Improving robustness of Chevrolet Silverado with exemplary design adaptations based on identified scatter sources

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Abstract:

The investigations described here are related to the unstable behavior of crash-simulations due to minor changes in the model. As a consequence the received simulation results become in some way unpredictable, whereby the causes can be various: e.g. modeling failure, contact issues, numerical instabilities, physical instabilities, etc..

To identify and separate these scatter sources the results are analyzed by means of visualizing the standard deviation of scatter itself and computing scatter-modes for selected parts of interest. Latter computations are based on the principle component analysis (PCA), and deliver new virtual crash results representing the most extreme geometrical shapes of the scatter-modes. This improves and speeds up the process of identifying scatter causes.

For illustration a realistic application case based on the freely available Chrysler Silverado from the National Crash Analysis Center (NCAC) of The George Washington University is analyzed by means of robust design of the crash model. Therefore 25 simulation runs were performed based on small random part thickness changes (representing production tolerances). The part of interest for the investigations is the variance at the fire-wall. As an outcome major scatter sources in the interaction of power-brake and suspension as well as at the longitudinal rail are found which are strongly correlated to the firewall scatter. Approving the software based prediction exemplary design adaptations lead to a significant reduction of scatter on the firewall. The described mathematical methods are part of the software DIFFCRASH, which was used in this study.

Additionally a perspective regarding the integration of these analysis methods into a simulation data management system is given.

Keywords:

Robustness, Principal Component Analysis, Chevrolet Silverado, Scatter, Production tolerances

1 Background

Since the past few years the overall awareness of variability and scatter for CAE predictions is steadily increasing. Giving the fact that variability is inherent in nature it is also a major task to master it during product- and in this case especially vehicle-development. As a matter of fact in car industry for many load cases there is only provision for a single performance confirmation test to verify the CAE model. As such a test is influenced by a series of potential variability sources like e.g. production tolerances and crash test parameter settings, the chance to run into unpredictable crash results rises. In case of unforeseen results this usually leads to expensive and inefficient design changes, at a late vehicle development phase.

To counteract the above mentioned the CAE model should already have a robust design which is not sensitive to small variations and still delivers predictable results. Thus before applying design optimizations, the overall robustness of the model needs to be ensured.

Taking a deeper look into the complex event of a car crash many reasons can be discovered why small variations actually lead to a big spread among the results. Just to mention a view, consider parts kinking in one direction or the other or parts passing each other instead of hooking up. As a consequence one approach to generate a robust design is to find these events (often referenced to as bifurcations) and derive design suggestions that can handle the variations and still deliver a deterministic crash behavior.

One way to achieve this is mainly based on Principle Component Analysis methods and standard statistics, which are both applied in the example case of the Chevrolet Silverado from the NCAC and described below.

2 PCA Analysis for crash simulation results

Given the fact that for a robustness analysis as described in this manuscript a set of 30 or more simulation runs is analyzed, the use of a dimensional reduction method is beneficial. In our case the Principal Component Analysis is used to easier extract the essence of the crash behavior for sets of simulations.

2.1 Principal Component Analysis for crash results [1]

According to [2], principle component analysis (PCA) was introduced by Pearson in the context of biological phenomena [3] and by Karhunen in the context of stochastic processes [4].

In [5], PCA was applied to full crash simulation results. Let $(p,)$ be the displacement of simulation run i out of n simulation runs at node p and time t. If $\bar{X}$ (p,t) is the mean of all simulation runs, the covariance matrix C can be defined as

The eigenvectors v_i of C form a new basis (principle components) and the λ_i (square roots of the eigenvalues of C) provide a measure for the importance of each component.

If this method is applied to crash simulation results, n^2 scalar products between the simulations runs of length $3 * \#P * \#T$ have to be computed ($\#P$ number of points, $\#T$ number of time steps.)

From

$$\hat{X}(a) := \sum_{i=1}^{n} a_i X_i$$

follows that

$$\lambda_i = \left\|\hat{X}(v)\right\|_2 \quad .$$

The $\hat{X}(v_i)$ show the major trends of the differences between the simulation results. The coefficients of the eigenvectors v_i correspond to the contribution of $\hat{X}(v_i)$ to $X_i - \bar{X}_i$ and can be used for cluster analysis and correlation with input parameters. If input parameters have been changed between the different simulation runs, the correlation analysis will indicate how certain trends can be avoided or increased by changing these inputs (e.g. thicknesses of parts) (c.f.[1], Chapter 2.4] for the properties of PCA analysis in general).

Principle Component Analysis is a mathematical method which determines mathematical trends in contrast to physical trends. To be more specific: λ, the square of the maximal eigenvalue of C, can be determined by

$$\lambda = \left(max_v \left\|\hat{X}(v)\right\| \middle| \|v\| = 1\right)$$

and therefore will be in general a mixture out of several physical effects, like buckling.

