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# A Cascade Optimization Strategy for Solution of Difficult Multidisciplinary Design Problems

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# A CASCADE OPTIMIZATION STRATEGY FOR SOLUTION OF DIFFICULT MULTIDISCIPLINARY DESIGN PROBLEMS

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## Abstract

A research project to comparatively evaluate 10 nonlinear optimization algorithms was recently completed. A conclusion was that no single optimizer could successfully solve all 40 problems in the test bed, even though most optimizers successfully solved at least one-third of the problems. We realized that improved search directions and step lengths, available in the 10 optimizers compared, were not likely to alleviate the convergence difficulties. For the solution of those difficult problems we have devised an alternative approach called cascade optimization strategy. The cascade strategy uses several optimizers, one followed by another in a specified sequence, to solve a problem. A pseudorandom scheme perturbs design variables between the optimizers. The cascade strategy has been tested successfully in the design of supersonic and subsonic aircraft configurations and air-breathing engines for high-speed civil transport applications. These problems could not be successfully solved by an individual optimizer. The cascade optimization strategy, however, generated feasible optimum solutions for both aircraft and engine problems. This paper presents the cascade strategy and solutions to a number of these problems.

## Introduction

Nonlinear programming algorithms play an important role in the design optimization of engineering systems. Several algorithms with computer codes have been developed during the past few decades. Recently, a CometBoards[1,2] test-bed project that evaluated the performance of 10 optimizers for structural design application was concluded at NASA Lewis Research Center. It showed that none of the 10 optimizers when considered individually could successfully solve all 40 problems in the test bed, even though most optimizers succeeded in solving at least a one-third of the problems. However, every structural problem in the test bed could be solved by at least one of the optimizers. Therefore, repeated attempts with different optimizers were found sufficient to solve structural design problems. These optimizers were used next to solve two sets of nonstructural problems: aircraft system optimization and variable-cycle multimission propulsion engine design. Even the most robust optimizer available in the CometBoards test bed encountered difficulty in generating optimum solutions for either problem set. The difficulty can be attributed to factors such as diverse design variables (the aircraft optimization problems, for example, required combining wing and engine sizes with pressure ratios) and distortion of the constraint space due to different constraint types (takeoff and landing field lengths, compressor temperatures, velocities, etc.). The complexity is further increased by the large sequences of optimization subproblems that have to be solved to design a variable-cycle engine. In brief, constraint formulations and design variable formulations[3] available in the CometBoards test bed that successfully alleviated deficiency and worked satisfactorily for structural problems were inadequate for solving aircraft and engine design problems.

Improving the two key ingredients common to most algorithms (the search directions and the step lengths) and thereby developing a superior optimizer were seriously considered but dropped. We believe that such aspects had been considered by the combined efforts of the developers of the 10 optimizers available in the CometBoards test bed. The optimizers available in the test bed are SUMT[4] (Sequential Unconstrained Minimizations Technique), SLP[5] (Sequential Linear Programming of DOT), FD[5] (Method of Feasible Directions of DOT), mFD[6] (Modified Method of Feasible Directions), SQP[7] (Sequential Quadratic Programming of IDESIGN), IMSL[8] (DNCONG routine of IMSL), NPSOL[9] (E04UCF of NAG library), RG[10] (Reduced Gradient Method), OC[11] (Optimality Criteria Methods), and FUD[11] (Fully Utilized Design). We conceived an alternative approach that derives benefit from the strengths of more than one optimizer, called the cascade optimization strategy, to solve aircraft and engine design

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problems. The cascade strategy uses a number of optimization algorithms, one followed by another in a specified sequence. A cascade strategy, for example, can be created by using three optimizers, such as SUMT, FD, and NPSOL. In this strategy the problem is solved first by SUMT, and an intermediate optimum solution is obtained. The second cycle is begun from the SUMT solution with some damping. The process is continued with the third optimizer (NPSOL). This cascade strategy was found to be superior to using any of the three individual optimizers, especially for multiple-mission engine problems.

