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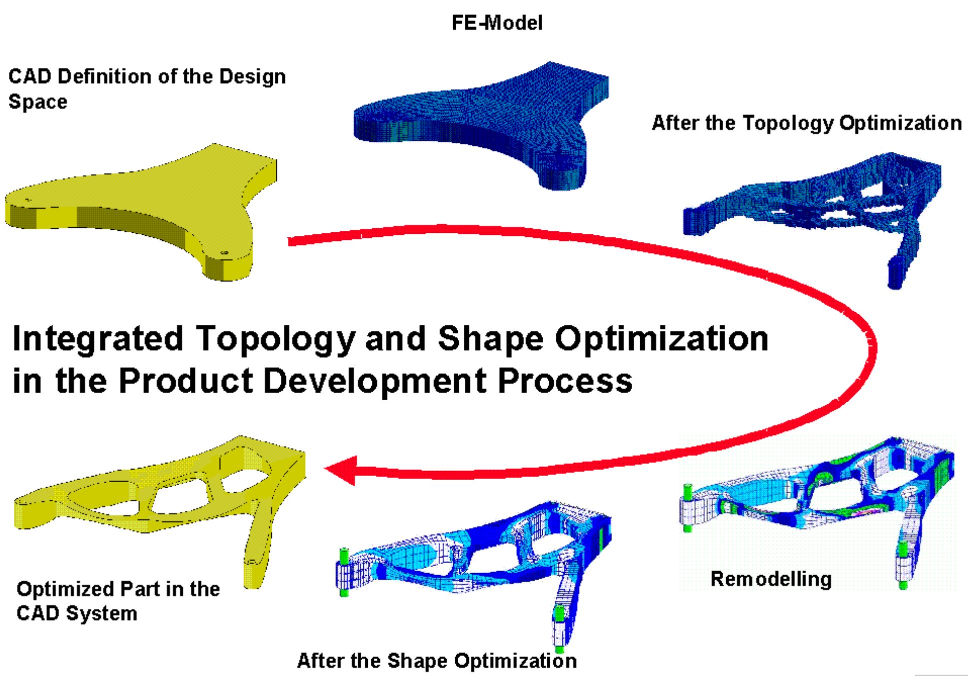

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Abstract

The paper first introduces the understanding of the different structural optimization types and positions their usage in the product development process.

After that, the software and hardware opportunities given through High Performance Computing (HPC) are explained shortly. The following section shows how performance and efficiency improvements of the topology optimization process were achieved by using HPC techniques. This work was conducted within the HIPOP (HIgh Performance OPtimization) project.

Finally topology and shape optimizations of real world examples show the successfull implementation and their benefits.

1 Introduction

In the tough international competition, companies can only survive if, besides highly innovative power they can provide strongly cost optimized products. Therefore in new procedures like the Simultaneous Engineering, the calculation engineer is already integrated into the concept phase of the product development process. Efficient methods of working require powerful optimization algorithms to be provided in addition to the discrete methods (FEM/ BEM) proved worth while to support the calculation engineer in the draft and design phase. Almost all FEM codes have integrated sizing optimization capabilities to support the calculation engineer.

In this context new optimization criteria and control strategies for sizing, shape and topology optimization (Figure 1) were found at the Institute of Machine Design from the University of Karlsruhe, Germany, in 1991. Based on these new strategies the computer program CAOSS (Computer Aided Optimization System Sauter) was developed from the institute together with FE-DESIGN, Karlsruhe, Germany. The program was awarded in 1994 from the European Commission, DG XIII with the European Academic Software Award for the best program in the field of mechanics.

