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CONCEPT FOR TOLERANCE DESIGN IN EARLY DESIGN STAGES BASED ON SKELETON MODELS

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ABSTRACT

A noticeable trend in mechanical industry is that the product lifecycle and within the product development phase shortens. One consequence is the necessity to perform product-analyses already in early design stages, even if the geometry of the product is only sketchy defined by skeleton models. For product functionality the dimensional and geometric variations of the product components play an important role, which are analyzed and limited by tolerancing. The lack of geometric information in the early design phase is challenging for tolerance analysis, but also offers chances by more flexibility of the product developer in changing the products geometry. Therefore, this paper presents the concept to perform tolerance design based on skeleton models.

Keywords: tolerance design, contributor analysis, early design phases, computational design synthesis

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1 INTRODUCTION

According to shortened product lifecycles, mechanical industry companies try to shorten the product development phase. As a consequence product-analyses should be performed as early as possible. For the functionality of a product and its components, dimensional and geometric variations play an important role. Tolerance analyses examine the influence of these variations on the functionality of the product. Usually tolerance analysis is performed, when the final geometry of the product is modeled. First, this paper examines which information is necessary for tolerance analysis and identifies the earliest stage of the product development process where tolerance analysis can be performed. In a next step, the capabilities of actual tolerance analysis software tools are compared, which delimit the following methodology. Furthermore, the possibilities which open up for tolerance analysis in early stages are detailed: comparison of small components with different operating principles for the same purpose and (restricted) flexibility in dimensioning. The framework closes with reflections about the functional geometric requirements (FGR), which are the bottleneck for performing tolerance analysis in the conceptual design stage. The complied conceptual idea extends the tolerance analysis by a previously performed geometric analysis, based on the method of Caro et al. (2005) and a feature based global sensitivity analysis method. The paper closes with a conclusion.

2 FRAMEWORK

Table 1. List of Abbreviations and Symbols

Abbreviation	**Explanation**
(F)KC	(Functional) key characteristic – characteristic of the product, which describes a function of the product, usually a geometric feature
FGR	Functional geometric requirement – requirements on the FKC, usually described by tolerances
FF	Functional feature – feature which has to fulfill the functional geometric requirements
SDT	Small displacement torsor – Concept to describe position and form deviations of surfaces
DOF	Degree of freedom
API	Application programming interface
Symbol	**Explanation**
RI_2	Robustness Index, based on the Jacobian-matrix's 2-norm of the function f – describes the general sensitivity of the functional feature to small disturbances
Ω_{FF}	Functional domain – stack-up of the clearance and deviation domains of all considered clearances and tolerated features
Ω_{FR}	Deviation domain of the functional feature – formulation of the functional requirements in means of the deviation domain approach

2.1 Tolerance management

During manufacturing, the real product geometry always varies from the nominal geometry. Additional product geometry variation effects of assemblies arise from variations in the interface positions between its components (e.g. fixture points). The products geometry is closely related to the functionality of the product. To ensure the functionality, functional product requirements have to be translated into functional geometric requirements of the product, which are restrictions for the accepted geometrical product variations.

Tolerance management is the process of restricting and analyzing the products variations to ensure that the product meets the functional geometric requirements (Dantan et al., 2009). The functional geometric requirements are restrictions to particular geometry elements (e.g. the axis of a screw hole) to a datum element (e.g. the surface of a flange). The restricted geometry element is commonly called functional key characteristic (FKC). This approach bases on features, so the functional key characteristics are mapped to so called functional features (FF). The geometric product variations are composed from a lot of single variations, due to the separate manufacturing and assembly steps. The chain of considered varying geometry elements of the product is called tolerance chain in the following. The main task of tolerance management today is therefore to identify the main contributing deviations (resulting in variations of the FF) and to control them.

