

New Strategies for Design Optimization in SOL 200

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ABSTRACT

The V70.7 release of MSC.Nastran and the upcoming 2001 release have added significantly to the Design Sensitivity and Optimization capability that is contained in SOL 200. Many of the added features were prompted by requests from automotive clients so that it is deemed appropriate that we take the opportunity of the MSC Automotive User's Conference to both review the new capabilities of the V70.7 release and to preview the upcoming 2001 release. A brief overview is given of all the major new optimization features. It is shown how the capability to designate material properties as design variables enables some innovative topology optimization techniques. The paper concludes by highlighting how the new features in dynamic response can be applied and provides results of applying these features to a particularly difficult design task.

INTRODUCTION

The general multidisciplinary optimization capability (SOL 200) was first introduced in Version 66 of MSC.Nastran and has been widely used in various industry applications (Ref.[1] – Ref.[9]). The latest released version V70.7 and the coming version, MSC.Nastran 2001 have added a number of new features to this powerful capability. For V70.7, the major new features are:

- (a) Allow material variables and element connectivity variables to be designed.
- (b) Support optimization with Beam Library using the PBEAML bulk data entry
- (c) Extend the capability of the DRESP2
- (d) More results in the .pch file
- (e) Additional DRESP1 responses
- (f) Additional results display

Each of these items is described in brief detail in a paragraph below. In addition, an innovative topology optimization design task is performed using the new material design variables.

The upcoming MSC.Nastran 2001 release has added yet more optimization features with the primary ones being:

- (a) Discrete variable optimization
- (b) Fully Stressed Design
- (c) Random response optimization
- (d) Complex eigenvalue optimization
- (e) Support of FREQ3/4/5 entries
- (f) A series of “ease of use” features primarily directed toward dynamic response optimization.

The Discrete Variable Optimization capability is being addressed at the conference with its own presentation (Ref.[10]) and won't be discussed further here. The Fully Stressed Design feature is regarded as primarily an aerospace prompted enhancement and also won't be discussed further here. The remaining topics are reviewed briefly and then the bulk of the remaining part of the paper is devoted to demonstrating a number of ways to approach an optimization task that involves the design of a structure being loaded across a range of frequencies. Although the example chosen is deceptively simple, it serves to expose a number of issues that arise when addressing this type of problem. MSC is aware that the automotive industry is very interested in this type of design task, particularly in the design of car bodies for NVH type applications. The alternative approaches that are presented are intended primarily to demonstrate the new features, but it is also possible to draw certain conclusions and to provide guidelines in the use of the techniques. Where there are alternative methods, the strengths and weaknesses of each is discussed.

MSC.Nastran V70.7

The MSC.Nastran V70.7 Release Guide (Ref.[11]) contains a complete description of the optimization enhancements for that version and that volume should be consulted to learn enough about these features to actually apply them. This paper serves to acquaint users with the capability, but does not attempt to be comprehensive.

Material and Connectivity Variables

Prior to V70.7, the design variables for the design optimization capability drove either shape (grid locations) or property (e.g., shell thickness or rod areas) variables. V70.7 has added significantly to this so that the design variables can also be referred to by material properties (e.g., material density or Young's modulus) and by connectivity properties (i.e., real numbers appearing on a bulk data entry that begins with 'C,' such as concentrated mass values and beam offset locations). Our users have begun to apply these new variables and several examples in this paper make use of them. An innovation that was made in the user interface is that the designed property is now referred to by name rather than the field location on the associated property entry. Also, MSC.Patran supports the selection of these new variable types.

Beam Library

The PBEAML dimensions can now be designed, greatly simplifying the data preparation when designing beams.

Extended DRESP2

The DRESP2 entry creates a synthetic response. The entry was extended in V70.7 to allow reference to the new material and connectivity variables. It also now allows the user to reference another DRESP2. This latter feature should be of major benefit to users who despair of constructing lengthy, repetitious DEQATN input.

New Punch Options

The major addition here is that it is now possible to punch out bulk data entries with the new property values after a redesign. This greatly facilitates moving the design optimization results to another solution sequence, such as nonlinear analysis.

Additional DRESP1 Response Types

Element Strain Energy and static SPC forces are additional response type on the DRESP1 entry.

Additional Results Display

Design results can be written to a special purpose file in a CSV (comma separated values) format. This is ideal for reading into spreadsheet software (such as Microsoft Excel) for data manipulation and display. The ability to scale and view sensitivity information is felt to be of particular utility.