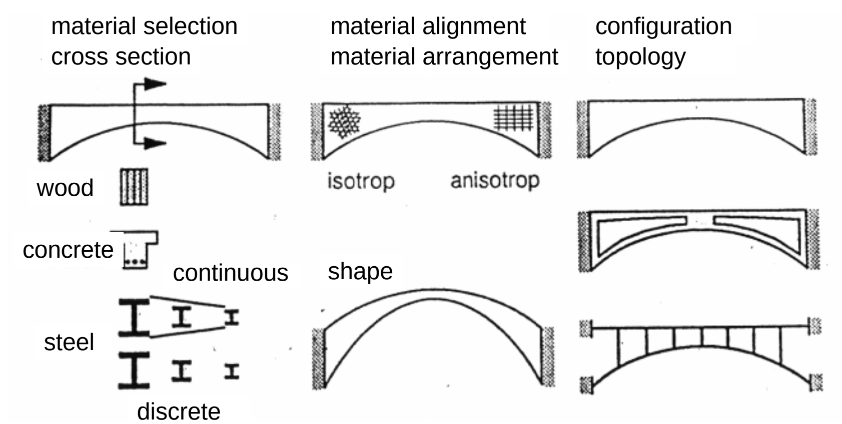

Figure 1 Types of Structural Optimization

For both sizing and shape optimization a first design proposal, which is used as the start design, exists. The objective of general structural optimization methods is to compute even this first design proposal (Figure 3). For topology optimization the designer creates only the design space, which includes the future component. Subsequently the functionally required boundary conditions are applied. The efforts for the modelling and preparation are extremely low. The optimum structural shape with the appropriate topology is calculated utilizing a FEM program and issued as a design proposal and might be refined by the designer.

Compared with the sizing and shape optimization the numerical efforts of this iterative process strongly increases. Therefore currently only components with 15.000 to maximum 30.000 elements can be calculated, even when powerful workstations are used. Due to the high number of iterations (typically between 20 to 30 iterations) and the fact that approx. 90 to 95% of the CPU time is used from the FEM program for the analysis, the performance and the resource requirements of the FEM program are of particular importance.

For the last two years certain FEM solvers (like MSC/NASTRAN) were ported to hardware platforms with distributed memory. With them a considerable reduction of the price/performance ratio was shown for the parallel code combined with impressive speedups. These facts make the utilization of these codes interesting for industrial users. Within the HIPOP (High Performance Optimization) project the coupling of the distributed parallel MSC/NASTRAN and CAOSS was realized. The benchmarking of real world applications from companies like BMW, PININFARINA, AUSTRIAN AEROSPACE and FE-DESIGN showed the reliablity and efficiency of the approach. Even for models far beyond 200.000 degrees of freedom for a number of load cases speedups of 3 to 4 were achieved.

The current institute research focuses on the improvement of the efficiency of the whole optimization process. This includes e.g. the utilization of parallel iterative FE solvers as well as the improvement of the solver efficiency itself by an adaption of the solver to the particular optimization properties.

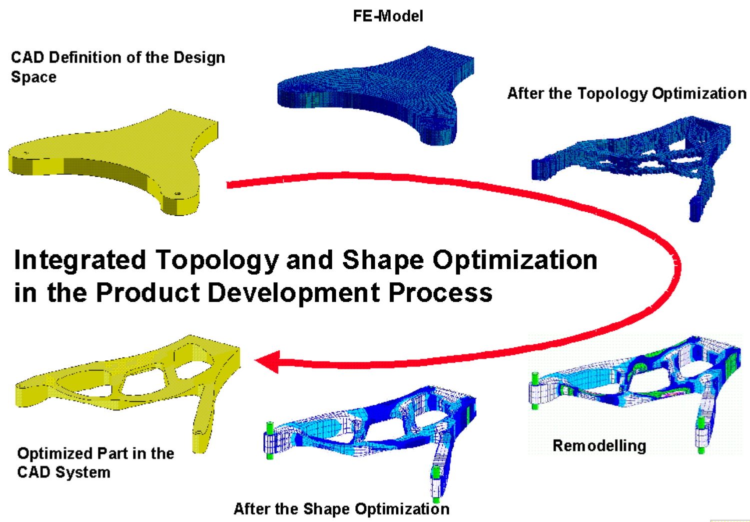

Figure 2 Topology and Shape Optimization in the Product Development Process

2 High Performance Computing and High Performance Optimization

2.1 High Performance Computing

PMN - Parallel MSC/NASTRAN

In the ESPRIT III project EUROPORT-1, Porting Work Area parallel MSC/NASTRAN (PMN), MSC started to port MSC/NASTRAN to distributed parallel hardware architectures. The distributed parallel modules developed in this project are available since September 1997 in the commercial MSC/NASTRAN release V69.2.

