SHAPE OPTIMIZATION IN THE *GENESIS* PROGRAM

Juan Pablo Leiva and Brian C. Watson
VMA Engineering

1. Abstract

While structural shape optimization has reached a relatively mature state, today the challenge is to develop and implement capabilities to enable engineers to solve very complex problems in an industrial environment. In this paper, some of the capabilities included in the GENESIS program to address these needs are discussed, namely: automatic generation of basis vectors; geometric responses; mesh smoothing; element distortion checking; mode tracking; and pre/post-processing capabilities. This work also briefly discusses the analysis capabilities and the type of responses available in the GENESIS program for shape optimization.

2. Keywords

Optimization, Design, Finite Elements, Shape, Structures, GENESIS

3. Introduction

Structural shape optimization has reached a relatively mature state. An optimal solution can typically be found in ten or fewer full-system analyses for almost any type of structural problem with almost any kind of structural response. This has become possible due to the approximation concepts introduced in the seventies by Schmit and co-workers [1,2] and enhancements to response approximations in the eighties [3,4]. High quality approximations are now able to capture the important physics of the structural optimization problem, substantially reducing the cost of performing multiple finite element analyses. Advances in the computer industry have also made possible the solution of very large problems, consisting of hundred of thousands degrees of freedoms with thousands design variables and millions constraints.

The first version of the GENESIS program [5], released in early 1992, included shape optimization capabilities. These capabilities, based on the basis vector approach, addressed the basic need of the designer to perform shape optimization. However, these capabilities alone did not satisfied the mainstream engineer that did not have the time or the expertise to manually generate the basis vectors and/or re-mesh problems when the mesh became too distorted. In subsequent releases, capabilities were added to automatically smooth the mesh (1995) and to simplify the creation of basis vectors (1996). In shape optimization, engineers may also need responses other than structural responses. In response to this need, geometric responses were added to GENESIS (1996-1998). Geometric responses allow quantities such as the interior volume of a fuel tank model to be used in an optimization problem. When significant changes in shape are obtained during shape optimization, many problems can arise. For example, the frequencies associated with natural vibration modes can switch order, so that a constraint put on a particular mode ends up constraining another. In response to that problem, mode tracking was added to GENESIS (1996). GENESIS also includes capabilities for sizing (property value) and topology (material distribution) optimization. Sizing optimization can be performed simultaneously with shape optimization.

4. Basis Vector Concept

Basis vectors are candidate designs or alternative locations of grids. In the basis vector approach to shape optimization, the total change of the grids' locations is calculated as a linear combination of perturbation vectors, each weighted with its respective design variable. A *perturbation vector* is simply the vectorial difference of a basis vectors and the original locations of grids. Figure 1 shows an example of a basis vector.

Figure 2 shows how different values of a design variable affect the final location of the grids. It can be seen that a value of zero causes the grids to remain at the initial locations, and a unit value of the design variable causes the grids to move to the basis vector. Values larger than one or smaller than zero produce a shape than is an extrapolation of the original shape and the basis vector. Values between zero and one produce a shape that corresponds to an interpolation between the original shape and the basis vector.

The problem to the user is that the creation of basis vectors can be very time consuming. To solve this problem, some facility must exist to help automate the generation of basis (or equivalently, perturbation) vectors. The next section explains the methods available in GENESIS for that task.

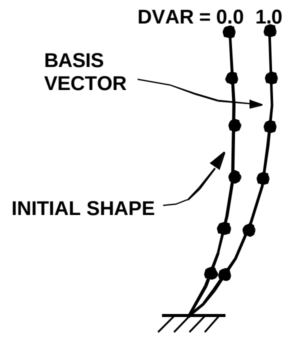


Figure 1. Basis vector example.

