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New Technology in Commercial Aircraft Design for Minimum Operating Cost

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In this paper the potential gains from the application of various forms of advanced technology to commercial aircraft are considered in terms of direct operating cost (DOC) and fuel consumed. It is shown that even relative to the standard of the most recent short and medium haul aircraft to enter service, substantial DOC and fuel reductions are attainable. These gains result mainly from the exploitation of advances in wing design, stability augmentation, load alleviation, and composite materials. Developments in these areas are taking place progressively and some results of this work are already being incorporated in production and planned aircraft programs. However, in some instances considerable development is needed to realise the full technical potential. For the most advanced designs, high aspect ratios are required for minimum DOC and may approach the limit of practicability for a number of technical reasons. When constrained in this way, optimization for minimum fuel consumption at a given cruise speed produced only a small additional fuel saving at the expense of some DOC penalty. Therefore it is anticipated that aircraft will continue to be designed, as in the past, for minimum DOC.

Introduction

TRAFFIC growth and the replacement of the older, less efficient, and noisier aircraft—60% of western world capacity may be regarded as in this category—provide the opportunity for applying new technologies to subsonic commercial transports. Reduction of operating cost continues to provide the major incentive, though increasing emphasis is being placed upon low fuel consumption and low noise.

For the purpose of this paper, the term "advanced technology" is taken to embrace significant engineering advances which are not commonplace in aircraft flying today. In general, it is wrong to think of such advances as new inventions. Almost without exception they have evolved over the years, with few quantum jumps. There are, of course, exceptions to this and a recent example with regard to engine development might be the introduction of high bypass ratio engines in the late 1960's, which brought about a 25% improvement in specific fuel consumption. However, even this major step could be regarded as an evolutionary development from engines of bypass ratio about 1.0, which themselves had conferred significant gains relative to the straight turbojet engines of the late 1950's.

If the market into which advanced technology might be sold is considered, it is found that despite setbacks traffic is increasing and this is expected to continue into the foreseeable future.

In the past there has been a continuing reduction with time of direct operating cost (DOC) per seat mile when adjusted to constant monetary values. This has resulted primarily from the increasing size and productivity of aircraft, though other technical changes have had considerable influence. It cannot necessarily be assumed that aircraft size will continue to increase, so that the challenge to improve DOC by use of new technology may be even greater than in the past; although, of course, "stretches" to current aircraft will continue. Some engineers have expressed the view that for subsonic commercial transport aircraft only small gains will be realized from advanced technology; others, less inhibited perhaps, believe that significant improvements remain to be made. It is the purpose of this paper to examine the likely prospects.

Choice of Reference Aircraft

The reference standard chosen for this paper implies a 1970 standard of technology, similar to that used for the latest short and medium haul aircraft to enter service. The aircraft (Fig. 1) is designed to carry 200 – 236 passengers (depending upon interior layout) over a maximum range of 2200 n.mi. at Mach 0.79, though in practice it would operate mainly over shorter ranges. Table 1 lists some leading particulars.

Because gains from the use of advanced technology are affected by specification and operational constraints, results quoted here are not necessarily applicable to all types of transport aircraft. Nevertheless, it is thought that the results presented give a good indication of what is possible. Figure 2 shows the effect of varying design speed and range on the DOC reduction from a particular advance in high speed wing design; as would be expected, the gain is greater at longer ranges and higher cruise speeds.

Scope for DOC Reduction

In what follows only those advances in design which provide significant operating cost reductions are considered. There are many valuable innovations (for example, improved flight deck presentation) which have only a small effect on operating costs; there are others (such as the use of digital electronic systems) where the benefits due to improvements in reliability and maintenance procedures are not reflected in conventional operating cost formulas. Improvements in engine design will, of course, have a direct and major effect on operating costs, but such improvements are outside the scope of this paper, which is concerned with airframe changes. System design changes which encourage fuel saving through improved operational procedures are also excluded.

With these exclusions, the developments are reduced essentially to advanced wing design, stability augmentation,

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Table 1 Leading particulars of reference aircraft

Passenger capacity	200-236
Max takeoff weight	245,000 lb
Wing area	2200 ft^2
Fuselage diameter	189 in.
Wing span	138.7 ft
Wing aspect ratio	8.75
Wing sweep (quarter chord)	27.5 deg
Max operating speed	$M = 0.81$
Normal cruise altitude	33,000 ft
Max range with full payload	2200 n.mile
Engine-out ceiling (ISA + 20°C)	7000 ft
Engine thrust (sea-level, static)	37,000 lb
Takeoff distance (ISA + 10°C)[a]	8000 ft
Landing distance[a]	4300 ft
Landing approach speed	120 knots E.A.S.
Max fuel capacity range	3000 n. mi.

[a] Sea level.

aerodynamic load alleviation, and carbon fiber composite structures.[1] Most of these changes lend themselves to a project parametric analysis and this approach has, in general, been followed.