On serial computers and for large problems, the numerical solution modules typically require 85% to 95% of the total elapsed time. Therefore, parallelizing just these modules on their own gives a significant increase of performance. This strategy is well suited to gove a good return from moderate parallel systems. By taking this approach, it is possible to gain benefits from parallelization without the need for extensive modification to the code structure.

In the frame of this project a considerable reduction of the price/performance ratio was shown for the parallel code, which makes the utilization of PMN interesting to industrial users.

IBM RS/6000 SP2

The benchmarks for distributed memory computers were executed on an IBM RS/6000 SP2, located at the Scientific Supercomputing Center (SSC) of the University of Karlsruhe, Germany. This is the currently most powerful IBM parallel computer in Europe. The machine was installed 1997 and comprises 256 nodes with a total peak performance of 107 Giga Flops, 130 Giga Byte Main Memory and 2.1 Tera Byte disk space.

Figure 3 Topology and Shape Optimization in the Product Development Process

2.2 HIPOP - HIgh Performance OPtimization

Standard simulation techniques become increasingly popular while the field of available application software and problems' complexity are rapidly changing. Therefore the availability of an optimization tool which is fully integrated in the CAD and CAE environment is of great advantage.

In the past, due to computer resources and the approaches used, a bottleneck was that the optimization approaches forced the user to simplify the simulation model. The approach implemented in the MSC/CONSTRUCT optimization software is different and showed already in the past outstanding performance. This allowed even real world models to be optimized. For MSC/CONSTRUCT the FEM solver was and is the limiting factor

The HIPOP (HIgh Performance OPtimization) project was funded by the European Comission. The project's main objective was the sound performance improvement of the topology (factor 3-5) and shape (5-10) optimization software MSC/CONSTRUCT through faster algorithms and the excellent performance improvement through the use of distributed parallel MSC/NASTRAN (PMN). HIPOP directly addressed the heart of the optimization: the finite elemente solver and the optimization engine and their interaction.

As a result, large and therefore real world structures can be now optimized without the need for severe simplification. Therefore the pre-processing effort is very little.

Besides aspects of streamlining the optimization process through adaption techniques, the major task within the HIPOP project was to replace the serial MSC/NASTRAN with the parallel MSC/NASTRAN (Figure 5).

Within HIPOP, a fast and efficient coupling of traditional shape optimization tools was realized for the first time, which led to tremendous reductions in pre-processing effort as well as computing time savings.

MSC/CONSTRUCT addresses the needs of designers and analysts. The topology optimization capability allows new designs to be found either from scratch or based on an already existing design within a very short time frame. With the shape optimization capability, existing designs can be further optimized to reduce weight and component stresses.

