

Lessons Learned During Solutions of Multidisciplinary Design Optimization Problems

Surya N. Patnaik*

Ohio Aerospace Institute, Brookpark, Ohio 44142

and

Rula M. Coroneos,[†] Dale A. Hopkins,[‡] and Thomas M. Lavelle[§]

NASA John H. Glenn Research Center at Lewis Field, Cleveland, Ohio 44135

Optimization research at NASA Glenn Research Center has addressed design of structures, aircraft, and aircraft engines. Four issues were encountered during the solution of the multidisciplinary problems. Strategy adapted for their resolution is discussed. Design optimization produced an inefficient design for an engine component. The deficiency was overcome through animation and weight was reduced by 20%. Infeasibility encountered in aircraft and engine design problems was alleviated by cascading multiple algorithms. The cascade strategy reduced aircraft weight and produced a feasible design. Profile optimization converged to an irregular shape for a beam. A regular shape was restored through engineering intuition, but the optimum weight was not changed. The subproblem optimization for a cylindrical shell converged to a design that might be difficult to manufacture. This issue remains a challenge. The issues are illustrated through design of an engine component, synthesis of a subsonic aircraft, operation optimization of a supersonic engine, design of a wave-rotor-topping device, profile optimization of a beam, and design of a cylindrical shell. A multidisciplinary problem might not yield an optimum solution in the first attempt. However, the combined effort of designers and researchers can bring design optimization from academia to industry.

I. Introduction

OPTIMIZATION research at NASA Glenn Research Center has addressed the structural design of airbreathing propulsion engines and space station components, aircraft synthesis, as well as performance improvement of the engines. The accumulated multidisciplinary design activity is collected under a test bed entitled COMETBOARDS.¹ It was observed that such problems might not be amenable to a solution in the first attempt. Solution, however, can be obtained through an augmentation of available tools and strategies. While generating solutions to the multidisciplinary problems through the test bed, several issues were encountered. This paper lists four issues and presents the strategies that were employed for their resolutions:

1) The optimization process produced a local inefficient design for a rear divergent flap of a downstream mixing nozzle. An augmentation of animation improved the design. The weight was reduced by 20%. The optimum structure exhibited a desirable breathing type of mode shape.

2) Solutions obtained for aircraft and engine problems, using a single optimization algorithm, encountered infeasibility even though the values of the merit functions were in the vicinity of the correct solutions. The infeasibility was alleviated through a cascading of multiple algorithms. The cascade strategy reduced aircraft weight by about 1%.

3) The shape optimization of a beam produced an irregular shape. The regular shape could be restored through engineering intuition. However the optimum weight remained the same for both solutions.

4) For a cylindrical shell the subproblem solution strategy converged to a local design that could be difficult to manufacture. Resolution of this issue is still a challenge. This paper expounds upon the lessons learned in solving multidisciplinary problems with little emphasis on the algorithm or analysis method. The paper is divided into five subsequent sections. An outline to the testbed COMETBOARDS is given in Sec. II. A description of the illustrative examples is given in Sec. III. The next section describes the four issues: the local solution and animation, infeasibility and the cascade strategy, irregular design and intuition, and substructure solution and manufacturability. Discussions and conclusions are given in Secs. V and VI.

II. COMETBOARDS Testbed

The design optimization test bed COMETBOARDS can evaluate the performance of different optimization algorithms and analysis methods while solving a problem. It is a research test bed but not a commercial code. The acronym COMETBOARDS stands for "Comparative Evaluation Test Bed of Optimization and Analysis Routines for the Design of Structures." The scope of the test bed has been expanded to include the design of structures, the synthesis of aircraft, and the operation optimization of airbreathing propulsion engines. COMETBOARDS has three different analysis methods and 12 optimization algorithms. It has a modular organization with a soft coupling feature, which allows quick integration of new or user-supplied analyzers and optimizers without any change to the source code. The COMETBOARDS code reads information from data files, formulates design as a sequence of subproblems, and generates the optimum solution. COMETBOARDS can be used to solve a large problem, definable through multiple disciplines, each of which can be further broken down into subproblems. Alternatively, it can improve an existing system by optimizing a small portion of a large problem. Other unique features of COMETBOARDS include design variable formulation, constraint formulation, subproblem strategy, global scaling technique, analysis approximation through neural network and linear regression method, use of sequential and parallel computational platforms, and so forth. The special features and unique strengths of COMETBOARDS assist convergence and reduce the amount of CPU time required to solve

Received 27 January 2001; revision received 11 October 2001; accepted for publication 12 December 2001. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States. Copies of this paper may be made for personal or internal use, on condition that the copier pay the \$10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0021-8669/02 \$10.00 in correspondence with the CCC.

*Senior Engineer, Structures and Acoustics Branch, MS 49-8. Associate Fellow AIAA.

[†]Mathematician, Computational Sciences Branch.

[‡]Structures and Acoustics Division. Senior Member AIAA.

[§]Aerospace Engineer, Aeropropulsion Analysis Office.

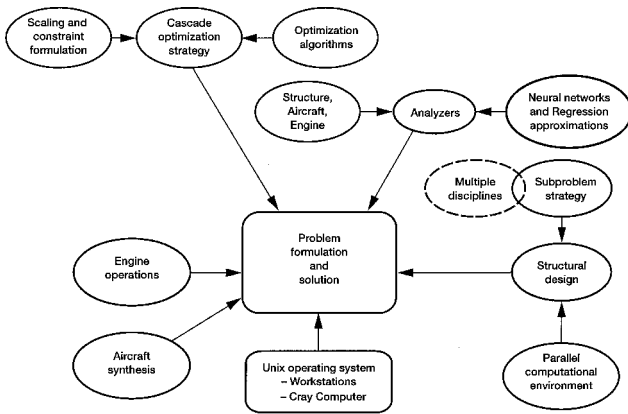


Fig. 1 Organization of the multidisciplinary design optimization test bed COMETBOARDS.

difficult optimization problems of the aerospace industry. COMETBOARDS has been successfully used to solve the structural design of the International Space Station components, the design of the nozzle components of an airbreathing engine, and airframe and engine synthesis for subsonic and supersonic aircraft, mixed-flow turbofan engine, wave-rotor-topped engine, and so forth. The modular organization of COMETBOARDS is depicted in Fig. 1. Brief descriptions of some of its modules follow.