The scope for DOC reduction will depend in part upon the method of calculation used. The Eurac method, which was developed recently in Europe, includes interest charges and landing and navigational charges which do not appear in either the 1977 Boeing method or the old 1967 ATA method. Since these charges relate to the characteristics of the aircraft itself, there is a case for including them in the DOC. For this reason, and because it is commonly employed in Europe, the Eurac method has been used in this paper. In general, experience with these formulas suggests that the percentage DOC reductions obtained from different forms of advanced technology are not much affected by the choice of formula used in the assessment, although the costs per seat mile do differ substantially from one method to another. There are exceptions to this; for a cruise speed increase, the Eurac method, with greater emphasis on first-cost-dependent items, gives larger gains than does the Boeing formula, which tends to favor fuel economy.

Figure 3 shows that DOC is strongly influenced by block time (climb/cruise/descent speed) block fuel (drag, weight,

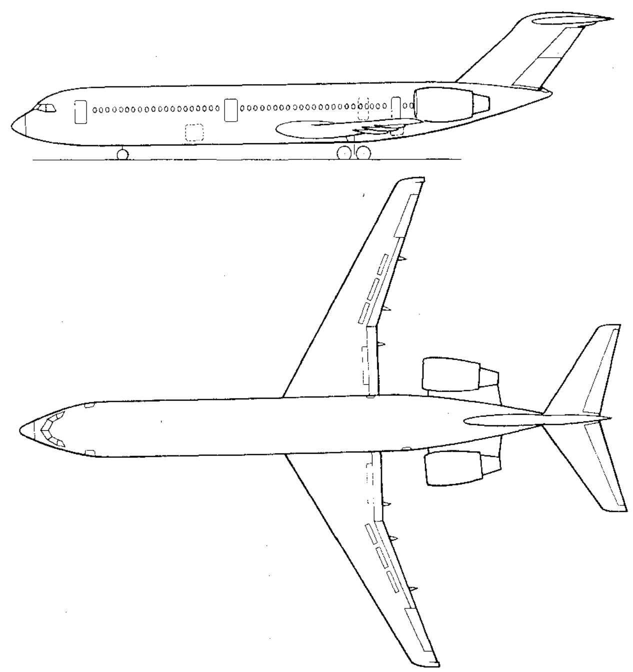

Fig. 1 Reference aircraft configuration.

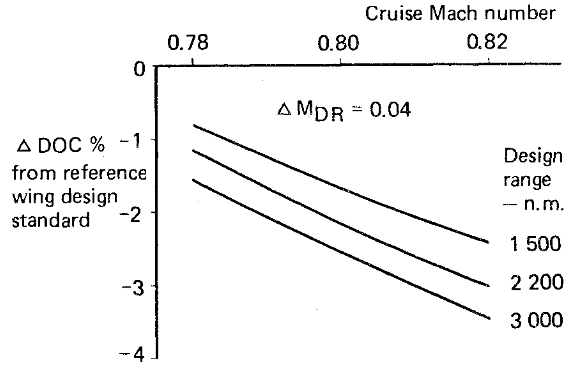

Fig. 2 DOC saving from improved high speed wing design.

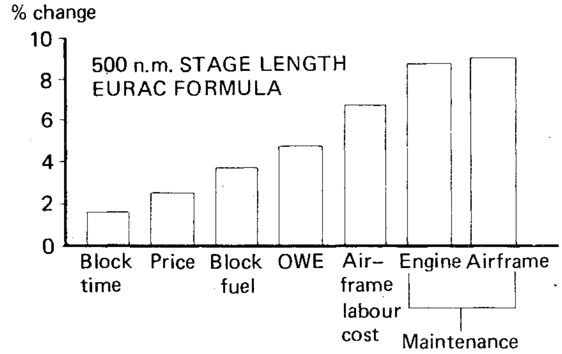

Fig. 3 Percent change to give 1% DOC change.

and engine specific fuel consumption), and aircraft price (airframe, engine, and equipment costs). The cost of research and development itself has very little influence on DOC, although the gains that result from it can be substantial. This is an important consideration when assessing the application of new technology. Aircraft price is strongly influenced by production costs, and for every 10% reduction in production cost the DOC will drop by about 2.5%.

Airframe and engine maintenance costs are variously accounted for in the DOC formulas. The relationship between "formula" and "real" maintenance costs is not clear and the difference in methods of accounting used by the various airlines does not help the problem. With regards to the items considered in this paper, however, the maintenance costs involved form a rather small part of the total airframe maintenance costs, so that changes in maintenance cost due to these technical advances are likely to be small in their effect on DOC.

Advanced Technology

Advanced Wing Design

Considerable advances have been made in high speed aerodynamic wing design and the shape of wings with substantial areas of supercritical flow can now be defined with far more confidence than was previously possible. In a somewhat simplified way, Fig. 4 illustrates the continued development that has taken place. In this figure, aerodynamic advance has been expressed in terms of an "equivalent drag rise Mach number." This parameter gives the variation in drag rise Mach number when differences in wing thickness, sweep, and cruise lift coefficient have been allowed for.

