Incorporation of Nonparametric Shape Optimization Capability in MSC.Nastran

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ABSTRACT

In order to provide all MSC.Nastran users with a more complete spectrum of design optimization analysis capabilities, the topology (or layout) optimization capability was successfully incorporated into MSC.Nastran in April of 1999 by the joint efforts of MSC Japan, Ltd. and Quint Corporation. As a continuous joint effort, we have been working on incorporation of another important feature, nonparametric shape optimization into MSC.Nastran since May of 2000. This nonparametric shape optimization capability can be used not only in the detailed design process for the final optimum shape, but also in the very beginning of the conceptual design process. This paper describes the new nonparametric shape optimization capability introduced in the first phase development, and includes several application examples.
1 Introduction

Design optimization is used to produce a design that possesses some optimal characteristics, such as minimum weight, maximum first natural frequency, or minimum noise levels. Design optimization is available in MSC.Nastran SOL 200, in which a structure can be optimized considering simultaneous static, normal modes, buckling, transient response, frequency response, aeroelastic, and flutter analyses. In SOL 200, sizing parameters (the dimension of cross-section of beam elements such as height and width, or the thickness of shell elements), shape (grid coordinates related) parameters and material properties, such as material density, Young’s modulus, etc., can be used as design variables.

In order to provide all MSC.Nastran users with a more complete spectrum of design optimization analysis capabilities, another category of optimization capability, so-called topology (or layout) optimization, which is used in the very beginning of the conceptual design process, has also been successfully incorporated into MSC.Nastran by adopting the topology optimization optimizer function of OPTISHAPE as function module of MSC.Nastran. This capability was successfully released by the joint effort of MSC Japan, Ltd. and Quint Corporation in April, 1999[1]. Through continuous and on-going joint effort, more features and enhancements are also under development, which will be described at another time. Since May, 2000, we have also been working on incorporating into MSC.Nastran another important feature, nonparametric shape optimization. This nonparametric shape optimization capability can be used not only in the detailed design process for the final optimum shape, but also in the very beginning of the conceptual design process. In addition to that, it may also be used to generate the shape basis vectors that are required in parametric shape optimization of MSC.Nastran SOL 200. This paper will describe the new nonparametric shape optimization capabilities introduced in the first phase development, and will include several application examples.

2 Nonparametric Shape Optimization Based on Traction Method

2.1 Traction Method

In CAE based shape optimization, there are, in general, three difficulties with which ones often meet:
- re-mesh difficulty,
- large design freedom problem,
- star shape phenomenon.

Much effort has been made in the past two decades to overcome the above difficulties, one of which is the famous shape basis vector approach proposed by Belegundu and Rajan[2]. This approach is adopted in MSC.Nastran shape optimization capability[3]. However, when shape basis vectors are used, the only final shape which can be obtained is a linear combination of original shape and the shape basis vectors. And in general, the generation of a set of good shape basis vectors is very tedious and difficult except those associated with some simple geometric parameters like
radius, length, etc.. In 1994, another method, traction method, was proposed by Azegami [4-5] as a procedure for solving shape optimization problems in elliptic boundary value problems. This traction method is able to overcome the above three difficulties. Also, it is unnecessary for the user to provide shape basis vectors. Recently, the traction method for shape optimization of structures has been extended to various applications, such as static, vibration and flow problems[6-10], as well as commercial applications[11].

The kernel of the traction method is to evaluate a so-called shape gradient function $G$ according to the behavior of structure. This shape gradient function $G$ is theoretically derived using the Lagrange multipliers and the material derivative method supposing that the objective function decreases. It is used as traction in a pseudo-elastic boundary value problem to obtain the domain variation. That is, the traction method is proposed as a technique for solving the velocity field $V$ as a pseudo-elastic boundary value problem, which gives the domain variation, based on the following governing equation [4]:

$$a(V, w) = -l_G(w)$$

In the pseudo-elastic boundary value problem, the boundary conditions, which are used to control the domain variation, are usually different from those used in the analysis as shown in the velocity analysis part in Fig. 1. The above equation shows that the velocity field $V$ could be solved as a displacement distribution when the negative shape gradient function $-G$ acts on the boundary of the domain as an external force. In other words, with the traction method, the domain variation is found as a displacement field when the shape gradient function is assumed to be an external force in a pseudo-elastic problem.

