



Research paper

Gap hull estimation for rigid mechanical joints considering form deviations and multiple pairs of mating surfaces

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ABSTRACT

The embodiment of mechanical joints is a demanding activity during the design of mechanism. In this context, particularly the assessment of the effects of geometrical deviations on the behaviour of the mechanical joint is of strong importance. This paper presents an approach to the gap hull estimation for mechanical joints considering form deviations. The novelty of this approach lies in the ability to analyse the behaviour of mechanical joints considering multiple pairs of mating surfaces. The application of this method to a prismatic as well as to a cylindrical joint prove the versatility of the method regarding different kinds of joints with multiple pairs of contact surfaces. Moreover, the results of the application of this approach to the tolerance analysis of a two-pin-two-hole assembly confirm the importance of considering form deviations in the tolerance analysis and in the design of mechanical joints and mechanism.

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1. Introduction

The embodiment of mechanical joints is both a highly demanding and responsible activity during the design of mechanism and machines. In this regard, the complexity of this activity particularly arises from the fact, that clearances play an important role in the behaviour of mechanical joints and thus influence the behaviour of the final product during use [1]. In order to predict these effects, models for the estimation of the gap hull, which can be considered as the set of all physically feasible rigid body transformations of a mechanical joint with clearance [2], are required. In this regard, the gap hull “represents the displacement space characterizing all possible relative displacements in a joint” [3]. The knowledge of the effects of different part deviations on the behavior of the mechanical system is of importance for the adequate design as well as dimensioning and tolerancing of the single parts. Thus, the gap hull estimation is of vital importance in the design and assessment of mechanical joints. Indeed, the assessment of the effects of individual geometrical part deviations on the behaviour of mechanical assemblies is indissolubly related to the issue of tolerance analysis. In general, tolerance analysis can be understood as an activity aiming at virtually predicting the effects of geometrical *specifications* on assembly or product key characteristics by building, evaluating, and interpreting adequate mathematical models for the representation of geometrical specifications as well as for their accumulation. In a wider sense, tolerance analysis and variation simulation also comprise the assessment of the effects of geometrical *deviations* on the product quality [4]. Until today, a wide variety of tolerance analysis approaches has been presented in scientific literature. In this regard, for example the following tolerance analysis methods have been presented: tolerance stacks and parametric tolerance analysis methods (for details see e. g. [5]),

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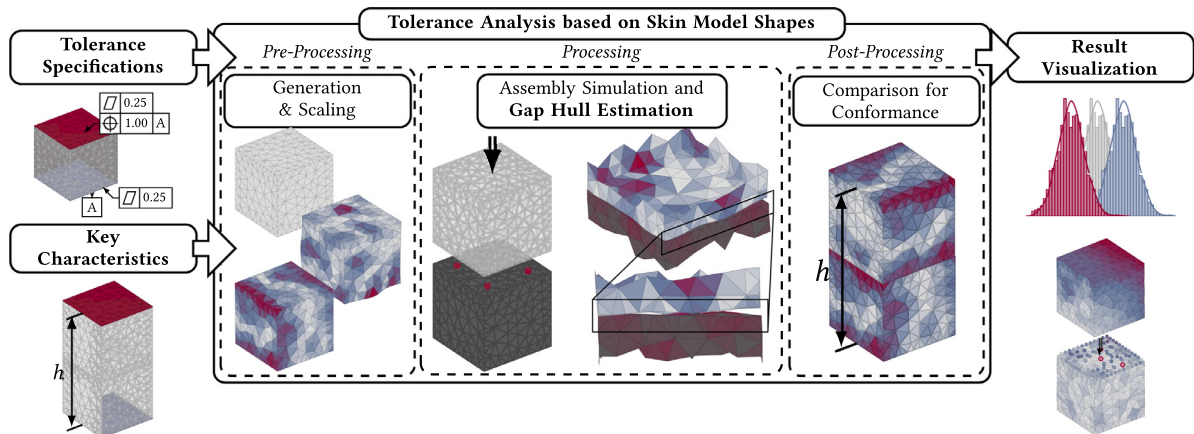