For scaling and constraint formulation a multidisciplinary design problem can have a distorted design space because its variables and constraints can vary over a wide range. For example, an engine thrust design variable, which is measured in kilopounds, is immensely different from its bypass ratio, which is a small number. Likewise, the landing velocity of an aircraft measured in knots and landing or take-off field lengths measured in units of thousands of feet differ both in magnitude and in units of measure. This module provides a scheme to reduce the distortion by scaling the design variables, the objective function, and the constraints such that their relative magnitudes during optimization calculations are around unity. The constraints are reformulated to alleviate redundancy without affecting the problem definition. Constraint formulation alleviates redundancy and reduces their number.² The cascade algorithm employs more than one optimizer to solve a complex design problem when individual mathematical programming methods experience difficulty.³

The module "Analyzers-Structure, Aircraft, Engine-Neural networks and Regression approximations" houses three different types of analysis methods. For structural analysis the methods available are COSMIC NASTRAN,⁴ MSC/NASTRAN,⁵ MHOST,⁶ Analyze/Danalyze codes,⁷ and IFM/Analyzers.⁸ Aircraft analysis can use the FLOPS code.⁹ The NEPP code¹⁰ is employed for airbreathing propulsion engine cycle analysis. Neural network¹¹ and regression techniques¹² can be employed to approximate analysis. A problem can utilize any one of three analyzers: 1) an original analyzer, for example FLOPS code, or one of the two derived analyzers based on 2) a neural network or 3) a linear regression approximation.

The module "Engine operations" in Fig. 1 refers to the performance optimization of airbreathing propulsion engines for multiple operation points.¹³ "Aircraft synthesis" refers to the airframe and engine integration for subsonic and supersonic aircraft.³

The module "Structural design—Subproblem strategy and Parallel computational environment" refers to design of structures through regular optimization or a subproblem strategy. This strategy is available in sequential and parallel computational environments.¹⁴ "Multiple disciplines" refers to the solution of a problem, which is defined through different disciplines. COMETBOARDS can accommodate several disciplines, each of which can be further divided into subproblems. Subproblem strategy is an attempt to alleviate convergence difficulties that can be encountered during the solution of a large optimization problem. In this strategy the large problem is replaced by a sequence of overlapping modest subproblems. The solution to the large problem is obtained by repeating the solution to the set of subproblems until convergence is achieved.

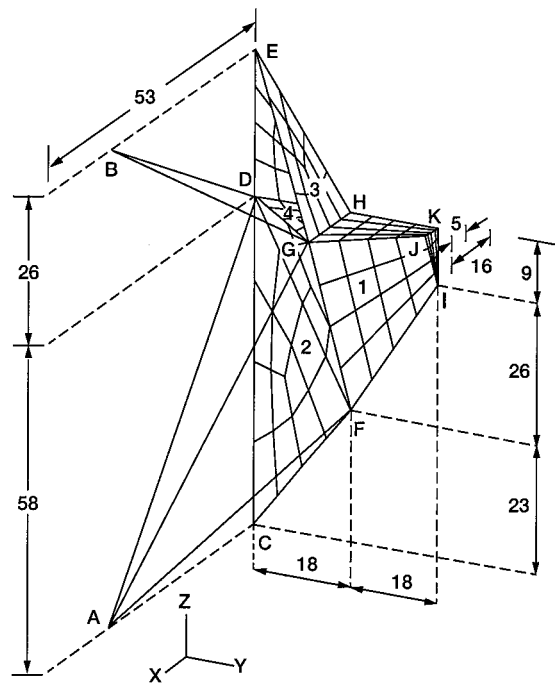


Fig. 2 Cargo-bay support system of the international space station (dimensions are in inches.)

Substructure strategy, a key component of COMETBOARDS, is further illustrated through the design of a cargo-bay support of the International Space Station. The support structure is fabricated out of four plates, a cluster of plates referred to as a box, and five beams, as shown in Fig. 2. For the purpose of design, the support system was divided into four active and one passive substructures. The first substructure was the closed box (FGHKIJ) consisting of five plates. Its finite element model was obtained by discretizing it into 72 (QUAD4) shell elements. The second substructure was a trapezoidal plate (FHEC), and its finite element model had 37 shell elements. The third and fourth substructures were triangular plates (GHE and GHD) with 12 finite elements each. The fifth substructure contained the five connecting beams BD, BG, AD, AG, and AF. The beam designs were not changed. These passive variables did not participate in the design calculations but were retained during reanalysis. Two independent finite analysis codes LE_HOST and MSC/NASTRAN were used to verify the finite element model of the support structure. The finite element model with a total of 133 QUAD4 shell and 20 beam elements was considered adequate for design optimization because both analyzers produced an acceptable level of accuracy for stress, displacement, and frequency. The substructures were clustered next to obtain a set of subproblems. A subproblem contains a substructure along with some or all of its neighboring substructures. The four substructures were clustered to obtain the following four subproblems: subproblem 1—substructures 3 and 4; subproblem 3—substructures 1 and 2; subproblem 2—substructures 1 and 4; and subproblem 4—substructures 2 and 3.

Notice the coupling between subproblems: substructure 1 is common to subproblems 2 and 3. Likewise, substructure 2 is common to subproblems 3 and 4, and so forth. Adequate coupling between substructures is required for convergence. Inappropriate coupling can increase the amount of computation and/or encounter convergence difficulties. At this time substructure coupling is decided intuitively. However, it might be possible to automate substructure coupling through the gradient scheme developed in Ref. 15. The COMETBOARDS testbed can optimize a system that can be defined in terms of 100 optimization subproblems.¹⁴

In the module "Problem formulation and solution" information is read from data files, the design is cast as a sequence of optimization subproblems, and the solution is obtained.

The COMETBOARDS testbed is written in the Fortran 77 language except for the neural network algorithm, which is written in

the C++ language. The test bed is available in the Unix operating system in workstations and Cray computers.

One dozen mathematical programming algorithms are available in COMETBOARDS. A list of the algorithms in no particular order follows: 1) method of feasible direction,¹⁶ 2) modified feasible direction method,¹⁷ 3) reduced gradient method,¹⁸ 4) generalized reduced gradient method,¹⁹ 5) sequence of unconstrained minimization technique,²⁰ 6) sequential linear programming,¹⁶ 7) sequential quadratic programming method,²¹ 8) IMSL optimization routine,²² 9) NPSOL package of NAG library,²³ 10) 16 different versions of optimality criteria methods,²⁴ 11) a genetic algorithm,²⁵ and 12) fully utilized design algorithm.¹⁵

Different algorithms employ different strategies to calculate the search direction and the step length. The comparative performance of the algorithms in solving a set of 45 problems is reported in Ref. 26. The performance of six algorithms in solving a set of medium and large structural problems is depicted in a bar chart in Figs. 3a and 3b, respectively. Examples with design variables in the range of 20 to 39 with about 200 behavior constraints are referred to as medium problems (see Fig. 3a). Examples with more than 40 independent design variables and several hundred constraints are referred to as large problems (see Fig. 3b). The success rate of different optimization algorithms for 10 large structural problems is also depicted in a Venn diagram in Fig. 3c. Cascade solutions for the problem are given in a table (see insert Fig. 3e). The success of an algorithm is represented by unity, which is the normalized value of the merit function (see Figs. 3a and 3b). A normalized value of less than unity (an infeasible solution) or greater than unity (an over-design condition) represents underperformance. Most optimizers available in the test bed solved at least one-third of the examples, but none of the optimizers could successfully solve all of the problems. Every structural problem could be solved by at least one of the six different optimization algorithms. However, even the

most robust optimizer encountered difficulty in generating optimum solutions for aircraft and engine problems.

