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Multidisciplinary Design Integration Methodology for a Supersonic Transport Aircraft

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An aircraft early preliminary design system that demonstrates the methodology for multidisciplinary communications and couplings between several engineering disciplines is described. A primary benefit of this system is the flexibility to demonstrate advanced technology concurrent multidisciplinary design integration techniques. The current version consists of the disciplines of aerodynamics and structures coupled aeroelastically. Contributing engineering disciplines concurrently influence a global design through the global sensitivity equation technique. A generic high-speed civil transport vehicle wing is designed for several variations of wing sweep and thickness. Forty-four independent structural design variables control the cross-sectional areas of wing rib and spar caps and the thicknesses of wing skin cover panels. A total of 300 stress, strain, buckling, and displacement behavioral constraints and minimum gauges on the design variables are used to design the wing structure for minimum mass.

Introduction

AIRCRAFT preliminary design is the process of determining an aircraft configuration that satisfies a specified set of mission requirements. Diverse engineering disciplines typically perform independent analyses with parametric information transferred between the disciplines. Each discipline has its own set of design goals and constraints. Information transfer between disciplines may or may not be formalized or automated. The results of these analyses are sets of thumbprint, carpet, and correlation plots from which a "best" design may be chosen for the specified mission. This process is very time-consuming, requiring many analyses that must be repeated for each variant considered, and that typically do not include all engineering disciplines early in the design cycle.[1,2]

Aircraft preliminary design traditionally deals with disciplinary sizing and shaping, with reliance on previous designs of a vehicle type. The vehicle must sustain several critical flight (loading) conditions throughout the operational envelope, and loads are typically redistributed due to aeroelastic effects. Analytical and test verification of designs may be performed throughout the design process.[1] Other conditions such as flutter, divergence, control reversal, and gust loading must also be accounted for, but may not be included in more detail until the static strength design is completed.[3–5] Information from each discipline is analyzed and modifies the design in a sequential iterative process.

The purpose of this article is to present current advanced aircraft design techniques of the Pathfinder multidisciplinary design and optimization (MDO) system under development for the high-speed airframe integration research (HiSAIR) program.[6] Pathfinder is used to evaluate advanced methodologies for multidisciplinary synthesis applied to preliminary aircraft design, and has the capability to consider the influence of all disciplines participating in the global design concurrently.[7] The uncoupled engineering disciplines contributing to the global design are coupled within Pathfinder through the use of generalized global sensitivity equations (GSE).[8,9] GSE computes a vector of total derivatives, representing the coupled global sensitivities of each discipline's analysis output with respect to the global system design variables. This sensitivity information is used to compute the objective function and constraints used by the design optimization algorithm (KSOPT), which updates the design.[10,11] KSOPT is recently developed software that replaced a commercial software package used earlier.[7] A generic high-speed civil transport (HSCT) aircraft is used for this investigation.[12] Results of minimum weight wing designs including static aeroelastic effects, for variations of wing depth and outboard leading-edge sweep are reported. Results show trends in structural weight, critical constraints, and cover panel skin thickness distributions. Furthermore, drag comparisons for the five variations are presented along with effects on mission range due to shape and thickness changes.

System Overview

Pathfinder is an automated system of uncoupled independent disciplinary analysis and design computer codes coupled through total derivatives computed using the GSE.[7,8] The GSE solves for the coupled total derivatives of the vector of response quantities of each engineering discipline with respect to the vector of design variables of the global system. Contributing disciplines supply uncoupled partial derivative sensitivity information to the GSE. This allows all contributing disciplines to influence the design concurrently. The total derivatives are used to solve for the objective function and constraints of the global system using locally accurate approximation techniques.[13] This methodology has been validated using other systems and disciplines.[14,15] Communication between the analysis and design codes is accomplished through a common data base, along with file sharing. The system executive is written in the UNIX command language.[16,17] This

