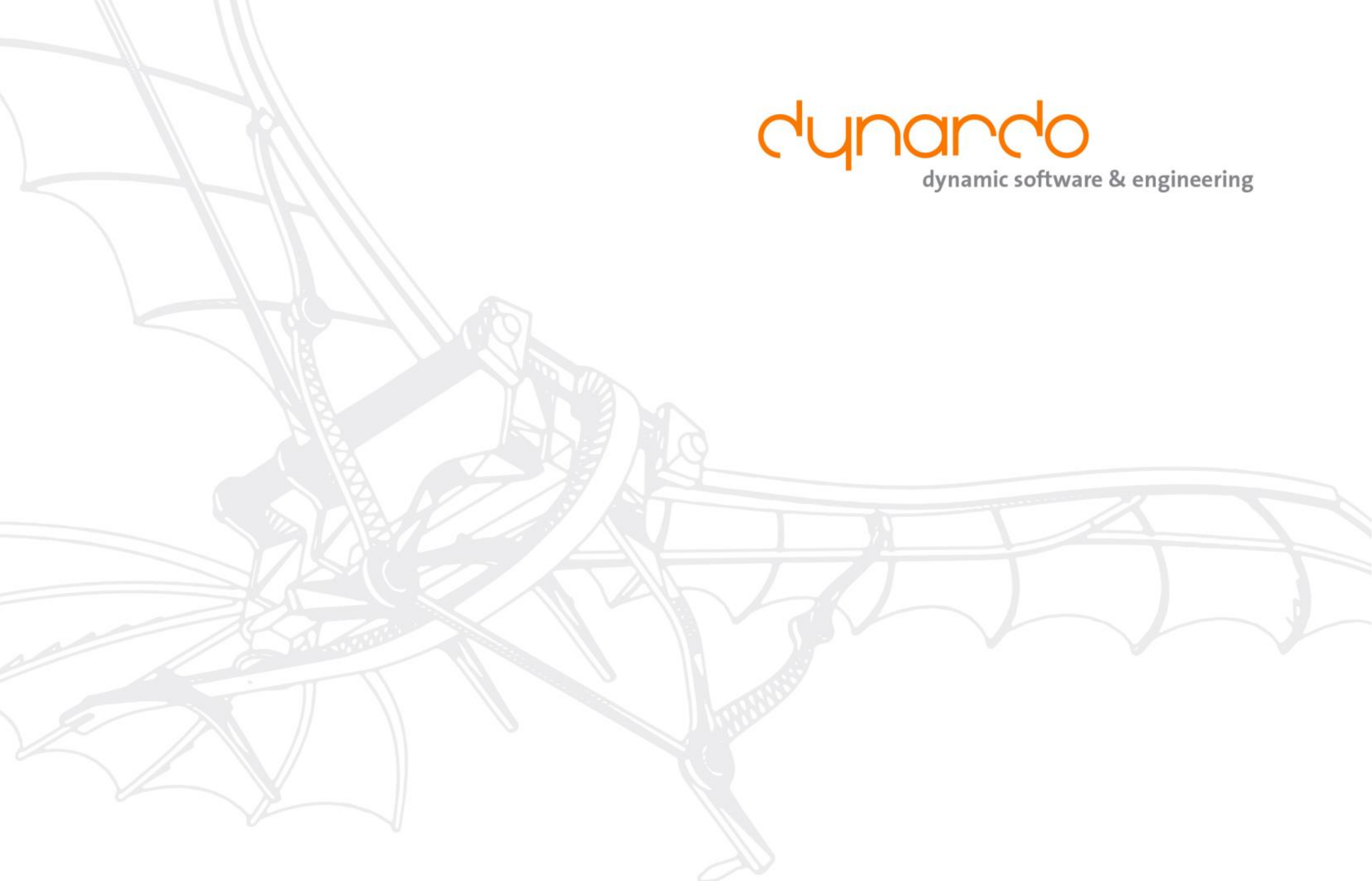

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Lectures

CAE-based Robustness Evaluation of Brake Systems

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CAE-based Robustness Evaluation of brake systems

Abstract

Original Equipment Manufacturers (OEM's) target lower probabilities of brake noise as part of quality requirements for disc brake systems. Since brake noise is significantly controlled by variations in environmental conditions or alterations of brake systems, the brake system needs "in build" robustness against those variations to minimize noise during its lifecycle.

