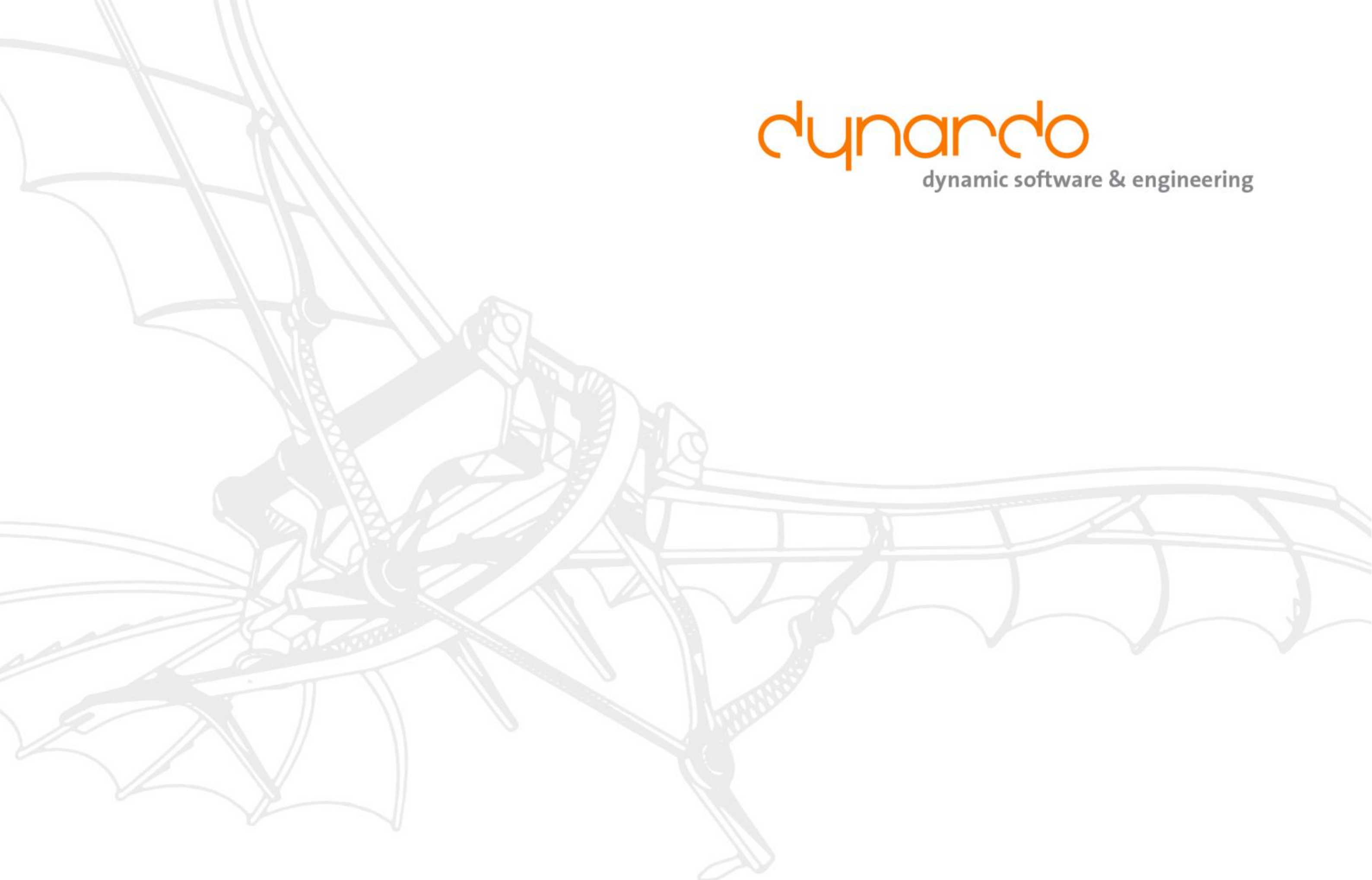

dynardo
dynamic software & engineering

Lectures

Virtual Robustness Evaluation Of Brake Systems as a Base for a Robust Design Process and as a Part of the Quality Control in the Early Stage of the Design Process

