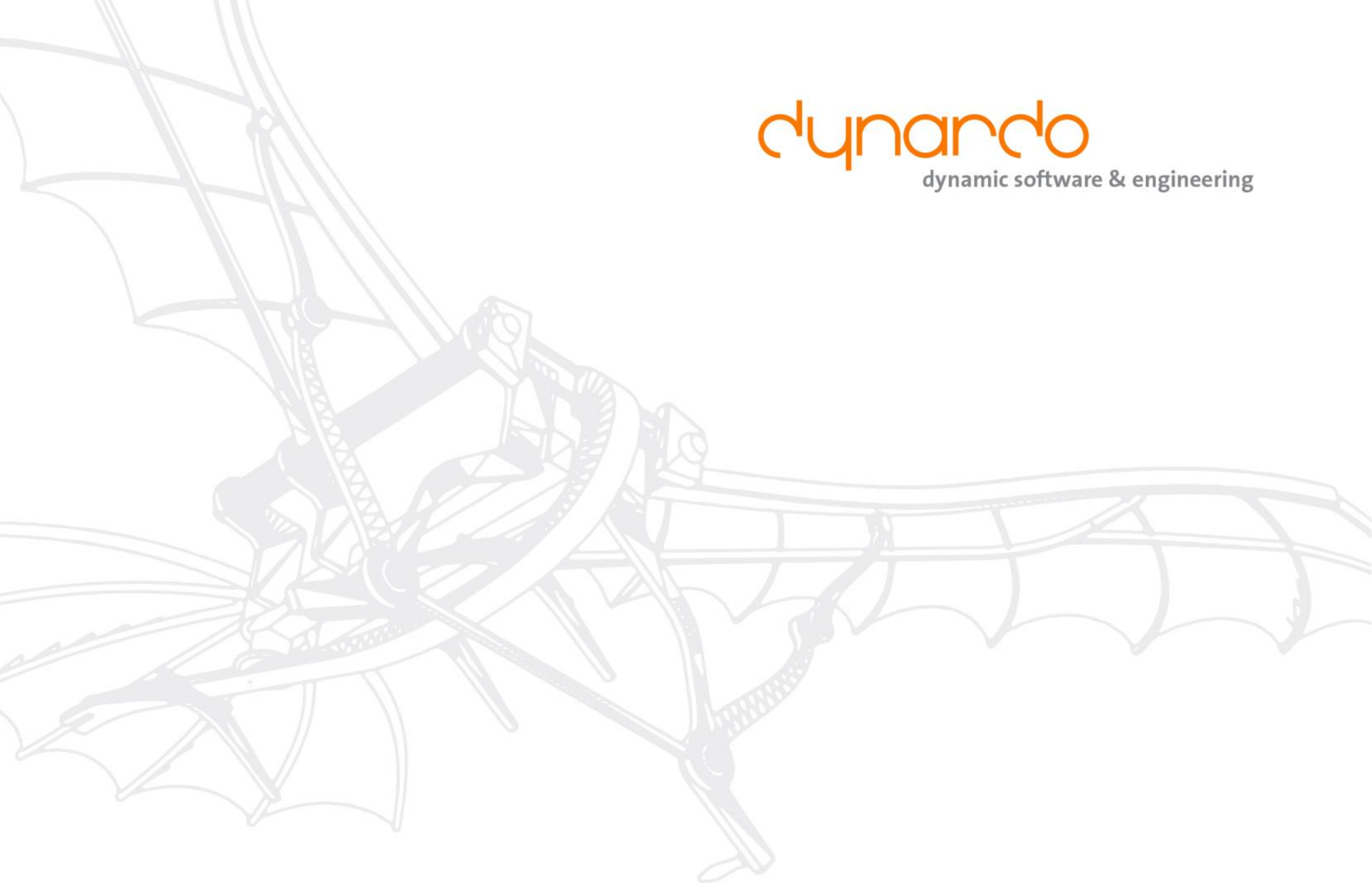

CAE-based robustness evaluation in virtual prototyping – luxury or necessity

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presented at the NAFEMS World Congress 2013
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CAE-based robustness evaluation in virtual prototyping – luxury or necessity

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Summary:

Today, one of the greatest challenges is the rising number of numerical simulations of large tests and analysis programs including CAE-based optimization and CAE-based robustness evaluation while reducing the number of hardware tests. Also, the increasing usage of structural optimization may require CAE-based robustness analysis of “optimized” designs. In many cases, the optimization of cost, performance and weight lead to highly sensitive designs which can lead to substantial robustness defects especially in nonlinear systems. It is no surprise that the increase of virtual prototyping in conjunction with the reduction of hardware tests and development times combined with a very high innovation speed of new materials or electronic components do have some risks. This can be seen in the statistics of product recalls, which have increased significantly in the last few years. Therefore, the topic of CAE-based robustness evaluation assuring serviceability, safety and reliability should be taken into account in virtual prototyping as early as possible.

