# Design Study for Problems Involving Responses over Multiple Disciplines

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## 1 Abstract

Simulation of automotive vehicles has recently become a more and more important step in car development. Rapid prototyping, which offers a close to market product, with less hardware, requires a fast and accurate computer-simulation to guarantee a quality product.

As long as the simulation itself can only provide information for the current design stage, it is also desirable to improve the design by improving certain functions or reducing the costs to achieve this design.

Applications of optimization techniques to design problems involving single analyses are well established as represented, for example, by capabilities implemented in linear finite element structural analysis programs. However, practical design problems often require simultaneous consideration of responses obtained from multiple disciplines. The required multi-disciplinary optimization techniques to solve these types of problems had been developed, but their practical implementation for solving *real world* problems has been lacking.

The following presentation will show in detail how such a large problem was solved using linear and nonlinear codes in a multilayer software environment.

## 2 Introduction and Problem definition

For structural design, there are multiple objectives. Besides improving functionality, costs have to be minimized. Even for responses which require stiffened structures, in general each response normally requires the material investment at different locations. The following case study shall demonstrate the current process involving multiple disciplines today with respect to durability and point mobility and point out further potential for software vendors to improve interoperability between different codes.

### 2.1 Durability

In this study, we would like to consider two sets of requirements computed by different analyses types for the design of shock tower structures. The first set is related to the durability

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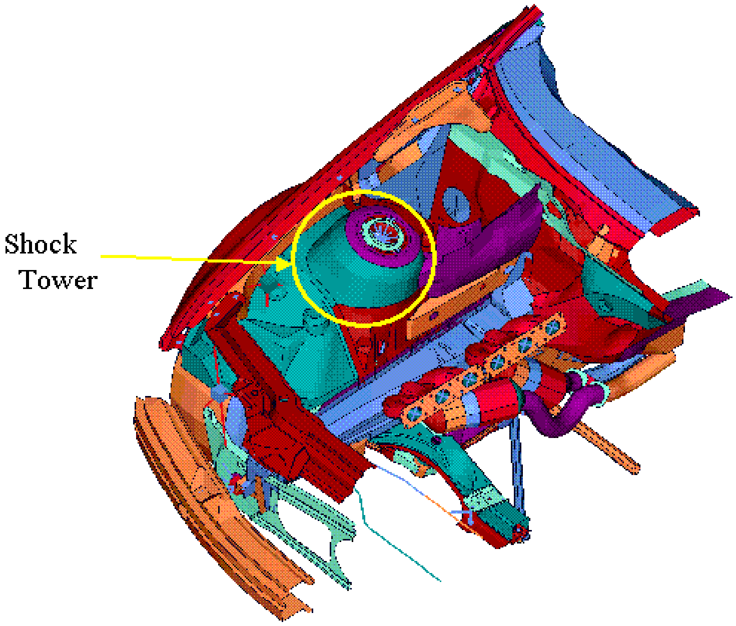

Figure 1: Front Right-side Body: Structural Arrangements

against excessive dynamic loads experienced by the key components. The measure of durability is the maximum plastic strain experienced within each part of the structure for the equivalent static loads. This phase of analysis involves material nonlinearity and the analysis code used is ABAQUS.

