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PROGRESS IN MULTIDISCIPLINARY DESIGN OPTIMIZATION AT NASA LANGLEY

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Abstract

Multidisciplinary Design Optimization refers to some combination of disciplinary analyses, sensitivity analysis, and optimization techniques used to design complex engineering systems. The ultimate objective of this research at NASA Langley Research Center is to help the US industry reduce the costs associated with development, manufacturing, and maintenance of aerospace vehicles while improving system performance. This report reviews progress towards this objective and highlights topics for future research. Aerospace design problems selected from the author's research illustrate strengths and weaknesses in existing multidisciplinary optimization techniques. The techniques discussed include multiobjective optimization, global sensitivity equations and sequential linear programming.

Introduction

The term Multidisciplinary Design Optimization (MDO) is defined by the AIAA Technical Committee on MDO as "a formal design methodology based on the integration of disciplinary analyses and sensitivity analyses, optimization and artificial intelligence, applicable at all stages of the multidisciplinary design of aerospace systems". Reference 1 summarizes the importance and current state-of-the art in MDO from the perspective of government and aircraft industry researchers.

Interest in MDO at NASA Langley Research Center originated as an interest in disciplinary optimization, particularly structural optimization. For instance, in the early 1970's, Stroud[2] experimented with optimization for preliminary design of wing structures. He concluded that structural optimization alone is inappropriate since aerodynamic flutter constraints in addition to strength and weight are essential ingredients in wing design. Stroud's success with multidisciplinary design of wing structures was an early indication of the difficulty and the rewards of combining engineering analysis and nonlinear programming.

Interest in MDO in the aerospace industry was fueled by an emphasis on concurrent engineering (CE)[1]. The basic tenet of CE is that products should be designed by a systematic approach which considers not only the peak performance of the product but also the cost of manufacturing, operating and maintaining the product. The aerospace industry observed that whereas traditional design methods employ a sequential process (e.g. aerodynamic design followed by structural design followed by controls design) concurrent engineering encourages a simultaneous multidisciplinary design process. This means that designers in each discipline have to understand the impact of their decisions on all other disciplines and have to exploit these interdisciplinary couplings.

The purpose of the present paper is to review progress in MDO research at NASA Langley. One approach is to overview all of the components of MDO citing references for each. Such an overview by Sobieski is available[3]. An alternate approach is to pick a few examples of MDO research for closer examination. In this paper, the author selects three examples to illustrate strengths and weaknesses in present MDO techniques when applied to preliminary design of space structures or advanced aircraft. The author chooses the examples from her own research for the sake of convenience and familiarity. She believes that the examples are representative of a large body of research surveyed in references 1 and 3.

The three examples of multidisciplinary optimization are presented in chronological order. The first is a flight trajectory planning exercise[4] which combines the disciplines of acoustics and flight dynamics. The second is a shape optimization of a 55 meter space radiometer[5] which includes structural and electromagnetic (EM) considerations. In these first two examples the analyses can be evaluated sequentially (e.g. structural analysis followed by EM analysis) but the optimization includes multidisciplinary objective and constraints. The final example is a simultaneous design of the structure and control systems for a large space platform in geostationary orbit[6]. In this final example, the disciplinary analyses are tightly coupled and require iteration to a converged solution. Thus, changes in any design variable affect all disciplines. Each of the three examples combines state-of-the art disciplinary analyses codes with constrained linear or nonlinear programming codes. The examples illustrate progress at NASA Langley from structural component design in 1970 towards full engineering system design in the 21st century.

Aircraft Trajectory Optimization

In the decade (1972–1982) following the cancellation of the United States plans for a national supersonic transport (SST) and following the first flight of the English-French Concorde, government researchers weighed new options for building a competitive version of a SST[7]. Each candidate SST design was assessed in terms of environmental impact, cost per passenger mile, life cycle costs and takeoff and landing noise. The goal was to design a profitable aircraft and one that could be certified to operate out of major US cities.

Some of the preliminary design studies for an American SST were conducted by the NASA. The flight simulators and test pilots at NASA Langley were an important part of those studies. As each candidate SST design was developed, a pilot would "test fly" the concept. If the design was acceptable in terms of pilot work load and safety considerations, then a standard takeoff procedure would be assessed in terms of aircraft noise. A simulated flight path including aircraft altitude and control settings (i.e. a schedule of angle-of-attack and thrust setting) was recorded on digital tape and the takeoff or landing noise was estimated by the Langley Aircraft Noise Prediction Program (ANOPP)[8]. Often the takeoff noise estimate would exceed the certification standards defined in Federal Air Regulations, Part 36 (FAR-36) and the pilot would be asked to find a quieter flight path. The iteration between simulator flights and noise estimates was time consuming and frustrating for the pilots who had little insight in the precise relationship between flight dynamics and noise.

An alternative to the above design procedure was proposed. A multidisciplinary optimization program was developed to predict a safe and quiet takeoff trajectory for each candidate SST design. If that trajectory met FAR-36 requirements, then the SST design could be assessed by the simulator pilots in terms of work load, safety and passenger comfort. Reference 4 describes the MDO procedure which combines flight dynamics and acoustic analyses.

