How Virtual Points, Component TPA and Frequency Based Substructuring Disrupted the Vehicle Suspension Development Process

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ABSTRACT

The high competition in the automotive industry has led to ever shorter development cycles and the introduction of modular vehicle designs. To succeed in this environment, engineers need to be able to make quantitative design suggestions as early as possible. For NVH-engineers this means to, e.g., make an optimal choice for the suspension bushings to compromise between driving dynamics, ride comfort, noise, and durability. This is a task wherein decisions involve many stakeholders, design parameters and targets and these need to be made before the first physical prototype exists. Thus, early phase insights are crucial.

In this paper we show how NVH-engineers conquer these challenges by applying state of the arts methods from structural dynamics: First, the source excitation and noise propagation is separated using component TPA. Then, a model of the car suspension including all the bushing degrees of freedom is measured using the virtual points. The bushing stiffnesses are virtually modified using a frequency based substructuring method called stiffness injection (SI). The bushing parameters are optimised using the genetic algorithm. Our results show how the combination of these technologies allows to efficiently produce optimal design choices considering various driving conditions, target quantities, and design constraints. It furthermore shows how modern software design easily allows this to become an integral part of the standard vehicle development process.

Keywords: NVH, blocked force TPA, frequency based substructuring, stiffness injection, virtual points

INTRODUCTION

The daily challenges of a noise vibration harshness (NVH) engineer have changed drastically over the last decades. Not just is the shift to electric vehicles causing a complete makeover of the design and sound of the cars, but also is the high competition within the field forcing the manufacturers to decrease the development cycles. The engineers at OEMs thus must understand and integrate new components into the nowadays modular vehicle designs with less time for testing. Especially, in the field of vehicle NVH, where the complexity of the systems makes it impossible to solely rely on simulation data, the analysis of experimental data is still of high importance. Many problems cannot be anticipated in the early design stages but need to be discovered, understood, and solved quickly once the first prototype arrives. The best engineers in the field manage to do so thanks to their great feeling for the cars, their experience. Once they emerge after many hours on the probing grounds and test labs, the development process is very close to the final design freeze. Hence, they need to think of good arguments for the expensive late-stage changes that they need to solve the problem at hand.

Besides this dilemma, NVH engineers are usually not the only ones who would like to make some alterations to the vehicle design. There are a couple of stakeholders from different departments involved in the development process. In the case of the suspension design, the system integration engineers need to consider driving dynamics, robustness, ride comfort, and tire noise (figure 1). It is obvious how late-stage trial-and-error is not the most cost and resource efficient strategy to solve the challenges in the development of complex systems like the suspension of a modern vehicle. Therefore, research departments in the automotive industry have been working hard to come up with technologies that allow NVH engineers to identify and solve design problems an early stage in the development process.