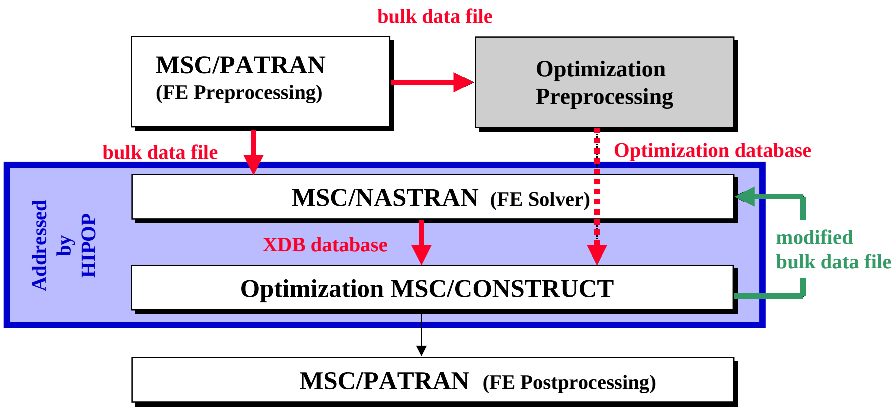

Figure 4 The HIPOP Approach

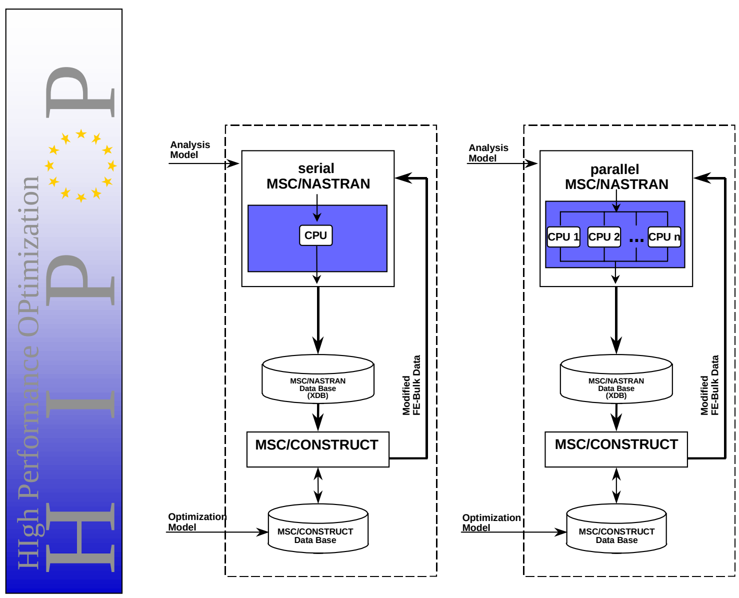

Figure 5 Embedding the Distributed Parallel MSC/NASTRAN

Summarizing the HIPOP project:

- within the same time frame real world models can be optimized without the time consuming need of further simplification
- much larger structures (>> 100.000 degrees of freedom) can be optimised in a reasonable time frame.

The efficiency and robustness was shown by benchmarking structures:

- from BMW where a half car model of a 3-series car, build of 80,000 solids and loaded with 6 different load cases, for running the topology optimization in one third of the time. Through the use of the HIPOP software the solids could be meshed with the CAD derived voxel technique which reduces the preprocessing time from 1 1/2 weeks to a couple of hours and which allow the full integration in the CAE process (see below, See Section 3.1“CAE Embedded Topology Optimization” auf Seite 7.).
- from PININFARINA which reduced with topology optimization the weight of a car bonnet frame maintaining critical stiffness values and who did the optimization

within a forth of the time.

- from INA who performed a topology optimization on a chain tensioner containing more than 200,000 nodes and elements.
- from IABG where a front mount with more than 120,000 nodes and elements for 5 different loadcases was topology optimized.
- from BMW who used a coupled shape optimization approach for a crankshaft optimization which resulted in a time reduction from 2 weeks pre-processing effort to 5 hours and computing time reduction to 1/10.

3 Applications

3.1 CAE Embedded Topology Optimization

The target of the BMW benchmark was to evaluate the use of current topology optimization in the design of extremely large and complex structures. To show this the shell structure of a BMW 3-series car was selected.

In this approach the sheet metal from the wheel housing was completely removed and replaced by solid elements. The topology optimization software should then find the maximum stiffness for a given amount of material which satisfies all 6 load cases. The four different boundary conditions simulate various driving situations, for instance cornering.

To get an adequate resolution for the resulting structure an extremely fine mesh is required. For testing and evaluation purposes firstly the wheel housing was filled with a relatively coarse tetrahedral mesh. This resulted in a model containing 20,718 nodes and 14,821 elements, the shell elements of the remaining structure already counted.

To achieve the required resolution and to simplify the setup of the topology optimization model a second structure was created using the voxel technology. The voxel technology has its origin in the CAD/CAE-world where it is used e.g. to simulate engine maintenance processes. For our purposes it allows a very simple representation of the wheel housing and furthermore voxels are extremely easy to generate.

Like 2-dimensional pictures are printed with simple pixels, any CAD model can be described with the 3-d pendant of the pixels: the voxels. A voxel is simply a small cube with a certain edge length. The smaller the edge length the higher the resolution of the model. The data volume is reduced dramatically (often the reduction to 1 per cent of the original data volume is possible) by transforming the description of volumes, planes and points of the original CAD model to a common voxel model (Figure 6).

