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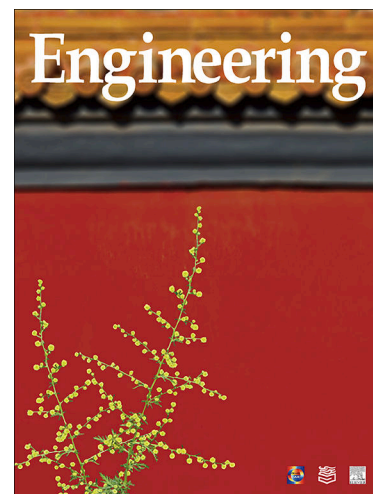
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Research

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A Surface Quality Evaluation Method for Establishing Image-Surface Causal Chain in X-ray Computed Tomography Measurement

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Abstract: Ensuring reliable measurement quality in X-ray computed tomography (XCT) dimensional metrology remains challenging, because the complete causal chain—from XCT influencing factors, through image quality, to final surface quality—has not yet been established. A key gap is the absence of a surface quality evaluation method with metrics directly linked to image quality metrics. This paper addresses that gap by introducing such a method which determines the metrological structural resolution (MSR), a critical resolution metric for XCT dimensional metrology. The method computes the two-dimensional surface amplitude transfer function (SATF) to evaluate XCT systematic and random errors and also to identify the measurable scale limit. The MSR can then be determined by either the permissible systematic error or the measurable scale limit. By providing metrics that map surface systematic error, random error and MSR onto image blur, noise and resolution, the proposed method effectively completes the XCT causal chain and enhances the understanding of how XCT influencing factors affect measurement quality.

Keywords: X-ray computed tomography; Dimensional metrology; Surface quality evaluation; Surface amplitude transfer function; Metrological structural resolution

1. Background

X-ray computed tomography (XCT) has gained significant attention in dimensional metrology due to its ability to obtain full three-dimensional (3D) geometric information of objects in a non-destructive manner [1,2]. XCT offers considerable advantages over conventional dimensional metrology techniques, such as tactile and optical methods, particularly in its capacity to capture internal geometries and free-form shapes [3,4]. Moreover, XCT can simultaneously perform multiple dimensional measurement tasks on a part at different scales, including length, form and surface texture measurements, which in contrast is often performed separately using different conventional techniques. The advancement of XCT as a dimensional metrology tool holds significant potential for a wide range of industries.

Despite its potential, XCT is not yet considered a fully mature dimensional metrology tool, as ensuring its measurement quality remains a significant challenge. This is primarily due to the limited understanding of XCT measurement performance. XCT measurement involves the transfer of image data to surface data; however, the complete causal chain—from XCT influencing factors, through image quality, to final surface quality—has not yet been established. A key gap is the absence of a surface quality evaluation method, with metrics, that can map directly to image quality [5].

One critical resolution metric for XCT dimensional metrology is the metrological structural resolution (MSR), defined as the size of the smallest structure that can be dimensionally measured within specified error limits [6]. MSR is determined using the final surface data and is expected to work as an effective indicator of measurement reliability and the overall suitability of XCT for metrology applications. Mirroring the determination of image resolution, it is also desirable to determine MSR of both system and random errors for comprehensive surface quality evaluation [7,8]. Since XCT measurement errors are often non-uniform across the measurement space [9,10], this spatial non-uniformity must be

considered for reliable MSR determination and effective causal chain establishment. There have been many methods proposed for evaluating XCT measurement errors and determining MSR, but none could effectively establish the causal chain.

Existing MSR determination methods for XCT are inherently limited to one spatial dimension, making them inadequate for assessing spatial non-uniformity [7–18]. Most of the methods account only for the systematic error while neglecting or suppressing random error, which may lead to overestimation of MSR and prevent investigations into random error sources and their impacts. The XCT total systematic error is generally characterised as a low-pass filtering effect, as measurement error tends to increase with decreasing geometry structure size. Some methods estimate the extent of this filtering effect (i.e., characterising the filter size) to determine MSR. For example, Bartscher et al. [12] proposed estimating the filter size using the radius of sharp step edges, while Illema et al. [19] evaluated the filter size based on the curvature of curved edges, assuming a Gaussian filtering effect. These methods only provide limited and rough evaluations of the XCT systematic error for MSR determination.

There are methods that provide a more complete characterisation of the XCT filtering effect. Zanini and Carmignato [13] proposed using the contacting area of two spheres to evaluate the effect at various heights generated in the contact zone, thereby characterising the XCT filtering effect in the spatial domain. However, the accuracy of this method is limited by the small number of data sampling points due to its spatial domain-based sampling strategy. Wohlgemuth et al. [10] and Arenhart et al. [11] proposed using the amplitude transfer function (ATF) of aperiodic profile samples to fully characterise the XCT filtering effect in the frequency domain. While frequency response analysis-based methods provide sufficient data for accurate characterisation, their evaluation results suffer from severe data noise introduced by XCT random errors. Spatial random error manifests as ATF noise across the entire frequency spectrum. Although noise reduction of ATF has been achieved by suppressing XCT random errors, the denoising performance is inefficient, and the evaluation of random error is impossible.

This work proposes a novel surface quality assessment method based on frequency response analysis, which enables the evaluation of both XCT systematic and random errors across a range of frequencies in a two-dimensional (2D) measurement space. The method calculates the 2D surface ATF (SATF) of XCT measurement using a single aperiodic surface consisting of various frequency components. Calculating the 2D SATF is more challenging than the one-dimensional (1D) ATF. While ATF calculations utilise averaging multiple identical profiles to reduce ATF noise, this denoising approach is unsuitable for SATF calculation due to the practical difficulty of manufacturing multiple surfaces with identical complex textures. To overcome this limitation, the multiple fast Fourier transform (FFT) averaging method was employed, enabling effective noise reduction in SATF computation using only a single surface. This denoising approach not only ensures an accurate characterisation of the XCT filtering effect but also incorporates the evaluation of XCT random error within the SATF. The MSR can then be comprehensively determined according to either systematic or random errors. The 2D error evaluation allows the examination of spatial non-uniformity. The quality metrics of the final surface data (including surface systematic error, random error, and MSR) can be linked to those of the initial projection image data (including image blur, noise and resolution) in the same measurement space.

In this paper, Section 2 describes the methodology and test sample for calculating the SATF. Section 3 examines the noise issue in SATF calculation and presents the denoising method. Section 4 presents the validation and interpretation of the SATF method for identifying different XCT measurement errors. Section 5 explains the determination of MSR from SATF. Section 6 illustrates the application of the SATF method in constructing the complete causal chain of an XCT influencing factor, linearisation-based beam hardening correction (BHC), in order to gain a deeper understanding of its impact on measurement quality. Finally, Section 7 provides the conclusions of this work.

2. Methodology and test sample

2.1. Methodology for developing the SATF method

Since SATF noise is the primary obstacle for accurate error evaluation, SATF noise was assessed first to identify an appropriate SATF denoising strategy. An XCT simulation measurement was conducted to obtain the SATF with minimal noise by minimising random errors. If SATF noise remains significant, it suggests that optimising the sample design or measurement performance could not achieve effective SATF denoising, indicating the need for advanced data processing techniques. Then the adopted SATF denoising method was examined using the practical SATF obtained from a physical XCT measurement. Finally, the error evaluation accuracy of SATF was validated through an algorithm-based measurement system with known systematic and random errors.

2.2. Definition of SATF

SATF is defined as the ratio of the amplitude of XCT measured surface frequencies to the amplitude of true surface frequencies, mathematically expressed as:

$$\text{SATF} = \frac{A_{\text{XCT}}}{A_{\text{true}}} = \frac{|\mathcal{F}\{\text{XCT measured surface}\}|}{|\mathcal{F}\{\text{true surface}\}|} \quad (1)$$

where A_{XCT} and A_{true} denote the XCT-measured and true surface frequency amplitudes, respectively; $\mathcal{F}\{\cdot\}$ denotes the N -point discrete Fourier transform, computed with a radix-2 FFT; and $|\cdot|$ refers to the absolute value. As the true surface is never known, a high-resolution measurement of the test surface is used as a reference to estimate SATF. In this work, an optical surface metrology instrument, focus variation (FV) microscopy, was utilised to obtain high-resolution reference measurements of the test surfaces to estimate the SATFs of physical XCT measurements.

2.3. Test sample

The test sample used in this work is a metal additively manufactured (AM) sample, specifically the 3D roughness standard sample (3DRS) developed by the National Physical Laboratory (NPL) [20,21]. The 3DRS sample is made of Ti64 alloy and manufactured by electron beam melting in a vertical building orientation, as shown in Fig. 1. The sample features four test surfaces labelled A, B, C, and D. Surface A is the as-built surface, while the others were bead blasted with beads of different sizes to achieve varying surface roughness. All four surfaces were used in this work to obtain generalised results and to examine the non-linearity of the SATF in XCT, that is, its dependence on the input surface. The test surfaces were measured parallel to the XCT rotation axis.

