Effective FE methodology for fully trimmed vehicle body NVH analysis in the mid frequency range applied to a Genetic Algorithm optimization process

Ciro Gaudino
Davide Caprioli
Rieter Automotive Switzerland

Leonardo Ferrali
Nihon Rieter Automotive Acoustics

Abstract

Extending the frequency range to calculate the vibration of a fully trimmed vehicle model and having an analysis methodology which can be efficiently employed by automatic optimization procedures based on statistical methods, have been among the main targets of Rieter Automotive in the low-mid frequency FE analysis field.

The main issues when a large FE model is calculated in a broad frequency range are hardware requirements and computational time. In particular, this becomes a major problem when FE analysis is employed by automatic optimization processes based on statistical methods like GOLD, the optimization program developed by Rieter Automotive based on genetic algorithms (GA). GOLD is able to find the optimum solution in terms of damping and shape design for vehicle body panels based on weight, cost, and NVH performance targets.

In order to have an efficient optimization process, the computational time of each single run must be minimized without deteriorating the result accuracy. For this purpose, Rieter Automotive has successfully combined the super-element approach with a new analysis methodology, which exploits the capabilities of sub-structuring techniques and a special MSC.Nastran module for the computation of frequency response functions when a large modal basis is available (more than 3000 modes).

The first results of this activity are presented in this paper.

Introduction

In the automotive field the frequency range between 200Hz and 600Hz is crucial for structure-borne noise.

In this frequency range, many local modes of vehicle panels can rise and local structural damping and stiffening effects become important.

To include layers of viscoelastic damping materials in Finite Element (FE) models without increasing the number of Degrees of Freedom (DoFs) of the problem, Rieter has developed a software package, named Emerald. Emerald calculates frequency dependent Young's Moduli and Loss Factors of bending and membrane deformation types of metal layers damped by viscoelastic damping materials [1].

Although modelling damped panels by means of Emerald does not increase the DoFs of the problem, performing a Finite Element Analysis (FEA) up to 600Hz of a whole trimmed vehicle is still an expensive calculation in terms of computational time and hardware resources.

The reason is that the most effective approach for vehicle vibration analysis is the modal frequency response approach, based on the block Lanczos eigensolver, which uses a sparse solver in the iteration process [2]. Moreover, once the modal basis is available, complex matrices are usually created during the solution process and the equation system generated to compute the frequency response function (FRF) is non-diagonal.

Rieter has reduced the hardware resources required to calculate the modal basis of a large FE model by using the sub-structuring technique in the computation of the modal basis and has applied a special MSC.Nastran module to compute response functions by employing a modal basis with more than 3000 modes.

The same analysis methodology integrated with the external superelement approach has been used to perform an automatic optimization in GOLD.

The results of a trimmed vehicle FE model of 3 million DoFs between 200HZ and 800Hz achieved by means of this analysis methodology, a short description of GOLD and the results of a damping and shape optimization will be presented.

1. Description of the analysis methodology and results.

The analysis methodology employed to calculate the modal basis of a large FE model in a broad frequency range exploits the sub-structuring technique of MSC.Nastran Automated Mode Component Synthesis (ACMS), based on the Craig-Bampton reduction method [3].

More in detail, MSC.Nastran ACMS divides the FE model automatically into geometric sub-domains (superelement-like), whose number depends on the size of the model. The geometric domains are organized in a tree and solved by taking into account the residual vectors.

The sub-domains are then solved one by one, remarkably reducing hardware resource requirements. By selecting the Distributed Memory Process (DMP) option, a number of geometric domains equal to the number of CPU's allocated for a run can be solved at the same time with an important reduction of computational time.

In the case of a trimmed vehicle model with damping treatments, once the modal basis has been calculated, the solution of the equation system in modal coordinates, which provides the FRF, can be a critical point due to the fact that complex matrices are usually generated during the solution process and the corresponding equation system defined in modal coordinates is non-diagonal.

Thus the solution of the equation system can be time consuming with the standard MSC.Nastran module in case of trimmed vehicle FE models.

To reduce this time, Rieter has employed a new special MSC.Nastran module named fastFRRD1 together with the sub-structuring technique described above.

