Defense Technical Information Center Compilation Part Notice

ADP010506

TITLE: Conceptual Design and Optimisation of Modern Combat Aircraft

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Aerodynamic Design and Optimisation of Flight Vehicles in a Concurrent Multi-Disciplinary Environment [la Conception et l'optimisation aerodynamiques des vehicules aeriens dans un environnement pluridisciplinaire et simultane]

To order the complete compilation report, use: ADA388284

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, ect. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:

ADP010499 thru ADP010530

Conceptual Design and Optimisation of Modern Combat Aircraft

C A Crawford, S E Simm

Defence Evaluation and Research Agency
Pyestock, Room S9, Building 401
Farnborough, Hants, UK

1.0 ABSTRACT

The design of a combat aircraft is an extremely complex task, due to the large range of design variables available. A fundamental understanding of the effects of changes to these variables, and to changes in design/performance requirements, is necessary to achieve a balanced design. At the Defence Evaluation and Research Agency (DERA) this is achieved with the help of conceptual design and optimisation programs, developed and used extensively over the past 20 years or so. These Multi-Variate Optimisation (MVO) programs are rapid assessment tools, enabling the effects of variations in design variables and performance requirements, in terms of overall aircraft sizing and geometric shape, to be quickly demonstrated.

The programs are used routinely within the Air Vehicle Performance Group at DERA to conduct trade-off studies. These include assessments of the benefits of new technologies (e.g. in the fields of structures, aerodynamics or engines) and the impact of setting various levels of performance requirement. The results provide information and advice to the military customer, aiding balance of investment decisions and helping with initial concept definition.

2.0 INTRODUCTION

The design of a modern combat aircraft is a highly complex task, due to the large number of design variables available. The selection of key parameters such as the wing planform, number of engines and their thrust, the degree of stability and control required and the means of attaining it, requires a careful and systematic approach to ensure that a satisfactorily integrated design is achieved. In addition to meeting performance requirements, the design will also be required to meet some other 'measure of success', such as minimum aircraft mass. The optimum configuration will be one which not only meets the requirements, but which also achieves the best 'measure of success'. The process of optimising the configuration is complicated by the subtle inter-relation between the design variables, the performance obtained, and the measure of success employed.

A good appreciation of this process is essential in the assessment of proposed aircraft configurations, and in the planning and execution of forward-looking research. Over the last 20 years or so, the aircraft performance community within DERA (formerly RAE and then DRA) has developed a number of multi-variate optimisation (MVO) computer programs which can be used for preliminary synthesis and optimisation of air vehicle concepts according to user-specified criteria.

The MVO method for conceptual aircraft design consists of a specific aircraft design synthesis program, which is linked to a general program for constrained non-linear optimisation. MVO gives a rapid method for initial aircraft sizing and trade-off studies in advance of going to detailed design. The mass and aerodynamic estimation methods employed are relatively simple first-order methods, based mainly on empirical correlations, but with sufficient accuracy for work at this level. In avoiding the computational complexity of finite element (FE) structural methods and computational fluid dynamics (CFD), the MVO approach lends itself particularly well to broad-ranging parametric investigations. It thus represents a complementary technique and is often used within DERA as a precursor to deeper FE and CFD based design studies, providing the essential requirements-based starting parameters for the latter.

By the early 1990s several versions of MVO were in regular use in combat aircraft studies at DERA, namely ASTOVL for short take-off vertical landing aircraft, CANDEL for canard-delta configurations, and SWEPT for aft-tailed combat aircraft, as well as other versions for civil aircraft. The combat aircraft SWEPT program was used extensively in many studies, and continued to give good results in terms of the trends produced[1-3]. However it was restricted to the conventional swept wing / aft-tailed configurations of the 1970s and 1980s, with cylindrical and/or rectangular fuselage cross-sections.

With the advent of aircraft such as the F-22, JSF and other future combat aircraft concepts, it was clear that requirements for low observables (LO), were having a considerable effect on combat aircraft design. The MVO methodology needed to take account of LO constraints, particularly with respect to radar and infra-red signatures. Designing for low radar signature requires very careful attention to the entire airframe shape, (and may well influence the choice of airframe materials). Attempts to reduce the infra-red signature may include engine cycle choice, nozzle shielding by tailplanes/tailfins, two-dimensional nozzles, and choice of airframe materials and coatings. To meet the resultant modelling needs a new MVO code has been developed, known as STEALTH. This paper describes the program and gives examples from some recent design trade-off studies to illustrate its use and versatility.

3.0 A NEW CONCEPTUAL DESIGN PROGRAM

The new program, STEALTH, has been developed over the last five years. It aims to represent as accurately as possible the geometry of modern combat aircraft designs, including the main features required for low signature, while still remaining within the confines of a rapid optimising approach. It does not

Paper presented at the RTO AVT Symposium on "Aerodynamic Design and Optimisation of Flight Vehicles in a Concurrent Multi-Disciplinary Environment", held in Ottawa, Canada, 18-21 October 1999, and published in RTO MP-35.

however include the calculation of the signatures themselves. This complex task requires specialist software tools and definition of aircraft shapes and features to a much greater level of detail even than that used in STEALTH.

The following geometry features can be modelled by the program:

- internal weapons carriage
- canted fuselage sides and option for twin canted tailfins
- forebody chines
- aligned planform edges
- wing and tailplane in same horizontal plane
- option for no tails
- scarfed and raked air intakes
- option for two-dimensional engine exhaust nozzles
- option for tailplane and/or tailfin trailing-edge to extend beyond nozzle exit

Explanations of how the above features contribute to achieving a LO aircraft are well documented.[4-6]

Aircraft such as the F-22 and the latest JSF concepts are clearly low-observable designs. However in terms of their basic configuration they are all relatively conventional, in the sense that they retain a fairly distinct wing and body, aft tailplane, air intakes mounted on or near to the fuselage side, and a straight tapered trapezoidal wing.

Although flying wing configurations are attractive in terms of LO and subsonic aerodynamic efficiency, modelling them would require the development of an entirely new design synthesis program, including revised aerodynamic and mass estimation methods. Restricting STEALTH, at least initially, to wing+body layouts, meant that program development could start from the SWEPT program as a baseline, effort being concentrated on updating the geometry routines only, the mass and aerodynamic estimation methods remaining essentially unchanged.

