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METHODOLOGICAL SUPPORT FOR ACCURATE MEASUREMENT OF GEOMETRIC PARAMETERS OF COMPLEX-PROFILE PARTS IN MECHANICAL ENGINEERING

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Abstract. *This paper proposes a methodological framework for accurate measurement of geometric parameters of complex-profile parts in mechanical engineering. The approach links GD&T requirements to a controlled workflow covering measurand definition, datum strategy, sampling design, alignment, and standardized data processing. Key uncertainty sources across the full measurement chain are systematized, and validation procedures are outlined to establish traceability and performance under industrial conditions. Uncertainty-aware conformity rules are emphasized to improve reliability near tolerance limits.*

Introduction

Accurate measurement of geometric parameters of complex-profile parts is a critical requirement in modern mechanical engineering, because such parts often determine the functional performance, reliability, and interchangeability of assemblies. Typical examples include turbine blades, impellers, molds and dies, medical components, and parts produced by additive manufacturing. Their geometry is characterized by freeform surfaces, variable curvature, thin edges, and functional regions that cannot be verified adequately by simple linear measurements. In these conditions, geometric inspection becomes a decision-making tool that directly affects process correction, acceptance of parts, and the prevention of costly rework.

In industrial practice, measurement accuracy is frequently associated with the nominal capability of the instrument, for example the class of a coordinate measuring machine or the resolution of an optical scanner. However, for complex-profile geometry the dominant factor is the measurement methodology. The reported result depends on how the measurand is defined, how datums and coordinate systems are established, how sampling points are distributed, how the part is fixtured and thermally stabilized, and how alignment and surface reconstruction are performed in software. The same part may yield different deviations depending on whether a datum-based alignment or a best-fit strategy is applied, or on how dense and where the measurement points are taken. Therefore, without a structured methodological framework, measurements of complex profiles may be reproducible in a narrow sense yet still insufficiently reliable for conformity assessment.

The aim of this paper is to develop a methodological approach that ensures accuracy and traceability in measuring geometric parameters of complex-profile parts in mechanical engineering. The paper systematizes the main uncertainty sources across the full measurement chain and formulates an applied workflow for planning, executing, validating, and reporting measurements under industrial conditions. Section 1 presents the metrological and methodological foundations of complex-profile geometry measurement, while Section 2 proposes an industrial framework for measurement planning, validation, and uncertainty-aware conformity decisions.

Metrological and Methodological Foundations for Complex-Profile Geometry Measurement

Accurate measurement of complex-profile geometry in mechanical engineering requires a methodological foundation that links design intent to measurable quantities and ensures that results are traceable and suitable for conformity decisions. Complex-profile parts typically include freeform surfaces, variable-curvature regions, blended transitions, thin edges, and multi-feature geometries where local deviations can strongly influence performance. The metrological difficulty lies not only in acquiring data, but in defining what exactly is being measured, how the geometry is referenced, and how the result is computed from the raw observations.

The primary requirement is a precise definition of the measurand. In practice, the measurand is a specific geometric characteristic derived from the real surface, for example profile deviation relative to a nominal curve, form error of a freeform surface, positional or orientation tolerance relative to functional datums, local thickness, or edge radius. This definition must be consistent with GD&T requirements and must explicitly specify the datum structure and the coordinate system. For complex profiles, the alignment strategy becomes part of the measurand definition. Datum-based alignment supports functional assembly intent, whereas best-fit alignment can reduce apparent deviations by redistributing errors. Neither is universally correct, so the chosen alignment must be justified by the function of the feature and the tolerance specification.

The second methodological element is the selection of measurement technology and its implications. Tactile coordinate measuring machines provide strong traceability but depend on stylus configuration, probing direction, access limitations, and sampling strategy. Optical scanning offers high data density and speed, yet it is sensitive to reflectivity, slope, occlusion, and registration quality, and its results strongly depend on processing algorithms. Computed tomography enables inspection of internal features but introduces voxel-related limitations, material artifacts, and segmentation uncertainty. Therefore, the measurement method must be selected based on tolerance level, surface and material properties, accessibility, and whether the critical features are external or internal.

