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Optimization of Air-Breathing Engine Concept

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Summary

The design optimization of air-breathing propulsion engine concepts has been accomplished by soft-coupling the NASA Engine Performance Program (NEPP) analyzer with the NASA Lewis multidisciplinary optimization tool COMETBOARDS. Engine problems, with their associated design variables and constraints, were cast as nonlinear optimization problems with thrust as the merit function. Because of the large number of mission points in the flight envelope, the diversity of constraint types, and the overall distortion of the design space; the most reliable optimization algorithm available in COMETBOARDS, when used by itself, could not produce satisfactory, feasible, optimum solutions. However, COMETBOARDS' unique features—which include 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 results converged to the same global optimum solution. This reliable and robust design tool eliminates manual intervention in the design of air-breathing propulsion engines and eases the cycle analysis procedures. It is also much easier to use than other codes, which is an added benefit. This paper describes COMETBOARDS and its cascade strategy and illustrates the capabilities of the combined design tool through the optimization of a high-bypass-turbofan wave-rotor-topped subsonic engine and a mixed-flow-turbofan supersonic engine.

Introduction

The NASA Engine Performance Program (NEPP) can be used for the analysis and preliminary design of subsonic and supersonic air-breathing propulsion engine concepts. NEPP can evaluate the performance of an engine over its flight envelope for various mission points, which are defined by different Mach number, altitude, and power-setting combinations. It also can optimize engine parameters at specified mission points. However, NEPP can experience difficulties with optimization, producing infeasible suboptimal solutions that require manual redesign. In an effort to eliminate the optimization deficiency of the NEPP code and improve its reliability, we combined NEPP with COMETBOARDS (Comparative Evaluation Test Bed of Optimization and Analysis Routine for the Design of Structures). This combined tool has successfully optimized a number of subsonic and supersonic engines. Some of COMETBOARDS' key features and unique strengths that assisted in optimizing the engines include a cascade optimization strategy, constraint and design formulations, and a global scaling strategy. This paper presents a brief introduction to the COMETBOARDS design tool and the NEPP analyzer. The design optimization capability of the combined tool is illustrated by considering a subsonic wave rotor topped engine and a mixed-flow-turbofan supersonic engine as examples.

COMETBOARDS Test Bed

The multidisciplinary design optimization test bed, COMETBOARDS, which is used in the design of air-breathing propulsion engines, has the modular organization depicted in figure 1. Some key features of the test bed are multidisciplinary optimization (with separate objective, constraints, and variables for each discipline), substructure optimization in sequential and parallel computational platforms, and state-of-the-art optimization algorithms. An analysis approximation by means of linear regression analysis and neural networks is being added. The COMETBOARDS system first formulates the design as a nonlinear mathematical programming problem, and then it solves the resulting problem. The problem can be formulated (variables, constraints, objective, etc.) by the analysis tools available in the "Analyzers" module reading specified data in the "Data files" module. A number of analysis tools (RPK/NASTRAN (ref. 1) for structural analysis, NEPP (ref. 2) for air-breathing engine performance analysis, FLOPS (ref. 3) for aircraft flight optimization analysis, etc.) are available in COMETBOARDS, and provision exists for the soft-coupling and quick integration of new analysis tools. The NEPP and FLOPS analyses are interfaced to COMETBOARDS through system calls. The COMETBOARDS solution technique exploits several of the unique strengths that are available in its "Optimizers" module, such as a cascade optimization strategy, the formulation of design variables and constraints, and a global scaling strategy. COMETBOARDS, which is written in the FORTRAN 77 language, is currently available for Cray and Convex computers and Iris and Sun workstations. Successful COMETBOARDS solutions for a number of diverse industrial problems (such as components of the space station, the rear divergent flap of a downstream mixing nozzle for a High Speed Civil Transport (HSCT) engine, system optimization for subsonic and supersonic aircraft, thrust optimization for multimission HSCT mixed-flow-turbofan engines, and optimization of a wave-rotor concept in propulsion engines) illustrate its versatility and robustness.

Cascade Optimization Strategy

COMETBOARDS can solve difficult optimization problems by using the cascade strategy depicted in figure 2. This strategy uses more than one optimizer to solve a complex problem when individual optimizers face difficulties. With COMETBOARDS, users have considerable flexibility in developing cascade strategies: selections can be made from a number of optimizers, their convergence criteria, analysis approximations, and the amount of random perturbations between optimizers. Consider, for example, a four-optimizer cascade (one optimizer followed by three other optimizers) that was used to successfully solve a subsonic aircraft problem. For such a cascade, individual convergence criteria can be specified for each optimizer. For example, a coarse stop criterion may be sufficient for the first optimizer, whereas a fine stop criterion may be necessary for the last optimizer. Likewise, an approximate analysis may suffice for the first optimizer, although an accurate analysis can be reserved for the final optimizer. The amount of pseudorandom perturbation for design variables may be specified between the optimizers at the discretion of users. A more indepth description of COMETBOARDS can be found in references 4 to 6.