Fig 1 shows a typical layout; the picture was generated by a commercial drawing package from geometry output by STEALTH.

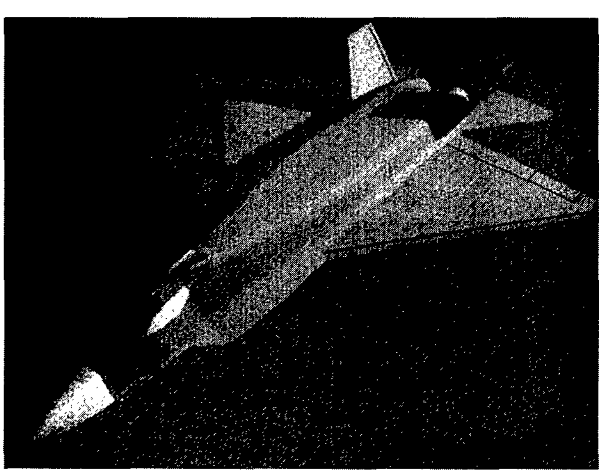

Fig 1: 3-D image of STEALTH-generated aircraft

3.1 Fuselage

3.1.1 External configuration

The longitudinal variation in fuselage cross-sectional area is governed by a 'fairing curve' to ensure a smooth distribution. This curve is defined by 5 independent variables in the optimisation process. STEALTH defines the external lines of the fuselage sections by Bezier splines and super-ellipses, and this detailed geometry definition enables both enhanced visualisation of the concept and improved accuracy of the mass and aerodynamic estimations.

3.1.2 Internal layout

In order to define the internal layout, the user must make a number of design choices at the outset

- Single or twin engine
- Number of internal weapons bays (0-3)

It must then be considered how these items, together with the main undercarriage bays and intake diffusers, are arranged within the fuselage, since all these items compete for space.

Illustrations of the 5 single-engine options and 6 twin-engine options catered for within the program are given in Fig 2. All are highly dependent on the weapons bay choice. A brief description of each layout follows.

Single engine options:

No weapons bays:

- main undercarriage bays canted with fuselage sides
- main undercarriage bays situated on fuselage bottom

One bay:

- single central weapons bay on bottom of fuselage beneath diffuser, main undercarriage bays canted with fuselage sides

Two bays:

- twin outer weapons bays canted with fuselage sides, main undercarriage bays horizontally housed in wing root

Three bays:

- main central weapons bay on bottom of fuselage beneath diffuser, twin outer weapons bays canted with fuselage sides, main undercarriage bays canted with fuselage sides aft of outer weapons bays

Twin engine options:

No weapons bays:

- main undercarriage bays canted with fuselage sides
- main undercarriage bays situated on fuselage bottom

One bay:

- Single central weapons bay on bottom of fuselage beneath intake diffusers, main undercarriage bays canted with fuselage sides
- Single central weapons bay on bottom of fuselage between intake diffusers, main undercarriage bays horizontal on bottom of fuselage beneath diffusers

Three bays:

- Main central weapons bay on bottom of fuselage beneath diffusers, twin outer weapons bays canted with fuselage sides, main undercarriage bays canted with fuselage sides aft of outer weapons bays
- Main central weapons bay on bottom of fuselage between diffusers, twin outer weapons bays in wing root, main undercarriage bays horizontal on fuselage bottom

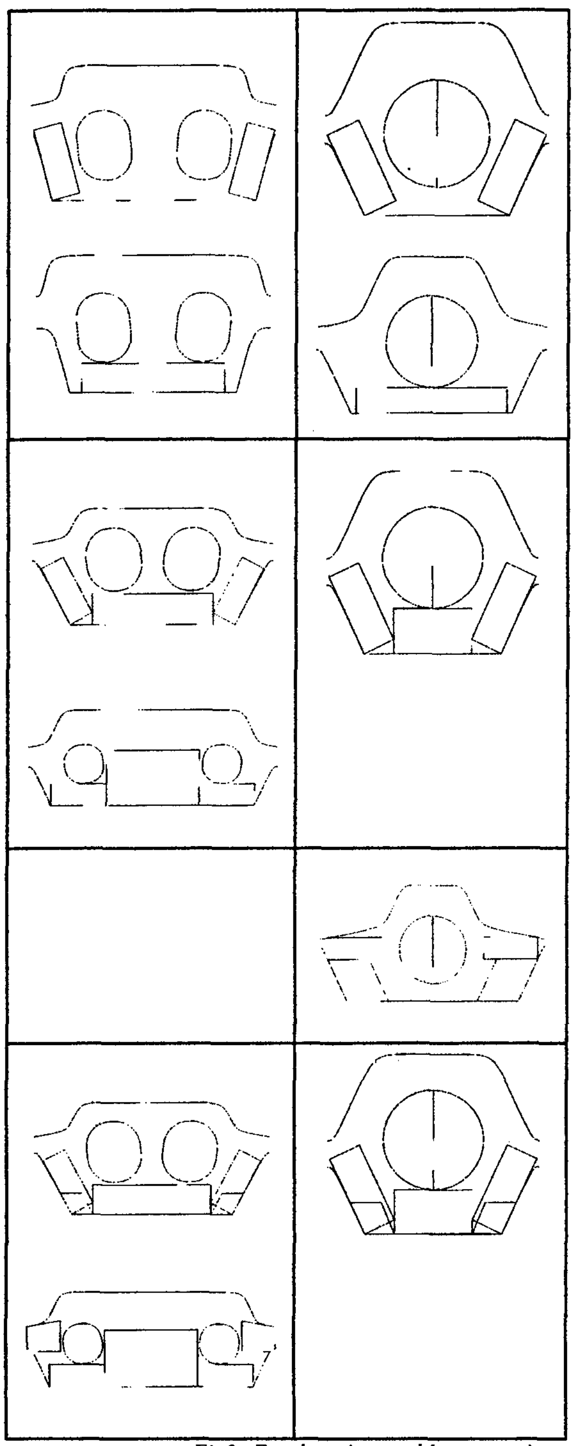

Fig2: Fuselage internal layout options

3.1.4 Geometry definition

The fuselage is modelled via the nine key reference stations shown in Fig 3. The location of these stations is chosen to coincide with major changes in fuselage cross section, and their shape is representative of the aircraft geometry at these points. The location of these stations is given below.

