9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization
4-6 September 2002, Atlanta, Georgia

AIAA 2002-5646

DISCRETE OPTIMIZATION CAPABILITIES IN GENESIS STRUCTURAL ANALYSIS AND OPTIMIZATION SOFTWARE

Naveen Rastogi†, Dipankar K. Ghosh + and Garret N. Vanderplaats*

ABSTRACT

A new approach to solve large-scale discrete variable optimization problems is presented. The discrete variable optimization algorithm in Vanderplaats Research and Development's GENESIS® is based on Sequential Unconstrained Minimization Technique (SUMT), which allows one to solve very large optimization problems with discrete design variables using limited memory. Numerical examples are presented to demonstrate the accuracy and efficiency of new computational algorithms to perform large-scale structural analysis and optimization involving discrete design variables.

INTRODUCTION

The objective of this work is to describe new optimization capabilities that have been added to the GENESIS program to solve discrete variable problems. Branch and Bound method can be used to solve discrete variable problem; however, it has limitations when there are more than ten design variables in the discrete optimization problem.

The initial effort was devoted to solving the problem using duality theory[1] together with convex linearizations. Experience with the prototype code, as well as theoretical and computational considerations, led us to abandon this approach in favor of a penalty function approach. Here, we briefly outline the penalty function approach to perform discrete-variable optimization and present examples to demonstrate its features.

PENALTY FUNCTION APPROACH

Vanderplaats Research and Development is presently developing methods for very large-scale optimization. A new code, called BIGDOT, has been developed and demonstrated on very large continuous variable problems[2]. Recently, the continuous optimization of BIGDOT was used to successfully solve a hundred thousand (100K) variable structural optimization problems within GENESIS[3]. This program is based on a modern Sequential Unconstrained Minimization Technique SUMT using an exterior penalty function. Here, the original constrained problem is converted to a sequence of unconstrained problems of the form;

$$\Phi(X) = F(X) + R_p \sum_{j=1}^{M} r_p^j MAX[0, g_j(X)]^2 \qquad (1)$$

Subject to;

$$X_i^L \le X_i \le X_i^U ; \quad \text{i=1, N} \qquad (2)$$

R_p is called the penalty parameter, which is initially set to a small value (say 1.0) and then increased (say by a factor of 5.0) for each subsequent unconstrained minimization. The individual multipliers, r_p^j, are

† Technical Fellow, Visteon Corporation, Senior Member AIAA
+ Product Manager, Vanderplaats Research and Development, Inc., Member AIAA
* President, Vanderplaats Research and Development, Inc., Fellow AIAA

calculated by a proprietary formula, but may be generally viewed as estimates of the Lagrange Multipliers.

We solve this unconstrained sub-problem using the Fletcher-Reeves method[4], which requires very little computational effort and/or computer memory.

During optimization, we need gradients of the pseudo-objective function, $\Phi(X)$, which is calculated as;

$$\nabla\Phi(X) = \nabla F(X) + 2R_p \sum_{j=1}^{M} r_p^j MAX[0, g_j(X)]\nabla g_j(X) \tag{3}$$

Here, we see the two key advantages to this method for large problems;

(i) Because Eq. (3) is the sum of vectors, it is possible to create the gradient by getting as little as one objective or constraint gradient at a time. This allows us to solve very large problems with very limited memory.

(ii) The Fletcher-Reeves algorithm requires very little memory or computational effort in calculating the search direction.

For these advantages, we do pay a price in efficiency. Typically, this algorithm is about 30-40 percent as efficient as modern methods, such as Sequential Quadratic Programming (SQP) contained in the Design Optimization Tools optimizer[5] from VR&D. In return, we now have the ability to solve nonlinear continuous optimization problems, which are orders of magnitude larger than before. Also, since this is applied to an approximate problem in GENESIS, the function and gradient computations are very cheap. Thus, the time spent in the optimization phase may grow from one-to-two percent to four-to-eight percent of the overall computational time, which is considered acceptable considering the increase in design capabilities.

Experience with this method has shown that it scales very well with increased problem size. That is, the number of analyses and gradient calculations is about constant, regardless of problem size.