The difficulty with voxel-based FE models is that one comes easily to extremely large structures and therefore require high resources. The voxel model generated for the HIPOP project contains 91,162 nodes and 81,254 elements resulting in 287,965 degrees of freedom (Figure 7). This model needs to be solved for the above mentioned 6 load cases with 4 different boundary sets.

In Figure 8 the resulting elapsed computing times (left axis) and the corresponding speedups (right axis) versus the number of processors are shown.

The data recovery operations were not part of the parallelization and do not scale with the number of processors. This can clearly be seen from the diagram when looking at the elapsed times of the optimization loop. The curve of the times for one optimization loop with the HIPOP improvements is parallel to the one with the initial software (1 Opt.-Loop (old)).

From the diagram one can see that the elapsed time required for one optimization loop was reduced from 79,000 sec. to 25,000 on 8 processors. That means that the improvements lead to a speedup factor of 3.17.

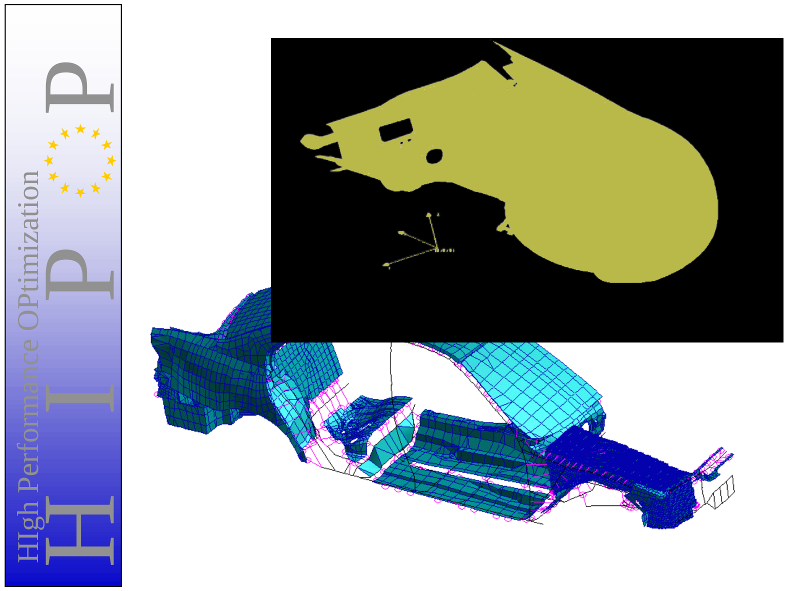

Figure 6 Half Model of the BMW 3-series and Voxel Model

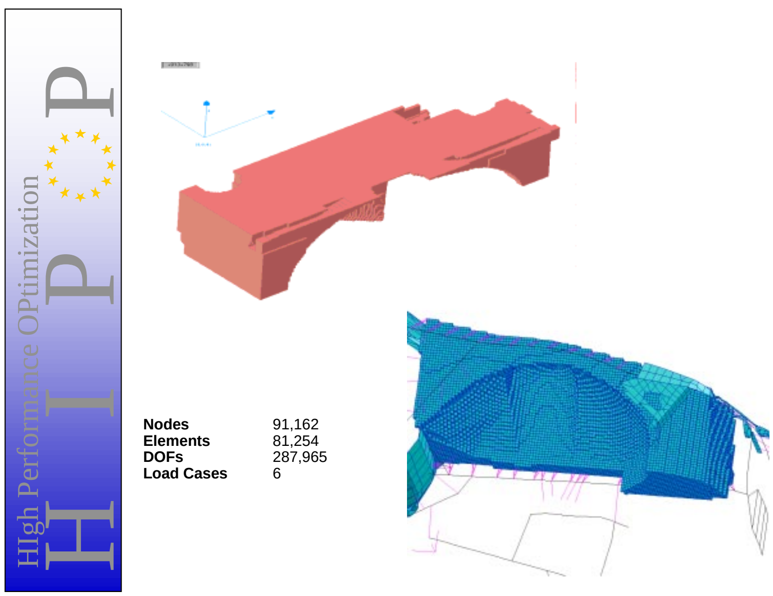

Figure 7 Voxel and FEM Model of the Wheel Housing

To fully integrate the process of topology optimization within the product development process it is necessary to get the resulting FEM structure (left plot in Figure 9) back to the CAD program. Within HIPOP this was done with an interim step using again a Voxeltool (see Figure 9). Today the final FEM model might be exported from within MSC/PATRAN as VRML file (Virtual Reality Markup Language) or as IGES.