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allows portability between computer platforms running under UNIX. A diagram of the system containing an outer analysis cycle and inner design optimization loop is shown in Fig. 1. The uncoupled multidisciplinary analysis is represented by the top block containing the aerodynamics, structures, and performance analysis. This traditional uncoupled analysis is performed once at the current design point. The design variables X_i are then perturbed for finite differencing to compute the uncoupled partial design sensitivity derivative (first-order) information required by the GSE. Derivative information may also be obtained analytically or semianalytically if practical.[18] Finite differencing is executed independently by each discipline without repeating the coupled analysis for each perturbed X_i. The design cycle of the inner loop is performed by approximation and optimization algorithms.[10,13] The approximation algorithm computes the current values of the objective function and behavior constraints using total coupled derivative information provided by the GSE. Approximations are required due to the large number of function evaluations required by optimizers. The updated vector of global design variables X_i is computed using any suitable optimization algorithm.

The diagram of Fig. 2 shows the information that is passed between the engineering disciplines. The subscripts a, p, and s represent the aerodynamic, performance, and structures disciplines, respectively. The X_i quantities represent independent global design variables belonging to discipline i that the optimizer computes during the design process. Y_{ij} quantities are dependent response quantities orginating from discipline i and used by discipline j, which measure the performance of the system. Currently, aerodynamics and structures disciplines that perform the static aeroelastic analysis are fully integrated into the system. The integration of mission performance analysis is under development. When performance is implemented, flexible drag polar and lift curve information will be supplied by aerodynamics to mission performance. This is represented as Y_{ap} in Fig. 2. Structural information to be used by mission performance Y_{sp} is the wing weight for

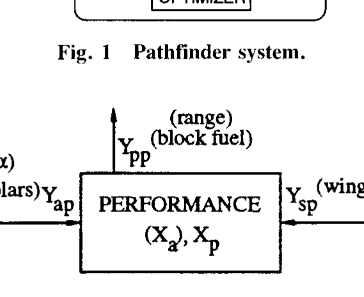

Fig. 1 Pathfinder system.

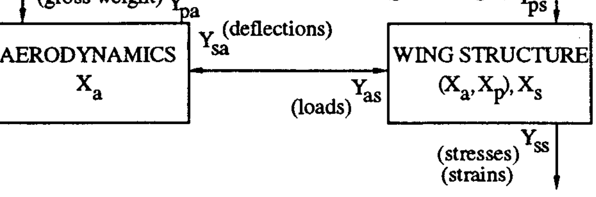

Fig. 2 Disciplinary interactions.

the current design cycle. Performance computes the gross weight and fuel weight Y_{ps} based on the mission requirements and constraints.

The analysis methods for aerodynamics, structures, and performance are well-tested but contain inherent limitations in their accuracy.[19-21] The codes were deliberately chosen for their computational speed that comes at the price of relatively low fidelity that was judged acceptable for the early preliminary design phase.[22] In addition, input information required by the lower fidelity codes is less complex and allows the modification of a starting configuration more rapidly than is typical with higher fidelity methods requiring detailed modeling techniques. The intent is to include progressively higher fidelities in the analysis as methodologies mature and computer hardware improves.[23]

Static Aeroelastic Analysis

The structure of the aircraft must sustain loads throughout the flight envelope. Criteria for certification are specified in the Federal Aviation Requirement Part 25 and Joint Air Worthiness Requirements.[24] For Pathfinder, the aeroelastic load distribution is calculated using a linear aerodynamic solution to compute the pressure distribution on the wing and an equivalent laminated plate solution to compute the resulting wing displacements.[19,20] These methods are coupled with displacements corresponding to a pressure distribution used to update the loads on the wing, which in turn update the displacements. This iteration continues until convergence, where displacements and loads no longer change significantly. Typically 5–10 iterations are sufficient for convergence. Due to the linearity of both the aerodynamic and structural analyses methods used, the iterative solution could have been replaced by the solution of a set of simultaneous linear equations. The iterative formulation is used to allow for the future use of nonlinear CFD codes in place of the linear aerodynamic analysis.