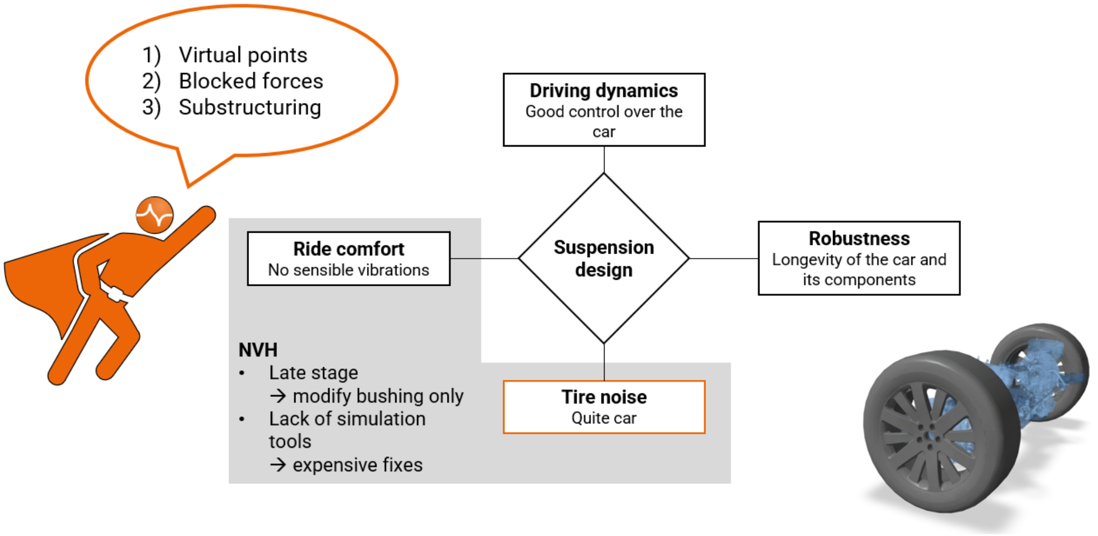

Figure 1: The different stakeholders and the role of NVH in the suspension design process.

Over the past years, in our collaboration with HMC, we have identified key technologies and established procedures that allow NVH engineers to solve tire noise challenges using virtual points, component-based blocked force TPA, and frequency based substructuring [1], [2], [3]. In this paper we present the workflow that combines these technologies in an optimisation of the tire noise while respecting the boundary conditions of other stakeholders. The following chapters describe the workflow and the technologies used within.

APPROACH

Road noise can be very unpleasant and tiring for the driver and passengers if not considered in the vehicle design process. It contains low booming noise (50-200Hz), the cavity noise (200-250Hz), and the rumble (200-500Hz). Any of these components can become troublesome for certain driving conditions (e.g., specific road conditions and driving speeds). The goal of NVH engineers is thus to identify the weaknesses of the suspension design for all relevant scenarios and tune the system parameters to remedy them. As the final cabin noise is a result of the complex vehicle design, it is important to cascade the targets from full vehicle level (cabin noise) to the different systems (suspension and car body) and to the parts that it is composed of (e.g., subframe, suspension arms, bushings, tire). Like this, problems can be attributed and tackled effectively by the development groups at OEMs or suppliers in the modular vehicle development process.

Our workflow was designed to fit the needs of this modular vehicle development process (see figure 2). It optimises targets on system or vehicle level, uses inputs on part level, and creates optimised targets on part level. All of these can be adapted to the available data of the different design stages and the constraints and modifications by other stakeholders throughout the whole development cycle. Models could first use simple numerical data combined with benchmark vehicle data and later be replaced by test-based models of prototypes. Tire excitation data can be updated once suppliers release new versions. The ranges of the bushing stiffnesses can be updated to the target ranges set by other groups. And cost functions can be designed in a wholistic approach to balance the interests of all stakeholders. These flexibilities make it perfectly suitable for the high-speed development process in the automotive industry.

The first step is the system modelling based on the principles of substructuring. The suspension system is divided into substructures which are described through their dynamics at the interface points using virtual points. The second step is the measurement of the test-based VP-FRF model. This is the initial configuration of the system. Next is the source characterisation of the tire/road excitation with blocked forces. These will provide the equivalent input excitation for the simulation of the system responses. Then the system modifications using the stiffness injection at the various bushing degrees of freedom are defined. And the genetic algorithm is used to compute the bushing configuration that optimises the tire noise for the given suspension. All these steps are explained and discussed in more detail in the following sections.