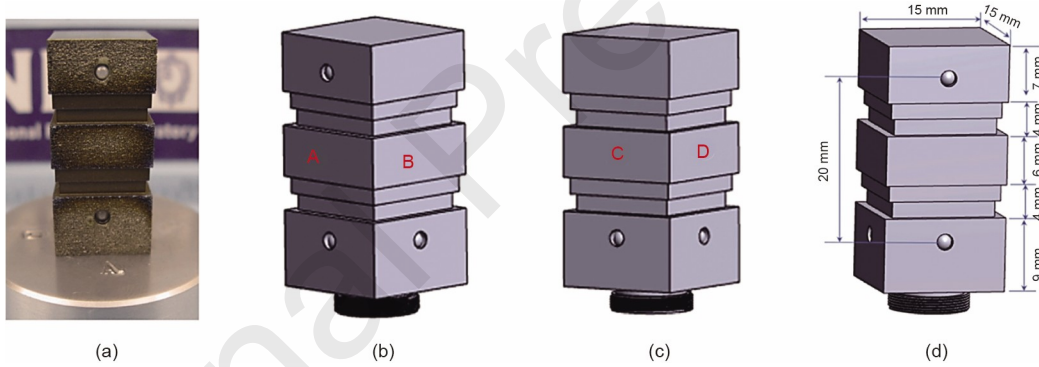


Fig. 1. NPL 3DRS sample: (a) photograph of the sample; (b, c) illustrate the positions of the four test surfaces; (d) shows the nominal size of the sample [20,21].

2.4. Optical (FV) measurements of test surfaces

To obtain high-quality, reliable reference measurements of the test surfaces, it is recommended that the reference method should offer at least three times the lateral resolution [41], five to ten times finer vertical resolution [42,43], and no more than one quarter of the uncertainty of the XCT measurement [39]. Typical optical areal surface metrology techniques, such as FV microscope, confocal microscope and coherence scanning interferometer (also known as white-light interferometry), are suitable candidates [40]. Given that the AM test surfaces exhibit high roughness (i.e., steep local slopes), an Alicona G4 FV microscope (Bruker Alicona, Austria) [22] was selected for its high slope acceptance (up to 85°) [44].

The FV measurement settings were: magnification $\times 20$, numerical aperture of the objective lens 0.40, sampling distance 1 μm , and with ring light illumination. The FV measured test surfaces are shown in Figs. 2(a)–(d). The roughness of surfaces A, B, D and C, characterised by the arithmetical mean height of the FV measured surface, is 34.5, 29.4, 29.1, and 22.2 μm , respectively. The 2D frequency-amplitude maps (referred to as amplitude maps) of the FV measured surfaces are shown Figs. 2(e)–(h), while the zero-crossing profiles of the maps are shown in Figs. 2(i) and (j). Generally, rougher surfaces exhibit higher surface amplitudes across the frequency spectrum. It is important to note that these amplitude maps have been denoised, with the denoising processing discussed in Section 3.2.

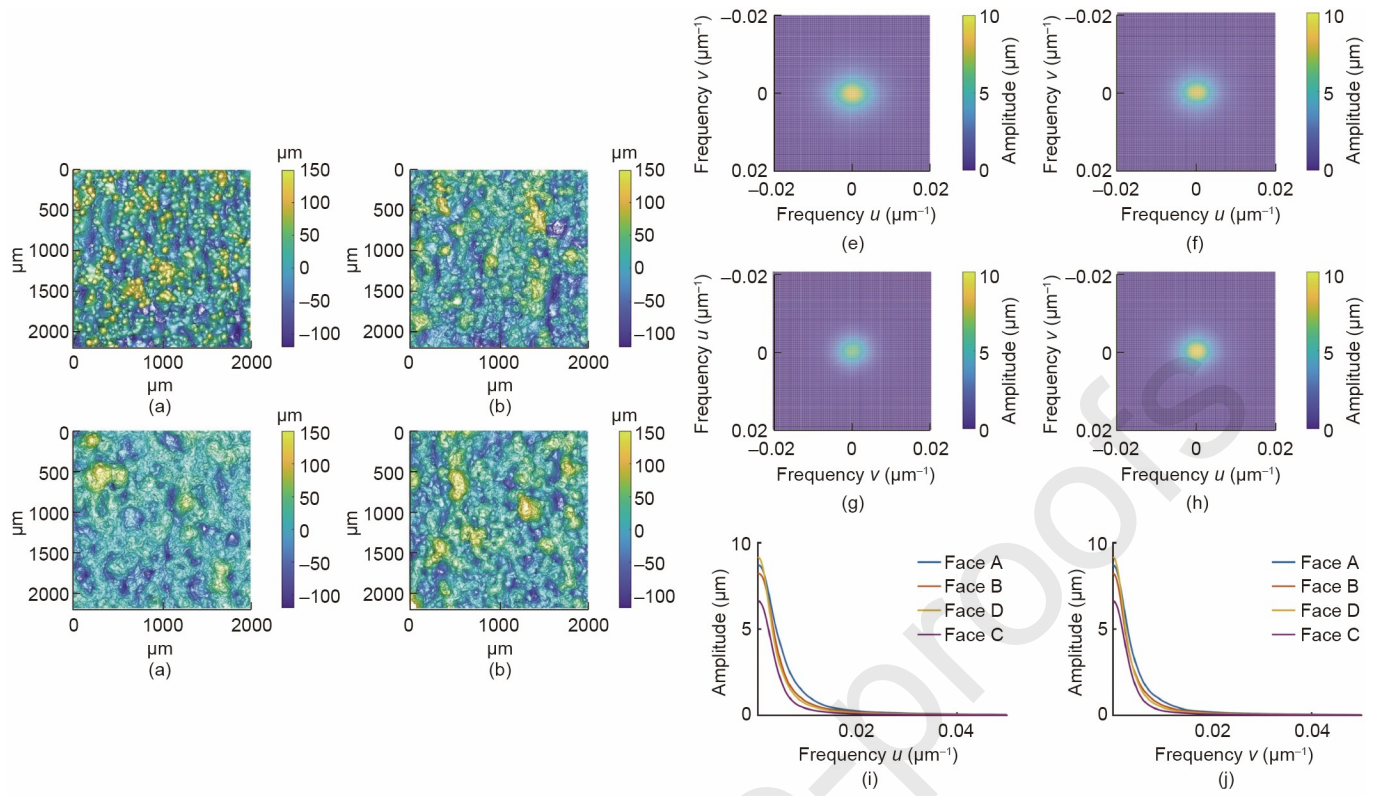


Fig. 2. Four test surfaces measured by an Alicona G4 FV microscope and their frequency-amplitude maps. (a–d) Surfaces A, B, C and D; (e–h) corresponding frequency-amplitude maps; (i, j) zero-crossing profiles of the frequency-amplitude maps along the u and v axes.

2.5. Simulated and physical XCT measurements of the test surfaces

The scan settings of the XCT simulation and physical measurement of the test surfaces are listed in Table 1 [23].

The XCT simulation measurement was performed by the software aRTist (BAM, Germany) [24]. The virtual sample for the simulation was a cube containing the four FV measured test surfaces, as shown in Fig. S1 in Appendix A. The dimensions of the test surfaces on the virtual cube sample were $2.3 \text{ mm} \times 2.3 \text{ mm}$, while the cube itself was $2.5 \text{ mm} \times 2.5 \text{ mm} \times 2.5 \text{ mm}$. In the simulation, the X-ray source (focal spot) was modelled as a 2D Gaussian function with a full width maximum height of $20 \mu\text{m}$. This focal spot size was chosen to mimic the physical XCT measurement. The digital focal spot had pixel dimensions of 301×301 . However, to reduce the computation load, the digital focal spot was resampled to five randomly distributed points. Scattering and noise options in the software were deactivated to minimise XCT random errors.

Table 1

Simulated and physical XCT scan settings.

Measurement index	Measurement 1	Measurement 2
Measurement type	Simulation	Physical
Measurement equipment	aRTist software	Nikon XT H 225M CT

X-ray-source	Monochromatic	Polychromatic
Voltage (kV)	180	180
Current (μA)	85	120
Exposure time (ms)	1420	1420
Voxel size (μm)	20	20
Focal spot size (μm)	20	Estimated 22.4 [23]
Prefilter	None	0.5 mm copper
Number of projections	3141	3141
Detector pixel number	2000×2000	2000×2000
Repeated measurements	1	3

The simulated radiographs were reconstructed into volume images using the filtered back-projection algorithm [25] in the CT Pro 3D software (Nikon Metrology, Japan) [26]. Surface determination was performed using VGStudio Max 3.2.5 (Volume Graphics, Germany) [27] with a local maximum gradient-based method [28,29]. The determined surfaces were exported as grid point clouds with a sampling interval of $5 \mu\text{m}$. These surfaces were then aligned with the reference surfaces (virtual sample) using an iterative closest point registration algorithm and resampled at the same locations, with $1 \mu\text{m}$ intervals, as the reference surfaces via linear interpolation in software CloudCompare (EDF R&D, France) [30].