Aerodynamic Analysis

Pathfinder uses the computer program WINGDES, a linear attached flow code, to predict the aerodynamic load distribution over the wing.[19] The code is valid for steady subsonic and supersonic speeds. The numerical method is based on the potential flow solution for a zero thickness lifting surface with estimated attainable leading-edge thrust and an approximation to vortex forces. Because the solution is based on the lifting surface geometry, the effect of twist and camber on pressure distribution can be accounted for. Since this is a linear code, it is executed once to obtain the pressure distribution for the rigid camber and twist shape, and then executed once for each camber and twist shape at zero angle of attack. These are referred to as pressure modes. The shapes are based on the polynomial coefficients used in the structural analysis code to represent deflections. There are 30 polynomial coefficients for each maneuver load case, producing a total of 120 pressure modes. The aerodynamic pressures for any set of structural deflection polynomial coefficients $\{C_i\}$ representing the deformed wing surface, can then be computed by linear superposition. The pressure on the deformed wing is

$$\{P_c\} = \{P_c\}_0 + \sum_{i=1}^{N} \{P_c\}_i \Delta C_i \tag{1}$$

and the total pressure due to the camber and twist plus the angle of attack is

$$\{P_T\} = \{P_c\} + \{P_\alpha\}\alpha \tag{2}$$

where the deflection coefficients $\{C_i\}$ are the Y_{sa} of Fig. 2, and the $\{P_c\}_i$ terms are the pressure distributions due to camber for the ith pressure mode. The $\{P_c\}_0$ term is the initial pressure distribution at zero angle of attack. Pressure is defined on a uniform grid for camber and twist for an angle of attack α equal to zero and over a flat plate for α equal to 1 deg. From this information the total pressure distribution $\{P_T\}$ for any α can be easily obtained by Eq. (2).

Structural Analysis

Pathfinder's structural analysis is an equivalent laminated plate solution (ELAPS) technique that uses the Ritz solution method to find a minimum energy state of the wing structure.[20] ELAPS can analyze multiple cambered trapezoidal plates. Rib and spar caps are attached to the plates, multiple-layered composite skins can be defined. ELAPS is used to compute the structural weight, static displacements, skin and cap stress and strain distributions, and vibration mode shapes and frequencies for the structure. The wing deflections Y_{sa} are used to compute the wing camber and twist shapes used by aerodynamics to compute the aerodynamic pressure distributions.

Skin thickness is prescribed by a set of polynomials for each plate in the spanwise and chordwise directions. The skins are made up of orthotropic layers with the thickness of each layer prescribed independently in polynomial form:

$$t_l(x, y) = \sum_{m=1}^{M} \sum_{n=1}^{N} t_{lmn} x^m y^n \tag{3}$$

The midcamber surface and depth of each structural plate is similarly described by polynomial coefficients. The midcamber surface is

$$zc_j(x, y) = \sum_{m=1}^{M} \sum_{n=1}^{N} zc_{mn} x^m y^n \tag{4}$$

and the plate depth is

$$h_j(x, y) = \sum_{m=1}^{M} \sum_{n=1}^{N} h_{mn} x^m y^n \tag{5}$$

Mass for the analytical model may be distributed over the wing planform and/or concentrated at specific locations. The loads can be applied either as pressure distributions over each structural plate or as point forces. Boundary conditions are enforced by fictitious springs connected to the structure and the reference system, or by eliminating selected polynomial coefficients from the static displacement definition.

Longitudinal Balance

The vehicle is balanced by distributing fuel mass between internal tanks until the vehicle center of gravity (c.g.) location is at the aerodynamic center. The balanced angle of attack at equilibrium is computed by setting the total aerodynamic lift equal to the load factor n times the total gross weight of the vehicle. There are 14 fuel tanks located in each wing and 3 located in the fuselage.

