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VIRTUAL VALIDATION OF FUNCTIONAL AUTOMOTIVE DOOR ASSEMBLY PROPERTIES BY MEANS OF SUPERPOSED CAT AND FEM ANALYSIS

Ehlert, Matthias (1); Heling, Björn (1); Wartzack, Sandro (2)
1: BMW AG, Germany; 2: Friedrich-Alexander Universität Erlangen-Nürnberg, Germany

Abstract

As with all industrially manufactured goods, it is generally necessary to ensure costumer requirements are met. Therefore, it is important to ensure that functional as well as optical specifications of a product are fulfilled for large quantities in series production.

The following piece of work demonstrates the effect that the elasticity of an assembly has on specific functional criteria in order to meet the aim of a robust design. For this purpose an automotive door assembly is examined, where tightness is one of the most relevant attributes from the customer's perspective. In the present case, the effect of the elastic sealing system on the development of the limiting positions of the observed assembly that result from a corresponding tolerance analysis will be examined in greater detail which, in turn, has an impact on tightness. The term 'limiting position' generally describes the largest deviation from the nominal dimension that can occur with a high level of statistical probability.

To that end, a simulation-based integrated process is introduced that covers CAT as well as FEM methods and in this way respects the elasticity of the system with its corresponding deformation.

Keywords: Computer aided design (CAD), Robust design, Virtual engineering (VE), Computer aided tolerancing (CAT)

Contact:
Matthias Ehlert
BMW Group
Tolerance Management Total Vehicle
Germany
matthias.ehlert@bmw.de

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1 INTRODUCTION

In the past, when thinking about the toleration of product features certainly a major part of engineers, product developers and others might not get the opportunity to understand the far-reaching consequences component deviations have for the design of a product both optically and functionally. For that and other reasons, intelligent computer aided tolerancing (CAT) approaches are increasingly in demand in industrial applications. Within the last decades a huge amount of scientists all around the world developed various virtual methods with the aid of statistical approaches to ensure a robust design, "which is one of the pivotal tasks during product development e.g. in automotive industry." Stockinger and Meerkamm (2009) The term Robust Design covers a wide range of direct and indirect requirements to ensure that components and products are robust to process variation resulting from the manufacturing process. Day et al. (2005), Stockinger et al. (2007), Thornton et al. (2000)

According to Hasenkamp et al. (2009) there are different reasons to use robust design methodology in different phases of the product design process. The following piece of work demonstrates the effect that tolerancing concepts have on specific (functional) criteria in order to meet the target of a robust design. Therefore, a simulation-based integrated process is introduced covering CAT as well as FEM methods (rigid and elastic tolerance simulations) in order to determine corresponding deformations of an assembly. These deformations can occur, whenever two or more components interact with each other. In the present case, all components do have geometric deviations as a result from their specific manufacturing process. These geometric deviations in turn have an impact on the corresponding deformation of the assembly. With reference to the automotive industry, an automotive door assembly is examined. The focus of all activities is on customer-relevant aspects, both optical and functional.

From the customer's perspective, one of the most relevant functional attributes is water tightness. In order to build a proper design, it is the goal to make sure that the observed system guarantees tightness against the permeation of dust or humidity such as rain and condensation. Similar to aspects like the handling comfort, opening forces, aerodynamics, etc., the sealing system is affected by the limiting positions of the observed assembly, i.e. the largest deviations from the nominal dimensions that can occur. Kapici et al. (2013), Ehlert et al. (2014b) These limiting positions are mainly influenced by functional relevant components, which themselves have nominal dimensions on the one hand and corresponding geometric deviations on the other. Ehlert et al. (2014b)

At this point, all relevant parts or main contributors, i.e. factors that have a significant influence on the key product characteristics (KPC), need to be found for the considered application. This happens through performing a corresponding contributor analysis. Therefore, it is now necessary to clarify which key product characteristic needs to be analysed. Ceglarek et al. (2004), Ceglarek et al. (2006), Prakash et al. (2009) Due to the fact that the topic of this contribution deals with tightness against the permeation of dust or humidity in the context of an automotive door assembly in the presence of geometric tolerances, the sealing gap close to the door main seal is used as key product characteristic. It can thus be stated that the target is to validate the impact of variable key product characteristics arising from geometric deviations and displacements on functional criteria, such as tightness. For this purpose a simulation-based integrated process is introduced that covers CAT as well as FEM methods and in this way respects the elasticity of the system with its corresponding deformation. Additionally, the planned experimental validation is described.

