2004-05AE-271

Multi-Disciplinary Optimization of a Sport Utility Vehicle

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ABSTRACT

One of the important challenges in the Auto industry is to reduce the mass of the vehicle while meeting structural performance requirements for Crashworthiness, Noise, Vibrations & Harshness (NVH) etc. With the onset of high speed computing power and the availability of process automation & optimization tools, Computer Aided Engineering (CAE) is playing a significant role in addressing this challenge. CAE tools can now be used to conduct design exploration studies and to perform Multi-Disciplinary Optimization (MDO), i.e., optimization involving multiple disciplines such as crash, NVH, durability etc.

This paper describes an MDO study carried out on a Sport Utility Vehicle (SUV). The aim of the study was to minimize the Body-In-White (BIW) mass of the vehicle while meeting Crash and NVH constraints. The crash events considered were frontal crash (NCAP), frontal offset crash (IIHS) and rear impact. The NVH attributes considered were peak acoustic and structural mobilities at key suspension and engine-to-body attachments, along with key global modes of vibration.

The Design Variables used for the MDO were 75 BIW sheet metal gauge variables. The design space for exploration was decided based on manufacturability, packaging space and vehicle-specific knowledge. A Design of Experiments (DOE) based Response Surface Model (RSM) was created using the Kriging formulation. The RSM was subsequently used for executing the MDO. The MDO process was constrained to stay within a specified band around design-of-record performance.

The optimum design obtained was 3% lighter and met all the prescribed Crash and NVH requirements. The RSM obtained in this exercise was used as a design tool for what-if studies. A reliability study was performed on the optimum design using Monte Carlo simulations. A detailed MDO process was developed from this exercise along with recommendations for ideal periods for application during the vehicle development cycle for maximizing value.

INTRODUCTION

Significant improvements in the following areas have been observed in the past few years, benefiting the CAE industry to a great extent:

- <u>Computing Power</u>: Processor speed, availability of large amount of memory & hard disk space, multiple processors and distributed computing
- <u>Solver speed</u>: Numerical method improvements to reduce solver execution time
- <u>CAE process integration & automation tools</u>: Availability of tools that integrate all the CAE software that is available at any customer location
- <u>FE/CFD model parameterization & morphing software</u>: Availability of tools that would serve as a parameterization engine which will transform a regular FE or CFD to an intelligent FE/CFD model

The powerful combination of the above factors has given the ability for the CAE engineer to transition from the traditional 'single point design' study to design exploration using Design of Experiments (DOE) studies, rigorous optimization, robustness studies, Design for Six Sigma (DFSS) studies etc. This is possible even for complex non-linear problems. Using the above combination, the CAE engineer can easily evaluate several design alternatives in the same time that would have otherwise taken for a single design earlier.

The optimization of the Jeep® Grand Cherokee (2005 Model Year) Sport Utility Vehicle for mass minimization is a large scale problem that requires significant utilization of all the above factors.

- Significant computing power is required to solve Crash and NVH analysis of the full vehicle FE models (500000 Nodes typical).
- Parallel processing capability of the solvers such as MSC/Nastran and LS-Dyna on multiple CPU's is required to reduce the analysis time.
- Parametrization capability of MeshWorks/MORPHER is required to parametrize the FE models, so that various designs can be generated rapidly and automatically by supplying values for the different parameters.
- Process automation capability of tools such as Isight is required to automate the process of generating new FE models (using the Morpher), running Crash & NVH analysis, extract results from the output files etc. Since the process is repetitive and has to be repeated several times (100 typical), automation is essential to ensure accuracy, consistency and reduce project execution time.
- Finally, optimization capability of tools such as Isight is required to arrive at an optimum design based on the multiple designs studied (or explored).

This paper describes how the Jeep® Grand Cherokee vehicle's body structure was optimized such that its weight was minimized while at the same time Crash & NVH targets were met. It describes the objective of the study, the optimization process used, the process as applied to the specific vehicle considered and the conclusions drawn.

The multi-disciplinary optimization (MDO) used in this study can be performed at different stages of vehicle development. At the initial concept stage, the design space for exploration is the maximum possible compared to any other stage. The ability to explore the shape of any part at this stage in addition to gauge helps in getting the maximum benefit through an MDO.