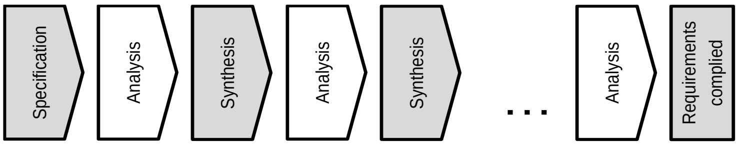

Figure 1. Tolerance Management Process

Commonly, tolerance management is performed in the later stages of the product development process, according to Pahl and Beitz (1996) the detail design. This placement comes from the comprehension of tolerancing as a detail determination and control process of the product geometry, after determining all dimensions. Tolerance management consists of three different steps: tolerance specification, tolerance analysis and tolerance synthesis, as seen in figure 1. The tolerance specification is the first step, where the product developer restricts single dimensions with the aim, to ensure the functional geometric requirements are fulfilled. The next two steps are an iterative process: first, tolerance analysis is performed to evaluate the chosen tolerances. The tolerance analysis can integrate information from different stages of the product lifecycle (Wartzack et al., 2011). If the functional feature meets the functional geometric requirements and additional aspects like manufacturing costs are satisfied, the tolerance management is finished. If not, the tolerances are amended, which is called tolerance synthesis.

2.2 Skeleton models

According to Vajna et al. (2009), there are several challenges (e.g. globalization) for companies in modern product development. These challenges force companies to ensure a product's functionality in earlier stages of product development, what also affects tolerance management. For performing a tolerance analysis, three kinds of geometric information about the product are necessary:

- Geometrical product structure
- Space claim of single structure elements
- Interface constraints between the structure elements (e.g. fixture type and position)

To identify the earliest possible design stage, actual product modeling has to be considered. According to Vajna et al. (2009) the current modeling practice in companies is based upon a top-down design approach. Top-down design consists of considering the product structure as hierarchical, where critical information is placed in a high-level location and then communicated to lower levels of the product structure (Sciortino, 2005). Therefore, three main tasks of top-down design are: defining the products hierarchy, identifying the highest associated hierarchical element for all critical information and ensure the communication of critical information to lower levels. The product's geometry reflects these facts. Assemblies as well as sub-assemblies and components can have a skeleton model (Bossmann, 2007). In a top-down design environment critical design information is stored in a so-called skeleton file (Sciortino, 2005). It contains the product structure, space claims of single components and interface locations. Generally, skeleton files contain non solid elements like points, curves, planes or coordinate systems, which represent the product's skeletal geometry, the behind-the-scenes backbone of its structure in space, as seen in figure 2. Although skeleton models are common objects in CAD systems (PTC, 2012), they are little noted in research. However, the necessary geometric information for performing a tolerance analysis is available first in the conceptual design phase. An important consequence of the early design stage is the unavailability of information about production deviations. Therefore, the proposed mathematical method takes the entire tolerance zones into account for the analysis.

2.3 Actual possibilities of tolerancing based on skeleton models

The possibility to perform a tolerance analysis based on skeleton models with commercial feature-based tolerance analysis software like VisVSA is actually available. However, these tools have another significant lack – limitations in considering all actual tolerances. *They are neither comprehensive nor accurate* (Ameta et al., 2011). The drafting community uses tolerance charts, which are compliant to Y14.5/ISO 1101 tolerance standards. However, tolerance charts are only capable to perform one-dimensional worst case analysis. Tolerance analysis software tools (like VisVSA) are commonly used by engineering analysts. These tools can do worst case as well as statistical analysis but are not fully compliant to the ISO 1101 standard (e.g. VisVSA is not capable of measuring plane-plane distance). The last group of common tolerance analysis tools is kinematics based (e.g. CE-Tol), which is also not full compatible to ISO 1101 (Davidson and Shah, 2004). A spatial math model for tolerance analysis which considers the skeleton-model framework and is ISO 1101 compliant is needed. Table 2 lists according to Davidson and Shah (2004) the actual types of tolerance software (without their approach, which is not available yet).