In the past, proof of brake noise quality was primarily based on tests. Currently, it is based on a combination of simulation and testing. Due to cost and time schedule constraints, improvement cycles late in the development process need to be reduced. That is only possible with an increase of Computer Aided Engineering (CAE) based robustness evaluation taking into account all relevant sources of variation which may have an influence on brake noise occurrence. Robustness evaluation is a methodology to investigate how input scatter affects response variation and helps to understand how causes connect to variation in responses.

The paper will discuss the challenges for software tools, CAE-modelling and CAE-processes to successfully apply a CAE-based robustness evaluation for brake noise application in virtual prototyping. It should be noted that Dynardo is a general purpose engineering consultant for CAE-based robustness evaluation and is not specialized for dealing with brake squeal simulation problems. Thus the paper does not address what methods of CAE modeling are appropriate to reflect the underlying physics of brake squeal accurate enough. However, since simulation is used today to investigate brake squeal and simulation models are successfully validated against hardware tests, it can be stated that appropriate CAE-models are available and can be successfully used to perform robustness evaluation.

Introduction

Brakes are one of the most important safety and performance components in automobiles. However, the refinement of vehicle acoustics and comfort by improvements in other aspects of vehicle design has dramatically increased the relative contribution of brake noise to these aesthetic and environmental concerns. Also brake noise is a financial issue, extensive warranty claims driving the research. As a consequence the minimization of noise excitation levels is the most important goal of the virtual product development for brake applications [5].

Today, brake noise excitation is still often verified mainly by using a hardware test matrix of different environmental conditions. This procedure can be interpreted as a test-based robustness evaluation of brake noise against a predefined variation window in pressure, temperature and friction. In the virtual world, this task can be conducted by using validated CAE simulation models combined with available methods of sampling for robustness evaluation [6].

However, using a test matrix of predefined "deterministic" situations, the quality can only be evaluated for "ideal" geometric conditions and single configurations of pressure, temperature and friction. In reality, there will always be additional important variations, such as variation of geometry or brake pad stiffness or pad surface conditions, which may have large influences to the frequency and amplitude of noise excitation [4]. Therefore when performing a CAE-based robustness evaluation of the test matrix (or parts of it) in the virtual world, the variation space should be enlarged to incorporate all potentially influencing sources of scatter and variation. During the last few years, numerous research publications have dealt with different aspects of integrating CAE-based robustness evaluation into virtual prototyping [3,4,5,7]. After introducing fundamental concepts of robustness evaluation and robust design optimization with practical applications, the paper will discuss the challenges of bridging between CAE-based robustness evaluation and quality control.

Product Robustness

There are multiple definitions of product robustness possible. Intuitively a product is called robust if the performance is largely unaffected by scatter. Therefore robustness often is translated to insensitivity to performance scatter. In order to use robustness as an evaluation and optimization criterion, there is a need to quantify how sensitive a design is allowed to be. Therefore probability of violating limits of brake noise is an appropriate indicator of robustness in brake design. If the probability of violating noise limits is small, then the product has enough "in-built" robustness against the expected scatter during product lifetime.

CAE-based Brake Noise Simulation

Brake noise occurs as an instability problem at different frequencies of excitation. In conjunction with an unstable mode, enough energy is available to excite the mode, which leads to build up of noise start. The general avoidance of brake noise over the whole frequency range is very difficult. Often design modifications which are beneficial to one brake noise phenomena move excitation energy to other instability frequencies. However, the minimization and balancing of all critical instabilities over the whole frequency range is going to be the final goal of the product development.