2 WORK METHODOLOGY

Different statistical methods are applied in the various disciplines of engineering in order to build a robust designed product that is based on geometric deviations and displacements and that needs to fulfil specified functional requirements. These methods are mainly used when speaking about (industrial) applications that go along with large quantities in series production. Talking about robust design evalution, the question which principally needs to be answered is how scattering input variables of a technical system affect the range of variation of all response variables. Flassig (2011) However, this quantification shouldn't only be conducted for single scattering input variables. The interdependencies between these single input variables can also be examined if necessary to better understand the substantial relationship between cause and effect. Will (2004), Flassig (2011)

The presented approach will be illustrated in connection with the environment of an automotive door assembly. In particular, the main components that belong to this assembly are the side frame, the door sealing system and the sub-assembly door (door inner + outer panel welded together), see Figure 1.

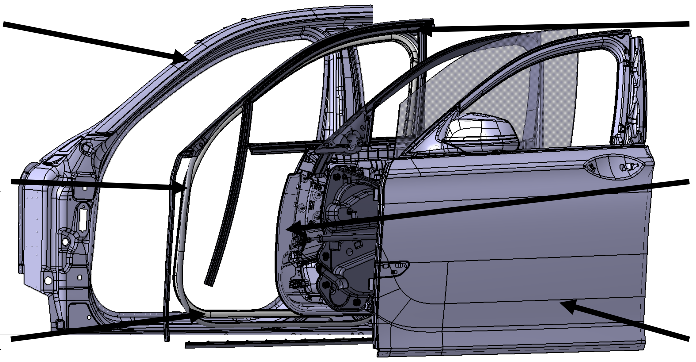

Figure 1. Schematic of the contributors belonging to the assembly

On the basis of an existing computer-aided design (CAD) model (implemented in CATIA V5), all deviations have to be determined statistically in order to quantify the impact of the (extremal) geometric deviations on the regarded features. The rigid tolerance simulation can be performed using the state-of-the-art tolerance analysis tool 3DCS Analyst (3DCS). This chargeable application is integrated into CATIA V5. This application takes into account deviations and displacements arising from the single contributors as well as their related adjustment concepts and mounting sequences. In the end, this combination, which contains the geometry data as well as deviation information, leads to the limiting positions that in general can be seen as the largest deviations from the nominal dimensions that can occur. Kapici et al. (2013), Ehlert et al. (2014b) These limiting positions are of crucial importance for the functional as well as robust construction and the corresponding validation. Ideally, they should be located within the tolerance specifications (requirements set by the designer), which is not always the case at present. Ehlert et al. (2014b)

2.1 Determination of the limiting positions by performing a rigid tolerance simulation

Each key product characteristic has its own limiting positions (LSL / USL ... lower / upper specification limit). These are the results of a process, that is presented in the following, see Figure 2.