The general trajectory optimization problem is illustrated in figure 1a. The objective is to find that takeoff trajectory which minimizes noise at selected observer (OBS) locations. The range of physically possible and acceptable trajectories is represented by the shaded region in the figure. The lower limit represents the minimal adherence to accepted safety practices and the upper limit represents the maximum power takeoff. Between these extremes lies at least one trajectory which produces minimum noise at the observers.

The SST trajectory optimization problem (see fig. 1b) is a simplified version of the general problem. The objective is to maximize the final altitude H_f with the constraint that the 108 decibel (dB) noise contour be contained within the airport boundaries. The dimensions of a typical airport, the minimum safe final altitude, and the locations of the four observers (or microphones) are prescribed by FAR-36. The trajectory optimization problem is stated:

$$\begin{aligned} &\textbf{maximize}: \; H_f \\ &\textbf{subject to}: \; EPNL_i \leq \; 108\,dB \quad i = 1,2,3,4 \end{aligned} \tag{1}$$

where $EPNL_i$ is the noise level predicted at observer location i and EPNL stands for effective perceived noise level, a weighed noise measure which accounts for the frequency content, duration and peak amplitude of the noise.

The flight trajectory optimization procedure met the needs of the NASA SST assessment team. It identified trajectories which could be reproduced by the simulator pilots and which did satisfy noise and safety regulations. In addition, the research challenged conventional assumptions about noise abatement strategies. It showed that a modest cutback in power early in the takeoff is more effective than a large cutback in power just before the aircraft passes the centerline microphone (i.e. OBS 4 in fig. 1b). The research was unique at the time, because it combined flight dynamics and acoustics with a standard constrained nonlinear optimization code, CONMIN[9].

Figure 2 contains a flowchart of the trajectory optimization process and reveals several unusual features of this research. First, the physical design variables, angle of attack and thrust, are smooth functions of time. However, the design variables defined for the optimization code are values of angle of attack and thrust at a few discrete times. A cubic spline is used to reconstruct the time dependent functions. A second unusual feature involves the implementation of the optimization procedure. The ANOPP executive language is used to invoke the flight dynamics, acoustics and optimization codes in a single iterative loop. The single loop is used to accumulate sensitivity derivatives using a forward difference scheme and to perform optimization. This implementation is flexible, easily admitting extra disciplinary analyses and alternate flight dynamics or acoustic modules.

Reference 4 acknowledges several weaknesses in the flight trajectory optimization. The most significant weakness involves the problem formulation. Often, there is no feasible solution to equation 1 and the optimization must be repeated using less stringent noise constraints. The MDO problem should have been formulated as a min-max problem (e.g. see ref. 5) or as a multi-objective problem (e.g. see ref. 10–11). That is, the objective is to find the best possible compromise between a safe trajectory and one which reduces noise. The solution to this revised MDO problem measures the acceptability of each candidate SST design and guides the redesign effort. The other weakness mentioned in reference 4 involves the "excessive" amount of computer time needed to converge to a solution. Today, the full ANOPP flight trajectory and EPNL noise estimates are executed quickly on desktop workstations, however in 1980 these estimates consumed a significant amount of time on the fastest mainframe computers. The trajectory optimization was possible because the full analyses were reserved for a postprocessing assessment of the optimum trajectory, and approximate analyses were substituted for some modules in the optimization loop. The creative formulation of multi-objective problems and the use of approximate analysis techniques are still important facets of MDO research.

Space Radiometer Design

A more recent multidisciplinary design effort at NASA Langley involved feasibility studies for large space radiometers. Very large aperture (about 50 meters in diameter) radiometers are envisioned to collect precise global measurements of soil moisture and other physical phenomena by measuring the amount of radiation reflected from the earth's surface. Figure 3 illustrates a typical radiometer configuration, a truss structure fitted with reflecting panels.

One barrier to progress in large space radiometer research is the lack of multidisciplinary design procedures. By convention, the structures group considers structural dimensions, load cases, and manufacturing tolerances while the electromagnetic (EM) group considers radiation wave length, frequency, side lobe levels and gains. The only measure which both groups share is a measure of the difference between the actual and the ideal radiometer surface shape, called root mean squared error (RMS). However, the EM experts tend to specify RMS requirements without considering the added cost and complexity of a precision structure while the structural experts ignore the fact that two surfaces with the same RMS measure can have very different EM characteristics.

Several optimization studies supported the radiometer design effort[5, 12–14]. Three of these studies use structural optimization techniques to minimize the RMS surface distortion. Reference 5 is unique because it is an MDO study combining the disciplines of structures and electromagnetism.

The optimization procedure proposed in reference 5 adjusts the shape of the reflector surface enough to explicitly satisfy EM performance criteria, while minimizing the total actuator effort required. The error in the shape of the radiometer is reduced using a set of actuators that can lengthen or shorten individual members of the backup structure. The measure of actuator effort is the maximum change in length of any control element (Δl). The measures of EM performance are that the maximum side lobe level (SLL) be at least 30 dB below the ideal peak gain (G_0), that the actual peak gain (G) be less than 0.3 dB below the ideal gain and that RMS error be much smaller than the wavelength (λ).