III. Illustrative Examples

For the purpose of illustration, we have selected six problems: problem 1—Structural design of an engine component, problem 2—Synthesis of a subsonic aircraft, problem 3—Operation optimization of a supersonic engine, problem 4—Design of a wave-rotor-topping device, problem 5—Profile optimization of a cantilever beam, and problem 6—Design of a cylindrical shell.

Augmentation of animation into optimization is illustrated through problem 1. Problems 2, 3, and 4 illustrate the cascade strategy. Problem 5 addresses shape optimization. The subproblem solution strategy is illustrated through problem 6. Brief definitions of the problems follow.

A. Problem 1: Structural Design of an Engine Component

A mixed-flow turbofan engine exhaust nozzle referred to as a “downstream mixing nozzle” for a High Speed Civil Transport aircraft to operate at a cruise speed of Mach 2.4 and in a range of 5000 nautical miles is shown in Fig. 4a. It is fabricated out of rear and forward divergent flaps, rear and forward sidewalls, bulkheads, duct extensions, six disk supports, and other components. The design complexity of the nozzle is increased with flight Mach number, pressure ratio, temperature gradient, dynamic response, and degradation of material properties at elevated temperature. The flap is made of Rene 125 material with a Young’s modulus of 30.4 million psi, a Poisson ratio of 0.3, a density of 0.308 lb/in.³ and an allowable strength of 117 ksi. The flap shown in Fig. 4b has a length of 96 in. and a width of 72 in. It is supported by two variable-depth edge beams with a maximum depth of 14 in. A grid with a spacing of 12 × 12 in. and a depth of 2 in. stiffens the flap. MHOST and MSC/NASTRAN analyzers were used for the static as well as

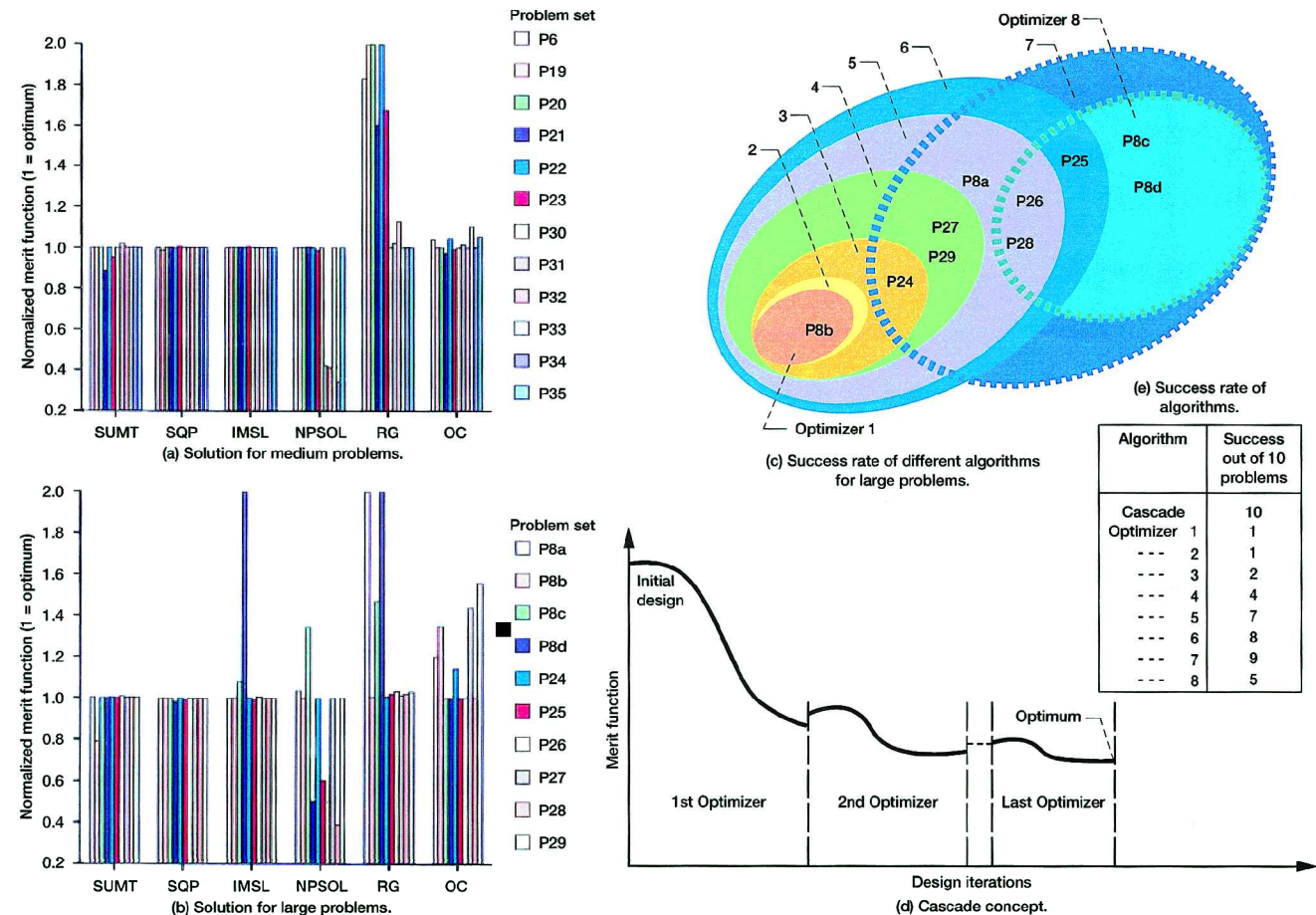


Fig. 3 Comparative evaluation of optimization algorithms.