The physical XCT measurement was performed using the Nikon XT H 225M (Nikon Metrology, Japan) [31], a cone-beam XCT system equipped with a flat plane detector. Volume reconstruction was similarly conducted using CT Pro 3D software with the filtered back-projection reconstruction algorithm. A linearisation-based BHC [32] was applied to mitigate beam hardening artifacts. The BHC correction function was set as a 2nd order polynomial: $Y = aX + bX^2$, where X is the initial intensity values of the XCT radiographs, Y is the corrected intensity values, a and b are specified correction coefficients [33], set to 0.75 and 0.25, respectively, for appropriate correction. In the case study presented in Section 6, different coefficients were used to investigate the impacts of varying the BHC strengths. Surface determination and alignment were performed in the same manner as in the simulation. Three repeated physical measurements were conducted.

3. Calculation of SATF

3.1. Noise in SATF

The XCT random error on the measured surface introduces random noise into the surface amplitude maps, causing the SATF calculated from these amplitudes (using Eq. (1)) to exhibit noise. The SATF of test surface A obtained from the XCT simulation measurement (Measurement 1 in Table 1) is shown in Figs. 3(a) and (b). While minimal SATF noise was expected due to the minimised XCT random error, this noise is still significant enough to affect the effective evaluation of systematic and random errors, highlighting the need for effective denoising in the SATF calculation.

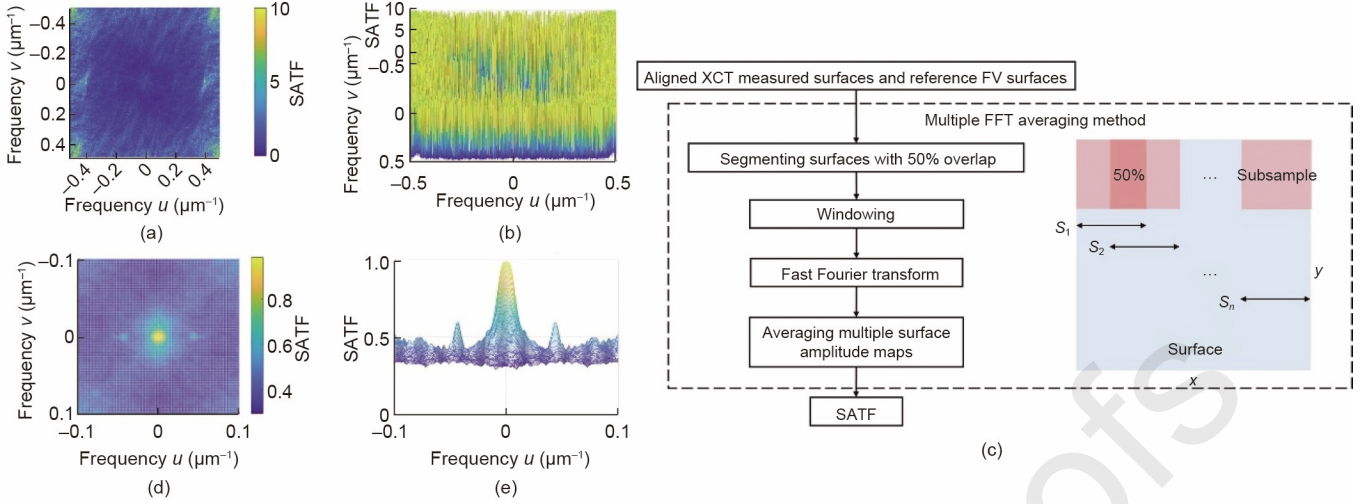


Fig. 3. SATF noise issue, denoising procedure and results. (a, b) SATF of test surface A from XCT simulation measurement (Measurement 1 in Table 1) without denoising: (a) top view and (b) oblique view. (c) SATF denoising procedure diagram showing the multiple FFT averaging method (i.e., SATF denoising algorithm). (d, e) Denoised SATF of test surface A from physical XCT measurement (Measurement 2 in Table 1): (d) top view and (e) side view.

3.2. SATF denoising

To reduce noise in the SATF plot while incorporating the evaluation of XCT random error, data averaging was performed on the surface amplitude in the frequency domain, called the Multiple FFT averaging method. The diagram of the SATF denoising method and its procedure are illustrated in Fig. 3(c). In calculating the surface amplitude, instead of performing a direct Fourier transform on a large surface, the large surface was first segmented into multiple smaller subsamples, and then the amplitude maps of all surface subsamples were computed and averaged, expressed as:

$$\bar{A} = \frac{1}{mn} \sum_{k=1}^m \sum_{j=1}^n |F\{S_{k,j}\}| \quad (2)$$

where S is the surface subsample data, k and j are the subsample indices along the x and y axes respectively, m and n are the numbers of subsamples along the x and y axes respectively, and $\bar{A}$ is the averaged amplitude. The subsamples can overlap by 50 % or less with adjacent subsamples. This averaging method reduces the variance of SATF noise to the level of $1/mn$ of the original variance while preserving the amplitude of the SATF noise. The reduced variance ensures accurate characterisation of the XCT filtering effect, while the preserved amplitude allows for evaluation of the XCT random error. The surface data was multiplied by the Hann function to reduce spectral leakage [34] during surface amplitude calculation, and the SATF calculation was performed in MATLAB (MathWorks, USA) [35].

The effectiveness of SATF denoising depends on the number of surface subsamples used in the calculation. For the XCT simulation measurement, 49 subsamples with a surface size of $500 \mu\text{m} \times 500 \mu\text{m}$ were sufficient for effective SATF denoising. In contrast, the XCT physical measurement, approximately 600 subsamples of the same surface size were required to achieve a satisfactory denoising effect. The effectiveness of the SATF denoising method is demonstrated in Figs. 3(d) and (e), which shows the denoised SATF of the test surface A in the physical XCT measurement, clearly revealing identifiable features. The computation time per subsample is 0.0218 s.

4. Accuracy validation, sensitivity analysis and interpretation of SATF

4.1. Accuracy validation of SATF

To validate the accuracy of the calculated SATF in evaluating the systematic and random errors of a measurement system, an algorithm-based validation measurement system was designed. This featured specific systematic and random errors, as illustrated in Fig. 4.

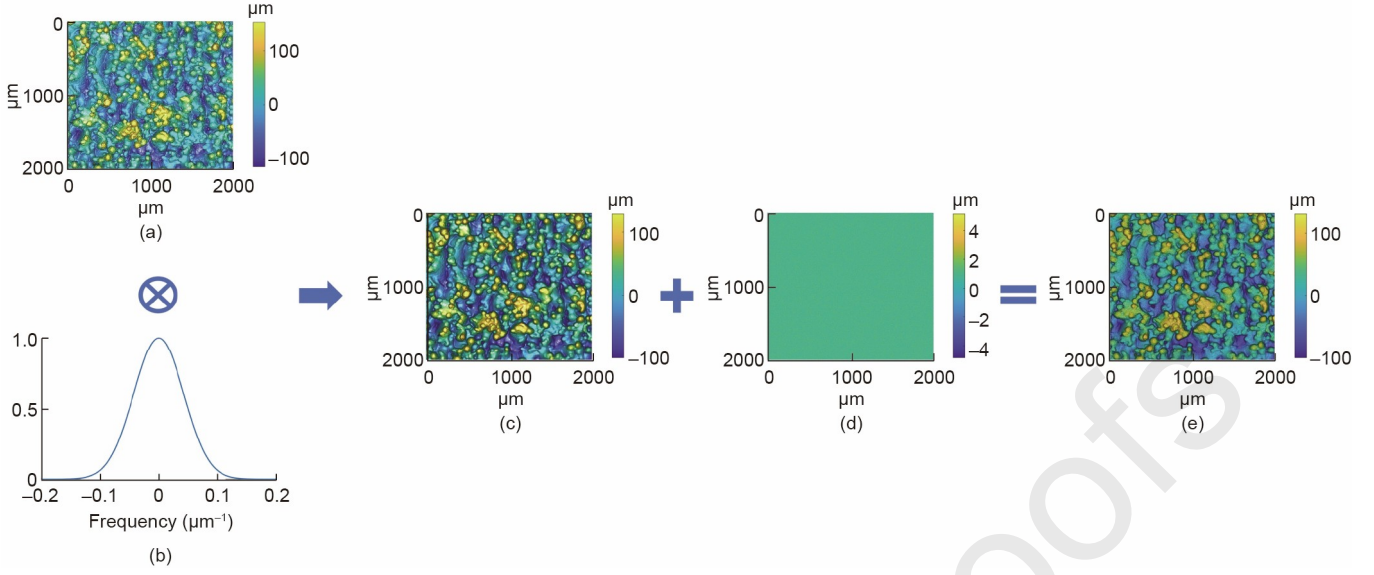


Fig. 4. A designed measurement system for SATF validation with a specified Gaussian filter and specified Gaussian noise. (a) Input surface; (b) Gaussian filter; (c) filtered surface; (d) Gaussian noise; (e) output surface.