Mission Performance Analysis

The Flight Optimization System (FLOPS) is an aircraft mission performance configuration optimization system.[21,25] FLOPS and the required aerodynamic analysis techniques for drag components and lift are currently being integrated into the Pathfinder multidisciplinary design system. The FLOPS system consists of the five primary modules: 1) weights, 2) aerodynamics, 3) mission performance, 4) takeoff and landing, and 5) life cycle cost. The weights module uses statistical data from existing aircraft that were curve fit to form empirical wing weight equations. This will be replaced with the wing weight computed by ELAPS Y_{sp}. Flexible aerodynamic drag polars Y_{ap} are generated by the WINGDES code described earlier along with codes for skin friction and wave drag for use by FLOPS.[19,26] The mission analysis module uses weight, aerodynamic data, and an engine deck to calculate performance. Performance analysis will provide the mission fuel weight Y_{ps} and gross weight to the structures discipline. Mission requirements for this vehicle specify a payload of 250 passengers cruising at Mach 2.4 and a midcruise altitude of 63,000 ft. The statistical wing weights from FLOPS were used in this report to compare with Pathfinder optimal wing weights. In addition, the effect of sweep and thickness on range is discussed.

Sensitivity Analysis

Sensitivity analysis requires that each discipline computes the partial derivative of its output with respect to the output of other disciplines in the system. In addition, a vector of partial derivatives of each discipline's output with respect to a set of design variables is also required. This information is used by the GSE solution that solves for the unknown coupled total derivative vector of each discipline's output quantities with respect to a vector of global design variables.[8] The set of equations representing the exchange of data between disciplines (Fig. 2), are

$$\begin{aligned} Y_{as} &= Y_{as}(Y_{sa}) \\ Y_{sa} &= Y_{sa}(X_s, Y_{as}) \\ Y_{ss} &= Y_{ss}(X_s, Y_{as}) \end{aligned} \tag{6}$$

It has been shown that differentiation of the functions in Eq. (6) as composite functions and application of the implicit function theorem leads to the GSE.[8] The general GSE, which accounts for coupling between the disciplines considered is

$$\begin{bmatrix} I & -\dfrac{\partial Y_{as}}{\partial Y_{sa}} & -\dfrac{\partial Y_{as}}{\partial Y_{ss}} \\ -\dfrac{\partial Y_{sa}}{\partial Y_{as}} & I & -\dfrac{\partial Y_{sa}}{\partial Y_{ss}} \\ -\dfrac{\partial Y_{ss}}{\partial Y_{as}} & -\dfrac{\partial Y_{ss}}{\partial Y_{sa}} & I \end{bmatrix} \begin{Bmatrix} \dfrac{dY_{as}}{dX_s} \\ \dfrac{dY_{sa}}{dX_s} \\ \dfrac{dY_{ss}}{dX_s} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial Y_{as}}{\partial X_s} \\ \dfrac{\partial Y_{sa}}{\partial X_s} \\ \dfrac{\partial Y_{ss}}{\partial X_s} \end{Bmatrix} \tag{7}$$

Equation (7) is formed after all disciplines have performed an analysis based on the latest global design variable information. At this point in the solution, all X_i and Y_{ij} are known. A forward finite difference scheme is used to obtain the partial derivatives in Eq. (7).

Global Disciplinary Coupling

The GSE matrix [Eq. (7)], is solved for the coupled total derivatives of all uncoupled discipline outputs with respect to each global design variable. This accounts for the global coupling between contributing disciplines. The total derivatives provide trend information that in traditional systems is obtained through parametric and statistical means. These derivatives are used in constructing objective and constraint function approximations (extrapolation techniques) for the optimization algorithm.[10,13] KSOPT attempts to minimize the objective function by searching the design space, using gradient guided information, within each design cycle.[10,27] A design cycle (Fig. 1), consists of a full uncoupled analysis by each discipline, the assembly and solution of the global sensitivity equation, and the inner design optimization loop. The cost of the inner design optimization loop, with information on the system behavior for every design variable change by the optimizer, is negligible in comparison to a full multidisciplinary analysis.