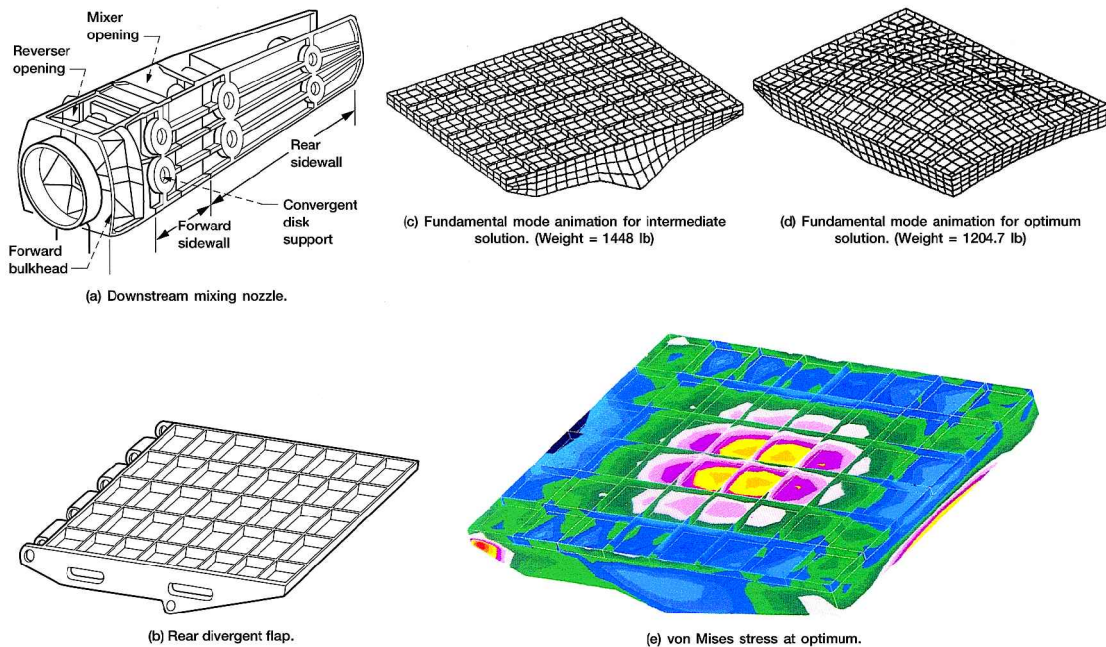


Fig. 4 Design of a rear divergent flap of a downstream mixing nozzle.

the dynamic analyses of the flap. A finite element model with 5593 degrees of freedom and 946 QUAD4 elements was used for analysis because both methods produced acceptable values for stress, deformation, and frequency. For this problem the thickness of the edge beams, stiffeners, and skin panel was considered as the design variables. The flap was designed for minimum weight for von Mises stress, local buckling, displacement, and frequency constraints. The problem had 946 stress and 946 instability constraints, as well as four displacements and one-frequency constraints.

B. Problem 2: Synthesis of a Subsonic Aircraft

The system synthesis capability of COMETBOARDS is illustrated through a subsonic aircraft to operate at Mach 0.85 cruise speed. Solution of this problem required a soft coupling of COMETBOARDS to NASA Langley's aircraft analysis code FLOPS. The FLOPS analyzer encompasses several disciplines: weight estimation, aerodynamic analysis, engine cycle analysis, propulsion data interpolation, mission performance, airfield length requirement, noise footprint calculation, and cost estimation.^{27–29} The objective of the synthesis problem was to determine an optimum airframe-engine design combination for a set of active design variables under specified engine and aircraft behavior parameters to minimize a composite merit function that could be generated as a linear combination of weight, mission fuel, lift-to-drag ratio, and NO_x emission. The design variables considered were engine thrust, wing area, engine design point turbine entry temperature, overall pressure ratio, bypass ratio, and fan pressure ratio. Constraints were imposed on mixed approach climb thrust, second segment climb thrust, landing approach velocity, takeoff field length, jet velocity, and compressor discharge temperature. For the subsonic aircraft model the gross takeoff weight was considered as the merit function.

C. Problem 3: Operation Optimization of a Supersonic Engine

The operation optimization of airbreathing propulsion supersonic engine required a soft coupling of the NASA Engine Performance Program (NEPP) analyzer to COMETBOARDS. The engine-cycle NEPP code can configure and analyze almost any type of gas turbine engine that can be generated through the interconnection of a set of standard physical components such as propellers, inlets, combustors, compressors, turbines, heat exchangers, flow splitters, nozzles, and others. An engine can be designed for different types of hydrocarbon jet fuels, cryogenic fuel, and slurries. For their thermodynamic analysis built-in curve fits generated from empirical results have been incorporated into the NEPP code. A description of the

NEPP code with typical input files for a set of engine configurations can be found in Refs. 30 and 31.

The engine operation optimization problem, with its associated design variables (such as the engine shaft speed, the wave-rotor speed, the flow area, the geometrical parameters of the ducts, etc.) and constraints (imposed on pressure ratios, surge margins, temperature limits, and entrance Mach number, etc.), was cast as a sequence of nonlinear optimization subproblems with thrust as the merit function. Engine operation design became a sequence of interdependent problems, or one optimization subproblem for each operating point. The optimization process typically adjusted a few engine parameters. The difficulty in the engine problem did not lie with the number of active design variables, but it was associated with its multiple operating-point character, constraint validity ranges, and the iterative nature of engine cycle analysis. The most reliable individual optimization algorithm available in COMETBOARDS could not produce a satisfactory feasible optimum solution for this engine problem because of the large number of operation points in the flight envelope, the diversity of the constraint types, and the overall distortion of the design space. However, COMETBOARDS' unique features—which included a cascade strategy, variable and constraint formulations, and scaling devised especially for difficult multidisciplinary applications—successfully optimized the performance of subsonic and supersonic engine concepts. Even when started from different design points, the combined COMETBOARDS and NEPP codes converged to about the same global optimum solution. This reliable and robust design tool eliminated manual intervention in the design of the airbreathing propulsion engines and eased the cycle analysis procedures.

Engine design is illustrated through a supersonic mixed-flow turbofan engine problem. It was configured with 15 components and was designed for a flight envelope with 122 operating points. The design required the solution of a sequence of 122 optimization subproblems. The objective was to maximize the net thrust of the supersonic engine at each operating point, accounting for an installation drag. Each subproblem had three independent design variables and 22 behavior constraints.

D. Problem 4: Design of a Wave-Rotor-Topping Device

A high-bypass-ratio subsonic wave-rotor-topped turbofan engine is made of 16 components that are mounted on two shafts with 21 flow stations. It was modeled with standard components that include an inlet and a splitter, then branching off to a compressor, a duct, and a nozzle. The main flow proceeded through a fan, a duct,

a high-pressure compressor, a duct, a high-pressure turbine, a low-pressure turbine, a duct, and a nozzle. The components mounted on the first shaft included the fan, the compressor along the secondary flow branch, the low-pressure turbine, and a load. The second shaft carried the high-pressure compressor along the main flow, the high-pressure turbine, and a load. The four-port wave-rotor (with burner inlet and exhaust, compressor inlet, and turbine exhaust) was located between the high-pressure compressor and the high-pressure turbine. The engine operating condition was specified by a 47-mission flight envelope, with altitude in the range (sea level to 40,000 ft) and speed between 0.0–0.85 Mach. To examine the benefits that accrue from the wave-rotor device, the engine was optimized considering several of its baseline variables and constraints, not explicitly associated with the wave rotor, as passive. The design objective was to maximize the net engine thrust at each of the 47 operating points. It had two design variables: heat added to the wave rotor and the wave-rotor speed. Its 16 behavior constraints included the corrected speed ratio for the compressor and the fan, the unmixed wave-rotor temperature, the surge margin on the compressor, and the fan pressure ratio for the turbine.

