

SUMMARY OF RESEARCH REPORT

PROJECT TITLE: Sensor/Actuator Selection for Gust and Turbulence Control

PRINCIPAL Investigator: Rex K. Kincaid
College of William and Mary
Williamsburg, VA 23187

PROJECT PERIOD: 12/11/97-6/10/98 (includes no cost extension)

FUNDING SOURCE I.D.#: NAG-1-1783

From aircraft fuselages and space stations to vacuum cleaners and automobiles, active control of noise and/or vibration has come of age. Determining the number of active control devices (e.g. actuators) to be placed and where they are to be placed is the prototypical location problem. However, unlike typical location problems, where the customer is readily identified and is actively engaged in the assessment of the performance of the chosen locations, the customers that active control devices serve are not so easily identified and their impact on system performance issues may be unclear. For example, consider the problem of where to locate actuators to attenuate cabin noise in a propeller driven aircraft (c.f. Palumbo et al. 1996, Kincaid et al. 1997, Palumbo and Padula 1997, and Kincaid and Padula 1998). Clearly, the ultimate customers are the passengers who will travel in these aircraft. But to decide whether one set of actuator locations is better than another it is unlikely we will ask passengers to fly in the aircraft and fill out a questionnaire about noise levels. Instead a set of sensors (pseudo-customers) are placed and the system performance of the actuators, as measured by these sensors, is recorded. Hence, we have yet another location problem. How many sensors should there be and where should they be located? In many instances collocation of sensors and actuators is the answer but in other instances it is not.

A variety of approaches have been taken to address these sensor/actuator location problems. With regard to damping vibrations in truss structures (space station prototypes) Kincaid and Berger (1993) and Kincaid (1995) formulated a new noxious location problem and generated high-quality solutions with a combination of LP-relaxations and heuristic search procedures. Other related efforts are summarized in Padula and Kincaid (1995). In Kincaid et al. (1997) the actuator location problem for a single frequency interior noise control problem was examined for an idealized aircraft cabin. A tabu search procedure was shown to generate better locations for the actuators than a modal decomposition approach. Kincaid and Padula (1998) extended the model to include multi-frequency information. The sensor location problem is addressed in both Kincaid et al. (1997) and Kincaid and Laba (1998). In the latter article a reactive tabu search scheme was shown to dominate a static tabu search approach.

Our focus here is to determine locations to control and/or sense vibrations on a truss structure. However, instead of using one of the earlier optimization models referenced in the above paragraph we adopt an experimental design approach. Given a matrix with one

column for each mode to be identified (or sensed) and one row for each potential sensor location, we seek a submatrix of maximal determinant—a D-optimal design. Our interest in this experimental design approach comes largely from a series of papers by Kammer (1991,1992,1996). Kammer demonstrates that D-optimal designs are good solutions for sensor placement. Our purpose here is twofold—(1) to improve upon the solution approach given by Kammer and (2) to show how the performance of traditional experimental design algorithms (see Miller and Nguyen 1994 and Nguyen and Miller 1992) can be improved by incorporating the basic elements of tabu search (see Glover 1996 and Glover and Laguna 1998).

Table 1 below illustrates the improvement in the determinant value obtained with our tabu search code versus Kammer’s EFI approach and a multi-start scheme. The runtime for both approaches is small (a few seconds) and is not an issue for the truss described in Section 2. The multi-start scheme calls DOPT 100 times, each time with a different random number seed. The number of replications, 100, was selected so that the multi-start scheme would examine at least as many 2-exchanges as our tabu search. Why did we pick the test cases in Table 1? Our goal was to find a difficult set of test cases.

Our computational experience indicated that when the number of sensors to be located was equal to the number of modes to be identified (or controlled) that the resulting D-optimal design problem was more difficult. For the modes equal number of sensors type problems, the local optima appear to have a wider range of values and appear to lie in steeper valleys. Moreover, the static tabu list has great difficulty escaping the local optima in these cases. Consider a 13 mode 13 sensor example. Here the range of the log of the determinant values is 58.94 to 88.92. In addition, only one of the frequency-based restarts produced a local optima that was improved upon by the use of the static tabu list. Now consider a 13 mode 39 sensor example. The local optima are easier to escape and the values of the local optima appear more uniform. The range of the log determinant values for this example was 102.86 to 102.94. In 7 of the 10 restarts the tabu list was able to escape at least one local optima. As a side issue we note that only when the number of modes equals the number of sensors is the DOPT procedure unable to construct an initial set of rows for which $\bar{X}^t \bar{X}$ is nonsingular (only 6 of the 10 restarts were able to find nonsingular initial solutions in the 13 mode 13 sensor example). Hence, Table 1 records the outcomes of four problems in which the number of modes equals the number of sensors.