NASA Engine Performance Program (NEPP)

The NEPP engine simulation computer code performs zero-dimensional, steady-state, thermodynamic analysis of turbine engine cycles. By using a flexible method of input, a set of standard components are connected at execution time to simulate almost any turbine engine configuration that the user may contemplate. Off-design performance is calculated through the use of component performance maps. The compressor and turbine performance maps are scaled by the code to match the design point pressure ratio, corrected weight flow, and efficiency of the engine being modeled. The default thermodynamic routine used in the code is preset for a mixture of air and JP4 fuel. A chemical equilibrium model is incorporated as an option to adequately predict thermodynamic properties when chemical dissociation occurs as well as when virtually any fuel is used. To determine the performance of an engine over a flight envelope, the user will define many different operating conditions representing different Mach number, altitude, and power setting combinations. Each one of these points represents a separate analysis problem. Often when a cycle is being studied there are several values that can be varied to give best engine performance. For example, an engine design may have a variable geometry fan that allows fan rotor blade angles to be set to give the best fuel consumption subject to certain performance constraints such as fan surge margin. Thus, when creating a simulation of this cycle, an optimization scheme is needed to determine the "best" fan rotor blade angles for a given engine operating condition. NEPP currently uses Powell's conjugate direction method for optimization, but experience in using this algorithm with NEPP has shown it to be lacking. Often the results are not the optimum values and require further fine-tuning by the engineer. One common problem is that the optimizer fails to push the design hard up against a constraint, even when doing so would improve the results. Combining COMETBOARDS and NEPP is an attempt to compensate for NEPP's deficiency.

Design of a Wave-Rotor-Topped Engine

Conceptually, a wave rotor replaces a burner in conventional air-breathing engines. The wave-rotor topping can lead to higher specific power in the engine, or to more thrust for less fuel consumption. Design optimization was carried out for a high-bypass-ratio-turbofan wave-rotor-enhanced subsonic engine with four ports (the burner inlet, burner exhaust, compressor inlet, and turbine exhaust ports). Figure 3 depicts the 47 mission points. NEPP generated the engine performance analysis and the constraint and objective formulations, whereas COMETBOARDS optimized the design. To examine the benefits that accrued from the wave-rotor enhancement, we designed the engine under the assumption that most of the baseline variables and constraints were passive and that the important parameters directly associated with the wave rotor were active. The active variables considered were the rotational speed of the rotor and the heat added to it. Important active constraints included limits on the maximum speeds of all compressors, a 15-percent surge margin for all compressors, and a maximum wave-rotor exit temperature. The engine thrust was selected as the merit function. The wave-rotor-engine design became a sequence of 47 optimization subproblems (one for each mission point). Only by using the cascade strategy could the problem be solved successfully for the entire flight envelope. Figure 4 shows the convergence of the two-optimizer cascade strategy for the mission point defined by Mach = 0.1 and altitude = 5000 ft. The first optimizer produced an infeasible design at 67 061-lb thrust in about five design iterations. The second optimizer, starting from the first solution with a small perturbation, produced a feasible optimum design with a thrust of 66 901 lb. For these 47 mission points, figure 5 shows the optimum solutions obtained with the combined tool and normalized with respect to the NEPP results. This figure depicts the benefits of optimizing wave-rotor design with the combined COMETBOARDS–NEPP design tool. Figure 5 shows that the combined tool produced a design with a higher thrust over all 47 mission points than did NEPP, with maximum increases around mission points 12, 26, and 32. Both NEPP and COMETBOARDS–NEPP produced identical optimum thrust values for a few mission points; however, the maximum difference in thrust exceeded 5 percent for several mission points. These differences could be significant if the design points with increased thrust were used to size the engine. The combined COMETBOARDS–NEPP tool successfully solved the subsonic wave-rotor-engine design optimization problem.