Looking at the obvious necessity of CAE-based robustness evaluation in virtual prototyping, it is surprising that still only a few publications exist about a successful introduction suitable for daily use. Is the CAE-based robustness evaluation seen as a luxury? Or if not, where are the bottlenecks at implementation.

In this paper, we discuss the status of application in three industrial examples including barriers, bottlenecks and challenges.

Keywords:

robust design, robustness evaluation, Coefficient of Prognosis

1 Introduction

Due to a highly competitive market, the development cycles of increasingly complex structures have to be constantly reduced while the demand regarding performance, cost and safety is rising. The development of innovative high quality products within a short time frame being successful in the international car producer competition is only possible by using CAE-based virtual prototyping. Herein, one of the greatest challenges is the rising number of numerical simulation of large test and analysis programs including CAE-based optimization and CAE-based stochastic analysis while reducing the number of hardware tests.

Also the increasing usage of structural optimization may require CAE-based robustness analysis of “optimized” designs. In many cases, the optimization of cost, performance and weight lead to highly sensitive designs which can lead to substantial robustness defects especially in nonlinear systems. It is no surprise that the increase of virtual prototyping in conjunction with the reduction of hardware tests and development times combined with a very high innovation speed of new materials or electronic components do have some risks. This can be seen in the statistics of product recalls which have increased significantly in the last few years. Therefore, the topic of robustness evaluation assuring serviceability, safety and reliability should be taken into account in virtual prototyping as early as possible.

Looking at the obvious necessity of CAE-based robustness evaluation in virtual prototyping, it is surprising that still only a few publications exist about a successful introduction suitable for daily use. Is the CAE-based robustness evaluation seen as a luxury? Or if not, where are the bottlenecks in implementation. In this paper, we discuss the status of application in three industrial examples including barriers, bottle necks and challenges.

2 Robustness evaluation

Robustness characterizes the sensitivity of all relevant system responses in respect to the scatter of all relevant input variables, like environmental conditions, material or production tolerances. Of course, designing a robust structure was always a goal in engineering. Therefore, design rules were established ensuring a safe distance from failure to make sure that scattering design responses do not overstep critical limits with a sufficient probability. To cover all possible uncertainties, the design rules need to be very conservative and formulated out of sufficient experience and experimental validation.

But today, we are driving often into situations where design goals, like saving material or going to the limits of material performance, are in conflict with conservative safety distances or safety factors are not available at all. Here, we need to verify the design robustness using real world test matrixes or a combination with virtual ones, We also can rely purely on CAE-based robustness evaluations.

