually using incremental electrical inputs.
- Checking, or simply noting, the spatial frequency response (transmission characteristics) of the instrument – in some cases using a vibrating platform whose amplitude was monitored by a variety of techniques. Such techniques have since been further developed [5,58,112], but are not widespread due to the need for another relatively complex instrument. Artefacts with a series of gratings, both sinusoidal (type C1) [156,171] and square-wave [144] have also been employed to determine the instrument spatial frequency response.
- Calibrating the magnification of the height response using step height artefacts (type A) [190] or a series of gauge blocks with a calibration lever.

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- Verifying the capability of the instrument to output an accurate value for *Ra* using regular (type C) and irregular (type D) specimens (see Section 7.2) on cylindrical [183] and flat substrates [67,181].

Work on the calibration and performance verification of optical instruments has also used a variety of approaches, for example:

Comparison with stylus instruments (for example, [35,36]).

- Calibration of the motion of scanners using traceable external or integrated sensors or through measurement of step height standards (for example, [29,32]).
- Comparison between instruments with different operating principles, for example comparing root-mean-square roughness obtained from total integrated scatter, stylus profilometry, optical heterodyne profilometry and a variable angle scatterometer [56].
- Determining the instrument transfer function [33].

In 1985, an ISO specification standard on instrument calibration artefacts was published (ISO 5436), which has since been superseded (see Section 3.2). There were no serious breakthroughs or deviations from the work presented in the above list for a number of years until the work undertaken in the EU project “CALISURF”, which was completed in 2000 [179]. CALISURF was a multi-partner project with the aim of developing calibration artefacts for profile measuring instruments, which mapped onto the type A–D artefacts in ISO 5436 part 1 (see Section 3.2).

As far as specification standards were concerned, all of the above work was concentrated at surface profile measurement; traceability and characterisation for areal surface texture were first discussed by Lonardo et al. in 1996 [122]. The first breakthrough work on areal surface texture characterisation was carried out by a consortium as part of a European project led by Ken Stout from the University of Birmingham [173]. This project ended with the publication of the “Blue Book” [167], which contained the definitions of the so-called “Birmingham-14” parameters and a number of suggestions for areal instrument calibration. Following this project, ISO initiated standardisation work on areal surface texture. However, ISO experts rapidly realised that further research work was needed to determine the stability of areal parameters and their correlation with the functional criteria used by industry. A further project (“SURFSTAND”) was carried out between 1998 and 2001, by a consortium of universities and industrial partners, led by Liam Blunt of the University of Huddersfield. SURFSTAND ended with the publication of the “Green Book” [9] and generated the basic documents for forthcoming specification standards. The various sections in this paper will pick up the story from this point onwards.

1.2. Breakdown of paper

The paper is organised as follows. The last part of Section 1 gives some terminology that is important for the rest of the paper. In Section 2 the instrumentation that is in use today, and which is covered by this review, will be briefly discussed. The latest specification standards are presented in Section 3, concentrating on ISO standards, and on the subjects of calibration and verification. In Section 4, traceability for areal surface texture measurement will be discussed and in Section 5, techniques for determining measurement uncertainty will be reviewed. In Sections 6 and 7, software measurement standards and material measures (physical measurement standards) are discussed respectively. Metrological characteristics and their determination are presented in Section 8 and methods to determine the spatial frequency response of an instrument are reviewed in Section 9. Performance verification techniques are discussed in Section 10. The future of areal calibration and verification is presented in Sections 11 and 12 is a discussion.

1.3. Terminology

There are a number of terms relating to the field of metrology that need to be discussed briefly. Any of these terms are used almost indistinguishably in practice, which can often lead to confusion when specifying instruments. The terms used in the paper are taken from the latest version of the BIPM International Vocabulary of Metrology (VIM) [8].

Traceability—The concept of traceability is one of the most fundamental in metrology and is the basis upon which all measurements can be claimed to be accurate. Traceability is defined as follows:

Traceability is the property of the result of a measurement whereby it can be related to stated references, usually national or international standards, through a documented unbroken chain of comparisons all having stated uncertainties.

It is important to note the last part of the definition of traceability that states *all having stated uncertainties*. This is an essential part of traceability as it is impossible to usefully compare, and hence calibrate, instruments without a statement of uncertainty. Uncertainty and traceability are inseparable [62]. Traceability applied to surface texture measurement is discussed in Section 4.

Calibration—is defined as follows:

Operation that, under specified conditions, in a first step establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

In simpler terms, calibration is a comparison between two measurements; one of which is a reference or standard value, and the other which is being tested. Calibration is the step from one box to another in the traceability diagram shown in Fig. 3. Again, note the use of the term uncertainty in the formal definition of calibration.

Commonly the term calibration is misused, which has led to confusion in understanding the aim of the calibration process. The frequent misuse of the calibration term is when it is confused with adjustment.

Adjustment—is defined as follows:

Set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured

The adjustment process physically changes some parameters of a metrological tool (it can be a mechanical adjustment or it could be the result of changing the value of a software constant) to provide an indication that is closer to a known value. The adjustment process does not provide information about measurement uncertainty. Similar results could be obtained by correcting the measurement result using the results from a calibration certificate. A meaningful measurement result can be presented without adjustment, but it must have an associated uncertainty.

An example of adjustment of a stylus instrument is the physical adjustment that is performed using a calibrated step height material measure (type A) or a sinusoid with a known *Ra* (type C). These material measures reproduce a height value known with an associated uncertainty. Generally, during the adjustment of the instrument, the response curve (see Section 8) is changed according to the result of a single measurement. The adjustment cannot account for the uncertainty associated with the measurement result; it only uses a value from the range of possible values that are within the limits given by the measurement uncertainty. After adjustment, the measurement of the same step height can provide a different result. The basic difference between calibration and adjustment is also illustrated by the requirement in ISO 17025 [77] that an instrument should be calibrated before and after adjustment.

Verification—is defined as follows:

Provision of objective evidence that a given item fulfils specified requirements.

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