Low speed improvements are also taking place, and the design of the wing must take account of the complete speed range of the aircraft. In practice, at least in the initial stages, this involves the use of some form of multivariate optimization process.[2]

The results of such a study are illustrated in Fig. 5 where the changes in DOC (at the design range) are shown as a function

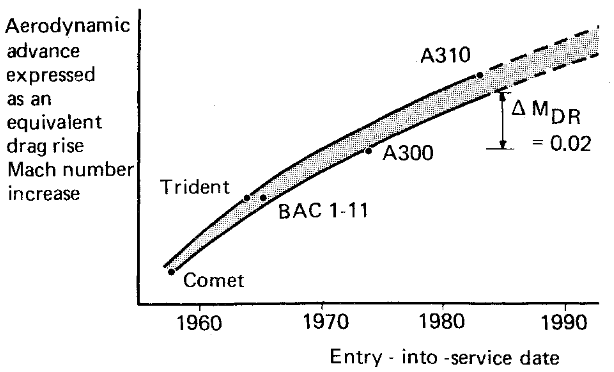

Fig. 4 Advance in high speed wing design.

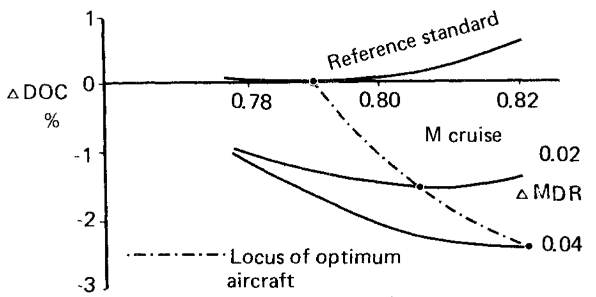

Fig. 5 DOC saving from advanced high speed wing design.

of design cruise Mach number and technology standard. The latter has been expressed in terms of the increase in drag rise Mach number (ΔM_{DR}) for a given wing sweep, thickness/chord ratio, and cruise lift coefficient relative to a reference standard. The aircraft have all been designed to meet the reference short and medium haul specification, with a fixed number of passengers. The curves are "envelopes" giving the optimum aircraft at each design cruise Mach number for a particular level of wing technology. The engine size required for these designs is determined by either a single-engine ceiling or a cruise requirement. The wing area and flap chord combination is in most cases determined by fuel volume and approach speed requirements. It is interesting to note that the optimum design Mach number increases at a slightly lower rate than the drag rise Mach number.

Wing sweep and thickness/chord ratio are shown in Fig. 6 for these optimum designs. The variation of aspect ratio has not been shown, as the optimum value is relatively insensitive to the improvement in drag rise Mach number.

Stability Augmentation

Stability augmentation, obtained from yaw dampers, Mach trimmers, autothrottles, and the like, has been in common use for many years on civil aircraft. The reliability of such systems is already good and with the new technology now becoming available there is confidence that the use of stability augmentation can be expanded.[3] If aircraft can be designed to stability levels lower than in the past, then tail sizes and loads can be reduced and there are consequent benefits in drag and weight, both directly and, through trim changes, indirectly.[4] The overall effect can be to reduce wing and engine size or to increase payload.

In practice, the stability requirement is only one of several which an aircraft has to meet. Trim and controllability may provide the critical design cases for an aircraft, or do so after only a small relaxation of the normal stability level. The second factor is that the conventional stability margin is itself quite small, and therefore only a modest relaxation is permissible before the handling becomes unacceptable after augmentation system failure.

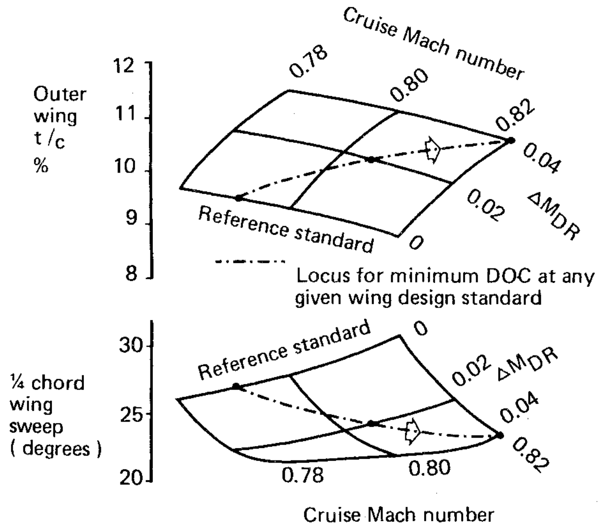

Fig. 6 Wing geometry for aircraft optimized to minimize DOC.

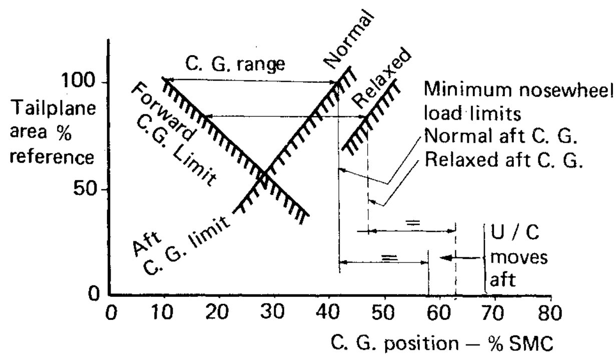

Fig. 7 Tailplane size, rear-engined configuration.