Theoretically, it is proved that in problems where convexity conditions are valid, this relationship will definitely
reduce the Lagrange functional in the process of varying the domain according to the velocity field $V$ determined by
the above equation which can be solved by using the finite element method (FEM). The domain is varied as follows
by iterating the stress and velocity analyses:

$$\Omega_{s+1} = \Omega_s + V \cdot \Delta S$$

where $\Delta S$ is a coefficient to adjust the amount of variation. It is proved that the domain variation $V$ reduces the
Lagrange functional if $\Delta S$ is sufficiently small [4-5]. The objective function is minimized to result in the optimized
shape. A schematic flow of the traction method is shown in Fig.1.

### 2.2 Domain Variation Restriction

In practical applications, the domain variation is sometimes restricted in certain design spaces because of reasons
arising from manufacturing and/or construction. In other words, the design domain is allowed to vary but limited to a
certain range, so that control of the domain variation is important in shape optimization. The shape constraint
conditions for velocity analysis in the traction method, of course, might be used to restrict the domain variation to a
certain extent. But in this way it is not easy to obtain a reasonable and smooth shape. The constraint displacements in
velocity analysis will result in a non-smooth shape.

In the present development, a numerical approach [12] to control the amount of domain variation is introduced in
velocity analysis of traction method. Fig.2 shows the velocity field which is applied with the shape gradient function
and which satisfies the shape constraint condition for an optimization problem. The amount of domain variation is
restricted within some allowed space.

![Fig.2 Restriction of domain variation](image)

For example, point $a'$ at the boundary could move from point $a$ to point $b$ during the domain variation. $\Gamma_c$ is the
admissible restriction surface. That is, point $a'$ can move only up to point $b$ on $\Gamma_c$, but not allowed to over-cross $\Gamma_c$.
during the domain variation.

2.3 Optimization Problem Statements
In MSC.Nastran-OPTISHAPE, the optimal shape of a structure with the highest stiffness or the highest eigenvalues is calculated by moving movable grid coordinates in the design domain as expressed by the following optimization problem statements.

2.3.1 Static Problem
Minimize the mean compliance subject to volume constraint:

$$\Phi = \frac{1}{2} \int_{\Omega} e^T D e \, d\Omega$$

Minimize $$\Phi$$ s.t. $$\int_{\Omega} d\Omega \leq V_c$$

2.3.2 Eigenvalue Problem
Maximize the mean eigenfrequencies subject to volume constraint:

$$\Lambda = \left( \frac{\sum_{j=1}^{m} W_j}{\sum_{i=1}^{m} \frac{W_i}{\lambda_i}} \right)$$

Maximize $$\Lambda$$ s.t. $$\int_{\Omega} d\Omega \leq V_c$$

3 Basic Design Notes
In the first phase of this nonparametric shape optimization development, both above mentioned static and normal modes nonparametric shape optimization analyses for either 2D or 3D problem, are introduced into MSC.Nastran. In order to develop an efficient and fully integrated solution sequence for nonparametric shape optimization analysis, the nonparametric shape optimizer function of OPTISHAPE is extracted and rewritten as the associated optimizer function modules of MSC.Nastran, and a new solution sequence, SHPOPT, is developed by modifying the DMAP of both SOL 1 and SOL 3 and adding a few new modules necessary for the purpose of nonparametric shape optimization and efficiency. In addition to that, a new SUBDMAP, SHPVEL, is also created for the velocity analysis as described in Chapter 2. Fig. 3 shows the conceptual flowchart of SHPOPT, where SHPOPT is the solution sequence name, and SHPDTI, SHPUPD, SHPGM4, SHPSUR, SHPSUR3 and SHPPHI are newly created function modules. In SUBDMAP SHPVEL, there are some other new modules created for some special purposes such as domain variation restriction processing and velocity analysis. Either static or normal modes nonparametric shape optimization can be performed by this solution sequence.
4 Additional Input Data and Data Entry Description