Topology Optimization with Material Variables

The introduction of material design variables in V70.7 makes it possible to perform special topology optimization tasks in SOL 200 using the density approach (Refs.[12,13,14]). Topology optimization is to find the ‘optimal’ material distribution of a structure by optimizing a design objective within the constraint limits by varying material densities. Its formulation is given below:

$$\begin{aligned} \text{Optimize} \quad & f(\underline{\mathbf{X}}) & (1) \\ \text{Subject to} \quad & g_j(\underline{\mathbf{X}}) \leq 0, \quad j=1,m & (2) \\ & \underline{\mathbf{0}} \leq \underline{\mathbf{X}} \leq \underline{\mathbf{1}} & (3) \end{aligned}$$

where f is the objective function such as compliance, natural frequency or a function of dynamic responses across the exciting frequency range. g_j is the j -th design constraint. A constraint can be displacement or natural frequency. In general, any response available in SOL 200 can be used as an objective or constraint for an topology optimization task. Design variable vector $\underline{\mathbf{X}}$ consists of ndv design variables, $X_i, i=1,ndv$. The problem defined in Eqs.(1) to (3) are solved using the mathematical programming techniques available in SOL 200.

The density design variables have the special meaning in a topology optimization task. Consider a single design variable case. The design variable, X is defined as the normalized density,

$$X = \rho / \rho_0 \quad \text{or} \quad \rho = \rho_0 * X \quad (4)$$

where ρ and ρ_0 are intermediate and physical densities. Further, Young’s modulus, E is related to design variable through the following experimental relation:

$$E = E_0 * X^{*n} \quad (5)$$

where E and E_0 are intermediate and physical Young’s modulus. The exponent n is a penalty number. The role of n is to drive X to either 0 or 1. When X varies between its lower and upper limits (0 and 1), E also varies between zero and E_0 . One can imagine that the associated element is removed from the structure when $X=0$ while the element is retained when $X=1$. Therefore, the different values (or distribution) of density variables can be used to represent the structure configuration. A common way to show the density distribution is to plot a contour picture of the structure based on the values of design variables. Since the final design variables take values between 0 and 1, the resulting distribution plot may not show the clear layout. In practice, a threshold value is judiciously selected to produce better configurations.

As a general guideline, the initial values of $\underline{\mathbf{X}}$ should be set corresponding to the limit state of a weight budget rather than be set to $\underline{\mathbf{1}}$. For example, if the weight is constrained within the 30% of the original design domain, the values of the initial design variables are chosen as 0.3. This is equivalent to the case in which the design task starts from the budgeted state and the ‘optimal’ material distribution is sought to minimize or maximize the objective while keeping the constraint on target.

In this paper, a multidisciplinary topology optimization task is solved with the new capability. A cantilever beam model is shown in Fig.1. Both the static analysis and the normal modes analysis are performed simultaneously. A static transverse load is applied at the free end. The design task

is to simultaneously minimize the compliance for the static case and maximize the first eigenvalue while the total mass is limited as 25% of the initial design domain. In addition, the second eigenvalue is constrained to be greater than a specified number. Each element density in the model varies independently. Notice the y-displacement at grid 683 is defined as the compliance response since the applied force is invariant.

The procedure to define a design model for topology optimization is similar to the one for a regular sizing or shape optimization task. The density design variables are defined using DESVAR entries. Relations shown in Eqs.(4) and (5) are defined using DVMREL1/2 entries. The mixed min-max objective is achieved using the beta formulation. The beta formulation is a general way to deal with the min-max type of problems and its formal definition and various applications can be found in Refs.[3,15]. The beta in the formulation is an artificial design variable and acts as a threshold. When the threshold is minimized (maximized) while the distance between the beta (the response) and the response (the beta) is constrained positive, the response of interest is minimized (maximized). In our example, two betas are introduced, one for the compliance and another for the eigenvalue. Notice that the compliance r_1 is reformulated as $-1/r_1$ since r_1 is negative. Therefore, when the sum of two betas is maximized while the distance between $-1/r_1$ and the first beta, and the distance between the eigenvalue and the second beta are kept positive, the compliance and the first eigenvalue are minimized and maximized, respectively.

The input data file (topopt.dat) can be obtained from the following web address:
http://www.mechsolutions.com/support/online_ex/Nastran/Sensitivity_Optimization.html.

The job is run with V70.7 and it converges at 30 design cycles. The contour plot of the final density distribution of the cantilever beam is shown in Fig.2. The cutting value of 0.23 is used. Notice that the final density distribution is plotted as the thickness distribution in MSC.Patran with the plate thickness being replaced by the final density values. For the solid elements, the temperature distribution may be plotted with the final density design variables as the new temperature values.