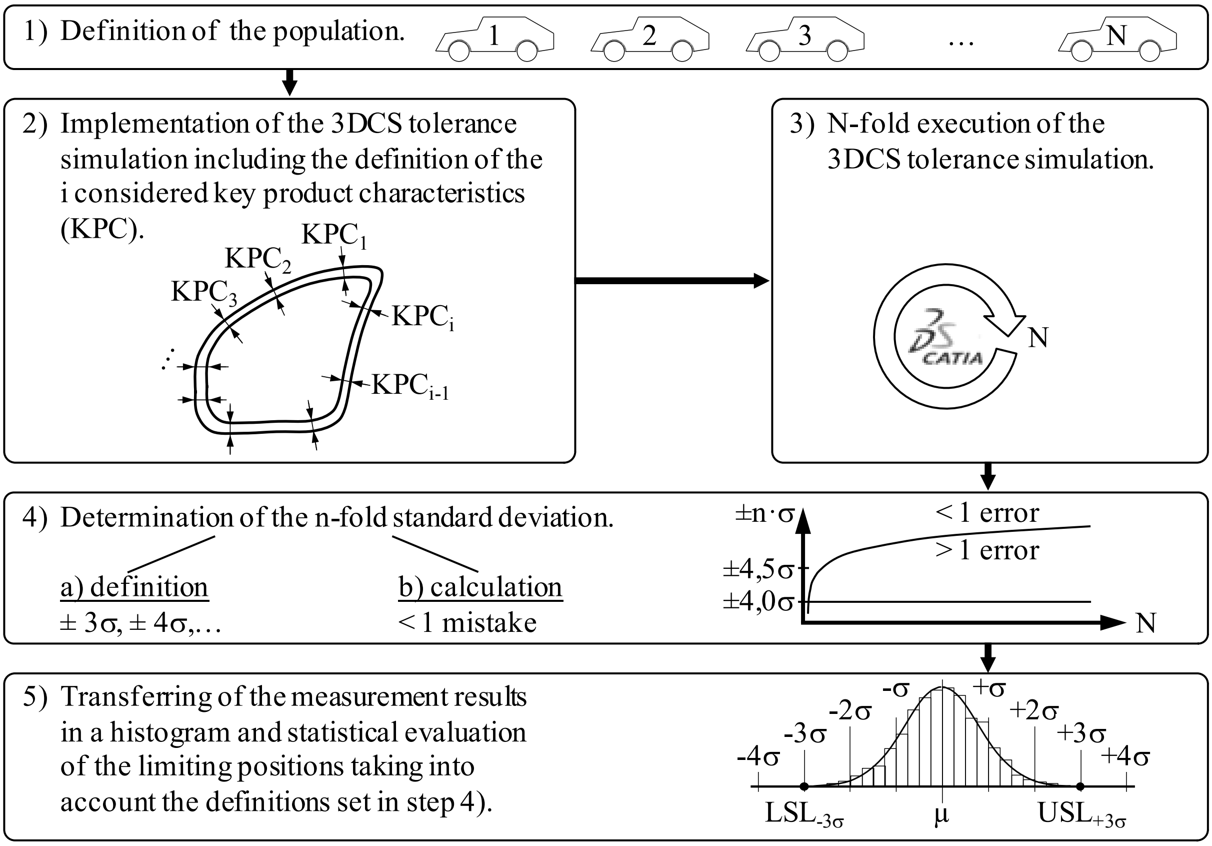

Figure 2. Search for the limiting positions by performing a rigid tolerance simulation

In conformity with Figure 2, the process steps shown in it are explained in the following sections.

2.1.1 Definition of the population N

At this point it is defined which population N is used as basis for the calculation. This number corresponds to the planned quantity of units in series production.

2.1.2 Implementation of the 3DCS tolerance simulation including the definition of the i considered key product characteristics

The implementation of the 3DCS tolerance simulation takes places in this step, corresponding to the scheme as described in Ehlert et al. (2014b). The specification of the key product characteristics that need to be investigated is based on optical and functional requirements and / or on experience.

2.1.3 N-fold execution of the 3DCS tolerance simulation

In this step the automated N-fold execution of the 3DCS tolerance simulation takes place. The resulting measurement belonging to each key product characteristic is getting stored after each simulation run. Afterwards, these results are provided for analysis purposes.

2.1.4 Determination of the n-fold standard deviation σ

At this point, it will be decided to what extent outliers are accepted in the validation process. On the assumption that the respectively regarded key product characteristic is distributed normally around a mean value μ, a $\pm\sigma$ value needs to be a) defined or b) calculated with respect to the considered quantity.

a) If the $\pm\sigma$ value is going to be defined for the determination of the limiting positions, the following assignment might be conceivable: $\text{LSL} = [-3\sigma, -4\sigma]$, $\text{USL} = [+3\sigma, +4\sigma]$.

b) If the $\pm\sigma$ value is going to be calculated with respect to the considered quantity for the determination of the limiting positions, a criterion for the evaluation of this value has to be found at first. For the upcoming calculations this requirement is defined as follows: less than one fault should occur for the whole population. On the assumption of a normal distribution that has a mean value μ and a standard deviation σ the following correlations arise:

For a continuous random variable x the probability density function is defined with