The basic requirement for CAE-based robustness evaluation is the availability of a simulation model which is validated to reflect important instability frequencies and related excitation levels. In order to model brake noise, a finite element method (FEM) based on complex eigenvalue analysis is widely used. The analysis is based on the modeling of a friction contact between brake lining and brake disc in vertical and tangential direction. This model results in a coupling with an asymmetric stiffness matrix and can help evaluate the instability problem based on stable and unstable vibrations in the brake system. For the instability case, a positive real eigenvalue is calculated with related squeal coefficient which indicates the amount of excitation energy for the unstable vibration mode. Usually the minimization of the squeal coefficients is used as the objective to improve brake design. It should be noted that the CAE-based robustness evaluation to simulate the brake squeal phenomenon proposed herein can be performed with any kind of CAE-process and is not specialized for complex eigenvalue analysis.

CAE-based Robustness Evaluation of Brake Noise

For CAE-based investigation of design robustness, stochastic analysis is the method of choice [1]. Within the last 10 years, robustness evaluations based on stochastic analysis have been successfully implemented into various applications in the automotive industry [8].

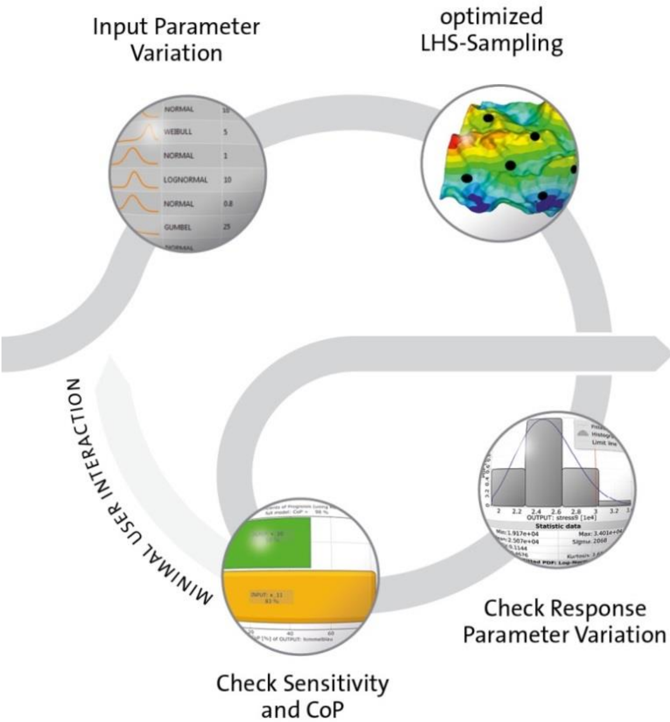

Figure 1. Workflow of CAE-based Robustness evaluation.

The basic workflow of robustness evaluation is the creation and evaluation of a set of possible design realizations (Fig.1). The design set represents a scan of the robustness space which is defined by all important scattering input variables.

The main focus of CAE-based robustness evaluation is the estimation of the variation of all important responses, like squeal coefficients of unstable vibration modes as a result of scattering material, geometry and environmental conditions. The variation is evaluated using minimum/maximum values, histogram and probability measurements. When design responses violate robustness limits, a correlation analysis provide an insight into which input scatter is responsible for the critical response scatter and quantifies their influence on the variation of the responses.

To make sure that measurements of correlation are reliable, a certain number of samples are necessary. However, the number of design evaluations necessary to estimate the important statistical measurements with sufficient confidence depends on the number of important scattering inputs and on the probability of the investigated excitation, which is unknown a priori. Within optiSLang this problem is solved by providing automatic procedures to verify forecast quality of correlation and variation measurements using a minimal design number of the stochastic sampling set [6]. With the help of optimized Latin Hypercube Samplings and variable importance filter technology, the best correlation function in the best sub space of important parameters is found. Thus, the best possible forecast quality of response variations is identified automatically. As a result the necessary effort of sampling-based robustness evaluations for brake systems is minimized. A very important measurement in this process is the Coefficient of Prognosis (CoP). It tells the engineer how much of the variation can be explained by the best possible correlation model between inputs and the result values. Therefore, the CoP safeguards the engineer to spend the amount of runs necessary to explain the correlation structure adequately and post process only relevant correlations. For an industrial example of robustness evaluation refers to [9].

