MULTIDISCIPLINARY OPTIMISATION IN AIRCRAFT DESIGN

D.L.I. Kirkpatrick
J.S. Smith
Royal Aerospace Establishment
Farnborough, Hampshire, United Kingdom

Abstract

This paper outlines the multivariate optimisation (MVO) program developed at RAE to help in the assessment of new aircraft projects and in guiding the aeronautical research programme towards the most - promising research thrusts. In this program the disciplines of aeronautical science are integrated in design synthesis equations which yield the optimum aircraft design which meets specified mission requirements using a given level of technology. This paper indicates that the MVO program can be used to investigate the effects on aircraft design of changed requirements or of advances in aeronautical technology.

The paper also emphasises the importance of the non-aeronautical disciplines of economic, social and operational analysis which influence the design of a transport or of a combat aircraft. Both sets of disciplines must be effectively combined to yield a successful aircraft design.

Introduction

In the United Kingdom some years ago, the Royal Aircraft Establishment (now the Royal Aerospace Establishment) and the British aircraft manufacturing companies mounted a major research programme on the high-lift systems suitable for the wings of transport aircraft. This research programme incorporated wind-tunnel tests to define the performance of alternative high-lift systems, and detailed engineering studies to determine the mass and cost of such systems. The programme yielded a large quantity of accurate data on the lift and drag increments, mass and cost of alternative high-lift systems, but did not indicate which systems would be the best choice for the next generation of transport aircraft and which therefore merited further development.

The choice of the best high-lift system for a new aircraft project is an integral part of the extremely-problem of identifying the best aircraft design to meet a particular requirement. That problem involves a large number of interacting technical factors drawn from several aeronautical disciplines (including aerodynamics, propulsion, materials, structures, and flight controls) in order to satisfy numerous mission requirements and constraints. In the UK the detailed design and development of new aircraft is the business of industrial companies, but the Royal Aerospace Establishment (RAE) is responsible for helping Government Departments to assess new projects and to guide the aeronautical research programme into the most productive channels. It is therefore necessary for the RAE to have a sound understanding of the aircraft design process, and to have the capability of studying the effects on aircraft design of technological, commercial and military developments. To help provide that capability - and in particular to identify the most - promising high-lift systems - the RAE developed a computer program for aircraft design synthesis and optimisation by combining aircraft preliminary design equations with a numerical optimisation technique. The program was designed to select up to 25 of the principal aircraft design characteristics to produce a design which gave the best value of a chosen criterion of merit and which satisfied the specified requirement, using a chosen standard of aeronautical technology. Because it incorporated a large number of independent design variables, the program became known as multivariate optimisation (MVO).

The initial version of the RAE multi-variate optimisation program was developed for transport aircraft,[1-4] and subsequently parallel development work was undertaken to develop a program for combat aircraft[5]. Throughout this development work, the design synthesis equations have been continuously refined and improved, the program has been restructured into a modular form and the original optimisation routine[6] has been replaced successively by more - sophisticated versions[7,8], all developed at RAE. The development has involved the participation of specialists in a wide variety of disciplines (aerodynamics, propulsion, materials and structures, mass and cost estimating), and has demanded a multi-disciplinary approach to the problems of aircraft design.

---

*Head, Aerodynamics Department
**DE(A)1, BDS Washington

Development of Multivariate Optimisation

The aircraft design synthesis method, given a particular set of design variables and design parameters, calculates the aircraft configuration which satisfies the specified mission requirements, mission constraints and design constraints. In the first version of the method, for transport aircraft, the design variables to be optimised included

Wing area, sweep, thickness/chord, taper and aspect ratio.

High-lift systems size and deflection at takeoff and landing.

Engine scale.

Cruising speed and altitude.

Because that version of the program was principally directed towards the geometry of the wing and its high-lift devices, that geometry was specified in more detail than the other parts of the aircraft. The mission requirements were

Number and mass of passengers.

Mass of baggage and freight.

Furnishing and galley standards.

Range with full payload.

Diversion distance and holding time.

In the transport aircraft program the first three of these requirements were used to calculate the size and mass of the fuselage, which thereafter remained fixed during the optimisation process. The mission constraints were (Fig 1).

