EB2018-SVM-019

A WORKFLOW TO CREATE A DATABASE FOR IMPLEMENTING MEASURED GEOMETRIC IMPERFECTIONS OF BRAKE PAD GEOMETRY INTO CAE-BASED ROBUSTNESS EVALUATIONS OF BRAKE SQUEAL NOISE

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KEYWORDS – Robustness analysis, Geometric uncertainties, Squeal noise, Laser scans, Random fields

ABSTRACT – The robustness of brake systems with respect to squeal noise is a very important topic. It is well known and understood that variations on the surface of brake pads have a large influence on noise occurrence. Until now, however, automotive suppliers and OEMs consider these variations in a very limited way only. The reasons are straight-forward: The creation of a database of measurements is time-consuming and expensive. Second, the transfer of the variation shapes into a CAE model is a complex process requiring expert knowledge and a lot of manual work today. The objective of the collaboration of DAIMLER and DYNARDO is to fill this gap and establish a closed and easy-to-use workflow to translate measurement-into CAE-models for brake squeal robustness analysis.

The geometric imperfections of the pad surfaces can be obtained using high-resolution laser scans. Their shapes are very different among the individual brake pad specimen depending on the pad model, used pad materials, driving conditions and environmental factors. A detailed and accurate description of the variation in geometric scatter is important for accurately predicting contact areas, contact pressures and, finally, noise phenomena. Nevertheless, by using a decomposition into scatter shapes and amplitudes it is possible to create a statistically equivalent model for the representation of geometric imperfections once a sufficiently large number of measured specimen is available. Such random field models can be created up to any scale of spatial resolution allowing a great accuracy in representing the geometric shape patterns as found in the measurements.

This article presents a new automated workflow which supports engineers in transferring the measurements to their CAE/FEM based robustness analysis. Once established, the workflow can be used to either automatically morph the FEM meshes to match the measured geometries 1-to-1. Second it can be used to generate new virtual pad geometries which obey the spatial variation patterns and probability distributions obtained from the whole set of measurements. Since in practice the number of measurements is quite small for the same pad geometry, the database allows to import and transform the variation shapes of different pad geometries to a single reference. Further, it also models the correlations between the variations of the outer and the inner brake pads. Typically, the variation shapes of the inner and outer side are very different from each other. Finally, the FEM model of the brake system may be changed regarding the geometric parameters of the considered pad, the used FEM software and the FEM meshing parameters. All these issues must be considered in the design of the workflow.
In this study, the workflow is applied to ABAQUS, but can be used in conjunction with other solvers (e.g. ANSYS, LS-DYNA, NASTRAN). DYNARDO develops the software Statistics on Structures (SoS). It is used to analyse the measurements and morph the FEM meshes. The

software optiSLang is used to organize and automatize the workflow and to perform the robustness evaluation. The FEM modelling and measurements are implemented by DAIMLER. They are used to demonstrate the influence of the imperfections onto the brake squeal noise and to validate the simulation results with respect to the measurements.

INTRODUCTION

This article presents a new workflow that tries to simulate brake squeal noise phenomena more accurately by considering the true surface geometries of worn brake pads and virtually created new random geometries based on true measurements. Although the employed methodology is rather complex and very specific, the workflow is designed to be so simple that it can be implemented by engineers at automotive OEMs, but also suppliers and other third party engineering offices. The article continues a development forced by DAIMLER in the last recent years who continuously published reports about details of the analysis, see for example the references (1-4). This article provides insight into the workflow as a whole including the analysis of the measurements, the storage of a database and the transition into FEM models. Emphasis is put on the reduction of user input and automatization of the individual process steps - what is needed to get a user-friendly application of the analysis.

The basic idea behind this article is that the true geometric shape of the brake pad surfaces have a significant influence on the brake squeal noise. Since this shape is dependent on numerous factors during the lifetime of a brake, it is most suitable to consider the large variety of possible geometric shapes in terms of a stochastic model. The basis of such a model is a test program, a database storing the measured data, a numerical model for the squeal noise and a software which connects the database of measurements with the CAE model. These components are described in the subsequent sections.