After solving the continuous variable problem, we resume from this point with the addition of the following constraints:

$$P(X) = R\sum_{i=1}^{NDV} 0.5\left\{1 - \sin 2\pi\left[\frac{X_i - 0.25(X_i^L + 3X_i^U)}{X_i^U - X_i^L}\right]\right\} \tag{4}$$

Where X_i^L is the next lower discrete value and, X_i^U is the next larger discrete value of X_i. We now solve the augmented problem as follows:

Minimize

$$\Phi(X) = F(X) + R_p \sum_{j=1}^{M} r_p^j MAX[0, g_j(X)]^2$$

$$+R_D P(X) \tag{5}$$

Subject to;

$$X_i^L \le X_i \le X_i^U ; \quad \text{i=1, N} \tag{6}$$

The additional penalty terms attempt to drive X_i to a nearby discrete value while at the same time maintaining feasibility with respect to the general constraints. This method is very similar to that presented by Shin, Gürdal and Griffin[6].

This method creates a non-convex problem with many potential relative minima. Also, it is possible to be trapped in relative minima that are infeasible. Thus, heuristic techniques are being developed to insure a reliable solution to a “good, feasible” discrete solution.

Just as with the duality approach using convex approximations, there is no guarantee that this method will produce the theoretical optimum. However, experience has shown that it provides a discrete design, which is far superior to simply rounding the design variables to their nearest discrete value.

GENESIS New Data Statements

In order to perform the discrete variable optimization, GENESIS software should be able to handle discrete variables. A design variable statement (DVAR) in GENESIS will need to refer to discrete/integer variable sets. This has been implemented in GENESIS Version 7.0. The details of design variable DVAR, and discrete variable sets DVSET are available in Reference[3].

User Interface for Input Data

DVAR and DVSET specifications have been implemented in GENESIS software. The implementation of DVAR and DVSET statements in GENESIS-SDRC/I-DEAS is complete. This process of creating DVAR and DVSET data is explained in detail in Reference[3].

Development and Testing of the Prototype Code, BIGDOT

A new code has been developed using the Exterior Penalty Function Method and including the discrete variable capability. The code is named BIGDOT, and this release has been incorporated into the GENESIS structural analysis/optimization program[3].

CASE STUDIES

1. Cantilevered Beam

Testing of discrete variable optimization has been performed using the cantilevered beam shown in Figure 1. The design variables are the height and width of each segment and the objective is to minimize the volume of material. Constraints include stress limits at the left end of each segment, and height to width limits. The discrete values of the variables were chosen to be increments of 0.1. Even though the analysis is very simple, computational times are high for large numbers of variables. This is due to the cost of calculating finite difference gradients. This has been improved by adding analytic gradient calculations to the test code for stress constraints, allowing us to test larger problems quickly.

Table 1 presents results using the current algorithm. Here, only stress constraints are considered to see if we can achieve a fully constrained design. If the beam is continuous, the theoretical optimum is known to be 53,714 when no side constraints are imposed.

