

# Increasing adjustability of acoustic system properties by activating fixed control levers

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## Introduction

Acoustic comfort of cars in everyday life is one of the important factors, influencing human health and state [1,2]. Achieving low sound pressure levels inside vehicles is essential to provide secure and comfortable driving conditions. One of the common techniques allowing to decrease sound levels is passive acoustic structural design that can be improved by acoustic optimization [3].

Generally, the level of structural uncertainties on early developmental stages (i.e. of cars) is overcritically high, leading to ineffectiveness in applicability of even the most robust optimization algorithms. For this reason, the idea of the current research is to develop a strategy to ensure the adjustability of the acoustic behavior by activating acoustic control levers on any of the developmental phases.

In the presented study an algorithm is developed and verified to target sensitivities of the desired acoustic criteria with respect to a set of design variables directly as optimization objectives. Reducing or increasing the influence of certain design parameters on the acoustic criteria already on early design stages, an engineer can ensure that the system behaves in a desired robust manner also on the late design phases. For instance, in a car design there are numerous structural parts that can easily be substituted by similar parts with adjusted properties. Thus, increasing/decreasing the stiffness of structural joints, wall thicknesses, changing material density properties etc. an engineer can find such a configuration of the system, that is prone to acoustic adjustments with respect to a chosen set of design parameters.

The focus of the conducted study is placed on the low frequency acoustic range, between 20 and 80 Hz. As the feeling of sound pressure comes from the resonance of mechanical excitations with the eigenmodes of vehicle parts being predominantly located inside the low excitation frequency range, it is meaningful to tackle this interval.

## Description of the FEM model

Within the framework of the conducted research study a simplified physical car model is developed. The outer frame of the box model is coupled with the inner fluid cavity (see Figure 1). Mathematically fluid-structure coupling can be represented in the combined fluid and structure equation of motion matrix form [8]:

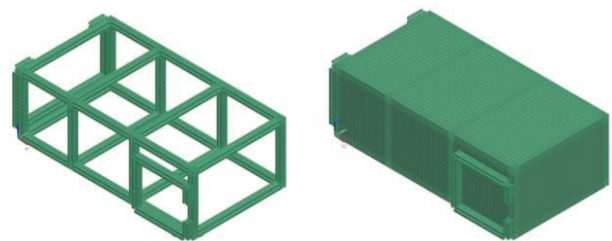
$$\begin{bmatrix} M_s & 0 \\ -A^T & M_f \end{bmatrix} \begin{Bmatrix} \ddot{u}_s \\ \ddot{p} \end{Bmatrix} + \begin{bmatrix} B_s & 0 \\ 0 & B_f \end{bmatrix} \begin{Bmatrix} \dot{u}_s \\ \dot{p} \end{Bmatrix} + \begin{bmatrix} K_s & A \\ 0 & K_f \end{bmatrix} \begin{Bmatrix} u_s \\ p \end{Bmatrix} = \begin{Bmatrix} P_s \\ P_f \end{Bmatrix}, \quad (1)$$

where  $u_s$  is the structural displacement;  $p$  is the acoustic pressure;  $A$  is the matrix, taking into account the fluid pressure effects on structural boundaries;  $M_s, M_f$  are mass matrices, re-

lated to structure and fluid, respectively;  $B_s, B_f$  - damping matrices and  $K_s, K_f$  - corresponding stiffness matrices;  $P_s, P_f$  are external pressures, applied to structure and fluid.

The frame structure is modeled within the solution SOL200 for sensitivity analysis in Simcenter 3D. Plates were modeled as 2D shell elements with CQUAD4 element discretization, whereas profiles – as 1D beam elements. Connections between the beam and shell elements are realized with the help of RBE2 and RBE3 Rigid Body Elements. Hinges and locks connecting the hatchback and the door to the structure are realized by CBUSH elements.

The fluid cavity is modeled with the help of CHEXA elements. For the sake of the minimization of computational costs the excitation range between 100 and 200 Hz was chosen for the study. The calculation is realized within the NAS-TRAN NX solver.



**Figure 1:** Frame structure of the model (left); full fluid-structure coupled model with plates and shells (right).

In Figure 1 the side door and the hatchback parts could be recognized. All in all, 2D model collectors include roof, side door, tailgate, car bottom and the rest of the car body.

## Optimization workflow

The developed optimization workflow begins with Simcenter 3D modeling and conducting a sensitivity analysis for the developed FEM model.

