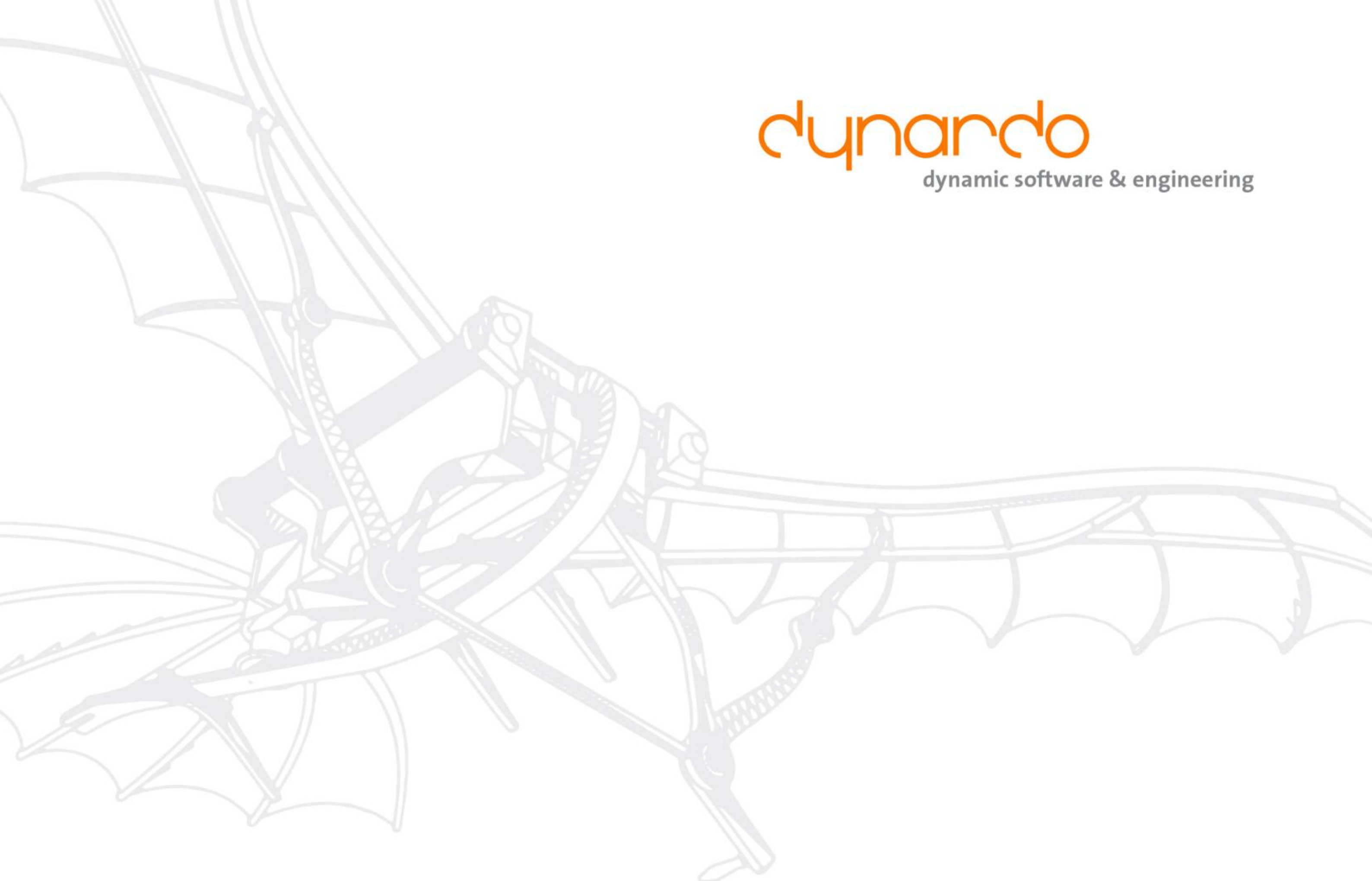

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Lectures

Interaction of simulation and test for the statistical validation of virtual product development