The mechanism behind the brake squeal noise and its relation to the worn brake pad geometry can be illustrated by visualizing an Eigenvector of a brake system, see figure 1. Therein, the Eigenshapes of two simulations are compared: One with flat brake pad surfaces, the other with the true brake pad surface as obtained from a laser scan. Both are different due to a different distribution of the contact pressure. Clearly, one can identify the gaps between disk and brake pad on the right of figure 1. This also explains the different frequency range of brake squeal phenomena associated with these mode shapes.

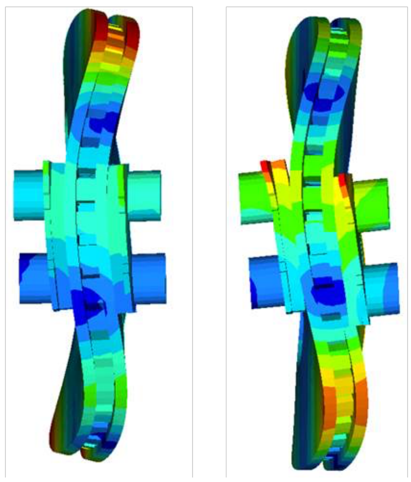

Figure 1: Comparison of the same Eigenvector of a brake system (pad + disc): Left with flat brake pad surface, right with true brake pad surface.

MEASUREMENTS OF BRAKE PAD SURFACE GEOMETRY

Todays optical measurement technology does not only allow geometric tolerance analysis at specific spots or along predefined lines/edges, but of complete boundaries of quite complex geometries ranging from very small to rather large sizes. Typically, the measured boundaries are represented as point clouds defining the spatial coordinates of the laser spots on the surface. From that post processing software can easily create a triangulation and export it through STL files. A first post processing (filling holes, removing outliers etc.) and data export is generally done by the test engineer.

In this study a regular grid was used with a high resolution of grid point distances and vertical resolution. Figure 2 illustrates a scanning process of a brake pad surface and its output. Each brake pad is represented by ~1.2 million grid points.

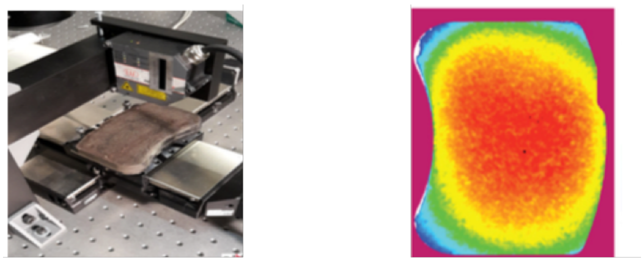

Figure 2: Measurement of a single worn brake pad surface.

AN AUTOMATIC APPROACH FOR USING MEASURED GEOMETRIES IN FEM SIMULATION

The measurements can be transferred into a CAE model nearly automatically. In classical approaches, the CAE mesh represents the “ideal” CAD0 geometry with plan/flat surfaces. If “true” geometries are to be used, often complex CAD models are created for each individual scanned specimen. This process is typically very time consuming and needs expert knowledge. One can automatize the process for numerous scans based only on the CAD0 geometry.

The information used is as simple as straight-forward. From the measurements the contour shape of the measured brake pad is known. From the CAD0 geometry one can extract the contour shape based on geometric entities (e.g. the FEM node sets). The algorithm first maps the geometric deviations between the measurement and the CAD0 geometry as a contour plot onto the CAD model. Instead of changing the CAD model, the algorithm modifies (morphs) the final FEM mesh by changing the positions of the FEM nodes according to the measurement.