The optimization problem is stated as:

$$\begin{aligned} \textbf{minimize}: \quad & \Delta l_{\max} = \max_i |\Delta l_i| \quad i = 1, 2, \ldots, n \\ \\ \textbf{subject to}: \quad & SLL \le G_0 - 30dB \\ & G \ge G_0 - 0.3dB \\ & RMS \le \lambda/50 \end{aligned} \tag{2}$$

where the design variables are the change in length of each of the n control elements and the goal is to minimize the maximum change in length.

Because Δl_{max} is not a smooth function of the original design variables, the optimization problem is reformulated with an extra design variable β as the objective function and with n additional constraints, thus,

$$\begin{aligned} \textbf{minimize}: \quad & \beta \\ \textbf{subject to}: \quad & |\Delta l_i| \le \beta \quad i = 1, 2, \ldots, n \\ & SLL \le G_0 - 30dB \\ & G \ge G_0 - 0.3dB \\ & RMS \le \lambda/50 \end{aligned} \tag{3}$$

The radiometer design effort uncovered several weaknesses in current MDO practise. The weaknesses involve the problem formulation, the continuous nature of some constraints and the discrete nature of possible design variables. The problem formulation is weak because it minimizes the maximum control setting for a single (worst case) surface distortion. In actual operation, the surface distortion is a function of orbital position and must be calculated using orbital mechanics and thermal analyses. The important MDO problem is to minimize the maximum control setting for any actuator and any orbital position.

The second weakness involves constraints such as side lobe level which are continuous functions in two or three dimensions. For instance, figure 4 contains gray scale contour plots of electromagnetic radiation for the uncorrected radiometer (see fig. 4a) and for the optimized radiometer (see fig 4b). Power levels from 0 to —30dB below G_0 are shaded gray. If equation (3) were successfully solved, then all the shaded regions in figure 4b would lie inside the dashed circle which signifies the main beam. Then no side lobe level would exceed G_0—30dB. The current optimization procedure fails this test because power levels are sampled along radial lines at discrete azimuthal angles (e.g. ref. 5 specifies four discrete angles, ϕ = 0, 45, 90, 135 degrees). Constraining SLL along radial lines for any number of discrete angles tends to reduce SLL in every direction but does not insure a feasible design.

The third weakness involves the choice of design variables. In reference 5, only the change in length of actuators is a design variable. The number and location of the actuators is predetermined and the mass of the actuator is fixed. Number, location and type (i.e. mass) of actuators are examples of discrete valued design variables which should be included in the problem formulation. References 12–14 discuss solution options for discrete (or integer) programming problems arising in radiometer design.

Despite weaknesses acknowledged above, the space radiometer design effort was a success. First, it provided designers with an integrated structure/EM analysis code and it increased their understanding of the relationship between surface distortion and electromagnetic performance. Second, it demonstrated that a multidisciplinary optimization procedure can identify a much better set of actuator length changes than the traditional procedure which minimizes RMS surface distortion. This is significant because the cost and complexity of the control system is directly related to the maximum change in length of any actuator.

The radiometer design problem involves computationally expensive analysis codes and six times as many design variables as the trajectory optimization. Thus, improved methods of implementation are essential. Figure 5 compares a flowchart of the radiometer design problem with a flowchart for the trajectory optimization. Notice that the trajectory optimization (fig. 5a) has a single iterative loop. The flight dynamics and acoustic analysis are invoked repeatedly by the optimization code to calculate sensitivity derivatives and to conduct a line search in the best feasible direction. Notice that the radiometer optimization (fig. 5b) has two inner loops within a single outer loop. In the first inner loop, the sensitivity derivatives of the structural and EM analyses are determined by finite difference approximation. In the second inner loop, first-order Taylor series approximations to the objective and constraint equations are linked with the optimization code. Move limits are added so that the design variables are constrained to the region where the linear approximation is valid. The outer loop is used to repeat the analysis and optimization until an acceptable design is identified. This procedure is often termed sequential linear programming (SLP) because the nonlinear programming problem in equation 3 is converted into a sequence of linear programming problems. The number of linear programming problems in the sequence depends on the feasibility of the initial design and on the size of the move limits compared to the size of the domain.

The space radiometer design is typical of many MDO problems at NASA Langley. First, the computational cost of evaluating structures and electromagnetic disciplinary analyses is substantial; the cost of executing the optimization code is negligible by comparison. Therefore, the efficiency of the optimization process is measured by the number of analyses required. This number is reduced dramatically by use of approximate analysis. Second, the global solution to the MDO problem is not necessarily the best possible design. This is so because the disciplinary analyses are an inexact simulation of the physical design and because the objective and constraints are discretized approximations to continuous functions. Thus, finding a variety of improved and feasible design points for further evaluation is emphasized over finding the global minimum. Finally, reliable convergence is more important than the actual solution. The goal of the optimization process is to explore trade-offs between competing designs and to establish the order of magnitude of each design variable, and to investigate the sensitivity of the optimal solution to changes in the fixed problem parameters. Thus, the flexibility and ease of use of the MDO procedure and its computational efficiency are more significant than the "exact" solution to any specific MDO problem.

Geostationary Platform Design

A relatively new research area at NASA is the Controls-Structures Interaction (CSI) Technology Program[15]. One aspect of the CSI program is to develop methods for optimization of large space structures with vibration control systems (e.g. ref. 6 & 16). Reference 6 addresses CSI problems for which there is implicit coupling between structural design variables and control design variables. These CSI optimization problems are challenging because they involve eigen solvers and transient response analysis which are computationally expensive. Moreover, these analyses must be iterated until all structural and control response quantities converge.