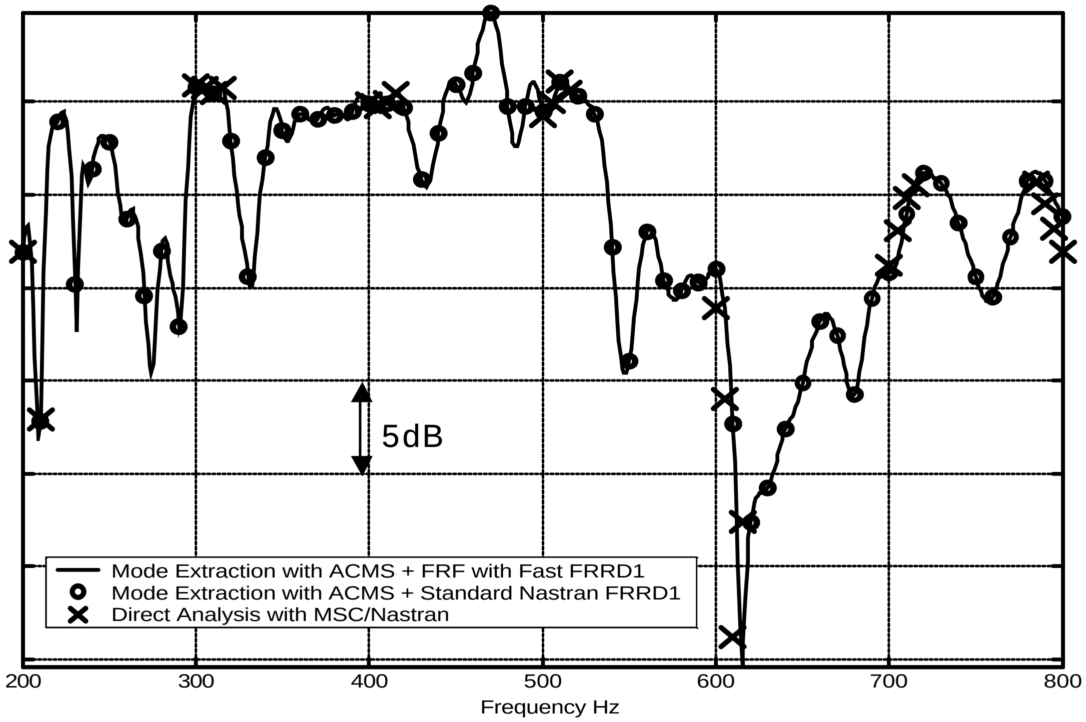

Fig 1: Numerical Validation of analysis methodology; Acceleration

Figure 1 shows a numerical validation of this methodology. The continuous curve represents the response calculated by means of the methodology employing simultaneously fastFRRD1, ACMS, and DMP of MSC.Nastran.

The circles are responses calculated by using MSC.Nastran ACMS for the modal basis and the standard MSC.Nastran module for the FRF. The crosses are responses calculated by using the standard MSC.Nastran direct analysis approach (sol108).

These results have been achieved employing a FE model with more than 1.5 million DoF.

5900 natural modes have been calculated up to 1200Hz and the FRF has been calculated with a frequency step of 1Hz.

The structure has been excited with enforced motions and the correct bending and membrane damping loss factor (DLF) have been calculated with Emerald and defined for the damped panels elements [1].

The validated methodology has been employed to solve a fully trimmed vehicle FE model of about 3 million DoF.

The FRF at 310 nodes between 200Hz and 800Hz has been calculated using a modal basis up to 1200Hz. Unit displacements have been enforced in locally stiff positions. Table 1 reports the computational time achieved with a HP Itanium workstation, and figure 2 shows the Mean Square Velocity (MSV) over the 310 nodes. The frequency step used for these calculations was 1Hz.