The morphing is applied through these steps: (1) The engineers defines the parts of the boundaries for which the measured geometry is to be applied. (2) The engineer defines the parts of the boundaries which are fixed – the other boundary parts are free. (3) The algorithm applies the measured geometry to the selected boundary. (4) The mesh quality of the final mesh is ensured by two strategies: The algorithm also changes the node coordinates inside the mesh interior underneath the selected boundary. Further, the algorithm applies stabilization and smoothening techniques that ensure positive element Jacobians and reduce finite element distortion. The workflow is independent from the used CAE solver and can export the morphed meshes to various formats (e.g. ANSYS, ABAQUS, NASTRAN, LS-DYNA to name a few).

This method needs no expert knowledge and can be easily automatized. In the project, the measured imperfections are applied to the inner and outer brake pads in a single analysis, see figure 3.

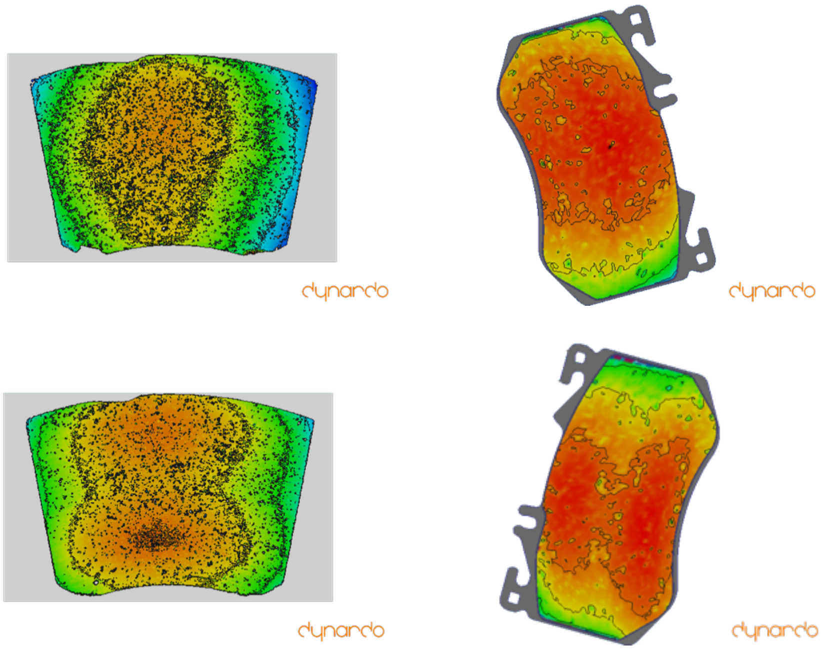

Figure 3: From measurement of inner and outer brake pad (left) to FEM mesh (right)

STATISTICAL MODEL OF IMPERFECTIONS

The algorithm automatically creates a statistical model based on the measurements. It only needs to import the data of multiple laser scans into its database, applies pattern analysis to the data. In the end the software proposes a parameterization and the statistical parameters (statistical distribution, mean, stddev etc.). A schematic representation of the geometric variations is shown in figure 4. Therein any geometric shape can be represented by a series where one takes the statistical mean geometry and adds variation patterns ("scatter shapes") scaled by some random number. This representation is also known as a *random field model*.

Noteworthy, the wear patterns of the inner and outer brake pads are correlated. Therefore, the statistical analyses of both sides is done in one model. The 4 most important scatter shapes for a pair of brake pads are shown in figure 5. Due to the correlation, each variation of the inner pad is accompanied with a very specific variation pattern of the outer side. This is reflected by the scatter shapes in the top and bottom row of figure 5. Also note, that each shape can be scaled with positive or negative numbers. For example, a positive scaling coefficient leads to material removal for the blue areas (in outer and inner pad at the same time!) and material addition for the red areas. For a negative scaling coefficient it is the opposite.

Further in reality, material is generally not added to the pad surface due to wear. This is to be seen in comparison with the mean value. In the statistical mean, material is removed among the whole surface. "Adding material according to a variation shape" means here that the removal of material is not as large as the mean value suggests.