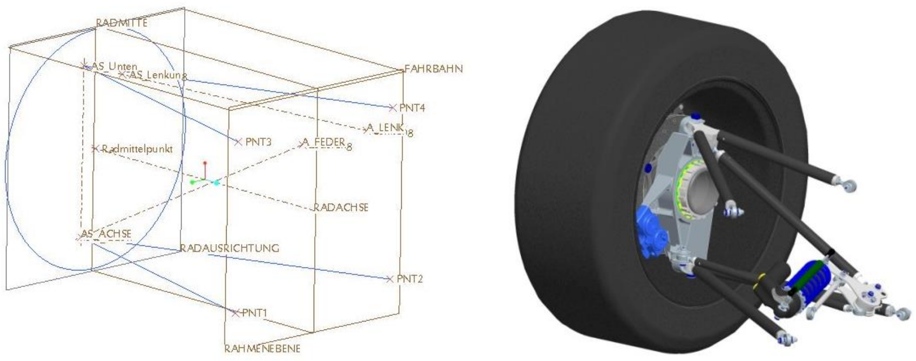

Figure 2. Skeleton model and volume model of a racing cars wheel suspension (Running snail racing team, RS 10)

Based on various publications in the last two decades on tolerance representation, there came up different mathematical models for representing the deviations of parts limited by dimensional as well as geometric tolerances, for example in Roy and Li (1999) and Teissandier et al. (1999). Two of these seem appropriate for this approach: Tolerance-Map® and Deviation Domain (Ameta et al., 2011). They just differ in detail, and are also very similar to other models like proportioned assembly clearance volume (Teissandier et al., 1999). Although they are limited by linearity, they are capable of an extended mapping of geometric tolerances. These concepts are not capable of mapping form deviations, which is no limitation in the early design stage. The concept of deviation domain seems more comprehensive, as Tolerance-Maps® operate with areal coordinates. This is a very abstract method for representing possible part deviations and it lacks of a suitable norm for the planned feature based contributor analysis (see the next but one paragraph).

Table 2. List of actual tolerance analysis software tools and techniques, according to Davidson and Shah (2004)

	Dimensionality	**Analysis Type**	**Tolerance Type**	**Y14.5 Compliance**
Tolerance Charts	1-D	Worst case	Dimensional, geometric	Full
Parametric TA-Software (VSA, Mech. Adv., etc.)	2-D constraints, 3-D history	Worst case, statistical	Dimensional *and* some geometric	Partial
Kinematic TA-Software (CE-Tol., etc.)	3-D	Worst case, statistical	Dimensional *or* some geometric	Partial

2.4 Necessities and potential of tolerancing in the early design stages

In the conceptual design phase, the product developer still has the freedom to change dimensions of components and even the operating principle of interfaces (e.g. using clamps instead of screws for fixture). This flexibility is a great chance for tolerance analysis and robust design.

A different view on variations of product functionality and behavior than tolerance management is robust design. According to Hasenkamp et al. (2009) *robust design methodology (…) comprises systematic efforts to achieve insensitivity of products or processes to sources of unwanted variations*. Chase and Parkinson (1991) alternatively called this in the context of dimensioning sensitivity reduction. In contrast to tolerancing, where single variations are restricted to reduce the variation of the functional feature, the robust design methodology aims to decrease the influence of the single variations on the variation of the functional feature. This is a completely different point of view, and is interesting in the context of tolerance management. A practical point of view on robust design can be found in (Ebro et al., 2012). Although several statistical methods for performing robust design in product development exist in literature (Hasenkamp et al., 2009), there is a lack of scope on robust design methods in tolerance management considering the geometric framework of tolerancing. Caro et al. (2005) developed evaluated different robustness indices for assemblies, based on the norm or the condition number of the Jacobian. Although this is a useful approach, it lacks from the local validity of the indices (Ziegler et al., 2012). For robustness analysis it is useful, for tolerance analysis where the variation limits are known this is a limitation.