Johannes Will

presented at the EUROBRAKE 2013
Source: www.dynardo.de/en/library

EB2013-MS-024

VIRTUAL ROBUSTNESS EVALUATION OF BRAKE SYSTEMS AS BASE FOR A ROBUST DESIGN PROCESS AND AS PART OF THE QUALITY CONTROL IN THE EARLY STAGE OF THE DESIGN PROCESS

[1]Will, Johannes
[1]DYNARDO GmbH, Germany

KEYWORDS - CAD-based robustness evaluation using stochastic analysis, robust design, CAE-based quality control

ABSTRACT – Because time to market becomes shorter the proof of design quality of brake systems needs to be moved into the virtual design process. CAE-based robustness evaluation, CAE-based robust design and CAE-based quality control including minimization of brake noise become more and more an important part of virtual prototyping. Because different frequencies of excitations needs to be taken into account the design and proof of deterministic design load cases, which ensure enough safety distances are difficult or not possible to derive. The alternative to deterministic design load cases is the direct investigation of robustness, robust design and quality control of the brake design in the windows of expected input variation, which are a result of scatter of environmental conditions and production tolerances. Efficient virtual methodology to investigate the robustness is using stochastic analysis to define the uncertainties, create and run the samples and measure the design robustness in terms of probabilities of violating noise excitation levels.

Because every design evaluation in the virtual world still needs significant amount of time 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 can be calculated these measurements are the bases to quantify the robustness of brake design as early as possible in the product development process. Using robustness evaluations selected hardware and test conditions at important gates of the product development are validated. Furthermore the identified sensitivities to important sources help to design worst case test configurations for virtual evaluation as well as hardware test cases. Therefore robustness evaluation can be a very valuable part of virtual prototyping to achieve robust designs fulfilling the quality requirements under all expected environmental uncertainties of brake production and brake use.

INTRODUCTION

Brakes are one of the most important safety and performance components in automobiles. However, the refinement of vehicle acoustics and comfort through improvement in other aspects of vehicle design has dramatically increased the relative contribution of brake noise to these aesthetic and environmental concerns. As a consequence besides braking power, the minimization of noise excitation levels is the most important goal of the virtual product development for brake applications (3).

Brake noise occurs as an instability problem at different frequencies of excitation. In order to model brake noise, usually the finite element method based on complex eigenvalue analysis is applied. The analysis is based on the modeling of a friction contact between brake lining and brake disc in vertical and tangential direction. This provides a coupling with asymmetric stiffness matrix. After that, the instability problem can be evaluated based on stable and unstable vibration 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 instability.

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 to other instability frequencies. Therefore the minimization of critical squeal coefficients over the whole frequency range will be the final goal of the product development.

Because multiple different noise phenomena at multiple frequencies needs to be taken into account and scatter of geometry and material are affecting the brake noise sensitivity the design of deterministic design load cases, which ensure enough safety distances are difficult or not possible to derive. The alternative to deterministic design load cases is the direct investigation of robustness of the brake design in the windows of input variation, which are a result of scatter and variation of environmental conditions, material parameter or geometric tolerances. Therefore CAD-based robustness evaluation considering scatter of geometry and material of brake components at different environmental conditions (friction, pressure) will become a very important part of the virtual design evaluation. Efficient virtual methodology to investigate the robustness is using stochastic analysis to define the uncertainties, effectively design a sample, run the samples and measure the design robustness in terms of probabilities of violating noise excitation levels.

EFFECTIVE USE OF STOCHASTIC ANALYSIS IN VIRTUAL ROBUSTNESS EVALUATIONS

In virtual prototyping it becomes more and more important to check the robustness of the system against present scatter of material parameter, geometry or environmental conditions as soon as possible in the design process (1). Therefore the integration of CAE-based robustness evaluation in the virtual product development process becomes urgent. For CAE-based investigation of design robustness stochastic analysis will be the method of choice. For the last 5 years robustness evaluations based on stochastic analysis are implemented successfully into different disciplines in the automotive industry (2).

