Table 1 Range of reduced frequencies used in flutter calculations for fitting the aerodynamic coefficients of the different modes

Mode	1	2	3	4	5	6	7	8	9	10
k_{min}	0.05	0.05	0.05	0.05	0.10	0.10	0.20	0.30	0.40	0.50
k_{max}	0.30	0.30	0.30	0.30	0.40	0.50	0.60	0.70	0.80	0.80

Table 2 Summary of the different flutter results

Flutter case	Exact results Pade with $n_L = 4$	Proposed method restricted k range	Proposed method unrestricted k range	Proposed method real coefficients restricted k range	Pade with $n_L = 1$	Pade with $n_L = 2$	Pade with $n_L = 3$
Open loop							
Q_F, psf	99.7	97.9	110.5	120.2	96.8	99.1	98.9
ω_F, rad/s	50.2	49.7	53.8	57.8	49.3	49.9	50.0
Closed loop							
Q_F, psf	174.5	175.7	171.6	166.6	181.3	172.2	173.5
ω_F, rad/s	48.7	48.5	50.9	53.4	46.4	48.9	49.3

about the same computational labor as a 30 × 30 eigenvalue problem having real coefficients obtained using the Pade representation with a single lag term. Hence, the method proposed herein can be justified in terms of computational efficiency only if it proves to have some advantages over the Pade representation with small number of lag terms. However, as stated earlier, the study of figures similar to Fig. 2 have shown that the proposed approximation yields an accuracy that is higher than the one obtained using Eq. (1) with two lag terms. Table 2 summarizes the flutter results obtained with various n_L lag terms. It can be seen that the results obtained using Pade representation with $n_L = 3$ are only very slightly superior to those obtained using the complex polynomial representation given by Eq. (2). Hence, even if we assume that the proposed method yields results comparable only to the Pade representation with $n_L = 2$ (a somewhat conservative assumption), then the open-loop case turns to be twice as fast compared to the Pade method (with $n_L = 2$). Lastly, it can be argued that good flutter results can be obtained using a smaller number of lag terms, when using the MS method. This is all true. However, the MS method requires an iterative double least-square method for fitting the aerodynamic coefficients, which needs to be taken into account when considering its relatively small number of lag terms.

Conclusions

In conclusion it can be stated that a method is presented by which a p-type flutter analysis can be performed using complex EOM with absolutely no lag terms and no iterations. It is shown that the combination of complex coefficients, together with a restricted range of k over which these coefficients are fitted, is responsible for the high accuracy obtained. This proposed method can replace the $p-k$ method and may readily be used to perform routine open-/closed-loop flutter calculations, or to design control laws using parametric optimization of selected variables. However, it cannot be used, in its present form, to design control laws using optimal control theory, since the resulting equations are complex.

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Cascade Optimization Strategy for Aircraft and Air-Breathing Propulsion System Concepts

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Introduction

DESIGN optimization for aircraft and air-breathing propulsion engine concepts has been accomplished by soft-coupling the flight optimization system (FLOPS)[1] and the

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NASA engine performance program analyzer (NEPP),[2] to the NASA Lewis Research Center's multidisciplinary optimization tool COMETBOARDS[3] (comparative evaluation test bed of optimization and analysis routine for the design of structures). The code FLOPS, which incorporates several disciplines: weight, aerodynamics, engine cycle analysis, propulsion data interpolation, mission performance, takeoff and landing, noise footprint, and cost, can analyze either subsonic or supersonic aircraft. To optimize the design of subsonic and supersonic aircraft, the FLOPS code was incorporated, as an analyzer, into the code COMETBOARDS. This combined design tool successfully solved both subsonic and supersonic aircraft problems. Likewise, air-breathing engines can be analyzed using NEPP, which can simulate almost any type of turbine engine configuration. NEPP can evaluate the performance of an engine over its flight envelop, with different mission points, each defined by a Mach number, altitude, and power-setting combination. In an effort to improve engine design we combined NEPP with COMETBOARDS. This combined tool has successfully optimized a number of subsonic and supersonic engines. The key features and unique strengths of COMETBOARDS that assisted in optimizing the aircraft and engines include the cascade optimization strategy, the constraint and design formulations, and a global scaling strategy. This Note demonstrates the capability of the combined tool by design optimization of a subsonic aircraft and a high-bypass-turbofan subsonic engine with a wave rotor.