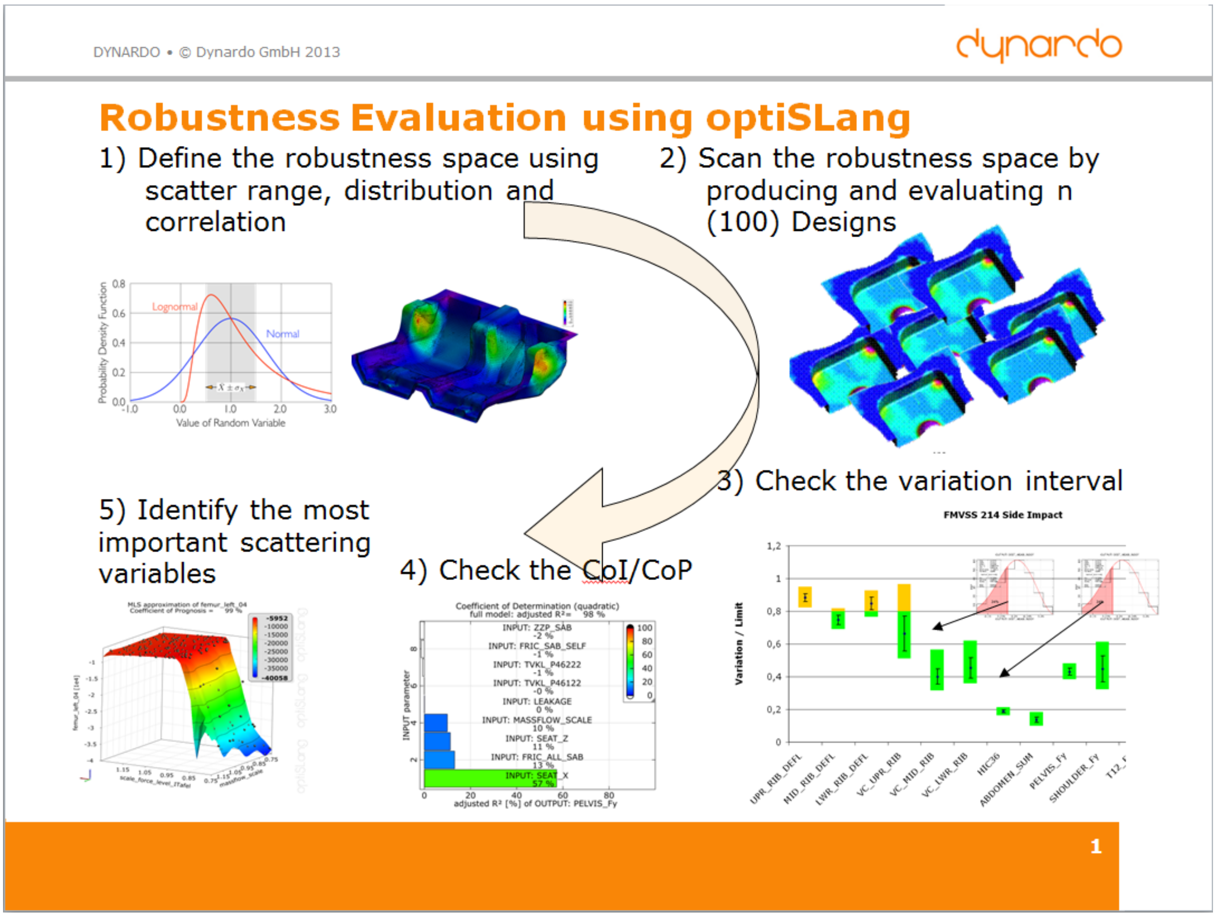
Having enormous time and cost pressure caused by the market competition, it is rather consequent that probabilistic methods using CAE-based stochastic analysis become mandatory in virtual prototyping in order to quantify robustness, safety and serviceability.

Dependent on the robustness evaluation criteria, variance-based robustness evaluation (robustness evaluation) or probability based robustness evaluation (usually called reliability analysis) has to be utilized [1]. In variance-based robustness evaluation procedures, a medium sized number (100 to 150) of possible realization samples among the input variables are generated by Latin Hypercube Sampling (LHS). After calculating the sample set, the variation of important system responses and their correlation to input scatter is investigated. By running a sample set of around 100 Latin Hypercube samples, reliable estimation of event probabilities up to 1 out of 1000 (2 to 3 Sigma range) is possible.

For rare event probability estimations, like 1 out of 1,000,000 (4 to 6 Sigma range), probability-based robustness evaluations using gradient (FORM) or sampling based (ISPUD, adaptive sampling, asymptotic sampling) stochastic analysis methodology [2] becomes necessary. Because effective algorithms of reliability analysis may fail to learn how to locate the rare event failure points in the space of uncertainties, we recommend using multiple algorithms to proof the forecast of rare event probabilities. Therefore, probability-based robustness evaluations usually require much more design evaluations than robustness evaluations especially in case of a large number of scattering variables. For computationally expensive simulation, the required large number of simulation was a significant barrier to start in the past. But with rising CPU power and the availability of intelligent load sharing systems that barrier melts down and will not be the main bottle neck in the future anymore.

From our experience, the key for a successful integration of robustness evaluation in virtual product development cycles is an appropriate balance between introduction of input uncertainties, stochastic analysis methodology and post processing. If we miss this balance, the main results of the stochastic analysis or the variation as well as the correlation estimation may become misleading, wrong or even useless. For example, if we miss the most important input scatter, the variation prognosis is useless. If we use the wrong sampling (like 100 Monte Carlo Sample), the reliability of correlation measurements is very low or if we only test linear correlation, we may miss the most important correlation between input and output scatter.

Consequently, the best possible translation of all knowledge about input uncertainties and the contribution of all potentially influencing uncertainties are very important. In real world applications, we therefore need to consider a large number of uncertain variables. A result of a robustness evaluation of full car applications may contain several hundred scattering inputs. Because the reduction to smaller sets of variables is only possible with a reliable knowledge of the variable unimportance, the use of objective measurements of variable importance, like the Coefficient of Prognosis (CoP) [3], is mandatory.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Robustness Evaluation using optiSLang

1) Define the robustness space using scatter range, distribution and correlation

2) Scan the robustness space by producing and evaluating n (100) Designs

3) Check the variation interval

4) Check the CoI/CoP

5) Identify the most important scattering variables

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Figure 1 Diagram of CAE-based robustness evaluation workflow