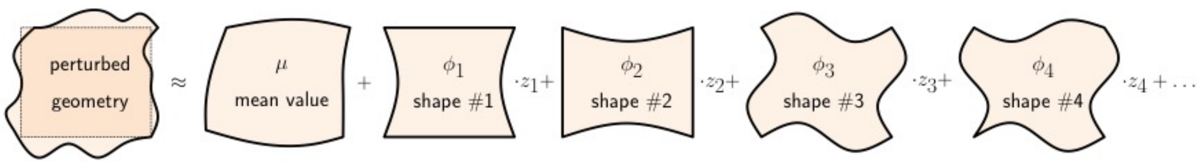

Figure 4: Schematic parameterization of geometric variations by random fields

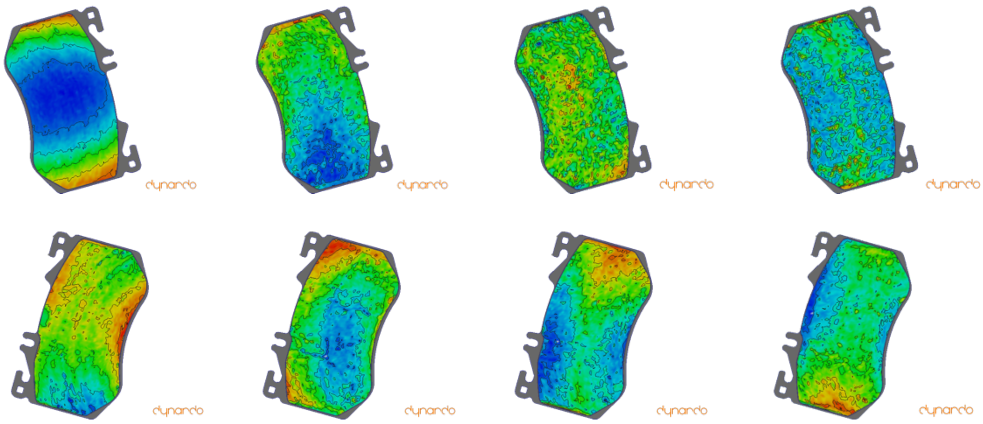

Figure 5: Variation shapes of a worn brake pad surface. Top row: Inner pad, Bottom row: Outer pad. Each column represents a scatter shape (1st column: 1st scatter shape).

A UNIFIED DATABASE FOR SCANS OF DIFFERENT BRAKE PAD TYPES

The most time-consuming part of the analysis is the preparation and implementation of the test series. This includes the laser scans, but also the preparation of the worn brake pad surfaces to be scanned. To this end, realistic driving long-term scenarios must be implemented. Further, these scenarios should consider different driver behaviour, different environment parameters (e.g. humidity, temperature), different car models, different brake pad material and geometry.

To obtain an accurate random field model one would need several (> 50) different specimen – for each brake pad type. This is typically not possible with acceptable effort. Therefore, a database is created for all tests collecting and connecting the measurements of different test series, e.g. also of different brake pad material and geometry.
The database can be extended by new measurements at any time. The new measurements can be implemented by different test laboratories because the implementation and format of scan data is independent from the storage in the database. New brake pad geometries can also be registered and added to the database. This is possible by assigning the geometries to a brake pad template. In the present case, the geometries are assigned to a unit rectangle. A transformation helps to map the surface data from an arbitrary brake pad geometry to such a rectangle. This simple assumption on the base geometry is acceptable with negligible errors. Errors can appear in areas where very local geometric features can not be represented by a transformation to a rectangle. The algorithm, however, handles such areas by detecting them reliably and proposing a suitable data interpolation. Figure 6 shows a variety of possible brake pad geometries and how they are represented in the unit rectangle.

During the CAE simulation the data from the unit rectangle are first transformed to the geometry of the brake pads as defined by the FEM model. Hence, in the simulation one can apply the data even to brake pad geometries which were not part of the original test series.