E. Problem 5: Cantilever Beam

Calculation of an optimum profile or depth along the length is illustrated considering the cantilever beam shown in Fig. 5. The beam is made of aluminum with a Young's modulus $E = 10 \times 10^6$ psi, a Poisson's ratio $\nu = 0.3$, and a weight density $\rho = 0.1$ lb/in.³. It is 240 in. long and 6 in. deep. The beam weight was the merit function, and stress and displacement were its behavior constraints. For the purpose of analysis, the beam was modeled with six 20-node-hexahedral elements of the IFM/Analyzers code.³² The finite element model with 160 displacement degrees of freedom was used for analysis because this model adequately predicted the stress and displacement responses of the beam. The profile optimization problem had nine depth design variables, and its nine constraints included eight stress and one displacement limitations.

F. Problem 6: Cylindrical Shell

A cylindrical shell with rigid diagrams under two line loads is shown in Fig. 6. It is made of steel with a Young's modulus $E = 30 \times 10^6$ psi, a Poisson's ratio $\nu = 0.3$, and a weight density $\rho = 0.289$ lb/in.³. It has a radius of 100 in. and length of 200 in. Because of symmetry, only one-eighth of the structure was considered for design optimization. A finite element model with 100 QUAD4 elements of the MHOST analyzer was considered adequate to predict its response. Its design was cast as an optimization problem with weight as the objective function, and constraints were imposed on stress and displacement. The thickness of the cylinder along its length and circumference were considered as design variables through a profiled depth link factor to provide a heavier design under the load. The one-eighth shell model was divided into four substructures along its length. The substructures were clustered to obtain three and four subproblems for sequential and parallel computations, respectively. To avoid convergence difficulty in parallel calculations, an additional (fourth) subproblem was required.

IV. Issues in Multidisciplinary Design Optimization

The four issues—1) local solution and animation, 2) infeasibility and cascade strategy, 3) irregular design and intuition, and

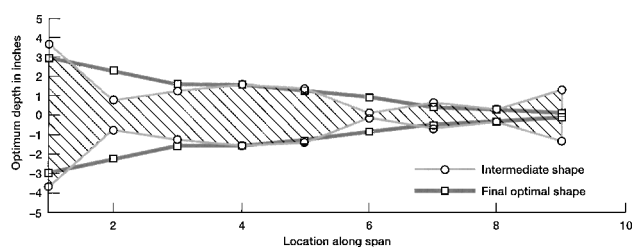


Fig. 5 Profile optimization of a cantilever beam for stress and displacement constraints.

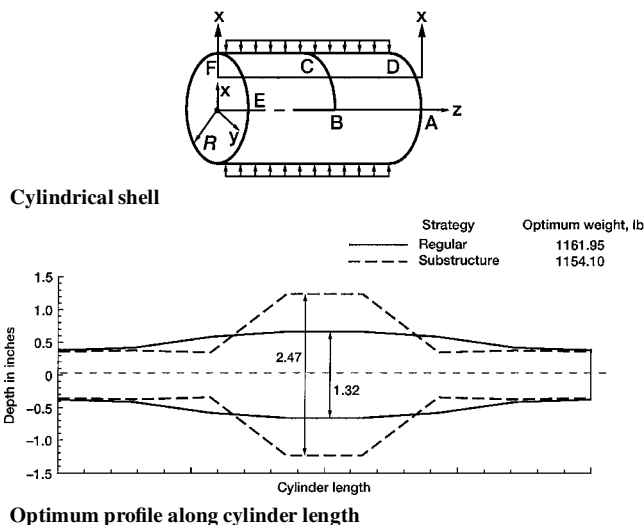


Fig. 6 Substructure optimization of a cylindrical shell.

4) substructure solution and manufacturability—are addressed in this section.

A. Local Solution and Animation

The design of the flap or problem 1, which is depicted in Fig. 4b, was obtained using three optimization algorithms. All three methods produced the same optimum weight of 1448.2 lb. At the optimum the frequency at 40 Hz and displacement at 1 in. were the active constraints. Stress and local instability were passive constraints. Its animation at the 40-Hz frequency was examined, and one frame is depicted in Fig. 4c. The animation exhibited a local frequency condition. The edge beams vibrated with significant amplitude, while the response of the bulk of the structure was insignificant. In other words, only a small part of the structure carried a major portion of the load. In this design the edge beams became more failure prone than other parts of the structure.

The configuration of the flap was modified through an examination of the animation of a series of designs. The final modified configuration was obtained by increasing the depth of a single edge stiffener to 6 in. from its original 3-in. depth. This configuration was optimized. The increase in the material for this stiffener was compensated for by a reduction in the thickness of the edge beam by 58% between the two configurations. The dynamic animation of the flap and the von Mises stress distribution are shown in Figs. 4d and 4e, respectively. The structure vibrated in a breathing type of mode, or the entire flap responded as a single unit. The optimum design also displayed a full stress condition for a major portion of the flap as shown in Fig. 4e. The optimum weight at 1204.7 lb was 20% lighter than the original configuration. Animation-assisted optimization reduced the weight and improved the overall design of the flap.

B. Infeasibility and Cascade Strategy

Individual optimization algorithms encountered difficulty in generating solutions to aircraft and engine problems. A useful strategy that combined the strength of more than one optimizer was conceived. This cascade strategy, using a number of optimization algorithms one followed by another in a specified sequence, was found to be superior to the component optimizers (see Fig. 3d). The cascade algorithm was employed to solve the 10 large structural problems referenced in Sec. II. The success rate of the cascade strategy and the individual algorithms is shown in Figs. 3c and 3e. The cascade strategy solved all 10 problems.

Cascade solutions to the subsonic aircraft, the supersonic mixed-flow turbofan engine, and the subsonic wave-rotor-topped engine are shown in Fig. 7. The subsonic aircraft system design problem was solved using a three-optimizer cascade algorithm: optimizer 1, followed by optimizer 2, and optimizer 1 again. The cascade solution,

