ADVANCED AERODYNAMIC DESIGN FOR FUTURE COMBAT AIRCRAFT

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Abstract

The operational requirements for future combat aircraft are reviewed briefly. Compared with their predecessors, combat aircraft of the 1990's will be required to be manoeuvrable over a wide range of subsonic and transonic speeds and have superior handling qualities to enable them to exploit their full lift capability without departure into uncontrolled flight. They will be required to have very rapid transonic and supersonic acceleration but with probably less emphasis on maximum Mach Number. They will be required to have excellent low altitude high speed ride qualities for precise navigation and weapon delivery, coupled with high penetration speeds with ground attack weapons carried. They will be required to have very short take-off and landing distances to enable operation from bombed runways and dispersed sites. Finally, efficient subsonic cruise and loiter performance is demanded in both air superiority and ground attack roles. These requirements represent a formidable challenge to the aerodynamicist and designer.

Aerodynamic developments aimed at meeting these requirements are reviewed and illustrated by examples of work carried out at the Warton Division of British Aerospace. The following topics are covered:

1. Wing Design

   It is shown that improvements in wing design using advanced theoretical methods enable much higher lift coefficients to be obtained at transonic speeds with attached flow on the upper surface. These improvements have yielded substantial improvements in lift/drag ratio enabling high sustained turning performance at subsonic and transonic speeds. The characteristics and resulting performance of an advanced supercritical variable camber wing section are compared with those of a 1960's 'off the shelf' design. The influence of wing root leading edge strakes and of aeroelastic tailoring are also mentioned and it is shown how these contribute to enhanced wing performance.

2. Jet-Wing Enhancement

   The effects of a jet exhausting close to the wing trailing edge on wing performance, particularly at high incidence, are illustrated and it is shown that substantial improvements in turning performance can be achieved by exploiting the favourable interference.

3. Active Controls Technology

   Improvements in weapon system performance offered by active controls technology applied to this type of aircraft are reviewed. It is shown that the most important applications are relaxed static stability enabling improved sustained and attained manoeuvre performance, carefree manoeuvring allowing the pilot to use his controls to exploit the full manoeuvre capability of the aeroplane without danger of departure into uncontrolled flight or of overstressing, and gust alleviation to improve ride qualities in low altitude high speed flight.

4. Intake Design

   Intake design features to enable trouble-free engine operation at high incidence and sideslip are reviewed. The effects of alternative intake locations and design features including scarfing and variable cowl lip geometry, on intake pressure recovery and distortion are illustrated.

5. Low Drag Store Carriage

   The effects on cruise economy and on penetration speeds of low drag carriage of ground attack weapons are illustrated.

6. Short Take-Off and Landing

   It is shown that with the thrust/weight ratios and wing loading required to meet the combat performance requirements, there is little difficulty in providing short take-off distances: the airfield distances required are dictated primarily by the landing performance. If the landing distance, taking account of scatter in pilot performance, has to match the very short take-off then this demands the use of vectored thrust.

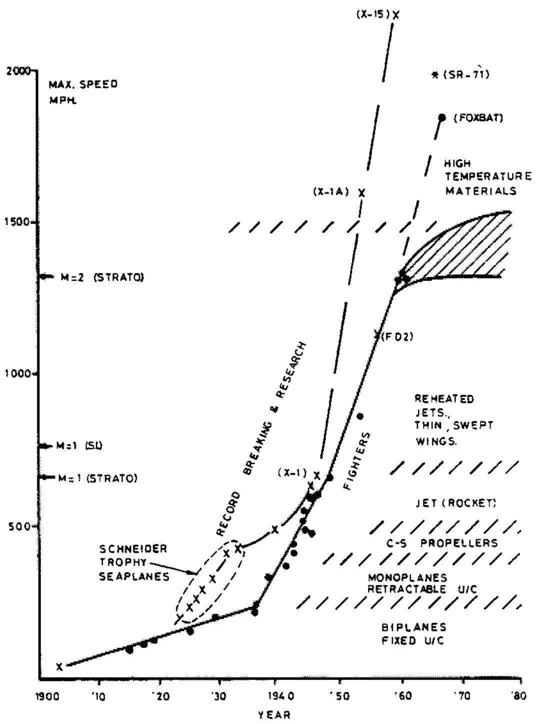
1. Introduction

Historical Note

For the first fifty years of combat aircraft, each new generation was marked by a significant advance in speed over its predecessors, as illustrated in Fig.1. The advances in speed were accompanied by obvious changes in airframe shape and in propulsion from the 100 mph biplanes of the 1914 - '18 war to monoplanes with retractable undercarriages in the late '30's exceeding 300 mph. Supercharged piston engines with constant speed propellers, increased top speeds to well beyond 400 mph. Introduction of jet propulsion in the mid '40's enabled 500 mph to be surpassed with straight wings; swept wings made transonic flight possible and by the late '50's Mach 2 fighters with thin swept wings and reheated turbo-jets, exemplified by the American Century series, the British Lightning, the French Mirage and the Russian Mig 21 were being developed. From that date only a very few specialised types of aeroplane have forged ahead towards Mach 3 and beyond and fighter speeds have settled at around the Mach 2 figure at high altitude.