A modular contributor which is adopted on a higher hierarchical level than common contributors would also be useful for comparison. Contributor analysis is a very important tool for tolerance synthesis. The application of variance-based sensitivity analysis by Stockinger et al. (2011) adopts actual sensitivity calculations to the field of tolerancing. However, actual contributors base on single distributions or directions. This leads in the worst case to multiple contributors for a feature, for example one shift contributor and two dumping contributors for a plane. A feature based contributor calculation which considers the complete tolerancing is necessary.

Furthermore, the functional geometric requirements have to be formulated, which is commonly done in later phases. To avoid delays for performing a tolerance analysis, required geometrical formulated functional requirements can qualitative be adopted from previous developed similar products. Qualitative functional characteristics means, that the functional characteristics are identified (e.g. variation-sensitive interface surface) and the form of the associated functional domain according to Giordano (Ameta et al., 2011), is determined. With this information, a tolerance management process extended with an upstream robustness analysis can be adopted.

2.5 Objectives

The limited geometrical information of the skeleton model do not allow a statistical tolerance analysis, which considers the whole geometry. However, the important information is the position of the interface features and their mode of action. This can be used for evaluating an upstream geometric design with the aim of making the assembly more robust against deviations in the interface positions. From the functional requirements, the functional key characteristics of the assembly are available.

The papers objective is to evaluate a suitable (F)KC flowdown for skeleton models. *A KC flowdown is the hierarchy of variation-sensitive product requirements and part and process features that contribute to their variation* (Thornton, 1999). The goal is here, to decompose the functional requirements of the assembly to functional requirements for all components. The decomposition is not unique, there are infinite possible decompositions. Therefore, a suitable method to optimize the decomposition by quasi-economically criteria has to be adopted. The early design stage usually lacks of manufacturing process information, therefore the criteria have a general formulation – they are quasi-economically. The functional component requirements restrict the components interface features to each other. To decompose the functional requirements, the influence of skeleton model features on the functional features variation has to be known. The influence of a feature has to be decomposed into the influence of its degrees of freedom to evaluate, which functional component requirements (the tolerances) have to be adopted.

The functional component requirements are the basis for dimensioning and tolerancing in the later design stages. If the requirements later can be directly claimed by tolerances, then they are the final tolerances. If not, then they are the components functional key characteristics for tolerance management in the later design stages.

3 METHODOLOGICAL CONCEPT

The adopted work methodology extends the classical tolerance analysis method by performing a geometric analysis step before the initial tolerance specification (figure 3). The following iterative process remains the same. This additional analysis step fulfills the following two purposes: to integrate the comparison of different operating principles and to perform robust design of the functional feature, due to the considered dimensions in the tolerance chain.

However, since tolerances and dimensions are related to each other, the separation of geometric analysis and tolerance analysis has to be declared. Although, a robustness analysis and a change in the interface feature operating principles could be performed in the following tolerance analysis steps, this would lead to vagueness, which action should be considered in the following synthesis – a change of tolerance values, dimensions or a change of small components.

This method bases on the small displacement torsor (SDT) (Bourdet et al., 1996), where the deviation of a part's feature is represented by translations and rotations of the nominal feature. The nominal feature can be varied with respect to its degrees of freedom (DOF). The SDT is very suitable for skeleton models, as the skeleton geometry consists of bounding-representation elements in CAD, where the SDT can be seen as a coordinate transformation of single geometry elements (e.g. planes). The main feature of this concept is the capability of representing geometric tolerances in contrast to commercial software approaches and the consideration of linked restrictions on single feature DOFs (if a parallel tolerated rectangular surface is tilted in one angle, the second angle may tilt lower). The functional geometric requirements are formulated as restrictions to the SDT entries, the so-called functional domain. Therefore, the following geometric analysis is based on the SDT.