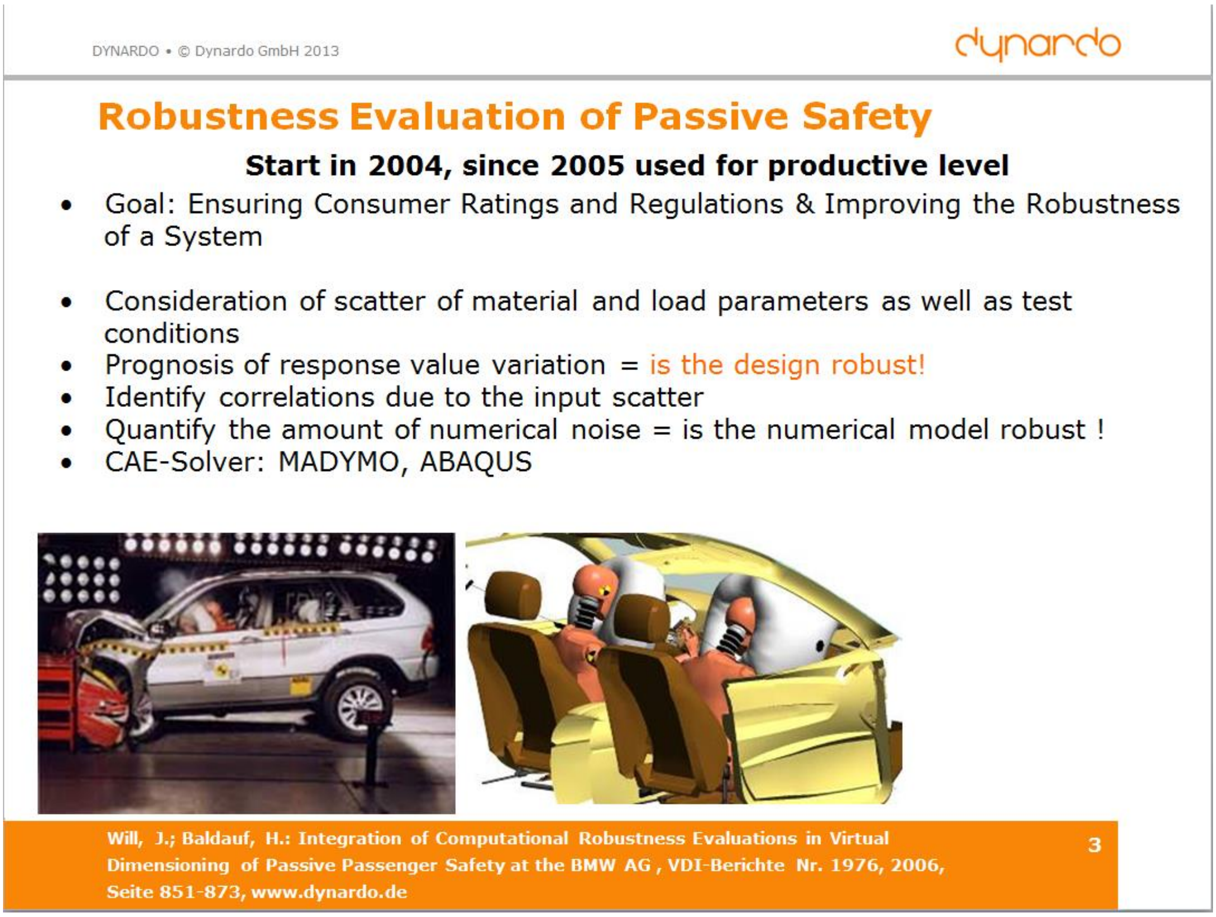
3 CAE-based robustness evaluation in passive safety [4]

Robustness evaluations are performed by the car producer as soon as possible after assembly of the numerical car model and the calibration of the most important passive safety test load cases to previous car lines. Important scattering input parameters which need to be considered are the definition of uncertainties in regard to test conditions (dummy positioning), environmental condition (friction) or uncertainties of airbag system (time to fire). Uncertainties of car interior or other components of the restraint system as well as load transmitting due to the car front represented by a “puls” loading also have to be taken into consideration.

Challenges of implementation: One of the main challenges during implementation in daily use is the parametric definition of varying dummy seat positions. Using multi body dynamic modeling approaches and after moving the seat position, it was necessary to implement a dummy positioner to correct the position of legs, feet, arms as well as hands for gaining valid dummy positions. Using the finite element modeling approach, it was necessary to run a “sit-in” simulation for every different seat position. A matrix of different seat positions which covers the test set uncertainties was finally used for the robustness evaluation.