FIG.1

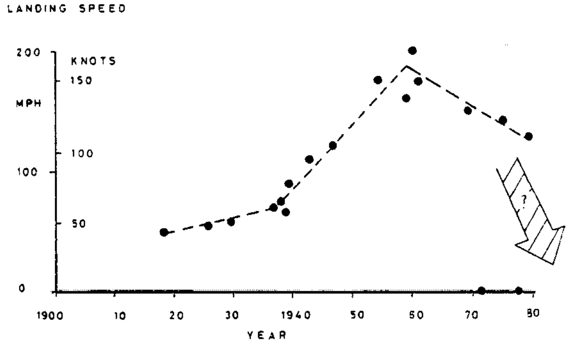
MAXIMUM SPEEDS OF FIGHTERS



This does not mean that aerodynamic development has stood still from that point - far from it. However, the emphasis has changed from the pure "get up and go" interceptor whose cruising economy, low speed manoeuvrability and airfield performance were sacrificed on the altar of speed, to versatile combat aeroplanes efficient in all phases of flight. For example, Fig.2 illustrates the history of landing speeds, increasing pro-rata with maximum speeds until the '60's, but indicating a downward trend in more recent years.

FIG.2

LANDING SPEEDS OF FIGHTERS



A typical list of requirements for a modern combat aircraft to fulfill Offensive Support, Air Superiority and Interceptor roles is set out in the accompanying table.

TABLE 1

ADVANCED COMBAT AIRCRAFT

TYPICAL REQUIREMENTS

S.E.P. (1g)	1000 ft/sec	
S.T.R. (S.L.)	20°/sec max 6°/sec max at 1.5M	
A.T.R.	30°/sec	
MAX M S.L.	1.1	
36000'	1.8	
ACCEL 0·9 to 1·6 at 36000'	60 secs	
T/O DISTANCE	500m IN G.A. ROLE	
LANDING DISTANCE	400m WITH 10% FUEL, BOMBS GONE	
MISSIONS: BATTLEFIELD AIR SUPERIORITY: (4 x S.R.A.A.M.)	ECON. CRUISE	150nm LOW ALT
	LOITER	30mins LOW ALT
	COMBAT	6 x 360° MAX S.T.R
	R.T.B. ECON	LOW ALT
GROUND ATTACK:	240nm R OF A (180 ECON 60 DASH 0.9M)	
8 x 500lb 2 x S.R.A.A.M.	WITH COMBAT ALLOWANCE	
CAP/INTERCEPT:	1 HOUR CAP AT 100nm	
4 x M.R.A.A.M	ACCEL TO 1·6M x 180° AT 1·6M	
2 x S.R.A.A.M.	MAX S.T.R. DECEL, R.T.B.	
	(ALL WITH 10% RESERVES FOR LANDING)	

ADDITIONAL FEATURES

CAREFREE MANOEUVRING
GOOD LOW ALTITUDE, HIGH SPEED, RIDE QUALITIES) ESSENTIAL

"POINTABILITY" BEYOND MAXIMUM LIFT)
POST-STALL MANOEUVRABILITY) DESIRABLE
DIRECT FORCE MANOUVRING)

The requirements for high sustained (thrust-limited) turning performance at subsonic speeds combined with economical subsonic cruise and loiter translate into a drive for high lift/drag ratio over the widest possible range of lift. Similarly high attained (lift-limited) manoeuvrability and STOL performance demand low wing loading and efficient high lift devices: alternatively, or additionally, vectored thrust may be employed. These subsonic requirements are not inconsistent in themselves but are not easily reconciled with the objectives of rapid supersonic acceleration, efficient low altitude high speed dash, good ride qualities in turbulent air and high SEP, all of which favour smaller, thinner, more highly swept wings. However, it is generally recognised that it is the fighter rather than the ground attack requirements that drive the configuration.

The challenge to the aerodynamicists and designers is therefore greater than ever. Succeeding generations of fighters have to last longer in service because they are more costly. This makes it increasingly difficult to justify the launching costs unless the performance and operational improvements represent a significant advance.

Some of the aerodynamic innovations studied by BAe Warton Division, which will enhance the performance of the next generation of combat aeroplanes are reviewed here in this paper.