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}. \tag{1}$$

Talking about the standard normal distribution it applies that $\mu = 0$ and $\sigma = 1$. The distribution function of the standard normal distribution is given by

$$F(x) = \int_{-\infty}^{x} f(t)\,dt = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{t^2}{2}}\,dt \tag{2}$$

and indicates the probability with which the random variable has a value smaller or equal to x. If N is the number of planned vehicles then the probability of an error should be smaller than $1/N$. Thus, less than 1 error would occur for the whole population, which means that there will be no functional problems. Therefore, the probability that the random variable x is located within the interval $[-n\sigma, +n\sigma]$ should be higher than $1 - 1/N$, whereas $\sigma = 1$ is the standard deviation and n is the requested factor. Thus, the equation

$$F(n) - F(-n) = \frac{1}{\sqrt{2\pi}} \left(\int_{-\infty}^{n} e^{-\frac{t^2}{2}}\,dt - \int_{-\infty}^{-n} e^{-\frac{t^2}{2}}\,dt \right) = 1 - \frac{1}{N} \tag{3}$$

must be solved for n. Figure 3 shows the result of this solution. The points across the horizontal axis represent the population N. The vertical axis indicates the n-fold standard deviation σ. The curve in this figure can be seen as a kind of border for the assessment criterion.

For example, this means that a population of $N = 500.000$ units (e.g. vehicles manufactured) needs to be statistically validated with a standard deviation $\pm n_{N=500.000}\sigma \approx \pm 4{,}75\sigma \cong 99{,}9995\%$ to ensure that there will be less than 1 error in series production.

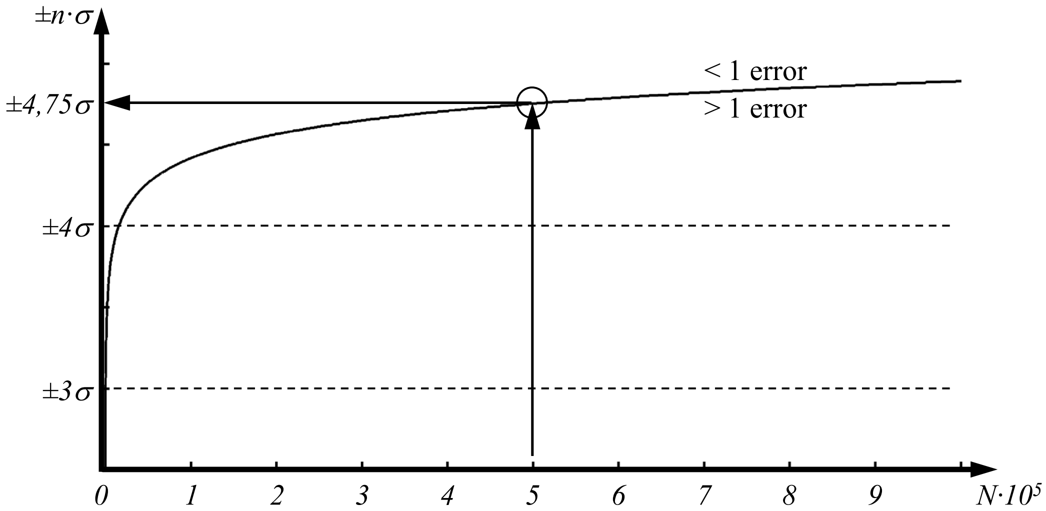

Figure 3. The evaluation effort depending on the population

2.1.5 Transferring of the measurement results in a histogram and statistical evaluation of the limiting positions taking into account the definitions set in step 2.1.4

Based on the selected n-fold standard deviation σ in step 2.1.4, the rigid limiting positions for every key product characteristic will now be determined. These single values for the limiting positions of each KPC derive from its corresponding statistical analysis.

The results of the latter are the definitions for the limiting positions for each key product characteristic using this rigid body approach, see Table 1.

Table 1. Data sets for the rigid limiting positions for the key product characteristics (KPC)

	KPC_1	KPC_2	KPC_3	...	KPC_{i-1}	KPC_i
LSL	11,6mm	15,7mm	15,7mm	...	10,5mm	10,2mm
μ	12,7mm	17,2mm	17,0mm	...	11,8mm	11,4mm
USL	13,8mm	18,7mm	18,3mm	...	13,1mm	12,6mm
$\pm n \cdot \sigma$	1,14mm	1,48mm	1,29mm		1,30mm	1,23mm

2.2 Result of the elastic behaviour of the system

The limiting positions that have an impact on functional requirements are not only founded on dimensional deviations arising from the rigid body in white, but from the door sealing system influences with its geometric deviations, stiffness conditions and corresponding reaction forces as well. Additionally, the elasticity of all parts, the process of closing and some other factors also have an impact on these positions.