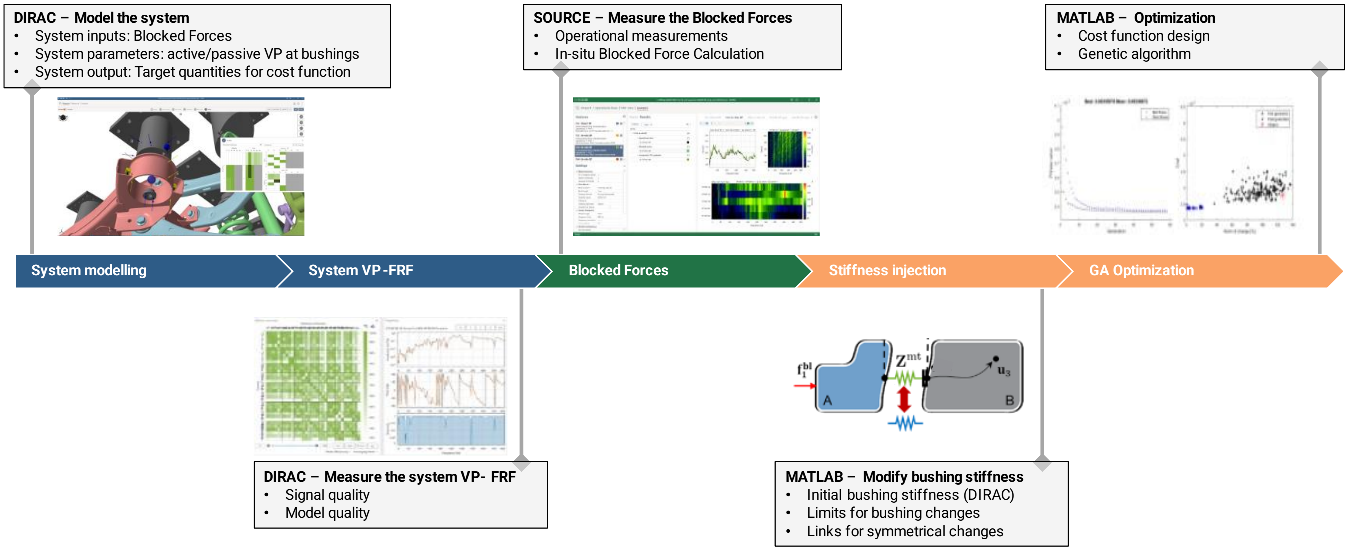

Figure 2: The workflow for optimising the suspension design.

System modelling

From the system engineering point of view, it is thus essential to differentiate sound phenomena into the source excitation and the sound transmission through the vehicle to the driver's ear. Problems can occur due to particularly high excitations or due to resonances in the transfer path. The system modelling needs to be able to display both. Hence, a clear definition of the substructures of the system and their interfaces is the first step in the workflow.

Figure 3 shows the modelling of a front suspension. The system input is the road excitation. It is modelled using blocked forces at the wheel hub (see respective section below). Note that the system excitation is modelled upstream of the design alterations. This is a relevant and necessary requirement for the validity of the response predictions of the modified systems. The stiffnesses of the suspension bushings are the system parameters which are used to optimise the tire noise performance. They are modified using stiffness injection between the active and passive side of the bushing (see respective section below). The system output can be defined on the level of the suspension system or on the vehicle level. When working with a suspension test bench [7], the target quantities are the blocked forces at body. They can measured on the rigid rig and used to predict the tire noise in the vehicle and thus are a possible choice for the target quantity [1]. When working on a vehicle setup or soft rig setup, a possible target quantity could also be the power input to the body [9]. For troubleshooting in the late design stage of a prototype vehicle, the obvious target quantity is the sound pressure level in the cabin.

During the different design stages, the most accurate data of the substructures can be numerical and/or experimental. To create high quality system models, it is important to ensure compatibility of all datasets at the interfaces. Modelling the interfaces with virtual points ensures compatibility of all setups and describe all relevant interface dynamics in test-based models [8].

System VP-FRF

The system FRF model used in the workflow can be updated and replaced by more refined ones throughout the whole development process. Engineers can use early-stage numerical models for first estimates, then improve their predictions with first suspension prototypes, and do quick late-stage troubleshooting with vehicle prototypes. The models can also be hybrid models using experimental and numerical data.

A key to high model quality is that compatibility of the is ensured at the interface degrees of freedom (especially when data from different test setups are merged). For test-based modelling this can be achieved by describing the interfaces with virtual points. This technology is implemented in the DIRAC software which we used to further ensure signal quality and data consistency.