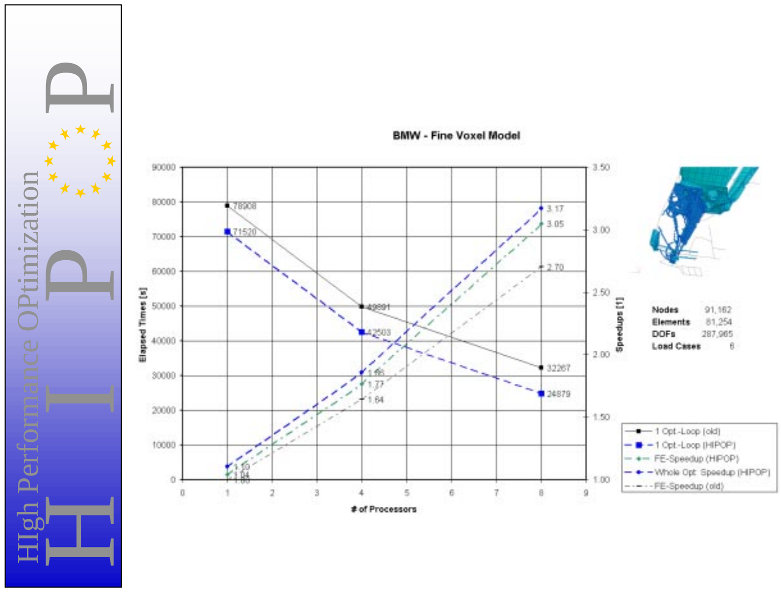

Figure 8 Performance Data

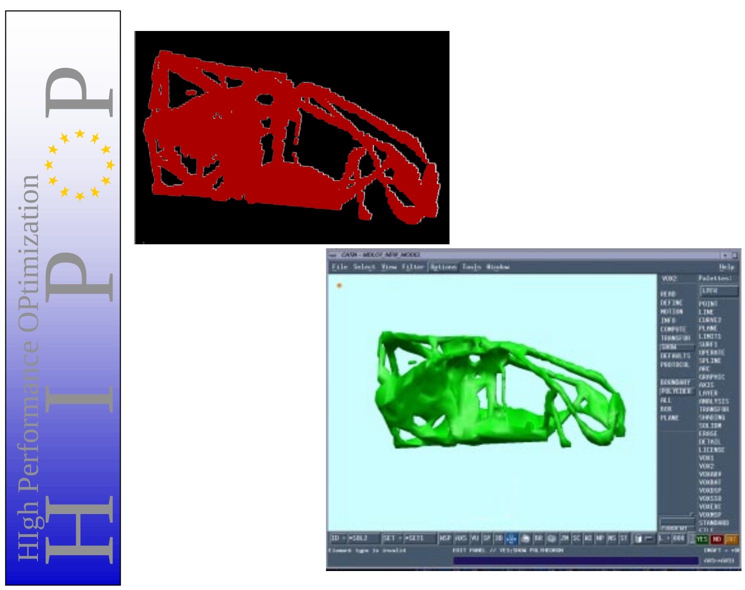

Figure 9 Exporting the final FEM Model to the CAD System

3.2 Coupled Shape Optimization with MSC/CONSTRUCT and SOL200

An optimization model is required for an optimization in the same way as an analysis model is required for a finite element analysis. For shape optimization this also covers the statement of allowable shape changes. In the MSC/NASTRAN SOL200 these shape changes are expressed by so called shape basis vectors ([MOO-94]). The numerical optimization algorithm then determines the best linear combination of these shape basis vectors.