Mixed-Flow-Turbofan Supersonic Engine for High Speed Civil Transport System

Optimization of a 122-mission-point mixed-flow-turbofan supersonic engine also was attempted with the COMETBOARDS–NEPP combined tool. This optimization required the solution of a sequence of 122 optimization subproblems (again, one for each mission point). For each subproblem, the thrust of the engine was considered as the merit function. The important active design variables considered were engine bypass ratio, fan operating point determined by fan speed, and surge margin. The important constraints considered were maximum speed on all compressors, acceptable surge margin for all compressors, compressor discharge temperatures, and maximum mixer corrected flow. Because of the sequence of a large number of optimization subproblems, the diverse constraint types, and the overall ill conditioning of the design space, the most reliable individual optimization algorithm available in COMETBOARDS could provide feasible results for only a portion of the 122-mission-point flight envelope. A four-optimizer cascade strategy could successfully solve the engine design problem for the entire 122-mission-point flight envelope. Furthermore, calculations for the cascade strategy converged to the same global solution when begun from different design points. The cascade solution was normalized with respect to the NEPP results, which were obtained by using an individual optimizer. This normalized solution, which is shown in figure 6, was found to be superior for most of the 122 mission points, except for a few cases for which both the COMETBOARDS and NEPP optimum results agreed. For flight around mission point 70, optimum thrust was about 10 percent higher for COMETBOARDS than for NEPP. COMETBOARDS successfully solved the 122-mission-point, mixed-flow-turbofan engine design problem.

Summary

The COMETBOARDS design tool, when augmented with the NEPP analyzer for air-breathing propulsion engines, successfully solved a number of subsonic and supersonic engine design problems. COMETBOARDS' advanced features and unique strengths made engine design problems easier to solve. Its cascade optimization strategy was especially helpful in generating feasible optimum solutions when an individual optimizer encountered difficulty. Calculations for the cascade strategy converged to the same optimum design even when they started from different initial design points. For most mission points, the combined tool increased the value of the optimum thrust by a few percentage points. Such improvements can become critical especially when engines are sized for such mission points. The research-level software COMETBOARDS, with some enhancements and modifications, can be used by the aircraft industry.

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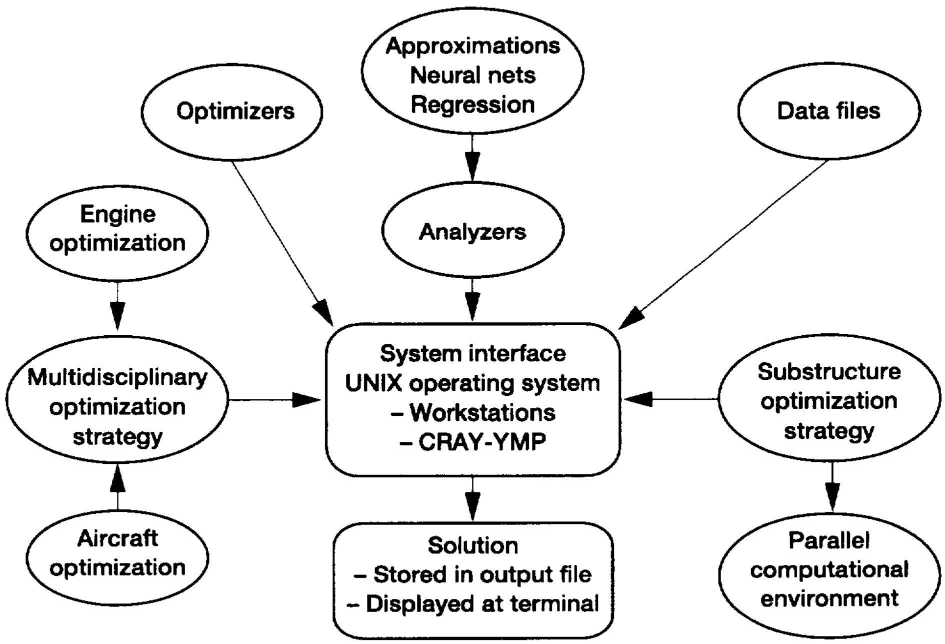

Fig. 1.—COMETBOARDS: General-purpose optimization engine for multidisciplinary design problems.

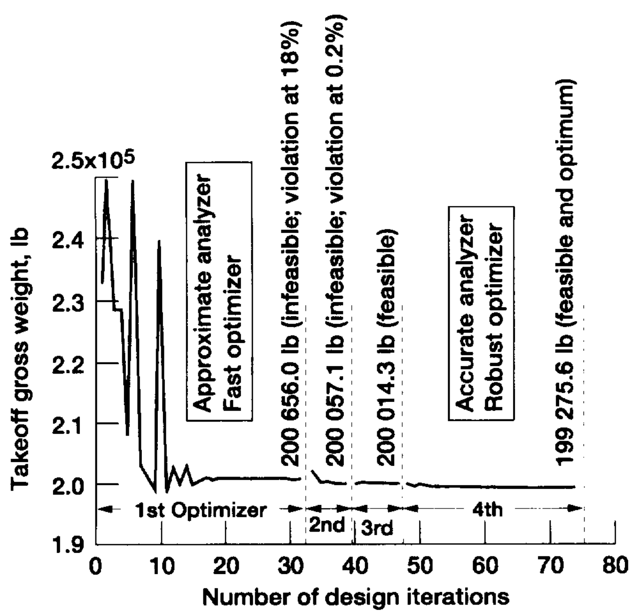

Fig. 2.—Cascade solution for a subsonic aircraft.