Robustness evaluation starts with the collection of all available knowledge about potentially influencing scattering variables. Typically, the stiffness of a brake pad or other parts of the brake sub system, including geometric tolerances, represents very important scattering variables. In addition, environmental conditions cause a significant variation of friction and pressure. Because the definition of uncertainties is the essential input to robustness evaluations, the best possible translation of all available measurements, experience and expectations of scattering variables is crucial. Minimal and maximal values, distribution functions and correlation between single scattering variables are an important part of the scatter definition.

Different investigations have shown that spatial correlations of geometry scatter of the brake pad or other parts of the system also have a significant influence on brake noise phenomena [3]. Therefore, the sensitivity toward spatial correlation of scattering variables, like geometry or pad surface conditions, should be investigated in addition to single scattering variables, like Young modulus or friction coefficient [9]. Figure 2 shows an example how uncertainties of geometry are measured, transformed into scatter shapes of variation and used to realize imperfect geometries in a CAE-based robustness evaluation. For more details refer to [4], [10] and [12].

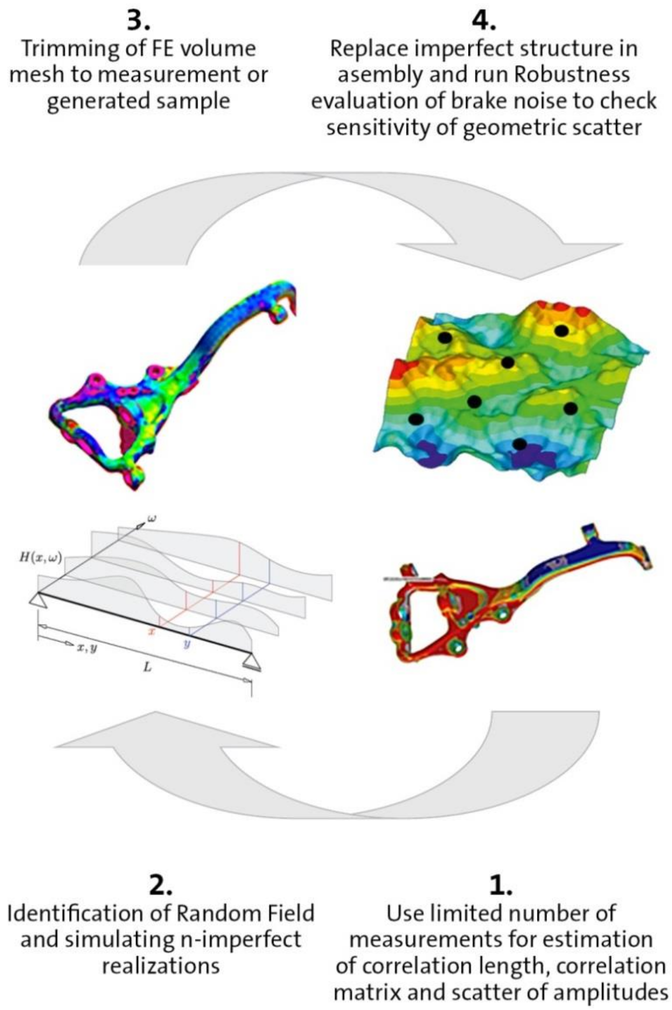

Figure 2. Example use of Random Fields to introduce geometric uncertainties.

It should be noted that if important input uncertainties are not considered appropriately, the results of a CAE-based robustness assessment might be useless for application. Therefore, in the process of integrating CAE-based robustness analysis into virtual product development, the assumptions for all important input scatter have to be checked and verified frequently. In practice, a robustness analysis often starts with conservative estimations of expected input scatter using uniform distribution between conservative lower and upper bounds. If the design is robust against conservative (larger than in reality) input scatter, the engineering task is successfully proven. If certain input scatter is identified to be important and the current variation estimation of squeal coefficient violates robustness limits, these assumptions about important scattering input variables should be verified and, if necessary, should become more detailed and realistic. All robustness quantification based on simulation or real world measures depend on the reliability of the estimation of variation. To rank CAE-based robustness evaluations as “having sufficient forecast quality to be used as a reliable measure for brake system robustness”, the proof that the forecasted window of variation includes all available real world measurements is very important.