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Interaction of simulation and test for the statistical validation of virtual product development

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Summary:

The interaction of simulation and test is a key factor of virtual product development. To stand the global competition, it is essential to combine simulation with an optimized test procedure. Whereas in the past the main focus was on the prognosis of single designs or in the adjustment of single experiments, the focus nowadays lies in the determination, definition and calculation of entire variation spaces via robustness analysis, reliability analysis and robust design optimization. The resulting variation windows have to be adjusted and verified with real tests.

For the numerical assurance of robustness for a virtual design against natural occurring scattering, the automotive industry is more and more using numerical robustness evaluation. For a realistic definition of the input scatter of robustness analysis, measures and experiences from tests are extremely important. Robustness evaluation of complex systems consists of various parameters, thus stochastic methods for the scanning of high-dimensional variation areas become necessary. At the same time, the criteria of adjustment between simulation and experiment as well as the assessment of robustness for virtual designs have to be enhanced by statistical measurements like coefficients of determination, correlation and determination.

This paper should also provide an outlook how the results of numerical robustness evaluation can be used for concrete tasks in the real design or in the test execution. Experimental phenomena can be found with help of the robustness analysis and their causes can be identified. Therefore, the methodology is increasingly used for the statistic (stochastic) validation of a virtual product design before the test is carried out. Here an interesting question is how the statistic measures are considered in the decision process of design changes or test executions.

Keywords:

numerical robustness analysis, scattering variables, distribution function, correlations, stochastic analysis, random fields

1 Statistical assurance of virtual product development

The interaction of simulation and test is a key factor of virtual product development. To stand the global competition, it is essential to combine simulation with an optimal planned test. Whereas in the past the main focus was on the prognosis of single design or in the adjustment of single experiments, the focus nowadays lies in the determination, definition and calculation of entire variation spaces via robustness analysis, reliability analysis and robust design optimization. The resulting variation windows have to be adjusted and verified with real tests. For the numerical assurance of robustness for a virtual design against natural occurring scattering, the automotive industry is more and more using numerical robustness evaluation. For a realistic definition of the input scatter of robustness analysis, measures and experiences from tests are extremely important.

Robustness evaluation of complex systems consists of various parameters, thus stochastic methods for the scanning of high-spatial variation areas become necessary [1]. At the same time, the criteria of adjustment between simulation and experiment as well as the assessment of robustness for virtual designs have to be enhanced by statistical measurements like coefficients of determination, correlation and determination [2].

2 Methods of stochastic analysis

Methods of stochastic analysis enhance the discretization of the numerical models by the uncertainty (scattering) of input parameters and carry out calculations more or less randomly in the uncertainty space using sampling methods. Statistical measures describe the variation of important input parameters, the probabilities of exceedance is determined and correlations between scattering result parameters and input parameters is searched [3,4]. Origin of stochastic analysis is the Monte Carlo sampling (Plain Monte Carlo – PMC). Here, random support points in the area of scattering variables are assessed. The necessary effort of Plain Monte Carlo method depends on the probability of the examined phenomena and the confidence of the correlation parameters. Thus it can require a lot of support points and can cause a high calculation expense. Therefore modern virtual product development is using stochastic methods that are adaptive regarding failure areas (methods of reliability analysis like FORM, ISPUD, Importance or Adaptive Sampling) or adaptive regarding the structure of support points (Latin Hypercube Sampling) [5-9].

The terminus reliability analysis is used in literature for stochastic analysis methods which calculate and assure small probability parameters. The calculation expense of efficient reliability analysis methods depends highly on the number of scattering variables which have to be considered. Therefore, robustness analysis for the identification of the most important scattering variables is an essential preliminary stage of reliability analysis [9].