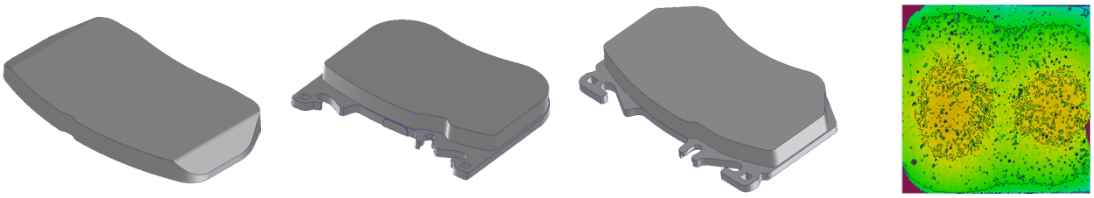

Figure 6: A variety of different brake pad geometries being part of the test series and their representation on the unit rectangle of the database (Right).

A USER-FRIENDLY WORKFLOW FOR ENGINEERS

The entire workflow consists of the following parts:

- Create the database of worn brake pad geometries
  - Prepare the inner and outer brake pads (test drives), also remember driving conditions
  - Perform the laser scan and export to appropriate format
  - If not yet done: Register the brake pad CAD geometry in the database
  - Load the scan into database
- Generate new random geometries for brake squeal noise simulation
  - Prepare FEM model using the CAD0 geometry.
  - Register the CAD geometry of the CAE model
  - Register the FEM mesh files
  - Perform a test run using the statistical mean geometry (mesh morphing, then acoustic-mechanical simulation – e.g. with ABAQUS)
  - Register the random field parameters as random variables
  - Create a random sampling (DOE) and analyse the results.

Most important is that the number of manual inputs is reduced and that the workflow is flexible. Information on the geometric transformations can be obtained by data stored in the CAD and FEM mesh files. This is also true for all information needed to implement the mesh morphing. Therefore, most geometric pre- and post processing remains in the software tools that are already in use in the mechanical analysis. Flexibility means that one is independent from third-party software. For example, the measurements can be done by different companies using different tools and providing the measurements in different formats (e.g. STL, structured or unstructured point clouds, etc.). the independency is obtained by storing them in a central database that is independent from the laser scan technology. Further, the database is also independent from the used CAE software. This is important since the creation and growth of such database can be a process of several years while it is not clear which CAE software is used to predict the squeal noise or other mechanical analysis in the future.

EXAMPLE: CONTACT PRESSURE DISTRIBUTION DUE TO “TRUE” PAD GEOMETRY

The first example analyses the effect of the geometric deviation of the brake pad onto the acoustic behaviour. Two different measured brake pad pairs were selected and a complex modal analysis was done. Due to the different geometry of each individual brake pad, different distributions of contact pressure were obtained. This is shown in figure 7. On top, the contact pressure distribution is shown. Below one can see the effect onto the squeal noise frequencies and the mode shapes.