CAE-based Robust Design Optimization

Of course, in case of design robustness problems, engineers are asked to optimize the design. A first possible approach could be the reduction of input scatter to decrease resultant output scatter. However, this is most likely going to be an expensive and limited procedure. A better approach would be to modify the design to become less sensitive regarding input scatter or have a sufficient safety distance to limit violations. It should be noted that the design space of optimization, usually defined by geometric modification of brake parts and the robustness space, defined by all relevant scattering inputs are different.

Since the main response to be optimized in brake squeal applications is the robustness measure, the optimization task, searching for the optimal design in the design space, has to be combined with robustness evaluation of all investigated designs during optimization– the so called Robust Design Optimization (RDO) approach.

Figure 3 to 5 refer to an industrial example of RDO for a brake noise application which was presented in [5]. Figure 3 shows two main excitation frequencies of the deterministic simulation. That two frequencies could also be found excited at the bench tests. After testing the brake configuration in an early phase of the product development, it was decided that the noise excitation should be reduced. Altogether the excitation levels for three frequencies did show to high excitation levels.

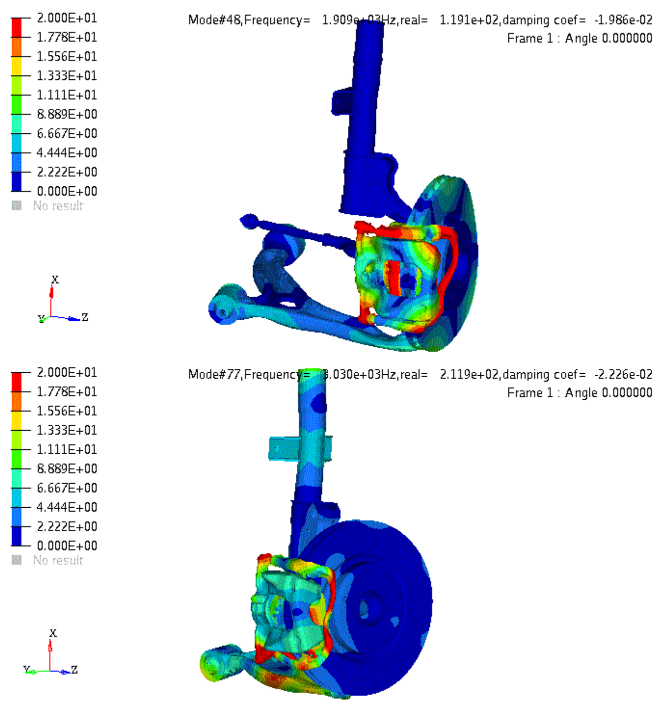

Figure 3. Excitation of two critical modes

It should be notes that the deterministic FE calculation was not able to identify the third squeal frequency found in the bench test. But because the robustness evaluation of the base design did show all three critical frequencies it was proven that all relevant frequencies could be identified using CAE-based robustness evaluation and the windows of variation caused by expected uncertainties covered the bench test results. Thus, a valid base was generated to start a robust design optimization.

To optimize the system, geometric variations of the brake disc were tested. Figure 4 shows the parametric modelling of the disc using morphing functions. Within the window of geometric variation described by the morphing function, the potential for minimizing the excitation of the three critical frequencies is investigated by performing a robust design optimization.

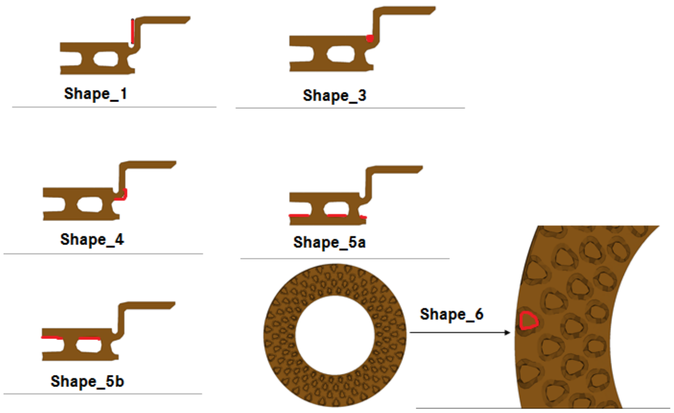

Figure 4. Parametrization of brake disc geometry using morphing functions (geometric variation windows marked in red)

