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Large Delta Wings for Earth-to-Orbit Transports

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Wings required for advanced Earth-to-orbit transports will differ markedly from current aircraft in geometry, structural concepts, materials usage, and lifetime requirements. For these reasons, special studies are warranted to identify some of the associated materials and design technology issues. Two basic wing configurations are described in which computer-aided methods are used for preliminary design. One wing is configured with a multilayered nickel base superalloy honeycomb which doubles as structure and thermal protection. The wing is braced internally with honeycomb-stabilized thin-walled tubing. A second wing is described which has a thick single-layered honeycomb. No ribs are used, and a separate bond-on thermal protection is assumed. By utilizing innovative structural configurations, such as honeycomb for wing covers, a 14% weight savings is shown. An additional weight savings of 23% is shown when titanium is substituted for aluminum, a portion of which is attributable to savings in thermal protection. Savings through the use of composites, such as graphite/polyimide and probabilistic design criteria, are discussed relative to the proposed wing concepts.

Introduction

VEHICLES which have been considered for Earth-to-orbit (ETO) transportation of cargo include both horizontal-takeoff (HTO) and vertical-takeoff (VTO) designs. Some of the wings for the vehicles have been configured to serve also as tanks for storage of either liquid oxygen (LOX) or a hydrocarbon. In this regard, a number of wing structural concepts has been identified in recent contractual studies.[1,2] In one study, spars in a truss-type construction were utilized with wing covers consisting of a thick single-layer honeycomb sandwich.[1] The vehicle was designed for HTO with LOX stored in the wing for load relief (a plan view of this vehicle is shown at the left in Fig. 1). Full ribs were utilized only at root and tip, while partial ribs were used only where needed to withstand elevon actuator loads. Honeycomb covers served as structure, fluid containment, and thermal protection. In a second study, the effort centered around the use of a VTO mode.[2] The vehicle was similar in design to that shown in the center drawing in Fig. 1. The wing structure consisted of open-rib and spar-truss construction. For wing covers, borsic aluminum honeycomb panels were assumed. A separate reusable thermal-protection system (RSI) was employed. No propellants were stored in the wing.

These wings, which are fairly typical for ETO vehicles, have delta planforms with aspect ratios of 2½-3 vs a value of about 7 for commercial transports (Figs. 1 and 2). Chord thicknesses range between 10 and 12% vs values as low as 3-½% for delta-wing military aircraft. The leading edges are highly swept, have large radii, and are unencumbered by high-lift devices. In general, wing size, planform shape, and location for a VTO vehicle are determined by hypersonic trim requirements. Thick airfoils lend themselves to this application because of the large leading-edge radii (i.e., low leading-edge heating rates), high strength efficiency, high internal volume for propellant storage when required, and high L/D for low-speed power-off landings. The high stiffness characteristics of the wings are desirable for the prevention of resonance coupling with engine-induced vibrations. High panel stiffness, an inherent property of honeycomb, is also required to inhibit acoustic fatigue and prevent separation of reuseable surface insulation tiles when utilized.

In addition to these factors, there probably will not be a structural requirement for engine pylons or main landing gear compartments; the latter being stowed in bodies having larger cross sections (compared to commercial transports). The wing carry-through structure may be nonexistent in these advanced vehicles with the wing-induced shear and moment loads carried by structural additions to the body. This concept is utilized on the shuttle orbiter. Typically, the wings of ETO vehicles are large compared to the shuttle (Fig. 1). If propellant is stored in the wings on these advanced vehicles, much higher volumetric packaging efficiencies are sought. Typical values for today's transports are 30-50%, whereas packaging efficiency factors in the range of 80% are sought for highly efficient HTO designs.

Whereas some of the world's largest transports carry 148 Mg of JP fuel, the ETO vehicles may carry as much as 600-700 Mg of propellant in the wings (for the HTO concepts). Much higher takeoff accelerations are required for the HTO's, namely 7-13 m/s^2 vs values in the range of 2.5 m/s^2 for commercial transports. Since the wings of the advanced vehicles are physically much larger and the stored liquid more dense, much higher hydraulic heads will be generated, requiring more wing structure to withstand the higher internal pressures. On the plus side, these new wings have to be designed for a life of only 500 missions vs a 50,000 flight-hour goal for a commercial transport.