The terminus robustness analysis is used for stochastic analysis methods when the sensitivity of a design regarding input scattering has to be assessed. Normally, then no small probabilities are assured and the variation of result parameters and the correlation between scattering input and result parameters have to be determined.

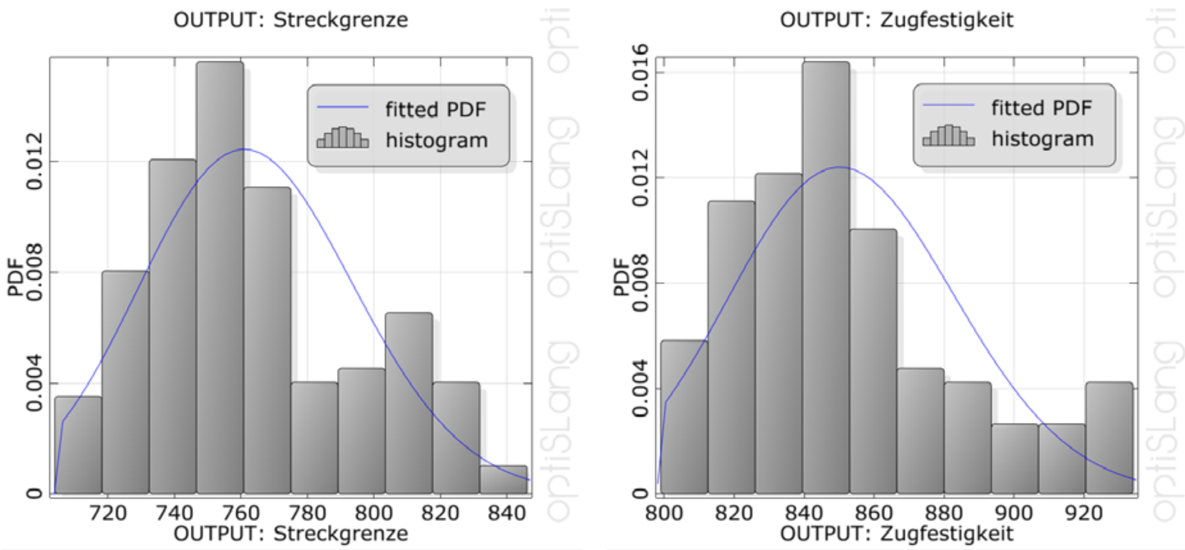
2.1 Robustness analysis in virtual product development

Robustness analyses are normally the first step for the introduction of stochastic analysis methods into virtual product development [10]. The statistic results of the variation of response parameters of a virtual design are product of the transfer function (the simulation model) and the definition of scattering input parameters. Therefore the definition of scattering response parameters is the essential input for the stochastic analysis. Consequently, it is discussed how input scatter is captured, extracted and then integrated into stochastic analyses.

3 Interaction of simulation and test for the consideration of scattering parameters in virtual product development

3.1 Extraction of single scattering parameters and integration into virtual product development

Single scattering parameters like yield strength or tensile strength of a metallic component are often described by minimum and maximum values or mean value and standard deviation extracted by measurements. In addition sampling methods of stochastic analysis require a definition of the distribution function. The transfer of existing knowledge about expected or measured scatter is therefore the first important step of a robustness analysis. Ideally, test results are available which can be read in and a distribution function can be fitted into the test data via best fit using Kolmogorov coefficients (figure 1).



Statistic data			
Min:	704	Max:	846
Mean:	763	Sigma:	32.13
CV:	0.04212		
Skewness:	0.5206	Kurtosis:	2.51
Fitted PDF: Log-Normal			
Mean:	763	Sigma:	32.13

Statistic data			
Min:	799	Max:	934
Mean:	852	Sigma:	32.22
CV:	0.03781		
Skewness:	0.8091	Kurtosis:	2.935
Fitted PDF: Log-Normal			
Mean:	852	Sigma:	32.22

Figure 1 - Fit of a distribution function into an examination data base

Here it has to be mentioned that, regarding the assurance against possible input scatter, it is recommended to enhance assumptions of measured input scatters and thus to adapt conservative values for the scatter. Often it can be seen that in the process of production different scatters of input parameters from different supplies can be found. Depending on the motivation of the robustness evaluation, this enhancement of measured scatters can be considered for example also for the purchasing specifications.