The CometBoards test bed is briefly described next, followed by the cascade strategy, solutions of aircraft and engine design problems, and finally conclusions.

## CometBoards Test Bed

The organization of the CometBoards test bed, which was developed for the performance evaluation of different optimizers for structural design applications, is depicted in figure 1. Reading analysis and design information through input data files (Analysis Data, Design Data, Optimizer Data), the software casts the design as a nonlinear programming problem with weight as the objective function and constraints on stresses, displacements, and frequencies. The code then solves the problem by using a user-specified optimization algorithm and a user-specified analysis method. There are 10 choices for optimizer. The analyzer options used in the comparative evaluation were the Air Force code ANALYZE/DANLYZE[12] and NASA IFM[13] (Integrated Force Method) codes along with a simplified IFM.[14] The CometBoards test bed has considerable flexibility in solving a structural design problem by choosing any one of the 10 optimizers and any one of the three analyzers. A more detailed description of the CometBoards test bed can be found in reference 1. It should be noted that the scope of the CometBoards software has been expanded since its inception several years ago. The original name however, is still maintained.

To introduce the performance of different optimizers, a set of 10 large structural problems (with more than 40 independent design variables and a few hundred behavior constraints) were solved and the solutions depicted in a bar chart format (fig. 2). In this figure the normalized optimum weights for the problem set are depicted (optimum = 1, overdesign >1, and infeasible <1). From figure 2, we observed that no single optimizer worked satisfactorily for all the large problems, even though most optimizers successfully solved at least one- third of the problems. However, every one of the 10 large structural problems was solved by at least one of the optimizers. Overall, three optimizers (IMSL, SUMT, and SQP) were found to be reliable and efficient for most structural problems.[2]

Take, for example, the design of an intermediate-complexity wing, which is problem 8d in figure 2. The merit function was weight. The problem had 57 independent linked design variables with 316 stress constraints, 4 displacement constraints, and 1 frequency constraint. The optimum weight was 388.25 lb and there were 119 active constraints (117 stresses, 1 displacement, and 1 frequency). For this problem the SUMT and OC optimizers converged to the correct optimum. Performances of other optimizers were not satisfactory for this problem. Fortunately, however, at least one optimizer was successful in solving any one of the structural problems. This was not the case for aircraft and engine problems. For a number of such problems a single individual robust optimizer converged to a solution that quite often was suboptimal, infeasible, and sometimes heavy. However, such results for some problems were quite close to the optimum with mild constraint violations. The cascade strategy has been developed to solve these difficult optimization problems.

## Cascade Optimization Strategy

The CometBoards system can solve a problem by using a cascade strategy created by reading information through an input data file. A cascade optimization strategy can be created by specifying a number of optimizers and their sequence in the input data file. For example, a four-optimizer cascade (SLP followed by SQP, then FD, and finally SQP) was successfully used to solve a subsonic aircraft problem. Note that the optimizer SQP was used twice, in the second and fourth stages of the cascade, which is allowed. Each optimizer can use its individual stop criterion at the discretion of the designer. For example, it may sometimes be preferable to specify a coarse convergence criterion for the first optimizer and a fine stop criterion for the last optimizer in the cascade. All parameters, such as the design variables, the behavior constraints, and the objective function, are scaled before beginning any optimization activity, so that their relative values are around unity. The first optimizer used in this example (SLP) is begun from a user-specified initial design; this procedure is called a cold start.

The intermediate solution from the first optimizer is perturbed by using a pseudorandom technique with a user-specified percentage variation read from an input data file. For example, 3% to 5% random perturbations can be used for the first optimizer solution. The second optimizer (SQP) is begun from the perturbed intermediate SLP solution; this procedure is called a hot start.