## 2.2 Point Mobility

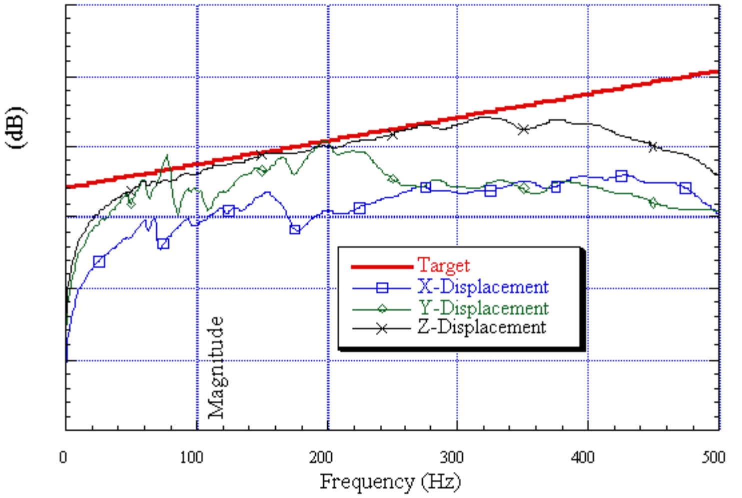

Figure 2: Point Mobility

The second set of requirements is imposed on the point mobility which characterizes the transmission of dynamic loads at the loading point, i.e., vibratory loads from the tire transmitted through the shock tower. If mobility is small, most of the vibratory loads are suppressed at this point and not transmitted to the body structure. Intuitively, the relationship between durability and mobility requirements is not obvious. It is easy to understand that increased protection against fatigue may be achieved by increasing the plate thickness, but the effects of increase in plate thickness in various parts of structures on the point mobility are not clear. The primary purpose of this study is to identify the nature of this interaction quantitatively. If the interaction is weak or nonexistent, these two requirements may be considered independently. However, if there are appreciable conflicts between them, the design process must be structured to obtain the best compromise between the two sets of requirements. The analysis code used for point mobility is MSC.NASTRAN.

# 3 Analysis

## 3.1 Analyses models

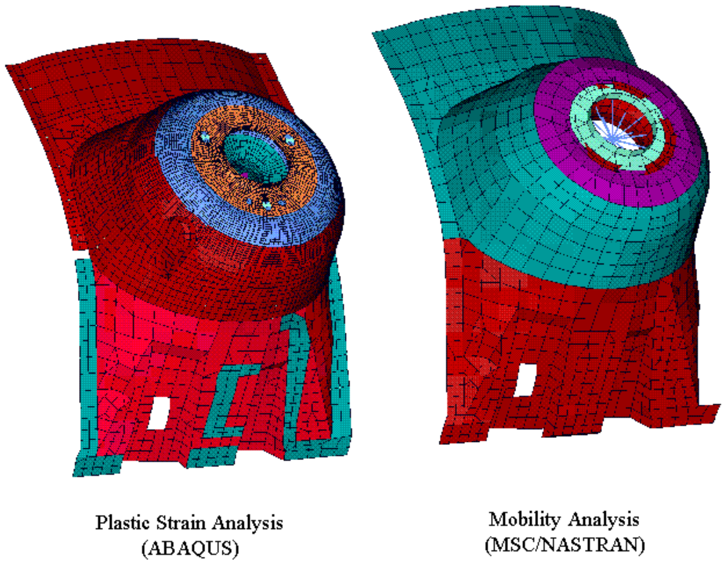

Figure 3: Analyses models for strength and point mobility

The structural assembly considered in this study is the right front shock tower shown in figure 1. Most of the vehicle weight supported by the front left tire goes through this assembly, which is then distributed to the body structure. Furthermore, dynamic shock and vibratory loads from the tire, while the vehicle is in motion, could be much higher than the static equilibrium loads, hence repeated application of high stress pulses exceeding the elastic range may initiate/propagate cracks and shorten the fatigue life. Fatigue life can easily be extended by using a thicker gauge. However, it is not necessarily desirable to make the shock tower excessively stiff. First, it will be heavy (expensive) and may transmit unnecessarily high dynamic vibratory loads to the body. The challenge is to find the best compromise for these potentially conflicting requirements and to find the values of each design variable.

The model for the elasto-plastic analyses must have a sufficiently fine mesh to capture the propagation of the plastic region as accurately as possible. Frequency sweep analysis up to 500 Hz requires a significant amount of computation, hence the model mesh must be just fine enough to capture linear dynamic responses accurately in this frequency range (at least 8 elements per wavelength).