Modal basis up to 1200 Hz - 14932 natural modes -	14 hours
FRF: 200Hz 800Hz – Step 1Hz - 310 nodes -	20 hours

Tab 1: Computational time of fully trimmed vehicle calculation

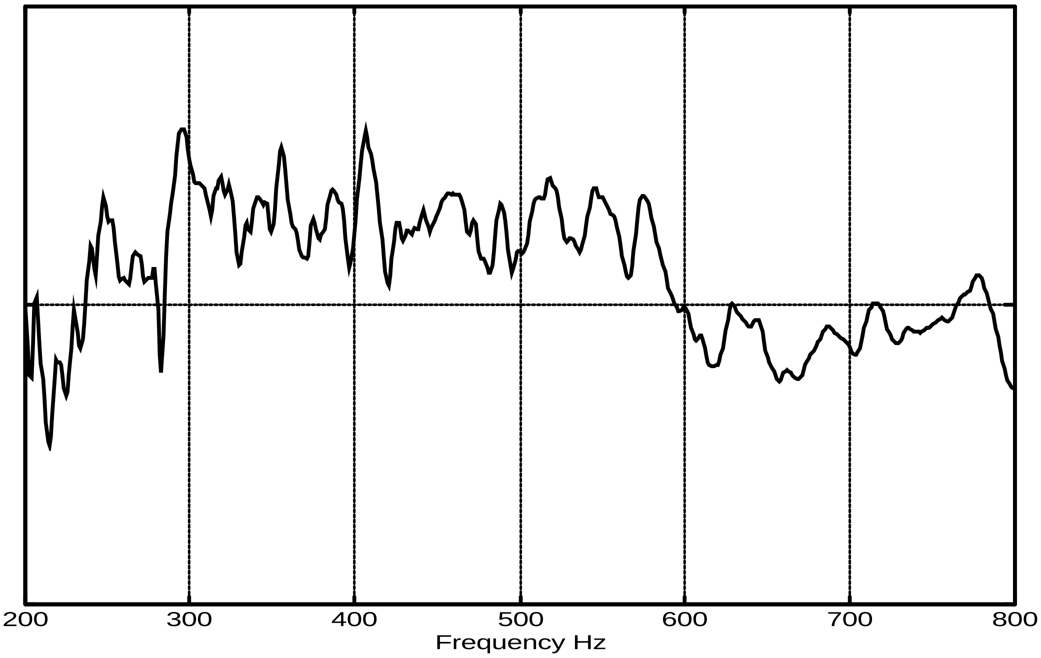

Fig 2: Trimmed Vehicle: MSV over 310 nodes

2. Analysis methodology applied to Genetic Algorithm optimization process and results.

2.1 GOLD: Rieter Genetic Algorithm optimizer

GOLD is a tool developed by Rieter, written in MatLab® software package, for the automatic optimization of vehicle damping treatments and panel shape. It is based upon Genetic Algorithms, which are recognized as the most powerful methodology to handle complex optimization problems with very large numbers of design variables [5-11] and exploits FE and BE (Boundary Element) simulation techniques.

As far as the damping optimization is concerned, the typical variables taken into account are:

- Panel material;
- Panel thickness;
- Damping treatment type;
- Damping treatment thickness;
- Panel area temperature: for instance, higher temperatures can be assigned to body panels in the tunnel or dash areas or a temperature distribution map derived from a thermal camera scan can be taken into account;
- Damping treatment local distribution.

In practice, GOLD can take into account a very high number of optimization variables, which in theory would lead to a huge number of possible damping treatment configurations (typically billions) and efficiently handle optimization problems practically impossible to be solved with standard Design of Experiment (DOE) techniques.

The necessary starting input data for the optimization are the following:

- FE model of the structure (vehicle body) on which damping has to be optimized;
- In case an acoustic target is required, BE or FE model of the vehicle acoustic cavity;
- Material parameters of all the possible damping treatments used in the optimization;
- Definition of the *damping patches*, i.e. the possible damping pads applicable on the vehicle body panels;
- If required by the user, more additional constraints in terms of weight and NVH performance (vibration or acoustic pressure) can be defined.