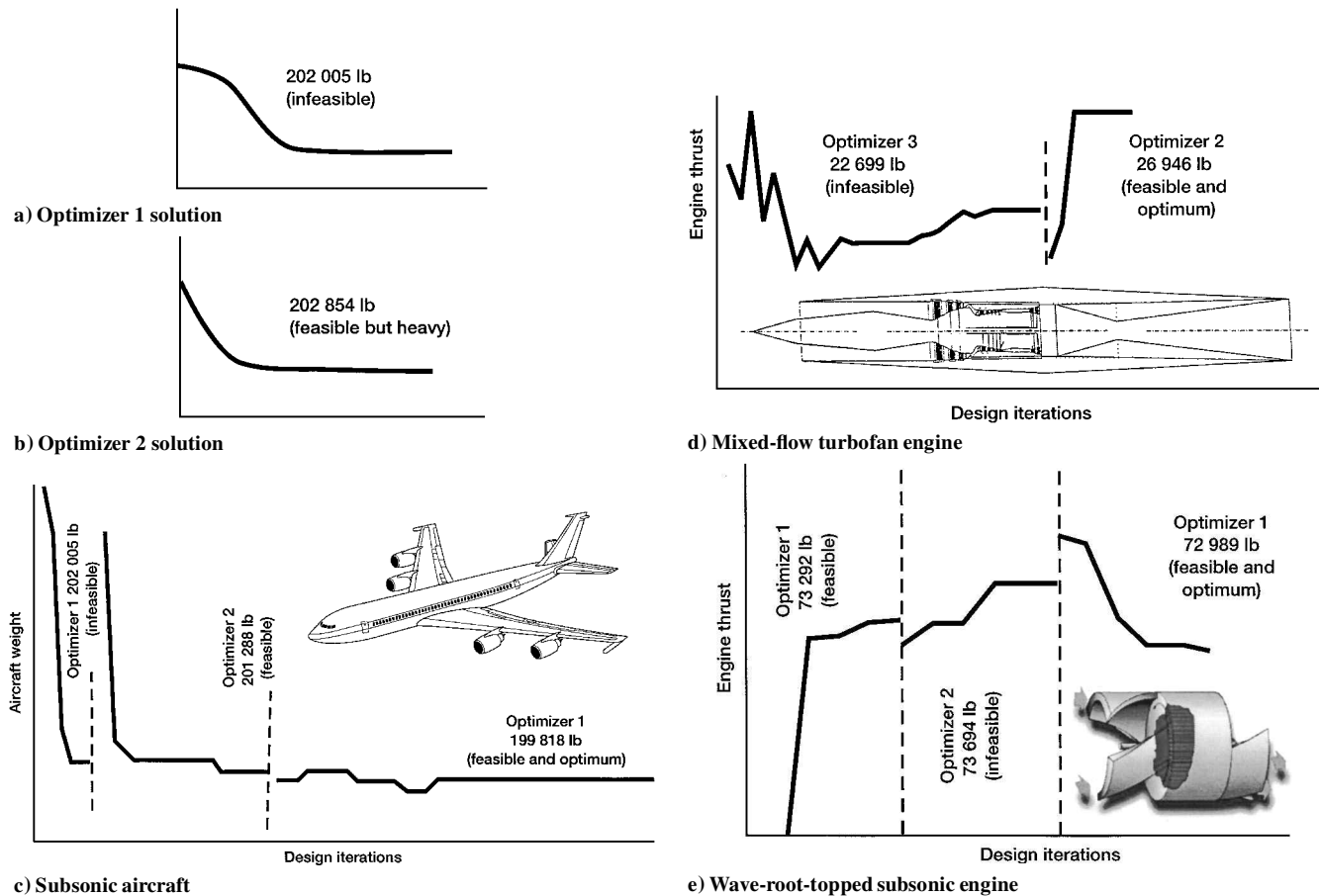


Fig. 7 Cascade solutions for aircraft and engine problem.

along with solutions obtained from individual algorithms, is depicted in Fig. 7 and Table 1.

Optimizer 1, when used alone, converged to a heavy infeasible solution at 202,005 lb for the aircraft weight (see Fig. 7a). Likewise, optimizer 2 alone also produced a heavy design at 202,854 lb, (see Fig. 7b). Optimizer 1 required a takeoff field length of 6282 ft against an available 6000-ft runway. Optimizer 2 overestimated the excess fuel requirement at 8150 gallons against a desired amount of 5000 gallons. The convergence rate of the two algorithms differed producing solutions that were 1 and 2% overweight, respectively, for the two algorithms (see Figs. 7a and 7b). The two solutions, although close to the optimum, were not attractive to industry because they violated the safety margins. A cascade algorithm created from the same two optimizers (optimizer 1-optimizer 2-optimizer 1) successfully solved the problem with a feasible optimum solution at 199,818 lb for the aircraft weight (see Fig. 7c).

Solution of the mixed-flow supersonic and wave-rotor-topped subsonic engines also required the cascade strategy. A two-optimizer cascade (optimizer 3 followed by optimizer 2) successfully solved the supersonic engine problem (see Fig. 7d). The solution to the wave-rotor-enhanced subsonic engine (see Fig. 7e) required a three-optimizer cascade algorithm: optimizer 1 followed by optimizer 2 and optimizer 1 again.

Aircraft (FLOPS) and engine (NEPP) analyzers are nonlinear codes that incorporate multiple disciplines. The analysis assumptions, dependent on altitude, Mach number, and engine power setting, can be challenged. The Newton-Raphson iterations during "engine-balancing" may not converge, leading to an engine "stall condition" with zero thrust, or the NEPP code producing a NaN (not a number) for some constraints. A single optimization algorithm can terminate abruptly, or hit a constraint boundary without any improvement to the merit function. To overcome the difficulties in aircraft and engine analysis codes, we employed two competing approximators: linear regression and neural network methods. Even then, the cascade algorithm was required because individual

algorithms encountered difficulty.¹³ The nature of engine and aircraft problems required the strength of multiple algorithms or the cascade strategy even with the analysis approximators, which, however, was not expected.

C. Irregular Design and Intuition

The profile optimization of the cantilever beam, or problem 5, was attempted with uniform upper and lower bounds for the design variables at 0.5 and 15 in., respectively (see Table 2). The optimization problem was solved using optimizer 4. The solution obtained is shown in Fig. 5 and Table 2. The optimum weight was 1697.5 lb, and the root stress was the only active constraint. An odd-shaped profile shown in Fig. 5 was obtained. The profile was peculiar because the free end, corresponding to a zero stress condition, had a depth of 5.14 in. instead of an anticipated lower bound depth of 0.5 in. The optimum solution most likely challenged linear structural analysis assumptions, and the optimization iterations encountered difficulties. The situation did not improve when a different optimization algorithm or a cascade strategy was employed. The problem was solved successfully with manual intervention. Instead of uniform upper or lower bounds and a single optimization algorithm, the design was cast as a sequence of subproblems. Upper and lower bounds and initial design—through engineering intuition—were progressively changed for the subproblems. This procedure produced a converged solution that is shown in Fig. 5. It had the same minimum weight of 1697.5 lb, which was identical to the odd-shaped design. Its root stress and tip displacement were the active constraints. For this problem optimization algorithms converged to two distinct local solutions with equal minimum weight. Industry will be more inclined to accept the monotonically profiled beam over the odd-shaped design.