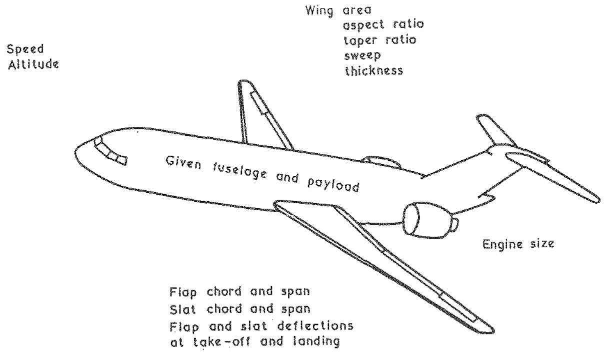

FIG.1 VARIABLES TO BE OPTIMISED

Cruise speed and altitude to exceed minimum values.

Take off distance at maximum take off mass to be less than a specified value.

Engine - failed climb gradient to exceed airworthiness requirement.

Approach speed at normal landing mass to be less than a specified value.

The constraints on takeoff distance and approach speed were associated with particular assumed values of runway roughness, altitude and temperature. The design constraints were

Satisfactory longitudinal and lateral stability.

Acceptable fuselage angles on takeoff and landing.

Adequate fuel tank capacity.

The design constraints on stability determined the size and location of the fin and tailplane, and constrained the wing sweep and aspect ratio to values with acceptable stalling characteristics. The fuel tank capacity was required to exceed that required for a flight at maximum takeoff mass but only a chosen fraction (40%) of the maximum payload. The design variables were used in conjunction with the design parameters to calculate aircraft performance, mass and other characteristics, the values of the design parameters being chosen to represent particular levels of aerodynamic structural and engine technology.

The design synthesis method was coupled with an optimisation routine, which systematically altered each of the design variables until the resulting aircraft design had the lowest possible value of mass, or direct operating cost, or some other chosen optimisation criterion. The use of an optimisation routine represented a departure from the traditional design approach, in which aircraft design teams produced a succession of designs varying a few of the key design variables and were guided towards the optimum design by the experience and understanding of the chief designer. This traditional design approach was entirely satisfactory for an aircraft manufacturing company because its chief designer (more perceptive than a computer) can approach the optimum design via fewer but more-detailed design calculations than MVO, and because its large design office can undertake such detailed designs. But this approach is slow because of the detailed and interactive work involved, and it may be distorted by local custom and practice. At RAE the scientists developing MVO recognised that a research establishment lacked this skill and resources, and chose instead to adopt an optimisation routine which quickly and consistently identifies the optimum design for each given requirement and level of technology. The quality of consistency is particularly important when seeking to distinguish the effects of changes to the requirement or to the level of technology employed. Calibrating the MVO program against an actual aircraft, designed to meet a known requirement, ensured that the design synthesis method contained no serious errors or omissions, which would have encouraged the optimisation routine to select a bizarre or unrealistic aircraft configuration.

In the years since their development the MVO programs have proved outstandingly valuable in:

a. exploring the effects on aircraft design of changes in the performance requirements, intended to yield some military or commercial advantage

b. discovering the best set of design changes to accommodate, at least, cost unfavourable alterations in the economic, regulatory or military situation

c. identifying the best way to exploit advances in the aeronautical technologies

d. comparing the benefits of such advances, in order to allocate research resources more effectively.

However it must be recognised that the MVO program has two important weaknesses. Its search for the optimum design cannot traverse discontinuous changes in design (arising, for example, from changing the number or location of aircraft engines) and it cannot venture into new aircraft configurations for which the design synthesis equations would not be valid. Within these restrictions, it has proved a most valuable tool.

Application to Transport Aircraft

In the years following the development of the transport aircraft version, the MVO program was used[9,10] to explore the effects of advanced aerofoil section design with well-ordered supercritical flow, of lighter high-lift systems with lower profile drag, of advanced engines with lower specific thrust and higher turbine entry temperature, and of the application of titanium and fibre-reinforced composites to the wing box and other parts of the aircraft structure. The MVO program was also used to investigate how the effects of higher fuel prices[11], and of more severe noise regulations[12], could each be partially offset by a coordinated set of changes to the characteristics of future aircraft. It was demonstrated that the re-optimised aircraft were significantly more economical than those in which the favourable or unfavourable changes were accommodated merely by scaling the datum aircraft configuration. It follows that the benefits of advances in technology would be significantly undervalued if the aircraft design were not re-optimised to take full advantage of such advances.

