Infidelity and the calibration of surface topography measuring instruments

Conference Paper · November 2018

3 authors:


Richard Leach
University of Nottingham


Peter J. DE GROOT
Zygo Corporation


Han Haitjema
KU Leuven

INFIDELITY AND THE CALIBRATION OF OPTICAL SURFACE TOPOGRAPHY MEASURING INSTRUMENTS

Richard Leach[1*], Peter de Groot[2], Han Haitjema[3]
[1]Manufacturing Metrology Team, Faculty of Engineering, University of Nottingham, Nottingham NG8 1BB, UK
[2]Zygo Corporation, Middlefield, CT 06455, USA
[3]KU Leuven, Mechanical Engineering Department, B-3001 Leuven, Belgium

1. INTRODUCTION

The ability to measure and characterise surface topography is vital in advanced manufacturing and to many precision engineering applications [1,2]. Modern advanced applications require surfaces with complex specifications and with a large range of topography structures. Such structures can vary from random to highly deterministic and can be a mixture of both.

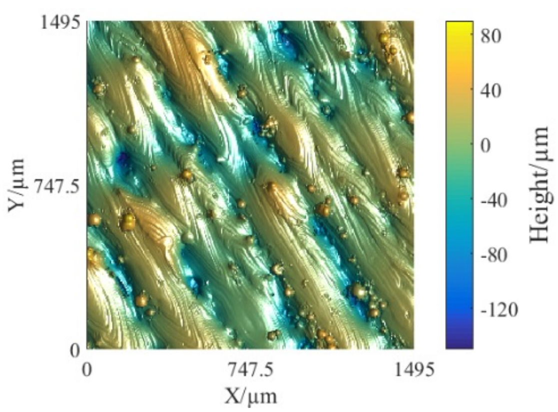

FIGURE 1: Surface manufactured using a laser powder bed fusion process, illustrating the mix of deterministic and random structures, measured with a focus variation microscope

An example of a complex structure that is receiving a lot of attention relates to the metal powder bed fusion processes for additive manufacturing. As shown in FIGURE 1, such surfaces have deterministic features that are the result of the path of the energy source (e.g. weld tracks) and random features that are the result of highly-complex fluid dynamic and high-speed thermal processes (e.g. spatter particles and cracks) [3,4]. High slope angles, both specularly and diffusely reflecting surfaces in the same part, re-entrant features, as well as highly-complex freeform geometries are some of the issues that challenge the use of conventional contact and optical instruments with such surfaces [5,6].

The question we address here is: can an instrument calibration framework be designed that will give a basis for the estimation of the measurement uncertainty when measuring such complex surfaces?

2. THE CURRENT SITUATION

Traditionally, instrument calibration for areal surface topography measurement has relied on a manageable, but arguably incomplete, subset of instrument checks for scale and non-linearity of the measurement axes. Often these use familiar calibration specimens, known as material measures, that carry certifications that provide traceability to the metre.

One well-known material measure for determining the height response of an instrument is the step height [7,8]. Along with grid artefacts for lateral dimensions [9], such material measures are used to calibrate the scales of an instrument. These calibrations, whilst essential, tell us little about how the instrument would respond to complex surface features, such as those shown in FIGURE 1. Material measures that only capture information about the ability of an instrument to measure a series of step-like transitions do not inform us about how the instrument responds to various slope angles [9].

With a few exceptions [10], it is uncommon in manufacturing applications to encounter an uncertainty budget based on calibrations and individual influence factors alone. Instead, quality control engineers perform gauge capability tests directly on the parts that they wish to measure. The results of gauge testing, instrument correlation and demonstrations of control of functional behaviour are the most common ways to qualify an instrument for manufacturing metrology [11]. This leaves a gap in our understanding of the origins of measurement error and how to improve metrological performance in manufacturing applications.