Depending on the combination of the damping patches, different damping packages are found. A global exploration of the optimization domain takes place in order to achieve the global

Objective Function (OF) maximum; unlike gradient-based optimization techniques, the optimization performed by GOLD is not stopped when a local maximum is found. The vibro-acoustic behaviour of an *individual* (i.e. a potential solution of the optimization problem) is calculated using the FE software package MSC.Nastran, which is automatically run by GOLD in case a potential optimum individual is found. In the end of the optimization process, a group (population) of best individuals is kept in memory and the optimum damping package can be selected and visualized by the user. The explored solution space (i.e. the domain containing all the possible solutions) has dimension m^N, where:

- N is the number of damping patches possibly treated
- m is the number of treatment solutions

The optimization target is typically the reduction of the following quantities:

- damping package weight;
- vibration response (FRF) as a function of frequency;
- Sound Pressure Level (SPL) response as a function of frequency.

The user can directly modify any of the above optimization targets separately or choose any combination of them just by changing some command lines contained into a simple text interface file. It is also possible to give priority to one special target instead of another. This enables the achievement of the best compromise between weight reduction and NVH performance improvement (either structural vibration or SPL), according to the particular constraints the user wants to apply.

The last GOLD release can combine simultaneously damping and shape optimization. The typical geometric variables taken into account for the shape optimization can be:

- flat shape
- rib;
- soap film;
- embossment.

The necessary starting input data to perform a shape optimization are the following:

- FE model of the structure (vehicle body) where the shape modification will possibly be applied;
- geometrical description of the soap-film or embossments;
- geometrical description of the ribs.

For a GOLD shape optimization, the initial FE model does not require any mesh modification. Special internal GOLD routines verify the mesh quality of any new shape configuration to be analysed. If checks are not successful, GOLD automatically updates the mesh in order to satisfy the necessary quality requirements without modifying the geometry. The slight differences introduced in this way ensure that results are not mesh-dependent, and the original level of quality for the FE mesh is kept. In case of simultaneous damping and shape optimization, the amount of information describing an *individual* (i.e. a potential solution of the optimization problem) is increased therefore the number of FE analysis runs is generally higher than a simple damping optimization.

GOLD has a control monitor, which allows the user to follow the optimization process in real time. As soon as a better configuration than the original one is found, the user is able to visualize it and get the corresponding results and FE model without stopping the optimization run. This feature is very useful, especially when the designer wants to achieve good results in short time or is under pressure, for instance because of a particularly demanding project schedule.

2.2 FE analysis methodology in GOLD.

The statistical optimization method embedded into GOLD is extremely efficient. Therefore the number of configurations that GOLD must analyse to achieve the solution of the optimization problem is usually not high, or even negligible, in comparison with the total number of potential design solutions contained in the whole optimization domain. However, since that domain can contain billions of possible solutions, the configurations that GOLD needs to analyse can still be many.

Performing an analysis of the full vehicle model for all those configurations (each representing a potential optimum design solution of the optimization problem) is generally not feasible. For this reason, the FE model analysed by GOLD is split into two main geometrical domains: the first one (superelement) includes the parts of the vehicle model not involved in the optimization, the second one (residual structure) includes the panels modified during the optimization.

After solving the superelement, the corresponding reduced matrices are calculated and stored in a convenient format [4].

By restarting a residual structure run including the reduced matrices, a possible optimal solution found by GOLD is evaluated.

Although the superelement reduction is performed once, it is an expensive operation in terms of hardware resources and calculation time.

In order to make the superelement reduction process more efficient, another new methodology has been set up combining MSC.Nastran ACMS with the MSC.Nastran external superelement reduction technique.

The accuracy of this methodology has been verified by comparing a full analysis run to a restart run including the external superelement generated by means of MSC.Nastran ACMS. The achieved results in the case of a trimmed vehicle body (TB) are shown in figure 3.