Success keys for implementation: The most important success keys were the process automation including preparation of all necessary parameters and the standardization of the post processing using normalized criteria status. Due to process automation and introduction of parametric models, no further modification of the model or the process chain was necessary after a robustness evaluation was performed.

Customer benefits: The main benefit is the early identification of critical load cases where important criteria overstep limits in the current design of the restraint system. For these responses, the responsible input variations were identified. Part of the post processing is the ranking of numerical robustness of the model using the Coefficient of Prognosis (CoP). For this ranking, the identification of modeling errors as well as response values that have a large amount of numerical noise were used. A ranking for design robustness was finally generated showing whether important responses stay within the limits. Another benefit was the ranking for the numerical robustness of the simulation model. Having this knowledge, necessary investments in design modifications or modeling efforts to improve the quality of the numerical models can be allocated. Numerical robustness evaluations help to reduce the number of hardware tests. For load cases having sufficient safety margins, virtual robustness evaluation is adequate to prove passive safety and no hardware tests are required.



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Robustness Evaluation of Passive Safety

Start in 2004, since 2005 used for productive level

- Goal: Ensuring Consumer Ratings and Regulations & Improving the Robustness of a System

- Consideration of scatter of material and load parameters as well as test conditions
- Prognosis of response value variation = is the design robust!
- Identify correlations due to the input scatter
- Quantify the amount of numerical noise = is the numerical model robust !
- CAE-Solver: MADYMO, ABAQUS

Will, J.; Baldauf, H.: Integration of Computational Robustness Evaluations in Virtual Dimensioning of Passive Passenger Safety at the BMW AG , VDI-Berichte Nr. 1976, 2006, Seite 851-873, www.dynardo.de

Figure 2 Robustness evaluations for passive safety

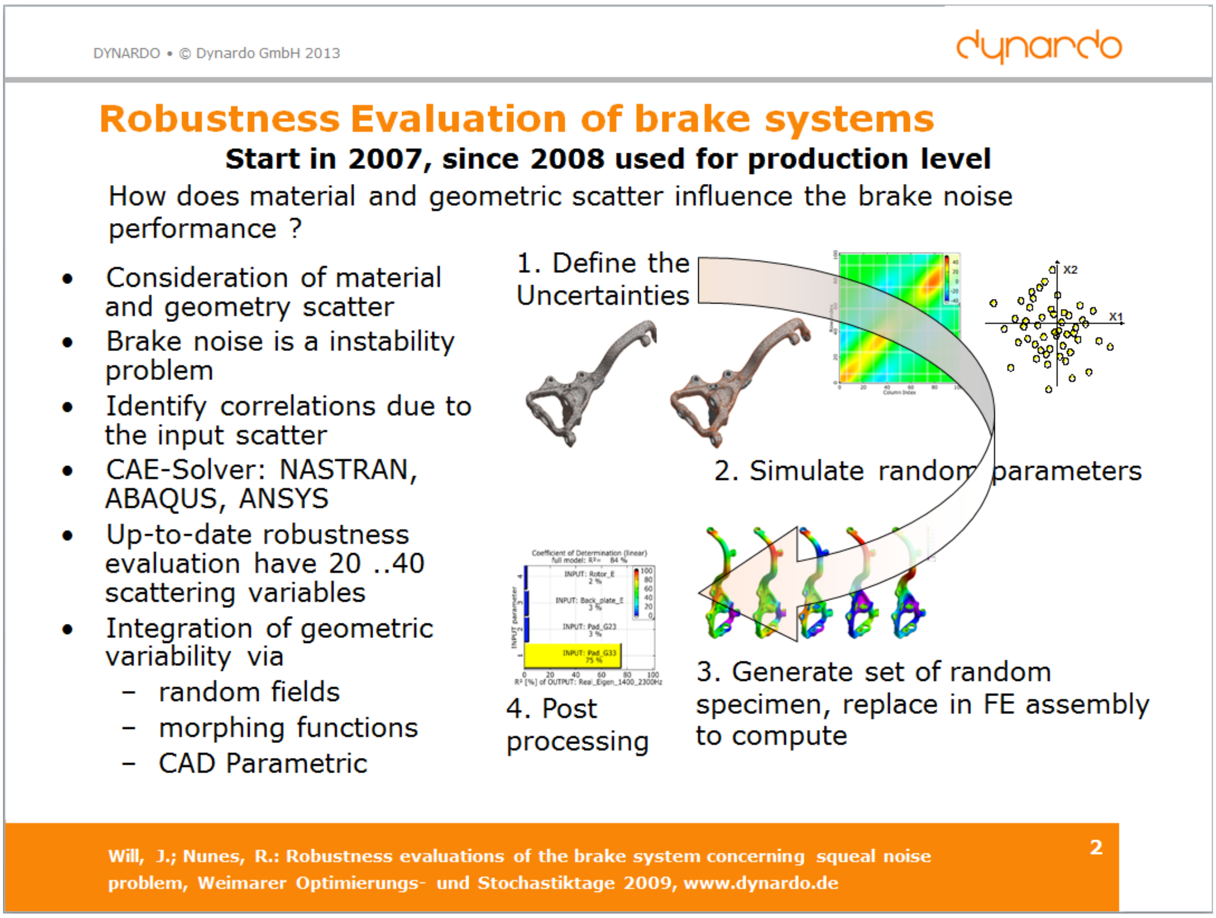
Bottleneck: Since there are several milestones in the development process defined for which robustness evaluation should be performed, the parametric model setup, the numerical model robustness and the status of limit violation sometimes postpone the robustness evaluation to later stages. If the CAE engineer does not see a chance to demonstrate robustness or if he still wants to improve the model or the design before starting the robustness evaluation, he may miss the time gates and the robustness evaluation is skipped or postponed to the next milestone.

