SHAPE OPTIMIZATION USING SHAPE BASIS VECTORS

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ABSTRACT

Most shape optimization methods require parametric modeling and automatic mesh generation. However, there are no robust tools available for parametric modeling and automeshing. This has resulted in few applications of shape optimization to large-scale industrial structures. Recently, the reduced basis method was introduced in shape optimization. Because it does not require the parametric modeling and auto-meshing, it has found wide applications in the automotive industry. Research engineers in Ford Motor Company have incorporated the reduced basis method in their design software. Development engineers in MacNeal-Schwendler Corporation also implemented this method in MSC/NASTRAN. They recently released MSC/NASTRAN version 68 which provides shape optimization capability with the feature of reduced basis vectors. In this paper, the shape optimization capability in MSC/NASTRAN V68 is discussed. The Modified Thermal Load Approach (MTLA) for generation of shape basis vectors is described. A procedure is developed for generating and inputting these basis vectors to the MSC/NASTRAN. The convergence characteristics and the efficiency of incorporating MTLA for MSC/NASTRAN optimization process are demonstrated through two numerical examples. The optimized results are presented and discussed.

INTRODUCTION

There is an increased demand for the application of shape optimization of structural systems for their weight reduction and performance improvement. Thus, shape optimization has been an active research area during the last two decades. Several shape optimization methods were developed. But most of these methods require robust parametric modeling and automatic mesh generation [1,2]. The shape optimization of large-scale structures was limited because the parametric modeling and automeshing of large-scale structures are computationally prohibited. The parametric modeling techniques are not robust.

Recently, the reduced basis method has been introduced [3-5] in structural optimization. The advantage of the reduced basis method for shape optimization is that parametric modeling and auto-meshing are not required. In the reduced basis method, the new shape of a structure is described by a set of shape basis vectors. These shape basis vectors can be generated from the finite element model of the initial structure. There are a number of ways to generate basis vectors. For example, deformed shapes can be taken as the basis vectors. In this case the deformed shapes result from the displacement response of the initial FEA model subjected to prescribed loads or displacements.

The researchers and engineers in Ford Motor Company have incorporated the reduced basis method in their design software. Design engineers have successfully used this method for the optimal shape designs of vehicle systems such as knuckles, lower control arms, engine mount brackets, and subframe systems. These applications have resulted in significant weight reduction and performance improvement. The development engineers in MacNeal-Schwendler Corporation also implemented the reduced basis method in MSC/NASTRAN. They recently released MSC/NASTRAN version 68 [6-7] which provides shape optimization capability with feature of the reduced basis vectors. In version 68, there are four different approaches to generation and/or input of basis vectors: manual grid variation, direct input of shapes, geometric boundary shapes, and analytic boundary shapes. These new features provide capabilities for wide applications in industrial practice.

In this paper the author will share with structural optimization community and MSC/NASTRAN users the experience in shape optimization using reduced basis method. To demonstrate the application of MSC/NASTRAN version 68, two examples will be presented: shape optimization of cantilever bar and shape optimal design of lower control arm - an automotive chassis component. In these examples, modified thermal load approach [3] was first used to automatically generate the basis vectors. Then the direct input of shapes approach was used to input the basis vectors into MSC/NASTRAN. A computer program was developed to provide an interface between the FE model and the NASTRAN input. It has been found that this procedure is very effective for shape optimization of most automotive systems.

METHODOLOGY

In this section, the modified thermal load approach, MTLA, [3] is briefly described, and then direct input of shapes in MSC/NASTRAN is introduced.

In the modified thermal load approach, shape basis vectors are generated by subjecting the initial structure to thermal (temperature) loads. The temperature distribution is determined based on the stress level of the structure under each physical load condition. Conceptually, high temperature is assigned in high stress area. Low temperature (or negative) is assigned in low stress area. The general expression of the temperature distribution is

$$T_{ij} = T_o \frac{\sigma_{ij} - \sigma_{oj}}{\sigma_{oj}} \qquad i = 1, 2, \ldots, n \quad j = 1, 2, \ldots, r \qquad (3)$$

where T_{ij} and σ_{ij} are the nodal temperature and nodal stress (usually von Mises stress) on the i-th grid for load case j, respectively, T_o is a positive reference temperature, σ_{oj} the stress target for load case j, n the total number of the grid points, and r is the total number of the load cases.

Since only a few load cases are considered in most design problems, the thermal load approach must be modified to increase the number of basis vectors for shape optimization. In the modified thermal load approach, each temperature distribution is divided into two sets about the average temperature. One set contains the higher temperature loads, and the other contains the lower temperature loads. By applying the two temperature loads to the FEA model of the initial structure, two basis vectors are generated. The number of the basis vectors are two times the number of the physical load cases to which the structure is subjected.