These effects have to be included from now on to correct the statements about the limiting positions (Table 1) by the influence of the elastic behaviour of the system. The approach required for this is described in Ehlert et al. (2014a, 2014b). First, the reaction forces of the sealing system caused by the limiting positions are calculated with Abaqus based on a 2D FEM simulation. The previous simplification of the geometry and the meshing was performed using HyperMesh. The specific setup and implementation of the simulation is not discussed within this contribution. As an example, Figure 4 shows feasible simulation results.

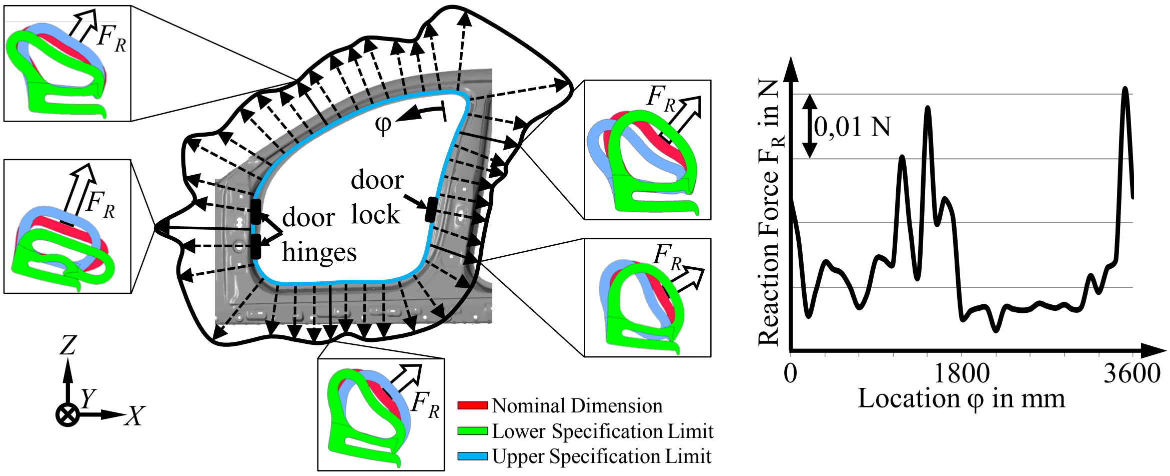

Figure 4. Reaction Force F_R of the sealing system as a result of specific tolerance situations (according to Battel (2014))

On the left side of Figure 4 the positions of the 2D planar section for the FEM simulations are illustrated. The resulting reaction forces (vectorial) along the periphery of the considered automotive entrance assembly are projected on the XZ plane in the illustration. In between these discrete forces an interpolation along the periphery coordinate φ is performed. The interpolated force path (illustrated in the right-hand side of the Figure 4) is required to determine both the deformation of the door assembly and the side frame at a later point. A quasi-static 3D FEM simulation is performed to determine these corresponding deformations at the door assembly and the side frame with respect to the imprinted loads (at the individual sections). Thereby, the subassemblies, including the components intended for structural reinforcement, are modelled on an elastic basis.

Preliminary studies have shown that there are no significant restoring forces arising from the side frame. That is why this contributor will not be considered in the further process.

To ensure a high quality of the results, the design of the quasi-static 3D FEM simulation has to be as realistic as possible. Obstacles that traditionally have to be taken in this context mostly refer to the quality of the mesh, boundary conditions in general and parallel processing to improve system performance. Figure 5 displays a part of the simulation model on the left-hand side and a typical result for the displacement of the flexible geometry on the right-hand side. Within this figure not all structural- and stiffness-relevant components are pictured. However, these relevant components were taken into consideration when building the simulation model.