One of these studies[12] illustrates the advantages of being able to use a compound optimisation criterion, COC. In this case the criterion was

COC = A (direct operating cost) +
B (80 dB noise footprint)

and the values of the weighting factors A and B were varied to show how the aircraft design could be changed to reduce its noise footprint with the smallest penalty on cost. This study showed how, by design changes which improved the low-speed aerodynamic efficiency of the wings thus permitting a smaller engine and a lower throttle setting on approach, the noise footprint could be substantially reduced at minimal cost. It is possible of course to achieve more dramatic noise reductions by acoustic treatment of the engines, but the economic penalties of such treatment become increasingly severe with each successive reduction in engine noise level. Hence it is more profitable to adopt a judicious blend of engine *silencing and airframe reoptimisation* rather than to depend on engine silencing alone.

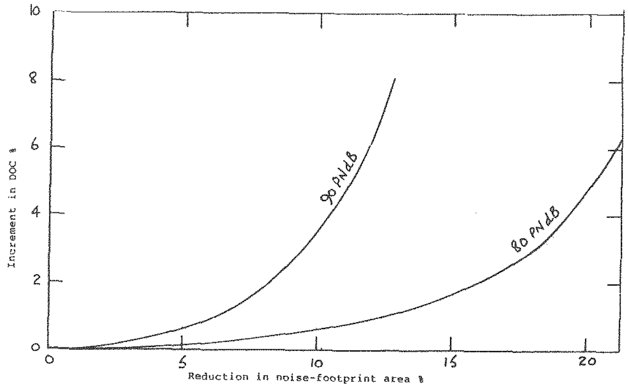

Fig 2 Reduction in noise-footprint area vs. penalty in direct operating cost for re-optimised designs

Application to Combat Aircraft

The development of design synthesis equations for combat aircraft presented some additional difficulties, notably those arising from the closer integration and interdependence of the aircraft components associated with lift, thrust, payload and fuel. In the design of a transport aircraft the size and shape of the fuselage is effectively fixed in advance by the specified number of passengers and the layout of their accommodation, but the fuselage of a combat aircraft has to accommodate a number of components (Fig 3)

Wing box

Engine bay

Intakes

Cockpit
Radar

Gun

Undercarriage bay

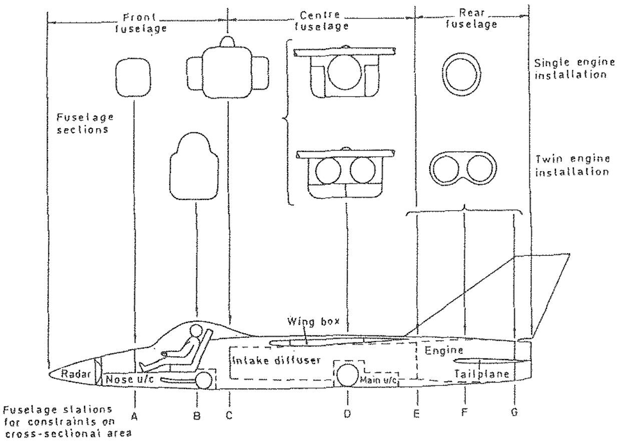

Fig 3 Aircraft layout showing fuselage sections for defining constraints

each of which has its own geometric requirements, and some of which may vary during the design optimisation. Having arranged these major items, it is then necessary to interject amongst them the necessary aircraft systems and fuel tankage and to allow for their mass and volume. All these components must be arranged to lie within a fuselage whose length and cross-sectional shapes yields acceptably-low drag at high speed. At each stage in the design this packaging process yields the fuselage dimensions, surface area and structural mass. The lifting and control surfaces of a combat aircraft are designed to provide the required performance in take off, transit and combat, to withstand the specified load factor and to accommodate sufficient fuel. The engine is scaled to provide adequate thrust to meet each of the performance requirements, and then demands adequate volume for itself, its intake(s) and nozzle.