Beyond the definition of the distribution function, it has to be checked if a correlation between single scattering variables exists. The correlation from yield strength and tensile strength is shown at the example of the metallic component (figure 2). If both input parameters are important for the description of the plastic material behaviour, the scatters of single values as well as the correlation between both scattering values have to be considered. The tool used for stochastic analysis has to be able to extract the correlation from the test data and to consider them by sampling methods of stochastic analysis.

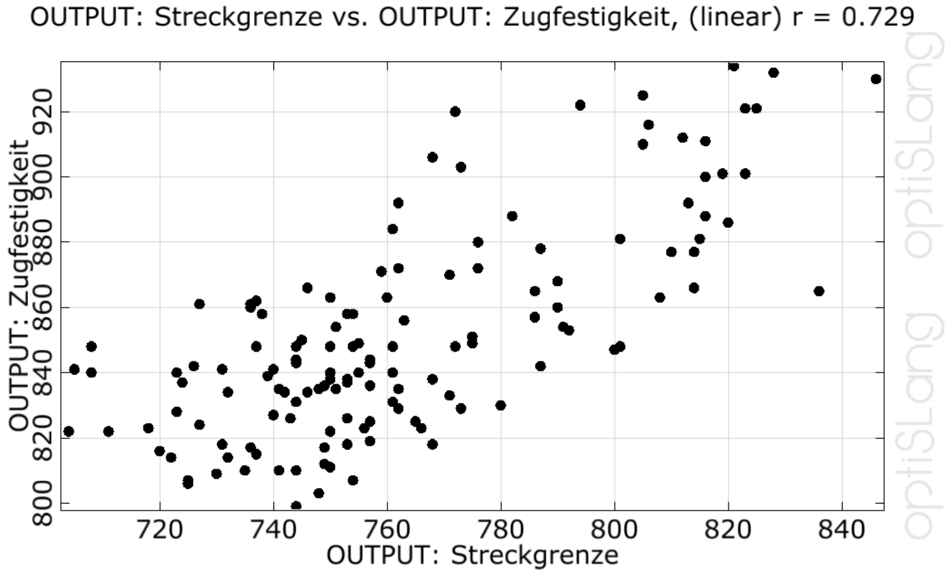


Figure 2 – Determination of linear correlation (r=0.729) between two scattering input variables: yield strength and tensile strength

3.2 Extraction of spatially correlated scattering variable and integration into virtual product development

Values are called spatially correlated values when the value of the input parameter is significantly dependent on a spatial coordinate. The wall thickness of formed sheet components for example is dependent from the thinning in the forming process and the thinning is very different all over the component. This idealisation can basically be transferred on every scattering input parameter, like geometric deviation or elastic modulus. The significance of spatial correlation (like does the spatial variation of geometry or the structural behaviour have a significant influence onto the response parameters) has to be checked in case of doubt. It has to be mentioned that the trend of more and more detailed CAE models most likely leads to a higher importance of the spatial correlated scattering values to the structural behaviour.

3.2.1 Integration of spatial correlated deterministic values into virtual prototyping

Consequently, today in the structural crash analysis of the automobile industry, the spatial distribution of sheet thickness and hardened effects of important sheet components is considered in case of doubt. As a example the distribution of thickness is determined by simulations of forming processes and it is mapped onto the finite element mesh of the crash meshing (figure 3) the influence of the spatially correlated thickness distribution at the crash performance criteria are investigated. The spatial distribution is here determined and transferred within the simulation.