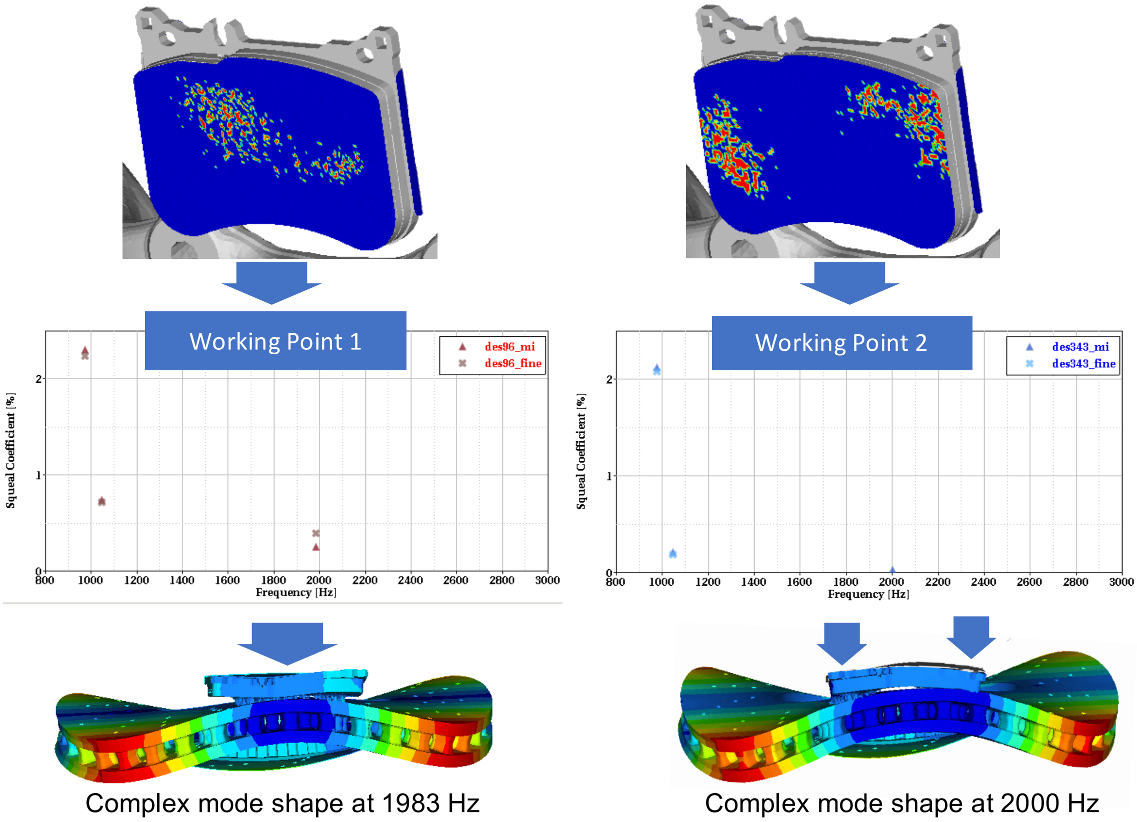

Figure 7: Comparison of two different brake pad geometries as obtained from measurements. Top: contact pressure distribution, Center: Frequencies, Bottom: Mode shape comparison

EXAMPLE: ROBUSTNESS STUDY BY VIRTUALLY CREATED MEASUREMENTS

In an initial study DAIMLER chose 30 measurements of inner and outer brake pad pairs from 3 different brake pad types. In the ongoing process this database will be extended adding more measurements and also more brake pad types. An example measurement is shown in figure 3. The transfer to the database and its "unit geometry" in transformed space is shown in figure 6 (right). The obtained scatter shapes of the random field model are shown in figure 5. The random field model was then used to create a random sampling with 100 designs.

A variance based numerical robustness study is typically based on a deterministic CAE simulation model, e.g. a FEM model for a static structural, transient or acoustic problem. Since any commercial software may be used by the engineer, this deterministic model is treated as a "black box". The stochastics is included into the model by varying selected input parameters of the CAE model and evaluating the results for each outcome. This involves the evaluation of several parameter combinations, called "designs". The analysis of the response of the CAE model then may provide information on the sensitivity of the structural performance with respect to variations of the input parameters, information on the ranking of the importance of input parameters with respect to the variations of the response quantities, or information on statistical properties of selected response quantities, for example mean and standard deviation of critical thresholds, exceedance probabilities etc. A schematic flow of such a robustness analysis is illustrated in figure 8. As mentioned in the previous paragraph, based on the measurements of the brake pad geometries one can generate (e.g.) 100 new virtual designs and use them in a robustness analysis for the brake squeal noise using an originally deterministic FEM model.