Another source of difficulty in the design synthesis of combat aircraft is the greater complexity of the specification. The specification for a transport aircraft can be defined by a relatively - small number of mission requirements and constraints. But the specification of a combat aircraft is likely to stipulate two or more air attack or air defence missions, each of which would involve several legs (MVO allows up to 10) to be flown at very different conditions of speed and altitude. There may be several additional performance requirements covering dash speed to penetrate or intercept, ride comfort at high speed and low level, acceleration in level flight, and sustained turn rate, attained turn rate and other qualitites related to close combat. Each of the missions specified will require a different payload of bombs, missiles and external fuel tanks which significantly affect aircraft performance. Even on one type of mission, a combat aircraft is required to operate at a wider range of flight conditions, and hence at a wider range of engine throttle settings, than a transport aircraft, and so requires a more - extensive database for this version of the MVO program.

Another complication for the combat aircraft design synthesis program arises because combat aircraft are designed for war but operate (we all hope) in peace. A transport aircraft may be expected to operate at the speeds and stage lengths for which it was designed, so it is relatively simple to predict its operating cost. But a combat aircraft in peacetime operates in a training mode, flying sorties whose frequency and severity may vary considerably at the discretion of the operating air force. The mix of training sorties may be different for different operating air forces which have different priorities on training for alternative missions. Furthermore the maintenance policies of air forces may vary considerably, with some relying on volunteer professionals, some on conscripts, and others on contractor support. Finally, developments in military technology during the life of a combat aircraft may radically change its preferred mode of operation. All these considerations make it more difficult to predict the operating cost of a combat aircraft with great confidence or exactitude. In face of such uncertainty, some design studies tend to use unit procurement cost or even basic mass empty as the optimisation criterion, rather than use an uncertain and potentially - misleading estimate of life cycle cost.

All these additional complexities in combat aircraft design indicate that the application of MVO to combat aircraft[5] represented a larger task than its application to transport aircraft. Further developments of the MVO program are in progress to provide a suite of combat aircraft design synthesis modules covering:

Swept wing and tail 12
Canard delta
Canard delta with tailplane
Short take off and vertical landing
(STOVL) configurations

A recent extension of the MVO program[13] for combat aircraft makes provision for estimating the radar cross section (RCS) of the designs generated during the optimisation process. The estimation procedure is based on simple empirical methods, and is applicable to conventional configurations which have been slightly modified to remove orthogonal junctions and other sources of high RCS and which have been treated with radar - absorbent materials (RAM) to reduce radar signature. This extension to the MVO capability allowed it to be used to study the trade offs in the design of a combat aircraft between unit procurement cost, radar cross section and an agility parameter ACP representative of the aircraft's capability in close combat. This study was based on a datum combat aircraft design which had sufficient performance to satisfy a recent UK specification for an air defence fighter, and which incorporated sufficient stealth technology to reduce its radar cross section below that expected for EFA. Successive design optimisations were made using compound optimisation criteria, and it was found that significant increases in agility at constant RCS, or significant reductions in RCS at constant agility, could be achieved by coordinated sets of changes to the aircraft design leading to only modest increases in unit cost. These results, shown in Fig 4,exhibit the usual characteristic of appreciable improvement at negligible cost close to the datum configuration, with cost increasing more steeply as a design or performance requirement becomes more demanding. This illustrative example represents only a very small part of the current extensive (and highly classified) studies of the application of stealth technology to the design of the next generation of combat aircraft, and is intended only to indicate how the compound optimisation criteria in the MVO program can be used to explore rapidly the possible trade offs around a particular design.

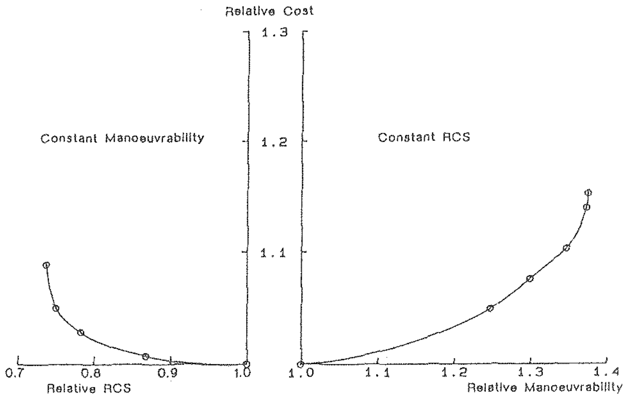

Fig 4 Variation of cost with manoeuvrability at constant RCS, and with RCS at constant manoeuvrability