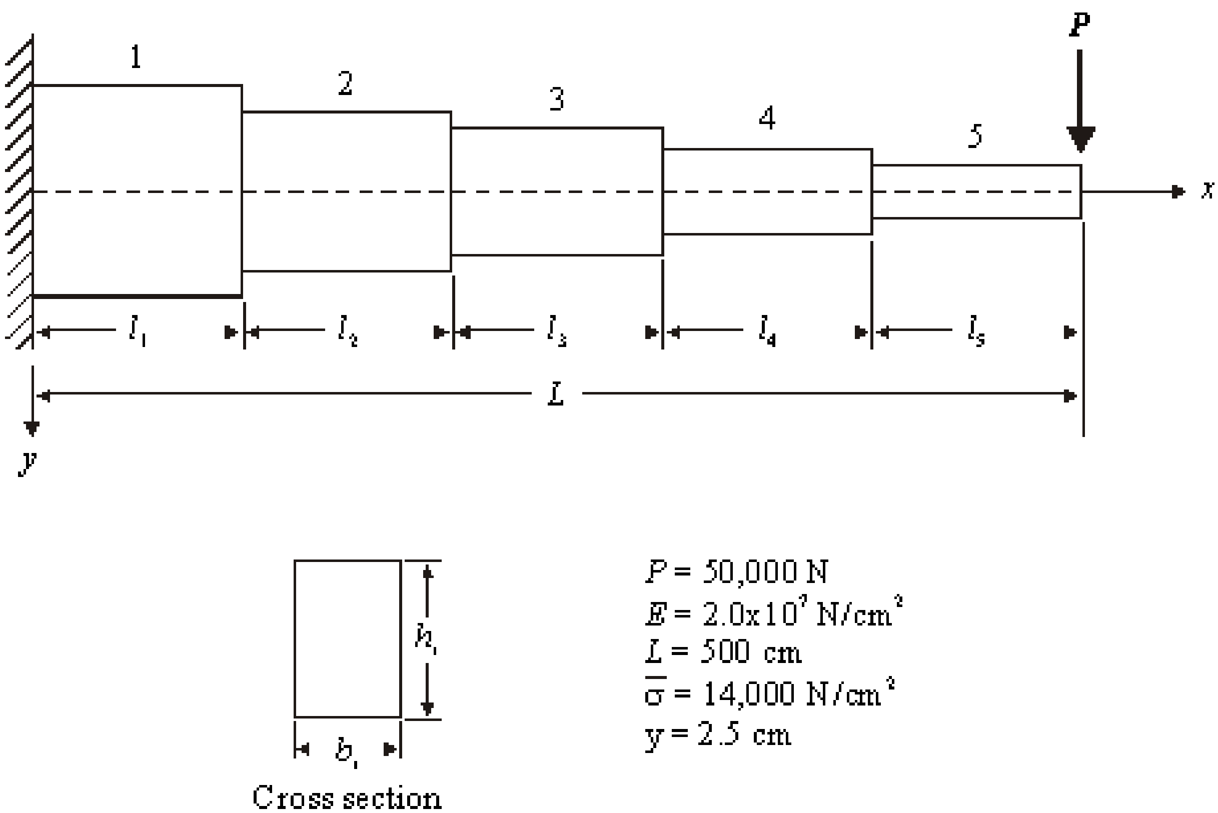

Figure 1: Cantilevered Beam

Table 1. Objective function and efficiency

	Number of Design Variables, NDV			
	1,000	10,000	25,000	50,000
CONTINUOUS OPTIMUM	53,827 (235/44) [1,000/0]	53,740 (239/45) [9,995/12]	53,728 (249/47) [24,986/30]	53,744 (243/46) [49,979/46]
DISCRETE OPTIMUM QUADRATIC	54,932 (107/20)	54,854 (86/16)	54,856 (72/13)	54,864 (92/38)

The initial design and all control parameters are the same for each case. In each case, the optimum objective function is listed along with the number of function and gradient evaluations (*/*). For the continuous optimum, the number of active constraints and the number of active side constraints are also listed [*/*]. For the discrete optimum, the number of function and gradient evaluations is the <u>additional</u> number after the continuous solution has been found. For the continuous optimization, we were able to achieve the fully constrained design as expected. Actually, the optimum appears to be over constrained when we include side constraints. This is because the active constraint count includes constraints that are within a tolerance of 0.05.

These results indicate that this algorithm provides a very good discrete solution with minimal effort.

<u>2. GENESIS Test Problem D027</u>

The simple cantilevered box beam shown in Figure 2 is very similar to a standard GENESIS test problem, D027[3]. This is a composite structure with 32 element thickness design variables. When solving the discrete problem, thicknesses were limited to increments of 0.005 to model the thickness of a single ply. Table 2 gives the results obtained using the standard DOT optimizer and the BIGDOT code.

Note that BIGDOT achieves a significantly better continuous optimum than did Design Optimization Tools. This is because this example is rather poorly conditioned, and is a known problem for Design Optimization Tools. The SUMT method in BIGDOT deals much better with problems like this where the design is not very sensitive to some variables unless they change significantly. The discrete solution found by BIGDOT appears quite good.