- Radome
- Station A: cockpit front bulkhead
- Station B: pilot's eyepoint
- Station C: intake face
- Station D: front of outer weapons bays
- Station E: front of main undercarriage bay
- Station F: engine front face
- Station G: rear of engine gas generator
- Station H: start of nozzles

Fig 4 presents the sections as they are situated longitudinally along the fuselage.

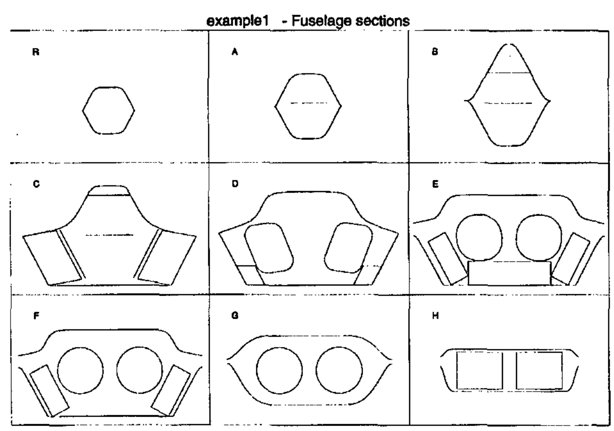

Fig 3: The 9 key fuselage stations (twin engine option)

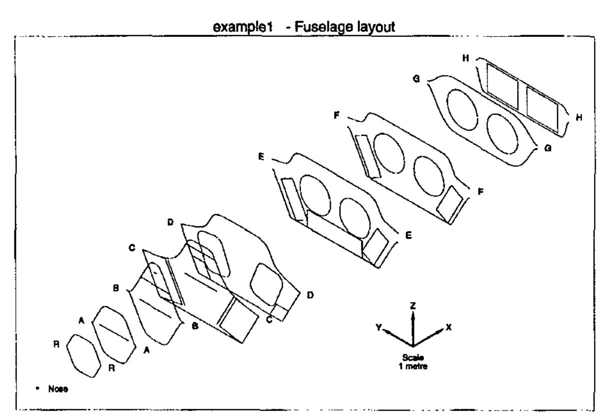

Fig 4: Key fuselage stations positioned along fuselage

3.1.4 Fuselage volume

Figure 5 gives a fuselage cross sectional area plot from a typical run of the STEALTH program.

When fuselage cross-sectional area is integrated along the length of the fuselage, an estimate of fuselage volume is obtained (V_F). This is a major parameter in the estimation of supersonic drag, volume available for fuel, and mass of internal structure. The detailed geometry definition of the fuselage sections provided by the Bezier splines and super-ellipses enables accurate estimation of fuselage volume, and thus of the parameters dependent upon it.

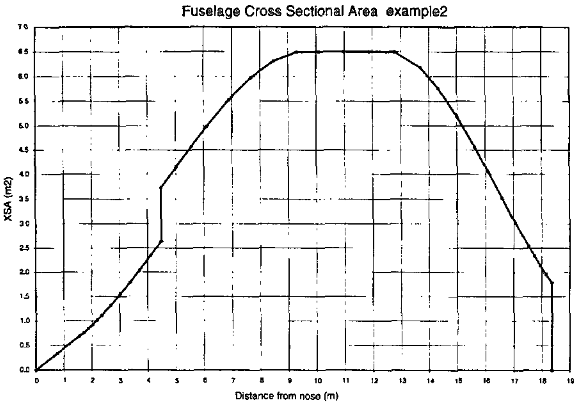

Fig 5: Fuselage cross sectional area distribution

The estimate of the fuselage volume available for fuel is a multi-stage process. The volume V_S, occupied by major items whose volumes are relatively easy to calculate (cockpit, undercarriage, intake diffusers, weapons bays, engines), is computed within the program and subtracted from the total volume obtained from the integration of cross sectional area described above. Then the volume occupied by the fuselage structure and the various systems (avionics, electrical, hydraulic, air etc) must be subtracted. This volume is very difficult to evaluate explicitly at the conceptual design stage, so here it is accounted for by defining a 'remainder fraction'. (A typical value for this parameter is 0.35, based on empirical analysis of a number of detailed aircraft designs. i.e. 35% of the *total* fuselage volume is assumed occupied by structure and systems). The remaining volume is available for fuel tanks, but some of this volume in turn will be occupied by tank structure, fuel pipes etc. A maximum fuselage fuel volume utilisation factor is therefore defined, usually 0.85. This leads to the following equation for useable fuselage fuel volume:

$$V_{fuselage\ fuel} = (V_F - V_S - 0.35 \times V_F) \times 0.85$$

3.1.5 Fuselage wetted area

Fig 6 gives a fuselage perimeter distribution plot from a typical run of the STEALTH program.

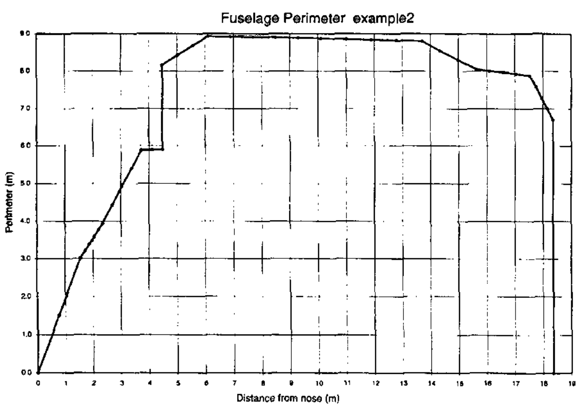

Fig 6: Fuselage perimeter distribution

When fuselage perimeter is integrated along the length of the fuselage, an estimate of fuselage wetted area is obtained. This is a major parameter in the estimation of subsonic drag, and the mass of the fuselage external shell. Again the detailed definition of the fuselage geometry enables an accurate estimate of wetted area to be made, improving the estimate of the parameters dependent upon it.