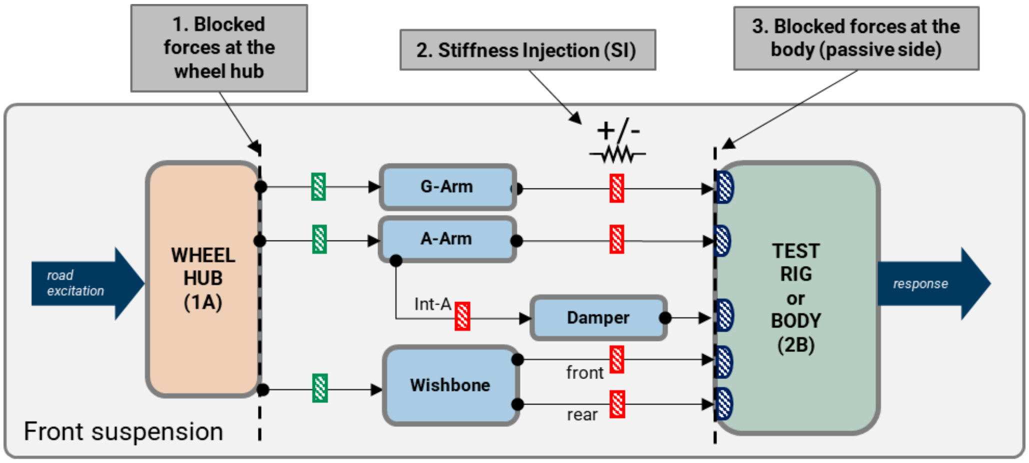

Figure 3: The workflow for optimising the suspension design.

Blocked Forces

Component TPA allows to characterise the road excitation with blocked forces in different test setups. The blocked forces can then be applied to the corresponding virtual point of the system model to predict the response of the target quantity [5],[6]. Since the goal of this workflow is to find an optimal modification of the system parameters, it is important to consider the point of application of the blocked force inputs. In order to remain representative of the source excitation, the clocked forces must be before the modified parts. Here, we model them at the wheel hub interface between the tire and the knuckle. The wheel hub is upstream of all suspension bushing in the transfer path which allows for the changes using stiffness injection. Modelling the blocked forces at the wheel hub is also favourable since the tires are produced by suppliers and thus provide a good basis for communication and target setting.

The choice of the blocked forces is very relevant for the optimisation results. It is important to include all relevant operational conditions in the combined set of blocked forces. These can be obtained from tire test benches or vehicle test drives at various speeds and surfaces for all the different tire options. Our calculations of the big blocked-force datasets were performed in SOURCE.

Stiffness Injection

In the classical sense, frequency based substructuring is used to couple two substructures at their interface. This technique can however also be used to modify the dynamics of an already assembled system. The stiffness injection method uses this to introduce additional stiffness and/or damping between the virtual points of the active and passive side of bushings:

$$\mathbf{Y}_{\mathbf{mod}} = \mathbf{Y} - \mathbf{Y}\mathbf{B}^{\mathbf{T}}(\mathbf{B}\mathbf{Y}\mathbf{B}^{\mathbf{T}} + \mathbf{Y}_{\mathbf{SI}})^{-\mathbf{1}}\mathbf{B}\mathbf{Y}, \tag{1}$$

where $\mathbf{Y}_{\mathbf{mod}}$ is the modified system FRF, $\mathbf{Y}$ is the original system FRF, $\mathbf{B}$ is the Boolean matrix of the active and passive bushing dofs, and $\mathbf{Y}_{\mathbf{SI}}$ the additional stiffness and damping FRF which is placed in parallel to the bushing [4]. Component TPA allows then to apply the blocked forces to the new system dynamics to compute the new response at the target points. All these computations can be done int the software COUPLE.

Stiffness injection can be used to increase and decrease the stiffness between the virtual points of the suspension bushings. The changes can lead to significant system alterations and instabilities if chosen too high. Thus, it makes sense to set limits to the design alterations based on the initial stiffness of the bushings. These initial values can be obtained from supplier test data or through inverse substructuring [10].

Genetic Algorithm Optimisation

The number of bushing design parameters can be higher than 20 for some suspension designs. This would result in a myriad of possible different bushing configurations. Hence, an algorithmic approach is required to solve the optimisation problem. The high cross coupling between the different suspension bushings leads to a high complexity of the system: Making one bushing stiffer changes the energy flow through the whole system – like water taking the path of least resistance. This results in many local optima which makes line search optimisers useless. A better way to solve this problem is to use global optimisation algorithms like the genetic algorithm (see figure 4). This allows to converge to the optimal bushing target stiffnesses within less than an hour. Such high-speed creation of early-stage development insights is game changing in NVH engineering.