The multi-start scheme was able to find the same maximum determinant solution as tabu search in 2 out of the 4 test cases. In the 16 mode 16 sensor problem, however, even with 500 replications multi-start was unable to find the best solution generated by tabu search. In all four cases the Kammer EFI approach is dominated by both multi-start and tabu search.

modes	sensors	EFI Det	Multi-start	Tabu Det
10	10	1.885 E+28	2.312 E+28	2.312 E+28
13	13	3.023 E+38	4.158 E+38	5.561 E+38
16	16	5.896 E+48	6.853 E+48	6.975 E+48
20	20	1.589 E+62	1.956 E+62	1.956 E+62

Table 1. Best Determinants for EFI, Multi-start, and Tabu Search

The usefulness of the D-optimal design as a solution for the location of sensors (and actuators) may depend on the number of sensors to be located. The D-optimal design appears to be quite effective when the number of sensors (actuators) to be located is close to the number of modes to be identified (or controlled). When many more sensors (actuators) are available than there are modes the D-optimal design solution tends to cluster locations. Of course, part of the clustering effect is due to the compression of the x , y , and z configurations to a single node, but since we must physically attach sensors devices to the nodes the clustering in the compressed space is important.

The observed clustering effect caused by the D-optimal design solution may not be desirable. Future experiments are underway to test the effectiveness of the D-optimal design solutions for an actuator location problem on an aircraft wing. Here the actuators are to be placed to aid in the control of gust and turbulence. The wing has already been built and tested for other purposes. The wing model was first tested in a wind-tunnel to obtain basic flutter characteristics and transfer functions. McGowan et al. (1996) summarize the data produced from ground vibration tests and two wind-tunnel tests. Piezoelectric actuators covered approximately two-thirds of the internal composite plate in the wing. The model has a total of 72 actuators.

References

- Glover, F. (1996) "Tabu Search and Adaptive Memory Programming—Advances, Applications, and Challenges," to appear in Interfaces in Computer Science and Operations Research, Barr, Helgason and Kennington (eds.) Kluwer Academic Publishers.
- Glover, F. and M. Laguna Tabu Search, Kluwer Academic Publishers, Norwell, MA, 1998.
- Kammer, D.C. "Sensor Placement for on-orbit modal identification and correlation of large space structures," *J. of Guidance, Control and Dynamics*, **14** (1991) 251-259.
- Kammer, D.C. "Efficient sensor placement for on-orbit modal identification of sequentially assembled large space structures," *International J. of Analytical and Experimental Modal Analysis*, **7** (1992) 95-109.
- Kammer, D.C. "Optimal sensor placement for modal identification using system-realization methods," *J. Guidance, Control, and Dynamics*, **19** (1996) 729-731.
- Kincaid, R.K. and R.T. Berger, "The Damper Placement Problem on Space Truss Structures," *Location Science* **1** (1993) pp. 219-234.
- Kincaid, R.K. "Solving the Damper Placement Problem using Local Search Heuristics," special issue of *OR Spektrum on Applied Local Search*, **17** (1995) pp. 149-158.
- Kincaid, R.K., K.E. Laba, and S.L. Padula, "Quelling Cabin Noise in Turboprop Aircraft via Active Control," *J. of Combinatorial Optimization* **1**, Issue 3 (1997) 1-22.
- Kincaid, R.K. and K.E. Laba, "Reactive Tabu Search and Sensor Selection in Active Structural Acoustic Control Problems," (with K. Laba) *J. of Heuristics*, **4** (1998) pp. 199-220.
- Kincaid, R.K. and S.L. Padula, "Actuator Selection for the Control of Multi-Frequency Noise in Aircraft Interiors", (with S.L. Padula) in *Proceedings of the 2nd International Conference on Metaheuristics*, Sophia Antipolis, France, July 21-24, 1997, Kluwer, Chapter 31, pp. 457-470.
- Kubrusly, C.S. and H. Malebranche, "Sensors and controllers location in distributed systems—a survey," *Automatica*, **21** (1985) 117-128.
- McGowan, A-M.R., J. Heeg, and R. C. Lake (1996) "Results of Wind-Tunnel Testing from the Piezoelectric Aeroelastic Response Tailoring Investigation," presented at 37th AIAA Structures, Structural Dynamics, and Materials Conference, April (AIAA 96-1511).
- Miller, A.J. and N.-K. Nguyen, "Algorithm AS 295: A Fedorov Exchange Algorithm for D-optimal design," *Appl. Statist.*, **43** (1994) 669-678.
- Nguyen, N-K. and A.J. Miller, "A review of some exchange algorithms for constructing discrete D-optimal designs," *Computational Statistics and Data Analysis*, **14** (1992) 489-498.
- Padula, S.L. and R.K. Kincaid, "Aerospace Applications of Integer and Combinatorial Optimization," (with S.L. Padula) NASA Technical Memorandum 110210, 1995.
- Palumbo, D., S.L. Padula, K.H. Lyle, J.H. Cline, and R.H. Cabell (1996) "Performance of Optimized Actuator and Sensor Arrays in an Active Noise Control System," presented at 2nd AIAA/CEAS Conference, AIAA 96-1724.
- Palumbo, D. and S.L. Padula (1997) "Optimizing an Actuator Array for the Control of Multi-Frequency Noise in Aircraft Interiors," presented at 3rd AIAA/CEAS Aeroacoustics Conference, May (AIAA 97-1615).