In this study however, the design of the vehicle body structure was almost fixed. At this stage only gauges of many parts were available for exploration. The design exploration process used during this study is explained in the next section.

OBJECTIVE

The objective of this study is to minimize the mass of SUV body structure while meeting crash and NVH targets. The crash events considered were NCAP, IIHS and Rear impact. The NVH attributes considered were peak acoustic and structural mobilities at key suspension and engine to body attachments along with key global modes.

OPTIMIZATION PROCESS

This section describes the optimization process (refer to Figure 1) used in the study. The process starts with a baseline study of the SUV body structure to evaluate the crash and NVH performance. This baseline analysis helps in understanding the current state of performance and also provides direction to choose the design parameters.

Based on the load paths observed in the baseline analysis for Crash and NVH and with the benefit of past vehicle experience, design parameters are selected. The Manufacturability and packaging space allowed locks the design space for exploration.

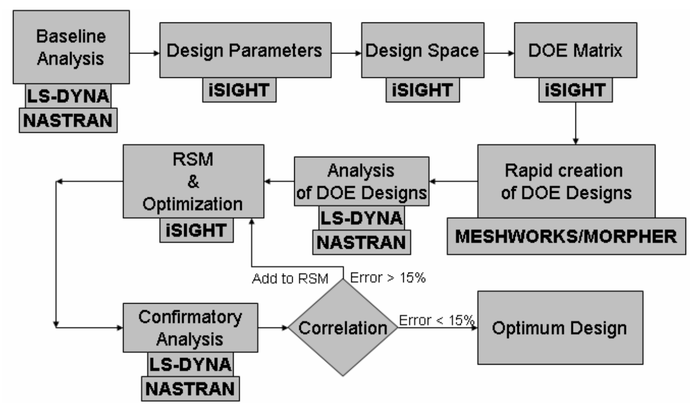

Figure 1: Flow-chart of DOE/RSM based optimization process.

A DOE matrix is generated using standard sampling techniques. The DOE matrix is comprised of several designs, wherein each design has specific values for all the design variables.

In order to generate the Crash and NVH FE models corresponding to these designs, the original model (in other words the baseline design) is parametrized. The FE models of all the DOE designs are generated rapidly by supplying values for the design parameters.

Crash and NVH analysis of all the designs is conducted and the output parameter values of each design is recorded. The output parameters for evaluating crash performance are dynamic crush, 'time to zero', toe pan intrusion etc. Output parameters for NVH are natural modes of vibrations of the vehicle and their corresponding frequencies, peak values of drive point mobilities and acoustic mobilities.

The results of the DOE analysis are used to create a mathematical model called a Response Surface Model

(RSM). The RSM is essentially a transfer function between the design parameters and the output parameters.

The accuracy of the RSM depends on the number of designs analyzed. The accuracy of the RSM is determined by comparing the results (output parameter values) for any given design as generated by the RSM and the analysis solver. The more the number designs analyzed at the DOE stage, the better the accuracy of the RSM.

Once the RSM is generated, the objective function and constraints are defined. Optimization is carried out using the RSM for the objective function within the constraints specified. The optimization results obtained provides the best combination of design parameters. This optimum obtained is called meta-optimum.

A confirmatory analysis is performed on the meta-optimum design. In the correlation stage, the results of the actual analysis are compared with the results of the meta-optimum. If the error percentage is greater than 15% then the results of the confirmatory analysis is added to the mathematical model. The addition of one more design improves the accuracy of the RSM. The optimization is re-performed on this improved mathematical model. The results obtained goes through the process of confirmatory analysis and correlation. This loop continues till the error percentage becomes less than 15%.

This process will result in an optimum design that would satisfy multi-disciplinary constraints imposed by crash and NVH criteria.

APPLICATION

This section describes the above process applied to the SUV Multi-disciplinary Optimization.

Baseline Analysis: The baseline design was analyzed for crashworthiness and NVH performance.

For Crash analysis, the events considered were:

1> NCAP: This is the frontal barrier crash analysis for which output parameters such as the deceleration curve (‘time to zero’ curve), dynamic crush, toe pan intrusion, etc. were monitored.