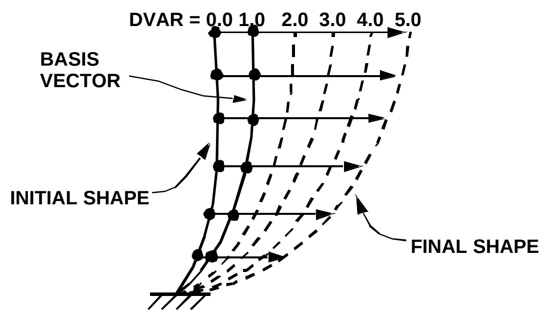


Figure 2. Possible shape changes with an example basis vector.

5. Automatic Generation of Basis Vectors

GENESIS has two methods available to automatically generate basis vectors. The first method is commonly known as the *natural basis vector method*. The second method is the *domain method*.

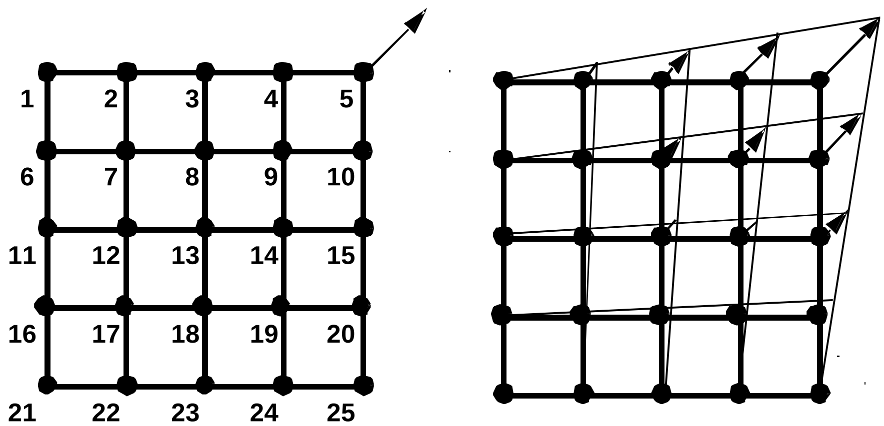
Natural Basis Vector Method

Natural basis vectors are created by adding displacements to the grid locations [5,6,7]. The displacements are created by special load cases that are created by the user to generate the patterns of the basis vector. Normally the user will use static loads and special boundary conditions to limit the scope of the basis vector to a certain region. The advantage of this method is that is easy to use and quick to generate the necessary input data. The disadvantages of this method are that the user does not have complete control on where interior grids will move and that this method is computationally expensive.

Domain Method

The domain method consists in adding non-structural regions to the model termed DOMAINS [5,8,9]. The DOMAIN typically resembles a finite element but they are usually larger and contain many internal grids. The user then perturbs the corner and/or mid-sides nodes of the DOMAINS with perturbation vectors. The program then perturbs all interior nodes using interpolation shape functions. The advantage of this method is that is easy to use and that the user has complete control on where interior grids will move.

This method is computationally cheap because it does not require solving a system of equations. In GENESIS, ten DOMAIN elements have been implemented to facilitate the creation basis vectors for 1D, 2D, 3D and axisymmetric structures. See reference [9] for details on nine of the ten DOMAIN elements currently implemented in GENESIS. Figure 3 show a QUAD4 DOMAIN and an automatically created perturbation vector.



(a) Input Data

(b) Perturbation Automatically Generated with QUAD4 DOMAIN 21-25-5-1

Figure 3. QUAD4 DOMAIN example.

6. Input Data Checking And Mesh Checking

In an industrial environment, it is essential that engineers be sure that the input data to their optimization program is correct, before spending possibly many hours or days of CPU time. Although is clearly impossible for a program to verify every single aspect of the input data, a lot can be done to verify many different aspects. GENESIS addresses this need by performing nearly three thousands checks. Every field in the input data is checked to see if the data is the right type. Every relationship in the file is checked. For example, a CBEAM element can only reference a PBEAM property. PBEAM properties can only reference MAT1 material properties. The connectivity of the element should be correct. The elements should not be distorted. Nearly all of the checks GENESIS performs are done at reading and preprocessing time. This allows the user to fix their input data before any analysis or optimization run is performed. That helps the user to avoid wasting valuable engineering time. GENESIS checks not only the input data. The changes produced by optimization are also checked since they could be substantial. For example, before performing the finite element analysis for each design cycle, the mesh is checked and if necessary, possibly fixed. The procedure to fix the mesh consists of moving internal grids to minimize distortion. This procedure is called *mesh smoothing* and is explained next.