The third element is systematic identification of uncertainty sources. Instrument-related components include calibration uncertainty, volumetric errors, probing system effects, and thermal drift. Setup-related components include fixturing stability, part deformation under clamping, and thermal gradients between the part and the environment. Method-related components are often dominant for complex profiles. Sampling density and distribution determine whether local deviations are captured and whether the surface is reconstructed robustly. Sparse sampling may miss critical zones, while excessive uniform sampling may increase time without improving decision reliability. For freeform surfaces, sampling should be functionally driven, emphasizing curvature transitions, interfaces, and regions with high sensitivity.

Alignment and data processing form another major uncertainty mechanism. Registration of multiple scans, outlier removal, smoothing, surface fitting, and the computation of deviation maps are not neutral steps. Different software settings or optimization constraints can lead to different reported deviations even for identical raw data. This is particularly critical for best-fit alignment, where the chosen criterion can shift the reference system and redistribute deviations. Consequently, methodological support must include explicit rules for alignment and processing, as well as strict documentation of settings to ensure comparability across instruments and sites.

A robust foundation also links measurement strategy to conformity assessment. For complex-profile parts, decisions are often made near tolerance limits, and uncertainty directly affects the risks of false acceptance and false rejection. Therefore, uncertainty evaluation should guide method selection, sampling design, alignment constraints, and validation effort rather than being treated as a formal appendix.

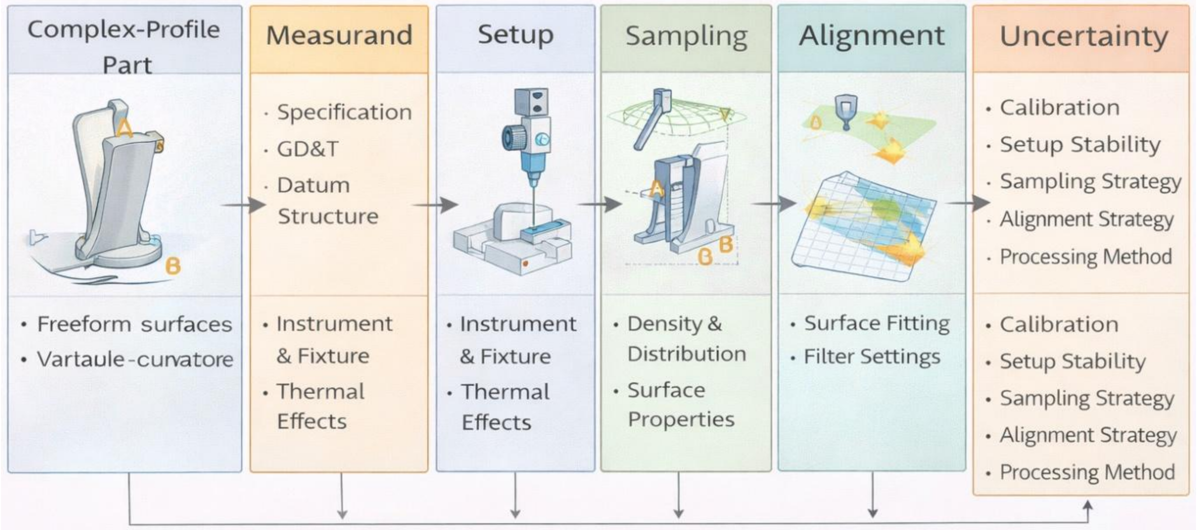

Fig. 1. **Measurement accuracy formation for complex-profile parts: measurand, setup, sampling, alignment, processing, and uncertainty**

In summary, measurement accuracy for complex profiles is determined by an integrated methodological framework combining measurand definition, datum strategy, technology selection, controlled sampling, disciplined processing, and uncertainty-aware interpretation.