Reference 6 describes an MDO project for the preliminary design of a conceptual geostationary platform shown in figure 6. The objective is to minimize the launch weight of the platform which includes the weight of the structure (m_S) and the weight of the control system (m_C). The mass m_C is estimated from the peak torque required to control vibrations. The actual constraint on vibrations involves vibration decay rate after a repositioning maneuver. The constraint is stated in terms of upper bounds on the real parts of the first m closed-loop eigenvalues (λ_i). The optimization problem seeks the best trade-off between a stiff and massive structure with little or no control system and a flexible and light structure with a substantial control system. It is stated:

$$\begin{aligned} \textbf{minimize}: &\quad m_S + m_C \\ \textbf{subject to}: &\quad \Re(\lambda_i) \leq \delta_i \quad i = 1, 2, ...m \end{aligned} \tag{4}$$

where δ_i is a negative real number specifying the required decay rate and the design variables are structural truss sizes and controller gains.

The solution to the geostationary platform design problem is complicated by the fact that structural analysis and optimal control analysis are handled by separate but coupled computer codes. The structural finite element code requires m_C and truss sizing information as input and produces m_S plus characteristic vibration modes and frequencies as output. On the other hand, the optimal controls code requires modes, frequencies and controller gains as input and produces m_C and λ_i as output. These two "black box" computer codes can be viewed as a coupled system of nonlinear algebraic equations which can be solved by either fixed point iteration or by Newton's method. Various options for solving optimization problems involving coupled systems of equations are discussed in references 17 and 18.

Figure 7 illustrates two options for solving coupled MDO problems which were tested in reference 6. Option 1 (fig. 7a) is similar to the standard SLP approach used in the radiometer design (recall fig. 5b) except that here the coupled multidisciplinary analyses require an iterative solution. Option 2 (fig. 7b) is essentially the global sensitivity equation (GSE) approach proposed by Sobieski[19].

The GSE approach consists of three steps: (1) find a converged solution to the coupled controls-structures analysis (2) calculate local derivatives of structural outputs with respect to structural inputs and controls outputs with respect to controls inputs and (3) solve a system of linear equations (the global sensitivity equations) to calculate global derivatives from local derivatives. The GSE approach requires local derivatives of each contributing analysis with respect to its input. For example, one output of the structural analysis is a set of characteristic frequencies and one input is m_C, therefore the partial derivatives of frequency with respect to m_C are required. The GSE approach is attractive because the iteration between controls and structures is performed once per cycle while in standard SLP approach the iteration is required once for each design variable. If the number of design variables is large as in reference 20, then the GSE approach is clearly advantageous. On the other hand, if the "front-of-interaction"[17] between the analyses is wide (i.e. if a large number of outputs from one analysis become inputs to some other analysis) then the cost of calculating local derivatives needed by the GSE approach can be prohibitive.

For the geostationary platform design, the GSE approach is superior even if the computational cost advantage is ignored. Using the SLP approach (fig. 7a), the quality of global derivatives produced by finite difference approximation is unacceptable unless both the proper perturbation step size for each design variable and the proper convergence criteria for the fixed point iteration are selected. Selecting the proper step sizes and the corresponding convergence criteria is difficult and requires many function evaluations prior to the start of optimization. In contrast, the GSE approach (fig. 7b) is not very sensitive to convergence tolerance and does not require selection of perturbation step size. Furthermore, reference 6 demonstrates the ability of the GSE approach to make steady progress from an infeasible initial guess to an acceptable design, and reference 20 demonstrates the ability of the GSE approach to optimize using a large number of design variables each with an extremely subtle effect on the global design.

The geostationary platform design shares features with many other MDO problems. Often design teams wish to utilize several familiar and validated "black box" analysis codes within a design study. These codes may require significant amounts of computer resources such as disk space and CPU time. The codes may require extensive modification in order to execute on any given computer architecture. Thus, it can be impractical to combine these "black box" codes into a single optimization code. Optimization procedures, such as the one described in ref. 6, anticipate these requirements by using operating system commands and preprocessor programs to link a set of disciplinary analysis codes.

Although the GSE approach works well for the geostationary platform design it is not the best choice for every coupled MDO problem. First, it is not appropriate for problems with a very wide front of interaction between disciplines nor for problems where the objective and constraints are highly nonlinear. Second, it is not appropriate for detailed refinement of an existing feasible design. Near the optimal solution, both of the (SLP and GSE) approaches in figure 7 tend to overshoot the solution unless move limits are very small. References 17 and 18 contain a discussion of these shortcomings and recommend solutions.

The geostationary platform design using GSE approach was successfully applied to problems with from 15 to 150 design variables[6, 20]. In each case, the platform is redesigned so that the mass distribution and dynamic characteristics of the structure enhance the use of rate and position feedback by the control system. Starting from an infeasible design, the procedure not only makes a favorable trade of structural mass for control effort, but also satisfies the vibration decay rate constraints. This research demonstrates that integrated controls-structures optimization can lead to significant mass savings, which would not have been revealed by traditional (i.e. sequential structural design followed by control system design) methods. The solution of the geostationary platform design problem is an important step toward a comprehensive preliminary design capability for controlled space structures.