COMETBOARDS Test Bed

Some of the key features of test bed COMETBOARDS are multidisciplinary optimization (with separate objectives, 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 using the analysis tools available in the analyzers module, reading specified data in the data files module. A number of analysis tools including (RPK_NASTRAN[4] for structural analysis, NEPP, FLOPS, etc.) are available in COMETBOARDS, and provision exists for the soft coupling of new analysis tools. 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 is written in Fortran 77 language and is currently available on the Cray and Convex computers and the Iris and Sun workstations.

Cascade Optimization Strategy

COMETBOARDS can solve difficult optimization problems by using the cascade strategy. The basic cascade concept is to use more than one optimizer to solve a complex problem when individual optimizers face difficulties. A COMETBOARDS user has considerable flexibility in developing a cascade strategy; 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 (optimizer one 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 may be reserved for the final optimizer. The amount of pseudorandom perturbation for design variables may be specified between the optimizers at the discretion of the user. Space does not permit a description of all the different features and unique strengths of COMETBOARDS.[3,5,6]

Design of an Aircraft Concept

Advanced subsonic and supersonic aircraft design concepts have been successfully optimized using a FLOPS and COMETBOARDS combined code. The FLOPS analyzer, through its control and eight discipline modules, can evaluate the performance parameters of an advanced aircraft concept and formulate its design as a nonlinear programming problem. There are options for a number of merit functions such as gross takeoff weight, weight of fuel burned, range, cost, NOx emissions, etc. Free variables for the purpose of optimization include wing area, wing sweep, wing aspect ratio, wing taper ratio, wing thickness–chord ratio, thrust or engine size, engine design–pressure ratio, and turbine inlet temperature. Important behavior constraints are approach velocity, jet velocities, takeoff and landing field lengths, missed approach thrust, and fuel capacity. The multidisciplinary optimization problem posed had a distorted design space since both the design variables and the constraints varied over a very 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, the 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 was further compounded by the statistical and empirical equations and the smoothing techniques employed in the FLOPS analyzer. In other words, the FLOPS analyzer can be numerically unstable for some combinations of design variables, especially for a subsonic aircraft.

The most robust individual optimizer available in COMETBOARDS could not provide a satisfactory direct solution of the problem. However, by applying some of the advanced features, such as the cascade strategy, state-of-the-art optimization algorithms, design variable formulation, constraint formulation, and global scaling strategy, a number of advanced aircraft design problems have been successfully solved. The cascade strategy can be illustrated through subsonic aircraft design optimization. The four-optimizer cascade shown in Fig. 1 successfully solved the problem. The first optimizer, which oscillated rather violently, initially produced a solution in about 30 iterations (see Fig. 1). However, the solution was infeasible and was 1380.4 lb heavier than the true optimum. The second optimizer was initiated from the first solution with a 4% random perturbation. As shown in Fig. 1, the algorithm converged

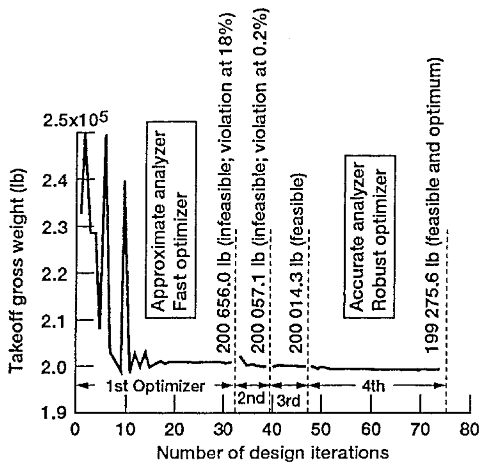

Fig. 1 Cascade solution for a subsonic aircraft.