To better understand the final configuration that simultaneously minimizes the compliance and maximizes the first eigenvalue, we also plot the final density distribution of the cantilever beam for the case of minimum compliance only. Both Fig.2 and Fig.3 show the similar exterior edges that are desirable to achieve the minimum compliance requirement. On the other hand, to achieve the maximum frequency, more elements are retained in the middle of the beam structure (Fig.2).

Although the 'optimal' topology solution is not unique because it can be derived from various cutting values, in the engineering practice, it provides valuable design insight and guidelines for future designs. The final design as shown in Fig.2 is either difficult or impossible to obtain by using the conventional sizing and/or shape optimization techniques.

If interested, the reader may consult Ref.[11] for one example of dynamic topology optimization.

MSC.Nastran 2001

MSC.Nastran 2001 has added significant new features in design optimization, reflecting an increased emphasis that has been placed in this area. As with the V70.7 features, a paper of this type can only provide a brief overview of the new capabilities and the interested user should consult the forthcoming Release Guide for MSC.Nastran 2001 for complete details. A theme of the release is an emphasis on dynamic response and this is reflected in the application examples that are provided here.

Random response optimization

A feature that should be of particular interest in automotive applications is the new DRESP1 response types that support random response. The available responses are grid point (displacement, velocity or acceleration) RMS responses that are computed based on input power spectra and frequency response information. The design of a suspension system response to an uneven pavement could benefit from this capability.

Complex eigenvalue optimization

MSC.Nastran 2001 also allows the user to specify the components of a complex eigenvalue as a design response quantity. An automotive application is to the design of brake systems to prevent brake squeal.

Support of FREQ3/4/5 entries

The FREQ3, FREQ4 and FREQ5 entries allow the user to request excitation frequencies that are derived from the structure's natural frequencies. This can be used to assure that the frequency response analysis is carried out near the resonance conditions. The 2001 release fully supports this capability in SOL 200 with the anticipated benefit that users can perform frequency response optimization with a limited set of excitation frequencies compared to what would be required if the excitation frequencies were invariant as the design evolved.

Ease of use features

The "Ease of Use" heading refers to a number of enhancements that have been made in the text user interface for design sensitivity and optimization. While they do not provide additional functionality, they greatly simplify the input preparation to the extent that design tasks that were previously too tedious to contemplate can now be formulated quite simply. Among the features that come under this heading are:

- (a) The DCONSTR entry has new optional inputs that allow the specification of the frequency range over which the constraint is to be imposed.
- (b) The FRxxxx response types on the DRESP1 entries can indicate an operation that is to be performed across the range of excitation frequencies. Available operations are SUM, AVG, SSQ, RSS, MAX and MIN which provide a scalar response that is the sum, average, sum of squares, square root of the sum of squares, maximum and minimum of all the responses across the frequency range.

- (c) The DRESP2 entry has been modified to allow the current EQID field to instead invoke a pre-defined function, removing the need for the associated DEQATN. The available predefined functions are the same SUM, AVG, SSQ, RSS, MAX and MIN operations mentioned above.
- (d) The DEQATN entry has additional functions SUM, AVG, SSQ, RSS, DB, INVDB, DBA and INVDBA, where the first four have same meaning as discussed above while the last four refer to decibel, inverse decibel, perceived decibel level and inverse perceived decibel level.

It is recognized that there is some overlap in these new options, but it should also be seen that there is greater generality in the DRESP2 terms than in the corresponding DRESP1 terms and that the DEQATN functions provide even more generality. Some of these 'ease of use' features are illustrated in the examples below.

ALTERNATIVES IN DYNAMIC RESPONSE OPTIMIZATION

Problem definition

The purpose of this section is to demonstrate how three new features described can be applied to solve an example problem. The problem chosen here is derived from an MSC's internal CSR report (Ref.[16]) and is a variation of the example shown in Ref.[9]. The structure is loaded with the uniform pressure in the z direction and is clamped at three edges. The unit pressure is applied across a frequency range of 20 to 750 Hz. Figure 4a shows the finite element model for the half of structure due to symmetry conditions. A structural damping coefficient $G=0.06$ is applied and the dynamic displacement response is solved with the modal frequency solution sequence. Figure 4b is the response plot for the z -displacement at grid 11. The major peak response 4.02 occurs at 42.5 Hz.

The task is to reduce the peak responses across the frequency range while maintaining weight invariant. The element density is chosen as the design variable to find the 'best' location for placing the concentrated mass in the plate structure. Each design variable is related to a group of element resembling an L shape. For example, the shaded L shape in Fig.4a is the first design variable. The last design variable is related to a single element connected with grid 11.