7. Mesh Smoothing

Mesh smoothing consists in changing the interior grids of a structure so that the distortions in the mesh are minimized [10]. This procedure is critical because allows for larger changes in the design variable to produce large shape changes. Also, this procedure is critical to maintain the quality of finite element results. In general a distorted element produces stiffer results than it should. Therefore the predicted results are not only unreliable but also on the non-conservative side.

In GENESIS, smoothing is performed on solid and/or planar shell elements. To avoid mixing material, property boundaries are not smoothed. It is interesting to note that mesh smoothing allows performing shape optimization by perturbing only boundary grids.
Figure 4 shows mesh smoothing in action. The left mesh can be seen to be distorted, while the right mesh has been fixed using mesh smoothing.

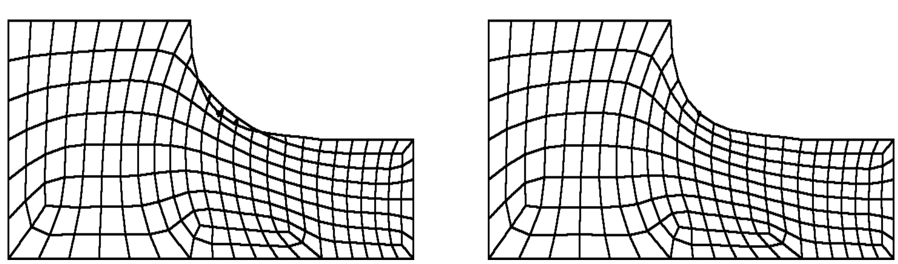


Figure 4. Example of mesh smoothing.

8. Geometric Responses

Geometric responses are responses that are only functions of the grid locations. If the grid locations change, these quantities change. In GENESIS, the following geometric responses are available to be used in optimization: location of center of mass; moments of inertia, angle; length; area; volume; point to plane distance; and point to line distance. Figure 5 illustrates some of these responses.

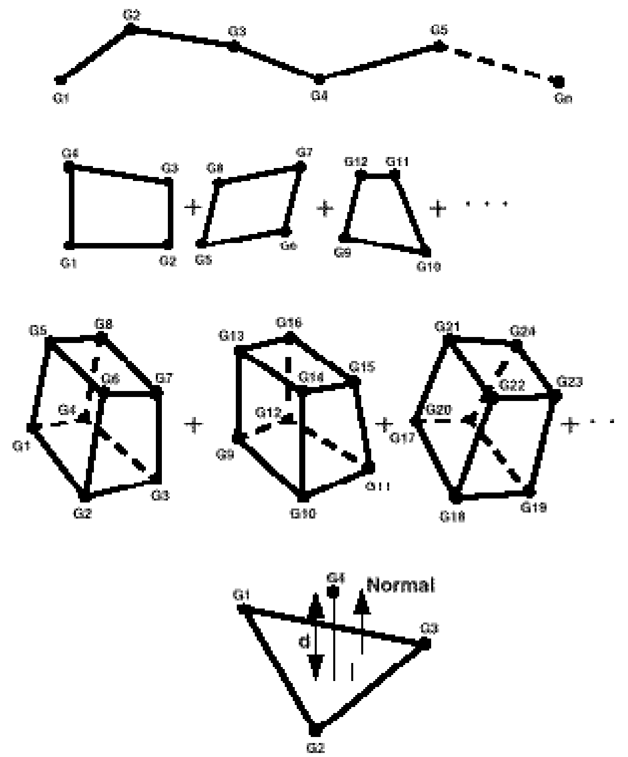


Figure 5. Geometric responses.

These responses can be used to solve tasks such as:

1) Maximize the interior volume of a fuel tank while keeping the structural mass low to save material.
2) Impose packaging constraints.
3) Avoid mesh distortion. For example, point to plane distances can be used to impose pass through constraints.