For the purpose of performing static or normal modes nonparametric shape optimization, a few additional parameters or data, such as constraint volume, move limit, design domain, etc., are necessary in addition to the common MSC.Nastran static or normal modes analysis bulk data. By using the same method used in topology optimization, the additional parameters are provided by using MSC.Nastran DTI (Direct Table Input) entry as described below. In addition to that, if one needs to restrict the shape variation of the design domain within certain spaces as described in Chapter 2, another new data input entry, SHPGRD, is provided to specify the allowable upper limit of surface as
described below. These entries can be inserted into MSC.Nastran bulk data file manually with some text editor like unix vi, or within MSC.Patran by using MSC.Nastran-OPTISHAPE preference, which is also enhanced to support the necessary pre/post processing associated with nonparametric shape optimization.

Table 1  DTI Input of SHPDT data block

**DTI Format**

$ 0 $ record, scalar control variables

```
1 2 3 4 5 6 7 8 9 10
DTI SHPDT 0 NGRID
KANALY IOPT ITERO ITERX CVOL XCI OPTCOV OCYCLE
KOBJ MULTIE DSAFLG
```

$ 1 $ record, design elements by property or element list

```
1 2 3 4 5 6 7 8 9 10
DTI SHPDT 1 POEFLG
POEIDi POEIDj POEIDk ...
```

$ 2 $ record, normal modes optimization inputs

```
1 2 3 4 5 6 7 8 9 10
DTI SHPDT 2
MODEi EIGRi WGI MODEj EIGRj WGTj ...
MODEk EIGRk WGTk ...
```

Field | Contents
--- | ---
NGRID | Indicator of surface restriction entry (Integer; default = 0)

- = 0 if there is no restriction surface data.
- = 1 if there is restriction surface data entry SHPGRD.

KANALY | Type of analysis. (Integer; default = 1)

- = 1 : static optimization problem.
- = 2 : eigenvalue optimization problem.

IOPT | Type of elements to be optimized. (Integer; default = 2)

- = 2 : shell elements ( CTRIA3, CQUAD4 ).
- = 3 : solid elements ( CTETRA, CPENTA, CHEXA ).

ITER0 | Start cycle. (Integer; default = 1)

- = 1 cold run.
> 1 restart run.

**ITERX**: Maximum allowable number of design cycles to be performed. (Integer; default = 50)

**CVOL**: Constraint value. (Real; default = 1.0)

**XCI**: Maximum move limit imposed. (Real; 0.01 < xci < 0.5, default = 0.3)

**OPTCOV**: Relative criterion to detect convergence. (Real; default = 0.0001)

**OCYCLE**: Output updated grid coordinates, DVGRIDs at every n-th cycle. (Integer)

  (default = -1, only output at the last cycle.)

  If OCYCLE > 0, then the updated grid coordinates, DVGRID will be output at first cycle; at every design cycle that is a multiple of OCYCLE; and the last design cycle.

**KOBJ**: Kind of objective function. (Integer; default = 0)

  = 0, minimize the mean compliance subject volume constraint.

  = 1, maximize eigenfrequencies subject to volume constraint.