2> IIHS: This is the frontal offset deformable barrier crash analysis for which output parameters such as intrusions at various vehicle locations were monitored.

3> Rear Impact: This is the rear impact analysis for which output parameters, such as door to body opening, were monitored.

For NVH analysis, the following were considered:

1> Normal Modes: Key body modes (global vertical bending, global lateral bending, global torsion, front end torsion and rear end torsion) were monitored.

2> Forced Response: Peak Acoustic and Structural mobilities at key suspension and engine to body attachment points were monitored.

Design Parameters: The design variables used for the MDO were 75 BIW sheet metal gage variables. Of these, 30 were independent design variables and 45 were dependent design variables. The limitation on the number of independent design variables (N) was imposed by the number of DOE runs (2N+1) that would be required for each event and the resulting increase in computation time. The final number of 30 independent design variables used struck a balance between accuracy of RSM and computational hours required so that project objectives of mass reduction as well as timing are met.

Design Space:

The sheet metal parts selected as candidates for optimization as well as their gage-ranges were pre-qualified on the basis of manufacturability, assembly, and knowledge of risk to crash, durability and NVH performance.

Apart from sanitizing the design variables selected, this process resulted in exclusion of some sheet-metal parts from the MDO either because of known sensitivity to gage and/or potential for performance risk due to reasons that would not be explicitly modeled in the MDO.

For instance, the underbody rail system which is made of dual phase steel was excluded due to the learning of the material behavior that was in progress at the time of this project. Figure 2.shows a schematic of the design parameters used for the MDO.

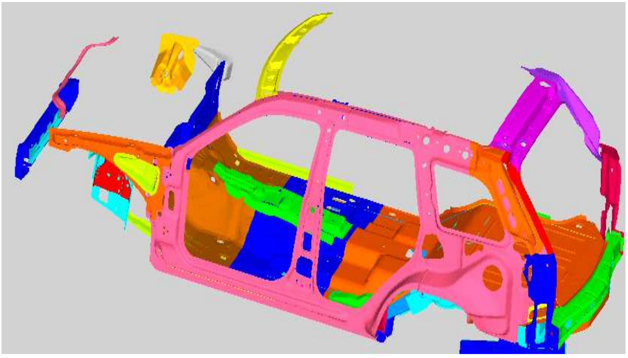

Figure 2: Design parameters

DOE Matrix:

The DOE matrix shown in Figure 3 was created using Latin Hypercube Algorithm using iSIGHT.

Des/PID	Gauge1	Gauge2	Gauge3	Gauge4	*	Gauge75
Des1	2.76	1.50	1.99	2.12	*	*
Des2	2.51	1.62	1.51	2.66	*	*
Des3	1.84	1.74	3.00	2.97	*	*
Des4	2.97	1.86	2.82	2.30	*	*
Des5	2.94	1.98	1.32	2.39	*	*
Des6	2.91	2.09	2.94	2.73	*	*
*	*	*	*	*	*	*
*	*	*	*	*	*	*
Des60	*	*	*	*	*	*