Concluding Remarks

This paper describes three aerospace optimization examples which illustrate progress in MDO research at NASA Langley Research Center. Each example includes a brief description of the problem and its origin, a discussion of implementation strategy and an analysis of the strengths and weaknesses of the selected MDO techniques. The examples indicate a maturing of MDO technology.

Several general characteristics of engineering design optimization are revealed by these examples. The first characteristic is the computational expense of the disciplinary analysis codes. This characteristic motivates the selection of optimization algorithms such as sequential linear programming which greatly reduce the total number of analysis evaluations required. The second characteristic is the use of "black box" analysis codes. This characteristic influenced the development of the GSE approach which encourages the use of existing disciplinary and sensitivity analysis codes. The last characteristic is that MDO problems are incomplete and approximate representations of the physical design problem. This characteristic reduces the importance of the "exact" optimal solution and emphasizes the robustness and feasibility of the final design point.

Some weaknesses in the current MDO techniques are revealed by these examples. These weaknesses indicate productive directions for future research. For example, mixed integer programming techniques are needed to select truly discrete design variables such as number of actuators and quasi-discrete design variables such as type (or mass) of actuator. Other important research areas are the incorporation of distributed constraints such as 2–D noise level contours and 3–D electromagnetic side lobe levels and the use of probabilistic techniques to deal with the uncertainties inherent in engineering design. A final challenge is the development of computer implementation strategies which encourage designers to use these new MDO techniques.

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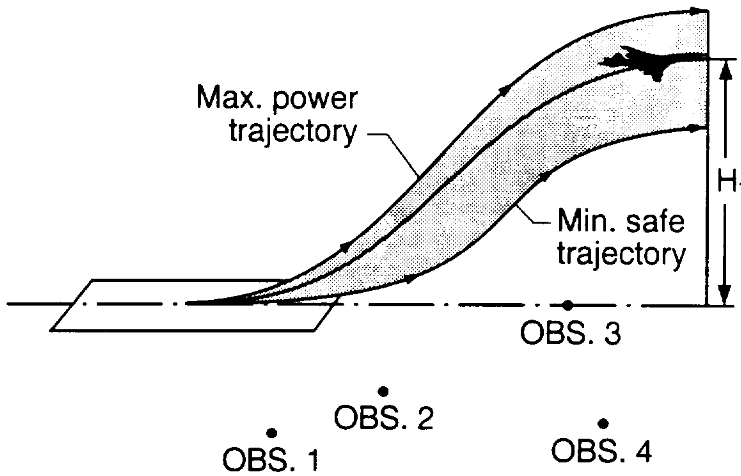
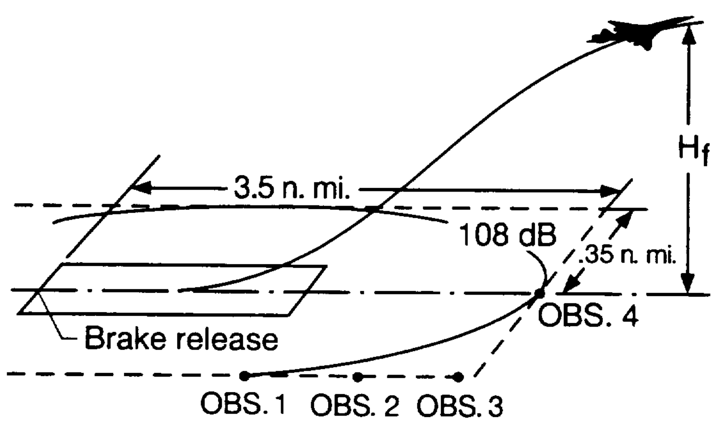


(a) Conceptual problem.



(b) Demonstration problem.

Figure 1. Schematic of takeoff trajectory configuration.