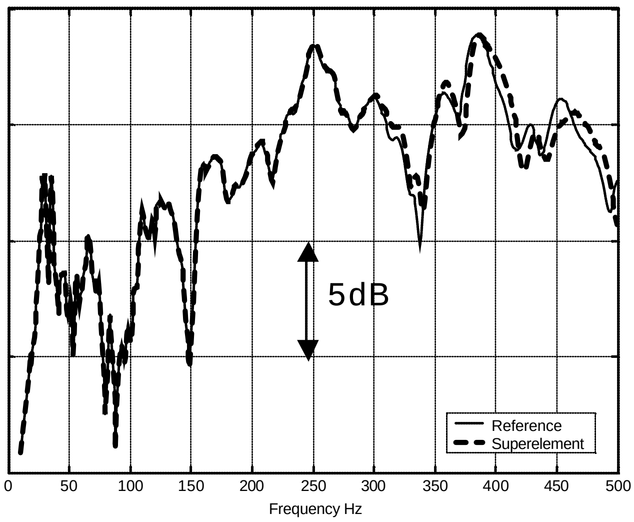

Fig 3: Superelement accuracy; MSV: TB model

In figure 3 the continuous curve represents the full analysis results and the dashed curve the restart run results. The accuracy of the restart run looks acceptable. It is worthwhile to mention that these results have been achieved by applying an enforced motion excitation.

By properly modifying the reduction nodes and generalized coordinates, a further considerable improvement in computational time and a decrease in exploited hardware resources can be achieved keeping the same result accuracy.

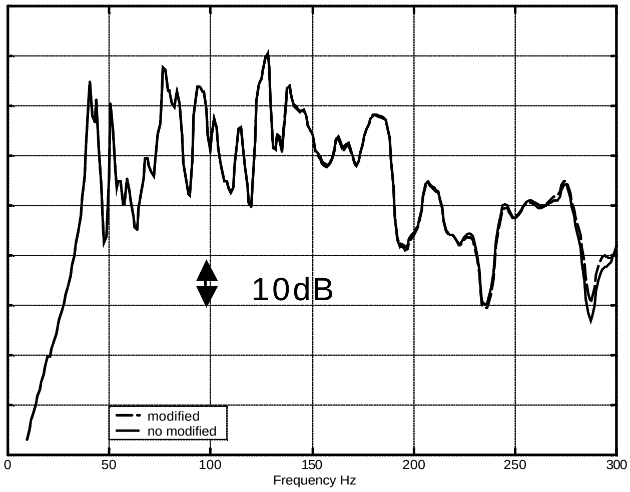

Fig 4: Results with reduction nodes modification; MLV

However, it must be remarked that this is a critical operation depending on several different factors and should be performed with care by the user.

As an example, figure 4 reports the square velocity at one residual structure node of a vehicle BIW model up to 300Hz before and after a reduction node modification. The model is the same and the result curves are almost superposed but the calculation time is five times faster after the modification.

The efficiency of this procedure is mainly dependent on the experience and familiarity of the user with the methodology presented in this paper, and is proven to be of great help, especially when the vehicle model is used for a GOLD optimization.

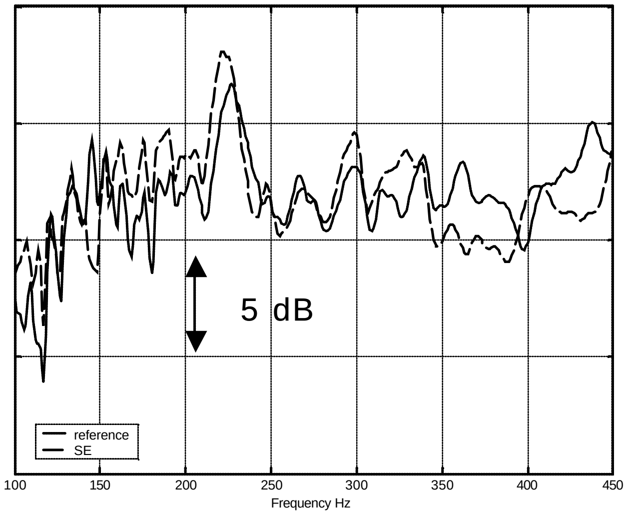

Fig 5: Trimmed vehicle, residual strucuture run - full run - MLV over 153 nodes

Applying all the described methodology steps to a fully trimmed vehicle FE model of about 3 million DoFs, it has been possible to calculate in 45 minutes the frequency response between 100Hz and 450Hz on a set of 153 nodes. Figure 5 shows the comparison between the Mean Linear Velocity (MLV) response of the full model (continuous curve) and of the same model calculated with the reduced approach (dashed curve). Even though the MLV responses do not perfectly match in the whole frequency range, the dynamic behavior of the full model is however represented by the residual structure with reasonable accuracy.