3.2 Wing

The wing is defined by the parameters

- area
- ¼ chord sweep
- aspect ratio
- thickness/ chord ratio
- taper ratio

all of which are independent variables in the optimisation process.

Currently the program does not cater for cranked wings, but this is an option which it is hoped will be incorporated in the near future.

The wing aerofoil section is a NACA 64 series.

3.2.1 Wing fuel volume

The volume potentially available for fuel tanks is calculated by integrating the wing section chordwise between the front and rear spars and spanwise between the fuselage side and a specified maximum spanwise position. Again a volume allowance must be made for the tanks themselves and associated pipework, so a maximum utilisation factor, usually around 0.7, is specified.

3.2.2 Controls

The program caters for the inclusion of leading and trailing edge devices, spoilers and ailerons. In previous MVO design syntheses, the chords of wing controls had been specified to be a constant percentage of wing chord. Now, as it is advantageous from the radar return point of view to have as few different angles as possible, the option for constant chord controls, giving hingelines parallel to wing leading and trailing edges, has been incorporated.

3.3 Empennage

The following empennage layouts are all catered for within the program

- No empennage
- Vertical (single or twin) tailfins, horizontal tails
- Canted twin tailfins, horizontal tails
- Butterfly tails

The sizes of the tailfins and tailplanes are governed by input values of fin / tail volume coefficients.

Tailplanes are assumed to be all-moving surfaces, so no elevators are modelled. The mass and geometry of the rudder(s) are calculated using input values of fractional chord and fractional span.

3.4 Mass estimation

First-order mass estimation methods from industry are used within the program to calculate masses of both structural components and systems. These are of sufficient detail to provide an aircraft mass breakdown to MIL-STD-1374A.

The methods for wing, fuselage, tailplanes and tailfins take conventional aluminium structure as the baseline, with 'technology factors' employed to account for alternative materials (e.g. composites) and/or other weight saving technologies such as advanced construction and manufacturing techniques. For example, for conceptual aircraft envisaged for the 2015 timeframe, typical factors used are 0.85, 0.90 and 0.85 for the wing, fuselage and tail surfaces respectively, these figures being chosen with industry guidance to represent aggressive targets. The additional mass due to the inclusion of internal weapons bays, associated with structural cut-outs, support structure, bay doors, actuation etc, is calculated within the program, using the same estimation methods as used in industry.

3.5 Aerodynamics

The aerodynamic estimations used within the program are simple first-order methods, based mainly on empirical correlations.

The aerodynamic drag coefficient of the aircraft is given by the expression:

$$C_D = C_{D0basic} + C_{D0base}(M<1.0) + C_{D0wave}(M \geq M_D) + C_{D0stores} + C_{DV}$$

where

M	= flight Mach number
M_D	= drag-rise Mach number
$C_{D0basic}$	= basic zero-lift drag
C_{D0base}	= zero-lift subsonic afterbody drag at reference condition
C_{D0wave}	= zero-lift wave drag (including supersonic afterbody drag)
$C_{D0stores}$	= zero-lift stores drag
C_{DV}	= lift-dependent drag

Zero-lift basic drag is calculated using empirical equations, and includes contributions from wing, tail, fin and fuselage including canopy, intake diverter and gun ports. In addition there are allowances to account for the drag due to interference effects between components and for excrescences and small surface irregularities.

Zero-lift wave drag is calculated, at M1.0 and M1.3, as the sum of contributions from wing, tail, fin, forebody (from aircraft nose to maximum fuselage cross sectional area), afterbody and canopy. The wave drag of the aircraft is assumed to be constant above M1.3. Variation of Mach number in the regions $M_D \leq M \leq 1.0$ and $1.0 < M \leq 1.3$ is determined according to expressions within the program containing empirical factors.

The drag-rise Mach number is the Mach number at which the drag of the aircraft rises sharply in the transonic region, due to supersonic flow over parts of the structure creating shock waves. This has some dependency on the overall aircraft shape, occurring earlier for aircraft of low fineness ratio. This parameter is not estimated by the program but provided as input data.

Lift dependent drag is defined in two regions, for lift coefficients above and below the 'critical lift coefficient' C_{Lcrit}, joined by a cubic transition region.

In the low C_L region

$$C_{DV} = k_1 C_L^2 / \pi . AW \quad \text{(AW=wing aspect ratio)}$$

In the high C_L region

$$C_{DV} = [k_1 C_{Lcrit}^2 + k_2 (C_L^2 - C_{Lcrit}^2)] / \pi . AW$$

k_1 is calculated by the program from major wing geometric parameters. C_{Lcrit} and k_2 are extremely difficult to estimate at the conceptual design stage. Therefore these parameters are provided to the program via input tables of C_{Lcrit} and k_2-k_1 against Mach number. Values appropriate for the class of aircraft under consideration are chosen on the basis of data gathered from existing aircraft of similar configuration, wind-tunnel test results and from CFD predictions.

The maximum useable lift coefficient, C_{Lmax}, is a further parameter which is difficult to estimate empirically, and therefore representative values, chosen on a similar basis, are input as a table against Mach number.

Afterbody drag, at a reference (nozzle fully open) condition, is estimated by the program and accounted for in aerodynamic subsonic zero-lift drag.

For internally carried stores there is no additional drag. For externally carried stores a table of drag areas, D_0/q (m^2), against Mach number is input, the values incorporating airframe/weapon interference drag for a representative airframe. Variations as the airframe shape changes are not accounted for, as these effects are assumed to be small.

3.6 Engine

Engine data are provided to the program via a look-up table of gross thrust, fuel flow, air flow, jet exit area and spillage drag against Mach number, altitude and engine throttle setting. These data are given for the whole proposed aircraft flight envelope, and are for an engine at a reference scale. The mass and geometry of the engine at the reference scale are included in the input data.

The engine size is varied from the reference using a scale factor based on thrust. This scale factor is an independent variable in the optimisation process. Engine diameters are scaled with the square root of this scale factor; the lengths and masses of the gas generator, jetpipe and nozzle are adjusted according to slightly more complex scaling laws.

The gross thrust data take account of power off-take, air bleed, and the pressure recovery of an appropriate intake configuration. Different intake assumptions can be made when the engine deck is formulated, giving different pressure recovery and spill drag characteristics.