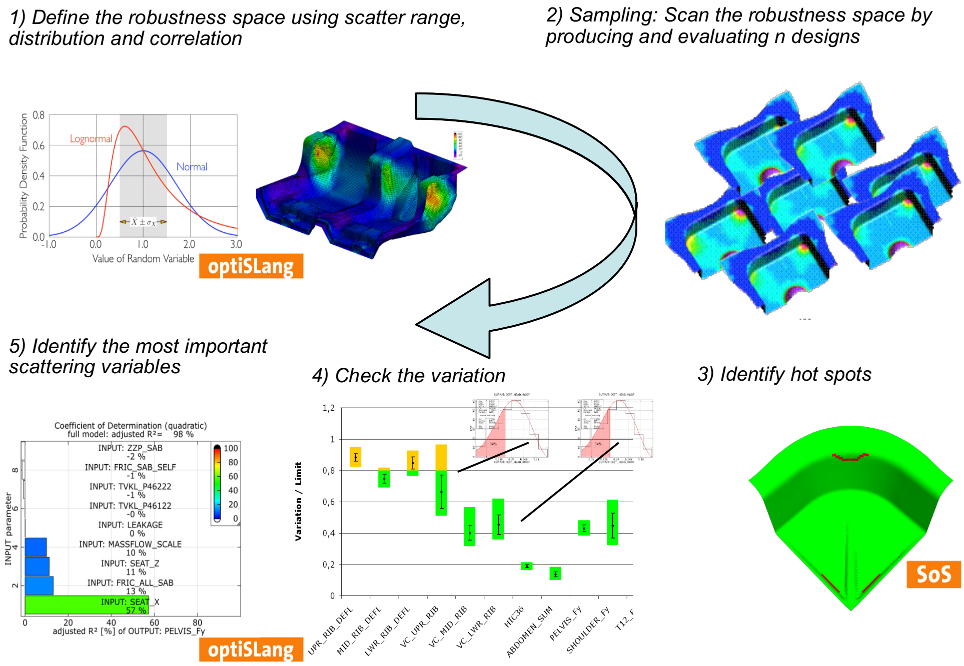

Figure 8: Schematic flow of a robustness analysis in CAE. Source: [5]

The deterministic simulation model does not only contain the contacting bodies, but most of the brake system including bell, pad, caliper, disc, joints, etc. The model is parameterized such that random variations can be applied to geometric parameters of bell, caliper, pad, disc and axle parts, but also to other parameters such as joint stiffness, brake pressure, velocities, friction coefficients. The combinations of these parameter variations simulate possible situations on the street and also the deviations due to production tolerances (see figure 9 for a schematic illustration). The idea is to simulate pseudo-random parameter combinations by their statistical properties. Hence, one can quantify the "quality" of a brake system through its insensitivity with respect to such changes.