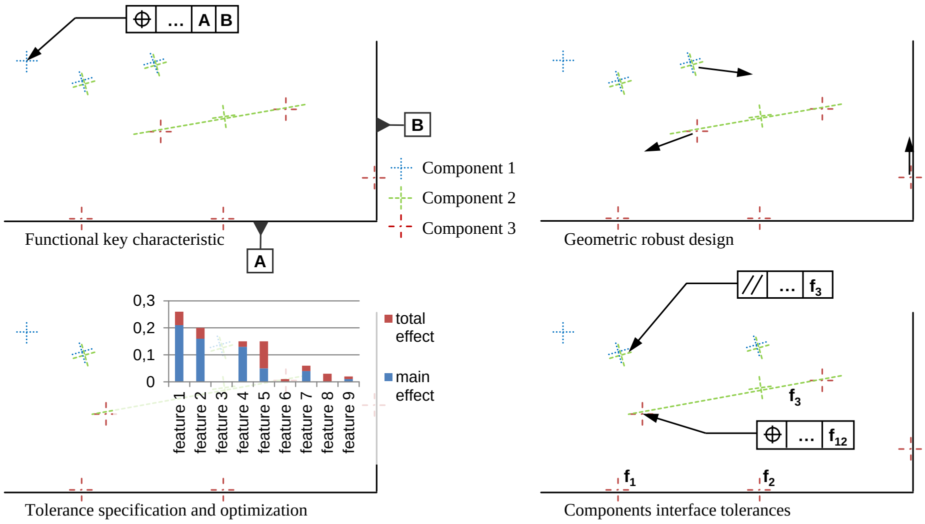

Figure 3. Skeleton model (upper left), robust design (u. r.), tolerance specification and optimization with contributors (l. l.) and final component interface tolerances (l. r.)

3.1 Preprocessing

The proposed analysis method is adopted directly on the CAD software, which is used to determine assembling the components. The preprocessing of the simulation includes the definition of the contact features and to position them with CAD coordinate systems (1st box in fig. 4). Positioning by coordinate systems is more general than with surfaces and also quite faster in CAD. All contact features have to be parameterized to control them through the application programming interface (API) by the tolerance analysis program (2nd box in fig. 4). Next, the functional geometric requirements and the functional feature have to be identified, which is the output of the solver. The functional geometric requirements have to be formulated as qualitative tolerances. This means, the type of tolerance and the associated datum's are necessary, while the size can be specified later. From the qualitative tolerances, the associated FF-DOFs have to be identified (3rd box in fig. 4). If the solver is prepared and connected to the tolerance analysis software, the preprocessing is finished.

3.2 Geometric design

In the geometric design stage, the functional feature's position is fixed, causing two consequences: First, the considered parameter combinations form the level set of coordinate system transformations which result in the functional features position. Resulting, the number of parameters is reduced by the number of the functional features degrees of freedom (FF-DOFs). For the geometric analysis we modify the method of Caro et al. (2005a). It consists of a sensitivity index, which maps the total sensitivity of a function to all input parameters. The authors dealt with two kinds of varying quantities, variables and parameters. While variables are controllable by the product developer, parameters are not. The same authors also evaluated different robustness indices from literature (Caro et al, 2005b), from which in the following two are used. As the proposed approach measures the influence of variables and strives to reduce them, it differs from the method in (Caro et al., 2005a). In the following, the nomenclature of Caro (variables and parameters) is *not* adopted.
The first aim is to spread the sensitivity as evenly as possible across all feature DOFs, according to Mannewitz (2005). This follows from the considered implicit situation: The FF is rigid in its datum