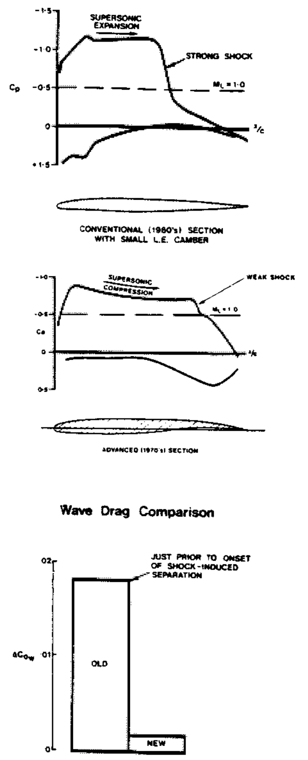
2. Wing Design

In recent years advances in theoretical methods (Ref.1) utilising large capacity computers have enabled wing design for a specified chordwise and spanwise pressure distribution with transonic flows. At a particular design point (Mach No. and lift coefficient) controlled supersonic flow on the upper surface and substantial rear loading can yield a much higher lift/drag ratio than that of an old fashioned "Off the shelf" section, either uncambered or with a conventional curved camber line.

The application to subsonic transport aircraft of advanced wing design is relatively straightforward, having a single design point at which the wing can be optimised. For combat aircraft, the wing designer's task is severely constrained by the requirements for transonic penetration and supersonic flight with low drag. Usually the dominant design point is set by the requirement for sustained turn performance, at medium altitude, high subsonic speed. Fig.3 shows a comparison of the wing sections and associated pressure distributions between a modern advanced section and an "off the shelf" section, at a high lift, high subsonic design point. Both sections have 5% thickness/chord ratio. The relative wave drags are also compared, clearly demonstrating the superiority of the advanced section design. The advanced section features significant nose and rear camber with a flat mid-chord profile. The same section would be unsuitable for low altitude transonic penetration in 1g flight at low C_L because the camber would cause supersonic flow under the leading edge and a large nose down moment, creating significant trim drag. By adopting variable camber, scheduled with incidence and Mach No., the section shape can be adjusted to achieve maximum lift/drag ratio over a wide range of flight conditions.

Section Shape and Pressure Distribution

FIG 3



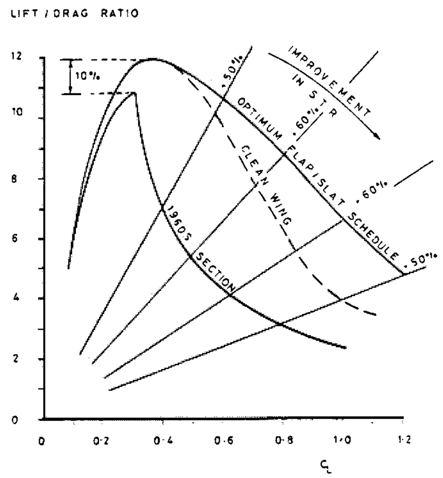
Wave Drag Comparison

Fig.4, which is based on high speed wind tunnel results, illustrates the benefits in lift/drag ratio achieved by the use of a variable camber advanced section compared with a conventional fixed geometry wing of the same planform shape and area. The benefits can be translated into 50 - 60% improvement in sustained turn rate at medium altitude and 10% improvement in loiter economy.

FIG 4

COMPARISON OF ADVANCED VARIABLE-CAMBER WING PERFORMANCE WITH 1960'S TECHNOLOGY WING

(H S W.T RESULTS M=0·7)



However, scheduled variable trailing edge camber, by generating increasing rear loading with increasing incidence, causes a rearward shift of the aerodynamic centre. If the c.g. is located for natural stability with flaps fixed, stability is excessive, leading to significant trimmed drag and lift penalties. The benefits of variable trailing edge camber can therefore be exploited fully only if associated with optimum rearward c.g. location, involving artificial stability.

The benefits of leading edge strakes on wing performance are now well known, namely increased lift combined with reduced drag at high incidence and suppression of some of the effects of flow separation. The undesirable effect of a simple uncambered strake is an earlier onset of flow separation with increased drag at moderate lift coefficients. Advanced computational techniques now enable the design of a non-interfering strake, contoured to the local streamlines at the design point, which eliminates such a penalty, as illustrated in Fig.5. However the camber may be such as to cause flow separation on the undersurface of the strake at low incidence: this can be avoided by the use of a variable camber strake as shown in Fig.6.