Today also examples exist, where discretizations of virtual models is mapped onto measurements like for example the consideration of measured tolerances of bodies-in-white for structural crash load cases or the consideration of measured thicknesses of cast components for comfort analysis of brake systems. Whereas the spatial distribution of geometrical deviation is measured by 3D laser measurements and the finite element meshes are mapped onto geometrical measurements of areas or volumes and are integrated into the virtual product. Using the mapping technology help to check if the deviations between virtual prototype and measurement have a significant influence onto the simulation results.

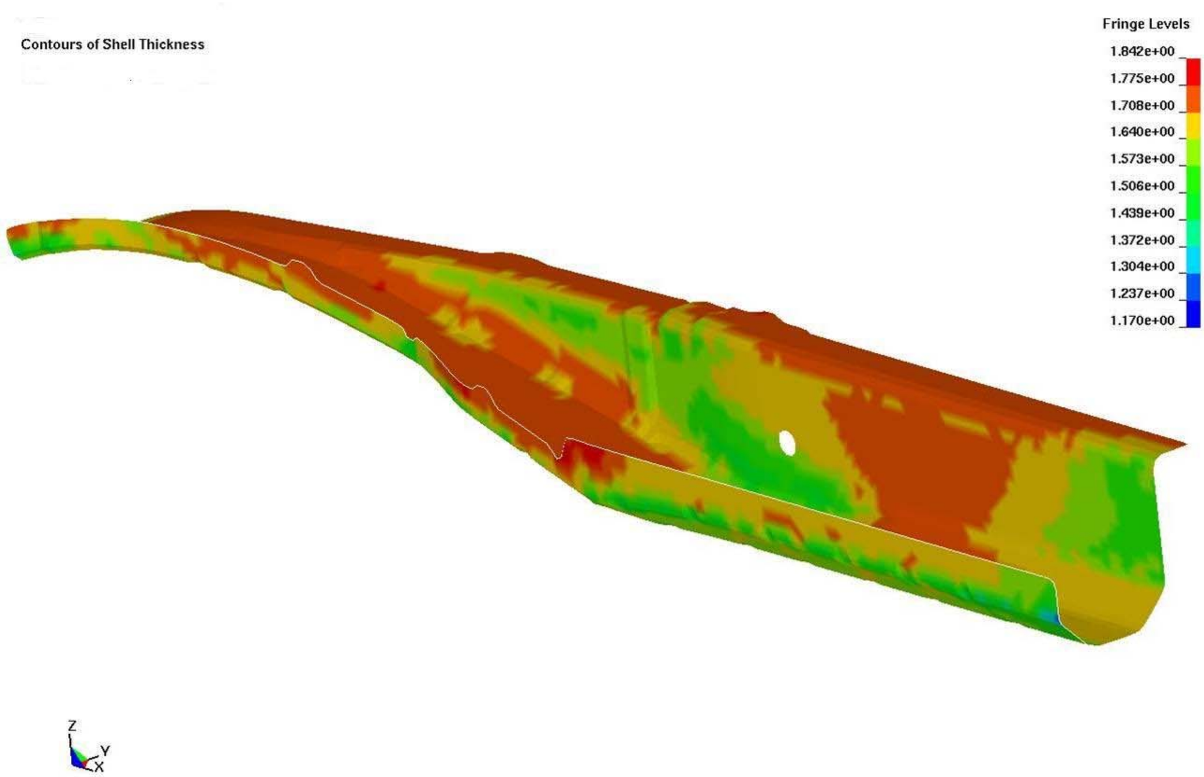


Figure 3 – Spatial distribution of thinning of a deterministic forming simulation mapped onto the FE-mesh of crash calculation

