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Status and Prospects of Skin Model Shapes for Geometric Variations Management

Benjamin Schleich[a,*], Nabil Anwer[b], Luc Mathieu[b], Sandro Wartzack[a]

[a] *Chair of Engineering Design KTmfk, Friedrich-Alexander-University Erlangen-Nürnberg, Martensstraße 9, 91058 Erlangen, Germany*
[b] *LURPA, ENS Cachan, Univ Paris Sud, Université Paris-Saclay, 61 Avenue du Président Wilson, 94235, Cachan, France*

[*] Corresponding author. Tel.: +49-(0)9131-85-23220; fax: +49-(0)9131-85-23222. *E-mail address:* schleich@mfk.fau.de

Abstract

Geometric part deviations, which are inevitably observed on every manufactured workpiece, have distinct effects on the assemblability as well as on the function and quality of physical artefacts. As a consequence, geometric variations management is an important issue for manufacturing companies. However, assessing the effects of form deviations already in virtual product realization remains an important challenge. This paper illustrates and summarizes the current status and development trends of the Skin Model Shape paradigm, which provides an operationalization and a digital representation of the Skin Model concept for modelling product shape variability and hence may serve as a comprehensive model for computer-aided variations management.

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1. Introduction

In times of fierce international competition and high requirements on the quality of mechanical products, there exists a necessity for companies to manage geometric variations along the whole product life-cycle as they distinctly affect the function and quality of mechanical assemblies [1]. In order to perform this within time and costs, computer-aided tolerancing tools support product and process development by enabling the early prediction of the effects of geometric part deviations on assembly characteristics without the need for cost and time expensive physical mock-ups. However, these established tools and their underlying mathematical approaches for the representation of geometric deviations, geometric specifications, and geometric requirements imply severe shortcomings regarding the consideration of form deviations and lack of a full conformance to international standards for the geometrical product specification and verification (GPS). With the aim to overcome these drawbacks, the concept of Skin Model Shapes has been developed, which is based on the Skin Model as a core concept of modern GPS standards and employs discrete geometry representation schemes for the representation of part geometry considering all different kinds of geometric deviations.

The aim of this paper is to present the current status as well as prospects and development trends regarding this model, where the main contribution lies in the comprehensive summary of the current development status. In this context, particularly the usefulness of Skin Model Shapes for the tolerance analysis is highlighted. The paper is structured as follows. In the next section, a brief state of the art regarding the virtual representation of geometric deviations and tolerances for computer-aided tolerance analysis with a focus on the consideration of form deviation modelling is given. Thereafter, the evolution as well as the fundamentals of the concept of Skin Model Shapes are presented. Following this, the current development status regarding the tolerance analysis based on this novel concept is highlighted and the results for an illustrative case study are discussed. Subsequently, future prospects and development trends are illustrated. Finally, a conclusion and an outlook are given.

2. Related Work

The modelling of product geometry employing computer models has gained vast attention during the last decades and the functionalities of modern computer-aided design tools have steadily increased. However, the underlying mathematical models for the representation of part geometry in these tools are suitable for modelling nominal part geometry, but imply shortcomings regarding the representation of form deviations, which are inevitably observed on every manufactured part. This

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also holds for most of the established approaches for the tolerance analysis such as the Small Displacement Torsor (SDT) [2], solid offsets [3], vector loops [4] and based thereon the direct linearization method [5], Deviation Domains [6], Polytopes [7], and T-Maps® [8], where their main shortcomings are the insufficient consideration of form deviations and the lacking conformance to international standards for the GPS [1,9].

However, the researches on form deviations modelling have adapted two main approaches. The so-called decomposition or separation methods use signal processing theories and spectral methods such as Direct Cosine Transfom, Discrete Fourier Transform, and Discrete Modal Decomposition to represent form deviations and errors as the first variation modes [10–12]. Despite their broad usefulness, they are limited to simple shapes such as planes and cylinders. Taubin [13], Vallet and Lévy [14] addressed spectral decomposition methods for general topological manifolds and used the Laplace-Beltrami Operator to solve the problem. This approach is also well adapted to discrete shapes and mesh-based representations. The other approaches for form deviations modelling use a deformation of morphing models to represent form deviations and errors [15]. The deformation can follow a physical law (elastic deformation, mass-spring, particle systems,...) or geometric considerations. Mesh deformation or morphing methods have been developed for non-rigid part tolerance analysis using free form deformation approaches [15] and FEA methods [16,17]. Other researches highlighted the non-deterministic or stochastic nature of form errors and deviations from the consideration of manufacturing processes and measurement characteristics [18]. Variability Analysis and reduction techniques such as Principal Component Analysis (PCA) have also been used to establish analytical models that highlight form deviations [19–22]. More recently, Statistical Shape Analysis techniques have been used to represent different kinds of geometric deviations from the observation and measurement of manufacturing processes and from simulation [23–25].