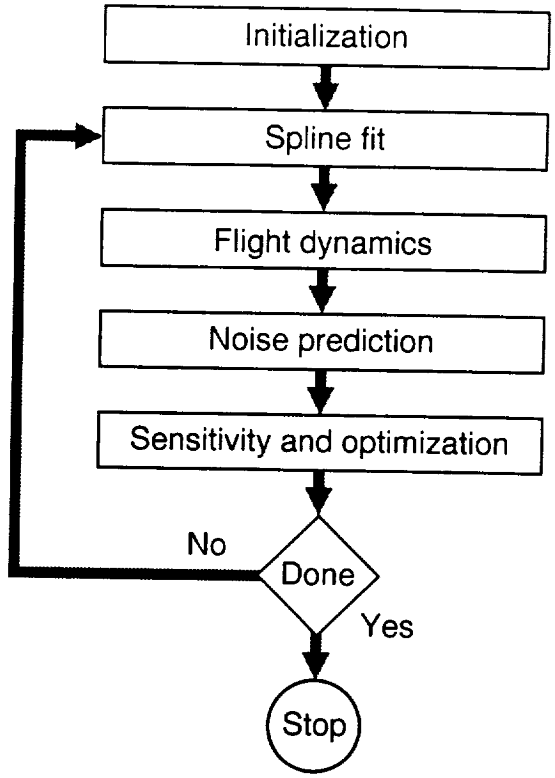
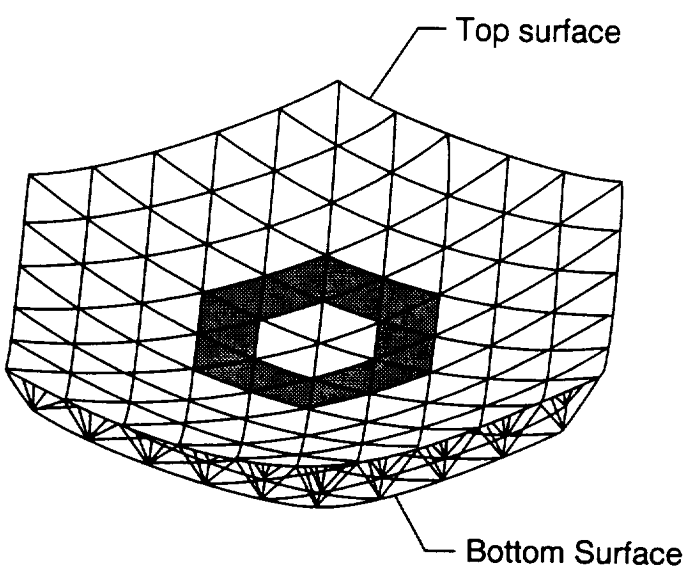
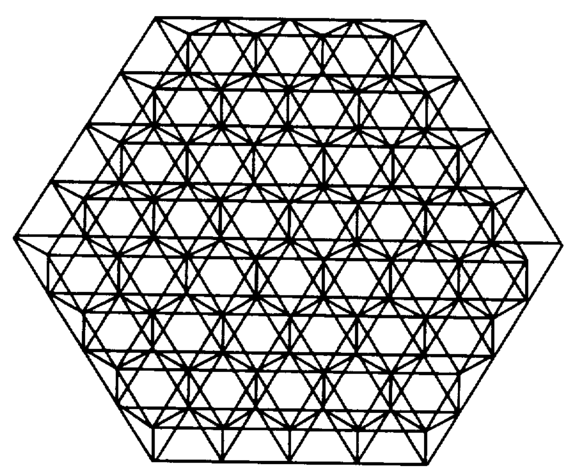


Figure 2. Flow diagram of trajectory optimization problem.

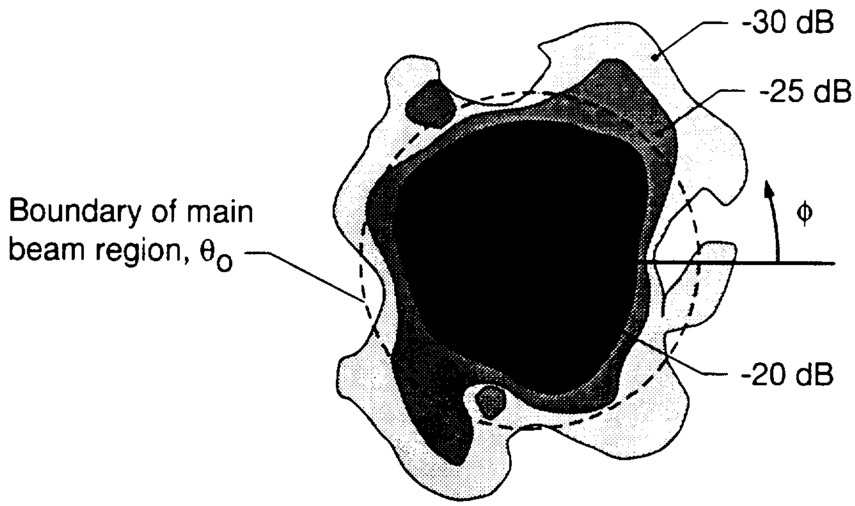


(a) Reflecting surface design.

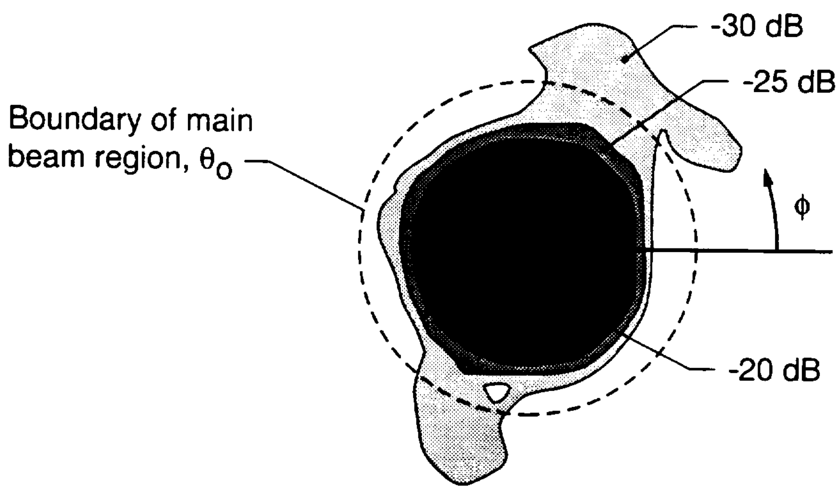


(b) Finite element model.