Unless the failure is extremely improbable (less than 1 in 10^9 h) the aircraft must have handling qualities which are as a minimum just acceptable in an emergency. For the next generation of aircraft, therefore, a limited application of stability relaxation is foreseen.

The constraints are different for underwing- and rear-engined aircraft, so that the potential gains are likely to be different also. Figure 7 shows the tailplane design chart for the reference rear-engined aircraft. The natural maneuver margin may be reduced by moving the most aft center of gravity (c.g.) behind the normal limit, while maintaining the required c.g. range. If the minimum maneuver margin is reduced in this way to approximately zero, the tailplane size may be reduced by about 15%. A limit on aft c.g. movement is set by the need to maintain sufficient load on the nose wheel during takeoff; consequently when stability is relaxed, the main landing gear must be moved back about 5% mean chord to maintain nose wheel load. With zero natural maneuver margin, a gently divergent mode is obtained in the event of an augmentation system failure. Calculations suggest that the gain in DOC to be made with this degree of stability relaxation is about 1.5%, after allowance has been made for systems weight and cost increases.

With an underwing-engined aircraft there is normally a substantial nose-up thrust moment at takeoff, requiring a further aft landing gear position to maintain nose wheel load. When stability augmentation is used it may, therefore, be more difficult to locate the landing gear satisfactorily without significant cost and weight penalties.

A flight simulator investigation on a rear-engined aircraft has suggested that, in the critical longitudinal flight condition, a mildly divergent mode was acceptable. Following these studies, flight tests were conducted on the BAC 1-11 aircraft in which the stability was reduced both artifically and by rearward movement of the c.g. In the latter case the c.g. was moved aft to coincide approximately with the maneuver point. The flight tests confirmed the findings of the simulator investigation. It follows that in this case quite simple augmentation systems can be used since failure of the system is acceptable provided warning is given. It has also been found that benefits are obtained with relaxed stability through the reduction of aircraft response to external disturbances.

In the case of directional stability and control, it is found that the scope for stability augmentation critically depends upon the configuration employed. For the "underwing" layout, the asymmetric thrust moment is usually so large that the rudder power required determines fin size. There is then no opportunity to relax other requirements and directional stability augmentation cannot be used. A rear-engined aircraft has a smaller asymmetric thrust moment and therefore a smaller rudder power requirement on this account. Relative to the underwing-engined configuration it will have lower weathercock stability, and sideslip cases with asymmetric thrust determine fin and rudder area. Using a rudder bias system to deal with the sideslip cases, a fin size reduction of as much as 15% may then be obtained. When various other forms of advanced technology are combined and applied to this type of configuration there will be substantial reductions in engine size (for a given payload requirement) and the consequent reduction in thrust moment may then permit larger overall fin size reductions when directional stability is augmented artificially. When stability is relaxed to this extent the aircraft will become naturally unstable and difficult to control without augmentation, so that significant problems will arise concerning system reliability in order to satisfy certification requirements.

With a 15% reduction in fin size on the reference aircraft, the DOC saving is about 0.8%, which suggests that in the near future only minor improvements may be expected. If a 30% fin size reduction were achievable in the longer term on an advanced aircraft this would result in a saving of about 1.5%.

It may be noted that for both longitudinal and lateral stability augmentation, gains in DOC are more readily realized on rear-engined than on underwing-engined aircraft.

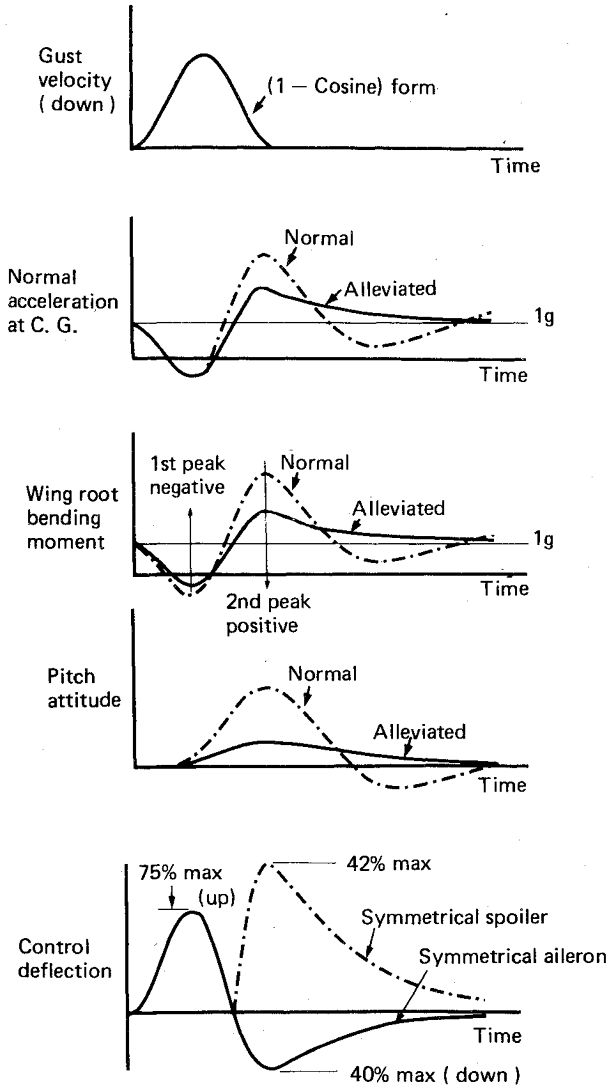

Fig. 8 Alleviation of long wavelength down gust.