To set up a SOL200 optimization model one major task is to derive shape basis vectors, which have sufficient influence on the optimization objective and constraints ([RAA-88], [CHA-90], [RAA-94]). Because the creation and definition of the shape basis vectors must be made manually, it is time consuming and costly especially for 3D structures.

Other optimization approaches are the optimality criteria procedures like the ones implemented in MSC/CONSTRUCT SHAPE. They often have the advantage to generate the new shape without the necessity of shape vectors. Their disadvantage is their lack of handling arbitrary object functions and constraints. Therefore the idea within HIPOP was to use an optimality criterion for the generation of shape basis vectors and to use the mathematical optimization approach of the SOL200 to fulfill arbitrary objective and constraint functions.

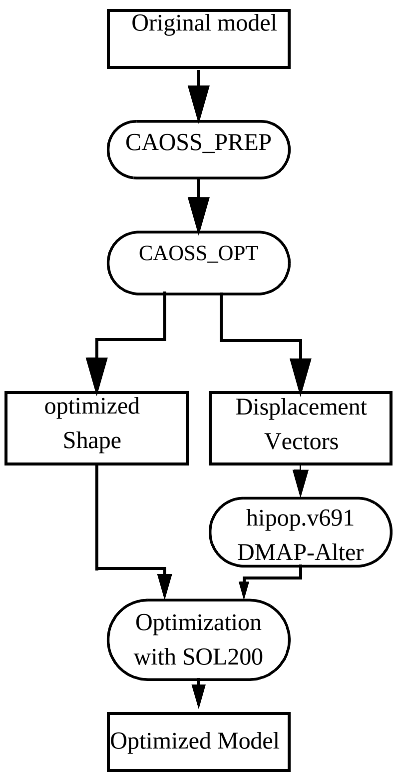

Figure 10 Data Flow for the Coupled Shape Optimization

This idea was realized as shown in Figure 10. The optimization preprocessing was made within MSC/PATRAN. Using the MSC/CONSTRUCT GUI within MSC/PATRAN the modifiable design nodes were defined and the optimization control file was generated. The optimization control file includes e.g. the definition of the objective function, the constraints as well as the optional restrictions. Then the nonparametric shape optimization with MSC/CONSTRUCT SHAPE was started. This resulted in an optimum shape and a corresponding displacement vector, which describes the change from the original shape to the optimum shape of MSC/CONSTRUCT. With the hipop.v691 DMAP alter a modal analysis was run providing eigenforms which were then considered to be further shape basis vectors. The above mentioned displacement vector from the MSC/CONSTRUCT SHAPE run and these eigenform shape vectors were the parameters for the SOL200 optimization which was finally started.

This approach of coupling the easy and efficient modeling and optimization using MSC/CONSTRUCT SHAPE with the robust and general shape optimization capabilities of the SOL200 was verified with the crank shaft model shown in Figure 11.

The left plot in Figure 12 shows the displacements through the shape optimization with MSC/CONSTRUCT SHAPE based on the start model. The objective of this optimization was the reduction of the stress levels of the design nodes and therefore the homogenization