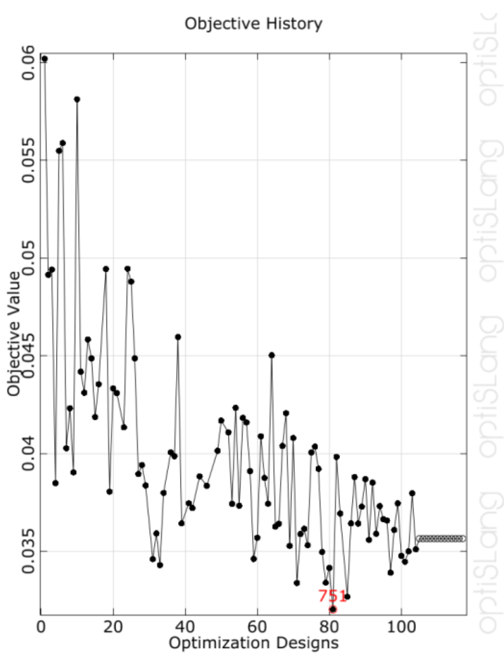

Figure 5. History of excitation levels of the three main frequencies during the robust design optimization

The RDO history is shown in Figure 5. More than 1000 designs were run for optimization and robustness evaluation. Because of the difference between the design space of the optimization defined by the morphing functions and the robustness space defined by 40 scattering variables, for every optimization candidate a robustness evaluation needs to be performed. An adaptive response surface method was conducted to minimize the number of solver calls in the optimization loop. For the robustness evaluation, a minimal Latin Hypercube Sampling of 10 designs was used. After 5 iterations of optimization, interesting candidates were identified and the RDO was stopped.

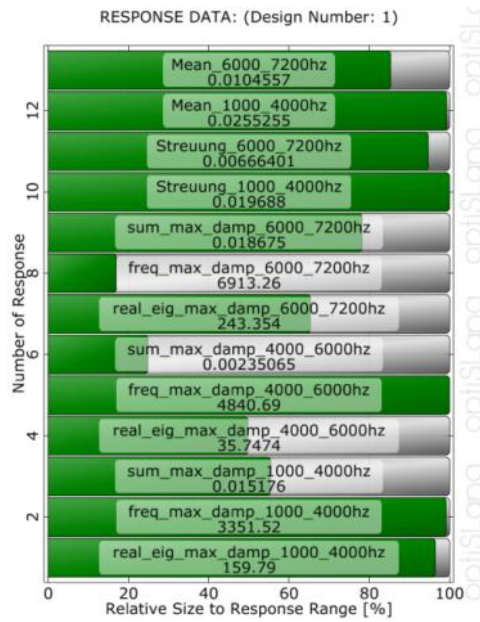

Figure 6. Evaluated responses during the RDO, start design #1,

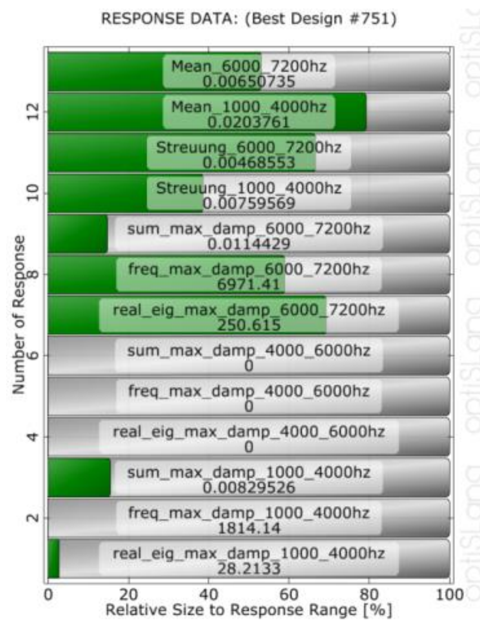

Figure 7. Evaluated responses during the RDO, best design # 751

At the best designs the excitation level of all critical frequencies could be reduced. Figure 6 shows the investigated response values of the start design. Figure 7 shows the same values at the optimized designs. The excitation, measured with damping coefficients as sum of damping coefficients within a frequency window, reduce for the first and second critical frequency (sum_max_damp_1000_4000hz) from 1.5% to 0.8% and for the third critical frequency (sum_max_damp_6000_7200hz) from 1.8% to 1.1%.