Note a very significant result. The design variable values for the discrete optimum are generally more than one discrete move from the continuous optimum. This is because, even though we move only plus or minus one step, the optimization problem is repeatedly solved by GENESIS. <u>This allows us to find a discrete solution that is many discrete steps from the continuous solution</u>.

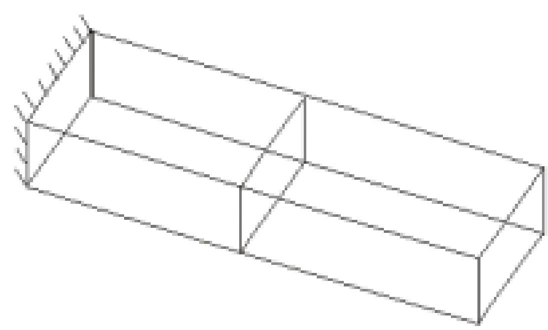

Figure 2: Box Beam

Table 2: Comparison of Results for box beam problem

	DOT	BIGDOT	
Design Variable	**Continuous Optimum**	**Continuous Optimum**	**Discrete Optimum**
1	1.79854E-01	1.88818E-01	1.90000E-01
2	7.25000E-03	1.00000E-03	1.00000E-03
3	1.01000E-03	1.00000E-03	1.00000E-03
4	1.42040E-03	1.13056E-02	1.50000E-02
5	1.00000E-03	5.47753E-03	1.00000E-03
6	1.00000E-03	1.00000E-03	1.00000E-03
7	1.00000E-03	1.00000E-03	1.00000E-03
8	3.58907E-01	3.54049E-01	3.50000E-01
9	1.26298E-01	1.31547E-01	1.35000E-01
10	1.01000E-03	1.00000E-03	1.00000E-03
11	1.01000E-03	1.00000E-03	1.00000E-03
12	4.61865E-02	2.87523E-02	2.50000E-02
13	1.76788E-02	2.08478E-02	3.50000E-02
14	1.11683E-03	1.00000E-03	1.00000E-03
15	1.10489E-03	1.00000E-03	1.00000E-03
16	2.67960E-01	2.65266E-01	2.65000E-01
17	5.09464E-02	4.21460E-02	4.50000E-02
18	1.20709E-02	1.00000E-03	1.00000E-03
19	1.32972E-02	1.00000E-03	1.00000E-03
20	1.34187E-02	6.66570E-03	1.00000E-02
21	1.72217E-02	3.40934E-02	5.00000E-03
22	1.00000E-03	1.00000E-03	1.00000E-03
23	1.00000E-03	1.00000E-03	1.00000E-03
24	1.26950E-01	1.28695E-01	1.35000E-01
25	1.69141E-02	2.03165E-02	3.50000E-02
26	1.28928E-02	3.61878E-03	3.00000E-02
27	1.78023E-02	3.72550E-03	3.00000E-02
28	3.27823E-02	1.27798E-02	3.50000E-02
29	6.48352E-03	1.91732E-02	2.50000E-02
30	2.79124E-02	1.07761E-02	5.00000E-03
31	3.43622E-02	6.22175E-03	1.00000E-03
32	1.00918E-02	7.95211E-03	2.00000E-02
Objective	6.50679E+02	6.28556E+02	6.51000E+02
Max g	3.82083E-05	9.50381E-05	-3.61190E-03

3. Composite lay-up optimization

The optimization of composite structures presents a formidable challenge, because it requires the solution of combinatorial optimization problems associated with obtaining the best lay-up sequence for composite laminates[7]. The composite laminate design process typically involves optimization of following four parameters:

1. Ply (or lamina) material,
2. Ply thickness,
3. Ply orientation, and
4. Stacking (or lay-up) sequence.

The optimization of ply material is, perhaps, the most complex of all because of the inherent possibility of designing a hybrid laminate consisting of two or more material types. Recent work by Grosset[8], et. al.

attempts to address the issue of multi-material optimization of hybrid composite laminates.
Numerous analytical techniques are available to optimize the ply thickness and orientation of a composite laminate. While the majority of the commercially available structural optimization codes treat ply thickness and orientation as continuous design variables, GENESIS 7.0[3] has been recently enhanced to specify them as discrete design variables during the laminate design process.