**MULTIE**: Total number of eigenfrequencies to be considered. (Integer)

**DSAFLG**: Method of re-analysis. (Integer; default = 0)

  = 0 select accurate re-analysis

  = 1 select design sensitivity analysis (only available in KOBJ = 3, 5, 7)

**POEFLG**: Method to be used to define design domain. (Integer; default = 0)

  = 0, specify design elements with element ID list

  = 1, specify design elements with property ID list

**POEiDi**: Element or property list of design elements. (Integer)

**MODEi**: Mode number to be considered. (Integer > 0)

**EIGRi**: Not used currently.

**WGTi**: Weighting factors. (Real; default = 1.0)

If one wants to restrain the movable space of some boundary grids by a certain amount for whatever reason, say, manufacturing consideration, the following new entry can be used to define the allowable changing limit.

Table 2  Shape restriction entry **SHPGRD**

<table>
<thead>
<tr>
<th>Field</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FLAG</strong></td>
<td>Method to define the restriction points. (Integer; default = 0)</td>
</tr>
<tr>
<td></td>
<td>= 0, define the restriction using the grid coordinates of the restriction points.</td>
</tr>
</tbody>
</table>
= 1, define the restriction using the coordinates difference between the restriction grid and the associated boundary grid.

GID  
Grid point identification number to be restricted. (Integer > 0)

CID  
Coordinate system identification number. (Integer ≥ 0; default = 0)

COEFF  
Multiplier of the vector defined by Ni. (Real; default = 1.0)

Ni  
Components of the vector measured in the coordinate system defined by CID. (Real; default = 0.0)

5 MSC.Patran Graphic User Interface Support

As described above, in addition to the common MSC.Nastran data deck, a few data lines should be modified and
added for nonparametric shape optimization. In order to do this with MSC.Patran, Nastran-OPTISHAPE Preference, which was developed for topology optimization, has been enhanced. Now, this preference can be used to prepare the necessary nonparametric shape optimization data entries and to perform the associated postprocessing. Fig. 4 shows several main menus of the newly enhanced MSC.Nastran-OPTISHAPE preference.

6 Application Examples

In order to highlight and illustrate the nonparametric shape optimization features of MSC.Nastran-OPTISHAPE, several examples are illustrated here.

6.1 Static Problem - A 2D Plate Model

The first example is a very simple 2D plate with a hole under a concentrated force as shown in Fig. 5. The constraint volume is set to 0.75, where one wants to minimize the mean compliance by removing 25 percent of the total material. The plate is fixed around the inner hole and loaded at the top right corner. The design domain is modeled with 575 CQUAD4 elements. The associated boundary condition used in velocity analysis is shown in Fig. 6. Table 3 shows part of input bulk data deck.

By looking at the bulk data deck, one can see that there are 5 changes/modifications as follows:

1) assign userfile='s2darm.inp',unit=32,form=formatted,status=unknown

to assign a file for updated grid coordinates, DVGRID entries and design history output;

2) sol shpopt

to select nonparametric shape optimization sequence;

3) subcase 999999
    spc=3

to define the velocity analysis subcase 999999 in addition to the normal analysis subcases;

4) dti  shpdti  0  1
    1  2  1  50  .3  0.75  .0001  5
    dti  shpdti  1  1
    1  endrec

to provide the nonparametric shape optimization parameters, define the design domain etc..

5) spc1  2  13456  ...
    spcad 3  1  2

to define the boundary conditions for velocity analysis.
Fig. 5  A 2D arm subject to force P

Fig. 6  Velocity analysis condition

Fig. 7  FEM mesh and resultant optimal shape

Table 3 Input bulk data

```
ID TEST2D, S2DARM
assign userfile='s2darm.inp',unit=32,form=formatted,status=unknown
sol shpopt
CEND

... ...

SUBCASE 1
   LOAD = 1
   SPC = 1
$velocity analysis conditions
subcase 99999
   spc = 3
BEGIN BULK
PARAM  POST     -1
PARAM  AUTOSPC YES
$ADDITIONAL BULK DATA FOR STATIC TOPOLOGY OPTIMIZATION
  dti  shpdti  0   0  
        1   2   1   50   .3  0.75  .0001  5
  dti  shpdti  1   1 
        1   endrec
$
PSHELL  1   1   1. 1   1
CQUAD4  1   1   1   2   43  42
... ...
```
… … all other data to define element connection, grid points, boundary and loading forces etc.