## 3.2 Design Model

### 3.2.1 Design Variables

In order to have a more detailed structure to understand the required load paths the shock tower was split into several parts using tailored blanks (see figure 3). For this problem, the design variables are selected to be the plate thickness for four components, in addition to a choice of steel materials out of three available choices. Parts 11302a, b, and c must be of the same steel, but Stuetzlager may be either steel or aluminum alloy in order to support stamping demands.

**Design Variables and Plate Thicknesses**

| | Range[mm] | Available discrete values |
|---|---|---|
| Part 11032a | 1.6-2.2 | 1.6,1.7,1.8,2.0,2.1,2.2 |
| Part 11032b | 1.6-2.2 | 1.6,1.7,1.8,2.0,2.1,2.2 |
| Part 11032c | 1.6-2.2 | 1.6,1.7,1.8,2.0,2.1,2.2 |
| Stuetzlager (steel) | 1.6-2.2 | 1.6,1.7,1.8,2.0,2.1,2.2 |
| Stuetzlager (alumn) | 2.2-3.8 | 2.2,2.4,2.6,2.8,3.0,3.2,3.4,3.6,3.8 |

Figure 4: Table of design variables

Total number of Design Variables is:

- for steel Stuetzlager: 6 (4 thickness and 2 materials)
- for aluminum Stuetzlager: 5 (4 thickness and 1 material)

If Stuetzlager happens to be steel, its material may be selected independent of the material selected for parts 11302a-c. The ranges of admissible variation for plate thickness are given for all parts as shown in figure 4. In reality, plate thickness may not be arbitrarily selected, thus it is assumed that steel plates are available in 0.1 mm thickness increments and aluminum alloy plates are available in 0.2 mm thickness increments. Actual design tasks should be carried out based on available discrete values for each design variable. However, it is often the case that important trends can be observed much more easily from the results obtained with continuous variation of design variables. For this reason, most of the plots in this report show the results obtained by continuous variation of design variables.

### 3.2.2 Design Targets

In this study, the dynamic characteristics of this structural component are represented by the magnitudes of mobility in x, y, and z directions. These magnitudes are required to be at least below the target profile, which is, in this case, a straight line in the log scale as shown in figure 2. To improve the dynamic characteristics further, after satisfying the requirements, it is desirable to reduce the peak responses as much as possible. Therefore, the requirements for dynamic characteristics are formulated such that the maximum of (computed mobility - target) is less than zero, and further decrease is permitted while making sure that other requirements are satisfied.

## 3.3 Analyses procedure

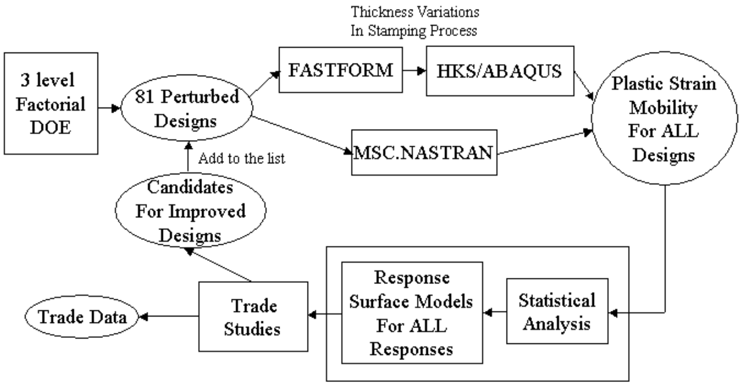

Figure 5: Analysis procedure using 3 level factorial DOE and several integrated solvers.

