Usage of Optimization Tools in the Design Process at BMW

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Abstract

The usage of optimization tools in structural mechanics has a long history at BMW, and it is very much connected with MSC/NASTRAN. Sizing is a standard procedure in body design with constraints on static and dynamic response. Shape optimization with MSC/NASTRAN was an initial success. However, at present it is performed most often with other programs owing to the ease-of-use and integration within CAD systems. The definition of shape vectors is still time consuming in both MSC/NASTRAN and other programs. Optimality-criteria methods such as MSC/CONSTRUCT SHAPE improved the ease-of-use, but with a sacrifice in the generality of the objective and constraints definitions. However, a combination of optimality criteria, mathematical optimization methods, and automatic shape generation has proven to be a more general and efficient approach.

Topology optimization is finally being used in the concept design phase. The definition of the design space can be accelerated tremendously by using the VOXEL technique of CAD systems. In this technique, a given volume is filled with cubes of equal size, in order to estimate the volume or detect component collisions. These cubes are directly used in the finite element design space definition.

Concept design relies heavily on beam/shell models with beam cross sections as design variables. However, given the short time frame for the concept design phase, optimization is still hampered by the lack of pre/processing tools for the design model definition and post processing of results, as well as the necessity for heavy computing resources.

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1. Usage of Structural Optimization at BMW in the Past

Sizing has been used in car body development since the late 80's. Initially, only static loading conditions were used. Today the range of analysis types are extended to modes and frequency responses under various boundary conditions for models of several 100000 dofs. These problems not only need a considerable amount of time in preparation, but also create a heavy load on the in-house computing resources. However, their contribution to the development process is not questioned even by the traditional, experimentally oriented automotive developers.

Shape optimization was used in the engine department long before this capability appeared in MSC/NASTRAN(1). Its value to the development was never questioned, however the effort involved in many projects was prohibitive, since there were no user friendly tools to define the shape vectors. Since the engine department uses Pro-Engineer as its CAD system, the shape optimization is performed within a closely integrated FEM-System. This switch was prompted by better integration and ease of use in defining shape vectors, not for stability or capability reasons. The shape vectors for MSC/NASTRAN applications were usually generated by special FORTRAN-programs rather than by the use of auxiliary structures, which apparently require too much abstract structural mechanics understanding.

2. Shape Optimization with Optimality-Criteria Procedures

During the development of components, new parts are routinely analyzed and optimized by trial and error. The tight time schedule very often does not allow for going from analyses to optimization, because of the preparation time involved. In the past, the development target was to ensure the functionality of a component, and only if there were severe problems, was an optimization approach considered.

The advantage of Optimality-Criteria procedures lies in its ease-of-use. In addition to the meshing process, there is only a very small amount of additional data necessary to start the optimization. The advantage in time is more important than the lack of generality in defining objectives and constraints. Furthermore, the required MSC/NASTRAN analyses are fairly simple solution sequences, such as SOL 101 or SOL 103, which are very well tuned and can be used effectively on massively parallel computers.

3. HIPOP Extensions

In a project sponsored in part by the European Community, the efficiency of the MSC/CONSTRUCT SHAPE approach was considerably improved by the usage of the parallel version of MSC/NASTRAN as the analysis engine. In order to overcome the restrictions in the objective and constraint definition, MSC/CONSTRUCT SHAPE was combined with SOL 200.

The procedure (Fig. 1) starts with a MSC/CONSTRUCT SHAPE optimization using constraints which can be defined and with minimum weight as the objective. After completion of this step, the design model is generated by covering the design surface with a shell element coating. The first shape vector is the shape change derived by MSC/CONSTRUCT SHAPE. Additional shape vectors are generated by a modal analysis of the design surface represented by the shell coating. This is done by an extensive DMAP Alter developed by CDH, a project partner. The fine tuning optimization step is performed in MSC/NASTRAN with its full range of capabilities for the definition of constraints and objectives. Since the computing costs for this analysis can be quite high, it is important that MSC/CONSTRUCT SHAPE comes fairly close to the achievable optimum. The cost of an iteration in MSC/CONSTRUCT SHAPE is equal to the cost of an MSC/NASTRAN analysis plus a 10% overhead for MSC/CONSTRUCT SHAPE. In the SOL 200 iteration, the total cost consists of the analysis cost and approximately 50% of an analysis cost for each shape vector and iteration. It is easy to generate many shape vectors with modal analysis. Therefore, a least square fit of the mode shape vectors to a vector generated by MSC/CONSTRUCT SHAPE provides a measure regarding the number of required shape vectors.

The results are demonstrated by a segment of a crankshaft (Fig. 2). Fig. 3 shows the surface which is considered for changes during optimization. The constraints are that the static stiffness and the first eigenfrequency should remain the same. Figure 4 shows the shape change generated by MSC/CONSTRUCT SHAPE. Figure 5 shows the additional shape change from the MSC/CONSTRUCT SHAPE result to the SOL 200 result. It is interesting to note that the SOL 200 optimization generates only local improvements since the overall improvements were obtained very efficiently from MSC/CONSTRUCT SHAPE. The optimality criteria optimization required about 30 minutes on 8 IBM SP2 CPUs and the SOL 200 optimization required around 300 minutes on a single CRAY C90 CPU.