In Fig. 4, the FV measured test surfaces Fig. 4(a) serve as the inputs to the validation measurement system and acted as the reference (true) surfaces for SATF calculation. Low-pass filters Fig. 4(b) were applied to the reference surfaces via convolution to represent the total systematic filtering effect. Because the Gaussian filter has an analytical form in both the spatial and frequency domains, it was adopted to enable accurate comparison with the calculated SATF. Additive noise Fig. 4(d) was subsequently applied to the filtered surface Fig. 4(c) to represent random error. According to the central-limit theorem (CLT), the sum of many independent random influences is approximately Gaussian [38], therefore, Gaussian noise was used as the additive noise. The final output is surface Fig. 4(e). SATFs were then calculated using the input and output surfaces. The validation process examines whether the calculated SATF can accurately characterise the specified Gaussian filter and evaluate the specified Gaussian noise. The Gaussian filters considered had cut-off wavelengths (i.e., the wavelength corresponding to 50% transmission) of 10, 20, and 30 μm , referred to as Gaussian filter 1, 2 and 3, respectively. The Gaussian noise was generated using the randn function in MATLAB. To vary the noise level, the generated Gaussian noise was multiplied by 0, 0.1, 1 and 10.

Fig. 5 presents the SATF results obtained using different filters, test surfaces and noise levels. Fig. 5(a) shows the SATFs obtained using test surface A under different filters but with the same noise level. The results show that SATF profiles closely align with the filter profiles at frequencies below a critical turning point. This turning point occurs when the amplitude of the surface components equals the noise components of the measured surface, as indicated by the cross points in Fig. 5(b). Fig. 5(b) shows that, at frequencies above the cross points, the noise component amplitude exceeds the surface component amplitude, indicating that these surface components were not effectively measured and were overwhelmed by measurement noise. Therefore, the turning point of SATF represents the limit of the measurable scale due to random measurement noise. Additionally, the SATF at frequencies above the turning point equals the amplitude ratio of the noise to-reference surface. This result is demonstrated in Fig. 5(a), which shows that the SATFs closely align with the noise-to-reference surface ratio profile. This ratio can be generalised as the random error-to-reference surface ratio for XCT measurement system. The SATF can then be described in detail as:

$$\text{SATF} = \begin{cases} \frac{A_{\text{filtered,surface}}}{A_{\text{reference,surface}}}, & A_{\text{filtered,surface}} \geq A_{\text{random,error}} \\ \frac{A_{\text{random,error}}}{A_{\text{reference,surface}}}, & A_{\text{filtered,surface}} < A_{\text{random,error}} \end{cases} \quad (3)$$

where $A_{\text{filtered,surface}}$ and $A_{\text{random,error}}$ denote the amplitude of the filtered surface in Fig. 4(c) and the Gaussian noise in Fig. 4(d), respectively.

Eq. (3) also indicates that the SATF turning point occurs at the intersection of the systematic filter profile and the random error-to-reference surface ratio profile, as shown in Fig. 5(a). This result suggests that the measurable scale limit is determined by the interplay of the systematic filtering effect, random measurement error and surface characteristic. Figs.

5(c) and (d) illustrate the impact of surface characteristic and noise level on the measurable scale limit, respectively. The results in Figs. 5(a), (c), and (d) show that the measurable scale limit of a measurement system decreases with increasing systematic filtering effect, increasing random error and smoother surfaces. In conclusion, the validation confirms that SATF can accurately characterise the system's filtering effect at frequencies within the measurable surface scale and the random error-to-reference surface ratio beyond this scale.

4.2. Sensitivity analysis of SATF

The accuracy of SATF calculation primarily depends on denoising effectiveness, which is governed by the total number of surface subsamples. For a fixed test-surface area, the number of subsamples varies with the subsample size and the overlap ratio. The sensitivity of SATF accuracy to these two parameters was investigated, as shown in Figs. 5(e) and (f). The SATFs were obtained using the validation measurement system, with test surface A as the input. The same Gaussian filter (cut-off wavelength: 10 μm) and Gaussian noise were applied in all cases. The surface area used for SATF calculation was held constant. Fig. 5(e) compares the SATFs obtained with different surface subsample sizes at a 50% subsample overlap ratio, whereas Fig. 5(f) compares the SATFs obtained with different overlap ratios at a fixed subsample size of 500 μm . The results indicate that SATF accuracy is robust to surface subsample size and overlap ratio. However, a large surface subsample size and a small overlap ratio reduce the number of subsamples available for amplitude averaging, thereby weakening the denoising effect at high frequencies. Because XCT random measurement error varies across measurements and samples, it is recommended to empirically determine an appropriate number of subsamples.

The spectral resolution of calculated SATF depends on the FFT window. Windows with wider main lobes reduce resolution and can blur the estimated surface amplitude, thereby degrading the SATF. To mitigate this, windows that balance narrow main-lobe width with low sidelobes are recommended, such as Hann, Kaiser, Nuttall, and Blackman–Harris. Fig. 5(g) shows the SATFs calculated with these windows. The results indicate that SATF calculation is largely robust to the choice of FFT windows.

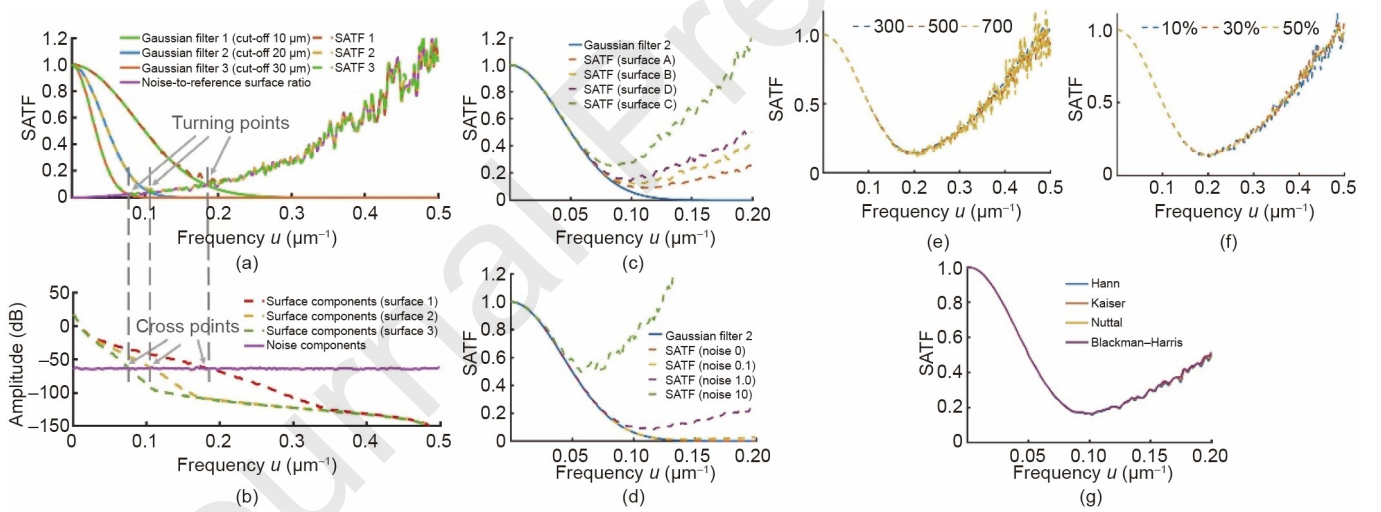


Fig. 5. SATF results obtained with various parameters: Gaussian filters, test surfaces, Gaussian noise levels, subsample sizes, overlap ratios and FFT windows. (a) SATFs obtained using test surface A under different filters but with the same noise level. The profiles of the Gaussian filters, SATFs and the noise-to-reference surface ratio are compared. (b) Amplitude comparison between surface components and noise components on the measured surface from (a). (c) SATFs obtained from different test surfaces under the same filter and noise level. (d) SATFs obtained using test surface A under the same filter but with different noise levels. (e–g) SATFs were obtained using test surface A with a Gaussian filter and Gaussian noise held constant. (e) SATF obtained with different subsample sizes (300, 500 and 700 μm) at a 50% overlap ratio. (f) SATF obtains with different overlap ratios (10%, 30% and 50%) at a fixed subsample size of 500 μm . (g) SATFs computed with different FFT windows.

4.3. Interpretation of the SATF of XCT

Building on the SATF accuracy validation results, XCT measurement errors can be distinguished via SATF analysis. As an example, Figs. 6(a)–(d) shows the 2D SATF of test surface C obtained from the XCT simulation measurement (Measurement 1 in Table 1). At low spatial frequencies (below the turning point), the SATF reveals the XCT system's filtering effect. At higher frequencies (beyond the turning point), SATF characterises the random error-to-reference surface ratio. Additionally, linear interpolation up-sampling introduces periodic errors that manifest as two-peak features

in the SATF map. Up-sampling occurs ① during surface extraction to achieve sub-voxel measurement accuracy and ② during SATF calculation to match the sampling distance of the reference surfaces. Both steps use the linear interpolation algorithms inherent to the surface determination and alignment software. The two-peak features appear at frequencies corresponding to the surface extraction sampling interval and the voxel size, as well as at their integer multiples.