coordinate system, while the single parameters can be varied, which is the situation of $f(x_1,\ldots,x_n)=const.$ for all FF-DOFs, with varying feature DOFs x_i. In this situation, a reduced sensitivity of f with respect to x_i increases its sensitivity towards all other x_j. As the proposed approach uses the CAD system for assembling, the solver is a black box program. Therefore, the partial derivatives of the explicit function of Caro have to be approximated by difference quotients of the FF-DOFs at the nominal position with respect to the DOFs of all varying features. First, the Jacobian matrix **J** of the FF-DOFs is calculated with respect to the varying feature DOFs. The matrix spectral norm RI_2 of **J** (it's largest eigenvalue σ_{max}) is the robustness index for the first purpose. The associated eigenvector ν_{max} to σ_{max} indicates, in which combination the nominal values have to be changed for most effective decreasing RI_2. This procedure is done manually several times. This also can be done by an optimization algorithm. In the case of determined operating principles the implementation of all geometric and functional boundary conditions for the skeleton model by the product developer seems to be too time consuming.

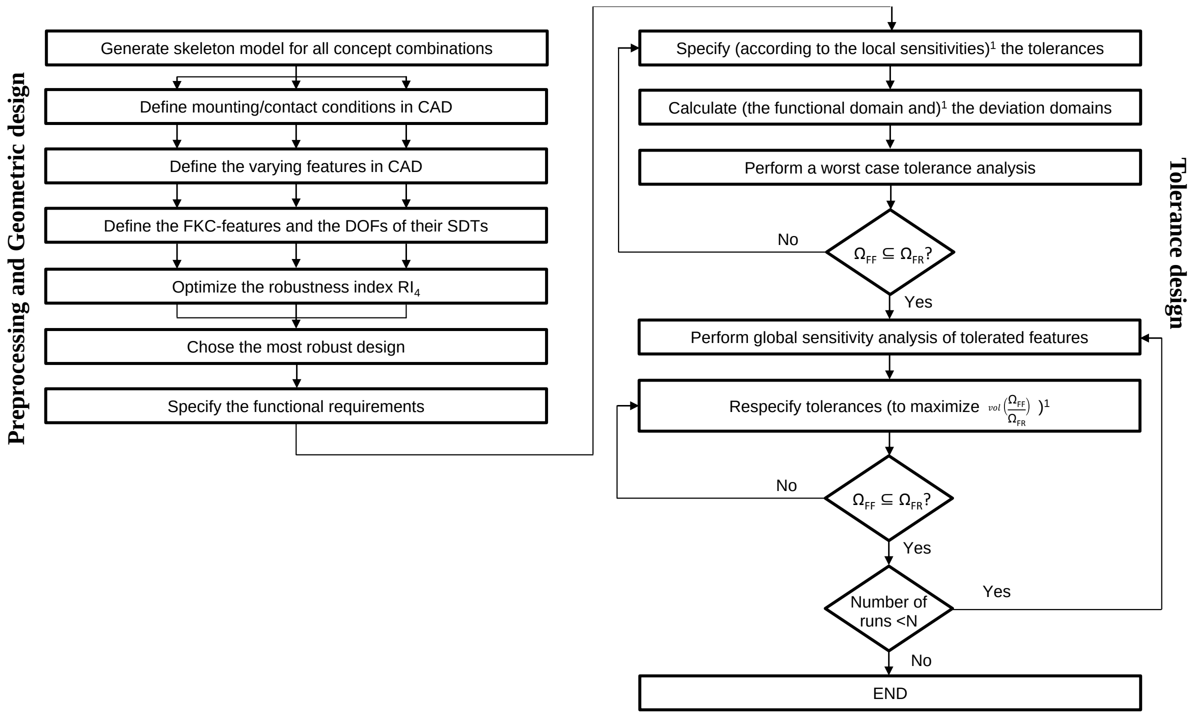

Figure 4. Scheme of the proposed tolerance management method, (…)[1] are notes for the first time the step is performed