Figure 3. Reference configuration of 55 meter radiometer.

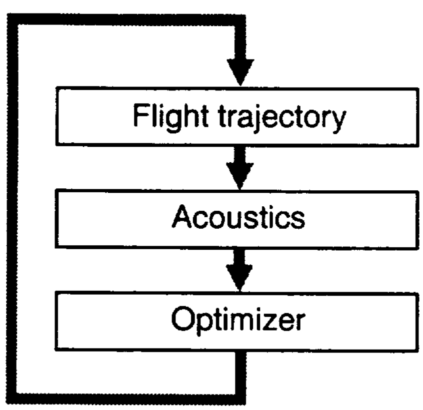


(a) Power level contours before optimization.

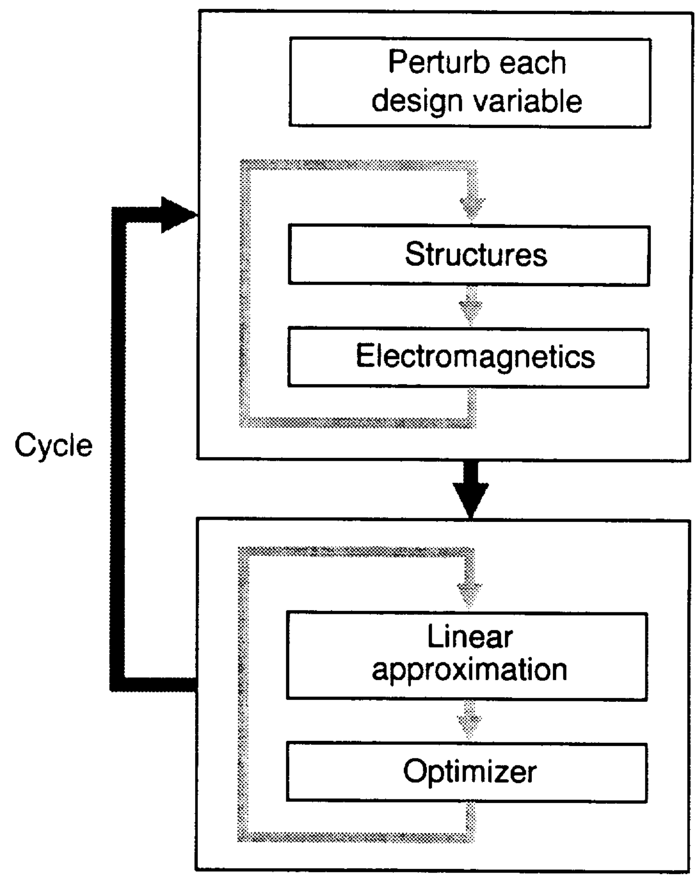


(b) Power level contours after optimization.

Figure 4. Predicted relative power levels on any plane normal to the reflecting surface axis.



(a) Trajectory optimization.



(b) Radiometer optimization.

Figure 5. Comparison of flow charts for trajectory optimization and radiometer design optimization.