9. Mode Tracking

Due to shape optimization, the grids of the structure shift locations. This can cause the order of the natural vibration mode shapes to change. For example, in the initial configuration, the first bending mode of a structure could be 27 Hz and the first torsional mode could be 31 Hz. After the design is modified, the first bending mode could be 36 Hz and the first torsional mode could be 34 Hz. Without mode tracking a constraint originally placed on the bending mode would end up constraining the torsional mode. The mode tracking capability will reorder the modes so that the mode shapes match those of the original ordering as closely as possible. This allows constraints to be placed on specific modes, rather than just on the lowest mode.

10. Analysis Capabilities Available For Shape Optimization

All analysis capabilities available in GENESIS can be used in shape optimization. These capabilities include: static; inertia relief; natural frequency; heat transfer; and dynamic frequency response. In addition, all elements in the finite element library of GENESIS are accounted for in shape optimization problems, including rigid and interpolation elements. This leads to reliable approximation problems.

11. Responses Available For Shape Optimization

Beside the geometric responses already mentioned above, there are four other types of responses available in GENESIS. If necessary, all these responses can be used simultaneously.

Finite Element Responses:

Almost every finite element response calculated for analysis can be used in optimization. These responses are: displacement; stress; strain; force; strain energy; natural vibration frequency; natural mode shape components; and temperature.

Equation Responses:

The user can specify nonlinear equations mixing finite element responses with design variables, grid locations and geometric responses to create responses.

Suroutine Responses:

User-written subroutines can be linked with GENESIS to mix finite element responses with design variables, grid locations and geometric responses to create responses.

Program Responses:

A user-written subroutine can be used to link GENESIS with other commercial programs.

12. Pre- And Post-Processors

The creation of data and the visualization of analysis and optimization results are undoubtedly fundamental capabilities needed in today's industrial environment. Most pre- and post-processing programs can create analysis data and display analysis results. However, few programs are available for creating optimization data and visualizing optimization results. To respond to this need, VMA Engineering has added optimization pre- and post- capabilities to the FEMB [11] program developed by Engineering Technology Associates, Inc. This product is commercialized under the name of Femb/Genesis [12]. This product allows an engineer to: create design optimization data; animate basis vectors; and animate shapes changes. In Japan, the CADAS program developed by Hitachi offers similar capabilities for GENESIS. Vanderplaats Research and Development is currently developing an interface to MSC/PATRAN [13] that also has similar capabilities.

13. Answers to 5 Questions

I) What is the State of the Art in Shape Optimization?

The GENESIS program contains state of the art shape optimization capabilities and this paper answer most of this question. Next a brief summary is presented.

- Full use of second generation approximations
- Complete integration between finite elements and optimization
- Integrate user responses, geometric responses and finite elements responses
- Mesh smoothing

In post processing, the following list summarize important capabilities that a state of the art program should contain:

- Shape optimization animation capabilities
- Objective function vs. design cycles graphs
- Maximum violations constraints vs. design cycle graphs
- Design variable vs. design cycles graphs

II) What are the Road Blocks?

- Education at university level is not generalized
- Training in companies is not generalized
- Software is not always available

III) What are the Research needs to promote the use of Shape Optimization?

To further enhance GENESIS for industrial use of shape optimization, the following challenges must be pursued:

- Provide a close coupling between GENESIS and CAD modeling programs
- Provide a close coupling between GENESIS and other existing analysis programs
- Integrate shape/sizing and topology optimization
- Improve mesh smoothing capabilities to work with nonplanar shell structures

It is interesting to note that the GENESIS program is now being used in several industries, however, most of the users are in the automotive or aerospace industries. Examples of the use of GENESIS for industrial applications can be found in references [14,15,16].

IV) What elements of design theory are needed to support distributed design?

Effective distributed design relies upon the partitioning of the design problem. Efficient methods to partition problems (both in the design space and in the analysis space) need to be developed. Communication strategies need to be developed to allow different engineers to work on different subproblems.