Future challenges: The main input for a robustness evaluation is the definition of uncertainties. The verification of the assumptions about uncertainties is therefore an ongoing process. Here, it is very important to improve the calibration with all available test results. The main results of the CAE-based robustness evaluation of course need to correlate to the results and the tests should be in the forecasted window of variation. Like every step in the virtual prototyping, optimizing of costs and the number of virtual robustness evaluations will be an issue. Optimal process automation and parametric modeling are the keys in this process. The next challenge to further shorten design cycles is to perform a robustness evaluation as early as possible also in the component level.

4 CAE-based robustness evaluation of brake squeal [5,6]

Robustness evaluations are one of the most important quality criteria for brake systems. Brake noise results from instabilities in the dynamic behavior if energy is moved from one mode to another. The function of brake systems is exposed to large variation in environmental conditions, production tolerances as well as fading effects on the brake pads. At the same time, the dynamic performance of the brake components interact with a large number of other parts in the car assembly. Up until now, a brake system functioning completely “noise-free” has not been achieved yet. Today, with a test matrix of different pressure and friction conditions, the brake performance is tested in hardware and virtual experiments. Since quality requirements even increase the challenge to design brake systems, production becomes prohibitively expensive or impossible especially if only hardware tests are conducted. As a result, OEM’s and brake producers worldwide are pushing CAE-based robustness evaluation into virtual prototyping making it a part of CAE-based robust design optimization strategies. The analysis method CEA (Complex Eigenvalue Analysis) is “linearizing” the system with the definition of contacts between the rotation parts of the brake system. This “linearization” needs to be verified with tests, i.e. critical Eigenfrequencies, which show negative damping ratios larger than 2% need to be verified to be critical in the real world using hardware tests. Only when the numerical model is validated against hardware test results is the model qualified enough to be used for forecasting the robustness against brake squeal and the minimization of the brake noise probability as a result of geometric modification.

Important scattering input parameters which need to be considered are uncertainties in regard to production tolerances, material tolerances, fading and temperature effects for different load scenarios of pressure and friction conditions.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Robustness Evaluation of brake systems

Start in 2007, since 2008 used for production level

How does material and geometric scatter influence the brake noise performance ?

- Consideration of material and geometry scatter
- Brake noise is a instability problem
- Identify correlations due to the input scatter
- CAE-Solver: NASTRAN, ABAQUS, ANSYS
- Up-to-date robustness evaluation have 20 ..40 scattering variables
- Integration of geometric variability via
  - random fields
  - morphing functions
  - CAD Parametric

1. Define the Uncertainties

2. Simulate random parameters

3. Generate set of random specimen, replace in FE assembly to compute

4. Post processing

Will, J.; Nunes, R.: Robustness evaluations of the brake system concerning squeal noise problem, Weimarer Optimierungs- und Stochastiktage 2009, www.dynardo.de

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Figure 3 Robustness evaluations for brake systems

Challenges of implementation: One of the main challenges during implementation for the daily usage is the parametric definition of production tolerances of the casted brake parts as well as the parametric definition of the brake pad geometry fading.

Success keys for implementation: Again, the process including parametric variation of geometry of brake parts needs to be automated first and a standardized post processing needs to be established. If system robustness has to be improved, the necessary geometry modifications define additional requirements for parametric geometry. Due to the significant CPU requirements of every design evaluation, it is necessary to establish a highly effective procedure for the combination of robustness evaluation with optimization procedures.