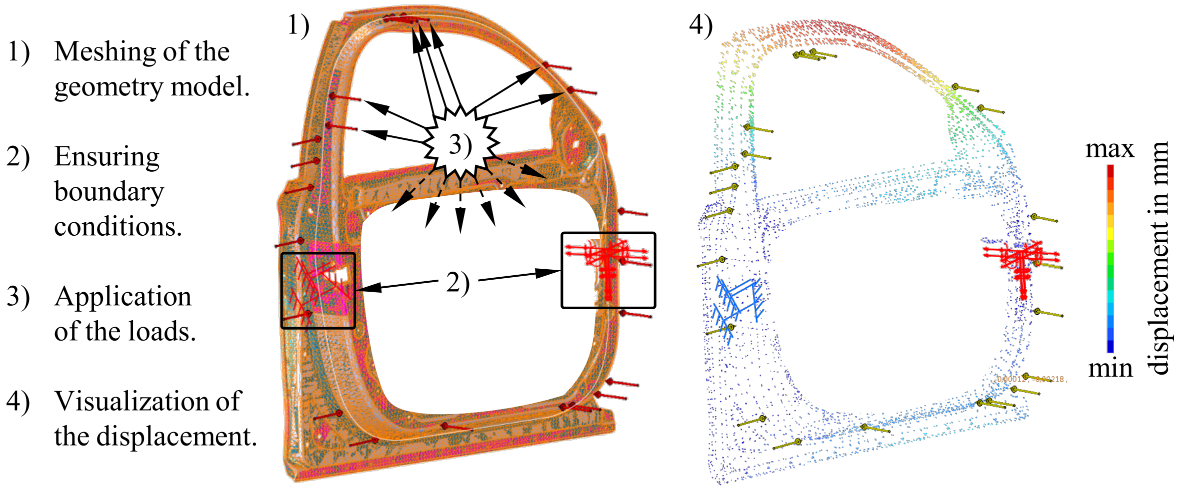

Figure 5. Application of boundary conditions and reaction forces on a simulation model and corresponding geometric deviations (according to Mueller (2014))

The generated FEM mesh is coloured orange (1)). The fixation of the door is realised by boundary conditions that represent the door hinges and the door lock (2)). The reaction forces arsing from the sealing system (here not drawn) are represented via red arrows (3)). It can already be maintained that the biggest impact on the development of the limiting positions occurs along the y direction. As the outcome of such quasi-static 3D FEM simulation, one does gain deformation information about the geometry considered (4)). In this way the user gets corrected statements about the limiting positions for each tolerance situation.

3 RESULTS OF THE PROCESS

As expected, the largest deformations can be observed along the roof edge between A- and B-pillar as well as on top of the B-pillar (door-sided). These sectors belong to the weaker structural ones leading to a lower stiffness and, therefore, to a maximum level of deformation. Additionally these areas are furthest away from the fixation points (door hinges and door lock), which likewise meets the expectations as well. Moreover, slight deformations can be observed in the sill area.

The following Figure 6 shows, by way of example, the results of the simulation-based integrated process developed so far for one considered tolerance concept.