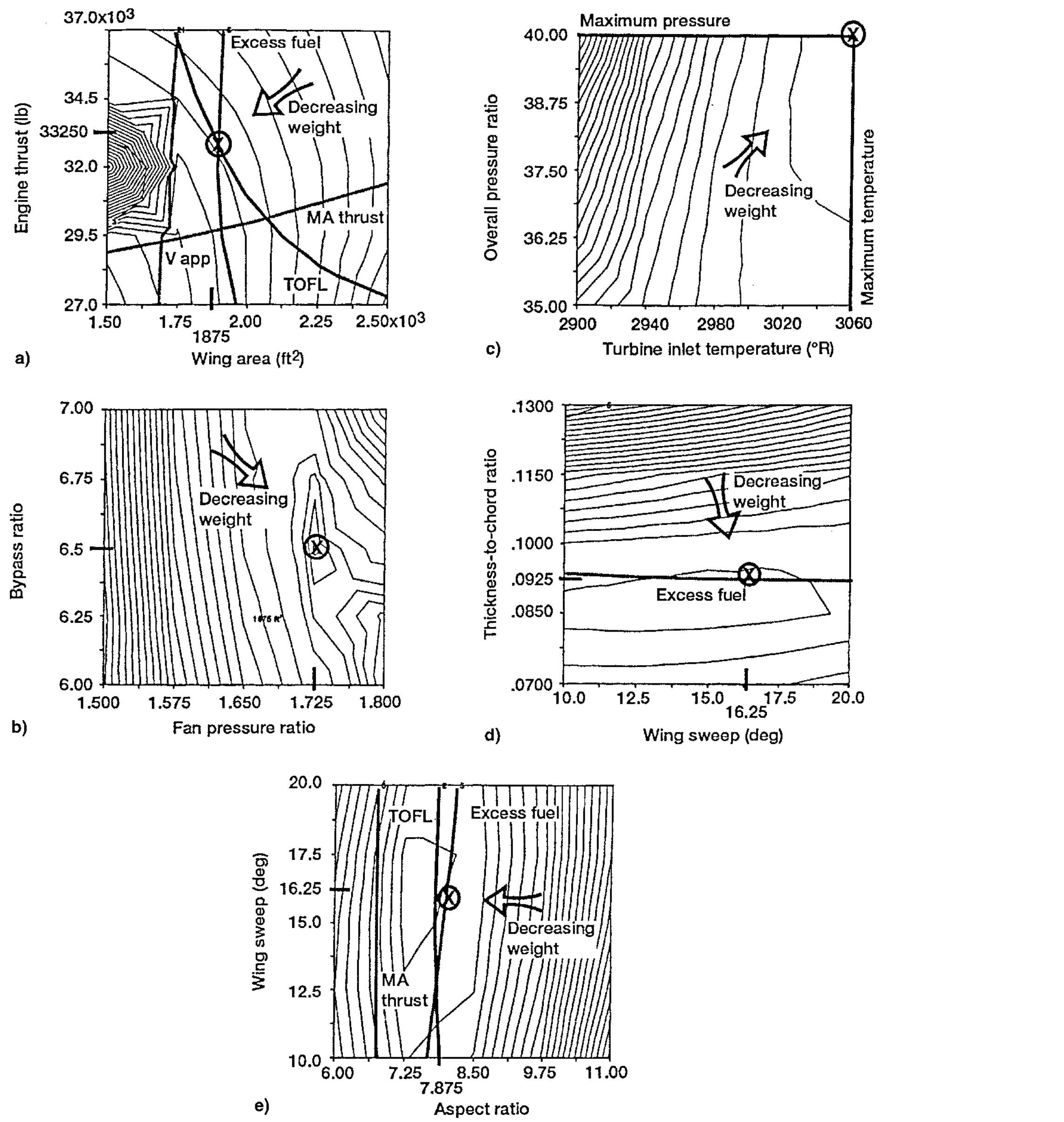

Fig. 2 Graphical verification of optimum design of subsonic aircraft. TOFL, takeoff field length; MA thrust, missed approach climb thrust; V_{app}, approach velocity; excess fuel, fuel storage available−fuel needed; and ⊗, optimum solution.

to an infeasible solution in about 10 iterations. This solution was 598.9 lb lighter than the previous result, but heavier than the true optimum by 781.5 lb. The third optimizer began from the second solution with a 1% perturbation and produced a feasible design in about 10 iterations, but it was suboptimal by 738.7 lb. Starting with a 1% perturbation from the previous solution, the final optimizer converged in about 25 iterations, producing a feasible and optimum solution of 199,275.6 lb for the takeoff weight of the subsonic aircraft.

The optimum design of the aircraft has been verified graphically, as shown in Fig. 2. Figure 2a depicts the constraints and weight function variation with respect to the engine-thrust and wing-area design variables. The optimum lies at the intersection, excess fuel, and takeoff field length constraint. With respect to the fan pressure and bypass ratios, the weight function reaches the minimum point without any active constraints as shown in Fig. 2b. Figures 2c–2e depict aircraft behavior constraints and weight function contours for three sets of design variables: 1) overall pressure ratio and turbine inlet temperature, 2) wing-thickness-chord ratio as a function of wing sweep, and 3) aspect ratio vs wing sweep. At optimum, the subsonic aircraft has a minimum takeoff weight of 199,275.6 lb and has four active constraints, which are 1) takeoff field length, 2) excess fuel, 3) maximum pressure ratio, and 4) maximum turbine inlet temperature. The combined COMETBOARDS–FLOPS tool successfully solved the subsonic aircraft design optimization problem.