3. EXTENDING THE MEASUREMENT RANGE

Considerable work has gone into improving the quality of non-contact, optical measurements so as to extend the range of applications to surfaces with steep slopes [5,9,12]. At the same time, however, the recognised advances in instrument design and performance have left unanswered the question of calibration for the purpose of a first-principles uncertainty assessment. Pressing the matter further, many optical instruments today take advantage of the scattering from fine roughness on slope angles greater than the classical aperture limit of the objective [13-15].

Calibration for slope effects is integral to some modern interferometry methods, using a purely empirical approach with a wide range of known sample slopes as the source of calibration data. Right-angle vee-groove surfaces can be measured using dual-probe configurations, where measurements from both probes are combined [16]. The slope range can even be extended to microlenses with highly aspheric departures, using field-stitching techniques enabled by correlation of surface roughness detection on the nanometre scale [17]. The measurement geometry of FIGURE 2 requires correction for distortion and field-dependent slope errors for each image tile prior to composition of the final aspheric form measurement of FIGURE 3. This empirical approach serves this application well, but the final performance specification relies on repeatability, reproducibility and tool matching results that are not easily incorporated in an uncertainty budget.

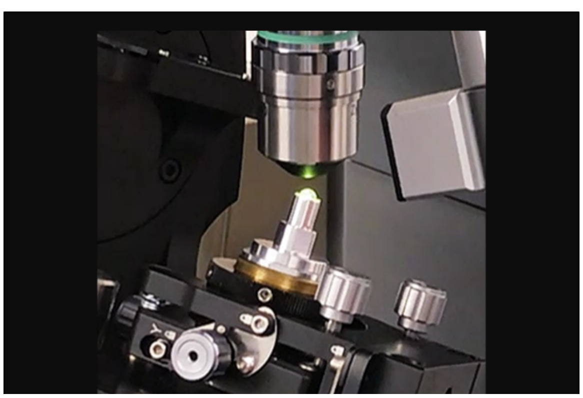

FIGURE 2: Micro-asphere metrology using high-slope measurements at multiple viewing angles in an interference microscopy.

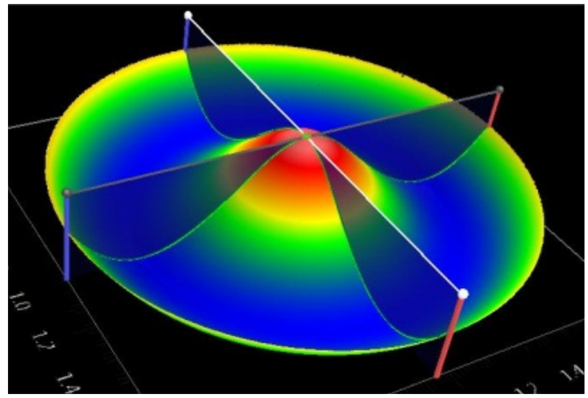

FIGURE 3: Example measurement of a 1.8 mm diameter microlens having 60 µm of aspheric departure. Cross-sections are indicated for illustration.

Focus variation microscopy uses incoherent illumination and detection and can take advantage of the scattering from high slope angles so long as the sloped surface has a certain degree of roughness [13,18] (which is also a basic requirement of FVM due to its use of contrast to detect height differences [18]). Recent advances in focus variation, however, allow high slope measurement even for relatively smooth surfaces, by employing advanced illumination techniques and multi-axis motion systems [19]. However, despite the theory of FVM being well advanced in the conventional Fourier optics regime [20], the combination of specularly reflected light with diffusely reflected light at high slope angles is not yet adequately captured in theoretical models. In the presence of multiple scattering, the spatial frequency response of FVM is not currently known, although there are plans to address this deficit (see section 4). The usual question springs to mind: with complex surfaces, how can we be confident with the resulting topography? FIGURE 4 shows an example of a hole measurement using FVM, where slopes can be seen that are clearly outside the conventional numerical aperture (NA) angle limit [20].