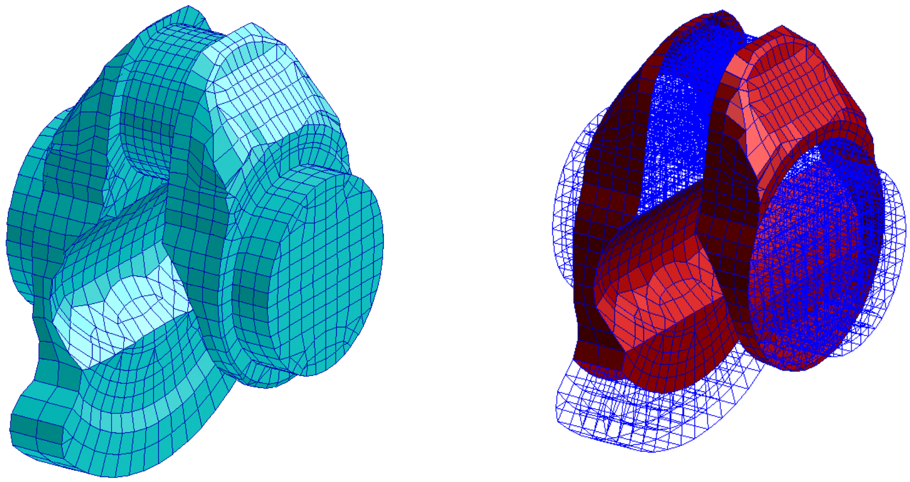

Figure 11 FEM Model and Design Surfaces

of these stresses. It led to a new shape of the crank shaft which formed the input model for a MSC/NASTRAN modal analysis for a couple of eigenfrequencies. The corresponding eigenmodes were then considered as further shape basis vectors for the following SOL200 shape optimization which included constraints on the eigenfrequencies.

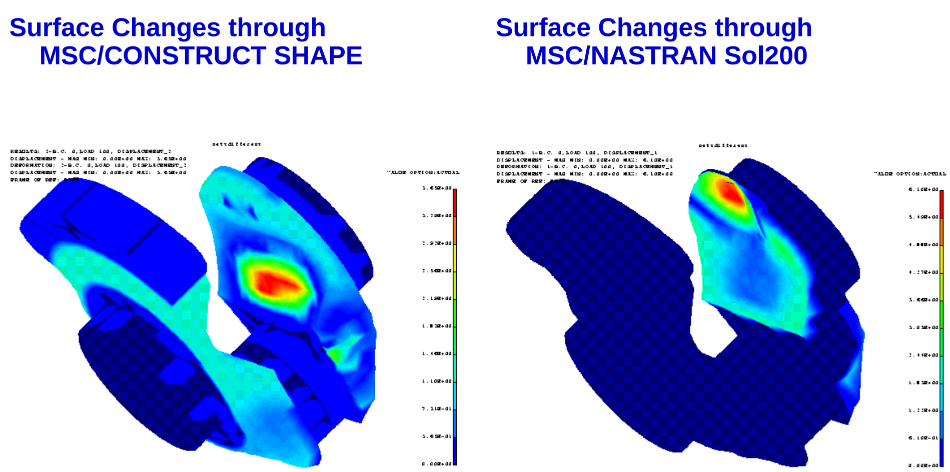

Figure 12 Shape Optimization Results

Comparing the plots of Figure 12 one may deduce that the shape optimization using MSC/CONSTRUCT SHAPE led to a design which was already very close to the optimum design found by the following SOL200 shape optimization. SOL200 then found only minor shape changes.

Besides cutting the preprocessing time from 2 weeks to 5 hours the use of MSC/CONSTRUCT SHAPE led also to a reduction of the computing time for the SOL200 run by a factor of 10. This is due to the fact that running the SOL200 shape optimization based on a good start design reduces the number of required iterations.

The shape optimization using MSC/CONSTRUCT SHAPE and the SOL200 therefore shows the following benefits:

- The generation of shape basis vectors could be performed automatically.
- This process is fully embedded in MSC/PATRAN and easy-to-use.
- The combination of this software resulted in tremendous time savings without losing generality.

4 Conclusion

The work done in the HIPOP (**HI**gh Performance **OP**timization) project resulted in sound improvements of the throughputs. With this software the topology and shape optimization of large real world models is possible and even much more important: efficient. With the performance improvements within MSC/CONSTRUCT the speedups of MSC/NASTRAN can directly be applied to the optimization and therefore result in the same speedups for the whole optimization. This was shown utilizing Parallel MSC/NASTRAN (PMN) on a distributed memory machine like the IBM-SP2 applying it to large test structures from the automotive industry.

Combining MSC/CONSTRUCT SHAPE with the SOL200 allows not only the automation of the shape optimization process but also results in tremendous time savings for the preprocessing and for the computing.

With the software modules presented in this article the design engineer as well as the analyst have tools to get clear design decisions throughout the product development process. The use of MSC/NASTRAN guarantees the robustness and reliability of the results.

The performance improvements and the functional extensions made in MSC/CONSTRUCT are available with release V2.5.

Acknowledgements

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