Structural Model Description

The representative HSCT configuration is shown in Fig. 3. Forty-four independent design variables are used to design

Table 1 Material properties and allowables

Material properties		Ti-6Al-4V
Young's modulus, E		16.0×10^6 psi
Shear modulus, G		6.20×10^6 psi
Poisson's ratio, υ		0.290
Density, ρ		0.160
	Stress and strain allowables	
	Yield[a]	Fatigue
σ_x, σ_y	86.7×10^3 psi	25.0×10^3 psi
τ_{xy}	50.7×10^3 psi	14.4×10^3 psi
ε_x, ε_y	0.00542	0.00156
γ_{xy}	0.00817	0.00232

[a]Ultimate allowables divided by 1.5.

Table 2 Load case descriptions

Case[a]	Load factor	Mach no.	Altitude, ft	Dynamic pressure, psf	Fuel weight, lb
1	1.0	2.4	63,000	535	63,175
2	1.0	1.2	29,700	644	167,000
3	1.0	0.9	42,500	199	18,450
4	2.5	2.4	57,000	723	150,000
5	2.5	0.6	10,000	367	174,200

Note: Fuel weight is for ½ airplane.
[a]Case descriptions: 1) midcruise, 2) transonic climb, 3) reserve cruise, 4) high-speed pull-up, and 5) low-speed pull-up.

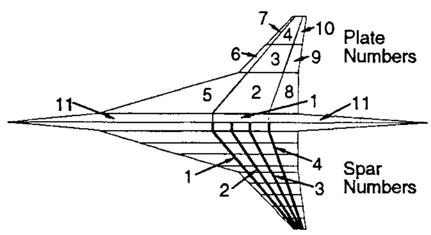

Fig. 3 Structural model.

the cross-sectional areas of the wing spar and rib caps and the thicknesses of the wing cover skin panels. The planform shape was obtained from a geometry description data file, known as the wave drag format.[26] The geometric data and other information needed for aerodynamic and structural analysis are stored in a common data base. This data is nondimensionalized as much as possible to facilitate configuration shape changes such as wing sweep. Symmetric boundary conditions are applied at the fuselage centerline location through the use of displacement polynomial coefficient elimination for symmetry in the plane normal to the spanwise direction. Two springs attached to the fuselage centerline are also required to prevent singularities in the vertical translation and pitch rotation directions. The wing cover skin consists of isotropic sandwich panels with a constant 0.75-in. honeycomb core thickness, so that the face sheet thicknesses are the only design variables of the cover skin. The model consists of 11 trapezoidal plates and is symmetric about the fuselage centerline. One plate (plate 11) represents the fuselage with concentrated masses placed along the centerline for vibration mode calculations. The internal wing structure consists of four spars with spar caps and 10 ribs with rib caps. The material used for this design is Ti-6Al-4V titanium alloy.[28] Material properties and stress and strain allowables are given in Table 1.

Load Cases

Five load cases have been selected (Table 2). The first three are used to calculate the vehicle's flexible drag polars to be used by performance Y_{ap}. In addition, load case 1 is used to compute a jig shape and accounts for fatigue. Cases 4 and 5 are critical load cases within the flight maneuver envelope that generate large wing root bending moments. In addition, inertia loads are included for each load case.