Non-Aeronautical Disciplines

But aircraft design is affected not only by the engineering disciplines discussed above but also by the non-aeronautical disciplines of market forecasting, fleet planning, military operational analysis and the economics of development and production. Transport aircraft manufacturers, before allowing their aeronautical engineers to embark on the design of a new project, undertake extensive and detailed forecasts of the market for that aircraft project. These forecasts consider the economic and social trends which influence the number of potential passengers, as well as the anticipated changes in the volatile price of fuel and in the legislation relevant to air travel. The market forecasts should also take account of developments (or the lack of developments) in the supporting infrastructure of airfields and air traffic control. When the market forecast has identified the likely demand for and constraints on a new transport aircraft, the manufacturer will then analyse the characteristics of the new aircraft which would allow it most easily to be integrated into the operations of the major airlines which form the target customers for the new project. Although the staff of individual airlines can contribute to such fleet planning studies, the transport aircraft manufacturers must always have regard to the wider market, and must avoid allowing his project to be unduly influenced by the requirements of any single customer. These market and airline studies must also address the most propitious timing of the project, taking account of the financial health of the manufacturer and his target customers, of the availability of new technology or equipment (such as a new aero engine) which might significantly enhance the performance of the project, and of the future levels of design and production capacity available to the manufacturer. The results of the studies in these non-aeronautical disciplines must then be satisfactorily integrated with engineering feasibility studies of new transport aircraft designs before the most - promising project can be identified and launched on its way to success. It is during this integration process that a design synthesis and optimisation program (like MVO) can be most valuable in rapidly producing a consistent set of aircraft designs to demonstrate the effects of alternative requirements and constraints.

The optimum design of a combat aircraft to fulfil a particular military function (from SACEUR's definitive list) is also influenced by non-aeronautical disciplines - those of military operational analysis and of the economics of aircraft procurement. The aeronautical disciplines can identify, at any level of technology, a range of designs which could fulfil the military function considered and can determine the intrinsic performance of each design, in absolute terms of speed, range, payload, etc. But before selecting one of these designs it is necessary to use military operational analysis to estimate their effectiveness in combat. The combat effectiveness of an aircraft design depends not only on its own intrinsic performance but also on the performance of enemy units which engage it and on friendly units which support its operations. Concurrently cost - forecasting methods can estimate the unit cost of each of the alternative designs, so that each design can be plotted as a point (or as a splodge to represent the lack of precision in this process) on a cost - effectiveness chart (Fig 5).

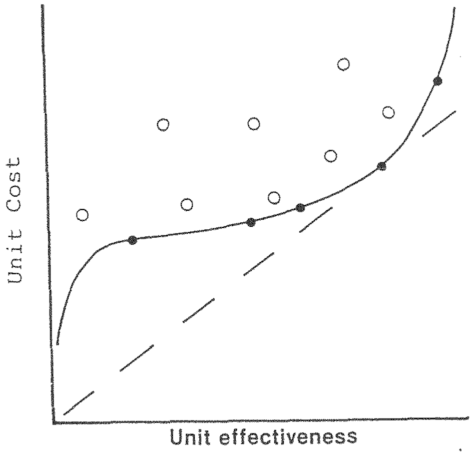

Fig 5 Variation of unit cost with unit effectiveness

Those designs which have the lowest unit cost at a given unit effectiveness lie on a cost - effectiveness boundary, and it is from this group that a design should be selected for procurement. The designs which lie above and to the left of the cost - effectiveness boundary are inferior to those on the boundary, and need not be considered further. The shape of the cost - effectiveness boundary is based on the presumption that very cheap aircraft have poor performance and are virtually ineffective in combat, but that once they have sufficient performance to survive in combat and to inflict appreciable damage on the enemy their effectiveness increases more rapidly than their cost up to the point at which unit effectiveness/unit cost is a maximum; beyond that point further increases in effectiveness are associated with rapidly - increasing cost as the designs approach the limits set by the available technology.