Difficulties in dynamic optimization

Although the example looks simple, it poses two particularly difficult issues in the study. One is the flat design space at the initial design stage. This is shown in Fig.5 for one design variable case. The RMS function of y -displacements at grid 11 across the frequency range is plotted against the ninth design variable. The flat design space occurs around $X_9=1.0$. It was reported in Ref.[16] that when the design task with 10 design variables started from such a stage, the task stopped in one design cycle without changing the objective. This difficult may be overcome in two ways. One is to avoid the initial flat design stage either by directly changing the design variables or increasing the damping coefficient. Another is to use the combination of smaller design move limit, the Sequential Quadratic Programming algorithm and the direct approximation approach for the optimization process. In this example, the latter is used. The

second difficulty is the local minimum. In fact, the first difficult will also lead to a local minimum. Figure 6 plots the RMS function showing such a phenomenon. The RMS function of the y-displacement at grid 11 is plotted as zaxis while the 3^d and sixth design variables, related to third and sixth groups of the element as shown in Fig.6, are used as the x and y-axes. Many peaks and valleys are observed from a single design space that is contrast with the local minimum observed in a disjointed design space as reported in Ref.[17]. Starting from different initial design stages is often used to obtain the global optimum. However, the general treatment of the global optimum is beyond the scope of this paper.

Although these difficulties can occur in any optimization task, they tend to show up more often in dynamic response optimization. This necessitates the use of different strategies to perform dynamic optimization tasks. In particular, three new features described in the previous section, random response optimization, a synthetic response using the custom function and the FREQ5 feature will be applied below. Three user input files (ranopt.dat, ssqopt.dat, freq5opt.dat) can be obtained from the following web address:

http://www.mechsolutions.com/support/online_ex/Nastran/Sensitivity_Optimization.html.

Random response optimization (ranopt.dat)

The minimum peak response task is attempted with the minimization of the RMS displacement function. Since this example is a non-random response optimization, The RANDPS entry specifies the same set number for the excited load set and the applied load set. In addition, the RANDPS entry points to the TABRND1 table that is unit at all frequencies. The RMS displacement response is defined by a DRESP1 entry whose attr-B field references to the RANDPS entry. The RMS displacement is chosen as the objective and is minimized. The weight is constrained to the original level.

The job is run with Version 2001 and is terminated after 25 design cycles. The objective, the RMS displacement function, is reduced from 9.55 to 5.52 with 42% reduction in RMS. Figure 7 shows the plot of initial and final displacements. It is interesting to notice that the peak response stays the same while the peak resonance frequency is shifted to 28 Hz from 62 Hz. However, the shape near the resonance is squeezed due to the reduction in the RMS function.

Use the custom function for a synthetic dynamic response (ssqopt.dat)

Reducing the peak responses across the frequency range is a min-max problem. One popular strategy is to define a function to convert the multiple frequency responses into a scalar number. Then, the scalar number is minimized. Prior to Version 2001, such a function requires creation of DRESP1, DRESP2 and DEQATN entries. For a task having many frequency points, the user input effort can be significant and is error prone. To simplify the user input preparation, Version 2001 allows the user to define a customized response with one DRESP1 entry.

The same RMS function used in the random response optimization is defined by a synthetic response that references to a custom SSQ response and two DRESP1 responses at first and the last exciting frequencies. The simulated RMS function is minimized. The weight is constrained to be invariant. The job is run with Version 2001 and converges in 29 design cycles. The

simulated RMS function is reduced from 9.55 to 7.96 with 17% reduction. Finally, Fig.8 shows the plots of the initial and final displacements. The peak value of the final displacement is reduced to 3.38 unit from 4.02. The peak frequency is slightly shifted to 56 Hz.

Use the FREQ5 feature (freq5opt.dat)

When the FREQ5 feature is applied for a dynamic optimization task, the frequency response analysis can be automatically carried out near and/or at the resonance conditions at each design cycle. Therefore, a small number of excitation frequencies can be specified for each analysis. For example, the FREQ5 entry for our example takes the following fraction numbers: (0.5,0.75,0.8, 0.92,0.98,1.0,1.02, 1.08, 1.20, 1.25, 1.50). This results in total 90 exciting frequencies being used comparing with 731 frequency points in the full frequency set.

Although selecting a small set of fraction numbers in a FREQ5 entry may reduce the time for a modal frequency analysis, limited experience shows that the saving in each analysis may be lost due to the increase in number of design cycles because of the changes in the search direction. Therefore, the selection of FREQ5 fraction numbers is problem dependent. However, in general, it is desirable to include the resonance response to reflect true dynamic behavior in the dynamic optimization task.