It should be noted that periodic errors introduced by data upsampling depend on the interpolation method. To aid interpretation of the SATF map, Figs. 6(e)–(h) compares SATFs computed without upsampling and with different interpolation methods. Fig. 6(e) shows the SATF of test surface C measured without upsampling, that is, with a sampling distance equal to voxel size ($20\ \mu\text{m}$). Here, the measurable frequency range is limited to $0.1\ \mu\text{m}^{-1}$. Figs. 6(f)–(h) show SATFs of test surface C that were upsampled from 20 to $1\ \mu\text{m}$ using linear, cubic, and spline interpolation in MATLAB. Upsampling extends the measurable frequency range, allowing more surface details to be preserved when sub-voxel surface determined has been performed. Different interpolation methods induce different periodic measurement errors. Linear interpolation produces the strongest periodic artefacts, whereas spline produces the weakest. To assess the impact of these methods on XCT measurement accuracy, the zero-crossing profiles of these SATFs are compared in Fig. 6(i). It shows that linear interpolation introduces an additional surface filtering effect, whereas cubic and spline do not.

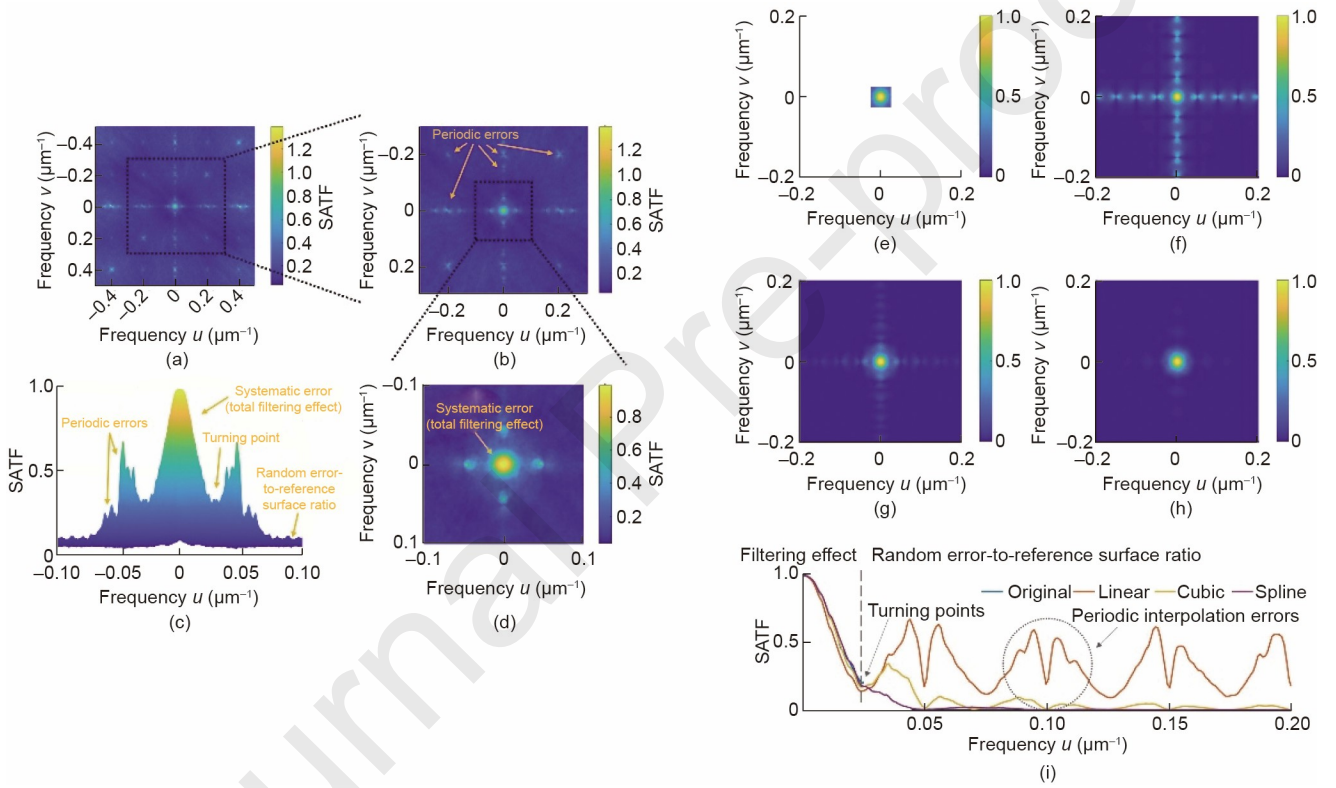


Fig. 6. SATFs of XCT measurement and the impact of surface data interpolation. All SATFs were obtained using test surface C from the XCT simulation measurement (Measurement 1 in Table 1). (a–d) Interpretation of SATF with linear surface data interpolation: (a) top view; (b, d) zoomed top views; (c) side view. (e–i) Sensitivity analysis of SATFs to different interpolation methods: (e) reference SATF (no upsampling, surface sampling distance equals voxel size ($20\ \mu\text{m}$)); (f–h) SATFs computed from upsampled surfaces upsampled from 20 to $1\ \mu\text{m}$ using linear, cubic, and spline interpolation in MATLAB, respectively; (i) zero-crossing profiles of the SATFs.

The linearity, such as, the dependence of XCT measurement error on the input surface, can be interpreted as the consistency of SATFs obtained from different surfaces. The SATF calculation assumes a linear, input-independent measurement system, whereas an XCT system includes both linear and nonlinear influences that need to be reliably identified. Figs. 7(a)–(d) displays the 2D SATF maps of the four test surfaces obtained from the XCT physical measurement (Measurement 2 in Table 1), and Figs. 7(e) and (f) displays the zero-crossing profiles of these SATFs. The results indicate anisotropic errors along the horizontal (the u direction, perpendicular to the sample rotation axis) and vertical (the v direction, parallel to the sample rotation axis) directions. The XCT systematic filtering effect appears approximately linear in the vertical direction but nonlinear in the horizontal direction, potentially due to horizontally dominant effects such as beam hardening effect or BHC.

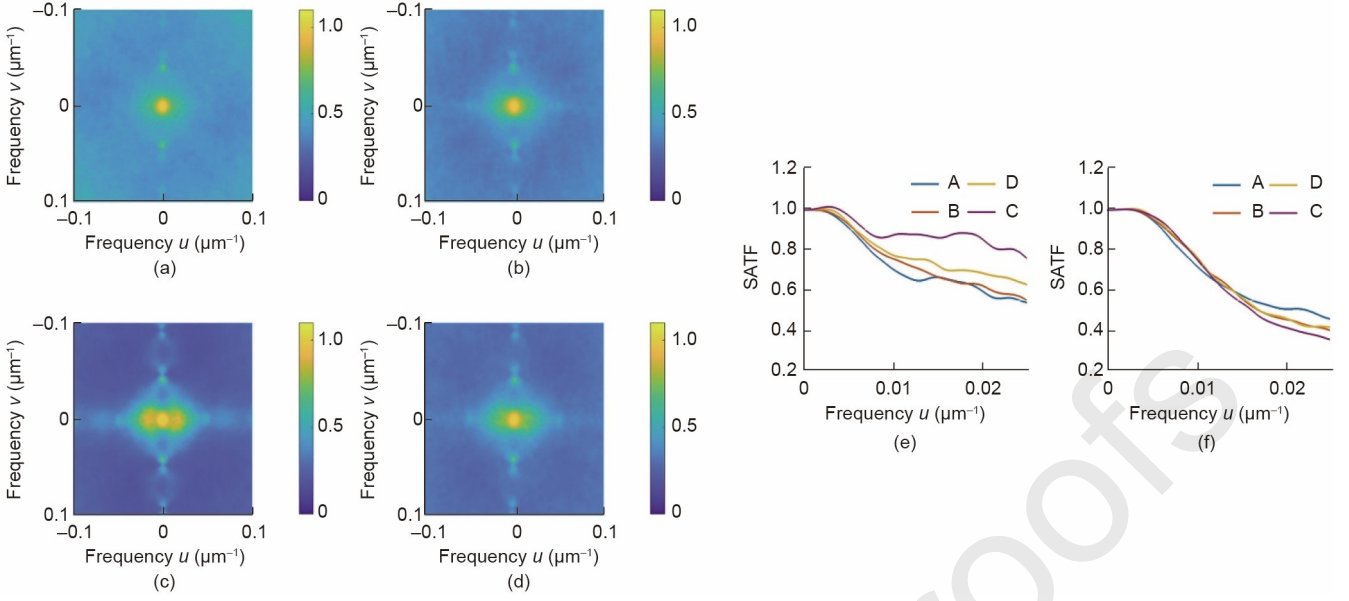


Fig. 7. SATFs of different test surfaces obtained from XCT physical measurement (Measurement 2 in Table 1). (a–d) SATFs of surfaces A, B, C, and D, respectively. (e, f) Zero-crossing profiles of the SATFs along the u and v axes.