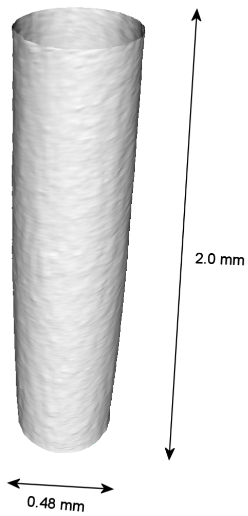

FIGURE 4: Hole measurement using FVM.

Similar arguments to those presented above for FVM apply to imaging confocal microscopy (ICM) [21], and slope measurement capabilities greater than the conventional NA acceptance angle are quoted on some commercial instrument specifications. However, high-slope angles can also cause significant issues for ICM, often resulting in spikes [5]. These sometimes can be avoided by careful tuning of the instrument settings, but this option is not always available when measuring highly variable surface topographies.

4. ADVANCED APPROACHES

It would be more than simply satisfying if the understanding of the fundamental physics of the measurement process could be advanced to the point where the uncertainty of high-slope measurements can be properly estimated from first principles.

In addition to retrace, image distortion and aberration errors that increase with surface slope, fundamental issues arise when light is reflected at angles greater than the NA slope limitation. At some spatial frequencies, there may not even be a useful correlation between the measured texture and the actual surface characteristics. A number of physical effects cause simple measurement models to become invalid and result in a non-linear response of the instrument to surface topography. Examples of such effects are multiple reflection, shadowing and surface plasmon resonance. The only way to model such effects is using rigorous approaches that significantly increases the complexity of the problem while reducing the speed at which solutions can be calculated.

Consider the comprehensive theory developed at the University of Nottingham and Loughborough University, leading to a 3D transfer function for the case of weak scattering [22]. This theory is only valid within the traditional aperture or NA slope limitation. An alternative boundary element method (BEM) promises to allow for predictive response of an instrument from almost any complex surface shapes [23]. With such models, it may be feasible in the future to establish task-specific uncertainty budgets for a wide variety of measurement applications with a common set of material measures. This of course presupposes that these theories can predict measurement values for a known surface topography, and that the inverse problem is soluble without ambiguity.

5. THE ROLE OF THE STANDARDS

ISO Technical Committee 213 Working Group 16 is currently working towards a framework for calibration of surface topography instruments [9]. The proposed framework involves the determination of a number of *metrological characteristics* that are designed to quantify the various influence factors that affect the uncertainty in a measurement carried out with a surface topography instrument [9,24,25]. These characteristics include established concepts such as scale linearity, amplification coefficient, flatness, noise, topographic spatial resolution and *x-y* mapping deviation for the response of an instrument. The corresponding calibration draft document is ISO 25178-700.

A metrological characteristic *Topography fidelity* has been introduced into the ISO framework as a kind of miscellaneous category for all contributions to the uncertainty budget—including surface slope-dependent errors—that are not captured by the more well-known calibrations.

An example calibration for topography fidelity is the determination of the instrument transfer function (ITF), defined as the square root of the ratio of the measured power spectral density (PSD) of a surface structure to its known or independently-determined PSD. In essence, the ITF quantifies the response of a topography-measuring instrument to specific spatial frequencies in the surface structure [26]. The ITF is widely used in the testing of optical components, such as lenses and mirrors, and can be calibrated using a variety of available artefacts, including small step features etched into glass [26]. However, it is understood that the range of applicability of the ITF is limited, particularly for technical surfaces with rough or complex textures or extreme slope angles. It is also not clear how an ITF evaluation can be incorporated into an uncertainty budget. Consequently, although the ITF concept is defied in the draft ISO 25178-700 document, methods of ITF calibration remain informative rather than normative.

A similar situation exists for other proposed methods of calibrating topography fidelity. A common theme is to use a material measure having a shape that is close to the measurand, and that has been calibrated independently and/or or manufactured in such a way that the real geometry is known. Measuring this specimen using the instrument to be evaluated may give quantitative information about the deviations that can be used in an uncertainty budget.