The shape of the cost - effectiveness boundary identifies the aircraft design which has the maximum ratio of unit effectiveness divided by unit cost. But the selection of the aircraft design which yields the maximum force effectiveness within the constraint of a given procurement budget must also take account of the advantage of superior numbers in combat and of economics of scale in production. Lanchester's theory of combat[14] suggests that force effectiveness is equal to the product of the individual effectiveness of the fighting units in the force and the number of units in the force, the number being raised by an index dependent on the conditions of combat. Lanchester quoted specific conditions of combat characterised by indices of 1 or 2, but in other situations the index may lie between or outside these values (see Fig 6.) The appropriate value of the index, for the operations of the type of combat aircraft considered, must be estimated by military operational analysis before the best aircraft design can be selected. For nations which develop and produce aircraft for their armed forces, it is also necessary to consider economics of scale in production; because the development cost is fixed and the unit production cost reduces as the length of the production run is increased (because the workforce learns to be more efficient), the procurement cost of a combat aircraft rises less rapidly than the number of units procured (see Fig 7). For nations which buy aircraft off the shelf economics of scale in procurement do not apply, unless they get discounts on large orders.

$$E = eN^{\alpha}$$

where

E is force effectiveness

e is unit effectiveness

N is the number of units

α is an index

Fig 6 Lanchester Theory of Combat

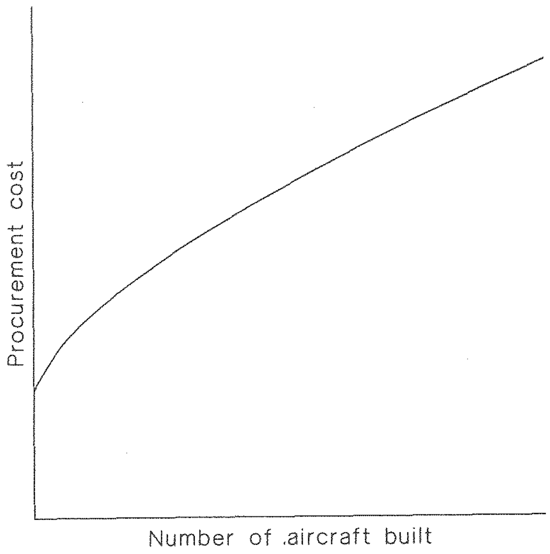

Fig 7 Economics of aircraft procurement

Having estimated the effect of superior numbers and the economics of scale in procurement, it is possible to define the variation in the military effectiveness of a force of combat aircraft, comprising the number of aircraft which can be procured from a given budget, with the unit effectiveness of the chosen aircraft design. Fig 8 shows that the force effectiveness is small both when the unit effectiveness is low and hence the aircraft are no match for the enemy, and when the unit effectiveness is so high that high development and unit production costs preclude the procurement of more than a few aircraft. The highest value of force effectiveness is obtained by the selection of a design which is on the cost - effectiveness boundary, is neither at the top nor the bottom of the range of designs achievable with current technology, and has a unit effectiveness slightly below the level at which unit effectiveness/unit cost is a maximum.