The flap design and beam profile calculations represent typical problems of the aerospace industry. Neither problem could be solved satisfactorily without manual intervention. The difficulties

Table 1 Solution to the subsonic aircraft design problem using a cascade strategy

Parameters	Cascade solution (optimizer 1–2–3) optimum design ^a	Optimizer 1 solution (as percent of cascade solution) Infeasible and heavy	Optimizer 2 solution (as percent of cascade solution) feasible but heavy
Weight, lb	199,818.00	1.01	1.02
Design variables			
Wing aspect ratio (from 5 to 12)	8.33	0.94	1.19
Engine thrust (from 20,000 to 70,000 lb)	31,228.21	0.94	0.99
Wing area (from 1000 to 3000 ft ²)	1,936.05	1.04	1.00
Quarter-chord sweep angle of the wing (from 0 to 45 deg)	11.63	0.93	2.32
Wing thickness to chord ratio (from 0.05 to 0.15)	0.09	0.89	1.22
Engine design point turbine entry temperature, °R	3,014.29	0.93	0.94
Overall pressure ratio (from 10 to 40)	39.12	0.83	0.86
Bypass ratio (from 0.1 to 15.0)	5.65	0.61	0.68
Fan pressure ratio (from 1.1 to 3.5)	1.83	1.16	1.14
Constraints			
Approach velocity (not to exceed 125 kn)	118.75	0.98	1.0
Takeoff field length (not to exceed 6000 ft)	6,000.00	6,282.00 ^a	6,000.00 ^a
Landing field length (not to exceed 6000 ft)	5,460.00	0.98	1.0
Mixed approach thrust (normalized with respect to 100,000 lb)	97,000.00	1.02	1.0
Second segment climb thrust (normalized with respect to 100,000 lb)	93,000.00	1.03	0.98
Compressor discharge temperature, °R	1,416.20	0.93	0.95
Excess fuel (normalized with respect to 5000 gal)	5,000.00	2,150.00 ^a	8,150.00 ^a

^aActual values.**Table 2** Intermediate and final solutions for the beam profile

Intermediate solution ^a					Final solution ^b				
Design variable	Lower bound	Initial design	Upper bound	Optimum design	Design variable	Lower bound	Initial design	Upper bound	Optimum design
1	0.5	10.0	15.0	14.68	1	10.0	12.0	13.0	11.72
2	0.5	10.0	15.0	2.98	2	9.0	8.0	12.0	9.00
3	0.5	10.0	15.0	5.04	3	6.0	7.0	10.0	6.22
4	0.5	10.0	15.0	6.27	4	5.0	6.0	9.0	6.17
5	0.5	10.0	15.0	5.41	5	4.0	5.0	8.0	5.02
6	0.5	10.0	15.0	0.50	6	3.0	4.0	7.0	3.67
7	0.5	10.0	15.0	2.49	7	2.0	3.0	6.0	2.00
8	0.5	10.0	15.0	2.67	8	1.0	2.0	5.0	1.32
9	0.5	10.0	15.0	5.14	9	0.5	1.0	4.0	0.50

^aOnly the stress constraint at the root was active. ^bTip displacement and root stress were the active constraints.

encountered to some extent justify the reluctance of the aerospace industry to accept advanced optimization methods, abandoning their time-tested design rules. Neither mathematical programming algorithms nor the traditional design rules could produce optimum hardware configurations that could be manufactured. Their combination, however, was a winner.

D. Subproblem Solution and Manufacturability

A nonmanufacturable solution obtained in the subproblem strategy is illustrated considering the design of a cylindrical shell problem, or problem 6. Solution to the problem was obtained using: 1) regular optimization, where the entire structure was considered as a single problem, and 2) subproblem solution, wherein four overlapping substructures were used. The optimum profiles for the cylindrical shell obtained using regular and subproblem strategies are depicted in Fig. 6. The two optimum weights obtained were 1161.95 and 1154.1 lb for regular and subproblem strategies, respectively. The difference of 0.676% in the solutions could be considered negligible especially for the problem complexity. The depth differed substantially between the two solutions. At the crown the optimum depths of 1.322 and 2.471 in. obtained by the two methods varied by 53%. At the optimum the regular optimization and the subproblem strategy produced a different number of active constraints. The subproblem strategy produced only active stress constraints, whereas

both stress and displacement constraints were active for the regular optimization. The profile obtained using regular optimization was more uniform than that generated through subproblem optimization. To verify the existence of two different designs (one obtained from the subproblem strategy and the other from the regular optimization), we resolved the regular optimization case by setting the initial design equal to the optimum solution that was generated from the subproblem strategy. The solution converged to the initial design, confirming the existence of the two local solutions with about the same minimum weight. For this problem the attractiveness of subproblem strategy has been challenged because the design thus obtained is more difficult to manufacture compared to the regular solution. The authors are not aware of a scheme to alleviate this limitation of the subproblem solution strategy.

V. Discussion

Discussion is given under multiple design solutions and the convergence of algorithms.

A. Multiple Design Solutions

More than one optimum solution can be obtained for engineering design problems. For example, different solutions were obtained for the nozzle flap, beam profile, cylindrical shell, subsonic aircraft, and engine problems. The values of merit function changed little

between the different solutions. The intermediate designs, however, could become nonmanufacturable or their safety could be questioned. These limitations were alleviated through animation and engineering intuition. The utilization of animation improved the design of the nozzle flap, and manipulation of the design bounds promoted the manufacturability of the beam.

Philosophically, we can arrange design methods into a spectrum. Experience occupies the bottom strata. Optimization methods belong to the upper spectrum. Popular design rules occupy the central spectrum. Design improved as we moved from the lower to upper spectrum methods but complexity increased. The design optimization method is in existence for about half a century, yet its full potential has yet to be exploited by industry. The situation can be improved by merging design optimization with the engineering knowledge contained in the broad spectrum methods. This goal can be achieved when proponents of the optimization method and industrial designers work in tandem.

B. Convergence of Optimization Algorithms

Consider the convergence of the subsonic aircraft weight by two different algorithms, shown in Figs. 7a and 7b. Convergence was monotonic by both methods even though the rate differed, as expected. A similar trend was observed for the engine problems. Convergence at times oscillated about a mean solution until the maximum iteration limit was reached. Redundancy of the active constraints, their continuity, and convexity may have created this situation. Engineering design problems might not satisfy some of the basic requirements that form the foundation of mathematical programming methods. For example, the stress and displacement constraints of structural problems are by nature redundant.² The specified range of the constraints of engine and aircraft problems are susceptible to violation during optimization calculations. Optimum solution to multidisciplinary problems of the industry have to be obtained utilizing available analysis and optimization capabilities. The cascade strategy was found successful in generating reliable solutions for structures, aircraft, and engine problems. The cascade strategy was required even when neural network and regression approximators were used to approximate constraints and merit functions of the engineering design problems—this however was not expected.