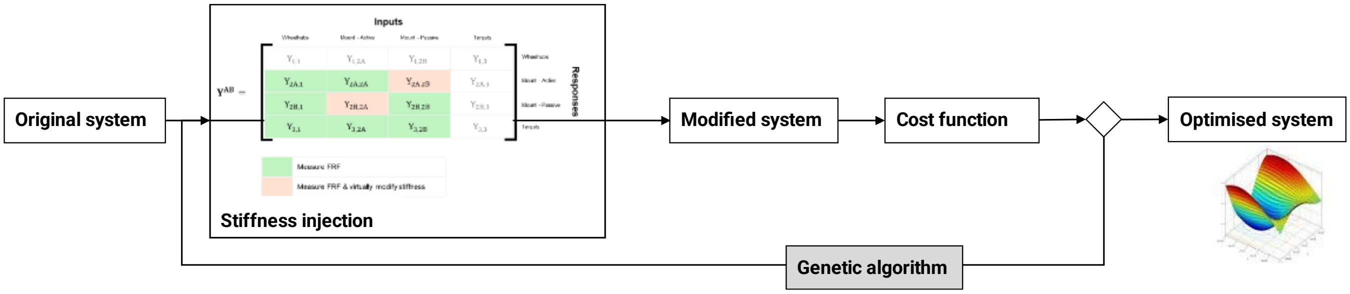

Figure 4: System optimisation using stiffness injection and the genetic algorithm.

The results in figure 5 show how the genetic algorithm converges over the iterations of the generations and how the populations converge in the solution space indicating that a global minimum is achieved (using MATLAB). The response of optimised system shows an improvement of the target quantity (see figure 6). The precise cost function design (the reduction of the multidimensional target response to a scalar value) can be shaped so that specific regions are improved more than others, or peaks are focused on more than broadband noise. Note that some areas outside the optimised frequency range can also become worse. Hence it is important to include the interests of tire noise and all other stakeholders in the design of the cost function for an optimal suspension design.

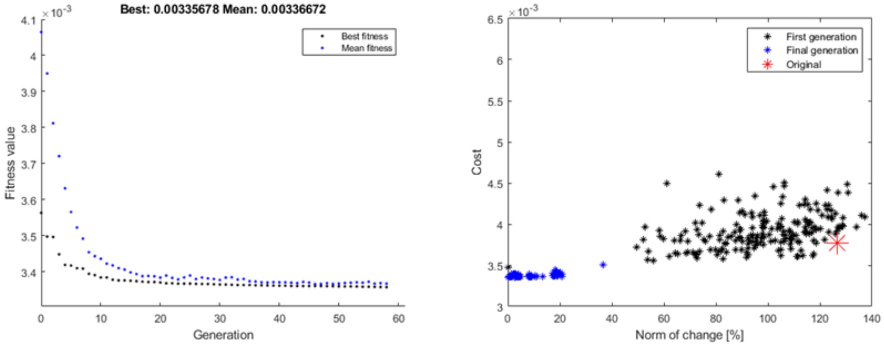

Figure 5: Convergence of the genetic algorithm over the generations (left). Convergence of the population in the solution space (right)

CONCLUSION

It was shown how the combined technologies of virtual points, blocked force TPA, stiffness injection and the genetic algorithm allow NVH engineers to approach in a completely different way. While common practices rely heavily on late-stage trial and error testing and the experience of the engineers, we presented a workflow that allows to optimise the design of vehicle suspension systems in a highly cost-efficient way. It can be used in many design stages using the most accurate numerical and/or experimental model data available. Furthermore, it approaches the challenges of the design process in a holistic way by incorporating the interests of all stakeholders in global cost functions.