For the purpose of applying design optimization during trade studies, it is necessary to separate this study into two problems, based on the material for Stuetzlager. This is necessary because the thickness range for steel and aluminum alloy plates are different. Since both analyses are relatively simple for these two models, a 3-level full factorial orthogonal table was used to create 81 perturbed designs. Frequency response calculation for point mobility was done using MSC.NASTRAN. For elasto-plastic analysis, plate thickness variation from the nominal thickness caused by plastic forming operation is calculated by FASTFORM and the modified thickness variations are implemented in the input data used by ABAQUS for strength calculation. Note that these multiple analyses have been processed in parallel on multi-processor systems and networked across heterogeneous computers. Once a sufficient number of analysis results is obtained, the results are processed by statistical screening to estimate whether the currently available analysis results are sufficient to determine each of the coefficients of the response surface approximations with more than 95% confidence level. Then, the response surface approximations are created for each of the responses. Since evaluation of response surface approximations will be almost instantaneous, we can evaluate them any number of times, for design optimization, robustness analysis, trade studies, etc.

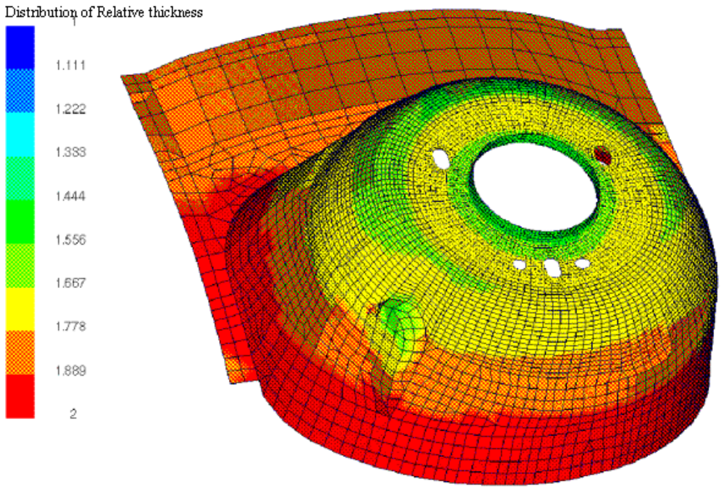

Figure 6: Thickness distribution caused by stamping. Simulated with one-step procedure using FASTFORM

As previously mentioned the influence of stamping for the strength load case is very important. This effect had to be considered. A full stamping simulation would require too much CPU time for a Multi-Disciplinary-Optimization. For simple stamping procedures like the shock tower it has shown that one-step procedures give sufficiently good results by using only a few minutes of computing time.

### 3.4 Response Surface Approximation

For the interpolation of the resultant data (point mobility target and maximum plastic strain) a response surface (RS) using second order Taylor series was used:

$$r_i \;=\; a_i + \vec{b}_i^T \vec{x} + \vec{x}^T C_i \vec{x} \tag{1}$$

Where $i$ indicates the $i$-th response variable, $b_i$ is a vector, $C_i$ a matrix and $\vec{x}$ represents the vector of design variables.

Both maximum plastic strain in 1103c and the measure of mobility are nonlinear functions of design variables, and they may not fit exactly to the response surface approximations. The plots in figure 7 give a qualitative level of accuracy for these two responses compared to the original data, based on which the approximate models are created.

