FINAL REPORT
NASA COOPERATIVE AGREEMENT NCC-1-268
March 2000

Mehmet A. Akgün   Raphael T. Haftka
Department of Aerospace Engineering, Mechanics and Engineering Science
University of Florida, Gainesville, FL 32611-6250

Overview

The objective of this cooperative agreement was to seek computationallly efficient ways to optimize aerospace structures subject to damage tolerance criteria. Optimization was to involve sizing as well as topology optimization. The work was done in collaboration with Steve Scotti, Chauncey Wu and Joanne Walsh at the NASA Langley Research Center.

Computation of constraint sensitivity is normally the most time-consuming step of an optimization procedure. The cooperative work first focused on this issue and implemented the adjoint method of sensitivity computation (Haftka and Gürdal, 1992) in an optimization code (runstream) written in Engineering Analysis Language (EAL). The method was implemented both for bar and plate elements including buckling sensitivity for the latter. Lumping of constraints was investigated as a means to reduce the computational cost. Adjoint sensitivity computation was developed and implemented for lumped stress and buckling constraints. Cost of the direct method and the adjoint method was compared for various structures with and without lumping. The results were reported in two papers (Akgün et al., 1998a and 1999).

It is desirable to optimize topology of an aerospace structure subject to a large number of damage scenarios so that a damage tolerant structure is obtained. Including damage scenarios in the design procedure is critical in order to avoid large mass penalties at later stages (Haftka et al., 1983). A common method for topology optimization is that of compliance minimization (Bendsoe, 1995) which has not been used for damage tolerant design. In the present work, topology optimization is treated as a conventional problem aiming to minimize the weight subject to stress constraints. Multiple damage configurations (scenarios) are considered. Each configuration has its own structural stiffness matrix and, normally, requires factoring of the matrix and solution of the system of equations. Damage that is expected to be tolerated is local and represents a small change in the stiffness matrix compared to the baseline (undamaged) structure. The exact solution to a slightly modified set of equations can be obtained from the baseline solution economically without actually solving the modified system.. Sherman-Morrison-Woodbury (SMW) formulas are matrix update formulas that allow this (Akgün et al., 1998b). SMW formulas were therefore used here to compute adjoint displacements for sensitivity computation and structural displacements in damaged configurations.

Results

A simple high-speed civil transport aircraft and various truss structures were investigated as examples. A large example used to demonstrate the efficiency of the adjoint method was a half-symmetric model of an entire high-speed transport aircraft. Scotti originally presented this model (Scotti, 1995). Runs were performed at NASA Langley Research Center. For timing purposes, the model was run for four optimization cycles using both the adjoint and direct methods. For each method, analyses were performed with 1, 7, 14, and 21 load cases. Figure 1 shows plots of the actual CPU time required to complete each of the four optimization cycles for the different analysis methods and load case scenarios. The lines in the figure show the best-fit averages of the run times of the four cycles.
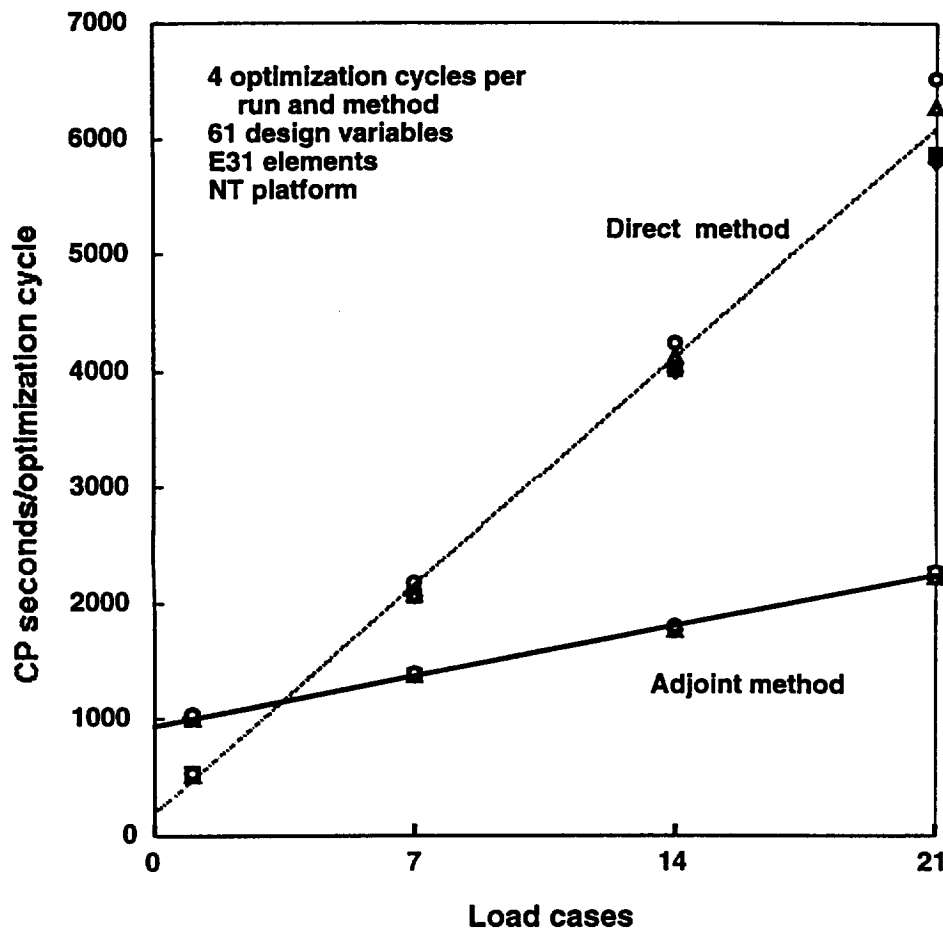
Figure 1. CPU timing as a function of the number of load cases for a large high-speed civil transport.