Inside SOL200 case a set of six design parameters for the sensitivity analysis is chosen, targeting mass and stiffness properties of selected structural elements. Among them linear elastic spring elements connecting the hatchback to the structural frame (labeled HEDGE02); the side door to the carrying frame (labeled DOOR02); the hatchback lock spring (labeled BUFF02); the material density parameter of the roof (labeled ROOF21); and concentrated masses, acting on the side door (labeled DOOR01) and on the hatchback (labeled HEDGE01).

Choosing one of the included in the software interface responses (DRESP1 responses), a user receives a sensitivity output matrix with sensitivity coefficients for each excitation frequency in the defined range, corresponding to each varia-

ble in the design parameter set. The sensitivity output is further used for the optimization processes inside the HEEDS optimization platform. As long as only a single sensitivity value for each of the parameters to optimize is required to be assigned to each of the optimization objectives, an acoustic sensitivity response, representative of the whole defined frequency range, is needed. The sum level of sound pressure was chosen for the response function (see Equation 2), as it accounts for all the acoustic pressures inside the defined frequency range and concentrates the optimization workflow on the pressure peaks in the range as main contributors to the response itself. The sum level of sound pressure was integrated as the sensitivity analysis response by the means of python interface inside HEEDS. Summing the squares of the acoustic pressures divided by squares of reference sound pressure,  $2 \cdot 10^5 \text{ N/m}^2$ , on each of the excitation frequencies under the logarithmic function, a response, representative of the whole frequency range, was received.

$$L_x = 10 \cdot \log_{10} \sum_{i=1}^N \frac{p_i^2}{p_0^2}, dB \quad (2)$$

To enable the conduction of the sensitivity analysis with respect to the chosen response, first the sensitivities for acoustic pressures on each frequency obtained during the sensitivity analysis in NASTRAN NX are extracted and forwarded to HEEDS, where the final sensitivities are obtained semi-analytically, using manual derivation (see Equation 3) and substituting in it previously saved coefficients for each frequency in the defined range.

A Matlab script was written to extract the necessary data from the output file of the sensitivity analysis with sensitivity coefficients for all the frequencies in the defined range and to restructure it to enable the tagging process inside HEEDS. Tagged sensitivities were saved in a vector form as intermediate responses. The final objectives in the form of sensitivities of the sum level of sound pressure were received with the help of python scripting. The semi-analytical derivation of the final sensitivities was obtained based on the intermediate sensitivities saved in the previous step, according to Equation 3.

$$\frac{dL_x}{dx_i} = \frac{10}{\ln 10 \cdot \sum_{i=1}^N \frac{p_i^2}{p_0^2}} \cdot \frac{2}{p_0^2} \left( \sum_{i=1}^N p_i \cdot \frac{dp_i}{dx_i} \right), \quad (3)$$

where  $x_i$  is a design parameter from the defined design parameter set.

The semi-analytical derivation described above provides a user with a certain flexibility, regarding the final response calculation. As long as the sensitivity equation is implemented manually, a user can include further optimization factors to improve the optimization outcome, i.e., weighting factors, concentrating optimization process on specific frequency ranges of interest could be added to the equation stated above. Moreover, a user is free to choose the desired acoustic response function and to adjust the derivation accordingly.

After the extraction step, the sensitivities are assigned to the optimization objectives. For each optimization iteration the same steps are repeated, starting with a new sensitivity analy-

sis in Simcenter 3D for an updated parameter set values, generated by HEEDS. The whole workflow scheme is represented in Figure 2.

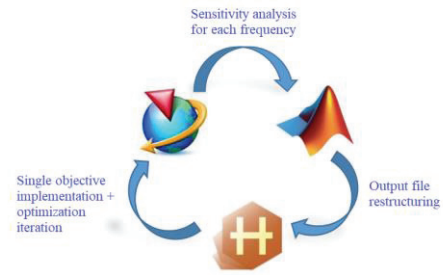


Figure 2: General optimization workflow.

### Optimization study

The goal of the conducted case optimization study is to minimize the influence of the HEDGE02 and DOOR02 parameters and to increase the influence of ROOF21 and BUFF02 to demonstrate the significance of the difference between activated and pacified parameters. The objectives are randomly selected to test the developed method.