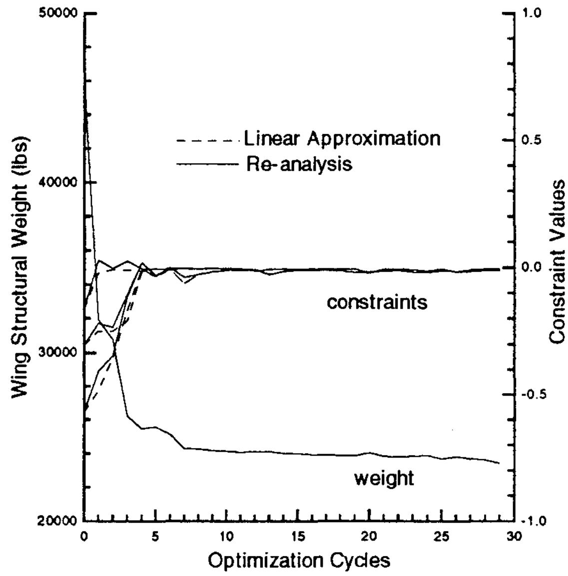

Fig. 4 Optimization convergence history.

Results and Discussion

Critical strength constraints and wing skin thickness distributions are discussed for five minimum weight designs of a generic HSCT aircraft wing for parametric changes in shape and thickness. The HSCT wing design presents unique challenges of interest to this discussion. The double delta shape and internal structural arrangement are not typical of present day large transport aircraft. The leading edge (LE) sweep angle of the outboard portion of the baseline configuration of the double delta wing (Fig. 3), and the wing thickness to chord ratio t/c along the span were independently varied by $\pm 10\%$ and held fixed for a design. The wing skins and wing spar and rib caps were resized for minimum weight with strength constraints. The external shape configurations were created from the baseline geometry with a geometry parameter (wing t/c or outboard LE sweep angle) perturbed and an uncoupled aerodynamic optimization performed to compute a midcamber surface optimized for minimum cruise drag.[19] In addition, range was computed by the performance discipline based on drag polar information, from rigid aerodynamics, for each wing shape configuration. All weights reported herein are for one-half of the aircraft.

A typical convergence history for a minimum weight design is shown in Fig. 4. the weight is reduced to 24,000 lb after 10 cycles of the design process, and is further reduced to 23,300 lb after 30 cycles. This final weight is 9% less than that obtained from the performance discipline statistical wing weight, and is representative of all variations. The convergence is smooth, but the objective function continues to decrease slowly and occasionally oscillates due to the approximations used in the optimization. Each design cycle required 1.5 h to complete using a SUN Sparc Station 1+ and IRIS 4D workstations. The SUN is used for the areoelastic analysis, and the IRISes are used to compute, in parallel, the uncoupled design sensitivity derivatives. Convergence is similar for each of the other four designs reported.

Results indicate that the wing, which has a panel buckling length of 3 ft, is designed by the panel buckling constraints for load case 5. The critical buckling constraints (Fig. 4), appear in plates 2–4 for the baseline, thickness t/c variations, and increased outboard wing sweep variations. Plates 2–4, 6, and 7 are critical in buckling for the decreased outboard wing sweep variation. Figure 5 shows typical buckling constraint contours for both sweep variations. The contour values closest to zero indicate the most critical buckling regions. A typical optimum wing skin thickness distribution is shown in Fig. 6. Figures 5 and 6 are representative of each of the variations investigated. Table 3 shows the optimum structural weight for all five variations. Both the increased and decreased LE outboard wing sweep variations have slightly increased structural weights compared to the baseline. This weight difference is primarily attributed to aeroelastic and optimization convergence. A separate study was conducted to examine the effect of the wing LE outboard sweep from −30 to +60 deg on wing weight. Results of this study indicated an insignificant effect on wing weight. This is partly attributed to the smaller area of the outboard wing section compared to the total wing area. In addition, aft swept wings tend to wash out, decreasing the bending moment. The increased wing depth t/c variation has a lower structural weight compared to the baseline due to the increased area moment of inertia of the wing structural box, which decreases wing bending and, hence, skin stresses and buckling loads. The decreased t/c variation has an increased structural weight due to behavior opposite of that described above for the thicker wing.