… …
FORCE  3  31  0   1.    0.   -1.    0.  
$ boundary conditions for velocity analysis
$ spc    2   13456 ...
spcadd  3  1  2
$ ENDDATA

Fig. 7 shows the resultant optimal shape obtained from MSC.Nastran-OPTISHAPE after 50 design cycle calculations. It is relatively apparent that the shape is quite reasonable.

Fig. 8  A solid cantilever beam and associated optimal shapes
6.2 Static Problem - A 3D Solid Cantilever Beam Model
The second example is a 3D solid cantilever beam model fixed at the left end and loaded at the central point with down-orientation on the right end. It is used to see if the code can give reasonable results that are simple to imagine from common engineering knowledge. It is also used to illustrate the domain variation restriction feature mentioned above. Fig. 8 shows a solid cantilever model of 5120 CHEXA elements and the associated optimal resultant shape. Fig. 8b shows the obtained resultant shape under the conditions removing 70 percent of the total material (CVOL=0.3) and without changing the original elements within the top and bottom layers. Fig. 8c shows the result under the conditions without removing any material (CVOL=1.0) but with the slide constraints on the top and bottom surfaces. Fig. 8d is the result under the same conditions used for Fig. 8c except there are side surface restrictions on the left and right hands. Very impressive conceptual results are obtained without any tedious data preparation. Although this model is quite simple, it clearly shows that this nonparametric shape optimization capability can be used in the very beginning of the conceptual design process.

6.3 Eigenvalue Problem - A 2D Plate Model
A 2D cantilever beam fixed at left end as shown in Fig. 9 (up) is used to illustrate the nonparametric shape optimization capability of eigenvalue problem by maximizing its 1st and 2nd modes of the problem without removing any material. There are slide constraints at both ends in the velocity analysis. The final shape after 80 cycles is also shown in Fig. 9 (down). The 1st and 2nd modes of optimized shape are 123.36 Hz and 794.52 HZ against the 92.00 Hz and 551.93 Hz of the original shape.

Fig. 9  Original and optimal shapes of maximizing the 1st and 2nd modes

6.4 Eigenvalue Problem - A 3D Solid Beam Model
The forth example is also a 3D beam model similar to the one used in Section 6.2. In this example, however, the beam is fixed at both ends rather than just one. The optimization job is to maximize the first elastic mode without reducing any material. In velocity analysis, slide ends are used at both ends. Figure 10 shows the original and optimal
shape of the beam model. The first elastic mode of final shape is 19.98 Hz against the 13.59 Hz of the original one. This final shape may not be used in real design, however, it provides designers with very useful hints on how to design a structure of higher elastic mode without using any more material.

![Original and Optimal Shape of Maximizing the 1st Mode](image)

**Fig. 10  Original and Optimal Shape of Maximizing the 1st Mode**

### 6.5 Shape Basis Vectors Generation for SOL 200

The application examples demonstrated above show the promising possibility of MSC’s newly developed nonparametric shape optimization capability. It can be used not only in the detailed design process for the final design shape, but also in the conceptual design. Since all grids in design domain are allowed to move together with the boundary grids, it is quite tolerant that the design domain can have very large boundary change.

Another natural extension is that, it may be used to provide the shape basis vectors that are required in SOL 200 in order to perform multidisciplinary structural optimization over a wide range of analysis types under many other design constraints, if one takes the difference between the updated grid coordinates and the original ones as the shape basis vectors. In order to illustrate this kind of possibility, a culvert structure from Reference 2 is used here. Actually this is the same example used in the parametric shape optimization examples of SOL 200 of MSC.Nastran in the Users’ Guide of MSC.Nastran Design Sensitivity [3]. Fig. 11a shows the finite element model of one half of a symmetric culvert structure (symmetry exists with respect to y-axis.) With the bottom surface fixed, pressure loads are applied to the top surface. The design task is to minimize the volume of the structure by changing the shape of the initially circular hole subject to von Mises stress constraints over the interior.