The optional second goal is to compare different operating principles for interface features. The former introduced robustness index RI_2 is an index for comparing the sensitivity of different DOFs *inside* the system with respect to the FF-DOFs. For comparing different operating principle features, the variation of the *whole* system has to be compared for the two different systems. For this purpose, the robustness index RI_4 (Caro et al., 2005b) is an adequate measure. RI_4 is the frobenius-norm of the Jacobian **J**, the square root of the squared partial derivatives. With rising influential features and feature DOFs of the operating principle RI_4 increases. This represents rising geometric variations resulting from rising interface complexity at constant tolerance size. The whole procedure is to minimize for all combinations of different operating principle features the index RI_4 and then select the combination with minimal RI_4. In the case of more than four combinations, this calls for numerical optimization to minimize RI_4, for example with a particle swarm optimization (with the functional feature position as constraint).

3.3 Tolerance design

Following, the tolerances have to be designed. The problem here is that the complete components geometry is not available yet. Therefore, just superior tolerances of the skeletal geometry can be allocated. Superior means that the interior dimensioning of components as well as the possible positioning deviations in the components interfaces has to be estimated by the product developer to get an appreciation, which tolerances he/she can demand from the skeletal features. This is a crucial point of the introduced method, since it depends strongly on the experience of the product developer. The tolerance allocation is owing to the skeleton model interface driven. This means, the major task of allocating superior tolerances is to map the functional requirements of the functional feature to requirements (the superior tolerances) inside the components between their interface features. Therefore, the interface features are separated into two groups: tolerated features and datum features (see fig. 3 l.r.).

In the first step, tolerance specification is done by analyzing the final entries of **J**, the local sensitivities for the chosen geometry. The robustness index RI_4 is calculated for every feature separately to have a feature-sensitivity with respect to *all* FF-DOFs, calculated from the sensitivities of single feature-DOFs with respect to single FF-DOFs. Additionally, the CAD system visualizes the important features, so the product developer gets an appreciation for the tolerancing framework. For every component, the feature-sensitivities are arranged in descending order. The most sensitive features should be tolerated to the most sensitive ones inside the components with respect to the important DOFs.

If all tolerances are assigned, a worst case tolerance analysis should be performed (figure 4). For this, the tolerances are converted to deviation domains for the associated features according to Giordiano. Additionally, the functional domain (Ameta et al., 2011) Ω_{FR} is calculated from the functional requirements. The deviation domains (Ameta et al., 2011) are combined with each other to get the deviation domain Ω_{FF} of the functional feature. Afterwards the inclusion of Ω_{FF} in Ω_{FR} is tested. If it is included, the next step can be done. If not, the tolerances have to be narrowed and the worst case analysis has to be repeated.

If the functional feature meets the functional requirements, the tolerance optimization can start (figure 4). The goal is to expand the tolerances as far as possible while the functional requirements are still fulfilled. For this, feature contributors are calculated to identify the most influential features for meeting the functional requirements. Then, from the most influential features the significant DOFs are identified and then their tolerances get expanded. The quantitative expansion should correspond to the difference between Ω_{FF} and Ω_{FR}. Then, the inclusion of Ω_{FF} in Ω_{FR} is checked again. If it is included, the contributor calculation starts again as well, if not the expanded tolerances should be stepwise narrowed until Ω_{FF} is included and then the contributor calculation starts again. After some optimization cycles, the procedure is finished.

The first step is to calculate the contribution of all varying features on the functional feature with respect to the functional requirements. The basis for calculating the contributors is the variance based sensitivity analysis method according to Sobol, see Saltelli et al. (2008). Variance based sensitivities calculate the influence of the variance of input parameters (here the deviation of single deviating features) on the variance of the output (here the deviation of the functional feature). We use the Jansen-algorithm, based on a uniformly distributed Monte Carlo sampling. The sample size has to be very large, minimum several hundred thousands of samples. The sampling is done separately for all DOFs of every varying feature with the same sampling size, scaled on the tolerance ranges of the DOFs. Following, the samples are tested for complying the tolerances, the failed ones are sorted out. In the next step, the single deviations have to be assessed with a quality measure, based on the tolerance zone of the associated feature. This is done by the deviation quality measure