The primary objective for conducting these preliminary studies of ETO wings for both HTO and VTO is to determine if, in fact, much lighter structure can be utilized. Since the wings are markedly different in geometry, materials usage, and mission from any wings previously built, existing weights, trending data, structural concepts, or material selections cannot be directly applied.

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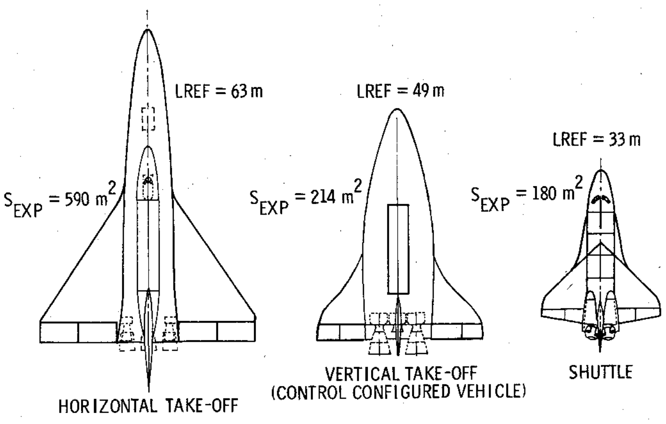

Fig. 1 Wing size comparisons for three ETO transports.

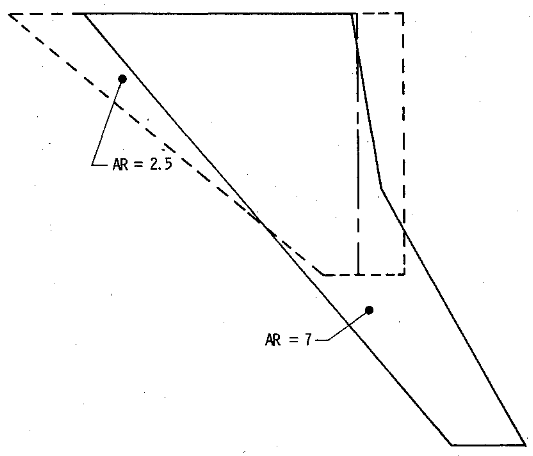

Fig. 2 Comparison of a typical single-stage-to-orbit VTO and 747 wings.

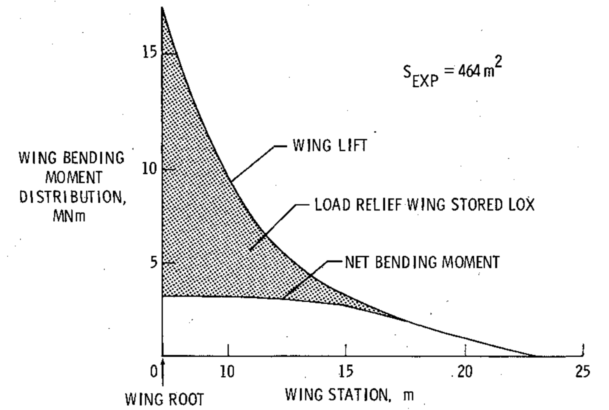

Fig. 3 Wing bending moment and load relief for an HTO vehicle.

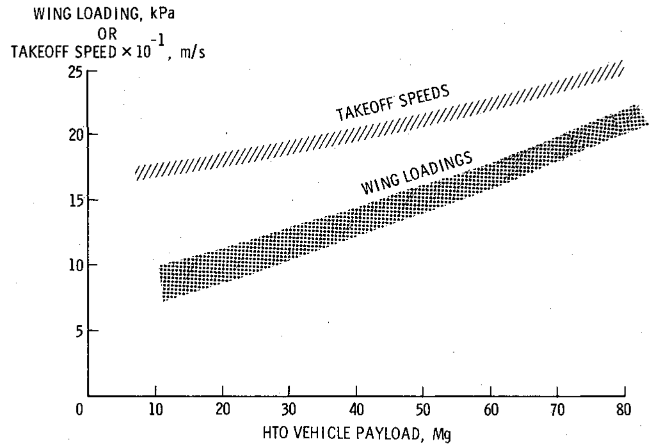

Fig. 4 Effect of vehicle payload on takeoff speeds and wing loading.