The preceding step is repeated for the remaining optimizers in the cascade (FD and again SQP). For each subsequent hot start the percentage of random perturbation can be reduced for numerical efficiency and fast convergence. If the solution generated by the cascade is unsatisfactory, a second cascade with a different sequence of optimizers should be attempted. Depending on the nature of the problem a specific optimization strategy may have to be developed for a successful solution. The important issues in designing a cascade strategy are the number of optimizers, their sequence, and the stop criterion for each individual optimizer.

## Design of Advanced Aircraft Concept

Design optimizations of advanced subsonic and supersonic aircraft concepts have been attempted successfully through a "soft coupling" of the Flight Optimization Systems (FLOPS[15]) analyzer to the design tool CometBoards. The FLOPS analyzer, through its control and eight discipline modules (weights, aerodynamics, engine cycle analysis, propulsion data scaling and interpolation, mission performance, takeoff and landing, noise footprint, and cost analysis), can evaluate advanced aircraft concepts and formulate their designs as a nonlinear programming problem. Options exist for a number of merit functions, such as gross takeoff weight, weight of fuel burned, range, cost, and oxides of nitrogen emissions. Free variables for the purpose of optimization include wing area, wing sweep, wing aspect ratio, wing taper ratio, wing thickness-chord ratio, and thrust or engine size. Important behavior constraints are Mach number, altitude, approach velocity, jet velocities, mixed thrust, climb thrust, takeoff and landing field lengths, maximum turbine temperature, overall pressure ratio, and bypass ratio for a turbofan.

The resulting multidisciplinary optimization problem has extremely distorted design space, since both design variables and constraints vary over a wide range. For example, an engine thrust design variable (which is measured in kilopounds) is immensely different from the bypass ratio variable (which is a small number). Likewise, landing velocity constraint (in knots) and field length limitation (in thousands of feet) differ both in magnitude and in units of measure. The difficult nature of the design problem is further compounded by statistical, empirical equations and smoothing techniques employed in the FLOPS analyzer. The FLOPS analyzer, in other words, can be numerically unstable for some combinations of design variables, especially for a subsonic aircraft.

Direct solution of the problem by using the most robust individual optimizer available in CometBoards could not provide satisfactory results. However, the application of some advanced features and unique strengths of the CometBoards design tool, such as a cascade strategy, state-of-the-art optimization algorithms, design variable formulation, constraint formulation, and global scaling strategy, successfully solved a number of advanced aircraft design problems.

The cascade optimization strategy is illustrated here for a subsonic aircraft takeoff weight optimization. No single optimizer (e.g., SLP, SQP, FD, SUMT, or IMSL) could provide a satisfactory feasible optimum solution. However, a four-optimizer cascade strategy was successful in solving the aircraft design optimization problem. The four optimizers used were

(1) Sequential Linear Programming. The SLP optimizer, which can provide a quick solution, was used as the first candidate in the cascade strategy. The SLP optimizer oscillated rather violently for the first few design iterations but produced a converged solution in about 30 iterations (fig. 3). For the problem the SLP solution was infeasible and 1380.4 lb heavier than the true optimum takeoff weight.

(2) Sequential Quadratic Programming: The SQP optimizer was begun from the SLP solution with a 4% random perturbation. The algorithm converged to an infeasible solution in about 10 iterations (fig. 3). This solution was 598.9 lb lighter than the SLP results but heavier than the true optimum by 781.5 lb.

(3) Method of Feasible Directions: The FD algorithm was begun from the SQP solution with 1% perturbation. The FD optimizer produced a feasible design in about 10 iterations that was suboptimal by 738.7 lb.

(4) Sequential Quadratic Programming: The SQP, which was begun with 1% perturbation from the FD optimizer solution converged in about 25 iterations. It produced a feasible optimum solution of 199 275.6 lb for the takeoff weight of the subsonic aircraft (which was subsequently verified graphically). The four-optimizer cascade strategy successfully solved the subsonic aircraft design problem.