The basic idea of robustness evaluation is the creation and evaluation of a set of possible design realizations. The design set represents a scan of the robustness space which is defined by all important scattering input variables. Main focus of CAE-based robustness evaluation is the estimation of the variation of important response variables as a result of scattering material, geometry or environmental conditions. Because every design evaluation needs significant amount of time it is a challenge to balance between the definitions and discretization of uncertainties, the reliability of stochastic analysis methodology and the reliability of the measurements of variation and correlation by using a minimum of design evaluations.

First task of the robustness evaluation is the collection of all available knowledge about potentially influencing scattering variables. Typically the stiffness of the brake pad, the stiffness of other parts of the brake sub system including geometric tolerances are very important scattering variables. In addition environmental conditions result in 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 or expectations of scattering variables should be introduced. Distribution functions, correlation between single scattering variables, like yield stress and tensile strength are important part of the scatter definition. Different investigations have shown that spatial correlations of geometry scatter at the brake pad or other parts of the brake system also may have a significant influence on brake noise phenomena (1). Therefore the sensitivity to spatial correlation of scattering variables should be investigated in addition to single scattering variables.

It should be noted that proper definition of input scatters is the essential input information for robustness analyses. If important input uncertainties are not considered appropriately, very often no valuable assessment of robustness in virtual prototyping can be achieved. Therefore, in the process of integrating robustness analysis into virtual product development, the assumptions for all important input scatter have to be checked, verified and secured frequently. In practice, we often start with rough assumptions and in the following robustness analysis these assumptions about important scattering input variables are verified and, if necessary, become more detailed. The goal of verification is the ability of the robustness evaluations to forecast a reliable bandwidth of possible system performance including available measurements.

The second step is the generation of a representative number of possible design realizations, sampling set of the stochastic analysis. After analyzing the designs of the sampling set, the next steps will be the evaluation of the variation, importance and correlation with the help of statistical measurements. It has to be noted that all these statistical measurements are estimated and the confidence, the reliability of the measurements, has to be verified before using them to make design decisions. To make sure that the statistical measurements of variation, importance and correlation are reliable, a certain number of samples are necessary. But the necessary number of runs to estimate the important statistical measurements with sufficient confidence depends on the number of important scattering inputs and on the non-linearity of the correlations between input and output parameters, which are both unknown in advance. Therefore the challenge of stochastic analysis is to ensure the balance between the number of analyzed designs and the confidence of the statistical measurements used for robustness evaluation.
During the last ten years Dynardo has done intensive algorithmic and software developments to provide automatic procedures to verify forecast quality of correlation measurements using a minimal design number of the stochastic sampling set (5). With the help of optimized Latin Hypercube Sampling procedure, filter technique and identification of the coefficients of importance and prognosis. As a result optiSLang can minimize the effort of robustness evaluations for brake systems which today are defined as using up to 30 scattering inputs and down to 50..100 design evaluations.

First the variation of important response values is evaluated using histogram, variation and probability measurements. When response variation violates limits correlation measurements provide insight which input scatter is responsible for the result scatter. Most reliable measurement is the coefficient of prognosis. That measurement tells the engineer how much of the variation can be explained by best possible identified correlations between inputs and the result value. Only if the majority of response scatters can be explained, the user goes into detail by monitoring pair-wise correlations using so-called anthill plots or monitoring response surface plots to visualize multi variable influences on the response value.

Also the challenges of the user-friendliness of setting up parametric models, running the stochastic analysis and performing the post processing will finally play an important role of user acceptance and successful application in regular product development processes. Providing all the evaluation functionality and providing the interactive post processing, optiSLang safeguards the user through the robustness evaluation. The goal of the predefined flow is to ensure that there is no need for a specialist in stochastic or statistic analysis to run robustness evaluation routinely in the virtual development process (4).