The idea of utilizing honeycomb all over the wing surfaces is merely an extension of a concept which has received increasing acceptance in the aerospace industry, namely, honeycomb covers in lieu of skin-stringer combinations. Honeycomb is now used in this way extensively in the wing of various transports (mainly, however, on the control surfaces); it is also used on the shuttle orbiter body flap and for the wing area ahead of the main gear well.[3] Also, brazed stainless steel honeycomb sandwiches were utilized extensively on the XB-70 airplane wing.[4]

Wing System Configuration Options

There are three distinct possibilities for ETO wings with regard to the main rocket-engine propellants: the wing could be a "dry" design (like the shuttle), it could be a wet wing used for the storage of hydrocarbons at 293 K, or it could be a wet wing for storage of LOX at 93 K. Each of these factors could radically alter the selction of the wing structural material and configuration.

For HTO, the much heavier LOX should be stored in the wings in order to take advantage of wing load relief. If this is not done, unreasonably large bending moments result. This effect is illustrated in Fig. 3, where the wing-root bending moment is shown to exceed 15 mega-newton-meters (MNm) at the root when the heavy LOX propellant is packaged in the body of the vehicle, but is reduced to less than 5 MNm when stored in the wing.

In addition to the packaging propellant options just described, a designer may want to consider a dual-fueled main propulsion system for HTO simply because the use of such a system leads to a reduction in vehicle dry mass, physical size, and cost.[5,6] Unfortunately, for HTO systems, the dual-fuel concept tends to cause an increase in wing loading and takeoff speeds for otherwise geometrically similar vehicles (upper boundaries of curves in Fig. 4).

For example, the bulk density of LOX and LH_2 at a mixture ratio of 6:1 (which is the ratio used for the shuttle engines) is 360 kg/m^3. A typical wing loading for a vehicle designed for HTO with these propellants is 11 kPa. On the other hand, the addition of a third (dense) hydrocarbon propellant, apportioned for maximum systems performance, raises the bulk density to 544 kg/m^3. The corresponding wing loading for a geometrically similar HTO vehicle packaged with these propellants of higher bulk density is estimated to be about 13 kPa (vs the 11 kPa for the all-LOX/LH_2 vehicle). These wing loadings are already high without the dual-fuel feature. For instance, a typical value for a wing loading for a large, fully loaded commercial transport at takeoff is only 6 kPa, or about half the value for the proposed HTO rocket-powered vehicles.

In addition to the effect of propellant bulk density, increasing vehicle physical size (such as increasing vehicle payload) also tends to increase vehicle wing loading. This is an expected trend, since vehicle internal volume (hence, propellant load) increases with the cube of dimension, whereas wing area increases only with dimension squared.

Since the wings are configured with a low aspect raio and, for weight and thermal reasons, are not equipped with special appendages for high lift, the consequence of all these factors is a very high vehicle takeoff speed. The all-LOX/LH_2 vehicle described in Ref. 1 requires a speed of approximately 180 m/s for takeoff. Since current tire technology limits takeoff speeds to about 125 m/s, either a new tire development is required or some other means is needed for takeoff, such as an auxiliary sled on rails. In no case is it practical, because of the weight penalty, to carry the wheels or other auxiliary takeoff systems to orbit. It is practical, however, to carry the necessary gear to land a returning vehicle when it has depleted its heavy rocket propellant.

One seemingly logical solution to the reduction of takeoff speeds is to increase wing size. If a designer attempts to match wing internal volume to the LOX requirement (a convenient packaging arrangement), then the wing chord thickness must be continuously reduced as the vehicle gets bigger in order to maintain the same wing loading. This is somewhat the approach taken in a combined airbreather/rocket-powered vehicle recently proposed.[7] The wing loading for this vehicle at takeoff with a 57-Mg payload was 5.8 kPa for a 3800-m^2 wing; takeoff speed was 116 m/s. Both wing loading and takeoff speed data points fall far below the curves shown in Fig. 4, which depicts trends for the HTO shown in Fig. 1. However, the penalties in structural mass and cryogenic insulation for this wing (which covers almost an acre) must be weighed against a more compact wing having a thicker chord section.