Variations in afterbody drag, from the reference condition accounted for in aerodynamic zero-lift drag, occur as the nozzle exit area varies from the fully open position. These throttle-dependent effects, strongly influenced by both engine characteristics and afterbody shaping, are very difficult to predict accurately. STEALTH incorporates a simple approximate expression for them, based on variation in jet exit area, but not considering the effects of nozzle pressure ratio. Lack of precision here is thought to be of secondary importance as these plume effects are normally a small proportion of the whole airframe drag. However this is an area of potential improvement in the future.

4.0 THE OPTIMISER

The program is linked to a general-purpose gradient search code for constrained non-linear optimisation, RQPMIN. This optimiser has been used throughout the history of DERA MVO codes, and has itself undergone frequent and regular enhancement, including the addition of graphical features to aid visualisation of the process.

The problem posed to RQPMIN is of the form

minimise $f(x)$

Where $f(x)$ is termed the objective function, and x represents a list of n real-valued independent variables $x_1, x_2, \ldots x_n$.

At the solution to the optimisation problem, each of the variables x_i must satisfy a pair of inequalities

$$x_{iL} \leq x_i \leq x_{iU} \qquad (i = 1, \ldots, n)$$

where the values x_{iL} and x_{iU}, the lower and upper bounds, are constants and are specified in the input data file.

In addition, the x_i may be required to satisfy a set of $m \geq 0$ constraints of the form

$$c_j(x) = 0 \quad \text{or}$$

$$c_j(x) \leq 0 \quad \text{or} \qquad (j = 1, \ldots, m)$$

$$a_j \leq c_j(x) \leq b_j$$

where a_j and b_j are constants specified in the input data file. It can be seen that these constraints can be one of three distinct types: an equality constraint, an inequality constraint, or a double inequality constraint.

4.1 Choice of objective function

Given the emphasis placed upon affordability in all modern combat aircraft procurement projects, the ideal quantity to optimise in a combat aircraft conceptual design program would be aircraft life-cycle costs. However cost data for such aircraft are notoriously difficult to establish, and thus creating a sufficiently reliable cost model is an extremely difficult task. Following work done at Cranfield University and continued at DERA[7], a study is underway to identify a first-order cost estimation method that would be suitable for incorporation into the STEALTH code in the future.

The parameter used to date as the objective function has in general been the Basic Mass Empty (BME) of the synthesised aircraft. This is in part because BME is a convenient and clear parameter to work with, but also because aircraft size has historically been seen as having a major influence on cost, and is therefore an indirect measure of the latter.

4.2 Independent variables

STEALTH uses 28 independent variables. 24 of these are geometric variables such as engine scale factor, wing area, fuselage fairing curve values, variables governing fuel distribution within the aircraft, longitudinal positions of the inner weapons bays etc. In addition there are 4 performance-related independent variables: Mach number and altitude in each of two specified sortie cruise legs, used when the option to allow these to be optimised is invoked.

4.3 Constraints

The program has 35 geometric constraints, to ensure that a sensible aircraft design is produced. For example there are constraints to ensure that there is sufficient cross-sectional area at the key fuselage stations to enclose the contents, that the centre of gravity is within the specified limits, and that geometric violations between parts of the structure and/or contents do not occur.

In addition there can be up to 18 performance related constraints. There is always a mission requirement to determine the payload-range performance of the aircraft, and this is formulated as a constraint to ensure that the aircraft carries the correct amount of fuel (including specified reserves) to complete this mission. Also there are always two field performance constraints, specified in terms of landing approach speed and take-off ground roll distance. In addition the user can specify up to 15 point performance constraints in terms of aircraft specific excess power, sustained turn rate, instantaneous turn rate, acceleration time, maximum Mach number etc.

5.0 PROGRAM OPERATION

The operation of the MVO process is outlined in Fig 7. As described previously, the program consists of aircraft design synthesis and performance estimation routines, linked to a general code for constrained non-linear optimisation. In the figure the parts of the operation undertaken by the synthesis program are represented by yellow boxes, while those involving the optimiser are shown as pale green boxes. Input consists of performance requirements (mission, point performance), design constants i.e. values for parameters which remain unchanged during the optimisation (e.g. cockpit length, weapons bay size, structural design factors), engine performance data at a reference scale (thrust, fuel flow etc throughout the flight envelope), and starting point values for those parameters which will change during the optimisation (e.g. engine size, wing area, fuselage length). The program then synthesises the aircraft geometry from the input data, estimates its mass and aerodynamic properties, and then, with the addition of the engine data, calculates its performance. Control now passes to the optimiser which considers whether the performance requirements are met, whether the design is sensible (e.g. centre of gravity within required range, fuselage volume sufficient to house the contents), and whether the synthesised aircraft is of minimum mass. If any of these considerations is not satisfied, the optimiser changes the value of one or more of the design variables, and a new aircraft geometry is synthesised. The process is iterated some several thousand times until all criteria are met and the details of the solution aircraft are then output. Time-history plots of the independent variables, constraint functions and the objective function are displayed to the workstation screen at run-time; a typical run takes in the order of 2-3 minutes.

Used in some complex optimisation problems, gradient search methods are known to be susceptible to finding local rather than global optima. Hence here, to ensure that the true optimum has been achieved, each case is generally run a number of times from a variety of start points. This can be performed automatically via a batch file which factors the values of key independent variables by specified amounts, runs the cases, and writes the results to a summary file to enable rapid selection of the best run.

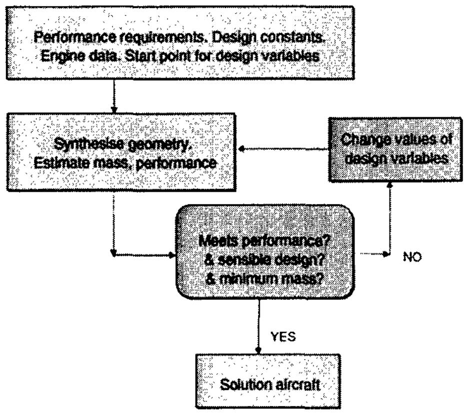

Fig 7: The MVO process

6.0 PROGRAM VALIDATION

MVO methods have been used within DERA for many years, resulting in the accumulation of considerable experience and confidence in the method. STEALTH uses the same optimiser as previous MVO programs, so the main effort of the validation concentrated on verifying the ability of the synthesis to model acceptable LO designs, rather than on the optimisation process.