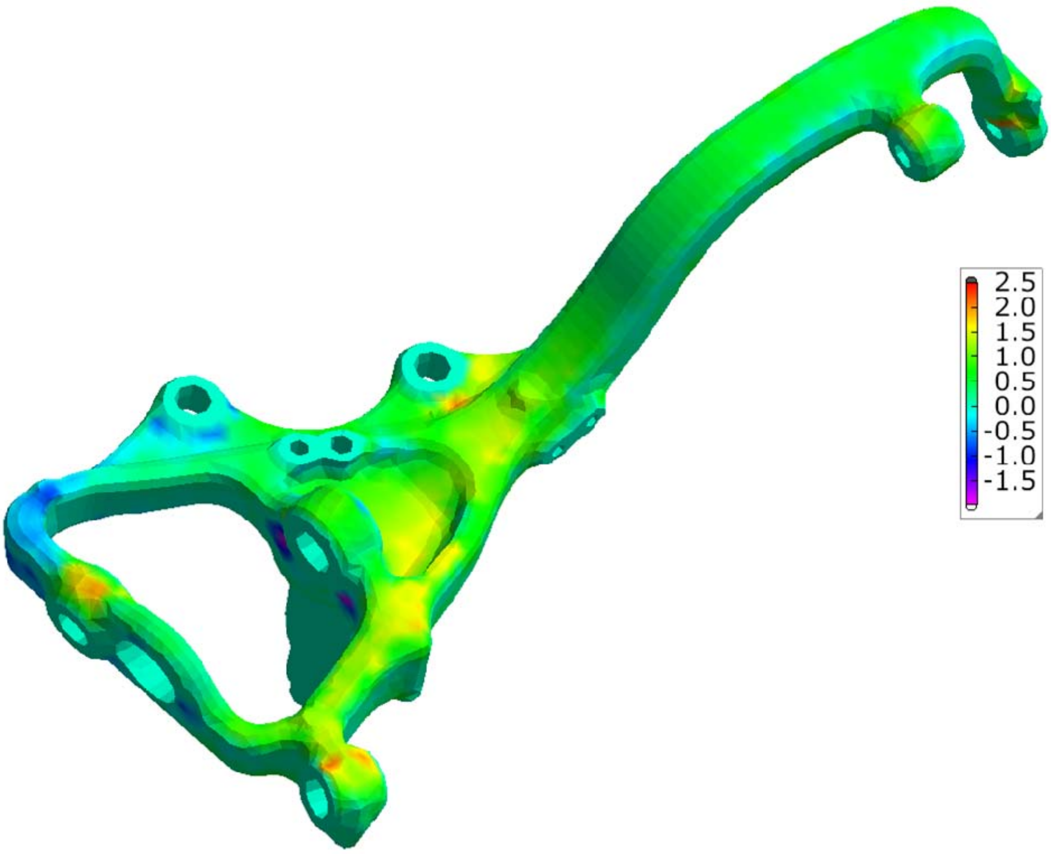


Figure 4 – Spatial distribution of tolerances of a casting component, shown as differences between finite element discretisation and measurement.

3.2.2 Integration of scatter of spatial correlated values in robustness analyses

If consideration of simulated or measured deterministic spatial correlation of input values has significant influence on response values, it has to be examined how strong the scatter of the spatial correlated input parameters is influencing the result parameters. Robustness analysis can provide the answer. Beyond the scatter of single input parameters, also scatters of spatial correlated input parameters are considered.

One approach of consideration of spatial correlated scattering values would be to measure n-components and to use the set of random realisations in the robustness analysis. The same procedure can be used if n-scattering realisations are generated via stochastic simulation of the production process, such as a forming simulation. Without any parametrization of spatial correlated scatter this approach only allows the determination of the resulting variation of response parameters. Typically, scattering of spatially correlated values occurs for different reasons and are related to different shapes of scatter. To determine the underlying correlations, it is necessary to introduce a parameterization of spatially correlated scatter.