The ply orientation optimization of a typical unitized-body automotive, all composite, floor-pan structure is presented here utilizing the discrete variable optimization capabilities of GENESIS. This is, perhaps, the first time that a large all-composite primary load carrying structure has been designed/optimized for discrete ply-orientations using commercially available general-purpose optimization software. A recently developed GENESIS/I-DEAS interface was used to create the input data for the discrete lay-up optimization analysis. For the purposes of demonstration, the floor-pan structure has been divided into six zones, namely Z-1 to Z-6 having variable thickness. A unidirectional carbon/epoxy prepreg material system is chosen to optimize the lay-up of the structure. The overall design problem is to find the RIGHT ply-orientations, using the unidirectional carbon/epoxy prepreg material, for the six zones, Z-1 to Z-6, of the floor-pan structure while MEETING or EXCEEDING the bending stiffness target of 960N/mm.

In order to benchmark the *new* discrete design variable optimization capabilities of GENESIS to perform discrete composite structure optimization, various design iterations are performed by (i) starting with two different lay-ups for the six zones, (ii) using two different step-sizes for the discrete ply-orientation variable, and (iii) varying discrete DOPT parameters such as DSTART, DDELA, etc. The results from the THREE BEST lay-up designs for the six zones as obtained from the discrete optimization process, and of a starting design using an all quasi-isotropic lay-up, are presented in Table 3.

Table 3: Lay-up optimization of six zones of the floor-pan to achieve bending stiffness target.

ZONE	DESIGN-1	DESIGN-2	DESIGN-3	DESIGN-4
Z-1	$[0_2/90_2/\pm 45]_s$	$[0_2/\pm 45/\pm 60]_s$	$[\pm 45/\pm 60/0_2]_s$	$[\pm 10/\pm 70/\pm 35]_s$
Z-2	$[0/90/\pm 45]_{2s}$	$[\pm 30/90_2/\pm 15/0_2]_s$	$[\pm 15/\pm 60/0_4]_s$	$[\pm 20/\pm 60/0_4]_s$
Z-3	$[0/90/\pm 45]_{2s}$	$[\pm 15/\pm 60/\pm 15_2]_s$	$[\pm 30/\pm 45/0_4]_s$	$[\pm 25/\pm 55/0_4]_s$
Z-4	$[0_2/90_2/\pm 45]_s$	$[\pm 15/\pm 90/\pm 15]_s$	$[\pm 60/0_4]_s$	$[\pm 60/0_4]_s$
Z-5	$[0/90/\pm 45]_{2s}$	$[\pm 45/90_2/0_4]_s$	$[\pm 75/\pm 30/0_4]_s$	$[\pm 50/\pm 65/0_4]_s$
Z-6	$[0_2/90_2/\pm 45]_s$	$[\pm 30/90_2/\pm 60]_s$	$[\pm 30/90_2/\pm 15]_s$	$[0_2/\pm 70/\pm 65]_s$
Bending Stiffness, N/mm	*831*	*949*	**968**	**968**
Number of Cycles	-	10	17	15
Remarks	(i) Starting lay-ups for DESIGN-2.	(i) Starting lay-ups same as in DESIGN-1. (ii) 15 degree step-size (iii) DSTART = 10: Force the discrete optimization cycle to start from the 10th cycle.	(i) Starting lay-ups $[\pm 1]_{6s}$ or $[\pm 1]_{8s}$ (ii) 15 degree step-size (iii) DSTART = -1: Start of discrete optimization cycles determined by the software.	(i) Starting lay-ups $[\pm 1]_{6s}$ or $[\pm 1]_{8s}$ (ii) 5 degree step-size (iii) DSTART = 0: Start the discrete optimization cycles from the beginning