In this example, the beta approach (Refs.[3,15]) is used to minimize the multiple responses selected by the FREQ5 entry. Therefore, it can further reduce the computational cost because the fewer number of responses are retained in the design sensitivity and optimization phase. The required design entries for the beta formulation can be found in freq5opt.dat. The job is run with V2001 and converges after 16 design cycles. Since the peak responses are directly minimized without using a scalar function, the difficulty associated with the flat design space is lessened. The larger design move limit, delx=0.2 and delp=0.2 are selected. The plot of initial and final displacements is shown in Fig.9. The maximum peak response is reduced from 4.02 to 3.12 with the resonant frequency being shifted from 62 Hz to 82 Hz.

Comparing with other two strategies, it is clear that when the design task is to minimize the peak responses, the beta formulation with the FREQ5 feature is more effective and efficient.

CONCLUDING REMARKS

This paper first reviewed the new features available in V70.7 release of MSC.Nastran and presented an innovative topology optimization task that simultaneously minimizes the compliance and maximizes the natural frequency using new material design variables. Next, the paper previewed the new features added to the upcoming 2001 release. Dynamic response optimization is the theme of the release and is reflected through the application examples solved in the paper. Through the examples, the paper showed that while the random response feature can also be used to solve non-random dynamic response optimization tasks, the new FREQ5 feature coupled with the beta formulation can minimize the dynamic peak responses effectively and efficiently.

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Web Address for the Input Data Files of the Examples:

Four input data files of the examples can be obtained from:

http://www.mechsolutions.com/support/online_ex/Nastran/Sensitivity_Optimization.html.

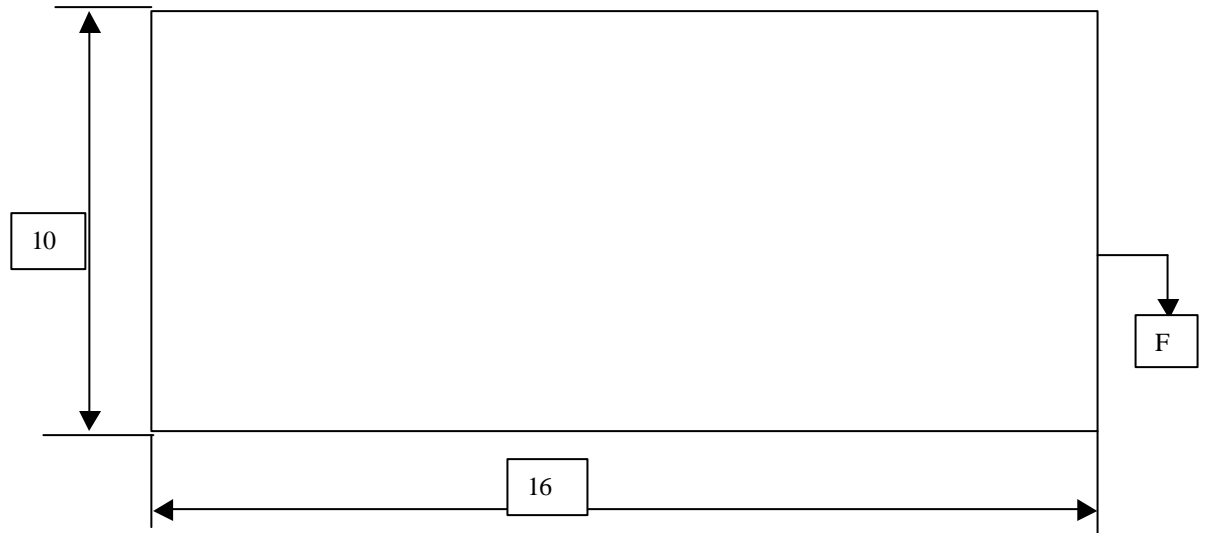


Figure 1 Multidisciplinary Topology Optimization with Minimum Compliance and Maximum First Eigenvalue