Aerodynamic Load Alleviation

Load alleviation may be used to reduce wing structure weight or, with a derivative aircraft, to develop existing structure to higher design weights. (A passive version of this is used on the VC10, where the flight crew adjust the aileron upfloat above a certain aircraft weight.) Operation of various control surfaces moves the load inboard (in the maneuver case) or partially cancels the induced load (in the gust case). Alleviation must be used in both gust and maneuver cases to be effective.

The concept of the isolated gust, used in the British and American requirements has been in recent years supplemented by the concept of continuous turbulence described by power spectra. With the latter, response is described statistically in terms of an implied amplitude probability distribution. It appears that with sufficient care a gust attenuation system can be designed which accommodates both approaches satisfactorily.

The maximum discrete gust loads on the unalleviated aircraft tend to occur broadly in two gust wavelength bands. The first peak, at a short gust wavelength, results from the initial impact of the gust modified by aircraft heave and structural response. In general the second peak, at a longer gust wavelength, occurs where the natural short period motion of the aircraft is excited. If the (gust wavelength)$^{1/3}$ law is accepted, then design loads in response to short wavelength gusts are reduced and the second peak gives the critical loading. Since this second peak occurs at a relatively long wavelength, the problems of alleviation are reduced.

Figure 8 shows the effect of an alleviation system, using ailerons and spoilers with elevator pitch compensation, on the response and wing-root bending moment for a typical long wavelength gust. The effect of alleviation on gust design wing loads is shown in Fig. 9. This is based upon the worst combination of multiramp gusts, with amplitudes dependent upon (wavelength)$^{1/3}$ and probability of encounter. The root bending moment is shown to be reduced by 33%. The torque, especially on the outer wing, has increased, but in practice will not equal that in the design case which is normally given by the aileron rolling maneuver.

Transport aircraft of the type considered are required to be designed to a maneuvering g of 2.5. This value is based upon experience and covers inadvertent or emergency maneuvering and the possibility of meeting gusts while maneuvering. It may well be that with a control limiting system the allowance for such excess inadvertent maneuvering g could be reduced without adversely affecting the normal turning or pullout ability.

There is likely to be a practical limit, certainly for some years, of about 33% for load alleviation. This is set by the condition that the ultimate strength is sufficient to meet the probable airworthiness requirements in the total alleviation system failure case. This would apply to a new design and would involve the use of ailerons, spoilers, and elevators, as well as fast-acting inboard flaps for the maneuver case. In practice the amount of inboard center-of-pressure shift achievable in the maneuver case will also be limiting, unless

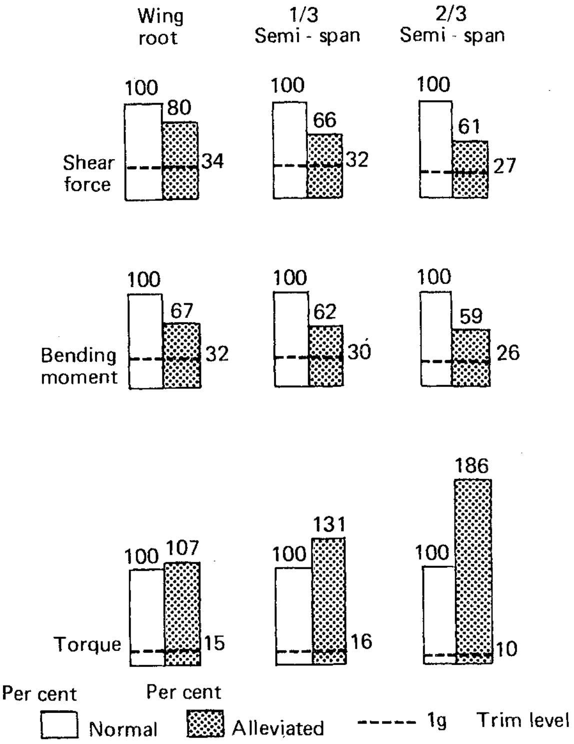

Fig. 9 Effect of load alleviation on gust design loads.

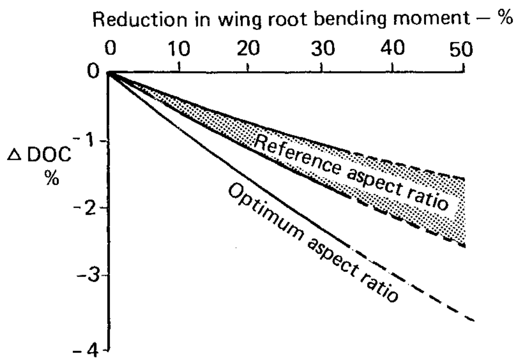

Fig. 10 DOC saving from load alleviation.

the requirement of 2.5 g for the design maneuver case can be reduced.