5. MSR determination based on SATF

SATF allows the comprehensive determination of MSR by considering not only aspects of the systematic error, as in existing methods, but also aspects of the random error, while examining spatial non-uniformity. $\text{MSR}_{\text{systematic}}$ was determined based on the systematic error, defined as the wavelength corresponding to an SATF threshold value between 0 and 1. $\text{MSR}_{\text{systematic}}$ values in two perpendicular directions can be obtained by fitting the SATF (prior to the turning point) using a 2D characterisation model. In this work, a 2D Gaussian function was employed, expressed as:

$$f(u,v) = \exp\left\{-\ln\left(\frac{1}{p}\right) \cdot \left[\left(\frac{u}{k_u}\right)^{n_u} + \left(\frac{v}{k_v}\right)^{n_v}\right]\right\} \quad (4)$$

where u, v are the spatial frequencies along the x and y axes (in μm^{-1}), n_u and n_v are orders greater than 1, k_u and k_v are the frequencies corresponding to the Gaussian function value p on the u, v axes (in μm^{-1}), and p is the SATF threshold value. The parameters k_u, k_v, n_u , and n_v are obtained during the fitting process. The wavelength $\frac{1}{k_u}$ and $\frac{1}{k_v}$ thus represent the $\text{MSR}_{\text{systematic}}$ values in the two perpendicular directions.

The SATF threshold is not yet standardized. Some studies adopt $p = 0.5$ by analogy with MTF50 [7,10,11], while others argue it should be tailored to the required measurement accuracy [37]. For example, Laquai et al. [37] recommend determining the SATF threshold p by convolving the fitted Gaussian filter with a rectangular surface whose width equals $0.5 \text{ MSR}_{\text{systematic},p}$. Under this criterion, $p = 0.8$ yields more than 98% accuracy for the surface height measurement [37]. In this work, the SATF threshold value was selected based on the robustness of the SATF fitting. SATF fitting is sensitive to the frequency range (0 to the maximum frequency k_c) of the SATF data used. Different choices of k_c produce noticeably different fits, as shown in Fig. 8. Yet the fitting remains stable near a SATF of 0.8. Therefore, the wavelength corresponding to a SATF of 0.8 can be determined reliably, and $p = 0.8$ is recommended.

The $\text{MSR}_{\text{random}}$ was determined according to the random error, defined as the wavelengths corresponding to the turning point of the SATF. $\text{MSR}_{\text{random}}$ values can be qualitatively estimated through visual observation or quantitatively determined using statistical methods. For example, the $\text{MSR}_{\text{random}}$ of the SATF in Fig. 8 was approximated by visual inspection.

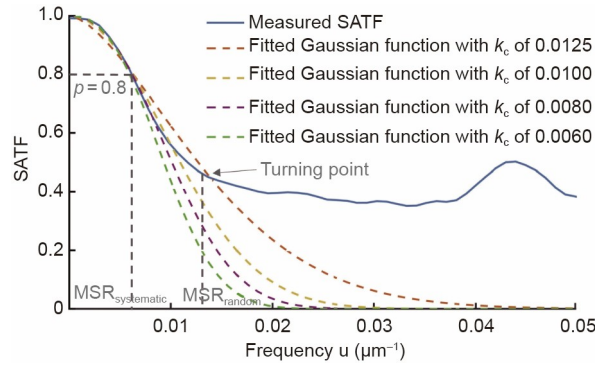


Fig. 8. MSR determination based on the SATF of test surface A obtained from the XCT physical measurement (Measurement 2 in Table 1). $MSR_{systematic}$ was determined by fitting the Gaussian function from Eq. (4) to the SATF data. The maximum frequency of the SATF data used for the fitting was denoted as k_c . Fitted Gaussian profiles with different k_c values were compared. The fitting was robust around the SATF of 0.8, therefore, the corresponding frequency was determined as $MSR_{systematic}$. MSR_{random} was roughly determined through visual observation.

6. Application of the SATF method—a case study

The SATF method allows a thorough investigation of the impact of XCT influencing factors through a complete causal chain. This section presents a case study illustrating the benefits and advantages of this method, specifically investigating the impact of linearisation-based BHC on XCT measurement quality.

Linearisation-based BHC is a crucial part of the correction routine for XCT volume images, addressing the image artefacts caused by the beam hardening effect [32]. While the impact of this factor on volume image quality can be easily qualified and quantified, its impact on surface quality is difficult to assess and predict. This challenge arises because Linearisation-based BHC can both enhance and degrade image quality in different aspects, and there is a lack of methods to comprehensively evaluate surface quality in these corresponding aspects. The unclear impact results in insufficient guidance for choosing the optimal correction strength.

To establish the causal chain, there is a need to figure out the corresponding changes in the surface quality caused by each significant change in the image quality. It is already known from both the literature and our experiment data that linearisation-based BHC increases image sharpness, reduces systematic error and improves $MSR_{systematic}$ [32]. Understanding the relationship between BHC strength and this improvement is critical. However, Linearisation-based BHC also increases image noise, and it's critical to know this impact on XCT random error and the measurable scale limit MSR_{random} . Since beam hardening artefacts primarily manifest as low-frequency structures in the XCT volume image along the horizontal direction (perpendicular to the sample rotation axis), this artifact correction may have different impacts at different frequencies and in different directions. These impacts need to be determined using the 2D SATF method.

To conduct the investigation, the XCT physical measurement data of the test 3DRS sample (Measurement 2 in Table 1) was used. Different levels of BHC strength were applied by varying the linearisation coefficients (a and b parameters of the 2nd order polynomial described in Section 2.4); NBHC (baseline, $a = 1$, $b = 0$), BHC1 (moderate correction, $a = 0.75$, $b = 0.25$), and BHC2 (strong correction, $a = 0.5$, $b = 0.5$). The corrected volume slices are shown in Fig. S2 in Appendix A. It was observed that the BHC1 coefficients provided an appropriate correction strength, whereas the BHC2 coefficients resulted in an over-correction.

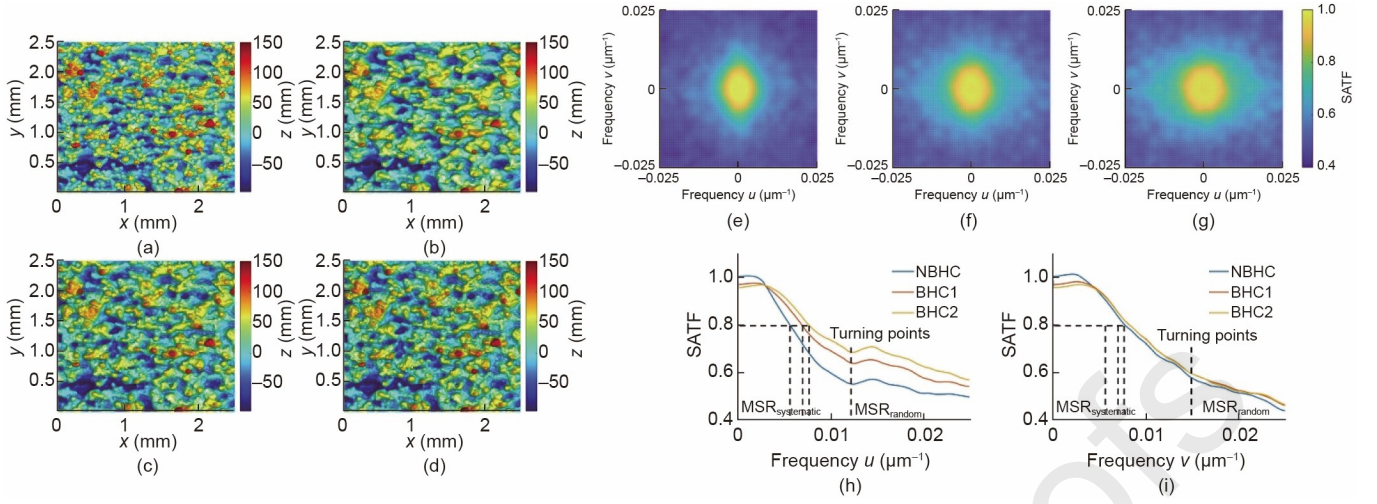


Fig. 9. Impact of linearisation-based BHC strength on surface and SATF. (a–d) Test surface A measured by optical FV and by XCT with different linearisation-based BHC strengths: (a) optical FV; (b) XCT-NBHC; (c) XCT-BHC1; (d) XCT-BHC2. (e–g) Corresponding SATFs: (e) NBHC; (f) BHC1; (g) BHC2. The u direction corresponds to the horizontal direction (perpendicular to the XCT rotation axis), while the v direction corresponds to the vertical direction (parallel to the XCT rotation axis). (h, i) Zero-crossing profiles of the SATFs along the u and v directions.