MSC/PATRAN Version 9.0 25-Jul-00 09:29:32
Fringe: Density Distribution Plot

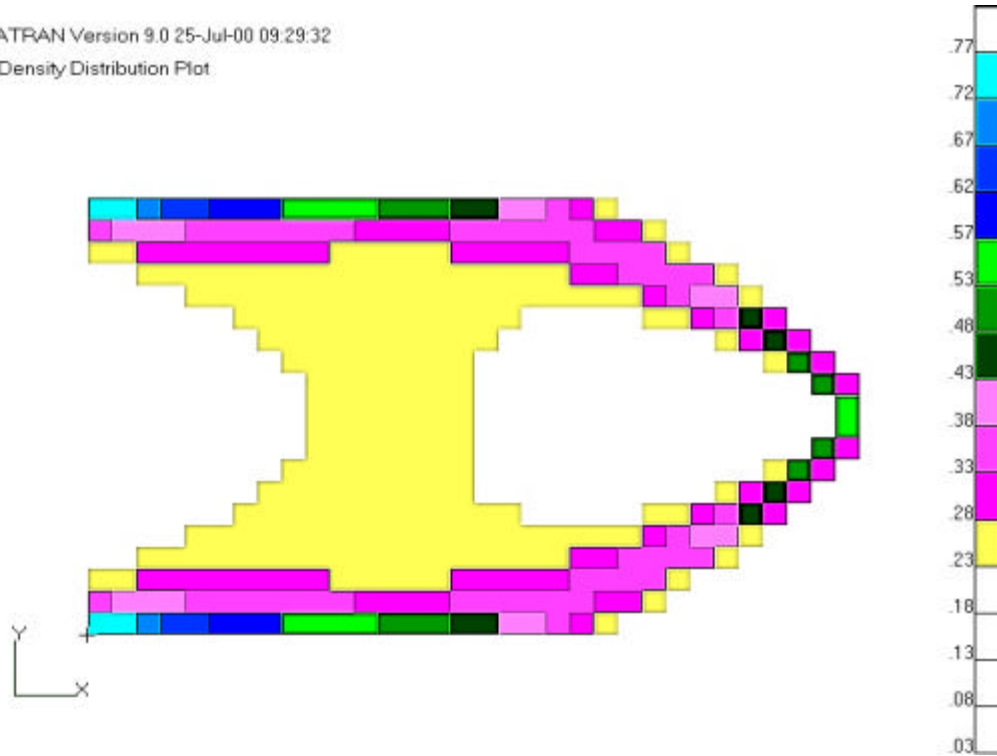


Figure 2 Final Configuration of Cantilever Beam With Minimum Compliance and Maximum First Eigenvalue (Cutting Value = 0.23)

MSC/PATRAN Version 9.0 25-Jul-00 16:51:38
Fringe: Density Distribution Plot

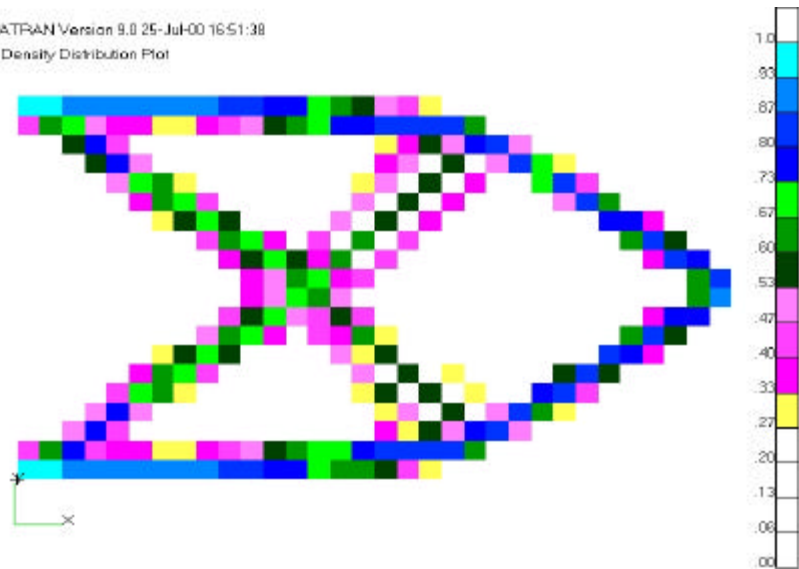


Figure 3 Final Configuration of Cantilever Beam With Minimum Compliance only (Cutting Value = 0.27)