Figure 3: DOE Matrix

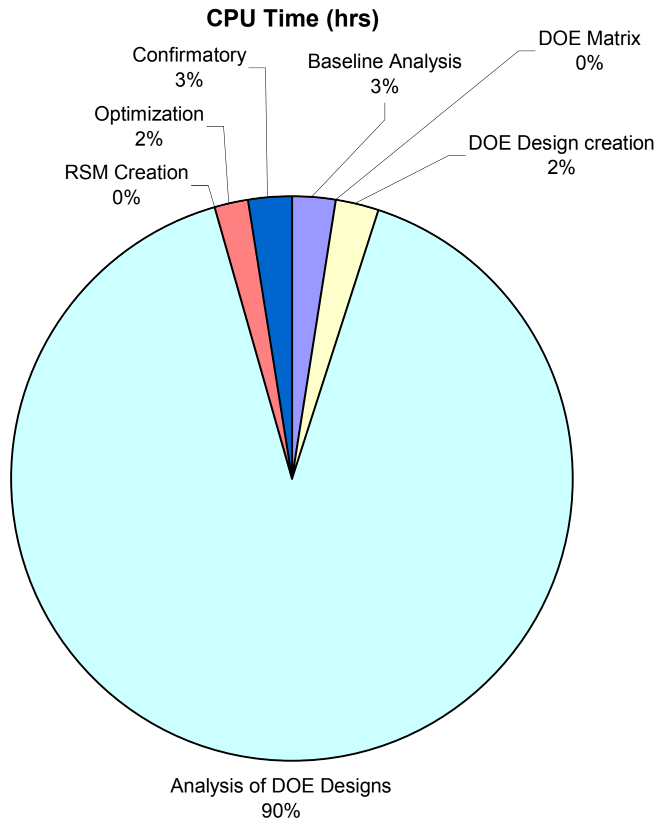

Figure 4: DOE Matrix

Creation of DOE Designs:

All the DOE designs were generated using Meshworks/MORPHER. The FE model was parametrized using this software. After parametrizing the model with gage parameters, the DOE Matrix was imported in to the Morpher. The Crash & NVH models were automatically generated by the Morpher for all the different DOE designs.

Analysis of DOE Designs:

The DOE designs were analyzed using LS-DYNA for Crash and MSC/Nastran for NVH. This stage of the process was the most time consuming one. Figure 4 shows that 90% of CPU time was consumed by this analysis phase.

RSM: A Kriging Mathematical model (using iSIGHT) was created using the results of all the DOE designs. The RSM represents the performance criteria (output parameters) as a function of the design parameters. The results of the baseline design were also used in addition to the DOE designs to construct the RSM.

Optimization: Mass minimization was the objective of the optimization. The performance constraints were to stay within a specified band around design-of-record performance. A gradient based algorithm (CONMIN) was used to do the optimization on the mathematical model.

Confirmatory Analysis: The meta-optimum design obtained from the previous stage using the RSM was then analyzed using the solvers. The results obtained were recorded as iteration1 optimum.

Correlation: The results of the iteration1 optimum were compared with the meta-optimum and the percentage deviation was more than 15%. This iteration1 optimum design was added to the RSM and the subsequent steps were repeated to obtain iteration2 optimum design. This loop was repeated thrice and a final optimum was obtained.

Optimization: Different optimization plans were tried out to search for different optimal solutions. Since all these plans were carried out using the RSM, each optimization run was completed rapidly in comparison to the time taken by full vehicle analysis using LS-Dyna and MSC/Nastran.

For each of the different optimization plans, the following different constraint combinations were evaluated:

- NVH and NCAP constraints
- NVH alone
- All impact constraints – NCAP, IIHS, Rear Impact
- All constraints – NCAP, IIHS, Rear Impact and NVH

In the first optimization plan, the start point was forced to be either the baseline design or the best DOE design. The best design obtained after nearly 5000 iterations violated three of the constraints and resembled close to the baseline design.

In the second optimization plan, the optimizer was forced to go through the DOE design points first, followed by a set of points defined by a Latin-Hypercube scheme. The objective in this plan was to minimize mass. It resulted in the following optimum designs.

	Baseline	NVH + Impact	NVH only	Impact only
Mass	576 lbs	575 lbs	571 lbs	568 lbs

Figure 5

Subsequently, using the same optimization plan, the objective function was set to maximize mass. However, the target for the mass was set to 565 lbs (less than the baseline design) and the optimization plan was set to violate some constraints if need be to achieve this target.

This was achieved and the constraints were satisfied. The crash & NVH performance of this optimum design was then verified by running the appropriate MSC/Nastran and LS-Dyna analyses. The results correlated very well with those predicted by the RSM.

Further studies using the RSM yielded an even higher weight savings of about 17 lbs (3%).

Optimum Design: The optimum design obtained was 3% lighter (17 lbs) and met design goals prescribed in the problem formulation

CONCLUSIONS

- Considering the significant weight reduction possibility at the full vehicle level, it is recommended to include this type of analysis exercise as part of the vehicle development process.
- Adding shape variables to the optimization plan can result in substantial weight reduction. So, it is recommended to perform MDO at an early stage of the vehicle development wherein shape changes are easy to incorporate in the vehicle design.
- Development of special utilities for results extraction is essential to speed up the project and to ensure accuracy.

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