$$\lambda(x) = \min\{\ \mu \mid x \in \mu \cdot \Omega_{DD}^{i},\ \mu > 0\},$$

whereby Ω_{DDi} is the deviation domain of the i^{th} feature and x is the sample of the SDT of the i^{th} feature. See figure 5 for the quality measure with respect to a parallelism tolerance of two deviating surfaces, which have the same deviation quality. Note, that the deviation quality λ=0.7 depends on the tolerance zone, if the plane would be limited by additional tolerances, the deviation quality of the two examples could change. Following, the final sampling is created. The final sample size is created with a Latin Hypercube Sampling (Saltelli et al., 2008). Therefore, for all separate feature samples it has to be tested which size of latin hypercube sampling can be created from the pool of samples. The highest matching number for all feature samplings is selected as the sample size. Important is, that for every λ-sample the associated SDT-sample has to be saved. The λ-samples (calculated from the deviation quality measure) are necessary for the sensitivity analysis algorithm, the SDT-samples for the CAD-system solver. The deviation quality measure is therefore a kind of translator of the deviating geometry for the contributor algorithm. Finally, the algorithm is performed and thöe contributors of single deviations are calculated.

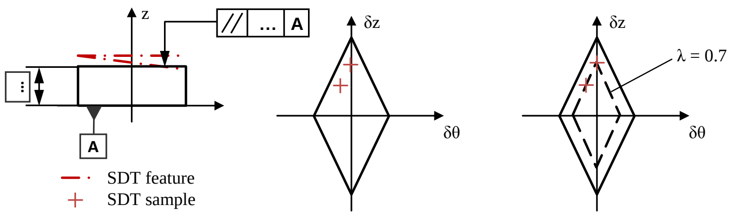

Figure 5. Deviation quality λ=0.7 for two deviated planes in two dimensions with respect to a parallelism tolerance to datum A

The contributor analysis displays two kinds of contributors: Main effects and total effects of features. The main effect quantifies the direct influence of deviating features to the functional feature, while the total effects additionally identify the interactions between the features deviation and deviations of other features.

The first action is factor fixing according to Saltelli et al. (2008). Features with a total effect nearly zero (which have minimal impact on the functional feature deviations) are extended to general tolerances. A following worst case analysis ensures that the requirements are still met. If not, the unimportant tolerances are stepwise reduced, until the functional requirements are fulfilled. In the next step, the other small contributing features are considered. The tolerances of these features then are extended. Additionally, the tolerances of features with high contributors are reduced. After a new query of requirement fulfillment, the procedure starts again with the contributor calculation. This is necessary, because with different tolerances the contributors also change. The aim is to have nearly equal contributors.

4 DISCUSSION AND CONCLUSION

The complied concept utilizes the early design stage by performing a robust design optimization of an assembly skeleton model with different interface connecting principles. With a robustness index the concepts are compared and the most robust one is chosen. For this, the robustness index is an indicator for assigning superior tolerances between interface features. Afterwards, a tolerance based feature contributor is calculated, and in several analysis and synthesis steps the superior tolerances are changed with the goal of having equal contributors (although this is mostly just partially accessible) and second to use as much permitted deviations as possible. Between different tolerance changes, a worst case tolerance analysis is performed to ensure that the functional requirements are fulfilled. The core concept is the feature contributor, as it leads to a natural parameter reduction in the contributor calculation. In conventional tolerance contributor calculations, every varying feature has several contributors, which doesn’t take interrelations between DOFs of features based on the tolerances into account.

However, the proposed concept is just a first step. The algorithmic problems have to be considered. Mainly the sampling for the algorithm is a complex problem, where a more elegant method seems necessary. Additionally, a calculation of mixed feature- and DOF contributors should be considered and invented. The aim is to have a modular contributor, which can calculate for unimportant features their whole contribution and for important ones the contribution of it’s DOFs.

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