Customer benefits: Numerical robustness evaluations help to reduce the number of necessary hardware tests. Geometric modification of brake components to reach a reduction of brake squeal can be investigated effectively and fast in the numerical world including an optimization being more or less weight neutral.

Bottlenecks: Current numerical brake models which are used in the car assembly to demonstrate the brake performance do not contain parametric geometry suitable for investigating sensitivity toward production tolerances or geometry modifications. Therefore, additional manual work is necessary to provide a parametric model of the geometry. Often the parameters are pure and show only a small potential of optimization or they are not suitable to represent tolerances sufficient enough for robustness evaluation.

Challenges in the future: The main input to the robustness evaluation is the definition of uncertainties, therefore the verification of the assumptions about uncertainties are an ongoing process. Current investigations try to find suitable parametric modeling of fading brake pad effects as well as for representing geometric tolerances of the castes parts. As a result, there will be a challenge for suppliers to provide CAE models of brake components with inbuilt geometric parameters for conducting a robustness evaluation and optimization.

5 CAE-based robustness evaluations in crashworthiness [7]

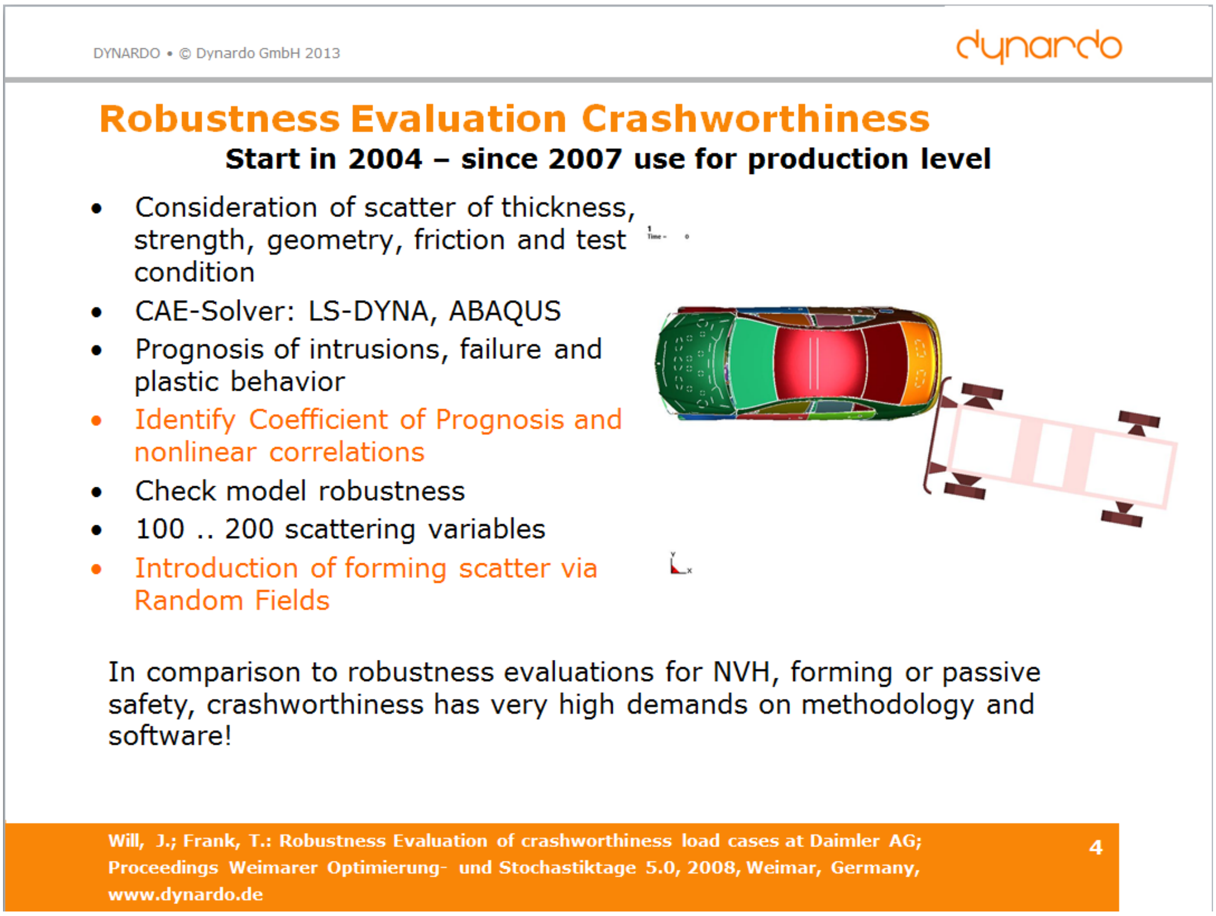
Robustness evaluations are performed by car producers as a part of the development process to fulfill the requirements of passenger crash test. Important scattering inputs which need to be considered are the definition of uncertainties in regard to test conditions (speed, barrier positioning), environmental condition (friction) and uncertainties of crash relevant structures. Also, sheet metal thickness, material energy absorption including damage and failure as well as spot welds or other connections within the body in the white structure state have to be taken into account.