## Wave-Rotor-Topped Engine Design

Conceptually, the wave rotor replaces the combustor in conventional air-breathing engines. Wave rotor topping can lead to higher engine specific power or more thrust for less fuel consumption. Design optimization was carried out for a 47-mission-point (specified through altitudes, Mach number, flow rates, etc.), wave-rotor-enhanced subsonic gas turbine engine with four ports (combustor exhaust and inlet ports, compressor inlet port, and turbine exhaust port).

The engine performance analysis and the constraint and objective formulations were carried out through a soft coupling of NASA Engine Performance Program (NEPP[16]) to the design optimization tool CometBoards. To examine the benefits that accrue from wave rotor enhancement, the engine was designed by declaring most of the baseline variables and constraints to be passive while considering important parameters directly associated with the wave rotor to be active. The active variables considered were rotational speed of the wave rotor, heat added, and fuel flow. Important active constraints included limits on maximum speeds on all compressors, 15% surge margin for all compressors, and maximum wave rotor temperature. The engine thrust was considered as the merit function.

The wave rotor engine design became a sequence of 47 optimization subproblems. Only the cascade strategy could solve the problem successfully for the entire flight envelope. For the mission point (defined by Mach = 0.1 and altitude = 5000 ft), the convergence of the two-optimizer (SQP followed by FD) cascade strategy is shown in figure 4. The first optimizer (SQP) produced an infeasible design at 67 060.87-lb thrust in about five design iterations. The second optimizer (FD), begun from the SQP solution with a small perturbation, produced a feasible optimum design with an optimum thrust of 66 901.28 lb (fig. 4). The optimum solution is verified graphically in figure 5. In this figure, observe the differences between the individual-optimizer (NEPP) solution obtained with manual intervention versus the cascade solution. The cascade (CometBoards) solution produced higher thrust than the NEPP. Furthermore, the compressor speed was an active constraint in the cascade technique but passive for the NEPP solution. In brief, the cascade strategy was successful for the subsonic wave rotor design optimization problem.

## Mixed-Flow Turbofan Engine Design

The design of a high-speed civil transport air-breathing propulsion system for multimission variable-cycle operations has been optimized successfully through a soft coupling of the engine performance analyzer NEPP to the design tool CometBoards. Design optimization of a mixed-flow turbofan engine with constraints specified on maximum compressor speed, an acceptable compressor surge margin with specified safety factors, discharge temperatures, pressure ratios, a mixer extreme Mach number, etc., has been cast as a nonlinear optimization problem. The engine thrust is the merit function; and bypass ratio, mixer pressure balance, r-values (safety factors) for fans and compressors, fuel flow, etc., are important active design variables. The most reliable individual optimization algorithm available in CometBoards could provide feasible results for only a portion of the aircraft flight envelope because of the large number of mission points, the diverse constraint types, and the overall ill conditioning of the design space. Only the cascade strategy could successfully solve the engine design problem for the entire 122-mission-point flight envelope. Furthermore, the cascade strategy converged to the same global solution even when begun from different design points. The cascade solution was normalized with respect to the NEPP solution, which was obtained by using an individual optimizer and manual interventions. The cascade solution (fig. 6) was found to be superior for most of the 122 mission points, except for a few cases (fewer than 10 mission points) for which both (cascade and NEPP) optimum results agreed. In brief, the cascade optimization strategy successfully solved the 122-mission-point engine optimization problem.

## Conclusions

Reliable optimum solutions for structural problems can be obtained through individual optimizers by using constraint and design variable formulations.

Individual optimizers, however, were found to be inadequate for difficult aircraft and engine design problems.

A cascade strategy designed by combining a number of robust optimizers successfully solved several subsonic and supersonic aircraft problems, multimission high-speed civil transport engine design problems, and wave-rotor-topped engine design problems.