Variable Complexity Optimization of Composite Structures

Final report for NASA Grant NAG 1-2000

Raphael T. Haftka, Principal Investigator
Department of Aerospace Engineering,
Mechanics & Engineering Science
University of Florida
Gainesville, FL 32611-6250
July 1999

This report summarizes the accomplishments and publications of the work done under NASA Grant NAG1-2000. It covers the period of 1/17/98 to 1/27/99

Introduction: The use of several levels of modeling in design has been dubbed *variable complexity modeling*. The work under the grant focused on developing variable complexity modeling strategies with emphasis on response surface techniques. Applications included design of plates with discontinuities subject to uncertainty in material properties and geometry, design of stiffened composite plates for improved damage tolerance, and the use of response surfaces for fitting weights obtained by structural optimization.

Design against uncertainty: Doctoral student Gerhard Venter (who has recently graduated) explored the use of fuzzy set techniques for design against uncertainty. First he considered design for worst case scenarios. He developed a two-species genetic algorithms for dealing with design under uncertainty in loading and applied it to composite panel design (Ref. 1). One species (akin to a parasite) attempts to find the worst possible loading, and the other (akin to a host) attempts to find the best laminate for that worst loading. A more conventional approach to this problem, alternating between designing the best structure, and finding the worst set of loads was explored in joint work with Dr. Lombardi of the University of Pavia (Ref. 2).

Next a fuzzy-set design of isotropic panels subject to uncertainties in geometry, loading and material properties was completed. The emphasis was on identifying intrinsic variables of the problem so that an efficient response surface for the optimum weight can be developed. The relationship between the weight of the design and the amount of uncertainty to be tolerated, was established using this methodology (Ref. 3).

Next the work shifted to the design of a composite plate with a drop-ply. Many more variables and sources of uncertainty were considered. A study considering the cost of reducing uncertainties by additional tests versus the cost of the additional weight when tests are not conducted was performed. The study indicated that performing additional tests for reducing uncertainties in material properties is cost-effective (Ref. 4, 5).

Response Surface Methodology: A study demonstrating the use of response surface for optimization of a plate with a thickness change was published (Ref. 6). A joint study with Willem Roux and Nielen Stander of the University of Pretoria on the application of response surface techniques to structural optimization was published (Ref. 7).

2

Design for Improved Residual Strength: Low fidelity and high fidelity models of through-the-thickness crack propagation in stiffened composite panels were combined (Ref. 8). The high fidelity model is based on a detailed finite element analysis of the structure with the crack, and the low fidelity model is based on the value of the stresses at the point in the undamaged structure where the crack will be. A response surface for the ratio of the high-fidelity failure load to the low-fidelity failure load is used to combine the two models for design purposes. This allows the design to proceed on the basis of the inexpensive low-fidelity model, with information from only a handful of high-fidelity analyses. Using a plate with two blade stiffeners, it was shown that this gives better results than a response surface that employs only the high fidelity model (Ref. 9).

Structural Weight Equations: Response surface techniques can be used to fit results of structural optimizations of structural elements, so as to produce weight equations that can be employed for overall design of the aircraft. As a first step towards understanding the utility of weight equations, a preliminary study of the effect of scale on aircraft structural weight has been completed (Ref. 10). The study showed that the weight savings due to smaller size are predicted by standard weight equations, but their magnitude is smaller than that expected from basic principles.

A study on increasing the accuracy of structural weight estimation through response surface approximation was completed (Ref. 11). The study demonstrated how to identify optimization runs that produce unreliable results because of various factors, so that these runs can be corrected and the accuracy of the response surface improved.

Analytical model for stitched stiffened panels: Two finite element based models were developed for analyzing stiffened composite panels with a partial skin-stiffener debond. Linear buckling and postbuckling analysis was conducted using STAGS. Effects of boundary conditions, stiffener geometry, stacking sequences on linear buckling loads were investigated. Computations of strain energy release rate to examine delamination or debonding propagation of the panel without stitches were also conducted using strain energy derivative method and virtual crack closure method (Refs. 12, 13). Preliminary study revealed that stitching is effective when debond length is longer than a critical length that depends on stitch density, materials and boundary conditions.