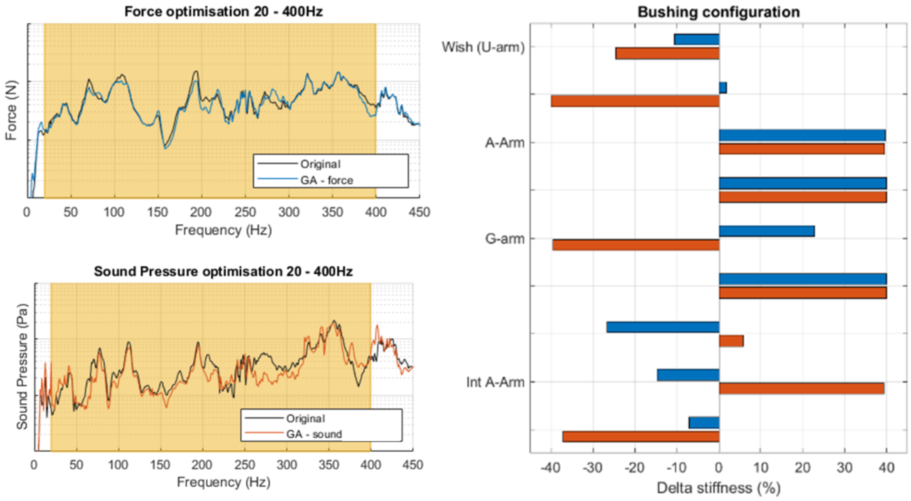

Figure 6: Target response of the original and optimised system when optimising for forces (top left, blue) and sound pressure (bottom left, orange). Suggested changes for the respective optimised bushing configurations (right).

ACKNOWLEDGEMENTS

We like to acknowledge NVH Research Lab of Hyundai Motor Company for funding this research. We like to thank Müller-BBM VibroAkustik Systeme Korea for their support in the measurement campaigns and coordination.

REFERENCES

[1] M. V. van der Seijs, J. M. Harvie, and D. P. Song. "Road Noise: Embedding Suspension Test Benches in Sound & Vibration Design using virtual points and the Transfer Path Analysis Framework." *Dynamic Substructures, Volume 4*. Springer, Cham, 2022. 99-106.

[2] J. M. Harvie, M. V. van der Seijs, D. P. Song, and M. Cho. " Road Noise NVH Part 2: Exploring the Capabilities of the TPA Framework with Interface Forces." *Dynamic Substructures, Volume 4*. Springer, Cham, 2023. 19-28.

[3] M. Cho, D.P. Song, M. Lee, J. Lee, et al., “Prediction and Optimization of Blocked Force Changes of a Suspension System Using Bush Stiffness Injection Method,” *SAE Technical Paper*, 2022-01-0956, 2022, doi:10.4271/2022-01-0956

[4] L. Gagliardini, and D. de Klerk., “Stiffness Injection: A Tool for Vehicle NVH Performance Optimization,” *SAE Technical Paper*, 2022-01-0976, 2022, doi:10.4271/2022-01-0976.

[5] A. T. Moorhouse, A. S. Elliott and T. A. Evans, "In situ measurement of the blocked force of structure-borne sound," *Journal of Sound & Vibration*, vol. 325, no. 4-5, pp. 679-685, 2009.

[6] M. V. van der Seijs, D. J. Rixen en D. de Klerk, „General framework for transfer path analysis: History, theory and classification of techniques,” *Mechanical Systems & Signal Processing*, vol. 68, pp. 217-244, 2016.

[7] D. P. Song, D. Min, Y. J. Kang, M. Cho, H. G. Kim and K. D. Ih, "A methodolgy for evaluating the structure-borne road noise prior to a prototype vehicle using direct force measured on a suspension rig," *Noise Control Engineering Journal*, vol. 64, no. 3, pp. 295-304, 2016.

[8] M. V. van der Seijs, D. D. van den Bosch, D. J. Rixen and D. de Klerk, "An improved methodology for the virtual point transformation of measured frequency response functions in dynamic substructuring," in *COMPDYN 2013: 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Kos, Greece, 2013.

[9] E. A. Pasma, S. W. B. Klaassen, A. V. V. Passanesi, J. Westlund, "Advanced complex power TPA studies for road noise NVH performance on a rear axle," in *ISMA2022: International Conference on Noise and Vibration Engineering*, Leuven, Belgum, 2022.

[10] M. Haeussler, S.W.B. Klaassen, D.J. Rixen, “Experimental twelve degree of freedom rubber isolator models for use in substructuring assemblies,” *Journal of Sound and Vibration*, Volume 474, 2020.