Figure 10 shows the predicted gain in DOC with degree of load alleviation for the reference aircraft. There is some degree of uncertainty regarding the wing weight saving likely to be achieved, depending upon the extent to which the wing is initially designed to allow for the use of load alleviation. This is represented by the shaded area in Fig. 10. When aspect ratio is increased using the wing weight saving, the DOC reduction is also increased as shown by the lower curve. It must be borne in mind that changes in the aerodynamic control configuration for load alleviation should not degrade the other aspects of performance, such as high lift, as otherwise the DOC gains from load alleviation could be partially offset.

Carbon Fiber Composite Structures

Advances in quality and manufacturing process control have made possible the production of consistent structural components in carbon fiber composite (CFC), which has emerged as a material with great promise for reduction in structure weight. In the civil field, manufacturers are progressively incorporating CFC—initially in secondary structures, subsequently in replaceable primary surfaces (e.g., tail units), and eventually in major primary structures. In the military field, major primary components in CFC are being developed for full-scale production in the not too distant future, and service experience with secondary structures will provide the confidence in composites needed before they can be used in primary components for civil aircraft.

Key factors affecting realization of the objectives for civil aircraft applications are: Manufacturing and maintenance costs; product consistency, with reference to design features and the associated manufacturing processes; and long-term integrity, particularly the effects of aging and environmental deterioration in service.

Studies show that for lightly loaded components sandwich construction provides an optimum solution, with weight savings of 25-30% compared with the light alloy equivalent. Since the number of parts in the CFC component can be significantly smaller, the high material cost can be largely offset and, as output is increased, the material cost will drop.

There is some doubt about the relative cost of carbon fiber structures, but with the assumption of a 40% cost increase per unit weight, substitution of a CFC wing for the light alloy original on the reference aircraft resulted in a DOC reduction of about 3%. Use of composites in primary wing structure increases the optimum aspect ratio, and the percentage weight savings relative to aluminium alloy construction also increase with aspect ratio.

Combination of Advanced Technologies

Because the various forms of advanced technology interact, especially in defining the wing configuration, it is desirable to use a multivariate analysis (MVA) approach to configuration definition. The reference aircraft was itself optimized for minimum DOC in this way, using a 1970 technology standard with a pitch-up limitation on aspect ratio. This limitation was thought to be inappropriate for an advanced aircraft, since pitch-up could be dealt with by automatic means or even by normal development. In order that technology gains should not be confused by the resulting aspect ratio change, a "datum" aircraft was derived (Table 2) by reoptimizing the reference aircraft without the pitch-up limitation. An optimum advanced aircraft with a wing employing advanced high speed wing design, load alleviation, and CFC construction was then obtained and Table 2 provides a comparison with the datum. It may be seen that substantial reductions in aircraft weight, engine thrust, engine weight, fuel used, and DOC have been obtained, and that the aspect ratio has risen to a high value.

Figure 11 shows the variation in DOC with cruise Mach number for various technology standards, each configuration being optimum for the given Mach number and standard. The

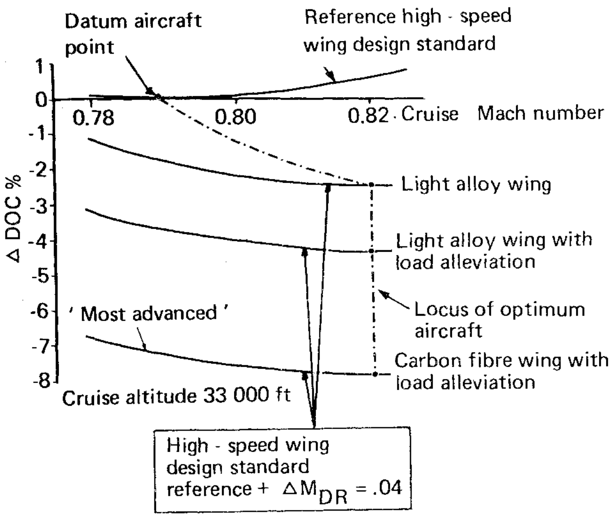

Fig. 11 DOC saving for optimum aircraft.

Table 2 Optimized aircraft using advanced technology

Reference Optimization type	Aircraft Aspect ratio limited		Datum aircraft Aspect ratio free	
Wing design standard	Reference	Reference	$+0.04M_{DR}$	$+0.04M_{DR}$
Load alleviation	No	No	Yes	Yes
Wing construction	L/A[a]	L/A	L/A	CFC
Cruise Mach number	0.79	0.79	0.82	0.82
Wing area ft^2	2200	2180	2020	1900
Wing loading, lb/ft^2	112	112	115	114
Wing sweep quarter chord, deg	27.5	27	23.5	25
Outer wing thickness/chord ratio, %	9.9	9.5	10.6	10.8
Aspect ratio	8.75	11.0	12.1	13.0
Engine thrust, Δ, %	+8.4	Datum	−5.8	−15.5
Operating weight empty, Δ, %	−1.6	Datum	−6.4	−16.0
Takeoff weight, Δ, %	+0.6	Datum	−4.3	−11.2
Block time, Δ, %	0	Datum	−3.0	−3.0
Block fuel, Δ, %	+5.4	Datum	−2.4	−8.4
DOC, Δ, %	+1.1	Datum	−4.3	−7.75

[a] Light alloy.