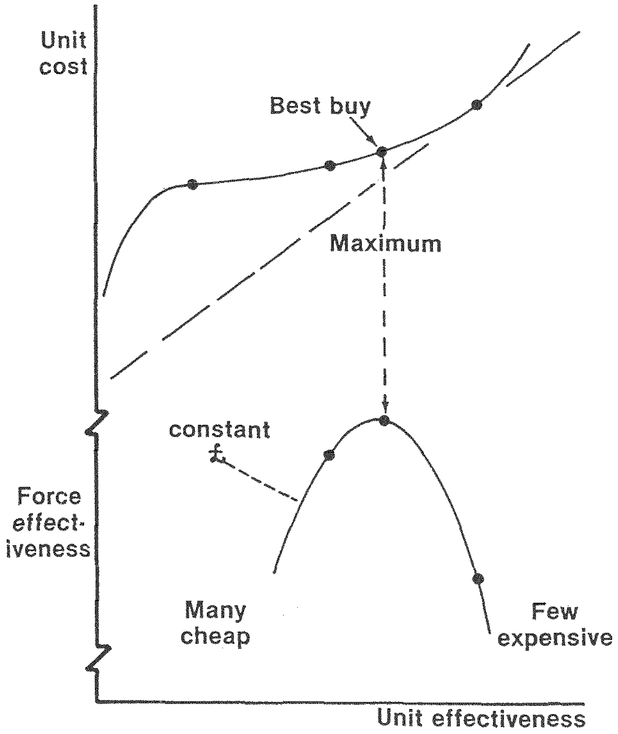

Fig 8 Maximising force effectiveness

It should be noted that if the selection of a combat aircraft design were distorted, by the arbitrary imposition of an excessively - high standard of performance or an unrealistically - low ceiling on unit cost, the resulting unit effectiveness would be different from the optimum and the force effectiveness would be less than could have been attained by a more - rational policy.

The above discussion of the design of a combat aircraft is based entirely on military and financial considerations. But the design may also be affected by other non-aeronautical disciplines, such as the manpower planning of the armed forces in the context of national demography, and the national objectives in industrial and foreign policies.

Most of these non-aeronautical disciplines are intrinsically ill-adapted to definitive quantification, so it would not be appropriate to incorporate them in the MVO design synthesis and optimisation program. Nevertheless these disciplines do exert strong influences on aircraft design, and determine the scenario(s) within which an aircraft designer must work. Hence, just as a structural engineer must take account of aerodynamics and the other aeronautical disciplines in optimising the structure of a wing, so aircraft designers must take account of commercial, military and other non-aeronautical disciplines in optimising an aircraft design.

Concluding Remarks

This paper describes the successful development at RAE of the MVO design synthesis and optimisation programs for transport and for combat aircraft. These programs integrate the aeronautical disciplines of aerodynamics, propulsion, materials, structures and flight controls, and have proved to be invaluable tools in aircraft initial-design studies. The results of these studies form one of the essential inputs to the assessment of transport aircraft projects and of military air systems. Such assessments involve the non-aeronautical disciplines of market forecasting, operational analysis and project cost forecasting which thus also exert a fundamental influence on aircraft design.

List of References

1. Multivariate analysis applied to aircraft optimisation - some proposals and data for an exploratory study.
   D H Perry
   RAE TM Aero 1237 (1970)

2. Multivariate analysis applied to aircraft optimisation - a first progress report.
   D H Peckham
   RAE TM Aero 1352 (1971)

3. Multivariate analysis applied to aircraft optimisation - a second progress report.
   D L I Kirkpatrick
   Joan Collingbourne
   RAE TM Aero 1553 (1973)

4. Multivariate optimisation applied to the initial design of transport aircraft.
   Joan Collingbourne
   RAE TR 84044 (1984)

5. The application of multivariate optimisation to combat aircraft
   D A Lovell
   RAE TR 88003 (1988)

6. Application of numerical optimisation techniques to the preliminary design of a transport aircraft.
B A M Piggott
B E Taylor
RAE TR 71074 (1971)

7. Fortran program for constrained optimisation.
A G Purcell
RAE TR 77142 (1977)

8. The method of RQPMIN (a program for constrained optimisation).
RAE Ae(88) WP15 (1988)

9. Multivariate analysis applied to aircraft optimisation - some effects of research advances on the design of future subsonic transport aircraft.
D L I Kirkpatrick
D H Peckham
RAE TM 1448 (1972)

10. Multivariate analysis applied to aircraft optimisation - five studies of the initial design of transport aircraft projects.
D L I Kirkpatrick
TAE TM 1610 (1974)

11. A forecast of CTOL transport aircraft developments, including the effect of a fuel price increase.
J B Edwards
D L I Kirkpatrick
J B W Edwards
RAE TM 1529 (1973)

12. Multivariate analysis applied to aircraft optimisation - reduction of noise footprint area by airframe design.
D H Peckham
Joan Collingbourne
RAE TM 1456 (1972)

13. Modification to the 'Swept' combat aircraft optimisation program to make provision for radar signature reduction.
J S Smith
RAE TM Aero 2166 (1989)

14. Aircraft in warfare: the dawn of the fourth arm.
F W Lanchester
Constable (1916)