After the deformed shapes are generated by applying the modified thermal loads to the FEA model, they are considered as basis vectors and input to MSC/NASTRAN. In the direct input of basis vectors in MSC/NASTRAN version 68, there are two formats to input the basis vectors. One is to use the ASSIGN and DBLOCATE cards before the ID card in the MSC/NASTRAN input deck, and another one is to use DVGRID cards in bulk data deck. In applying the first format, a user saves the deformed shapes as basis vectors in a database. Then the ASSIGN and DBLOCATE cards direct the MSC/NASTRAN program to the directory and file where the basis vectors are located. In applying second format, the user executes a program to read the basis vectors and write them in the DVGRID format.

Because the amplitudes of each basis vector are usually not in the same orders, it is challenging in deciding the limits to be imposed on each design variable. Improper scaling can lead to a failure in convergence. Users determine the adequate scaling factors by trial-and-error. But it is not practical for a large-scale structure. To solve this problem, the author proposed a procedure, in which all the shape basis vectors are first normalized. Then the limit on each shape design variable is approximated by the allowed shape change divided by the number of basis vectors. For instance, if the shape change is allowed within twenty millimeters and five basis vectors are used, the limits on design variables are four millimeters (twenty divided by five).

NUMERICAL EXAMPLES

A suspension lower control arm and a cantilever bar are used to demonstrate the effectiveness of the procedure. In both examples, the design objective is to minimize the weight subjected to a constraint on von Mises stresses. The von Mises stress constraint is imposed on each element of the finite element models. The modified thermal load approach is used to generate basis vectors. Direct input of basis vectors is used in MSC/NASTRAN shape optimization.

Lower Control Arm

The first example is a suspension lower control arm. The finite element model for this automotive component is shown in Figure 1. This FEA model contains 504 solid elements and 812 grids. A fixed boundary condition is applied around the left hole. In addition, a packaging constraint is imposed on the model. The packaging constraint is that the distance between the holes can not be changed during the optimization process. Five different loads are considered. The loads are applied at the central points of the middle and right holes in different directions. Rigid elements are used around those holes to transmit the loads. The allowable stress is 450 MPa. Young's modulus and Poisson's ratio are 2.068×10^5 MPa and 0.32, respectively. The mass density is 7.862×10^{-9} N*sec^2/mm^4.

In the initial design, the objective function (mass) is 2.14 kilograms. The maximum element stress is 546 MPa, 21.3% higher then the allowable stress. To reduce the weight and stress through shape optimization, ten shape basis vectors are generated based on the initial design. The design is converged in six design iterations. The objective function is reduced to 1.33 kilograms (38% reduction), while the maximum stress is reduced to the allowable stress. The design histories are shown in Table 1. The final design of the arm is shown in Figure 2.

Table 1. Design History of Lower Control Arm

Iteration #	Objective (mass)		Stress Constraints	
	Kilogram	% Change	Max. Stress (MPa)	Max. Value of Constraints
0	2.14	-	546	0.213
1	2.04	-4.67	N/A	Infeasible
2	1.95	-8.88	N/A	Infeasible
3	1.78	-16.8	228	-0.494
4	1.46	-31.8	370	-0.178
5	1.33	-37.9	460	0.022
6	1.33	-37.9	449	-0.002