The open issues with the cascade strategy include the sequencing of optimizers, the individual stop criterion, and the pseudorandom damping for specific problems. Careful planning and strategizing of the issues can provide a successful cascade strategy that will be robust and numerically efficient. The cascade strategy may be problem dependent.

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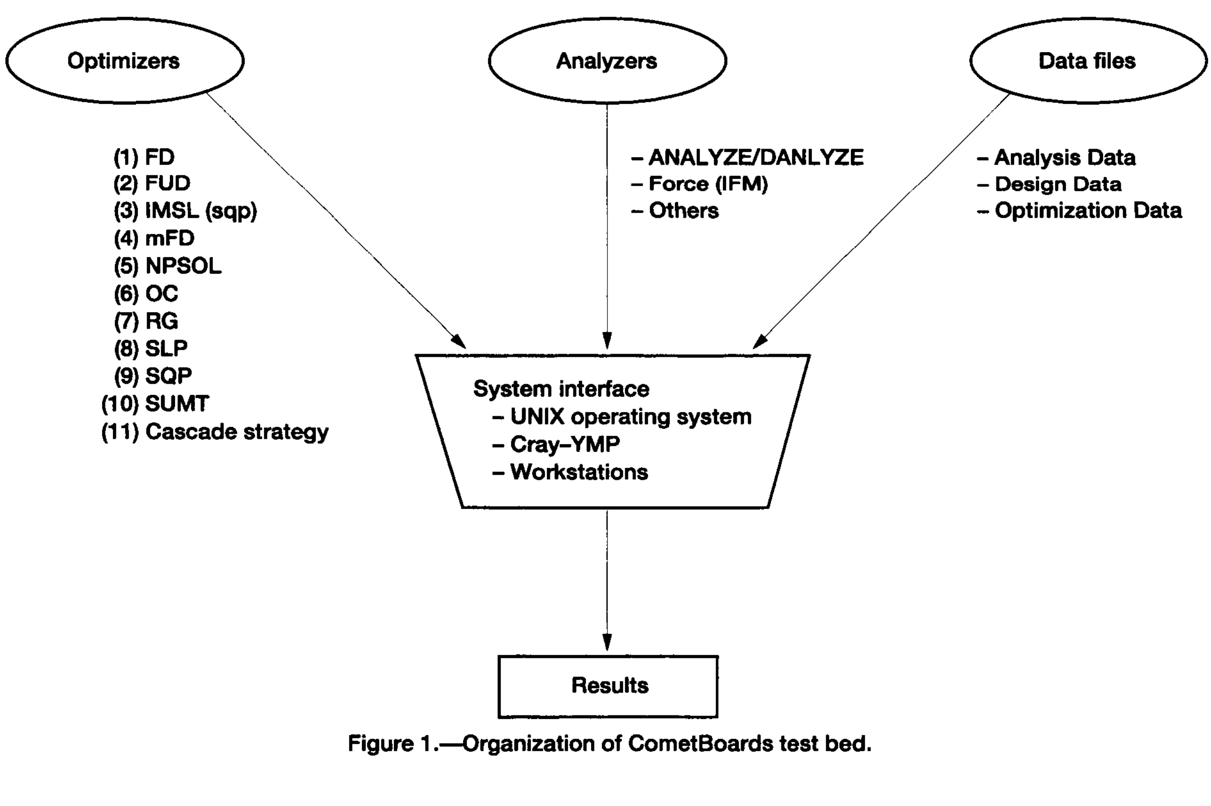


Figure 1.—Organization of CometBoards test bed.