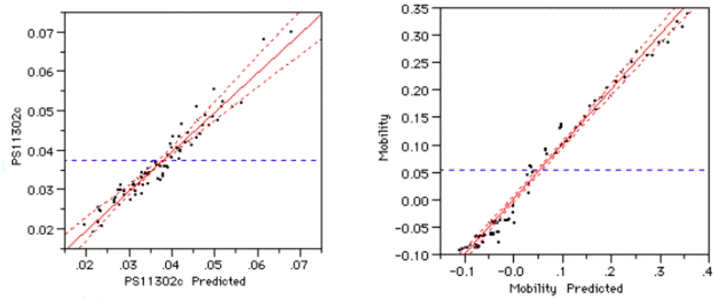

Figure 7: Accuracy of Response Surface using 2nd order Taylor series

# 4 Discussion of the results

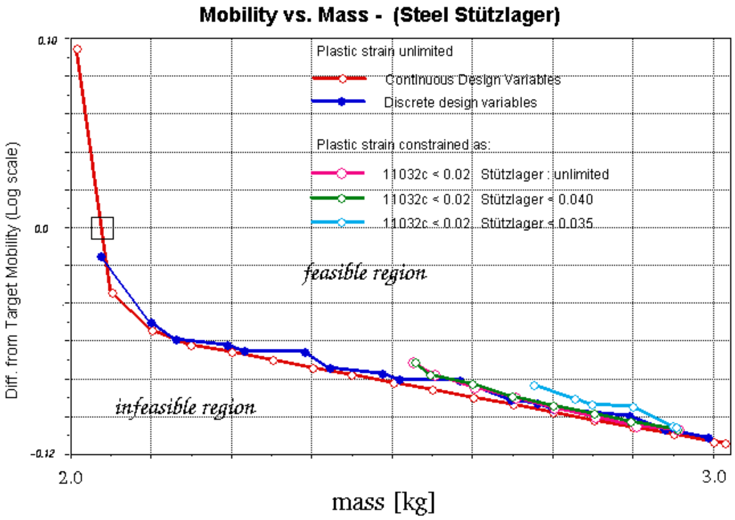

Figure 8: trade off study for point mobility versus mass for different plastic strains

As the first step, it is important to check whether requirements imposed on each discipline can be satisfied if some or all of the requirements on other disciplines are modified or ignored. The curves in figure 8 show that the requirements for point mobility may be satisfied if the structural mass is 2.21 kg or heavier. Since less mobility and less mass will be a desirable design feature, we would like to find a design near the left bottom corner. However, the plot above indicates that by adjusting the design variables values, any status above the given lines may be achieved, but any status below these lines cannot be achieved by adjusting currently available design variables. The red line indicates the boundary if each design variable is allowed to change continuously, while the blue boundary is obtained when design variables are permitted to assume only discrete values. The difference between red and blue lines may be interpreted as discrete penalty.

In figure 8, it was shown that the mobility requirements are easily satisfied, if we relax/ignore

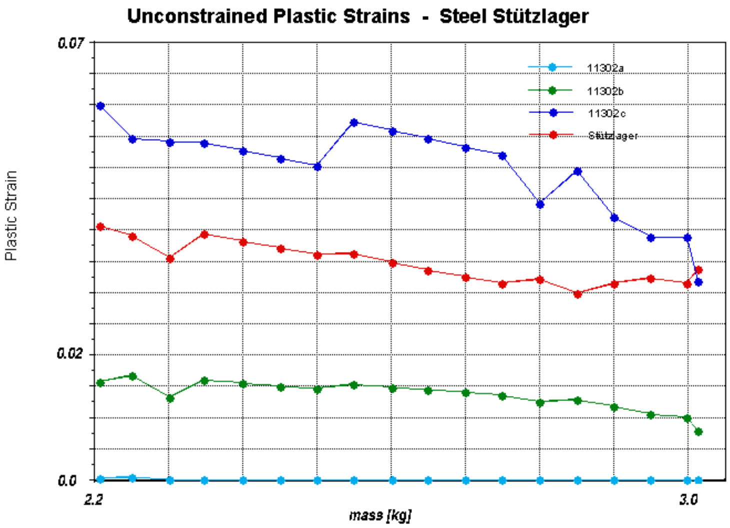

Figure 9: Unconstrained plastic strains for Stuetzlager made of steel

requirements on plastic strains. However, the plastic strains corresponding to the designs plotted in the previous chart violate the specified design requirements by the factor of 2 to 3. Maximum plastic strains for parts 11302a and 11302b stay below 0.02 for all the designs. However, for the part 11302c and Stuetzlager, plastic strains are way above the permissible bounds as shown in chart 9. This type of excessive violation of constraints should be of serious concern from the very beginning. We must expect that it could be very difficult, or even impossible, to bring these plastic strains below 0.02.