The resulting surfaces are shown in Figs. 9(a–d). It is visually apparent that the measurement of small structures, such as particles, improved with increasing BHC strength, even with over-correction applied. The resulting SATFs of test surface A are shown in Figs. 9(e) and (f), where a comprehensive and quantitative analysis can be achieved. The non-uniform shape of the SATFs indicates that XCT measurement errors are spatial non-uniform, exhibiting a greater filtering effect in the horizontal direction (the u direction) compared to the vertical direction (the v direction).

In the horizontal direction, the SATF values to the left of the turning points increase with increasing BHC strength, demonstrating the reduction of systematic error and the improvement of $\text{MSR}_{\text{systematic}}$, consistent with findings in existing literature. However, a novel finding is that over-correction (BHC2) can lead to further performance improvements. Additionally, the SATF values to the right of the turning points also increases with increasing BHC strength, confirming the rise in XCT random error due to increased image noise. However, it is noteworthy that the measurable scale limit $\text{MSR}_{\text{random}}$ was not reduced accordingly. In the vertical direction, the SATF changed little, which aligns with the observation that beam hardening effect and linearisation-based BHC primarily affect the data in the horizontal direction. In both horizontal and vertical directions, the low-frequency part (around 0–0.004 μm^{-1}) of the SATF is evidently affected by linearisation-based BHC. Specifically, an amplitude reduction was produced, indicating that an additional systematic error may be introduced on large-scale dimensions by linearisation-based BHC.

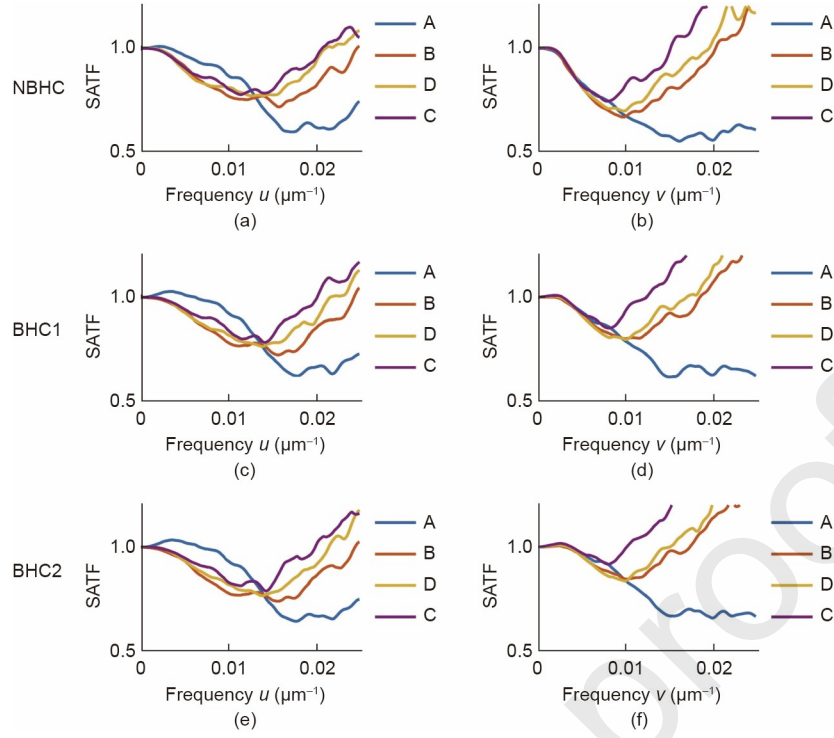


Fig. 10. SATF zero-crossing profiles of the four test surfaces measured with different BHC strengths.

As discussed at the end of Section 4.3, beam hardening (and thus BHC) is horizontally dominant and may be a nonlinear influence. The nonlinearity of the linearisation-based BHC was assessed by examining how the consistency of the SATFs across different surfaces changes with BHC strength, as shown in Fig. 10. The results show that SATF deviations increase as BHC strength increases, indicating that linearisation-based BHC causes a nonlinear impact in the horizontal direction (u direction).

In conclusion, the SATF method enables comprehensive assessment of how variations in image quality propagate to surface quality, thereby establishing a complete causal chain of XCT influencing factors. In the application to investigate the impact of linearisation-based BHC, SATF provides comprehensive, in-depth and novel insights. SATF identifies that linearisation-based BHC induces a nonlinear effect in the horizontal direction and suggests that an appropriate overcorrection strength yields optimal performance improvement.

7. Conclusion

This work has introduced the SATF method for comprehensive evaluation of surface quality in XCT measurement. SATF is grounded in frequency response analysis, computing the SATF of XCT measurement system using a single aperiodic surface. SATF enables the evaluation of both systematic and random measurement errors as well as examination of their spatial non-uniformity in a 2D measurement space. The MSR of an XCT can be determined from both systematic and random error. $MSR_{\text{systematic}}$ is determined as the wavelength corresponding to a SATF of 0.8, whereas MSR_{random} is determined as the measurable scale limit, identified by the turning point of the SATF.

Compared with current methods for evaluating final measurement quality and determining the MSR of an XCT, the proposed SATF method offers the following advantages:

(1) Simple test sample. The method does not require a high precision manufactured or specially designed test sample. Any surface that provides a suitable range of spatial frequency components within the investigated measurement range can be used.

(2) More comprehensive and accurate error evaluation. SATF employs multiple FFT averaging method for denoising. This approach not only provides more effective noise suppression and more accurate evaluation of systematic error but also enables estimation of the random error-to-reference surface ratio and a novel determination of the measurable scale limit. In addition, this denoising strategy makes 2D analysis feasible, allowing examination of the spatial non-uniformity

of XCT measurement errors.

The accuracy of SATF has been validated through an algorithm-based surface measurement system. Results show that the SATF characterises the systematic filtering effect when the amplitude of the measured surface signal exceeds that of the random error signal, and the random error-to-surface signal ratio when the random error signal overwhelms the measured surface signal. The transition between the two parts results in a turning point in the SATF trend, occurring at the frequency where the amplitude of the measured surface signal equals that of the random error signal. This turning point represents the measurable scale limit. Sensitivity analysis further indicates that SATF accuracy is robust to processing-parameter choices.

(3) In-depth system analysis and broad application. SATF can determine the MSR of XCT, quantify the influence of XCT factors and establish a causal chain from image quality to surface quality. This work has briefly illustrated these applications.

The determined MSRs can help assess whether a given XCT machine or measurement configuration is suitable for specific tasks. The impact of XCT influencing factors can be investigated comprehensively. SATF analysis of data interpolation and linearisation-based BHC yielded practical recommendations. Linear interpolation is not recommended because it introduces additional filtering effect, whereas cubic and spline interpolation are preferred due to insignificant information loss and lower interpolation error. For linearisation-based BHC, appropriate overcorrection is recommended to achieve optimal performance improvement. Results also show that changes in image quality can be traced to corresponding changes in final surface quality, making it feasible to establish an image-surface causal chain for measurement prediction and control.

However, although SATF has been validated to theoretically achieve high accuracy, its practical accuracy primarily depends on the accuracy of the reference measurement. In this work, the FV optical surface metrology technique was used as the reference due to its high resolution and high measurement efficiency. However, the impact of FV measurement error on SATF accuracy remains unclear and requires further investigation. In applying SATF to investigate the impact of XCT influencing factors, a linear-effect assumption is made, which cannot fully characterise non-linear influences. Advanced methods to address this limitation will be explored in future work. SATF was proposed to establish a causal chain between projection image quality and final surface quality, and the case study has demonstrated the feasibility of a qualitative image-surface causal chain. Future work will conduct quantitative analyses and assess the feasibility of predicting and controlling final surface quality from projection images.

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References

- [1] Sun W, Symes DR, Brenner CM, Böhnelt M, Brown S, Mavrogordato MN, et al. Review of high energy X-ray computed tomography for non-destructive dimensional metrology of large metallic advanced manufactured components. *Rep Prog Phys* 2022;85(1):016102.
- [2] Villarraga-Gómez H, Herazo EL, Smith ST. X-ray computed tomography: from medical imaging to dimensional metrology. *Precis Eng* 2019;60:544–69.
- [3] Lou S, Brown SB, Sun W, Zeng W, Jiang X, Scott PJ. An investigation of the mechanical filtering effect of tactile CMM in the measurement of additively manufactured parts. *Measurement* 2019;144:173–82.
- [4] Townsend A, Racasan R, Leach R, Senin N, Thompson A, Ramsey A, et al. An interlaboratory comparison of X-ray computed tomography measurement for texture and dimensional characterisation of additively manufactured parts. *Addit Manuf* 2018;23:422–32.
- [5] Dewulf W, Bosse H, Carmignato S, Leach R. Advances in the metrological traceability and performance of X-ray computed tomography. *CIRP Ann* 2022;71(2):693–716.
- [6] VDI/VDE 2630 BLATT 1.3-2011: VDI/VDE 2617 Blatt 13: computed tomography in dimensional measurement—guideline for the application of DIN EN ISO 10360 for coordinate measuring machines with CT-sensors—VDI/VDE 2630 Blatt 1.3: computed tomography in dim. Germany standard. Berlin: VDI; 2011.