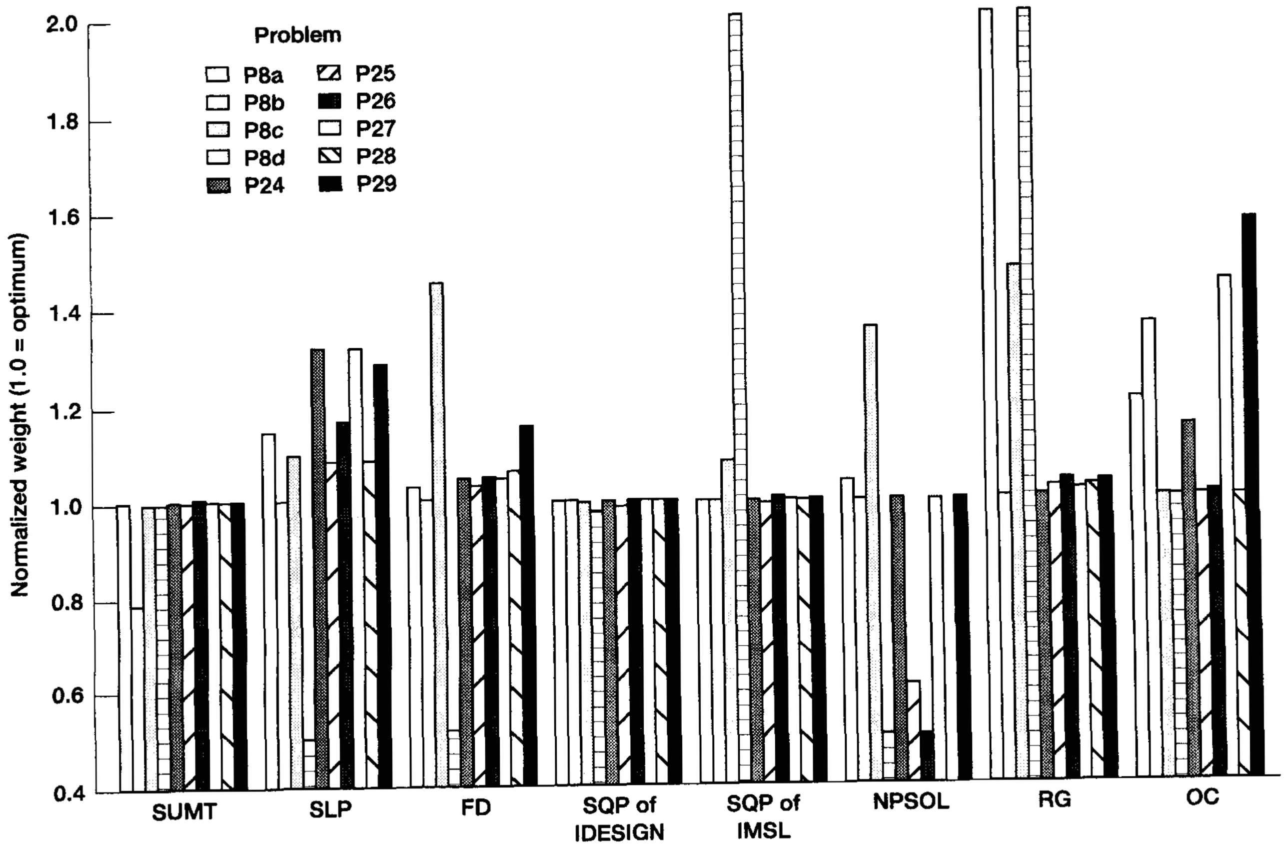


Figure 2.—Performance of different optimizers for large problems.