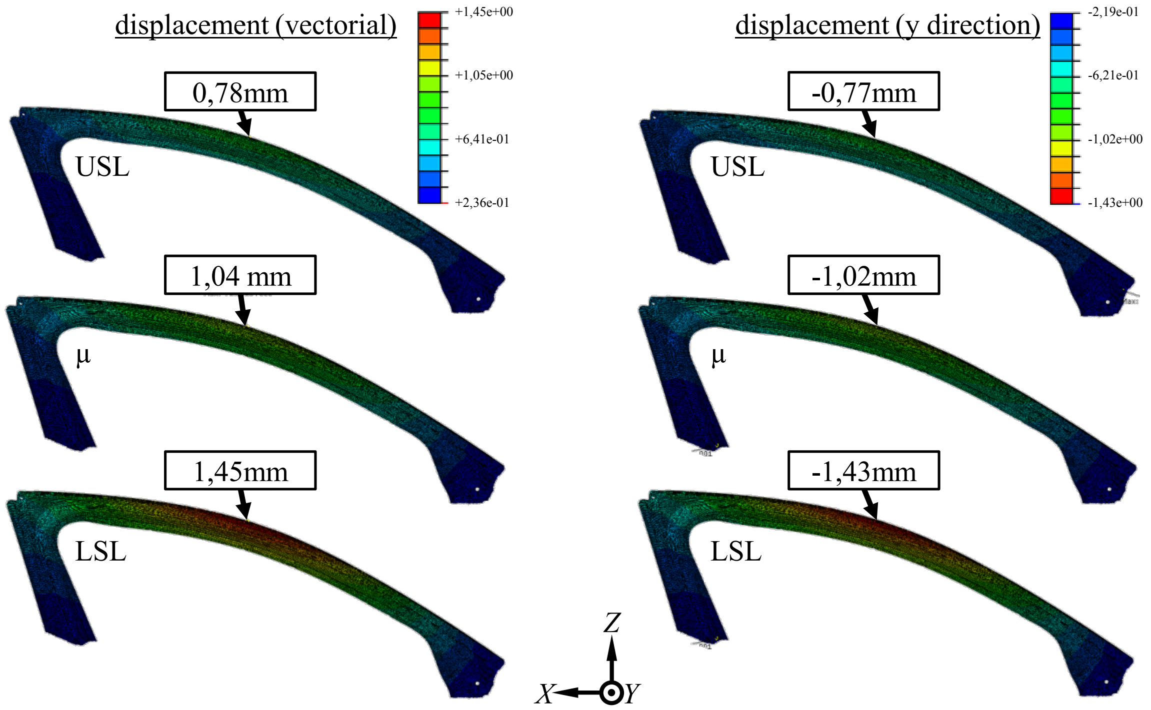

Figure 6. Results of the simulation process (according to Mueller (2014)

It is looked at the area above the door balustrade in this figure, due to the fact that the largest deformations take place in this sector. On the one hand, a distinction is made (vertical) between different tolerance situations (USL, μ, LSL). On the other hand, a distinction is made between total deformation (left) and proportional deformation (right). First, the hypothesis is confirmed that a significant impact on the limiting positions is given arising from the elastic behaviour of the system. This can be seen when looking at the maximum deformations. In the presented case the maximum value is $d_{max} = 1{,}450mm$. Considering that modern tolerance concepts have to fulfil goals and objectives in the range of one tenth of a millimetre, this value can definitely be described as "significant". Thus, on the basis of the data it can be seen that the assumption pointed out in the previous paragraph regarding a dominant proportion along the y direction did prove true (in each case $> 98\%$).

4 EXPERIMENTAL VALIDATION OF THE LIMITING POSITIONS AND FURTHER WORK

The geometrical deformations shown in Figure 6 correspond to a superposition of their respective rigid limiting positions with the belonging elastic system behaviour. The key product characteristics (LSL, μ, USL) listed in Table 1 have to be adapted respectively.

One substantial task in this context is the experimental validation. On the one hand this validation is required to evaluate the limiting positions. On the other hand it is required to make sure that the observed system guarantees tightness against the permeation of dust or humidity for all considered tolerance situations. To this purpose, a specific test rig was developed.

The test rig consists of a full-scale model of the side frame and the door with its door lock, both door hinges and the sealing system. The side frame can be moved via a kinematic to adjust the geometric limiting positions while the door is fully decoupled from this kinematic. Due to this decoupling, the door can be closed after moving the side frame to a defined position, which is more realistic. This also has a positive effect on the dynamic creeping behaviour of the sealing system when closing the door. There are several tactile sensors integrated in the side frame for measurements between the side frame and the door inner panel (next to main seal) in order to be able to compare the adjusted geometric limiting positions with the corresponding CAT and FEM simulations.

By comparing the limiting positions arising from the simulation approach with reality, not only the position of the door can be quantified, but also the deformation of the door caused by the sealing system.

It is now possible to evaluate customer-relevant criteria once the setting is successfully adjusted for every tolerance situation (by the actuator) and the sensors validate each specific chosen tolerance situation (i.e. limiting positions). To this end, there will be water tightness tests in future that will provide several results. On the one hand, a leak detection test can be performed. This test helps the engineers to evaluate their concepts before starting with series production but also implies rework costs (e.g. design, tolerance concept, validation) at least if there are leakage problems. On the other hand the goal of finding a tightness parameter in simulation that can be validated within this test rig can be pursued. Therefore, the counter-pressure of the sealing system is one conceivable possibility. Taking into account tolerance situations, it is additionally planned to perform measurements with this test rig concerning the handling comfort as well as opening and closing forces. This will help to determine a suitable mathematical model that supports the objective of finding a robust design. Corresponding explanations will be addressed in future publications as well as the statistical design of experiments.

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