The program was used to model a number of existing or projected combat aircraft with low observable features. Aircraft were selected for which sufficient design information, in particular performance requirements, were available, and which would exercise the different geometry layout options of the program.

The approach used was to fix the independent variables associated with the major geometrical features of the aircraft (e.g. fuselage length, wing and empennage geometries) at their known values. Thus the exterior airframe shape was, by definition, as representative as possible of the aircraft being modelled, but the program had freedom to manipulate all the interior packaging. The mission profile chosen was one for which the radius of action, with the given weapons load, was known; this profile and radius was then input as a requirement into the program. The 'measures of success' were then how well the synthesised aircraft BME and fuel load matched the real aircraft. A set of point performance parameters were also defined; these were not allowed to influence the optimisation process, but were calculated by STEALTH as a further comparison with the real aircraft.

Table 1 gives the comparison, in ratio terms (STEALTH prediction/real value), for two aircraft. BME, fuel load and a typical transonic sustained turn rate point performance parameter are presented.

	BME	Fuel load	Performance
Aircraft A	0.98	1.00	1.00
Aircraft B	1.02	0.99	0.94

Table 1: STEALTH validation

The results indicated not only that the geometry and packaging were being modelled correctly, but also that the relatively simple mass and aerodynamic estimation methods incorporated were adequate at this conceptual sizing level.

7.0 EXAMPLE STUDY RESULTS

This section illustrates the uses and capabilities of the program, presenting results from a number of recent studies. These studies are quite different in nature, demonstrating the versatility of the program.

7.1 Engine technology study

This was a study into the impact of engine technology and performance requirements on the sizing of a future offensive aircraft. The work encompassed the effects of engine technology advances in the areas of aerothermodynamics, yielding engines of higher thrust / reduced fuel consumption, and materials and structures, giving engines of lower mass. A range of bypass ratios was considered, the study attempting to determine the optimum bypass ratio choice for a datum set of performance requirements.

Fig 8 presents aircraft BME v engine bypass ratio for three levels of engine technology. Each point represents an individually optimised solution aircraft, incorporating the specified engine cycle, and meeting the datum set of requirements. It can be seen that each step in advancing engine technology gives strong benefits in terms of a lighter aircraft capable of achieving the same performance. The figure also shows that there is a strong increase in aircraft mass with increased bypass ratio, this trend being strongest at low technology.

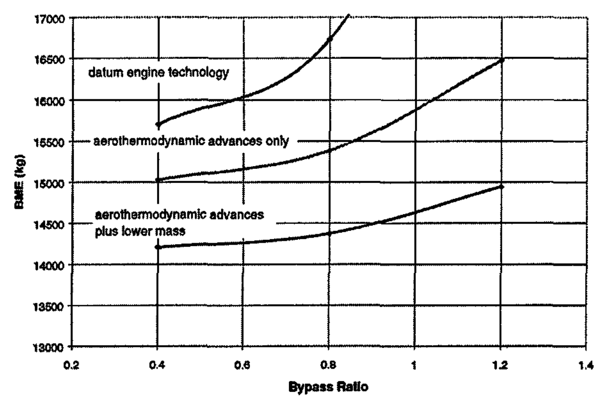

Fig 8: Engine technology effects

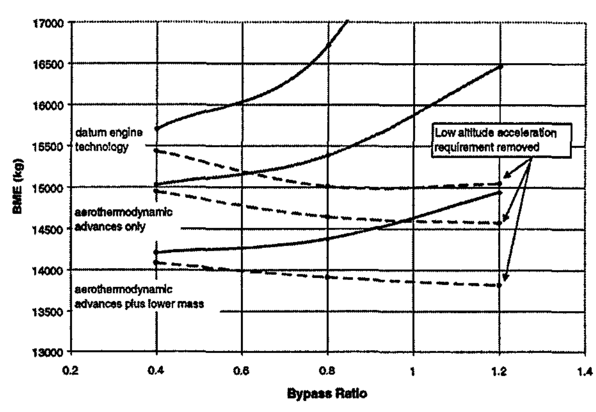

Fig 9: Effect of low-level acceleration constraint

It was discovered that the optimised solutions presented in Fig 8 were all strongly driven by a particularly demanding requirement for low-altitude ingress/egress acceleration. The dashed lines in Fig 9 show the results with this requirement deactivated; the solid lines, as shown in Fig 8, are included for comparison. With this new revised set of requirements the pay-off from increased engine technology is seen to be less than before, but still significant. The trend with bypass ratio is reversed.

Here the program has been used to show how engine technology can give substantial benefits in terms of a smaller, lighter aircraft able to achieve a specified level of performance, and how both BME and the optimum engine bypass ratio are very dependent on the performance requirements demanded at the outset.

7.2 Novel wings study

The aim of this study was to generate a family of conceptual aircraft designs, based around a selection of advanced wing planforms, to assist an informed selection of an aerodynamic configuration for a high speed wind tunnel model. Using the STEALTH program the aircraft were sized to a given level of mission, manoeuvre and field performance, enabling a comprehensive assessment to be made of the pros and cons of each planform when integrated into a complete configuration.

All aircraft had a single crew and twin engines. The air intakes were at the fuselage sides, with the intake ducts running up and over the main weapons bay to the engines, which were placed close together at the rear of the fuselage. The two smaller bays for the air-air missiles were situated immediately outboard of the main bay, with the main wheel housed parallel to the fuselage side. All aircraft had twin tailfins, canted parallel to the fuselage sides at 30°. Minimum leading and trailing edge sweep angles of 55° and 25° respectively were assumed.

A number of the wing planforms considered were of cropped trapezoidal shape, characterised by a trailing-edge crank, with the inboard trailing edge swept aft and the outboard trailing edge swept forward. Because STEALTH is currently unable to model cranked wings explicitly, these wings were emulated in the program by modelling an 'equivalent' uncranked wing. A cropped trapezoidal wing can be regarded as a trapezoidal wing with part of the inboard trailing edge 'cropped' or by an aft-swept wing with part of the outboard trailing edge 'cropped'.