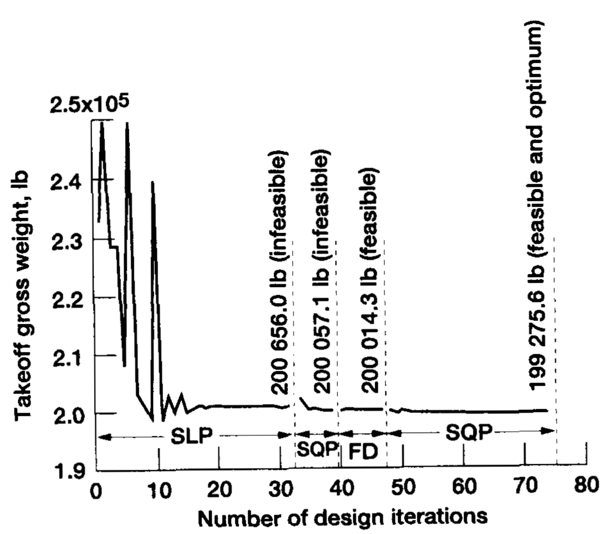


Figure 3.—Cascade optimization strategy for design of subsonic aircraft.

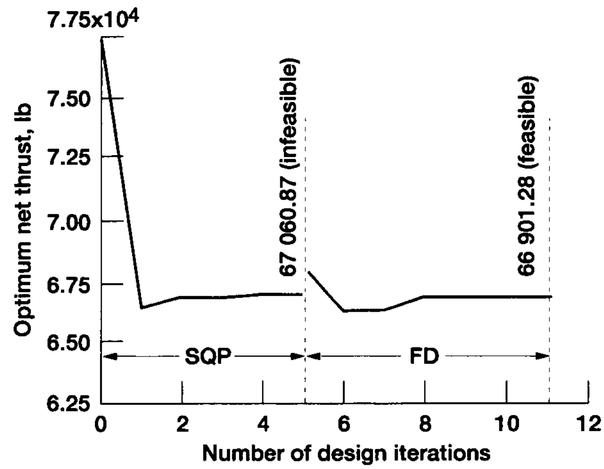


Figure 4.—Convergence of cascade solution for subsonic wave rotor.

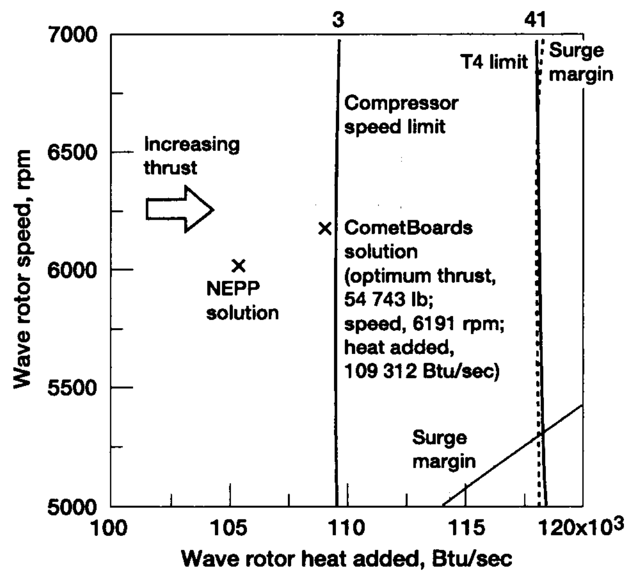


Figure 5.—Graphical verification for subsonic wave rotor.

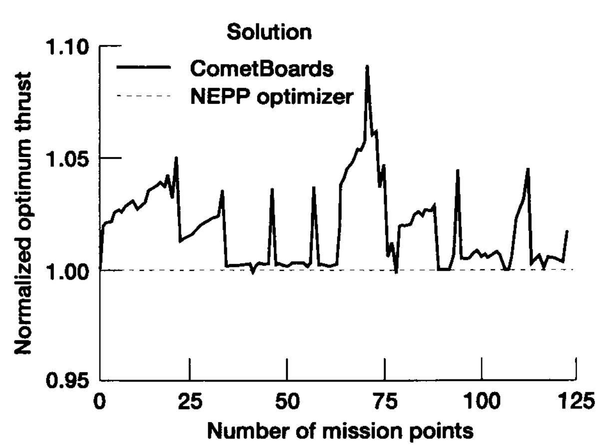


Figure 6.—Value-added benefit in design for mixed-flow turbofan engine.

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