Wing Structural Material Options

If the wing is a "dry" design, current technology projections suggest that one of the composites with a separate external thermal-protection system may yield the lowest mass. Graphite/polyimide is a likely choice since it has an exceptionally high strength-to-density ratio and an operating-temperature capability to about 589 K to withstand "heat soak" after re-entry. Also, it has an expansion coefficient which closely approximates that for a reuseable surface insulation (RSI), making the elimination of the strain isolation pad (SIP) possible.

In a recent study of the Shuttle Orbiter body flap, a combined savings of 27% in structure and thermal protection (TPS) was realized by using graphite/polyimide (G/P) in lieu of aluminum.[8] The reduction in TPS mass was possible inasmuch as the G/P structure has a higher allowable operating temperature than aluminum (590 K vs 450 K for aluminum). Similar benefits should accrue when G/P is used for wing structure. The current shuttle orbiter wing (primarily for reasons of economy) is constructed of aluminum skin stringer, rib, and spar construction with a separate RSI. The wing is "dry" and has a main gear well. Approximately 500 kg of the body structure can be attributed to wing load carry-through. If the Shuttle Orbiter wing were to be required for storage of a hydrocarbon fuel, special provisions would have to be made around rivets, at the edge of cover panels, and in other areas to insure integrity as a tank. The same is true of any riveted wing dualing as tankage.

For the advanced transports, thick honeycomb wing covers are being considered. Honeycomb appears attractive because it serves to stabilize the wing panels and, if evacuated, it serves as an insulator. In addition, honeycomb is one of the most efficient structural configurations for axial compression, being lighter than practically all other concepts including isogrid, Z-stiffened, truss-core, or multiwall construction.[9] The only major deterrents to even wider acceptance in the industry for a specific application is the development of fabrication, quality testing, and inspection techniques. If honeycomb can be perfected for the current application, it would result in a large reduction in parts count and design costs, substantial reductions in weight, and would provide a smooth external surface for the attachment of RSI or metallic external thermal protection.

Multilayer Honeycomb Wing

Two structural concepts for advanced ETO transport wings have been studied. Both are dry-wing designs. The first wing concept was for a 61-m long dual-fuel vehicle designed for a 30-Mg payload (Fig. 5). The wing covers on this design consist of multilayer diffusion-bonded Inconel 718. Five distinct

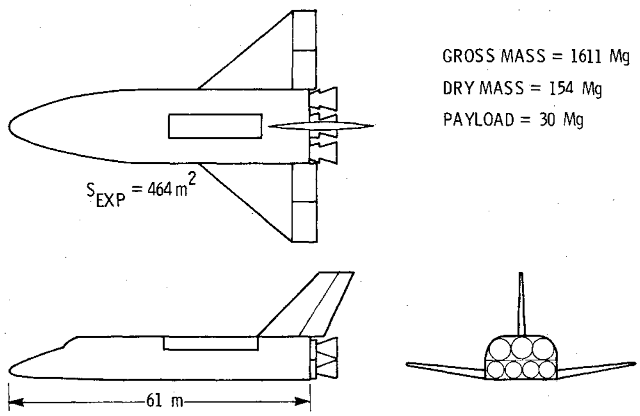

Fig. 5 Dual-fuel single-stage VTO winged vehicle.

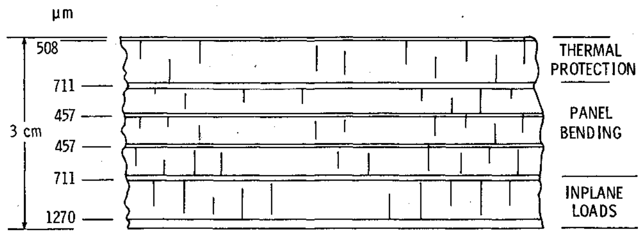

Fig. 6 Multilayer wing cover showing integrated thermal protection.