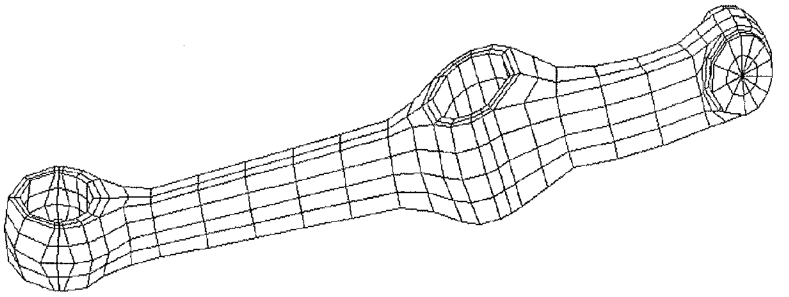

Figure 1. Finite Element Model of Lower Control Arm

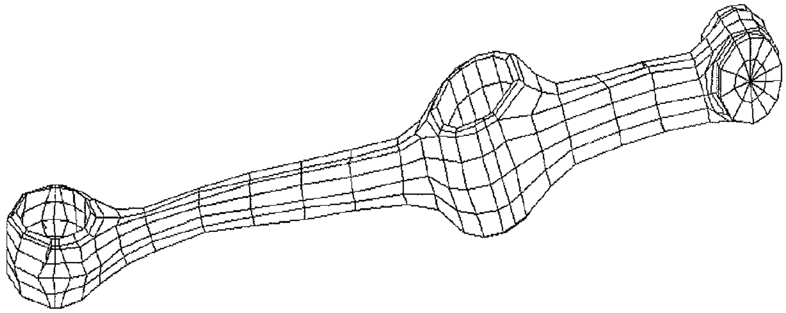

Figure 2. Final Design of Lower Control Arm

Cantilever Bar

The second example is a solid cantilever bar. The finite element model for this component is shown in Figure 3. The FEA model has 60 solid elements and 132 grids. The bar is clamped at one end. Two bending loads and one torsional load are applied at the free tip as shown in Figure 3. The length of the bar is fixed during the optimization process. The allowable stress is chosen as 260 MPa. The material properties is the same as those used in the lower control arm example.

In the initial design, the objective function is 0.472 kilograms. The maximum von Mises stress is 197.7 MPa. Six shape basis vectors are generated based on the three load cases. After six iterations, the objective is reduced to 0.325 kilograms in the feasible design domain. The design histories are given in Table 2. The final design of the bar is shown in Figure 4.

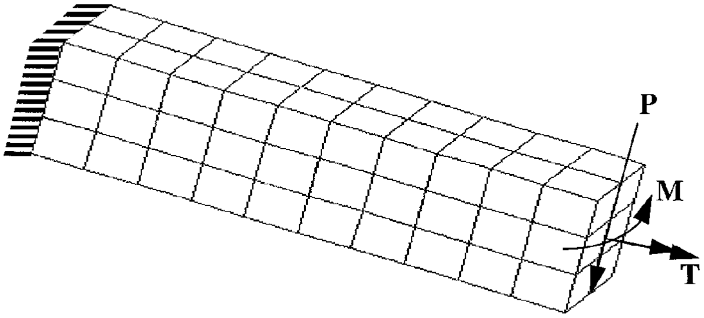

Figure 3. Finite Element Model of Cantilever Bar

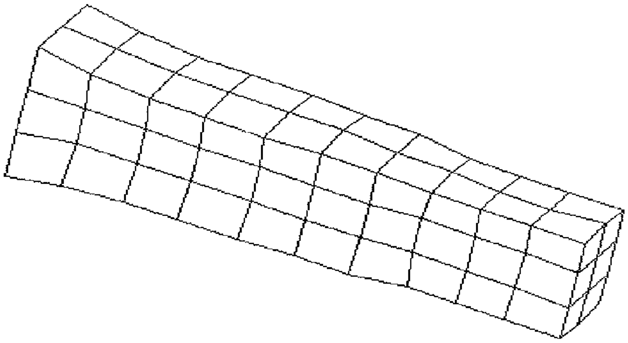

Figure 4. Final Design of Cantilever Bar

Table 2. Design History of Cantilever Bar

Iteration #	Objective (Weight)		Stress Constraints	
	Kilogram	% Change	Max. Stress (MPa)	Max. Value of Constraints
0	0.472	-	198	-0.240
1	0.436	-7.63	226	-0.130
2	0.402	-14.8	261	0.002
3	0.373	-21.0	261	0.002
4	0.346	-26.7	268	0.030
5	0.330	-30.1	259	-0.004
6	0.325	-31.1	260	0.001

CONCLUSIONS

The new shape optimization capability in MSC/NASTRAN version 68 was discussed. The Modified Thermal Load Approach (MTLA) for generation of shape basis vectors was also described. A procedure was developed for inputting the basis vectors generated by MTLA to the MSC/NASTRAN through DVGRID entries. The new capability, MTLA approach, and integration procedure have been investigated through two numerical examples. From this study, following conclusions can be drawn:

1) MSC/NASTRAN incorporated the reduced basis vector method in its version 68. In this version, there are four different approaches for generation and/or input of basis vectors: manual grid variation, direct input of shapes, geometric shapes, and analytic shapes. Because the reduced basis method does not require the parametric modeling and auto-meshing, MSC/NASTRAN version 68 provides capability and flexibility for wide applications of shape optimization to large-scale industrial structures.

2) Modified Thermal Load approach generates the shape basis vectors which reflect the local and global behavior of a structure. It is very useful for automatic generation of basis vectors. It enables engineers to perform shape optimization with minimum requirement of optimization background.

3) In applying "direct input of shapes" approach, it is wise for a user to develop a small program to normalize the basis vectors and write them in the DVGRID format. It is convenient to read the basis vectors generated by MTLA approach. Combining the modified thermal load approach with MSC/NASTRAN version 68 will effectively promote industrial applications, specially for large-scale structures.

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