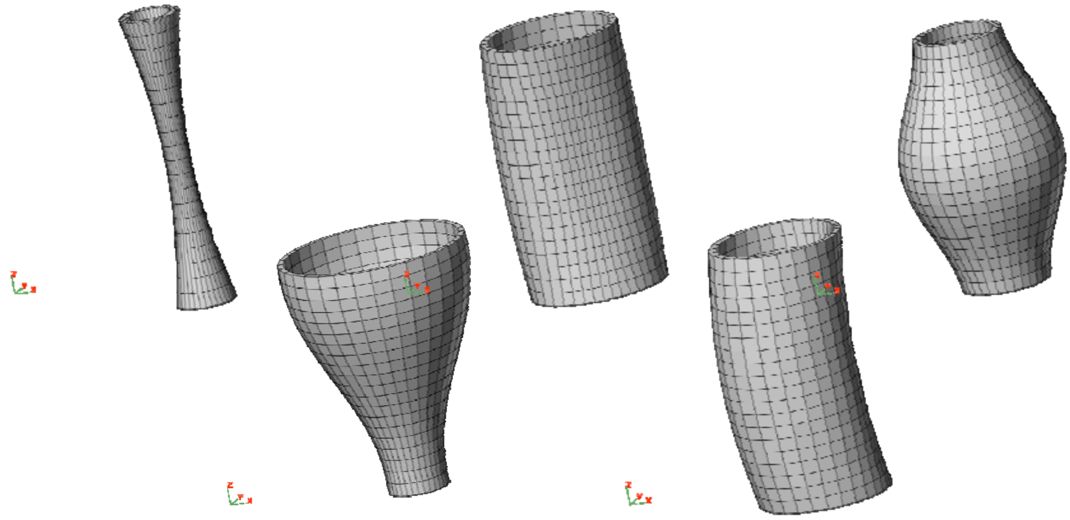


Figure 5 – different shapes of geometry scatter of a cylinder, used to parametrize spatial correlated scatter

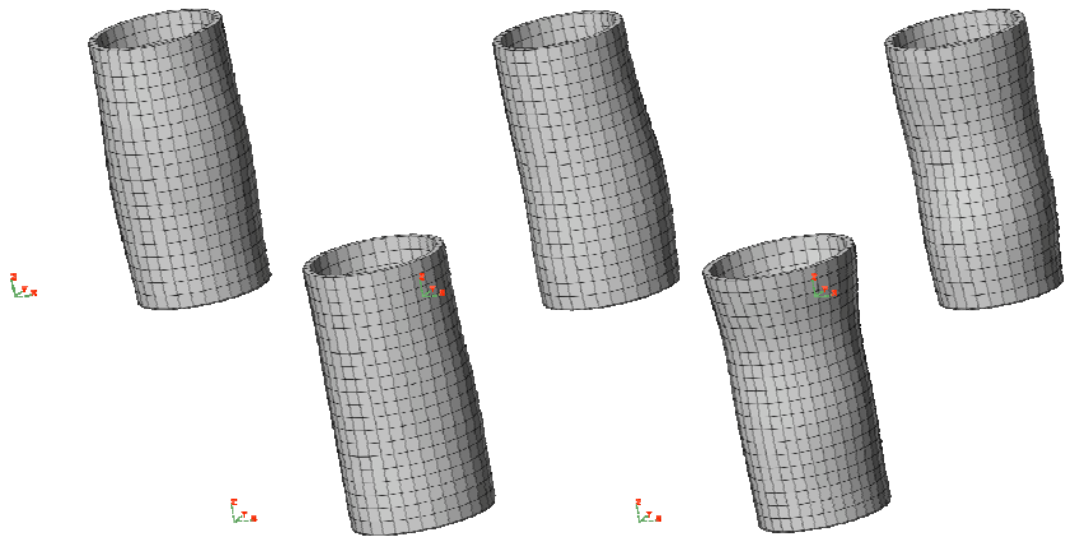


Figure 6 - Realization of the imperfect structure from n-random fields with n-random amplitudes