Artefacts are under development that include a multitude of established difficult-to-measure features such as steep steps and grooves of various spacings and depths. Example artefacts under development include the chirp standard [27] that is comprised of square-waves of varying lengths and depths, and a sample (in fact a collection of samples) [28] that contains a multitude of surface structures on a limited area. Recently a circular chirped specimen with several degrees of randomness in lateral size has been presented to ISO 213 [29]. In addition to these artefacts, there have been proposals for metrics or measures of agreement to allow for reporting and specifying of topography fidelity [30].

It seems, however, unrealistic to suppose that we can design a single artefact that includes all possible surface structures. For less defined structures than the reference specimen, estimates of the uncertainties are not sufficiently reliable. A further issue is that many of these proposed structures have sharp edges or other features that result in measurement outliers, false data or, with interferometry, fringe-order errors that are not easily summarised as statistical variations for the purpose of an uncertainty budget. Finally, for many of these proposed calibration specimens, not much more can be done than taking deviations for granted and trying to quantify these without a solid understanding as to the origins of the errors.

6. THE WAY FORWARD

In the short term, we would argue that it is not yet feasible to establish an instrument calibration framework that would allow for the estimation of uncertainty for general, practical applications in manufacturing metrology. The basic calibrations of scales are a necessity for traceability and verification of instrument function; but they do not replace the traditional gauge capability test on actual parts. Consequently, there is an emerging consensus that it would be premature and perhaps misleading to include in the ISO 25178-700 calibration document specific methods regarding topographical fidelity that go beyond the definition of terms and description of example artefacts.

To advance further, it is clear that additional theoretical work is essential to understanding and reducing the errors resulting from complex surface structures and high slopes. Concurrently, work will continue on the development and proof of the value of material measures, alternative procedures, and quantifiers for calibrating slope-dependent response. These efforts will progressively close the gap between calibration and gauge capability, allowing for a more predictive estimate of instrument performance for diverse applications, and increased confidence in results.

The first but significant step in our current plan is to develop a series of "virtual instruments" that can predict the response of a number of optical instruments (initially CSI, FVM and ICM) for surfaces that have features which cause traditional linear transfer function theories to be invalid. This will be done by developing a 3D implementation of the BEM [23] described above (which is currently only available in 2D) and modelling the source and optics for each instrument modality. Once verified, such virtual instrument models can be used in uncertainty estimations for complex surfaces and perhaps to correct some systematic errors, therefore, improving the response of instruments to complex surface features. As the writer Jonut Díaz says: "Infidelity raises profound questions". By chipping away the major causes of infidelity in surface topography measurement, we will also gain a deeper understanding of how instruments operate and, potentially, how to improve them.

AKNOWLEDGEMENTS

The authors would like to thank the members of the ISO committee 213 WG 16 for contributing to much of this work. RKL would like to acknowledge funding from EPRSC project EP/M008983/1.

REFERENCES

[1] Whitehouse DJ. Handbook of surfaces and nanometrology, 2nd Edition. CRC Press: 2010.

[2] Leach RK, Smith ST. Basics of precision engineering. CRC Press: 2018.

[3] Senin N, Thompson A, Leach RK. Characterisation of the topography of metal additive surface features with different measurement technologies. Meas. Sci. Technol. 2017;28:095003.

[4] Fox JC, Moylan SP, Lane BM. Preliminary study toward surface texture as a process signature in laser powder bed fusion Additive manufacturing. Proc. ASPE Summer Topical. 2016;168-173.

[5] Thompson A, Senin N, Giusca CL, Leach RK. Topography of selectively laser melted surfaces: a comparison of different measurement methods. Ann. CIRP. 2017; 66:543-546.

[6] Townsend A, Senin N, Blunt LA, Leach RK, Taylor J S. Surface texture metrology for metal additive manufacturing: a review. Prec. Eng. 2016;46:34-47.

[7] Leach RK. Is one step height enough? Proc. ASPE. 2015;110-113.

[8] de Groot D, Fitzgerald D. Measurement, certification and use of step-height calibration specimens in optical metrology. Proc. SPIE. 2016;10329.

[9] Leach RK, Giusca C L, Haitjema H, Evans CJ, Jiang X. Calibration and verification of areal surface texture measuring instruments. Ann. CIRP. 2015;64:797-813.