Design of a Wave–Rotor-Topped Engine

Conceptually, the wave rotor can replace the burner in a conventional air-breathing engine. The wave–rotor topping can lead to higher specific power in the engine or 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). Its 47 mission points are specified by Mach number, altitude, and power-setting combinations. The engine performance analysis, and constraint and objective formulations were generated with NEPP, whereas design optimization was carried out with COMETBOARDS. 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 asso-

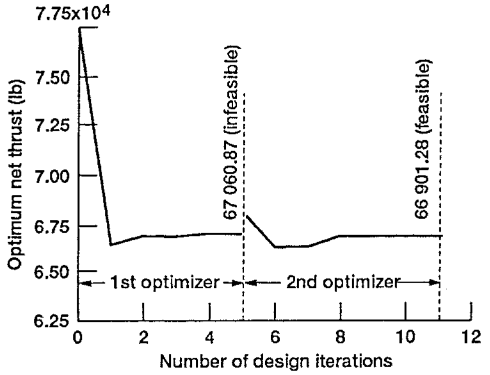

Fig. 3 Cascade solution for a wave–rotor-topped subsonic engine.

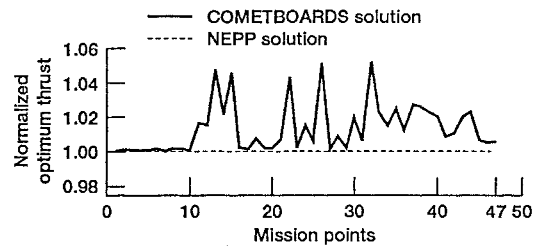

Fig. 4 Value-added benefit in design of a 47-mission-point, high-bypass-turbofan subsonic engine using a wave rotor.

ciated with the wave rotor were active. The active variables considered were the rotational speed of the wave rotor and the heat added to the wave rotor. Important active constraints included the limits on maximum speeds of the compressors, a 15% 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 envelop. For the mission point defined by Mach number = 0.1 and altitude = 5000 ft, the convergence of the two-optimizer cascade strategy is shown in Fig. 3. The first optimizer produced an infeasible design at 67,060.87-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 an optimum thrust of 66,901.28 lb. The optimum solutions for the 47 mission points obtained by using the combined tool were normalized with respect to the NEPP results and are shown in Fig. 4. The combined tool produced a higher thrust than the NEPP for mission points 12, 26, and 32. Both NEPP and COMETBOARDS–NEPP produced identical optimum thrust values for a few mission points. The maximum difference in thrust exceeded 5% 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.

Conclusions

Combined code COMETBOARDS with FLOPS and NEPP successfully solved a number of aircraft and engine design problems. The advanced features and unique strengths of COMETBOARDS made subsonic and supersonic aircraft design problems and engine-cycle design problems easier to solve. The cascade optimization strategy was especially helpful in generating feasible optimum solutions when an individual optimizer encountered difficulty. The cascade strategy converged to the same optimum design, even when it started from different initial design points. The research-level software COMETBOARDS, with some enhancement and modification, can be used by the aircraft industry to design aircraft and their engines.

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Aerodynamic Characteristics of the F/A-18 at Large Roll Angles and High Incidence

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Introduction

WIND-TUNNEL measurements on various models of the F/A-18 aircraft have been conducted in several laboratories in the U.S. The scales of the models range from full size at NASA Ames Research Center[1] to 16% at NASA Langley Research Center,[2] and 6% at David Taylor Research Center.[3] By and large, the wind-tunnel programs have been devoted to force, moment, and pressure distribution measurements, in symmetrical flow conditions, at angles of attack up to 50 deg with some emphasis on flow visualization.

In Canada, a wind-tunnel program was initiated in 1988 to investigate tail buffet on the F/A-18 using a 6% scale model. Tests were performed with the model oscillating in pitch and roll to study the hysteresis effect of vortex burst on tail buffet.[4] In those experiments, stability derivatives were measured, but the oscillation frequencies were very low because of limitations of the Institute for Aerospace Research (IAR) sting support system, thus making the results of limited use. However, static lateral stability characteristics were also investigated. This Note presents some results on roll stability that complement the weathercock stability data given by Erickson et al.[3]

Model

The model used is a rigid 6% scale model of the F/A-18. It consists of three major pieces: 1) an aluminum forebody with integral leading-edge extension (LEX) and a single seat can-

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