Fig. 1. Overview of the general framework for the tolerance analysis based on Skin Model Shapes acc. to [31,49].

variational solid models [6], tolerance envelopes [7], the vector loop approach and based thereon the direct linearization method [8,9], the matrix approach [10,11], the torsor method [12], deviation domains [13], polytopes [14], Tolerance-Maps® [15], the Jacobian [16] and the Jacobian-Torsor method [17], the analysis line approach [18,19] and constraint-solving methods [20]. Beside this, a considerable number of review papers is available (see e. g. [5,15,21–26]). Moreover, there exists a number of commercial tolerance analysis and tolerance simulation software tools, where reviews of the most common ones can e. g. be found in [15,22,27]. However, the established tolerance analysis methods, which also form the basis of commercial computer-aided tolerancing tools, lack a comprehensive consideration of form deviations and are consequently not fully conform to international tolerancing standards [28], such as the ASME Geometric Dimensioning & Tolerancing (GD&T) and the ISO Geometrical Product Specification (GPS) standards. As an answer to these shortcomings, the concept of Skin Model Shapes, which refers to the use of point-based models in the tolerance analysis, has been developed [29–31] and has been adopted by a considerable number of researchers (see e. g. [32–35]).

Beside the general issue of tolerance analysis, particularly the consideration of joint clearance in the design and dimensioning of mechanical joints and mechanism is a steady research topic. In this context, the concept of the clearance space [2,36] has been proposed to describe and represent clearances in mechanical assemblies. Furthermore, for example the effects of joint clearances on the position and orientation deviation of linkages have been studied in [37,38], a kinematic sensitivity analysis of linkages with joint clearance has been performed in [39], and a clearance influence analysis is described in [40]. Moreover, a comparison of revolute joint clearance models is provided in [41], whereas computer models for the dynamic analysis of multibody systems with joint clearance is presented in [42], and a robust tolerance design for mechanism with joint clearance is presented in [43].

Indeed, few works consider form deviations of the mating parts in the analysis of joint clearance. In this regard, form defects of a single pair of mating surfaces in a planar joint have been analysed in [3] employing the concepts of the gap hull and the difference surface [44]. Moreover, a bijective relationship between these concepts has been derived in [3].

However, the main shortcoming of these aforementioned methods is that they do not consider multiple pairs of mating surfaces in the gap hull estimation. This leads to an overestimation of the gap hull in that sense that part positions are considered, which are physically not feasible. As a response to this, an approach to the gap hull estimation for rigid mechanical assemblies based on the concept of Skin Model Shapes considering form defects of multiple pairs of mating surfaces is presented in the following. It employs and strongly extends the fundamental background provided in [3] and supports the design of mechanical joints as well as their geometrical specification. The method is capable of considering deviations of form, orientation, and location of the mating parts, but does not aim at considering tribological phenomena, such as the dry contact between rough surfaces, friction, lubrication, and wear, which are typically neglected in tolerance analysis.

The paper is structured as follows. In the next section, the general approach to the gap hull estimation is presented. It is then applied to a prismatic and a cylindrical joint as well as to a two-pin-two-hole assembly. Thereafter, the gap hull estimation approach is critically discussed. Finally, a conclusion and an outlook are given.

2. Novel approach to the gap hull estimation

2.1. Overview of the general framework for the tolerance analysis based on skin model shapes

The overall framework for the tolerance analysis based on Skin Model Shapes is shown in Fig. 1. It starts with the generation of deviated workpiece representatives using methods for the deviation modelling based on predictions about expectable part deviations in early design stages (prediction stage) or employing approaches of statistical shape analysis based on observations (manufacturing process simulation results or measurement data) in later design stages (observation stages) [29].

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