The best compromise design was selected and investigated with an extensive robustness evaluation using 50 Latin Hypercube samplings. The design did not show excitations levels which violated targeted limit.

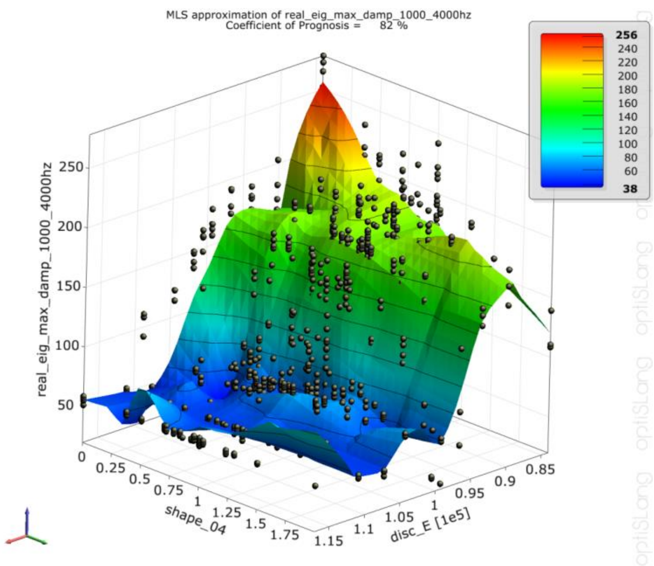

Figure 7. Visualization of interaction of most important optimization variable (shape_04) and most important scattering variable (disc_E)

By investigating the correlations between input variation and response variation using Metamodels of optimal Prognosis (MOP) [6] it was identified that the target design improvement was connected to stiffer brake disc. Thus along with a modification of the most important geometric optimization variables a stiffer brake disc was introduced in hardware. Finally, the changed disc design was successfully proved in a hardware bench test regarding its reduced noise excitation.

Challenges of Implementing RDO into Standard Processes of Virtual Prototyping

The methodology of CAE-based RDO is available in multiple software tools. Together with the increasing hardware power to run multiple designs there seems to be no limits of CAE-based RDO implementation. On the other hand, publications about CAE-based RDO for real world applications are still rare. Most publications still deal with demo or research applications. With other words, where are the bottle necks of an RDO implementation in virtual prototyping?

After more than 10 years of experience in introducing CAE-based robustness evaluation and CAE-based RDO for different applications in the automotive industry, we summarize the main bottlenecks as follows:

- The availability of parametric models in the current simulation processes supporting the automatic generation of geometry variation for optimization purpose. Although shape functions on FE-surface meshes (refer to Fig. 4), CAD parametric [3] or parametric geometry in CAE design modelling environments [2] are available for geometry variation, some of them still need a lot of manual preparation and have a lot of limitations to result in sufficient geometry variation freedom.

- The availability of parametric models which support the automatic generation of imperfect geometries of brake components for robustness evaluation purpose. Here, today, often parametric models from optimization tasks are recycled to mimic imperfect geometry. However, there are many limitations to gain realistic imperfect geometries using artificial deformation shapes from optimization. A more appropriate way to introduce geometric imperfections would be the identification and introduction of more realistic shapes of geometry variation using random fields [4]. Furthermore, the generation of synthetic random fields [7] would represent more realistic spatially distributed uncertainties, like for brake pad profiles.

- The availability of knowledge about all relevant input variations and the appropriate translation into variation windows and distribution functions. Especially, the identification of valid scatter shapes requires a valid base of samples generated out of virtual simulation of production processes (like cast simulation) or out of multiple real world component measurement. Both are usually not part of current product development or quality management processes.