2.2 Difference PCA [1]

Instead of considering the whole simulation results, correlation matrices can also be defined for the simulation results at parts of the model and for specific time steps. If P is a part of the model and T subset of the time steps, then , can be defined as follows:

$$C_{P,T} := \left[c_{i,j}^{P,T}\right]_{1\le i,j\le n} \text{ and } c_{i,j}^{P,T} := \frac{1}{N_{P,T}} \sum_{p\in P,t\in T} \left(X_i(p,t) - \bar{X}(p,t)\right) * \left(X_j(p,t) - \bar{X}(p,t)\right).$$

($N_{(P,T)}$ denotes the size of P times the size of T.)

The intrinsic dimension of the set of simulation results can be defined as the number of major components in its differences (for more formal definitions see [1], Chapter 3]). Buckling or any other local instability in the model or numerical procedures increase the intrinsic dimension of simulation results at parts which are affected compared to those, which are not affected. Therefore in the context of stability of crash simulation, those parts and time steps for which the intrinsic dimension increases are of particular interest.

Numerically this can be evaluated by determining eigenvectors and eigenvalues of

$$C_{P1,T1} - \tau C_{P2,T2}$$

for the covariance matrices of the simulation results at two different parts P_1 and P_2 and two different sets of time steps T_1 and T_2. If there are positive eigenvalues for a certain choice of τ (which separates noise from real signals), the simulation results at (P_1, T_1) show additional effects compared to those at (P_2, T_2). If v_{P_1,T_1} is the corresponding eigenvector, $\hat{X}\left(v_{P_1,T_1}\right)$ shows the effect on (P_1, T_1) and also the impact on the other parts of the model. Similar methods can be used to remove those effects from this result, which do not affect (P_1, T_1) directly.

This approach has been filed for application of a Patent at the German Patent office (DPMA number 10 2009 057 295.3) by Fraunhofer Gesellschaft, Munich.

3 Firewall example

As mentioned in the Background chapter a robust model should be able to handle small variations within the model and still produce predictable results. Taking production tolerances into account is a common approach also in other areas of product development and shall be the point to start for us. The variability induced into a vehicle due to the uncertainty/variation during the production phase can have several different origins. Just to mention a few this can be due to material tolerances, uncertainty within production processes like e.g. stamping processes and others. This results in a slight variation of all parts with respect to their specification. While this is inherent in the vehicle production it is not part of the simulation model itself. So introducing the production based variability of parts into the robust analysis is a more detailed representation of the real world and allows us to improve model robustness as well as it helps understanding more about the crash behavior of the model. The risk of running into unforeseen results in the vehicle confirmation test will also be decreased.

Especially for the analysis of front crash results the intrusion of the firewall is an important safety parameter. Thus having a predictable behavior at the firewall is important to fulfill safety requirements so our focus for this analysis lies on the scatter at the firewall. The model investigated here is the Chevrolet Silverado available from the NCAC ("The model has been developed by The National Crash Analysis Center (NCAC) of The George Washington University under a contract with the FHWA and NHTSA of the US DOT").

Following the prescribed approach a set of 30 simulation runs was generated based on a random variation of part thicknesses within the range of ±3%. Within a first statistical analysis the maximal variation among all the simulation runs is computed and visualized on the contour of the geometry in Figure 1.

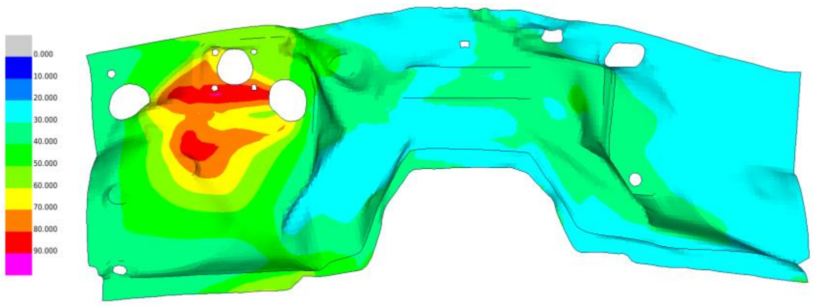

Fig.1: Scatter of 30 simulation runs on the firewall for initial design in mm

As can be seen the 30 simulation runs vary with a maximum of almost 90mm at the firewall although only a small overall variation has been applied. The effect of production tolerances therefore can have a heavy impact on the simulation results. Having the intention to improve robustness of the model the next task is to find out where this result dispersion comes from. What are the key events within the model causing the strong scatter occurrence at the firewall? Using PCA now for the firewall delivers the important scatter modes, rather than having to analyze the complete set of 30 simulation runs. In Figure 2 and Figure 3 the dominating scatter mode of the firewall is seen in his characteristics for other parts of the model. As can be seen, the shape deformation information contained in this mode reveals a different crash behavior for the shock absorber (Figure 2) on the one hand, and for the longitudinal rail on the other (Figure 3) hand.