EXAMPLE OF ROBUSTNESS EVALUATION

In case of robustness evaluation of brake systems it is known that the scatter of material properties is one of the main sources of uncertainty. Especially the pad material shows a high amount of stiffness scatter. Therefore we often start our investigation with introduction of scatter of Young's modulus of different brake parts. Based on the measurements and experience, estimation of the stiffness scatter using truncated normal distribution ranging from +- 5% at 2 Sigma level for steel parts up to 50% for the brake pad material is used. The referred example is described in detail at (3). The monitoring of instabilities is carried out for two critical frequencies using two frequency windows around 2 kHz and 6 kHz. The CAE process using NASTRAN NX was introduced into optiSLang and the Robustness analysis is carried out using a Latin Hypercube sampling of 100 designs. After NASTRAN calculation, optiSLang was used to perform statistical evaluation and correlation analysis to get a clear picture of the scatter of response parameter resulting from the scatter of design parameters. Squeal coefficient in the window around 2 kHz of the 100 designs is plotted in Fig. 1 left. Fig. 1 right shows that the input scatter leads to a high variation of the response parameter squeal coefficient, which was used as measurement for squeal propensity.

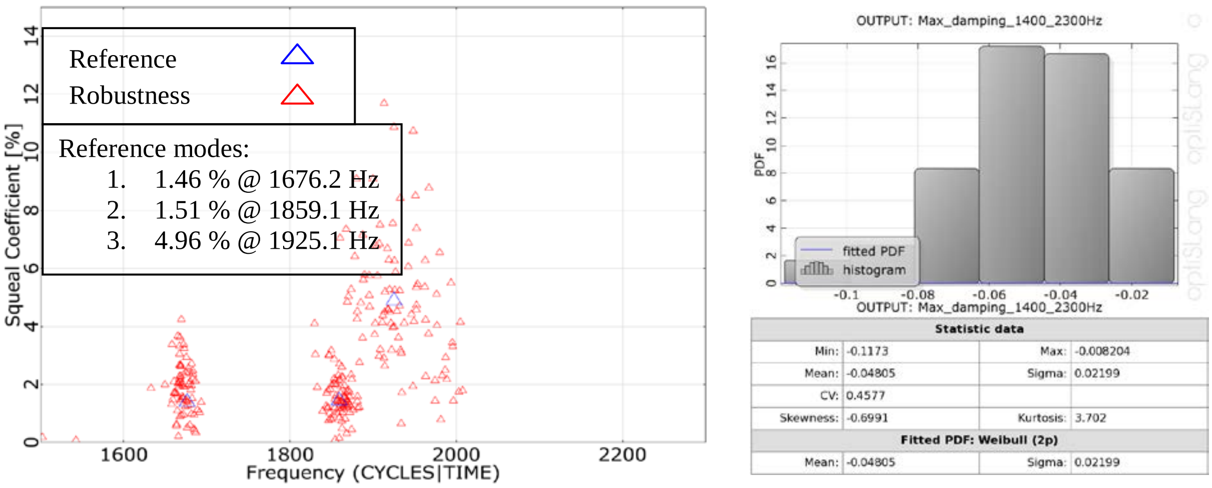

Fig. 1: Graphical (left) and Histogram (right) of Squeal Coefficient for all Designs at 2 kHz

The mean of the squeal coefficient for all designs using a frequency window is -0.048, 4.8%. It is also observed that the coefficient of variation (CV) is about 0.45, which means there is huge variation in the responses due to the variation in the input parameters, which in turn indicates that the brake system is sensitive to material scatter.