After the optimization study is completed, the parallel plot of the optimization designs is created (see Figure 3). The first four values on the left of the horizontal axis stand for the optimization objectives. The six right values are the design parameters. The blue and gray lines connect the design parameter and objective values, belonging to the same design. The performance indicator estimates, how good a design managed to satisfy the targeted goals. The parallel plot presents all the designs, created throughout the optimization. Setting different values for parameter constrains, a set of similar design configurations with the optimal performance can be selected. Different configuration sets most likely indicate different local optima. Depending on the size of the design parameter intervals and on the target function, there can be several local optima in the design space. In Figure 3 the blue lines correspond to the set of the manually filtered designs, selected in terms of high performance and similarity in corresponding configurations. The results were obtained, applying a hybrid, self-adaptive optimization algorithm SHERPA [4].

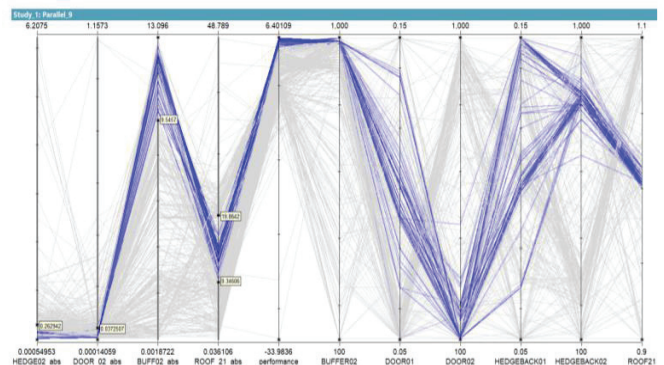
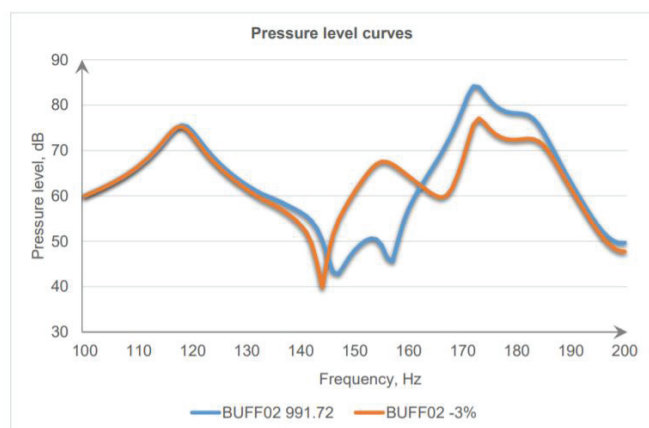


Figure 3: The parallel plot of the optimization designs.

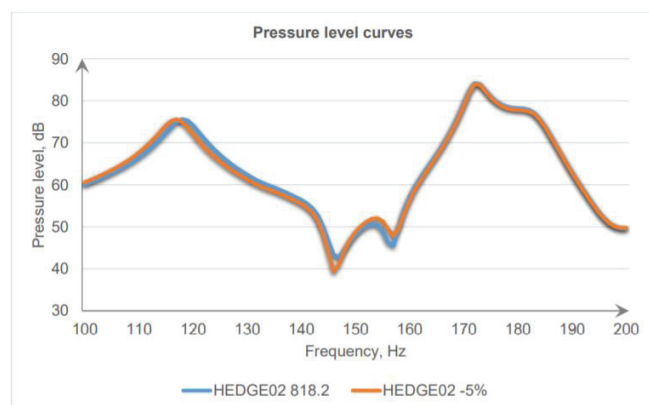
On Figure 4 the pressure level curves for the baseline and for the design with an adjusted BUFF02 parameter value are de-

picted. According to the optimization objectives, the optimized design is supposed to be sensitive with respect to the BUFF02 design parameter. Even a slight variation of the BUFF02 value (by  $\pm 3\%$ ) triggers a significant improvement in the pressure level distribution. It should be mentioned that the effect of an activated design parameter is not reflected in the same manner for each of the excitation frequencies. Depending on the pressure curve distribution either global or local effects can be observed. Typically, the pressure level peaks get reduced significantly, compromised by pressure level increases at frequencies with lower dB levels. Thus, a more pleasant pressure level distribution can be achieved in terms of human perception. In the current study the pressure level peak at 173 Hz is reduced by nearly 7 dB through the activation of the BUFF02 acoustic level (see Figure 4).