4. Topology Optimization

Topology optimization has proven its capabilities for component development. In this process the design space is filled by volume elements. The objective is to find the best distribution of elements if only a fraction of the design space volume is allowed to be filled.

For car body applications there are three challenges:

a) the ratio of used volume to design space must be extremely small,
b) obtaining a reasonable resolution of the mesh, and
c) the design space, which is normally only a small portion of the body, has to be connected to the complete body model.

However, the biggest challenge is the generation of a volume mesh for the design space. This is a typical application for an automatic mesh generator. Unfortunately, this is an iterative process which does not necessarily converge. The typical problems which have been experienced are:

- the mesher does not complete the mesh with the current set of parameters;
- the mesher completes the mesh, but generates bad elements which cannot be improved by its repair procedure;
- the mesher completes the mesh and is satisfied with the mesh quality, but MSC/NASTRAN rejects some elements;
- finally, both the mesher and MSC/NASTRAN accept the mesh, but still there is a problem of mesh coarseness.

Figure 6 shows a very coarse mesh of a wheel house design space imbedded in conceptual body model. It is obvious that for useful results the mesh is far too coarse and one would need a much finer mesh. However, these big volume meshes are difficult to handle in any mesh program. This makes manual iterations, in many cases, a prohibitively time consuming task.

5. Voxel Mesh

CAD systems have a tool for interference investigations which fill the space of a component with cubes of equal size. The size of the cubes is determined by the precision of the result. This technique is known as Voxel Technique. If these cubes are written as finite elements, the difficult part of the mesh generation is accomplished. The fact that the surface of the design space is only roughly approximated is not a drawback since the final result will have a rough surface in any case.

This approach was used with MSC/CONSTRUCT TOPOLOGY in Fig. 7 and Fig. 8 shows the result. It gives the analyst an indication of where the new structural elements should be located. It does not lead directly to a model which can be used for shape optimization. The advantage of this approach is its straightforward mesh generation and very few hours in preparation. The computing resources, however, are considerable, approximately 1.200 minutes on a single IBM SP2 CPU.

6. Conceptual Design Models

Owing to the lack of sufficient geometry definition and time available for generating results, conceptual design at BMW still relies heavily on beam/shell models. The objective is minimum weight subject to constraints on static stiffness, stresses under various loads, and eigenfrequencies of the trimmed body. The related design model consists of about 800 design variables and 650 constraints on relationship between design variables, required to create reasonable beam cross sections. In addition, there are about 500 stress constraints and a few displacement constraints.

Many standard FEM preprocessors do not support the generation of a design model. Those which do, are focused strongly on the shell type models. It is simply infeasable to define a single design variable by a mouse click or two based on the number of required clicks for the above example. Design variables are restricted by their absolute values, by a fractional factor of change, and by the relationship to the other design variables defining the same cross section. These restrictions usually exist for large groups of design variables and should be handled in groups. In concept design it is important to generate the design model quickly, since the time span of a concept idea is rather limited. In order to influence the concept idea, the results have to be obtained within this time span. Even though concept models are fairly small, optimization creates a big burden on computing and disc resources.

7. Optimization in Conceptual Design(2)

The optimization procedures typically use gradient methods, which find the next local optimum. However, in concept design one is interested in obtaining information about the complete design space. Therefore, it is necessary to develop tools which can generate information about a design which is potentially much different from the current design, which is typically derived from an existing design. These new tools could point to true innovations, not only improvements. Some type of response surface approach would be helpful, if it can generate results in the available time frame.

An optimum structure, with respect to structural mechanics, will never be built because of constraints from other requirements. Therefore, trade off studies are extremely important, i.e., comparing optimum designs with different levels of constraints. This requires results from many optimization runs for which the constraint definitions should be automatically generated. Figure 9 shows which cross sections have to be changed if the cross section of the rocker is limited to a smaller size than the optimum.

The generation of these trade off curves creates a problem which is not currently solved. The optimization is started at a point where most of the design variables are very close to their optimal values and their contribution to the change in objective is very small. The design variables which are far from their optimum values also contribute very little to the change in the objective. Since their contribution to the total objective is very small, the optimization procedure is considered to be converged. Therefore, in addition to standard constraint screening, it is also necessary to perform design variable screening and use approximate models based only on design variables which contribute to the change in the objective and/or constraints.

Whichever process or procedure is developed and used, it is extremely important to remember that decisions are made on a prescribed timetable and not on the availability of CAE results.