For a single load case, the direct method is twice as fast as the adjoint method. However, as the number of load cases increases, the adjoint method becomes more efficient. The efficiency of the adjoint method as the number of load cases increases is greater, and the break-even point appears to be around three or four load cases. For 21 load cases, the problem solution with the adjoint method requires only about one-third of the time required by the direct method.

Topology optimization subject to damage scenarios was investigated as a conventional optimization problem subject to stress constraints, starting with a highly redundant ground structure. Truss structures were employed as examples. It was shown that the cost of topology optimization as a conventional problem can be reduced significantly by using the Sherman-Morrison-Woodbury (SMW) formula that is a matrix update formula. Use of the SMW formula reduces the memory requirement as well. For small system sizes, the driving factor for the CPU time is the number of structural elements in the ground structure whereas for large problems both the system size and the number of structural elements are expected to be the driving factors. Use of the SMW formula is advantageous in both cases because it is used for both system solution and sensitivity computation. The SMW formula is more advantageous than the non-SMW approach for larg number of damage configurations. Figure 2 shows a comparison of the CPU times per cycle for the SMW and non-SMW methods for a 3x3 truss with 78 members. It may be desirable to optimize aerospace structures under hundreds of damage scenarios. The figure demonstrates the potential advantage of the SMW formula in suc a case.
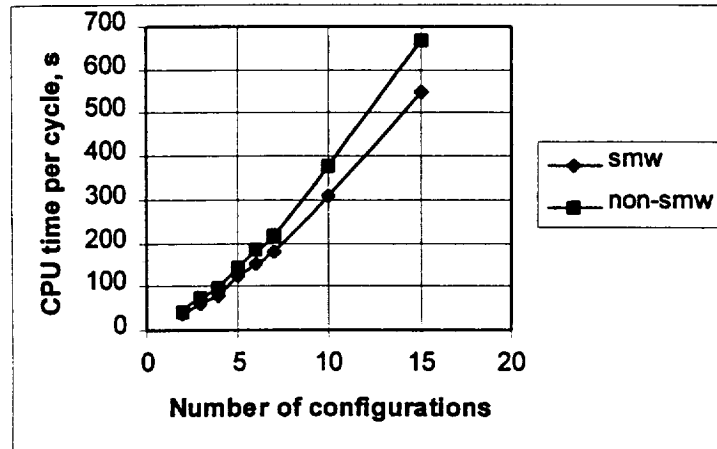
Figure 2. CPU times for a 3x3 truss as a function of the number of configurations in an optimization run.

References

Akgün, M. A., Haftka, R. T., and Garcelon, J., 1998a, "Sensitivity of Stress Constraints Using the Adjoint Method", AIAA Paper 98-1752, Proceedings of the 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 20-23, Proc. pp. 441-448.

Akgün, M. A., Garcelon, J., and Haftka, R. T., 1998b, "Fast Exact Linear Structural Analysis and the Sherman-Morrison-Woodbury Formulas", ISSMO/NASA/AIAA First Internet Conference on Approximation and Fast Reanalysis Techniques in Engineering Optimization June 14-27, to be published in Computer Methods in Applied Mechanics and Engineering.

Akgün, M. A., Haftka, R. T., Wu, K. C., and Walsh, J. L., 1999, "Sensitivity of Lumped Constraints Using the Adjoint Method", AIAA Paper 99-1314, Proceedings of the 40th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, St. Louis, MO, April 12-15, Proc. pp. 1003-1013.

Bendsøe, M. P., 1995, Optimization of Structural Topology, Shape, and Material, Springer.

Haftka, R. T., and Gürdal, Z., 1993, Elements of Structural Optimization, 3rd edition, Kluwer Academic Publishers.

Haftka, R. T., Starnes, J. H., and Nair, S., 1983, "Design for Global Damage Tolerance and Associated Mass Penalties", Journal of Aircraft, 20, 83-88.

Scotti, S. J., "Structural Design Using Equilibrium Programming Formulations", NASA TM-110175, 1995.