Challenges of implementation: Because the process automation of running crashworthiness load cases is not a problem, the parametric definition of scattering crash relevant structures represent a real challenge. Almost all crash codes use a part structure allowing material definitions to be shared with multiple parts. However, if we introduce material and production uncertainties, every physical part needs to have its own material definition including thickness definition, stress strain curves and failure strain parameters. Because a large number of parts will play an important role within the crash loading, this results in hundreds of scattering parameters and correlated values. To be ready for daily use, it became mandatory to have an automatic parameterization tool. Starting from the current crash deck and a list of parts for which uncertainties need to be introduced, the parameterization tool modifies the crash input deck and introduces all uncertainties based on a database of material variation definitions.

Success keys of implementation: Beside process automation, the standardization of post processing is very important. First of all, limit violations need to be investigated. If limits are violated, minimal and maximal values and statistics need to be post-processed for some results on the finite element structure. Part of the post-processing is the ranking of numerical robustness of important response values using the Coefficient of Prognosis (CoP). Thus, the numerical noise at response values can be adequately quantified.

Customer benefits: Numerical robustness evaluations help to reduce the number of hardware tests. If experience from previous car line and CAE-based robustness evaluations show no robustness problems, hardware tests for these load cases can be minimized. Because the goals are conflicting in different disciplines like NHV, crash and weight optimization, there will be crash load cases where criteria are in danger to be violated. Here, numerical robustness evaluations are necessary to evaluate the robustness as early as possible to improve the design and finally to prove the design robustness as early as possible in virtual prototyping.

Bottlenecks: If the CAE engineer does not see a chance to demonstrate robustness or if he still wants to improve the numerical model or the design before starting the robustness, he may miss the time gates and the robustness evaluation is skipped or postponed to the next milestone.



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Robustness Evaluation Crashworthiness

Start in 2004 – since 2007 use for production level

- Consideration of scatter of thickness, strength, geometry, friction and test condition
- CAE-Solver: LS-DYNA, ABAQUS
- Prognosis of intrusions, failure and plastic behavior
- Identify Coefficient of Prognosis and nonlinear correlations
- Check model robustness
- 100 .. 200 scattering variables
- Introduction of forming scatter via Random Fields

In comparison to robustness evaluations for NVH, forming or passive safety, crashworthiness has very high demands on methodology and software!

Will, J.; Frank, T.: Robustness Evaluation of crashworthiness load cases at Daimler AG; Proceedings Weimarer Optimierung- und Stochastiktage 5.0, 2008, Weimar, Germany, www.dynardo.de

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Figure 4 Robustness evaluations for crashworthiness

Challenges in the future: The main input to the robustness evaluation is the definition of uncertainties. Therefore, the verification of the assumptions about uncertainties is an ongoing process. For some high speed front and rear load cases, the forecast quality of the variation of important responses quantified by the CoP is very low. On one hand, this indicates different mechanisms finally resulting in an unidentifiable response variation with the current number of runs (100-150 designs) or, on the other hand, numerical noise or extraction noise might overlay the results. Here, improvements of numerical modeling of cars and barriers to reduce the numerical noise or alternative response values which are less sensitive to numerical noise need to be investigated.

6 Summary

CAE-based robustness evaluation needs significant additional input regarding the definition of the variation of system uncertainties. In addition, CAE-based robustness evaluations require parametric CAE-models for automatic generation and evaluation of possible design configurations as well as for standardization of post-processing procedures to quantify robustness in terms of variation and identify correlations which explain the majority of the variation using CoP measurements.

From our experience, the key for a successful integration of robustness evaluation in virtual product development cycles is the balance between an appropriate introduction of input uncertainties, stochastic analysis methodology and post-processing. If we miss this balance, the main results of a stochastic analysis, the variation or the correlation estimation may become misleading, wrong or useless. Consequently, the best possible translation of all knowledge about input uncertainties and the contribution of all potentially influencing uncertainties is very important.

The validation of design robustness with experience and experiment are necessary to prove the reliability of the CAE-based robustness evaluation. The connection of CAE-based robustness evaluation and experiments is therefore very important to increase the acceptance of CAE-based robustness evaluation and to establish the methodology in daily use.

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