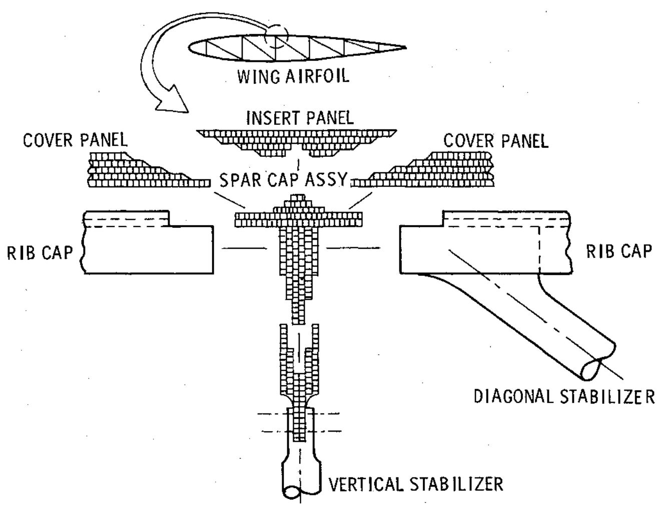

Fig. 7 Spar-cap assembly for multilayer wing.

honeycomb layers are utilized (Fig. 6). In the analysis, the outermost layer is assumed to be structurally redundant and is only intended for high-temperature thermal protection. (Note: An Inconel honeycomb is already being utilized on the shuttle for the main rocket engine heat shield.) The middle sections of the proposed design are sized to withstand panel normal loads (panel bending), whereas the innermost face sheet is sized to withstand inplane tensile and compressive loads. The assumptions are made in order to simplify the analysis; each element, however, contributes to the various loads imposed. The NASTRAN analysis program was used.[10]

For ribs and spars, an open-truss structure is assumed with tubular struts whose walls are stabilized with honeycomb. A spar-cap assembly, also fabricated from multilayer honeycomb, is bonded to the wing-cover panels and rib caps (Fig. 7). An insert panel is used to close out the assembly. By diffusion bonding, the mass normally associated with a brazed alloy system is reduced or eliminated. This penalty for braze alloy could easily constitute 15-20% of the mass of the

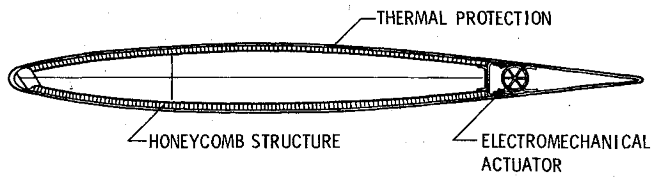

Fig. 8 Single-layer honeycomb wing design with separate thermal protection.

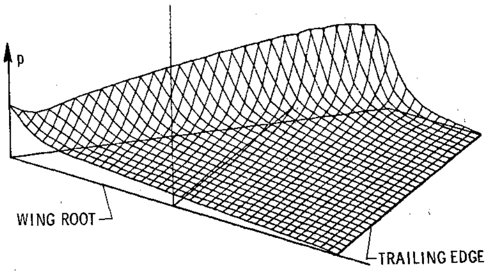

Fig. 9 Wing pressure distribution.

panel for a single honeycomb core (two face sheets) and, of course, would be compounded for multicore honeycomb. Even the major subassemblies are diffusion-bonded to eliminate almost all fasteners. One process for diffusion bonding of the Inconel is described in Ref. 11. Although this particular technique has been perfected for components, the projection of diffusion-bonding joints for an entire wing assembly certainly cannot qualify as current technology.[12]

The mass of the multiwall honeycomb wing design with integrated thermal protection is 25,204 kg for a unit mass of 54.3 kg/m^2 (approximate unit mass for the shuttle wing without RSI). The wing has a separate carry-through structure which is typical of current aircraft. Since a hot-wing structural design was selected, the storage of a hydrocarbon fuel probably would not be practical in the wing because of "coking," a phenomenon which occurs when the fluid attains temperatures of approximately 750 K.