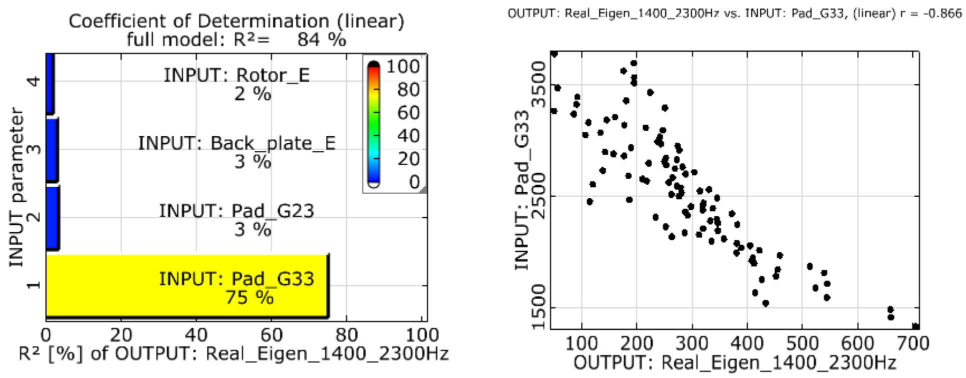

Fig. 2: Most important parameters (left) for variation of eigenvalue at 2 kHz and Anthill Plot (right) between Pad G33 and eigenvalue at 2 kHz

Fig. 2 shows the most influential scattering input parameters and how they influence the responses, from which it is observed that Pad G33 (stiffness of pad in out of plane direction) is the most important design parameter and that it has a high linear correlation with the response. The value of pair wise linear Coefficient of Determination (CoD) indicates how many percent of the variation can be explained by the variation of the input parameters. In this case, the coefficient of pair wise linear determination is 84%, which is quite high.

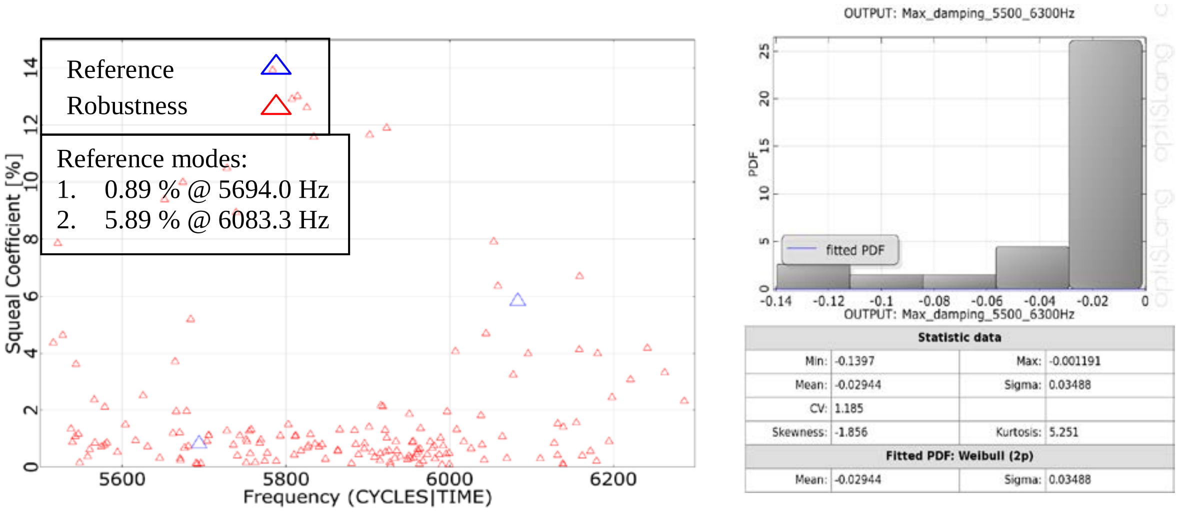

Fig. 3: Graphical representation (left) and histogram (right) of squeal coefficient for all designs at 6 kHz