Therefore, its crucial to improve the generation of a parametric CAE-process including appropriate parametric for optimization as well as robustness evaluation before we will see more successful industrial applications. At the same time knowledge and proper translation of uncertainties in parametric CAE needs to be improved.

Same kind of importance is to be given to improve the efficiency of software solution, meeting the challenging requirements of the software tools for stochastic analysis and optimization. Still a single evaluation of brake noise consumes significant CPU requirements. Therefore software to address Robustness and RDO needs to have most efficient sampling based robustness evaluation as well as most efficient optimization technology. It has to be capable of processing a large number of potentially influencing scattering parameter using a minimal number of design evaluations. Robustness evaluations with sufficient forecast quality in regard of the variation window of brake noise needs to address 20 to 40 scattering variables (see application example figure 5) including stiffness and geometric scatter of all parts of the brake system, joint stiffness as well as scatter of environmental conditions.

Finally the challenges of providing a user friendly interface for generating parametric models, running stochastic analysis and performing post processing will play a significant role in providing a successful application in regular virtual product development processes. A user-friendly interface needs to account for predefined flows of best practice and avoid the need for a specialist in stochastic or statistical analysis to run robustness evaluation routinely in the virtual development process. Providing all necessary functionality and providing interactive post processing, optiSLang [11] and SoS [12] safeguards the user through the robustness evaluation.

Bridges to Quality Control

After a successful implementation of CAE-based robustness evaluation, the following bridges to quality management can be built:

- Brake noise quality can be checked at early stages in virtual prototyping as a part of quality management
- Improvement of "in build" robustness of the systems to defined production tolerances and expected variation of environmental conditions to increase safety distances to noise excitations and minimize probability of noise event
- Quantification of noise probabilities can be introduced to quality management
- Identification of critical tolerances and loading configurations to forecast critical test configurations
- Identification of non-critical tolerances to address cost saving potentials in production
- Identification of non-critical test conditions at matrix (bench) test to address cost saving potentials in testing

Summary

The paper discussed CAE-based robustness evaluation and RDO as methods to achieve a more robust brake system in virtual prototyping as early as possible in the product development process. Stochastic analysis was introduced to quantify robustness and the necessary balance between the definition of uncertainties, stochastic sampling methods and the evaluation of robustness was discussed. Main result of a robustness evaluation is the estimation of variation windows of important design performance criteria, like squeal coefficients of unstable vibration modes which are used to check and prove robustness of the designs. In addition, the sensitivities of material, geometry and environmental scatter toward brake noise phenomena is investigated. CAE-based robust design optimization is applied to minimize sensitivities to brake noise and minimize noise probabilities.

Because every design evaluation in the virtual world needs significant amounst of simulation time, CAE-based RDO is both time- and resource-consuming. Still it is a challenge to balance between the definitions and discretization of uncertainties, the reliability of stochastic analysis methodology and the reliability of the results of variation and correlation using a minimum of design evaluations.

After reliable measurements of robustness are derived, these measurements are the basis to quantify the robustness of brake design. With the help of CAE-based robustness evaluations, critical hardware and test conditions can be defined and validated with real world experiments at important gates of product development and production. With the identified sensitivities to important variation sources, worst case scenarios can be defined and investigated virtually or by hardware tests. An efficient combination of CAE-based robustness evaluation and hardware quality management leads the focus to the most important production steps and critical brake conditions. Furthermore, quality control can be optimized regarding sensitive scattering material parameter or tolerances. Quality and associated costs towards insensitive tolerances can be decreased. Therefore, CAE-based robustness evaluation can play a very valuable part to optimize costs during the quality management process.

The main benefits of CAE-based RDO can be summarized to:

- Better understanding of the brake system
- Identification of sensitive designs parameter and sensitive scatter parameter
- Improving "in build" robustness of the brake systems
- Limiting hard ware tests and placing hardware tests to critical configuration
- Explore cost saving potentials for insensitive tolerances
- Finally minimize warranty costs by minimizing brake squeal probability

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