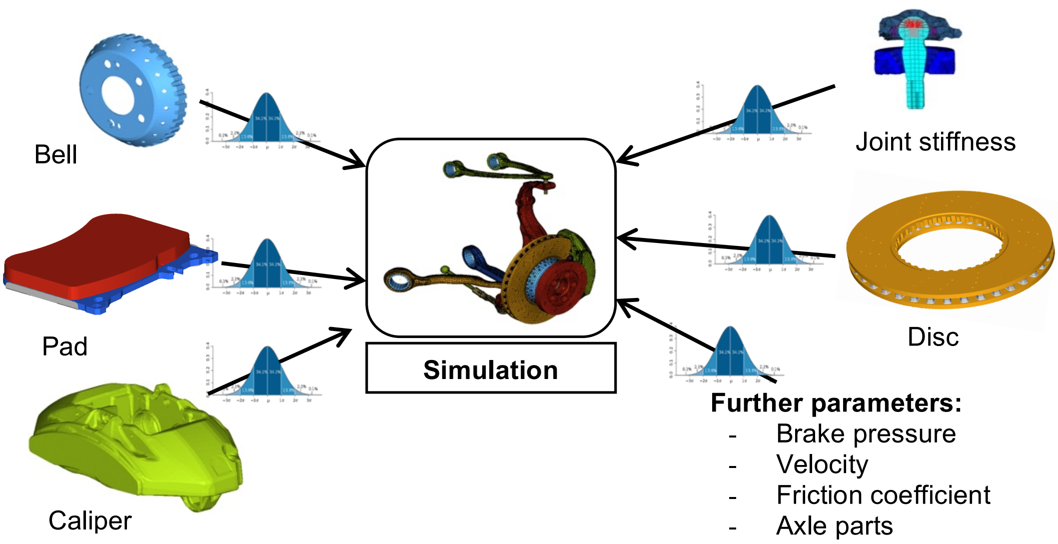

Figure 9: Parameters being varied in a robustness and sensitivity analysis using a brake system CAE model.

A first result is shown in figure 10. Therein, the results of the simulated brake squeal frequencies obtained with flat brake pad surfaces (red) are compared with the results obtained with randomly generated brake pad surfaces (blue). The simulation results are shown to be much closer to the true observed frequencies in the test laboratory (green intervals) when using the brake pad surfaces as generated by the presented workflow.

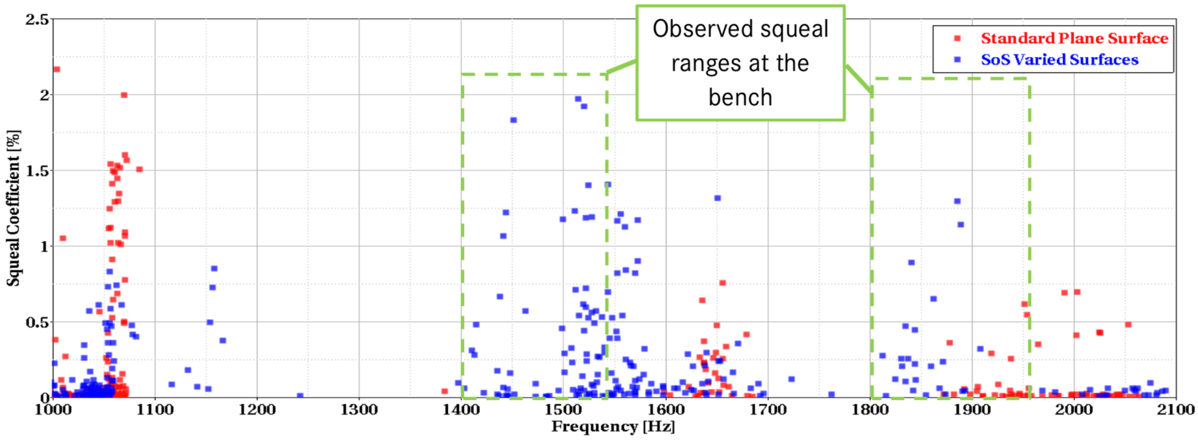

Figure 10: Brake squeal noise frequencies predicted by simulations using flat brake pad surfaces (red), random field modified brake pad surfaces (blue) compared with observations from experiments (green).

CONCLUSIONS

Based on the assumption that not only individual uncertain parameters, but also geometric deviations of brake pad surfaces are responsible for variations in brake squeal noise frequencies, a workflow was developed that allows engineers to vary all these parameters together with the brake pad surfaces in a numerical robustness and sensitivity study.

The workflow is simple to use, flexible and is fully based on commercially available software. The geometric deviations of the brake pad surfaces are based on the true deviation shapes of worn pads as obtained through measurements. The database and the workflow allow to simulate the brake squeal behaviour by any CAE software with respect to geometries as obtained from measurements 1-by-1. Alternatively, the geometries can be virtually created by the computer (but are based on the realistic variation patterns as seen 1-by-1 in the measurements). Therefore, engineers of automotive suppliers have the chance to employ this workflow increasing the accuracy of the prediction of brake squeal frequencies. The improvements were validated by frequency measurements in this study.

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ACKNOWLEDGEMENTS

Thanks to DAIMLER AG for the past and future collaboration and for supporting this article.