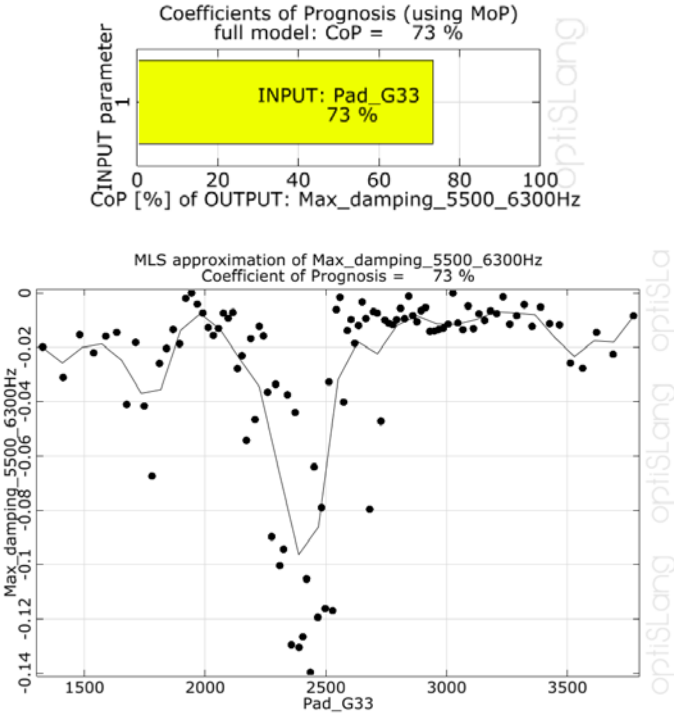

Fig. 4: Most important parameters (above) at variation of squeal coefficient and anthill plot with nonlinear correlation assumption between Pad G33 and squeal coefficient at 6 kHz

Squeal coefficient at 6 kHz of each of the 100 design is plotted in Fig. 3 left. Fig. 3 right shows that the scatter of the input parameters leads to a high variation not only in squeal coefficient but also in the frequency at which instability occurs. To find out which is the most important input parameter, correlation analysis using different measurements of importance (5) was used. Due to the high nonlinearities between the response and input variables, only Coefficient of Prognosis (CoP) identified and quantified the main correlation properly. As it is seen in Fig. 4, only one scattering variable dominates the variation in the response values, but the correlation is highly nonlinear and could not be identified with classic correlation analysis using linear, quadratic or monotonic nonlinear (Spearman) correlation assumptions. The correlation of Pad G33 to the squeal coefficient is complex in the case of 6 kHz. At the mean value of Pad G33, a high variation can be observed. Increase or decrease of Pad G33 from mean value yields lower real eigenvalue. From the histogram it is noted that the coefficient of variation is 1.18 which is extremely high. From the robustness analysis it can be stated that for the investigated brake the scatter of the stiffness of the parts of the brake system have a huge influence on the response, of which scatter of the stiffness of the brake pad in the out of plane direction plays the dominant role in both the 2kHz and 6kHz case.

CONCLUSIONS AND OUTLOOK

The paper offers a new direction to achieve a more robust system using CAE-based robustness evaluations as part of the virtual design process. In this paper, CAE-based robustness evaluation of a brake systems using stochastic analysis are introduced. The necessary balance between the definition of the uncertainties, the stochastic sampling method and the evaluation of robustness is discussed. Main result of robustness evaluation is the estimation of variation windows which are used to check and proof robustness of the designs. In addition the sensitivities of material and geometry scatter to brake noise phenomena is investigated. In case material or geometry scatter is critical to brake noise CAE-based robust design optimization can be applied to minimize the sensitivities. Furthermore quality control can be optimized to sensitive material parameter or tolerances as well as quality effort and related costs to insensitive parameter can be relaxed.

REFERENCES

(1) Bucher, C.: Basic concepts for robustness evaluation using stochastic analysis; Proceedings EUROMECH colloquium Efficient Methods of Robust Design and Optimization, September 2007, London, www.dynardo.com

(2) Will, J.: State of the Art – robustness in CAE-based virtual prototyping processes of automotive applications, Beiträge der Weimarer Optimierungs- und Stochastiktage 4.0, 2007, Weimar, Germany, www.dynardo.com

(3) Nunes, R. F.; Will, J.; Bayer, V.; Chittipu, K.: Robustness Evaluation of brake systems concerned to squeal noise problem; Proceedings Weimarer Optimierung- und Stochastiktage 6.0, 2009, Weimar, Germany (www.dynardo.de)

(4) Moosrainer, M.: Brakes without squeal; CADFEM International JOURNAL 01, 2012, (www.dynardo.com)

(5) Most, T.; Will, J.: Sensitivity Analysis using the Metamodel of Optimal Prognosis (MOP); Proceedings Weimarer Optimierung- und Stochastiktage 8.0, 2011, Weimar, Germany (www.dynardo.de)