The results presented in Table 3 show that multiple feasible designs are possible in a composite material optimization process. These results also CLEARLY demonstrate the strong influence of ply orientations on the mechanical response of a large automotive composite structure. An approximately 17 percent increase in bending stiffness is achieved when using optimized lay-ups as given in DESIGNS-3 and 4, rather than using the quasi-isotropic lay-ups of unidirectional prepregs in DESIGN-1. Note that in composite material applications across various industries, it is common to use quasi-isotropic lay-up laminates of unidirectional or woven composite prepreg material systems as an initial estimate. It may be of interest to note that the bending stiffness target is off by approximately 27 percent when all carbon/epoxy material plies in the six zones are oriented at 0 degrees, and by approximately 62 percent when all those plies are oriented at 90 degrees. Thus, as expected, the ply orientations significantly influence the mechanical response of multi-layered composite structures.

CONCLUSION

A new approach to solve large-scale discrete variable optimization problems is presented. The discrete variable optimization algorithm in GENESIS® is based on SUMT using Lagrange multipliers, which allows one to solve very large optimization problems with discrete design variables using limited memory. New set of data statements such as DVSET, DVSET1 are introduced, and DVAR, DVPROP4 have been modified to support the new features. Several new DOPT parameters such as DSTART, DISCRETE, DVINIT2, DDELL, DDLMIN, DDELA, DDAMIN, PENLTD, and PMULTD have been introduced to tune the discrete optimization process for the problem in hand.

A GENESIS/I-DEAS interface tool has been created to fully support the data I/O for discrete ply orientation and thickness optimization for composite structures. This CAE tool completely supports the creation of DVAR, DVSET, DVPROPi (layer angle and thickness), DRESP, DOBJ entries, and new DOPT parameters through user-friendly GUIs. For composite structure optimization, there are options to export only PCOMP and DESIGN data for very large problems such as the one under study. Currently, the work is in progress to develop the post-processing capability to visualize optimum laminate designs, ply stresses/strains and ply failure indices in I-DEAS using the results written in .PST file by GENESIS. Furthermore, a new computationally efficient approach has also been developed to perform laminate stacking sequence optimization for large composite structures using the current optimization capabilities of the GENESIS program[9].

ACKNOWLEDGMENT

The work described herein was partly supported by Visteon Corporation.

REFERENCES

1. Fleury, C. and Braibant, V., “Structural Optimization: A New Dual Method using Mixed Variables,” Int. J. of Numerical Methods in Engineering, Vol. 23, No. 3, 1986, pp. 409-429.
2. Vanderplaats, G. N., “Very Large Scale Optimization,” Proc. 7th AIAA/USAF/NASA/ISSMO Multidisciplinary Analysis and Optimization Conference, Long Beach, CA, Sept. 2000, (AIAA Paper No. 2000-4809).
3. GENESIS V 7.0 Reference Manual, Vanderplaats Research & Development, Inc., Colorado Springs, Colorado, 2001.
4. Fletcher, R. and Reeves, C. M., “Function Minimization by Conjugate Gradients,” Br. Computer J., vol. 7, no. 2, 1964, pp. 149-154.
5. DOT Design Optimization Tools, V 5.1 User’s Manual, Vanderplaats Research & Development, Inc., Colorado Springs, CO, 2001.
6. Shin, D. K., Gürdal, Z. and Griffin, O. H., Jr., “A Penalty Approach for Nonlinear Optimization with Discrete Design Variables,” Eng. Opt., 1990, vol. 16, pp. 29-42.
7. Gurdal, Z., Haftka, R, T. and Hajela, P., Design and Optimization of Laminated Composite Materials, Wiley, 1999.
8. Grosset, K., Venkataraman, S., and Haftka, R. T., "Genetic Optimization of Two-material Composite Laminates", Proc. of the American Society of Composites: Sixteenth Technical Conference, Blacksburg, VA, September 10-12, 2001.
9. Leiva, J. P., Ghosh, D. K., and Rastogi, N., “A New Approach in Stacking Sequence Optimization of Composite Laminates using GENESIS Structural Analysis and Optimization Software”, Proc. of 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, September 4-6, 2002 Atlanta, Georgia, AIAA-2002-5451.