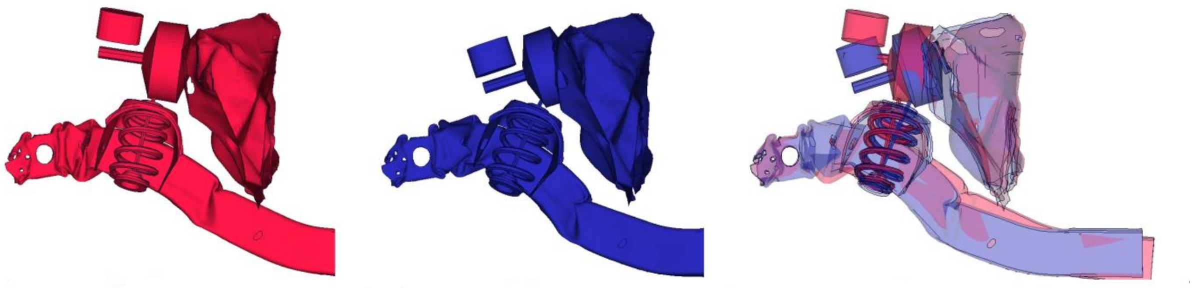

Fig.2: Scatter mode deformation shapes for shock absorber – brake unit interaction

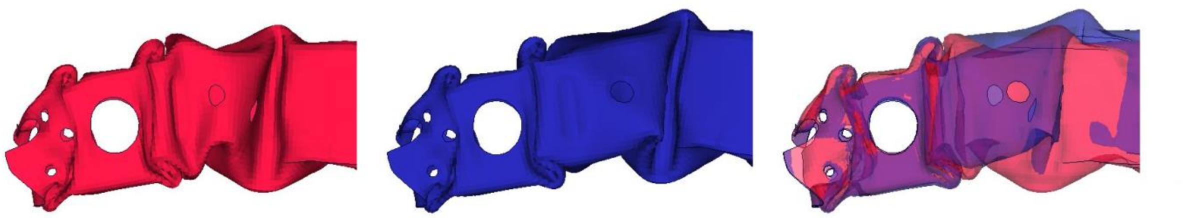

Fig.3: Scatter mode deformation shapes for left longitudinal rail

The shock absorber hooks up to the power brake unit for some runs, while for others they pass each other. The former pushes the power brake unit towards firewall and leads to a higher intrusion of the firewall.

At the longitudinal rail the kink is not triggered as intended for all runs, so that for some runs the area around the kink stays stiff (no kink). As a consequence the longitudinal rail pushes further towards the rear and also works as a lever elevating the wheel case. Further investigations have shown that latter event does not solely trigger the shock absorber hooking up to the power brake unit, even though it supports it. To counteract the bifurcation points a deterministic behavior is intended with two design adaptations. Exemplary the shock absorber was smoothened and cut so that it is way more difficult to have an interaction with the brake unit. On the other hand the notch at the longitudinal rail was slightly moved and adapted to allow a more consistent kinking behavior.

To verify the design adaptations and test whether the adapted model is more robust it is necessary to rerun a set of 30 simulation runs including production tolerances to be able to make a comparison before and after the design changes. The outcome can be seen in Figure 4. The adaptations made lead to a significant reduction of our target part the firewall. While there was scatter occurrence of up to 90mm for the unchanged model the improved design delivers way more robust results with only a variation of around 20mm at the firewall.

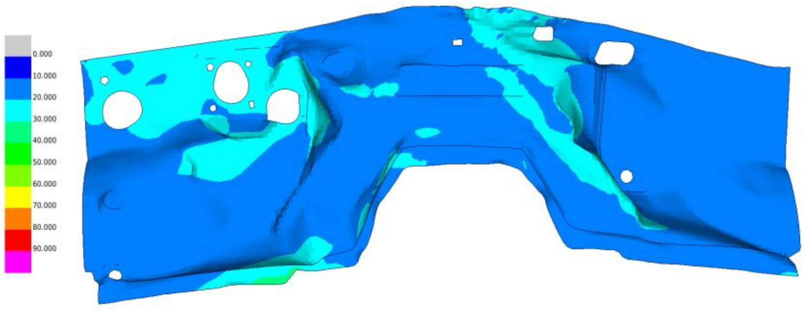

Fig.4: Scatter of 30 simulation runs on the firewall for revised design in mm

4 Summary

Improving the robustness of a crash model is still a challenging topic but especially important before applying optimization technics. One approach based up on PCA based scatter modes was illustrated which allows finding instabilities within models and deriving design suggestions to improve the robustness of the crash model. The mixture out of standard statistics to highlight critical areas in combination with the derived scatter modes allows improving model robustness and also speeds up the process of analyzing a set of simulation runs.

5 References

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