V) What new analysis and optimization methods are needed to exploit massively parallel processing?

The biggest drawback to the use of massively parallel processing in traditional analysis and optimization is the communication requirements. Typically, there is one problem, and one result (either analysis or design) is required. This requires communication both to spread the problem out, and to collect and collate the results (as well as any communication required by the solution algorithm itself). This one problem/one result concept typically rules out efficient use of *massive* numbers of processors. Methods that will efficiently exploit massively parallel processing need to move away from solving a single problem to solving families of problems. Then, data and visualization procedures (using a distributed database) should be used to interpret the results and create the final engineering design.

14. Conclusions

The GENESIS program has capabilities to enable engineers to solve very complex problems in an industrial environment. Among those capabilities, automatic generation of basis vectors, geometric responses, mesh smoothing, element distortion checking, mode tracking, and pre/post-processing have been described.

15. References

1) Schmit, L. A. and Farshi, B., "Some Approximation Concepts for Structural Synthesis," AIAA J., Vol. 12(5), pp. 692-699, 1974.

2) Schmit, L. A. and Miura, H., "Approximation Concepts for Efficient Structural Synthesis," NASA CR-2552, 1976.

3) Vanderplaats, G.N. and Salajegheh, E., "A New Approximation Method for Stress Constraints in Structural Synthesis," AIAA J., Vol. 27, No. 3, pp. 352-358, 1989.

4) Canfield, R. A., "High-Quality Approximations of Eigenvalues in Structural Optimization of Trusses," AIAA J., Vol. 28, No. 6, pp. 1116-1122, 1990.

5) *GENESIS* Structural Optimization Software, Version 5.0. User's Manual. VMA Engineering, Colorado Springs, CO, USA, November 1998.

6) Kodiyalam, S., Vanderplaats G.N. and Miura, H., "Structural Shape Optimization with MSC/NASTRAN", AIAA/ASME/ASCE/AHS 31St Structures, Structural Dynamics, and Materials Conference, Long Beach, CA, pp. 150-160, April 1-4, 1990.

7) Zhang, J., "Modified Thermal Load Approach for Automatic Generation of Basis Vectors in Shape Optimization", 5th AIAA/USAF/NASA/ISSMO Symposium On Multidisciplinary Analysis and Optimization, pp. 384-390, 1994.

8) AUTODV, A Fortran77 Code for Generating Basis Vectors for Shape Optimization, Altair Engineering, Inc. pp. 1-17, 1994.

9) Leiva, J.P., Watson, B.C., "Automatic Generation of Basis Vectors for Shape Optimization in the Genesis Program," 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, Missouri, pp. 1115-1122, Sep 2-4, 1998.

10) Hwang, Y.T. and Fleury, C., "Finite Element Grid Optimization with Geometric Approach," AIAA/ASME/ASCE/AHS 33rd Structures, Structural Dynamics, and Materials Conference, Dallas, TX, pp. 2708-2716, April 13-15, 1992.

11) FEMB, Version 26.5. User's Manual. Engineering Technology Associates, Inc., Madison Heights, MI, USA, 1996.

12) Femb/Genesis, Version 2.0. User's Manual. VMA Engineering, Colorado Springs, CO, USA, August 1997.

13) GENESIS/PATRAN Interface, Version 1.0. User's Manual. Vanderplaats Research and Development, Colorado Springs, CO, USA, January 1999.

14) Thanedar, P.B., Sankaranarayanan, S. and Chirehdast, M., "Topology & Shape Design Optimization," AMD-Vol. 227. Design Optimization with Applications in Industry. ASME, pp. 163-174, 1997.

15) Chen, C.J., Maire, S. and Usman, M., "Improved Fuel Tank Design Using Optimization," AMD-Vol. 227. Design Optimization with Applications in Industry. ASME, pp. 177-188, 1997.

16) White, J.A. Jr. and Webb, J.C., "Air Cleaner Shell Noise Reduction with Finite Element Shape Optimization," Proceedings of the Society of Automotive Engineers Noise and Vibration Conference and Exposition. Detroit, MI, USA, 1997,