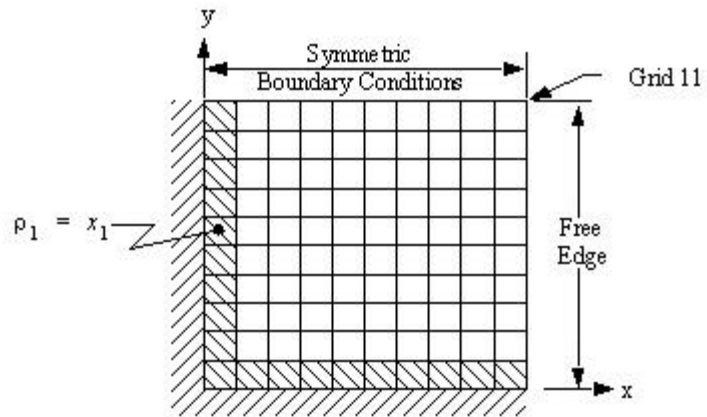


Figure 4a FE Model of the Clamped-Free Plate Structure

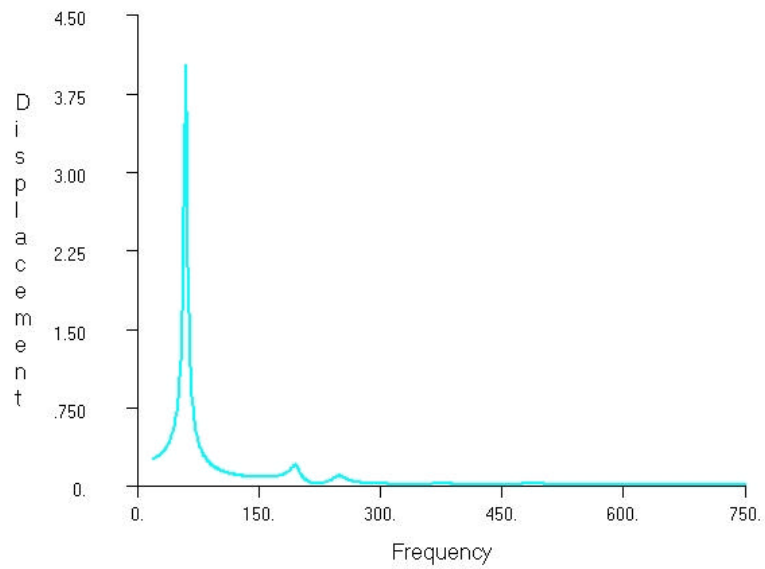


Figure 4b FE Model of the Clamped-Free Plate Structure

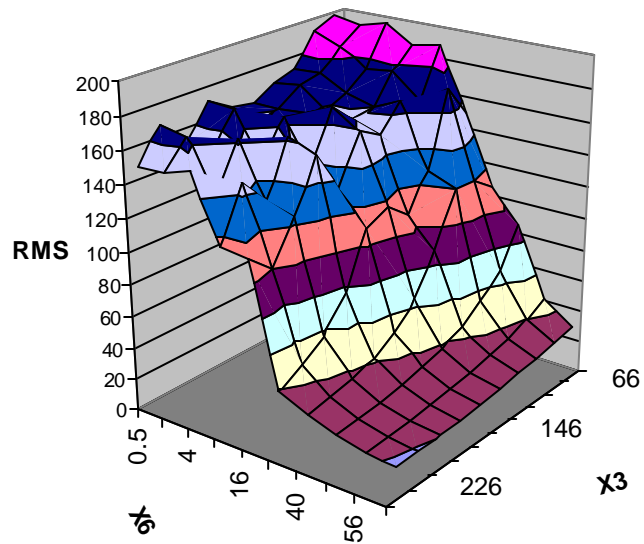
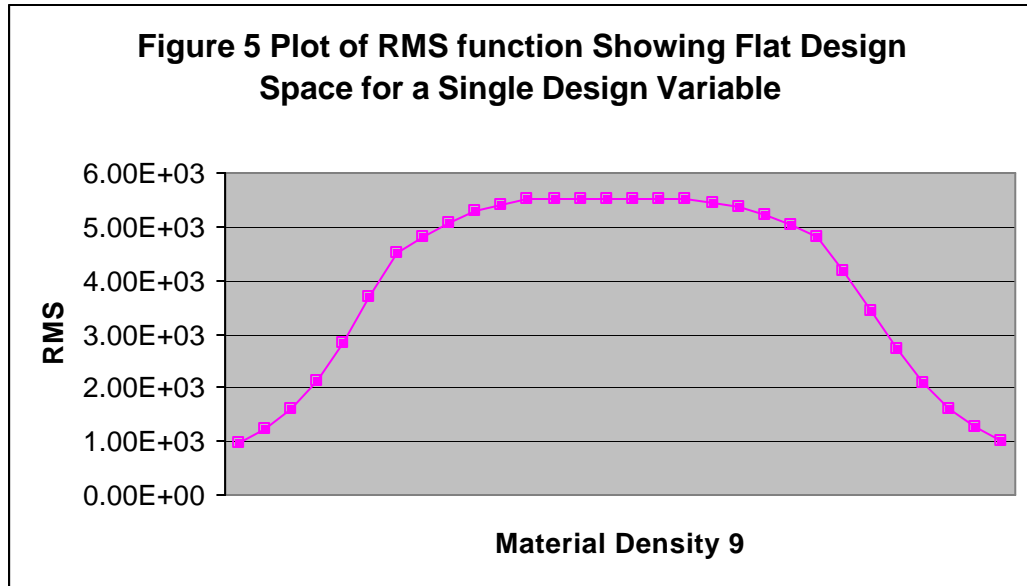