**Figure 4:** Pressure level distributions of the optimized design before and after BUFF02 leverage.

On the contrary, the effect of the HEDGE02 parameter on the sound pressure is reduced, as the corresponding sensitivity is minimized during the optimization process (see Figure 5).



**Figure 5:** Pressure level distributions of the optimized design before and after HEDGE02 leverage.

Although the sensitivity of the sum level of sound pressure is chosen as the study objective, involving sound pressures of all frequencies in the defined range in a single value, the change in this value itself does not yet give any information about the change in the magnitude of the pressure level peaks. Thus, taking a closer look at the pressure level distribution curves after optimization gives a better impression of the achieved results.

## Verification study

To verify the developed optimization algorithm the Morris sensitivity analysis is applied. Being one of the most widespread sensitivity techniques [5-7], the Morris method offers an effective screening tool to identify both influential and non-influential design variables. The algorithm itself is based on the calculation of parameter specific elementary effects, obtained after generating design variable trajectories in the parameter design space [7].

A very important issue in the Morris algorithm is the sampling quality. The original method, proposed by Morris [5], suggests the generation of trajectories in the design space, starting at random points. This strategy does not take into consideration the possibility of uneven trajectory distribution, which results in poor space coverage. For this reason, an improved strategy, developed by Campolongo [6], is used in the current study. The space sampling technique of the method is further modified by the introduction of quality parameters of the distribution of trajectories to ensure the applicability of the analysis to the low frequency range, as described in [7].

As the outcome of the Morris study the mean values of the elementary effects of each design variable are calculated together with the standard deviation of the elementary effects from the corresponding mean value, demonstrating the amount of interaction between selected optimization parameters.

As soon as a Morris study is conducted, each design parameter is plotted as a point in a 2D graph with axes, indicating the magnitude of the elementary effect the parameter poses on the system and with the amount of interaction the parameter has with the rest of the parameters in the set. The activated parameters are expected to be positioned on the right side of the graph, where high values of elementary effects are observed.

Two Morris studies are conducted. The first study aims at estimating the sensitivities of the design domain, created by restricting the maximum and minimum values of design variables to 1% variation from the baseline value, to the right and to the left respectively. Thus, with the restriction to very small variations of design parameters in the design space local effects of activated levers could be estimated in the context of the global sensitivity analysis method. The mean of elementary effects are plotted against the interaction coefficient for each design variable (see Figure 6).

The second study is conducted to find the sensitivities of the sum level of sound pressure with respect to the design variables in the design domain around the optimized parameter values. The interval is chosen to be 1% to the right and to the left from the optimized design variable values, as for the first study. The Morris graph is again created, plotting the mean of elementary effects against the interaction coefficient (see Figure 7). Depending on the parameter characteristics the corresponding units for the elementary effects and for the standard deviation values are: dB·mm/N for stiffness parameters (labeled DOOR02, HEDGE02, BUFF02) and dB·mm<sup>3</sup>/kg for the mass density parameter (labeled ROOF21).

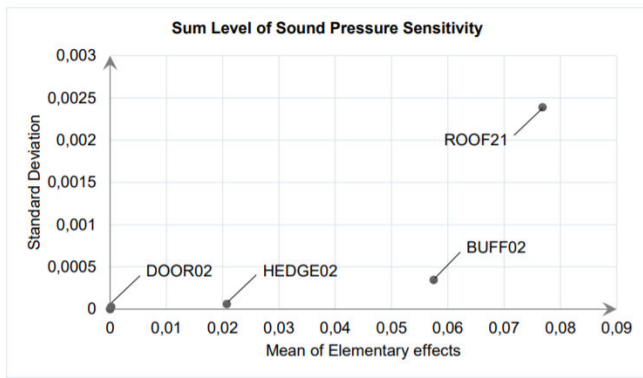


Figure 6: Baseline model Morris sensitivities.

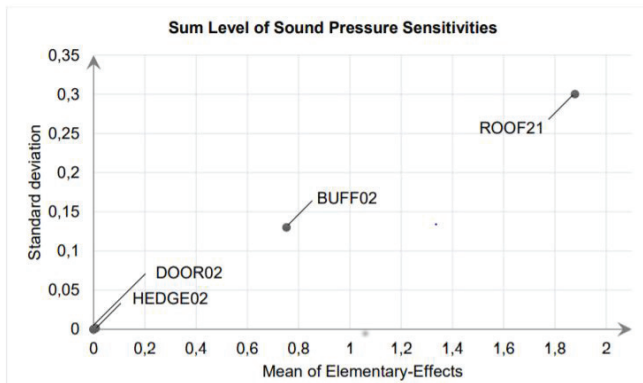


Figure 7: Optimized model Morris sensitivities.