Table 3 Structural weight comparison

Configuration	Wing structural weight, lb	Change from baseline
Baseline	23,300	——
Increased wing sweep	23,700	1.7%
Decreased wing sweep	24,000	3.0%
Increased wing depth	21,800	−6.4%
Decreased wing depth	24,700	6.0%

Note: Wing structural weight is for ½ airplane.

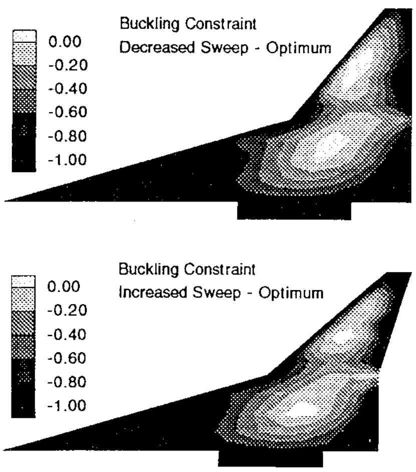

Fig. 5 Subsonic maneuver case buckling constraints.

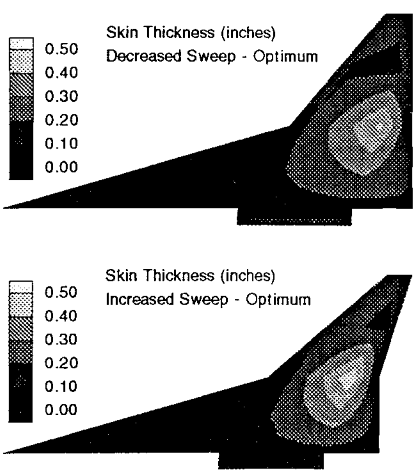

Fig. 6 Optimum wing skin thickness distributions.

Table 4 shows the aerodynamic drag comparisons at trimmed angles of attack for the supersonic midcruise load case (case 1, Table 2). Drag components were obtained from a separate set of linear aerodynamic codes that are not integrated into the Pathfinder system. Drag coefficients indicate that the changes in camber and twist resulting from optimizing the wing structure change the corresponding lift related drag coefficients between −1 and 5% from the baseline case. When the contribution of wave drag is included, reflected in the total drag coefficient column of Table 4, the smallest thickness t/c variation has the lowest drag. The smallest thickness variation also has the highest wing structural weight (Table 3). This drag vs weight conflict demonstrates the need for the mission performance analysis in the design cycle (Fig. 1), to couple the aerodynamic and structures disciplines. Changes in fuel and vehicle gross weights (computed in the performance discipline) resulting from changes in the drag polar of the flexible vehicle (computed in the aerodynamics discipline) should be available to the structures discipline. Likewise, changes in the gross weight (computed in the performance discipline) resulting from changes in wing weight (computed in the structures discipline) should be available to the aerodynamics discipline for computing required lift.

An effort was made to illustrate the effect of coupling the aerodynamic and structural analysis. For this purpose, the FLOPS program was used to calculate the mission performance of the baseline variation and of the variations with modified sweep and thickness. As mentioned previously, the FLOPS analysis utilizes rigid aerodynamic data and a statistical weight prediction algorithm. The aerodynamic data used by flops consists of a buildup of wave drag, skin friction and roughness drag, and induced or vortex drag. Figures 7 and 8 show the integrated sensitivity effects for the modified sweep and maximum thickness ratio cases, respectively. In Fig. 7, it can be seen that the wave drag and wing weight trends are

Table 4 Midcruise drag comparison

Configuration	Drag[a] coefficient	Change from baseline	Total[b] drag coefficient	Change from baseline
Baseline	0.00435	——	0.00588	——
Increased sweep	0.00446	3%	0.00600	2%
Decreased sweep	0.00455	5%	0.00617	5%
Increased depth	0.00428	−1%	0.00598	2%
Decreased depth	0.00443	2%	0.00580	−1%

[a]Induced drag, vortex forces and leading-edge suction.
[b]Including wave drag, excluding skin friction drag.