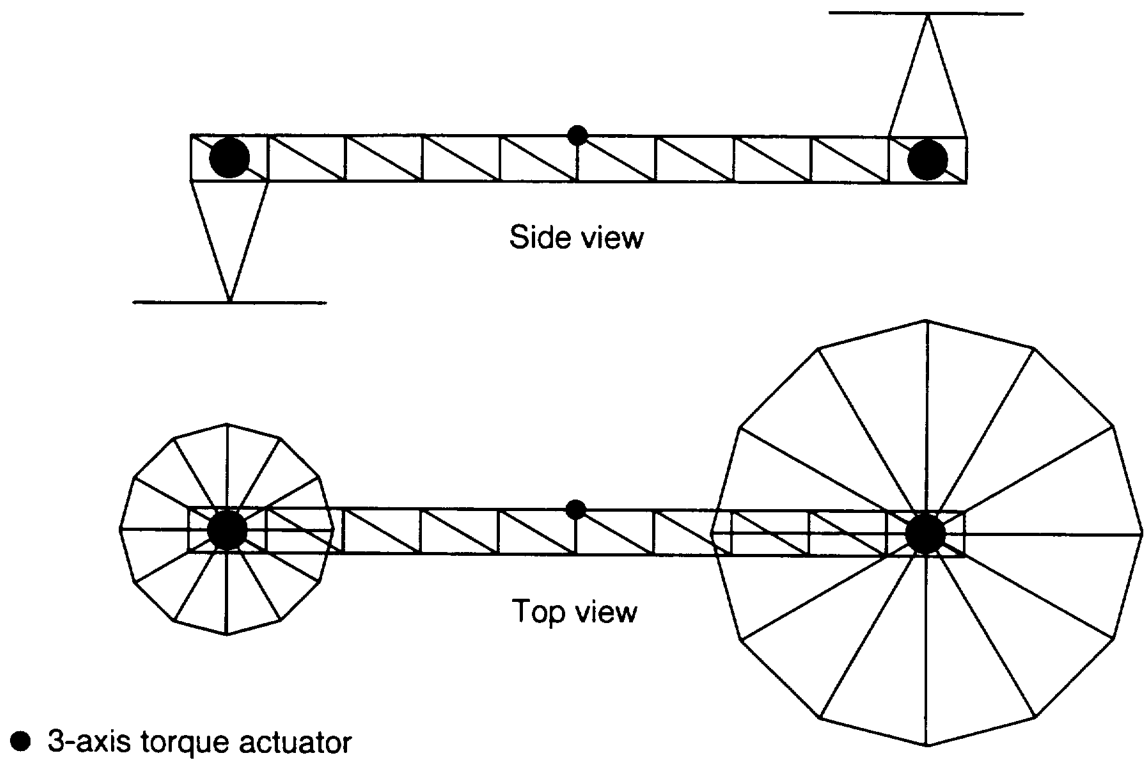
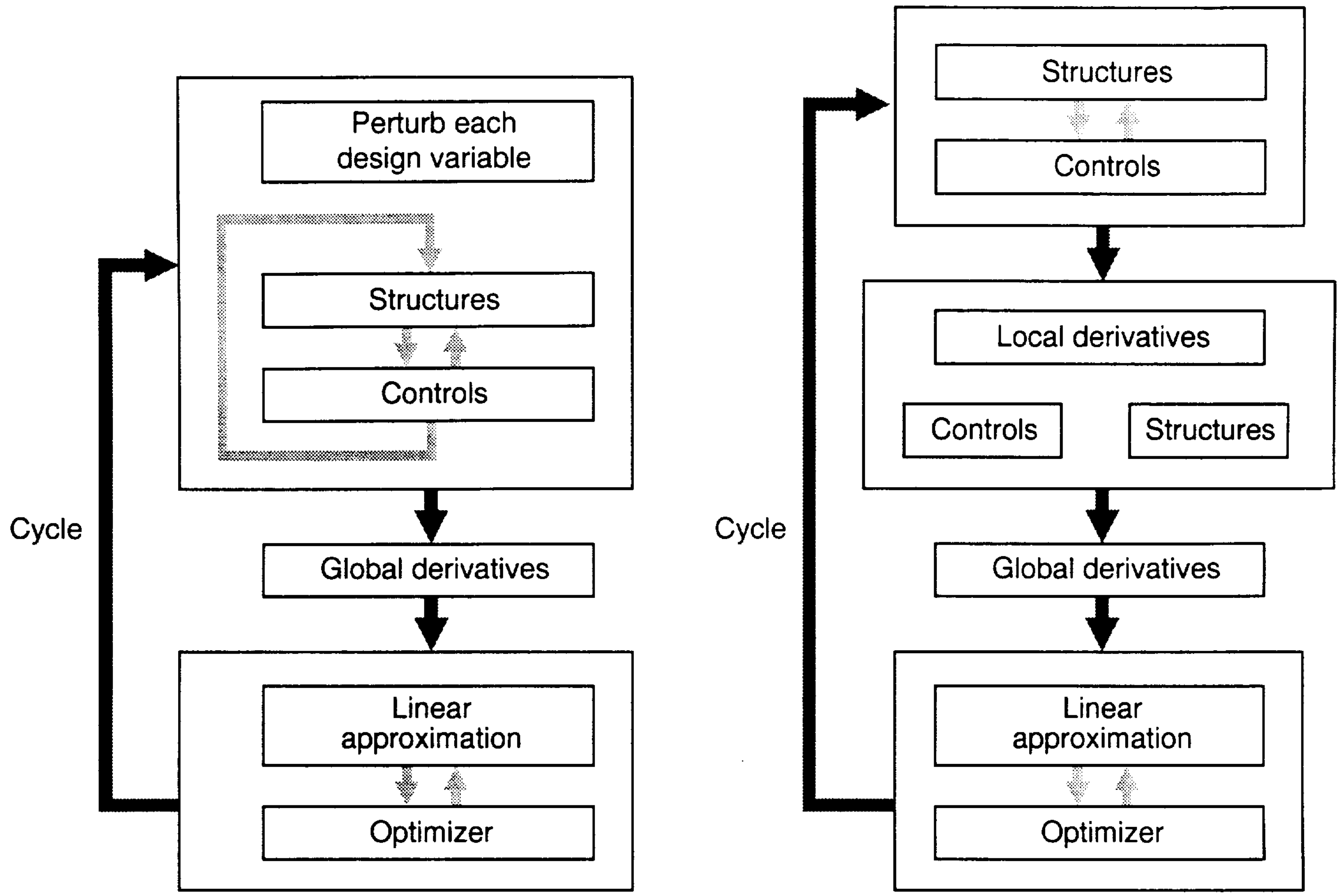


Figure 6. Reference configuration of geostationary platform.



(a) Sequential linear programing (SLP). (b) Global sensitivity equations (GSE).

Figure 7. Optimization approaches for coupled MDO.

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Multidisciplinary Design Optimization refers to some combination of disciplinary analyses, sensitivity analysis, and optimization techniques used to design complex engineering systems. The ultimate objective of this research at NASA Langley Research Center is to help the US industry reduce the costs associated with development, manufacturing, and maintenance of aerospace vehicles while improving system performance. This report reviews progress towards this objective and highlights topics for future research. Aerospace design problems selected from the author's research illustrate strengths and weaknesses in existing multidisciplinary optimization techniques. The techniques discussed include multiobjective optimization, global sensitivity equations and sequential linear programming.

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