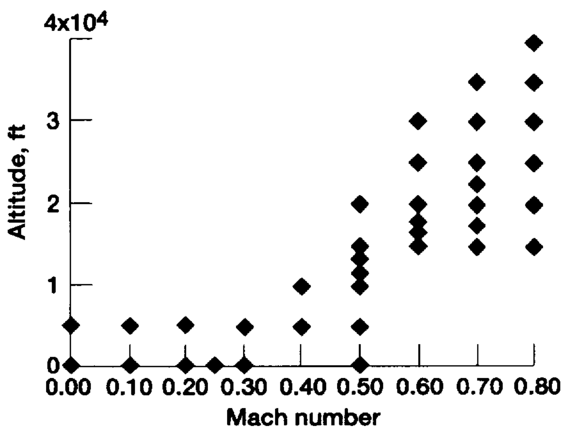

Fig. 3.—Forty-seven mission points for high-bypass-ratio-turbofan wave-rotor-topped engine.

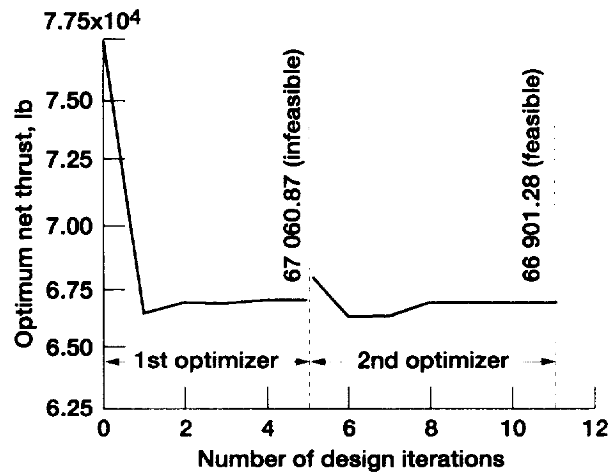

Fig. 4.—Cascade solution for a wave-rotor-topped subsonic engine.

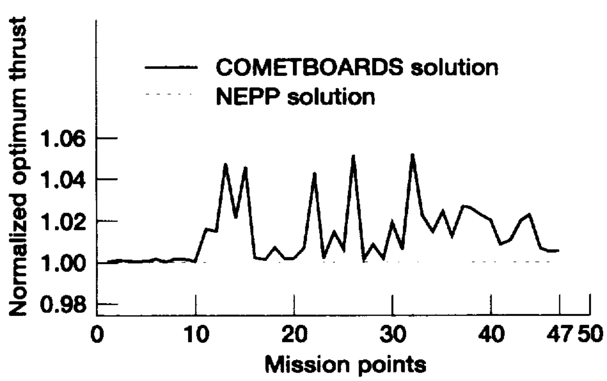

Fig. 5.—Value-added benefit in design of a 47-mission-point, high-bypass-turbofan subsonic engine using a wave rotor.

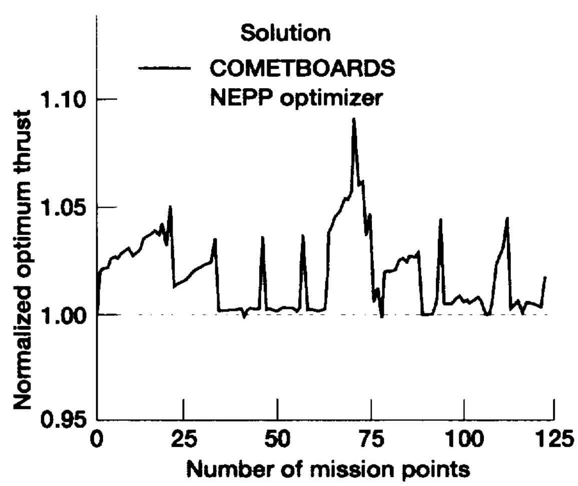

Figure 6.—Value-added benefits in the design of a mixed-flow turbofan engine.

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