Single-Layer Honeycomb Wing

For the second design study, structural simplicity is sought. In this regard, initially, only leading-edge and trailing-edge spars are employed (Fig. 8). Unlike the previous wing design, a separate TPS system is assumed. Also, no ribs are utilized. Thick integral honeycomb cover panels are employed, and honeycomb skin and core thicknesses varied in order to satisfy structural material property margins and wing-panel buckling criteria for the design-load conditions.

The integrated synergistic system (ISSYS) program was used to study these wing concepts. The ISSYS program uses SPAR as a structural-analysis tool.[13] The computer-generated pressure distribution for the design condition is illustrated in Fig. 9. The corresponding average wing loading is 8 kPa, which corresponds to the 2.5-*g* subsonic maneuver case.

Two materials were considered for this wing concept, titanium and aluminum. For the assumptions made, the minimum mass aluminum honeycomb wing utilized a honeycomb core thickness of 76 mm. In the optimized wing, honeycomb skin gages varied from 2.7 mm at the root to a minimum gage of 0.5 mm at and near the tip. The titanium wing honeycomb core thickness for the minimum mass design was 102-mm honeycomb. Skin gages varied from 1.2 mm at the root to a minimum allowed gage of 0.3 mm at the tip. Both designs were sized to withstand the static limit load times a 1.4 factor. In the program, the titanium principal stresses were limited to 345 MPa, and the aluminum to 207 MPa. From the final wing optimizations, the aluminum wing did not buckle until a load of $1.09 \times 1.4 \times$ (the static limit load) was reached. Likewise, the titanium showed a positive margin at $1.23 \times 1.4 \times$ (the static limit load). No attempt was made to vary honeycomb thickness within a given wing design, only from one design to another. Also, skin gages on the inside and outside of the wing covers were assumed to be the same at a given location.

A simplified dynamic analysis showed that the wing covers were marginal from the standpoint of flutter. Moreover, the effect of moving shock waves in the transonic range and the adverse effect of high angles of attack in the supersonic range have not been considered. This latter phenomenon is discussed in Ref. 14. Because the wings are marginal in this way, strategically located dampers may be required in the wing cavities between top and bottom surfaces. The surfaces would still be permitted to move relative to one another for various loading conditions, a relative motion which is correctly limited in conventional wing designs because of the presence of a multiplicity of ribs and spars.

Comparison of Concepts

A comparison of the masses of four wings as determined from the ISSYS, SPAR, and NASTRAN programs is shown in Table 1. An all-aluminum wing of conventional skin/stringer construction was modeled as a reference. The second and third wings listed are the single-layer honeycomb designs, while the fourth is for the multilayer honeycomb wing with lightweight tubular struts for internal bracing.

Reading from left to right in Table 1, wing cover masses increase when considered as a percentage of total wing mass; and, in fact, the absolute magnitude of the mass of the

Table 1 Weight comparisons of wing-design concepts

	$S_{exp} = 214\ m^2$						$S_{exp} = 464\ m^2$	
	Aluminum skin/stringer		Aluminum honeycomb		Titanium honeycomb		Inconel-718 multilayer honeycomb	
Component	kg	%	kg	%	kg	%	kg	%
Basic structure	5,531	39	4,747	39	4,218	44	16,621	66
Covers	(2,373)	(17)	(3,381)	(28)	(2,975)	(31)	(14,294)	(57)
Caps and webs	(3,158)	(22)	(1,366)	(11)	(1,243)	(13)	(2,327)	(9)
Secondary structure	571	4	514	4	463	5	1,660	7
Control surfaces	1,095	8	965	8	786	8	2,439	10
Thermal protection	4,782	34	4,782	39	2,786	30	526	2
Nonoptimums	2,264	15	1,282	10	1,237	13	3,958	15
Totals	14,243	100	12,290	100	9,490	100	25,204	100
Wing unit mass, kg/m^2	66.6		57.4		44.3		54.3	

honeycomb covers is greater than a skin/stinger cover. The net savings in overall mass, however, for the advanced wing designs is brought about by reductions in internal structural mass and nonoptimums such as fasteners.

In order to complete the comparison in Table 1, a shuttle bond-on RSI was assumed for the three 214-m^2 wings. For the titanium honeycomb wing, a reduction in RSI mass is realized since approximately 60% of the upper surface of the wing would not require thermal protection. Paradoxically, in those regions where RSI is applied, the wing must be protected to 500 K because of the limitations of the bond system; this temperature being about 170 K below the capability of the titanium.