The approach used was to model these wings as aft-swept wings, making some modification to the wing mass estimation. A mass saving of 5% was assumed since the redistribution of area - more inboard and less outboard – placed the spanwise centre of lift further inboard, reducing wing bending moment. The aerodynamic characteristics were assumed unchanged from those of the equivalent aft-swept wing.

The aft-swept wing of the solution aircraft was converted to an equivalent cropped trapezoidal wing of the same aspect ratio, area and leading & trailing edge sweep angles. By observing a minimum taper ratio of 0.10 for the cropped trapezoidal wing, the spanwise position of the crank could be calculated.

Figures 10-13 give some example solution aircraft from the study.

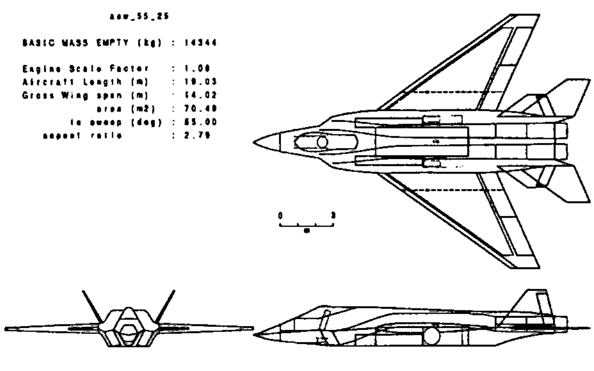

Fig 10: Aft-swept wing planform

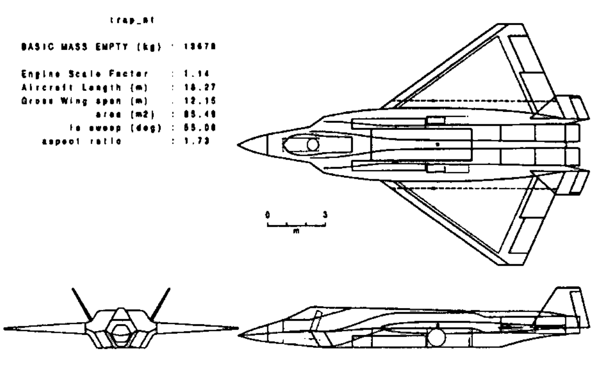

Fig 11: Trapezoidal wing planform

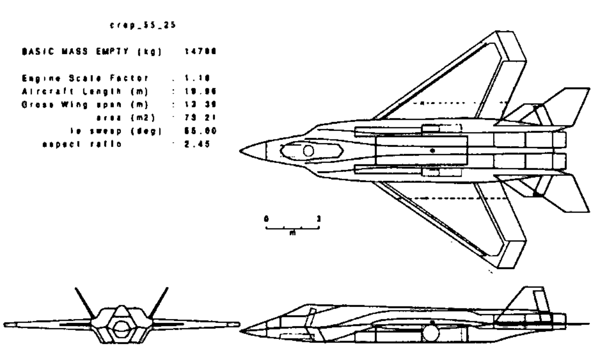

Fig 12: Cropped trapezoidal, 25° trailing edge sweep

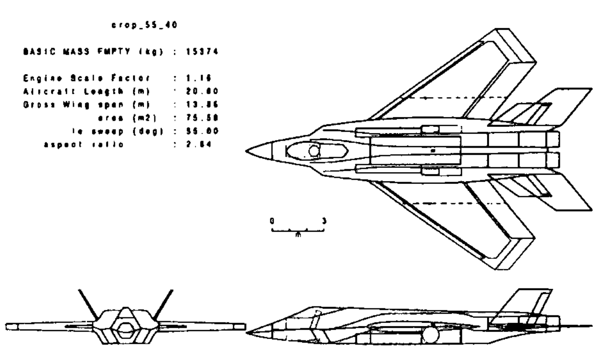

Fig 13: Cropped trapezoidal 40° trailing edge sweep

The trapezoidal wing planform of Fig 11 gives rise to the lightest aircraft. The wing is structurally efficient and has high internal fuel volume. The lightest of the tailed aircraft is that shown in Fig 10 with the relatively conventional aft-swept wing. The cropped trapezoidal wings lead to heavier aircraft, the comparison between Fig 12 and Fig 13 illustrating the mass penalty associated with moving to a higher trailing edge sweep.

This study example demonstrates how the program can provide an effective and rapid means of comparing different wing concepts on a consistent basis. Even where the program does not represent a selected planform explicitly (eg the cranked trailing edge), it is often possible to approximate the configuration in order to reach an MVO solution with sufficient fidelity for valid first order comparisons to be made. Once a suitable planform has been identified using STEALTH, design refinement can proceed using more detailed CFD-based and finite element methods.

7.3 LO trade-off study

The STEALTH program has been designed to model internal weapons carriage and other desirable features of low observable concepts. However, as indicated earlier, it is equally able to represent external carriage by specifying 'no weapons bays' and defining the locations of external stores hard points. This versatility is illustrated by our third example, which is taken from a study to investigate the penalties, in terms of aircraft mass and overall size, of designing for low observability. In this exercise, the STEALTH program was used to compare a 'conventional' aircraft (i.e. external carriage and no shaping concessions to LO requirements) with a low observable baseline aircraft.

The baseline was chosen to be similar to the trapezoidal wing design of Fig 11, although somewhat different mission requirements and technology assumptions between the two studies have led to differences in numerical results. Within the LO trade-off study, identical requirements and assumptions were of course used for both baseline and conventional designs. The essential differences in design constraints are set out in Table 2. Figs 14 and 15 show the resulting aircraft generated by STEALTH.

'Conventional' aircraft	Low-observable aircraft
No wing sweep constraints	Wing leading edge sweep 55° Wing trailing edge sweep 25°
External weapons carriage	Internal weapons carriage
Vertical tailfins	Canted tailfins
Fuselage cant angle small (15°)	Fuselage cant angle 30°
	Additional mass to account for inclusion of Radar Absorbent Material (RAM)
Conventional propulsion installation effects	Propulsion installation effects due to LO design

Table 2: Modelling differences for conventional / LO aircraft.