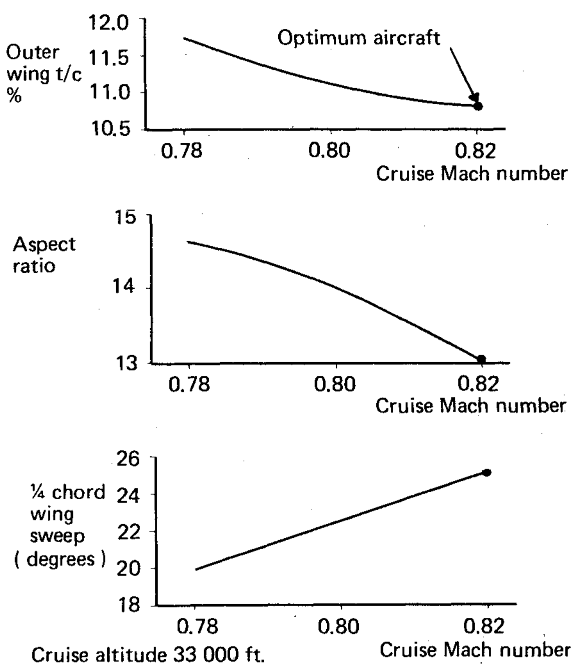

Fig. 12 Wing geometry for minimum DOC, "most advanced" designs.

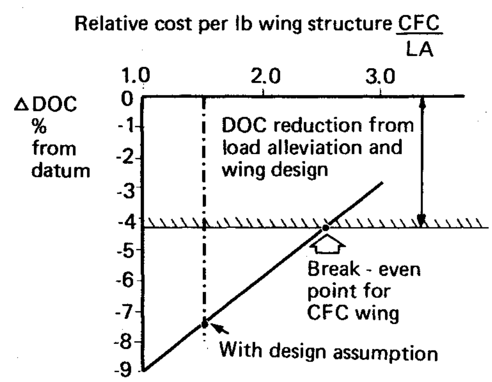

Fig. 13 Effect on DOC saving of CFC wing cost.

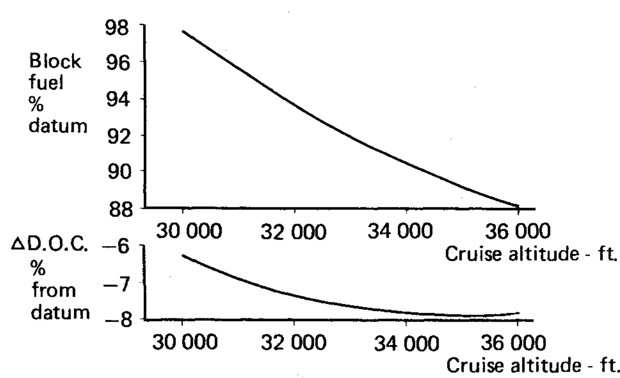

Fig. 14 Effect of cruise altitude, "most advanced" designs.

largest single gain at all Mach numbers derives from use of CFC construction.

The variation of optimum wing geometry with Mach number is shown in Fig. 12 for the "most advanced" aircraft. As would be expected, with high speed the optimum thickness/chord ratio decreases and the sweep increases. Aspect ratio is reduced to avoid the wing weight increase that otherwise occurs with reduced thickness and as a result of the reduction in lift-dependent drag.

It is important to note that where CFC is used the DOC gain is especially dependent upon the manufacturing cost. In obtaining the DOC reductions given in Fig. 11 it was assumed that the CFC wing cost 40% more per pound of weight than an equivalent light alloy wing. Bearing in mind the weight reduction achieved, this gives close equality in cost per component. There is some uncertainty regarding the costs likely to be experienced in production and Fig. 13 shows the effect of varying the relative cost per pound of wing structure for the "most advanced" configuration. It may be seen that the breakeven point for which CFC construction gives no overall gain occurs when the cost per pound is 2.5 times the light alloy value.

In the above work optimization was done at a fixed cruise altitude of 33,000 ft. (At this altitude the reference aircraft was limited by buffet requirements.) Figure 14 shows that when the "most advanced" aircraft is optimized with altitude as a variable the minimum DOC occurs at 35,000 ft. The

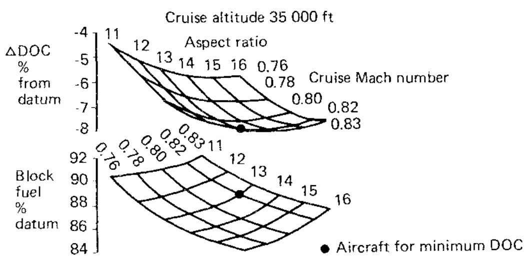

Fig. 15 Effect of cruise speed and aspect ratio, "most advanced" designs.