[10] de Groot, P., Biegen, J., Clark, J. et al. Optical Interferometry for Measurement of the Geometric Dimensions of Industrial Parts. Applied Optics. 2002; 41: 3853-3860.

[11] Montgomery D. Statistical quality control: a modern introduction. Wiley, New York: 2009.

[12] Badami VG, Liesener J, Evans CJ, de Groot P. Evaluation of the measurement performance of a coherence scanning microscope using roughness specimens. Proc. ASPE 2011;23-26.

[13] Hiersemenzel F, Petzing J, Leach RK, Helmli F S, Singh J. Areal texture and angle measurements of tilted surfaces using focus variation methods. Proc. 3rd Int. Conf. Surface Metrology, Annecy, France, Mar. 2012;85-89.

[14] Fay MF, Colonna de Lega X, Schmidt M. Measuring high-slope parts using coherence scanning interferometry. Proc. ASPE. 2014.

[15] Li L, Liu J, Liu Y, Liu C, Zhang H, You X, Gu K, Wang Y, Tan J. A promising solution to the limits of microscopes for smooth surfaces: fluorophore-aided scattering microscopy. Nanoscale. 2018;10:9484-9488.

[16] Zhang T, Feng G, Martin T, Xiangqian J. A method for inspecting near-right-angle V-groove surfaces based on dual-probe wavelength scanning interferometry. Int. J. Adv. Manuf. Technol. 2018:1-7.

[17] Colonna de Lega X, Dresel T, Liesener J, Fay M, Gilfoy N, Delldonna K, de Groot P. Optical form and relational metrology of aspheric micro optics. Proc. ASPE 2017;20-23.

[18] Danzl R, Helmli F, Scherer S. Focus variation – A robust technology for high resolution optical 3D surface metrology. J. Mech. Eng, 2011;57:245-56.

[19] Zangl K, Danzl R, Helmli F, Prantl M. Highly accurate optical µCMM for measurement of micro holes. Proc. CIRP. 2018;In press.

[20] Nikolaev N, Petzing J, Coupland JM. Focus variation microscope: linear theory and surface tilt sensitivity. Appl. Opt. 2016;55:3555.

[21] Artigas R. Imaging confocal microscopy. In: Leach RK. Optical measurement of surface tomography, Spinger, 2011.

[22] Su R, Wang Y, Coupland JM, Leach RK. On tilt and curvature dependent errors and the calibration of coherence scanning interferometers. Opt. Express 2017;25:3297-3310.

[23] Simonsen I. Optics of surface disordered systems. Eur. Phys. J. Special Topics. 2010;181:1-103.

[24] Haitjema H. Uncertainty in measurement of surface topography. Surf. Topog. Met. Prop. 2015;3:035005.

[25] Haitjema H., Leach RK. (2018) Surface texture metrological characteristics. In: The International Academy for Production, Chatti S., Laperrière L., Reinhart G., Tolio T. (eds) CIRP Encyclopaedia of Production Engineering. Springer, Berlin, Heidelberg.

[26] de Groot P, Colonna de Lega X, Sykora DM, Deck L. The meaning and measure of lateral resolution for surface profiling interferometers. Optics and Photonics News. 2012; 23:10-13.

[27] Seewig J, Eifler M, Wiora G. Unambiguous evaluation of a chirp measurement standard. Surf. Topog. Metr. Prop. 2014;2:045003.

[28] Eifler M, Hering J, Freymann GV, Seewig J. Calibration sample for arbitrary metrological characteristics of optical topography measuring instruments. Opt. Express 2018;26:16609-16623.
[29] Dai, G et al, Circular chirp for determination of the instrument transfer function and topographic fidelity, ISO/TC 213, WG 16, London, Feb 7, 2018, Document N771.
[30] Vorburger TV, Song J-F, Chu ML, Bui SH, Zheng A, Renegar TB. Applications of cross-correlation functions. Wear 2011;271:529–533.