3. The Concept of Skin Model Shapes

As a response to the shortcomings of established models for the computer-aided modelling and representation of part geometry considering geometric deviations, the concept of Skin Model Shapes has been developed [25,26]. It is based on the Skin Model, which is a fundamental concept of modern standards for the geometrical product specification and verification and can be regarded as a model of the physical interface between a part and its environment [27]. The Skin Model concept was developed by Ballu and Mathieu [28] and is a purely conceptual, infinite model in order to allow the consideration of all kinds of geometric deviations and to enable the unambiguous definition of geometrical specifications.

As the Skin Model is an infinite model in order to allow the consideration of all different kinds of geometric deviations, it can neither be identified nor simulated. In contrast to that, Skin Model Shapes are specific outcomes of the Skin Model employing discrete geometry representation schemes, such as point clouds and surface meshes, which can hence serve as part representatives in simulations and virtual mock-ups. The difference between the nominal model, the Skin Model, and the concept of Skin Model Shapes can be seen from Fig. 1.

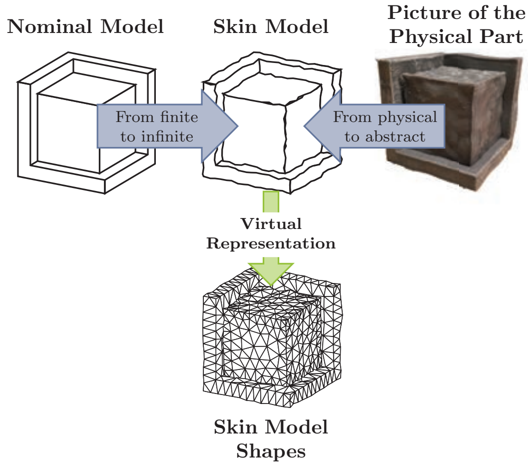

Fig. 1. The Skin Model and the Concept of Skin Model Shapes.

4. The Current Status of the Skin Model Shape Paradigm for Tolerance Analysis

The concept of Skin Model Shapes is a quite novel approach for the representation of part geometry considering geometric deviations. As it enables the representation of parts and assemblies considering deviations at different levels, such as macro, micro, or nano, it can be used for many applications in the context of virtual product realisation. However, as tolerance analysis is a key tool for supporting the tolerancing activities in design [26], the focus of ongoing research works is to enable the tolerance analysis based on Skin Model Shapes. In the following, the main procedure for the tolerance analysis based on Skin Model Shapes is highlighted and every stage of this procedure is detailed. The case study comprises three parts as can be seen from Fig. 2, where a beam is positioned on a base part according to a 3-2-1 positioning scheme [29] (three-point move in negative z-direction, two-point move in negative x-direction, and one-point move in positive y-direction), and a pin is assembled to the beam with "best-fit" condition. The single parts are specified by geometric tolerances and dimensional tolerances with material modifier as can be seen from Fig. 2 and the functional key characteristic of the assembly is the position deviation pos of the pin with reference to the datum system spanned by the base part. Worst-case and statistical tolerance analyses for the case study have been performed with and without consideration of form tolerances, respectively. For the worst-case analyses, the parts conform to the (maximum) specified tolerances but are randomly assembled, whereas Gaussian input probability densities for the tolerances as can be seen from Fig. 3 have been assumed for the statistical analyses. The procedure of the tolerance analysis based on Skin Model Shapes as well as the results of the analyses are highlighted and discussed in the following sections.

4.1. *Procedure for the Tolerance Analysis based on Skin Model Shapes*

The tolerance analysis based on Skin Model Shapes can roughly be divided in a pre-processing, a processing, and a post-processing stage [30] (see Fig. 4). In the pre-processing