The fact that the differences are essentially concentrated in the higher frequency range seems due to modal truncation in the residual structure. The results of the residual structure have been achieved with an HP Itanium machine in 45 minutes against many hours for the full model.

The computational time needed for the residual structure run has been considered acceptable for a simultaneous damping and shape optimization performed by GOLD on a TB model.

This activity has been performed within a project for a car constructor.

In this project, after an initial phase in which the FE panel response was successfully validated against experiments, GOLD has been able to optimize the complete damping package of a vehicle using the two types of damping materials originally applied, each with two possible different thickness configurations, without changing the weight of the original damping package. More in detail, GOLD has successfully improved the MSV response over 153 nodes placed on the lower dash and floor panels, which in the

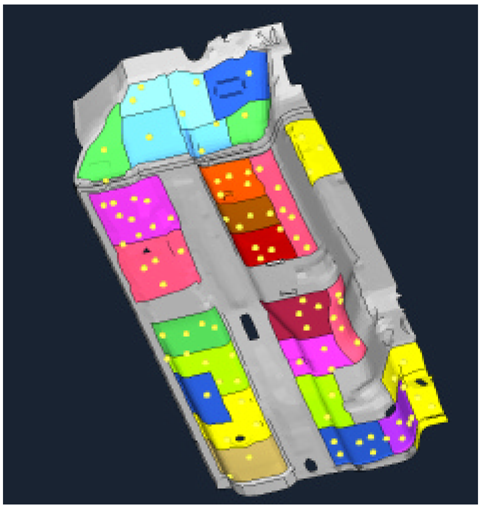

Fig 6: Panels to be optimised, GOLD patches, output nodes

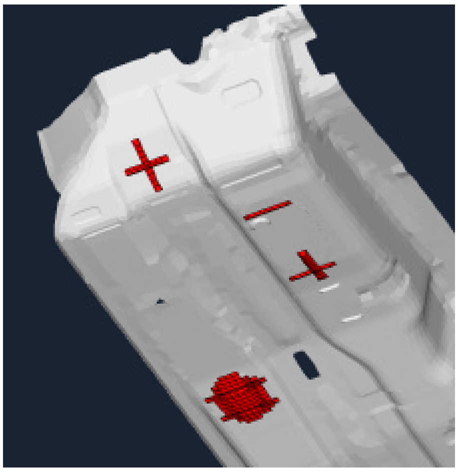

Fig 7: shape configuration: Driver side

original configuration were fully covered by damping materials. Figure 6 shows the panels location the response points and the patches where GOLD was allowed to possibly place damping material. Concerning the shape optimization, GOLD was able to generate any possible shape configuration choosing among 11 transversal ribs, 9 longitudinal and 8 soap-films.

The vehicle was excited at the engine mount, front strut and rear suspension. The overall number of possible solutions of this optimization problem was $3.6*10^{19}$.

Among them, GOLD found the optimum solution shown in figures 7 and 8 in about one week. Figure 7 shows the optimized shape configuration and figure 8 the optimized damping package.

Fig 8: Damping configuration: Driver side

The comparison between the original MSV response and the optimized one is reported in figure 9. It can be noticed that from 100 to 300Hz the difference between original and optimized damping package is remarkable and rises up to 5dB and more at the highest peaks. The optimized shape and damping layouts have no remarkable effect on the panel vibration at higher frequencies.