- [7] Arenhart FA, Baldo CR, Fernandes TL, Donatelli GD. Experimental investigation of the influencing factors on the structural resolution for dimensional measurements with CT systems. In: Proceedings of the 6th Conference on Industrial Computed Tomography; 2016 Feb 9–12; Wels, Austria. 2016.
- [8] Vanrusselt M, Haitjema H, Leach R, de Groot P. International comparison of noise in areal surface topography measurements. *Surf Topogr Metrol Prop* 2021;9(2):025015.
- [9] Li H, Kingston A, Myers G, Recur B, Sheppard A. 3D X-ray source deblurring in high cone-angle micro-CT. *IEEE Trans Nucl Sci* 2015;62(5):2075–84.
- [10] Wohlgemuth F, Fleßner M, Hausotte T. Determination of metrological structural resolution using an aperiodic spatial frequency standard. In: Proceedings of the International Symposium on Digital Industrial Radiology and Computed Tomography–DIR2019; 2019 Jul 2–4; Fürth, Germany. NDT.net; 2019.
- [11] Arenhart FA, Nardelli VC, Donatelli GD. Characterization of the metrological structural resolution of CT systems using a multi-wave standard. In: Proceedings of the XXI IMEKO World Congress “Measurement in Research and Industry”; 2015 Aug 30–Sep 4; Prague, Czech Republic. 2015.
- [12] Bartscher M, Bremer H, Birth T, Staude A, Ehrig K. The resolution of dimensional CT—an edge-based analysis. In: Proceedings of the 4th Conference on Industrial Computed Tomography (iCT); 2012 Sep 19–21; Wels, Austria. NDT.net; 2012. p. 191–200.
- [13] Zanini F, Carmignato S. Two-spheres method for evaluating the metrological structural resolution in dimensional computed tomography. *Meas Sci Technol* 2017;28(11):114002.
- [14] Fleßner M, Vujaklija N, Helmecke E, Hausotte T. Determination of metrological structural resolution of a CT system using the frequency response on surface structures. *PTB-OAR* 2015;1–10.
- [15] Thompson A, Senin N, Maskery I, Leach R. Effects of magnification and sampling resolution in X-ray computed tomography for the measurement of additively manufactured metal surfaces. *Precis Eng* 2018;53:54–64.
- [16] Muralikrishnan B, Shilling M, Phillips S, Ren W, Lee V, Kim F. X-ray computed tomography instrument performance evaluation, Part II: sensitivity to rotation stage errors. *J Res Natl Inst Stand Technol* 2019;124:124015.
- [17] Jaganmohan P, Muralikrishnan B, Shilling M, Morse E. X-ray computed tomography instrument performance evaluation, Part III: sensitivity to detector geometry and rotation stage errors at different magnifications. *J Res Natl Inst Stand Technol* 2021;126:126029.
- [18] Muralikrishnan B, Shilling M, Phillips S, Ren W, Lee V, Kim F. X-ray computed tomography instrument performance evaluation, Part I: sensitivity to detector geometry errors. *J Res Natl Inst Stand Technol* 2019;124:124014.
- [19] Illemann J, Bartscher M, Jusko O, Härtig F, Neuschaefer-Rube U, Wendt K. Procedure and reference standard to determine the structural resolution in coordinate metrology. *Meas Sci Technol* 2014;25(6):064015.
- [20] Sun W, Chen X, Giusca C, Lou S, Jones CW, Boulter H, et al. Evaluation of X-ray computed tomography for surface texture measurements using a prototype additively manufactured reference standard. In: Proceedings of the 11th Conference on Industrial Computed Tomography (iCT); 2022 Feb 8–11; Wels, Austria. NDT.net; 2022. p. 1–7.
- [21] Sun W, Giusca C, Lou S, Yang X, Chen X, Fry T, et al. Establishment of X-ray computed tomography traceability for additively manufactured surface texture evaluation. *Addit Manuf* 2022;50:102558.
- [22] Bruker Alicona. Optical 3D metrology & surface roughness measurement [Internet]. Graz: Bruker Alicona; 2025 [cited 2025 Aug 15]. Available from: <https://www.alicon.com/>.
- [23] Shovkun VY, Kumakhov MA, Pirshin IV, Gelever VD. Investigation of micro-focus X-ray tube for radiography. In: Kumakhov MA, Hoover RB, editors. X-ray and neutron capillary optics II. Bellingham: SPIE; 2006. p. 59430Z.
- [24] BAM. aRTist-analytical RT inspection simulation tool [Internet]. Berlin: BAM; 2019 Sep 23 [cited 2025 Aug 15]. Available from: <http://artist.bam.de/>.
- [25] Kak AC, Slaney M. Principles of computerized tomographic imaging. Philadelphia: Society for Industrial and Applied Mathematics; 2001.
- [26] Nikon Metrology. Inspect-X for 3D CT reconstruction software [Internet]. Brighton: Nikon Metrology; 2025 [cited 2025 Aug 15]. Available from: <https://www.nikonmetrology.com/en-us/x-ray-ct/x-ray-core-products-and-services-inspect-x-for-3d-ct>.
- [27] Hexagon. VGSTUDIO MAX [Internet]. North Kingstown: Hexagon; 2025 [cited 2025 Aug 15]. Available from: <https://www.volumegraphics.com/en/products/vgsm.html>.
- [28] Yang X, Sun W, Giusca CL. An automated surface determination approach for computed tomography. *NDT& E Int* 2022;131:102697.

- [29] Lifton JJ, Liu T. Evaluation of the standard measurement uncertainty due to the ISO50 surface determination method for dimensional computed tomography. *Precis Eng* 2020;61:82–92.
- [30] CloudCompare.org [Internet]. CloudCompare; 2025 [cited 2025 Aug 15]. Available from: www.danielgm.net/cc/.
- [31] Nikon Metrology. XT H series-helical CT Scanner [Internet]. Brighton: Nikon Metrology; 2025 [cited 2025 Aug 15]. Available from: <https://industry.nikon.com/en-aom/products/x-ray-ct/xt-h-series/>.
- [32] Ahmed O, Song Y. A review of common beam hardening correction methods for industrial X-ray computed tomography. *Sains Malays* 2018;47(8):1883–90.
- [33] Léonard F, Brown SB, Withers PJ, Mummary PM, McCarthy MB. A new method of performance verification for x-ray computed tomography measurements. *Meas Sci Technol* 2014;25(6):065401.
- [34] Prabhu KMM. Window functions and their applications in signal processing. Boca Raton: CRC Press; 2014.
- [35] MathWorks. Makers of MATLAB and Simulink-MATLAB & Simulink [Internet]. Natick: MathWorks; 2025 [cited 2025 Aug 15]. Available from: uk.mathworks.com/?s_tid=gn_logo.
- [36] Lyons RG. Understanding digital signal processing. 3rd ed. Noida: Pearson Education India; 1997.
- [37] Laquai R, Illemann J, Bartscher M, Neuschaefer-Rube U. The metrological structural resolution for dimensional X-ray CT: analysis of the comparability between the CEB and the PBS method. *Meas Sci Technol* 2023;34(8):084002.
- [38] Zhang X, Astivia OLO, Kroc E, Zumbo BD. How to think clearly about the central limit theorem. *Psychol Methods* 2023;28(6):1427–45.
- [39] Mimbs SM. Measurement decision risk-The importance of definitions. In: *Proceedings of the 2008 Measurement Science Conference*; 2008 Mar 10–14; Anaheim, CA, USA. Washington, DC: NASA; 2008. p. 20130012508.
- [40] Thompson A, Senin N, Giusca C, Leach R. Topography of selectively laser melted surfaces: a comparison of different measurement methods. *CIRP Ann* 2017;66(1):543–6.
- [41] Por E, van Kooten M, Sarkovic V. Nyquist–Shannon sampling theorem. [dissertation]. Leiden: Leiden University; 2019.
- [42] Mínguez Martínez A, Gómez Pérez Z, Pérez-Caballero DC, Carcedo Cerezo L, de Vicente y Oliva J. Design of industrial standards for the calibration of optical microscopes. *Materials* 2020;14(1):29.
- [43] Leach R, Haitjema H, Su R, Thompson A. Metrological characteristics for the calibration of surface topography measuring instruments: a review. *Meas Sci Technol* 2021;32(3):032001.
- [44] Danzl R, Helml F, Scherer S. Focus variation—a robust technology for high resolution optical 3D surface metrology. *J Mech Eng* 2011;57(3):245–56.

Declaration of Interest Statement

☒ The authors declare that they have no known competing financial interests or personal

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