Figure 6 Plot of RMS Function Showing Local Minimums

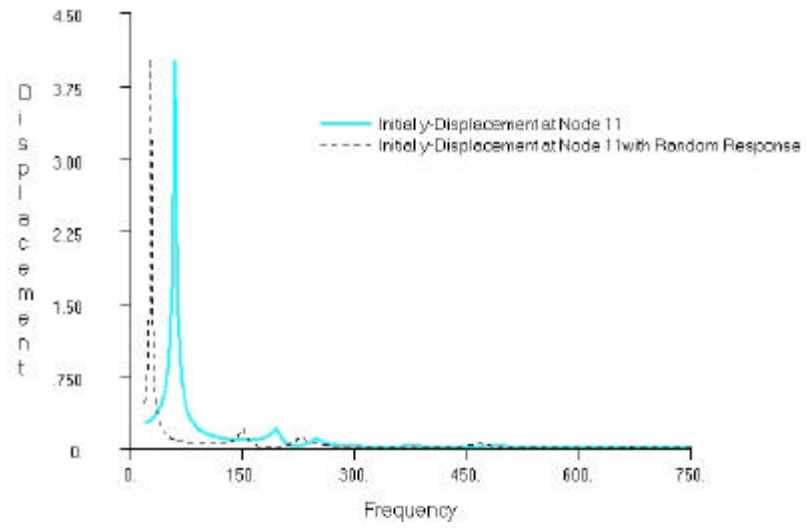


Figure 7

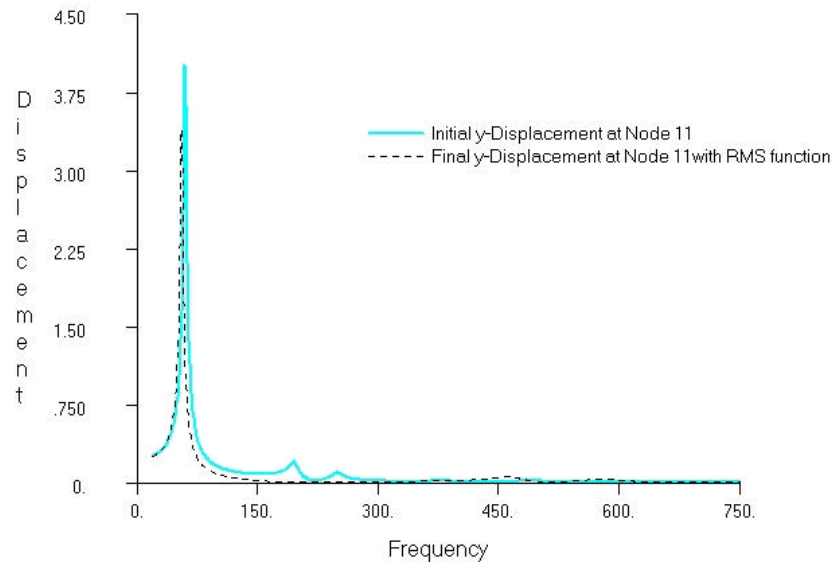


Figure 8

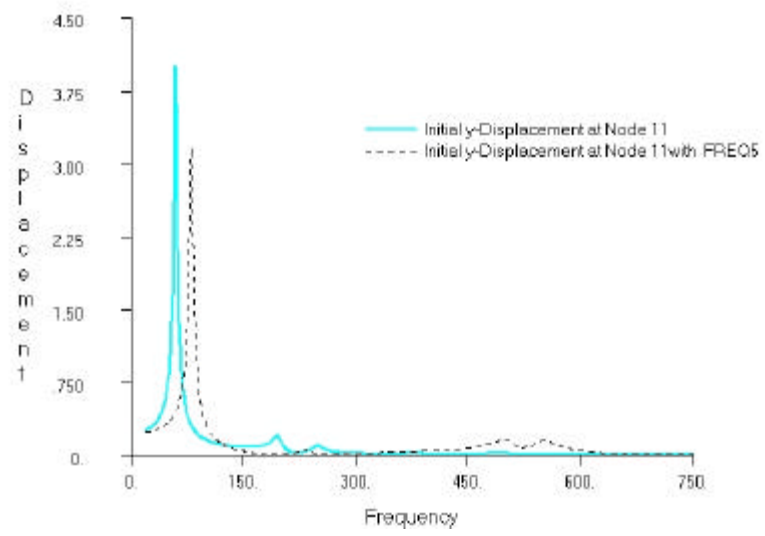


Figure 9