For the 464-m^2 multilayer honeycomb wing shown at the right in Table 1, the covers constitute 57% of the total wing mass. This is not only due to a concentration of the wing structure in the covers, but is also due to the integration of the thermal-protection function into this structural element. The 526 kg shown for TPS is required for localized regions of high temperature such as the leading edges where temperatures exceed the capabilities of the Inconel.

When comparing the unit masses of the concepts summarized, a reduction of approximately 14% in wing mass was obtained by changing the wing-structural concept from skin/stringer to honeycomb, and an additional 23% by changing materials. There is little doubt that the use of composites for the wing-structural material would result in further reductions in structural mass.

In regard to the unit mass of 54.3 kg/m^2 shown, direct comparisons are difficult to make since experience shows that geometrically similar (but larger) wings tend to be heavier on a unit-mass basis. However, if it were to be scaled to the size of the 214-m^2 wing, its unit mass would be comparable to, but only slightly heavier than, the titanium honeycomb wing listed.

New Technologies Applicable to Advanced Wing Designs

In the computer study models, only "dry" wing designs have been considered to date. For wet wings and high propellant packaging efficiencies, more compact actuators may be required. One candidate actuator (electrically powered and acting as a power hinge) affords one possible solution.[15] A motor for this application is being developed and tested for possible future space use. The operational constraints of the shuttle orbiter elevons are being applied. This dc motor delivers approximately 17 hp in a compact 11-cm diameter, a design achieved through the use of advanced technologies in permanent magnet materials, motor controls, and other new technologies. The use of the power hinge makes it possible to eliminate large cut-outs in the rear spar that are normally required for linear actuators. This design approach results in reduced wing structural mass in addition to any weight advantages which might accrue in the actuation system.

Not involving hardware, but an equally important technology directed toward wing mass reduction, is the application of probabilistic design.[16,17] This is a needed discipline since the practice of compunding margins of safety is fairly common. In the interest of low structural mass, both material properties and expected loading conditions should be treated in a statistical way. For a wing design, this would involve consideration of known statistical data on expected wind shears and wind gusts, vehicle trajectory with expected control forces, wing material properties distributions, and many other factors. The standard deviation to be used (whether 2σ or 3σ, for example) would be part of the design analysis and could change from one component to another depending upon risk involved, design criteria, and failure modes. The probabilistic design disciplines need to be applied, of course, not just to wing structure, but also to all of the advanced vehicle's structures and other subsystems.

In a recent design criteria study,[16] the author indicates that the mass reduction associated with a probabilistic treatment of design criteria is quantitatively equatable to innovative subsystem improvements or advances in material technology. In applying the methodology, one would prepare histograms, or probabilistic density functions (PDF), so that assigned values to engineering random variables could be selectively made for all elements of a design on the basis of risk/reliability in lieu of margins or factors of safety. Presently, factors and margins of safety are applied to allow for unknowns in loadings and materials, and do not, in reality, identify the degree of safety of a system.

Research Needs

The results of this study indicate that the following areas of research should be pursued:

1) Development and adaptation of structural programs to new wing structural concepts and new materials.

2) Development of lightweight wing covers such as honeycomb and the associated manufacturing technologies such as diffusion bonding.

3) Development of technology in electromechanical control surface actuators since they show promise of reductions in wing structural mass (as well as some of the related subsystems, such as prime power).

4) Study of design criteria, particularly regarding the probabilities associated with material properties and applied loads.

Conclusions

Three wings involving new approaches to structural design have been studied for Earth-to-orbit transports. Characteristically, the wings configured for Earth-to-orbit transports are much "stiffer" in bending and torsion than conventional wings. These wings differ in many respects from current wings in materials and geometry. By utilizing innovative structural configurations, such as honeycomb for wing covers, a 14% weight savings is shown. An additional weight savings of 23% is shown when titanium is substituted for aluminum, a portion of which is attributable to a savings in thermal protection. Savings are also available through the selection of advanced materials and the use of probabilistic approaches to new design.

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