8. Conclusions

There is no question that structural optimization is an important tool in the design process. However, the process in which this tool is used is not at its optimum. The lack of integration is to a large extent caused by the narrow focus of various developers in the CAE environment. The software development should focus on a timely process from a design idea to its structural evaluation, rather than the precise simulation of a complex physical phenomenon.

New meshing ideas using the Voxel technique of CAD systems and powerful computers can make topology optimization a timely and useful addition to the CAE tool box.

The combination of optimality criteria and mathematical shape optimization with automatic shape vector generation should alleviate the problems of time constraints in its usage.

The problem of many design variables must be addressed by the preprocessing and optimization methods developers.

If the narrow focus of various CAE developers continues, their respective disciplines will be absorbed by CAD developers in a less sophisticated, but much more integrated manner. This will advance the design process much more than the most advanced non integrated CAE tools.

References:

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(2) Raasch, I., “***Even Concept Design Needs Super Computing***,” Conference on High Performance Computing, Paris, October 1996

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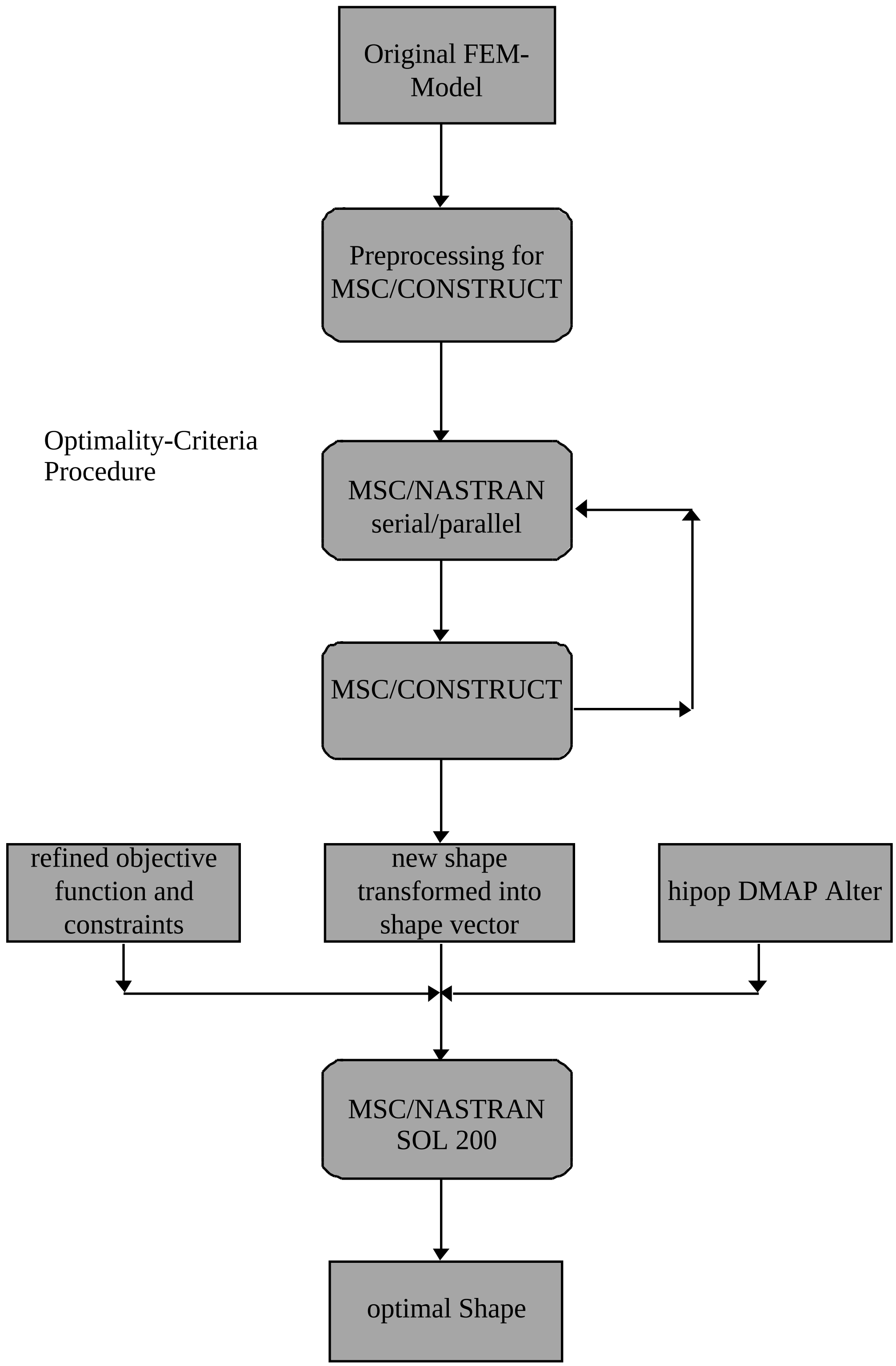

Fig. 1: Shape Optimization: Combination of MSC/CONSTRUCT SHAPE with MSC/NASTRAN SOL 200