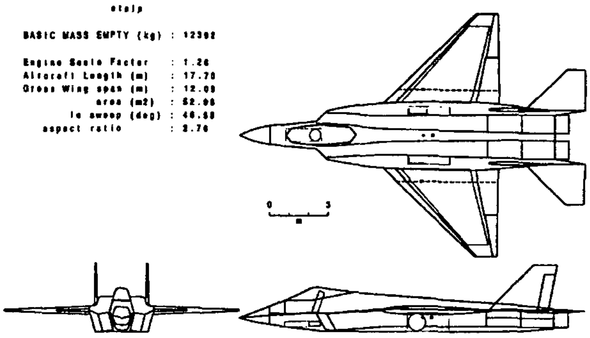

Fig 14: 'Conventional' aircraft

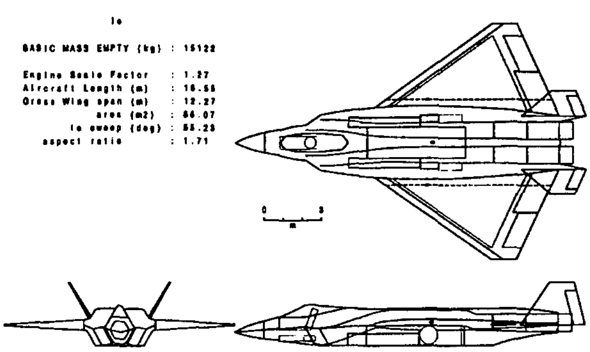

Fig 15: Low-observable aircraft

The resulting conventional design has considerably lower wing sweep and wing area, while aspect ratio is higher. Eliminating the need for internal weapons bays leads to a significantly smaller fuselage, with secondary benefits resulting from rather more freedom to distribute systems equipment and fuselage fuel efficiently within it. The conventional design is also not burdened with the weight penalty assigned to the incorporation of RAM. However it is not all gain for the conventional design. External carriage of weapons adds to aircraft drag and the effects of this are felt in the mission performance calculation part of the optimisation loop. Nevertheless the results of the exercise show a considerable net advantage in terms of BME for the non-LO design, because of its greater overall aerodynamic efficiency. Naturally, the extent of the difference will be mission-dependent and sensitive to the particular LO constraints chosen. Differences in any of these input specifiers will lead to different numerical results. Discussion of such issues lies beyond the scope of this paper.

8.0 FUTURE DEVELOPMENT

There is a program of work planned for the continued development and improvement of the STEALTH code.

As new airframe shapes develop there is a continuing need to ensure that the incorporated estimation methods correlate as closely as possible with a revised database of current combat aircraft. The mass estimation methods have undergone a recent overhaul, prior to a similar forthcoming review of the aerodynamic methods.

There are plans to add further geometric options to the program e.g. cranked wings and chin intakes. Also work is to take place to assess whether a suitable cost estimation method can be incorporated.

There is the potential to improve links with other more complex methods e.g. computational Fluid Dynamics (CFD), Finite Elements (FE) and programs for Radar Cross Section (RCS) estimation. STEALTH output geometry has on previous occasions been input to a CFD package, enabling a more accurate estimate of the aerodynamic parameters to be made for use in the next iteration of studies. However it is not intended to incorporate these methods within STEALTH, as the main value and versatility of the program is in its ability to carry out quick assessment studies. It is considered to be complementary to the Multi-Disciplinary Optimisation (MDO) programs currently in the early stages of development.[8]

It is envisaged that MVO methods like STEALTH will continue to be a major tool for initial conceptual and optimisation studies. Once the basic configuration and sizing has been established in this way, MDO methods will provide a means of refining the concept into an optimised structural/ aerodynamic design at a more detailed level.

9.0 CONCLUSIONS

In summary, a new rapid design synthesis program has been developed which is capable of modelling low-signature combat aircraft. Incorporated with a code for constrained non-linear optimisation, the resulting MVO program has been demonstrated to be a powerful tool for initial aircraft sizing studies, and for illustrating the effects of advancing technologies and varying performance requirements.

10.0 REFERENCES

1 J A Kirk
The use of multi-variate analysis to optimise design parameters for extended-range combat aircraft
AIAA 92-4707 September 1992

2 S D Hodder, S E Simm
The impact of advanced engine technology on combat aircraft performance
AGARD-CP-572 June 1996

3 C A Crawford
The impact of engine technology advancements on the range v performance trade-off for a future combat aircraft
ICAS-98-1,10,1 September 1998

4 A C Brown
Fundamentals of low radar cross-sectional aircraft design
Journal of Aircraft, vol 30, no 3, 289-290 1993

5 A E Fuhs
The no-see-um book: radar cross-section lectures
AIAA New York 1982

6 D Howe
Introduction to the basic technology of stealth aircraft (Parts 1&2)
ASME/90-GT-116&117 in Transactions of ASME Journal of engineering for gas turbines and power, Vol 113, no 1, New York 1991

7 S Woodford
Recent combat aircraft life-cycle costing developments within DERA
RTO specialists' meeting: Design for low cost operation and support
Ottawa 1999

8 D Lovell, P Bartholomew
Progress towards a multi-disciplinary analysis and optimisation capability for air vehicle assessment and design – a UK view
RTO conference: Aerodynamic design and optimisation of flight vehicles in a concurrent multi-disciplinary environment
Ottawa 1999

DISCUSSION

Session I, Paper #8

Dr Nicolai (Lockheed Martin Skunk Works, USA) asked the authors to itemize the 22% empty weight increase shown for a stealth fighter when compared to a non-stealthy baseline. He asked how much of this difference was due to coatings and edges, to external v internal weapons carriage, and to propulsion installation.

The authors noted that largest impact was due to internal weapons carriage and that the additional mass of radar absorbent material was the second strongest effect. In the example shown the propulsion effects were only modest because the concept had only a "limited LO propulsion installation. They noted that other studies had shown that this impact could be significantly greater with more stringent propulsion requirements.

Dr Render (Loughborough University, UK) asked how sensitive the optimization results were to the aerodynamic inputs.

The authors concurred that the results can be very sensitive to aerodynamic input. They noted that the degree to which this is true, and just which inputs are particularly important, depends on the particular requirements driving the concept under study.