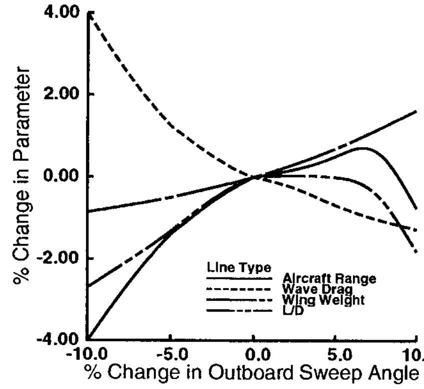

Fig. 7 Effect of outboard LE sweep on performance parameters.

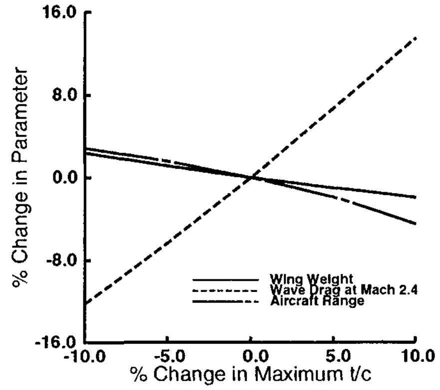

Fig. 8 Effect of t/c on performance parameters.

as expected. That is, wave drag decreases and wing weight increases as the wing sweep is increased. The overall range however, does not follow the expected trend, but rather decreases as the wing is swept forward from the baseline and increases slightly, but then decreases as the wing is swept aft from the baseline. The reason for this trend can be found by examining the cruise L/D trend which, due to changes in the induced drag characteristics, exhibits the same behavior as the range variation. Figure 8 shows the results for the modified wing thickness cases. Here, as expected, the wave drag decreases, and the wing weight increases as the wing thickness-chord ratio is decreased. The magnitude of the wave drag changes is larger, and therefore, causes an increase in the overall range to occur as the thickness is decreased. It remains to be determined if this trend would continue if the effects of flexibility were considered in the weight analysis.

Conclusions

A multidisciplinary design integration system for early preliminary design, Pathfinder, is described. In addition, a conceptual generic HSCT intended for supersonic cruise at Mach 2.4 is designed for minimum weight, using wing cover panel skin thicknesses and spar and rib cap areas as design variables. Results are described for the static aeroelastic design of five wing shape variations: a baseline, two wing outboard sweep angles, and two wing thickness variations.

Minimum weight designs were obtained considering five load cases within the flight envelope. The wing weight converged to within 3% of the minimum within 10 cycles and typically settles to a minimum within 30 cycles for all configurations investigated. Each cycle typically converges in 1.5 h using a SUN Sparc Station 1+ and IRIS 4D workstations running in parallel. Results indicate that the vehicle is strength designed by wing cover panel buckling constraints for the low-speed pull-up load case (Mach 0.6; $n = 2.5$) for all variations of wing thickness and sweep.

Comparisons demonstrate the classic design conflict with structures and aerodynamics where the lightest structural configuration is one with increased wing depth and the lowest drag configuration is one with decreased wing depth. Since different configurations produce a best design for structures vs aerodynamics, this demonstrates the requirement for mission performance to take into account the influence of aerodynamics and structures in the design cycle. Furthermore, the effect of outboard LE sweep angle on wing weight is small for the strength design due to wash out and the smaller area of the outboard wing region.

An early preliminary design system that will allow for the global coupling of several uncoupled engineering disciplines has been demonstrated using the GSE technique. Convergence to optimal designs were robust. Typically, 10 cycles were required to obtain near optimal designs. Contributing engineering disciplines function independently and concurrently. Design trends will deviate from those presented in this article when additional disciplinary contributions are accounted for in Pathfinder, constraining the design further.

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