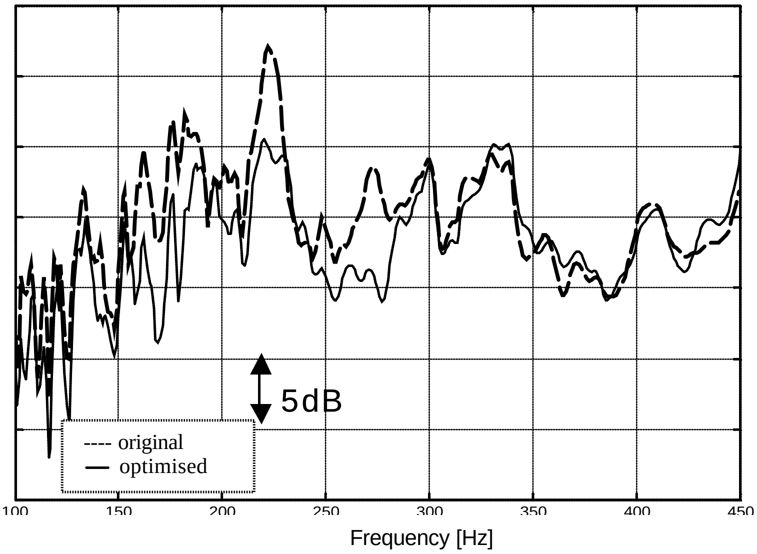

Fig 9: MSV comparison, original and damping-shape optimized configuration

3 Conclusions

Rieter has set up a new efficient methodology combining ACMS, fastFRRD1 and DMP of MSC.Nastran to calculate the FRF of large FE models and has successfully applied it to a 3 million DoF trimmed vehicle FE model from 200 to 800Hz by employing a modal basis up to 1200Hz.

This new methodology, in combination with the MSC.Nastran external superelement technique, can dramatically reduce the hardware resources and computational time required for the solution and can be used to perform automatic damping and shape optimization by means of GOLD software package by Rieter.

The reliability and accuracy of this methodology in comparison with a standard time consuming computation of the whole vehicle model have been positively tested.

A proper modification of the superelement reduction nodes and general coordinates has further remarkably reduced the computational time from many hours to only 45 minutes keeping acceptable results accuracy.

The results of a practical damping package and shape optimization on a trimmed vehicle model have been presented.

New optimized damping package and shape layouts have been achieved showing better vibration performance with nearly the same mass in comparison with the original vehicle condition.

The methodology described in this article has been embedded into GOLD and is currently used at Rieter as a standard tool for practical vehicle development based on FE-BE simulation in the low-mid frequency range.

References

[1] Masataka Akagi, Jun Yoshida (Daihatsu Motor Co.), Shu Wang, Leonardo Ferrali (Rieter Automotive Systems): "*Simulation by EMERALD/NASTRAN of non-flat vehicle panels with multi-layer damping treatment*", 17th MSC Japan Users Conference '99

[2] Grimes, R. G., Lewis, J. G., and Simon, H. D.: "*A shifted block Lanczos algorithm for solving sparse symmetric generalized eigenproblems*", SIAM J. Matrix Analysis and Applications, 15 (1994), pp 228-272.

[3] Craig, Roy R.:"*Structural Dynamics - An Introduction to Computer Methods*", ISBN 0-471-04499-7

[4] Superelement handbook

[5] Goldberg D.: " *Genetic Algorithms in search, optimisation and machine learning* ", Addison Wesley Publishing Company, 1989.

[6] Blickle T.,Thiele L.: " *A comparison of selection schemes used in genetic algorithms* ", Technical report 11, Computer Engineering and Communication Network Lab.

[7] Wright A.: " *Genetic algorithms for real parameter optimization*", Proceedings of the 1st Workshop on foundations of genetic algorithms, ED: Morgan Kaufmann, 1991.

[8] Agapie A.: " *Genetic algorithms: minimal conditions for convergence*", Lecture notes in Computer Science, Vol. 1363: Artificial Evolution: 183-193.

[9] Dozier G., Bowen J., Bahler D.: " *Solving small and large constraint satisfaction problems using a heuristic-based microgenetic algorithm*", Proceedings of the 1st IEEE Conference on evolutionary computation, 306-311,1994.

[10] Bulmer M. G.: " *The mathematical theory of quantitative genetics*", Claredon Press, Oxford, 1980.

[11] Strasser P., Ferrali L., Caprioli D.: " *Emerald: an FE-tool for the optimal design of damped vehicle bodies with respect to low-middle frequency range*", Rieter Automotive Conference, 2001.