As it can be concluded from the graphs above, the influence of design variables BUFF02 and ROOF21 is significantly increased, which is exactly the goal of the optimization process. The increase of the influence can be inferred, looking at the shift of the corresponding points to the right along the horizontal axis, denoting the mean of elementary effects. On the other hand, the influence of the HEDGE02 design variable is reduced, as prescribed by the optimization goals. The DOOR02 design variable remains to be non-influential.

## Conclusions

Within the framework of the current study an optimization algorithm is developed, aiming at using sensitivity coefficients of the acoustic response with respect to various design parameters directly as optimization objectives.

Depending on the optimization goal, the influence of a group of parameters can be maximized or alternatively minimized. Both applications can be useful, as not only activation of acoustic levers can be desirable, but also the minimization of the influence of parameters with poor potential for regulation. As well the effect of parameters, demonstrating highly unstable impact on the system behavior in terms of acoustics can be minimized.

As long as acoustic behavior is generally very sensitive towards any changes in the structural model, ensuring acoustic levers already on early design stages is a desirable goal. The range of applicability of the optimization results was found to lie within 10% of the design parameter value variation; i.e., after activating an acoustic level, the corresponding parameter

can be changed up till 10% in both directions from the baseline value to still achieve the expected effect on the acoustic response.

Generally, the algorithm can be extended for more microphone points, including the corresponding sensitivity coefficients inside the sum level of sound pressure function. Moreover, the superposition of acoustic waves, generated by separate load cases, can be implemented in the python interface, based on the sensitivity output files.

The verification studies, based on the Morris sensitivity analysis, supported the effectiveness of the developed algorithm and demonstrated the expected behavior of design parameters.

Further investigations need to be held to study the influence of design parameter interactions on the optimization outcome, in case of using more than one design parameter in the set. It might be the case that the optimization objectives are contradictory to each other, resulting in lower performance of the optimization itself. On the other hand, the selected parameter set might be strongly interacting with some of the other structural parameters, which can reduce the robustness of the obtained optimization results.

## References

- [1] M.J.M. Nor, M.H. Fouladi, H. Nahvi and A.K. Ariffin: Index for vehicle acoustical comfort inside a passenger car, *Applied Acoustics*, Vol. 69, Issue 4 (2008), 343-353.
- [2] M. Brandstätter: Tieffrequente Geräusche in einem Kraftfahrzeug bei Unebenheitsanregung, PhD thesis, TU Berlin, 2014, Berlin.
- [3] M. Ranjbar: Eine vergleichende Studie zur Optimierung in der Strukturakustik (A Comparative Study on Optimization in Structural Acoustics), PhD thesis, TU Dresden, 2011, Dresden.
- [4] RED CEDAR TECHNOLOGY: An Efficient and Robust Optimization/Search Algorithm, URL: <http://www.redcedartech.com/pdfs/SHERPA.pdf>, date of retrieval: 04.12.20.
- [5] B. Iooss, P. Lemaître: A review on global sensitivity analysis methods, *Uncertainty Management in Simulation-Optimization of Complex Systems* (2015), 101-122.
- [6] F. Campolongo, J. Cariboni, A. Saltelli: An effective screening design for sensitivity analysis of large models, *Environmental Modelling & Software*, Vol. 22, Issue 10 (2007), 1509-1518.
- [7] L. Berk, C. Adams, E. Slomski-Vetter and T. Melz: Identifikation sensibler Parameter zur Systemabstimmung in der niederfrequenten Fahrzeugakustik, In : *Proceedings of the DAGA 2020 – 46. Jahrestagung für Akustik, 2020, Hannover*.
- [8] Siemens: Acoustics User's Guide, URL: [https://docs.plm.automation.siemens.com/data\\_services/resources/nxnastran/11/help/t doc/en\\_US/pdf/acoustic.pdf](https://docs.plm.automation.siemens.com/data_services/resources/nxnastran/11/help/t doc/en_US/pdf/acoustic.pdf), date of retrieval: 04.12.20.