![Finite Element Model of Culvert Structure](image)

Fig. 11b is the auxiliary velocity analysis model used in nonparametric shape optimization, in which
the design job is defined by minimizing the mean compliance subject to a volume constraint of 0.80. The difference of updated grid coordinates obtained from the traction method is output as DVGRID entries in a separate ASCII history file. By including these DVGRID entries into a corresponding SOL 200 bulk data as shape basis vectors, in which the optimization job is defined by minimizing the volume of the structure subject to von Mises stress constraint over interior elements.

Fig. 11  One half of a symmetric culvert model

Fig. 12 shows the original shape versus the final shape with their corresponding stress contours. One can see that a favorable distribution of von Mises stresses for the final shape is obtained. In addition, the volume of the culvert has been reduced by about 20% while the strength constraint is satisfied.

Fig. 12  Comparison of stress distribution of original shape and final shape
7 Concluding Remarks

In this development, by combining the nonparametric shape optimization optimizer function of OPTISHAPE into MSC.Nastran as functional modules, both static and normal modes nonparametric shape optimization analysis capabilities are incorporated into MSC.Nastran as a new solution sequence **SHPOPT**. These capabilities can be used not only in the detailed design process for the final optimum shape, but also in the conceptual design process. The principal features of the new capabilities are as follows:

1) **Static nonparametric shape optimization** : to minimize mean compliance subject to volume constraint.
2) **Normal modes nonparametric shape optimization** : to maximize a few eigenfrequencies subject to volume constraint.
3) **Shell or solid design elements** : either first-order shell (plane stress or strain) or solid elements can be used as design elements. All other elements that can be used in linear static (SOL 1) or normal modes (SOL 3) analysis can also be used to model the non-design part of the optimization analysis model.
4) **MSC.Patran integration** : MSC.Patran’s MSC.Nastran–OPTISHAPE preference, have been enhanced so that all pre and post processing for both static and normal modes nonparametric shape optimization analyses can be carried out within MSC.Patran.
5) **MSC.Nastran bulk data format** : all input bulk data are provided in MSC.Nastran bulk data format – compared with the common MSC.Nastran static or normal modes analysis jobs, only a few additional data lines are sufficient to perform the associated static or normal modes nonparametric shape analysis. MSC.Patran can add these additional data lines. It is also quite easy to manually insert these additional lines once the common MSC.Nastran static or normal modes bulk data are generated by any other preprocessors.
6) **Efficient solution of very large models** : by using MSC.Nastran advanced elements and efficient solver engines for static or normal modes analysis, very efficient solution to very large-scale nonparametric shape optimization models can be realized.
7) **Generation of shape basis vectors** : the difference between any intermediate shape change and its original shape can be output as shape basis vectors that are required in MSC.Nastran SOL 200. This could avoid the tedious work of preparing the shape basis vectors.

In the 2\textsuperscript{nd} phase development, the following static nonparametric shape optimization capabilities are going to be incorporated:

1) Minimize volume subject to mean compliance;
2) Minimize maximum stress subject to volume constraint;
3) Minimize volume subject to maximum stress constraint;
4) Minimize maximum displacement subject to volume constraint;
5) Minimize volume subject to maximum displacement constraint.

References


[12] Li, Y. M. and Ishii, K., “Minimizing mass subject to displacement and restriction to design space in shape,” Proc. of the 1st China-Japan-Korea Joint Sym. on Optimization of Structural and Mechanical Systems, Xi'an, China, 1999, 49-56