Applied Framework: Planning, Execution, Validation, and Conformity Assessment

Accurate inspection of complex-profile geometry in industrial practice requires an applied framework that converts design requirements into a controlled measurement workflow with documented traceability and uncertainty-aware decisions. The framework starts with requirement translation. GD&T specifications must be converted into measurable characteristics by defining the target features, datum structure, coordinate system, evaluation criterion, and acceptance rule. At this stage, it is essential to clarify whether functional datums must dominate alignment, or whether a constrained best-fit is permissible for the specific feature. The outcome is a measurement model that links the specification to the data that will be acquired and processed.

Measurement planning follows and typically determines the final reliability of results more than instrument class alone. The selection of technology should be based on tolerance level, accessibility, surface condition, and production constraints. Tactile CMM measurement is preferred when traceability and low uncertainty are critical and access is available, while optical scanning is effective for dense coverage of freeform surfaces but requires careful control of reflectivity, occlusion, and registration. CT may be justified when internal features or assembled geometries are critical, but its voxel size and artifact behavior must be matched to the tolerance. Planning also includes fixture design to ensure stable referencing without deforming the part, definition of thermal stabilization conditions, and selection of measurement volume and probing or scanning parameters. The sampling plan is central for complex profiles. Instead of uniform sampling, the point distribution should be functionally driven and concentrated in curvature transitions, interfaces, and regions with high sensitivity to deviation. Where feasible, adaptive sampling can be applied by increasing density in zones where preliminary measurements indicate higher gradient or larger deviation.

Execution should be treated as a controlled procedure rather than a routine acquisition step. Before data collection, instrument status verification and environmental checks must be completed. During acquisition, data quality indicators should be monitored, including probe hit quality, scan completeness, signal saturation for optical systems, and repeatability of key reference features. When multi-position setups are required, a documented referencing strategy must be applied to avoid hidden alignment drift between setups. Data processing must be standardized. Registration, outlier removal, smoothing, surface fitting, and deviation computation should be performed with fixed and documented settings, because algorithmic variation can shift results and reduce comparability. For complex profiles, alignment is the most sensitive computational stage. Datum-based alignment should be used when the specification is functionally datum-driven, while constrained best-fit may be applied only when justified, with explicit constraints and objective functions documented.

Validation is necessary to demonstrate that the workflow meets the accuracy requirements of the task. It should combine reference artefacts and part-based validation. Certified artefacts support periodic checks of volumetric performance, while a reference part representative of the actual geometry and surface condition reveals application-specific effects. Repeatability and intermediate precision studies should include repeated measurements, repositioning, and operator variation. Where feasible, cross-validation against an independent method, such as tactile CMM versus optical scanning for critical features, improves credibility and helps detect systematic biases associated with surface interaction or processing assumptions.

Uncertainty evaluation must be integrated into validation and reporting. Type A components are derived from repeated measurements, while Type B components are obtained from calibration data, instrument specifications, thermal effects, fixture influence, and processing sensitivity. The result is an expanded uncertainty for key characteristics, which becomes the basis for conformity assessment. For decisions near tolerance limits, explicit decision rules should be applied to manage false acceptance and false rejection. Guard bands provide a practical mechanism for incorporating uncertainty by narrowing the acceptance interval in a transparent way. This approach improves decision defensibility and reduces disputes when measurement results are borderline.

In summary, the applied framework for complex-profile measurement integrates requirement translation, method and sampling design, disciplined execution, validated processing, and uncertainty-aware conformity decisions. When implemented as a unified workflow, it strengthens traceability, improves comparability of results across instruments and sites, and supports reliable quality control for complex-profile parts in mechanical engineering.

Conclusion

Accurate measurement of complex-profile geometric parameters depends primarily on methodological support rather than on instrument specifications alone. A defensible result requires an explicit measurand definition, functionally justified datum and alignment strategy, and a sampling plan aligned with curvature transitions and critical interfaces. Standardized processing settings and task-specific validation are essential because registration and fitting algorithms can materially affect reported deviations. Uncertainty-aware conformity assessment, including clear decision rules near tolerance limits, reduces false acceptance and false rejection and improves the reliability of industrial quality decisions.

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