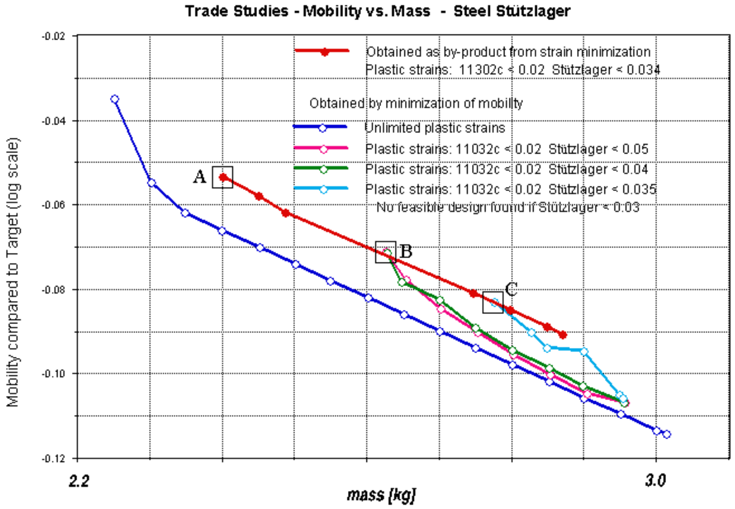

Figure 10: Final trade off study demonstrating mobility versus invested mass for different plastic strains

A good overview of the situation which couldn't be given using traditional optimization techniques is demonstrated in figure 10.

The red curve is probably the best trade curve obtained by minimizing plastic strain in 11302c while obtaining probably very near the lowest plastic strain in Stuetzlager. On this curve, the design with the lightest weight was selected for verification A. All other curves are the trade-off Pareto fronts obtained by minimizing mobility under various constraint combinations on plastic strains. The least mass designs obtained by the upper bounds in plastic strain in Stuetzlager of 0.04 and 0.035 are selected for verifications as B and C, respectively.

Also, it can be seen quite clearly here, that certain desired targets such as the 0.02 bound for plastic strain can be difficult to achieve using the available design variables.

## 5 Conclusion

It has been shown that *real world* multi-disciplinary optimization (MDO) tasks are doable today concerning hardware requirements and available software resources. Some of the potential which these methods provide, such as overall optima and Pareto studies, have been shown.

Nevertheless, there are still huge problems concerning integration of different software packages. Open data structures and open solvers are the key points in order to combine the best software resources that are needed to solve these kind of problems.

MSC.NASTRAN's DMAP and OUTPUT2/4 capability and ABAQUS script provide methods of interoperability, but they are still not sufficient.

Different input and output formats and the need for file translators for ANY kind of data are a huge hurdle to make MDO usable in daily project work.

For this case study more than 80% of the invested man power was spent in *gluing* the software components together, 10% in running and maintaining the job procedure and about another 10% in doing the real engineering job, such as describing the problem and interpreting the results.

As long as it is not possible to reduce the *software gluing* by 90%, MDO is not applicable for daily project work.

To reduce the amount of time spent in gluing different software packages together some key functionalities have to be added to each package:

- capability for compact ASCII output (in addition to the MSC.NASTRAN punch file), a plain ASCII matrix MATLAB-like file (n lines for n rows, m columns for m columns) would be of great benefit.
- Application Program Interfaces (API) for C, C++, and scripting languages like *perl* and *phyton* which allow seamless integration of the solver into efficient scripting procedures. These API's must be capable of reading and writing any kind of data to and from the solvers database as well as accessing and steering any functional module of the solver.

## References

[1] A. Osyczka H. Eschenauer, J. Koski. *Multicriteria Desgin Optimization.* Springer-Verlag, Berlin, 1. edition, 1990.