VI. Conclusions

An animation-assisted optimization successfully solved the flap design problem. The final design was lighter. The entire structure responded as a single unit in the fundamental mode. Cascading of multiple algorithms solved aircraft and engine problems. The design infeasibility was alleviated. The optimum weight was reduced through a redistribution of the parameters of the design. The beam profile problem was solved through engineering intuition. A regular shape was obtained, but there was no change in the optimum weight. Generating a regular manufacturable design using a subproblem optimization scheme still remains a challenge. The process produces different designs with about the same optimum weight. Bringing optimization methods to their rightful industrial environment from the academic plane would require the combined effort of designers and optimization researchers. Industry can benefit from the design optimization methods.

References

- Guptill, J. D., Coroneos, R. M., Patnaik, S. N., and Berke, L., "COMETBOARDS User's Manual," NASA TM-4537, Oct. 1996.
- Patnaik, S. N., Guptill, J. D., and Berke, L., "Singularity in Structural Optimization," *International Journal for Numerical Methods in Engineering*, Vol. 36, No. 6, 1993, pp. 931-944.
- Patnaik, S. N., Lavelle, T. M., Hopkins, D. A., and Coroneos, R. M., "Cascade Optimization Strategy for Aircraft and Air-Breathing Propulsion System Concepts," *Journal of Aircraft*, Vol. 34, No. 1, 1997, pp. 136-139.
- RPK_NASTRAN, COSMIC-12, Univ. of Georgia, Athens, GA, 1984.
- MSC/NASTRAN Quick Reference Guide, Ver. 68, MacNeal-Schwendler Corp., Santa Ana, CA, 1992.
- Nakazawa, S., MHOST, Ver. 4.2, Vol. 1: User's Manual, NASA CR-182235-VOL-1, 1989.
- Vance, V., and Tischler, V. A., "ANALYZE-Analysis of Aerospace Structures with Membrane Elements," Air Force Flight Dynamic Lab., Rept. AFFDL-TR-78-170, Wright-Patterson, AFB, OH, Aug. 1978.
- Patnaik, S. N., Coroneos, R. M., and Hopkins, D. A., "Dynamic Animation of Stress Modes via the Integrated Force Method of Structural Analysis," *International Journal for Numerical Methods in Engineering*, Vol. 40, No. 12, 1997, pp. 2151-2169.
- McCullers, L. A., "Aircraft Configuration Optimization Including Optimized Flight Profiles," *Symposium on Recent Experiences in Multidisciplinary Analysis and Optimization, Part 1*, edited by J. Sobieski, NASA CP2327, Hampton, VA, Jan. 1984.
- Klann, J. L., and Snyder, C. A., "NEPP Programmers Manual," NASA TM-106575, Sept. 1994.
- Hafez, W. A., "Cometnet-User Manual," IntelliSys, Beachwood, OH, July 1996.
- Press, W., Teukolsky, S., Vetterling, W., and Flannery, B., *Numerical Recipes Example Book (C)*, Cambridge Univ. Press, New York, 1987, p. 7.
- Patnaik, S. N., Guptill, J. D., Hopkins, D. A., and Lavelle, T. M., "Optimization for Aircraft Engines with Regression and Neural Network Analysis-Approximators," *AIAA JP*, Vol. 17, No. 1, 2001, pp. 85-92.
- Patnaik, S. N., Coroneos, R. M., and Hopkins, D. A., "Substructuring for Structural Optimization in a Parallel Processing Environment," *Computer-Aided Civil and Infrastructure Engineering*, Vol. 15, No. 3, 2000, pp. 209-226.
- Patnaik, S. N., Gendy, A., Berke, L., and Hopkins, D. A., "Modified Fully Utilized Design (MFUD) Method for Stress and Displacement Constraints," NASA TM 4743, Aug. 1997.
- Vanderplaats, G. N., "DOT Users Manual," Ver. 2.0, Engineering Design Optimization, Inc., Santa Barbara, CA, 1989.
- Belegundu, A., Berke, L., and Patnaik, S. N., "An Optimization Algorithm Based on the Methods of Feasible Directions," *Structural Optimization Journal*, Vol. 9, No. 2, 1995, pp. 83-88.
- Gabriele, G. A., and Ragsdell, K. M., "OPT A Nonlinear Programming Code in Fortran Implementing the Generalized Reduced Gradient Method User's Manual," Univ. of Missouri, Kansas City, MO, 1984, pp. 1-52.
- Lasdon, L. S., and Waren, A. D., "GRG2 User's Guide," Univ. of Texas at Austin, Jan. 1986, pp. 1-60.
- Miura, H., and Schmit, L. A., Jr., "NEWSUMT—A Fortran Program for Inequality Constraint Function Minimization—User's Guide," NASA CR-159070, June 1979.
- Arora, J. S., "IDesign User's Manual," Ver. 3.5.2, Optimal Design Lab., Univ. of Iowa, Iowa City, IA, 1989.
- IMSL MATH/LIBRARY FORTRAN Subroutines for Mathematical Applications, IMSL Inc., Houston, TX, Vol. 3, 1987, Chap. 8, p. 903.
- NAG FORTRAN LIBRARY: MARK 15:E04UCF NAG Fortran Library Routine Document, NAG Inc., Downers Grove, IL, Vol. 4, 1991.
- Patnaik, S. N., Guptill, J. D., and Berke, L., "Merits and Limitations of Optimality Criteria Methods for Structural Optimization," *International Journal for Numerical Methods in Engineering*, Vol. 38, No. 18, 1995, pp. 3087-3120.
- Belegundu, A., and Murthy, P. L. N., "A New Genetic Algorithm for Multiobjective Optimization," *AIAA Paper* 96-4180, Sept. 1996.
- Patnaik, S. N., Coroneos, R. M., Guptill, J. D., and Hopkins, D. A., "Comparative Evaluation of Different Optimization Algorithms for Structural Design Applications," *International Journal for Numerical Methods in Engineering*, Vol. 39, No. 10, 1996, pp. 1761-1774.
- Geiselhart, K. A., "A Technique for Integrating Engine Cycle and Aircraft Configuration Optimization," NASA CR-191602, Feb. 1994.
- Geiselhart, K. A., Caddy, M. J., and Morris, S. J., Jr., "Computer Program for Estimating Performance of Airbreathing Aircraft Engines," NASA TM-4254, May 1991.
- Sommer, S. C., and Short, B. J., "Free-Flight Measurements of Turbulent-Boundary-Layer-Skin Friction in the Presence of Severe Aerodynamic Heating at Mach Number from 2.8 to 7.0," NASA TN-3391, May 1955.
- Caddy, M. J., and Shapiro, S. R., "NEPCOMP—The Navy Engine Performance Computer Program, Version I," Naval Air Development Center-74045-30, April 1975.
- Plencner, R. M., and Snyder, C. A., "The Navy/NASA Engine Program (NNEP89): a User's Manual," NASA TM-105186, Aug. 1991.
- Patnaik, S. N., Coroneos, R. M., and Hopkins, D. A., "Compatibility Conditions of Structural Mechanics," *International Journal for Numerical Methods in Engineering*, Vol. 47, Nos. 1-3, 2000, pp. 685-704.