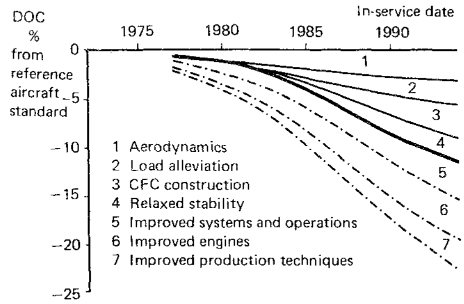

Fig. 16 Time scale of DOC reductions.

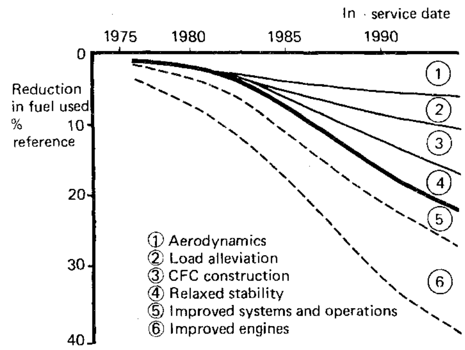

Fig. 17 Time scale of fuel savings.

effect of the altitude change on DOC is quite small, but there is a significant saving in fuel of about 3%.

It may be seen that for the "most advanced" aircraft there is a DOC reduction from datum of nearly 8%. The cruise speed has increased from $M = 0.79$ to 0.82, and the optimum aspect ratio is now about 13. Figure 15 shows the sensitivity of the DOC reduction and fuel used to variations in the major parameters, cruise speed and aspect ratio. The aspect ratio could be somewhat reduced from the optimum without significant worsening of the DOC (but with a small penalty in fuel consumption). It is probable that the "practical" optimum aspect ratio would be in the region of 12. Preliminary studies of high aspect ratio wings suggest that when carbon fiber is employed to vary stiffness directionally aspect ratios of about 12 are feasible from the aeroelastic standpoint.

Undercarriage stowage, although difficult with such wings, appears to be possible, judged by the engineering studies conducted to date.

In obtaining the results presented above, it was assumed that optimization for minimum DOC was desirable. While in the past this has been the aim with good reason and is likely to remain so in principle, there are other important considerations. It must be remembered that "formula DOC" gives considerable emphasis to reductions in block time, which may in practice be lost due to delays and vicissitudes of airline scheduling. Savings in fuel will, however, produce clear cost benefits to the airline.

In the light of these considerations, a similar study has been made of optimizing for minimum fuel consumption. The aircraft geometry obtained was, of course, somewhat different than that of minimum DOC. The most significant parameters for both minimum DOC and minimum fuel consumption were cruise speed and aspect ratio. The cruise speed for the minimum fuel aircraft was $M = 0.76$ giving 5.5% less fuel than the minimum DOC aircraft which cruised at $M = 0.82$. However, due mainly to the lower cruise speed, the minimum fuel aircraft had a 3% worse DOC. The aspect ratio of the aircraft with minimum fuel consumption was higher, but studies conducted to date suggest that the aspect ratio of the minimum DOC design is itself near the limit of practicability with regard to structural deflections and undercarriage stowage. (In some instances there may also be a nominal limit on airport "gate" size.) Within such limitations, optimization for minimum fuel consumption produced only small additional fuel savings for a given cruise speed. For example, if the minimum DOC aircraft is cruised more slowly, say at the reference aircraft design speed of $M = 0.79$, the fuel used is less than 1% greater than for a minimum fuel aircraft designed for this speed and with the same aspect ratio. The aircraft with minimum fuel consumption is marginally worse in DOC. Even if the cruise speed is reduced further to $M = 0.76$ (optimum for the minimum fuel consumption aircraft) the fuel consumption and DOC differences are little changed. If, as expected, fuel costs rise relatively more than other costs, the minimum DOC aircraft will cruise correspondingly more slowly but aspect ratio will continue to be limited as described above, so that in practice there is likely to be little advantage in designing exclusively for minimum fuel consumption.

Conclusion

The results of the studies have indicated that substantial reductions in DOC and fuel consumption can be obtained from the exploitation of advanced technology in its various forms. In some areas the technical advances are already being partially incorporated in production aircraft. In others, gains may be made in the near future, while in some instances considerable development is needed to realize the full technical potential. Figure 16 shows an approximate time scale for the achievement of reduction in DOC as technical development occurs. The corresponding reductions in fuel consumption are indicated in Fig. 17.

It has been shown that for the most advanced designs, high aspect ratios are required for minimum DOC and may approach the limit of practicability for a number of technical reasons. When constrained in this way, optimization for minimum fuel consumption at a given cruise speed produced only a small additional fuel saving at the expense of slightly worse DOC. Therefore it is anticipated that aircraft will continue to be designed, as in the past, for minimum DOC. Through price increases, fuel scarcity will provide a stimulus to technical advance which will influence aircraft design in the usual course of optimization to achieve minimum operating cost.

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