For the parameterization of scattering spatial correlated input variables, the theory of random fields can be used. It is assumed that the resulting scattering consists of n-possible forms (figure 5) with n-scattering amplitudes. These forms can be calculated from several measurements of the scatter by estimating co-variance matrices and correlation lengths. Like modal shapes there exist as many shapes as degrees of freedom of the underlying matrices. From the n-possible forms, the important random fields to represent the measured variation and their random amplitudes can be extracted like the selection of important modal shapes regarding the participation factors. With this parameterization of random fields, n-realizations of components can be simulated which correspond in sum to the statistic of measured components (figure 6). In the correlation analysis of the robustness analysis, this parametric allows the identification of forms which are responsible for the result variation of interest. With this approach, important scatter shapes of spatial correlated values from n-measurements or n-process simulations can be extracted. At the best, the underlying mechanisms which lead to the scatter can be identified.

4 Search for single test results in the variation space of robustness analysis

Today in virtual product development tests are carried out at different mile stones to validate and verify virtual prototyping. Unfortunately some time phenomena can be detected in tests which have not been assessed in the virtual calculations before it. Then the question occurs is the input scatter the reason of the test phenomena. Consequently it is analysed by robustness evaluation, if the scatter of input parameters can be identified as reason.

Before single simulations were compared with single measurements. Now robustness analysis allows the comparison of the scatter band with the comparison of single or several test values. Thus it is expected that every test lies within the scatter band of the robustness analysis. If this is not the case, not all physical phenomena are sufficiently considered by the simulation model or the naturally existing scatter might not be described good enough with the so fare used statistical definitions of scatter. In reverse, if experimental phenomena can be found within the scatter bands which before could not be explained in single calculations of the virtual prototype, the therefore responsible input scatter can be identified.
In case of successful applying robustness analysis to discover of test phenomena that is often the first step of integration of stochastic calculations into virtual product development processes.

5 Follow-up actions for the real design, the test planning and virtual product development

After successfully discovering experimental phenomena by robustness analysis and identifying their causes, the methodology is gradually used for the statistic (stochastic) validation in virtual product development before tests are carried out. Statistical response parameters are used for actions in the simulation model, the real design and the test execution. Here the question arises, how statistical values which are attached with errors are integrated into decisions regarding design modifications or test executions.

Like stated in paragraph 3.1, conservative input scatter can be recommended for robustness analysis. That is why the exceedance of performance criteria with small probabilities (e.g. 1 or 2%) does not necessarily lead to an exceedance of these criteria in reality and does not necessary call for a design change. Small exceedance probabilities can rather indicate relatively small safety distances.
If small probabilities of exceedance have to be ensured in the virtual prototyping it is recommended that the probability values are recalculated in sub-spaces of the most important scattering variables using more precise scatter input combined with methods of reliability analysis. But of course the results of the robustness analysis can be used as motivation to increase safety distances – with or without the verification of small probabilities.

If the exceedance of objective criteria occur with a high probability (e.g. >10%) and the assumptions for the therefore responsible input scatter can be expected in reality, design modifications are recommended that increase the safety distance. After the design modifications, it is useful to validate the achieved improvement by using a robustness analysis. Often literature of design for six sigma or robust design strategies stress the fact that in case of robustness evaluation the input scatter should be decreased. Our experience over the last five years introducing robustness evaluation at different industrial areas tell us that very often input scatter cannot be reduced at all or such actions are very expensive.

Other benefit of the robustness evaluation is that the knowledge about the most important input scattering can be used for the following validation test of the real design to optimize the test planning so that relevant areas of the robustness space are assured by the test.

The generated knowledge about which input scatters are important for the performance criteria can be used for formulation of design load cases for virtual prototyping. Design load cases are typically used to generate critical test configurations or worst case configurations of material parameters. Then the safety distance is introduced at the input side by worst case configuration of input variables.
On the other hand the knowledge about typical scatter bands of the performance criteria can be used to determine safety factors regarding the performance criteria. Then the safety distance is introduced on the output side for deterministic design load cases using mean values on the input side.

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