Miscellaneous: A survey of the relationship between Optimization and Experiments was published together with Professor Elaine Scott of Virginia Tech and Juan Cruz of NASA Langley (Ref. 14). Finite element models were developed for tests of stiffened panels performed by Dr. Starnes and Mr. Waters at NASA Langley Research center (Ref. 15). Three papers with Professor Todoroki of Tokyo Institute of Technology on the use of genetic algorithm for laminate design were completed (Refs. 16-18).

References

1. Venter, G., and Haftka, R.T., "Two-Species Genetic Algorithm for Design under Worst Conditions," Short Papers Proceedings, 3rd World Congress of Structural and Multidisciplinary Optimization, Buffalo, New York, May 17-21, 1999, pp. 183-185.
2. Lombardi, M., and Haftka, R.T., "Anti-optimization Technique for Structural Design under Load Uncertainties," Computer Methods in Applied Mechanics and Engineering, 157(1-2), pp. 19-31, 1998

3. Venter, G., and Haftka R.T., "Using Response Surface Methodology in Fuzzy Set Based Design Optimization," AIAA Paper 98-1776, Proc. 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Long Beach, California, April 22 - 23, 1998, Vol. 1, pp. 641-652.
4. Venter, G., Haftka, R.T., and Starnes, J.H., "Response Surface Approximations for Designing Dropped-ply Composite Laminates with Uncertainty," 13th US National Congress of Applied Mechanics, Gainesville, FL, June 1998.
5. Venter, G., and Haftka R.T., "Response Surface Approximations for Cost Optimization of Dropped Ply Composite Laminates with Uncertainty" AIAA Paper No. 98-4856, Proceedings, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, pp. 1145-1163, St. Louis, Missouri, September 2-4, 1998.
6. Venter, G., Haftka, R.T., and Starnes, J.H., Jr. "Construction of Response Surface Approximation for Design Optimization," AIAA Journal, 36(12), pp. 2242-2249, 1998.
7. Roux, W.J., Stander, N., and Haftka, R.T., "Response Surface Approximations for Structural Optimization," International Journal for Numerical Methods in Engineering, 42, pp. 517-534, 1998.
8. Vitali, R., Haftka, R.T., and Sankar, B. V., "Response Surface Approximations for Crack Propagation Critical Loads," AIAA Paper 98-2047, Proceedings, 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Long Beach, California, April 20 - 23, 1998, Vol. 4., pp. 2917-2922, 1998.
9. Vitali, R., Haftka, R.T., and Sankar B.V., "Correction Response Surface Design of Stiffened Composite Panel with a Crack", AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Material Conference Paper AIAA-99-2231, St. Louis, Missouri, April 12-15, 1999.
10. Papila, M., Sugavanam, S., and Haftka, R.T., "Scale Effects on Aircraft Structural Weight," AeMES-TR-97-3-01, University of Florida, Oct.1997, 13th US National Congress of Applied Mechanics, Gainesville, FL, June 1998.
11. Papila, M., and Haftka, R.T., "Uncertainty and Wing Structural Weight Approximations," AIAA Paper 99-1312, Proceedings, AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Material Conference, pp. 988-1002, St. Louis, Missouri, April 12-15, 1999.
12. Park, O., Sankar, B.V., and Haftka, R.T., "Analytical Model for a Stitched Stiffened Panel subject to Axial Compression," presented to the 13th US National Congress of Applied Mechanics, Gainesville, FL, June 1998.
13. Park, O., Sankar, B.V., and Haftka, R.T., "Buckling and Postbuckling Analysis of a Stiffened Panel with Skin-Stiffener Debond," presented to 13th American Society of Composites Technical Conference, Baltimore, ML, September 1998.
14. Haftka, R.T., Scott, E.P., and Cruz, J.R., "Optimization and Experiments: A Survey," Applied Mechanics Reviews, 51(7), pp. 435-448, 1998.
15. Park, O., Haftka, R.T., Nagendra, S.N., and Sankar, B.V., "Analytical and experimental study of a blade stiffened panel in axial compression," AIAA-98-1993-CP, 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Long Beach, California, April 22 - 23, 1998.
16. Todoroki, A., and Haftka, R.T., "Stacking sequence optimization by a genetic algorithm with a new recessive gene like repair strategy," Composites Part B, 29(3), pp. 277-285, 1998.
17. Todoroki, A., and Haftka, R.T., "Stacking Sequence Optimizations for Composite Plate Buckling by Genetic Algorithm with Response Surface in Lamination Parameters," Transactions of JSME, A 64(621), pp. 8-15, 1998 (in Japanese).
18. Todoroki, A., and Haftka, R.T., "Lamination Parameters for Efficient Genetic Optimization of the Stacking Sequences of Composite Panels," AIAA Paper 98-4817, Proceedings, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, pp. 870-879, St. Louis MO, Sept. 2-4, 1998.