FIG. 5

NON INTERFERING STRAKE
M=0·80
(H.S.W.T. RESULTS)

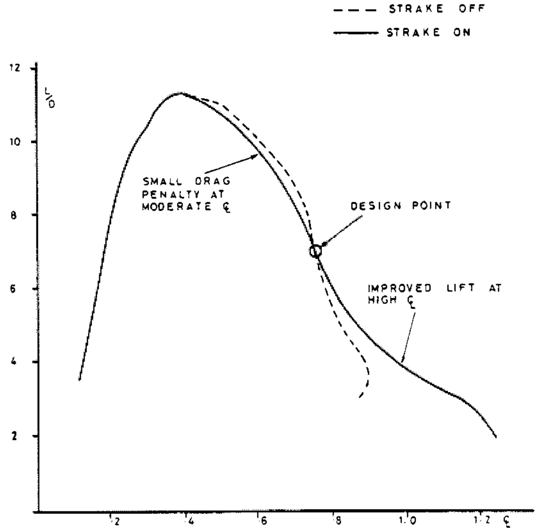
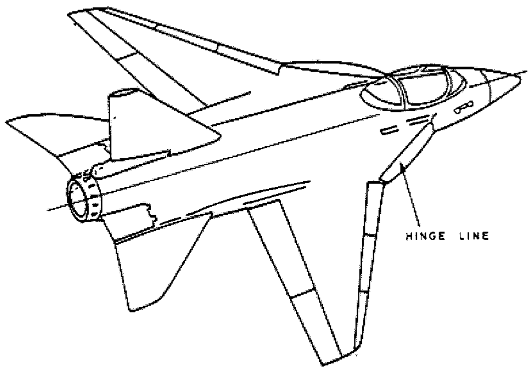


FIG. 6

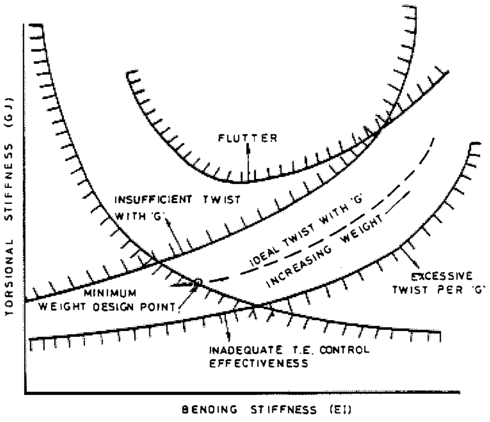
VARIABLE CAMBER L.E STRAKE
(PAT. APP 34058 / 78)



Fine tuning of wing performance may be achieved by aeroelastic tailoring. Carbon fibre composite structures allow adjustment of the torsional and bending stiffnesses of the wing within certain limits enabling a prescribed variation of wing twist with loading to be achieved. By this means the desired spanwise lift distribution can be obtained at a high g design point without excessive jig-built twist which could lead to transonic low incidence problems. These considerations must of course be reconciled with stiffness requirements to respect trailing edge control effectiveness (dominantly torsional stiffness) and of flutter (separation of torsion and bending frequencies). Fig.7 illustrates this process.

FIG. 7

AEROELASTIC TAILORING
(SWEPT BACK WING)



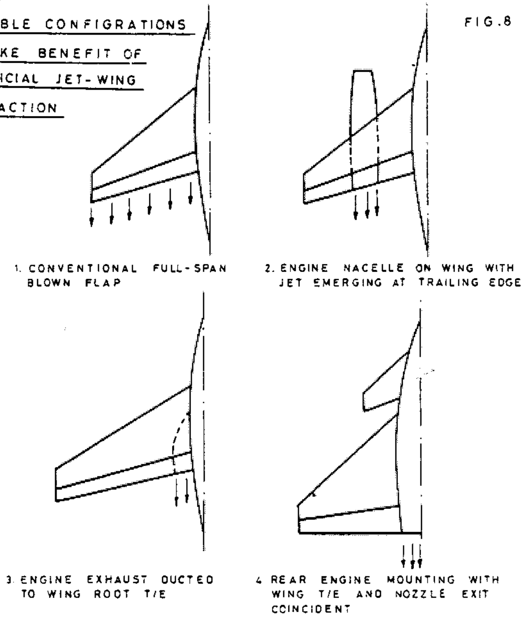
3. Jet-Wing Enhancement

In the mid 1950's innovative work in the UK, both experimental and theoretical, showed that very high lift coefficients could be generated by means of a jet exhausting in a thin sheet along the trailing edge of a wing. This was known as the jet flap. Its invention generated a great deal of enthusiasm at the time, giving promise of short take-off and landing distances. However, this enthusiasm evaporated when the internal plumbing difficulties and associated weight penalties were identified from more detailed design studies.

More recently work in the USA and in the UK based on jet flap theory and backed up by experimental data has shown that significant improvements in wing performance can be achieved by the influence of a concentrated jet exhausting close to the trailing edge of a wing. Preliminary work carried out at BAe Warton in this field is described in Ref.2 and some fighter configurations designed to take advantage of the effect are illustrated in Fig.8.

FIG.8

POSSIBLE CONFIGRATIONS TO TAKE BENEFIT OF BENEFICIAL JET-WING INTERACTION



1. CONVENTIONAL FULL-SPAN BLOWN FLAP

2. ENGINE NACELLE ON WING WITH JET EMERGING AT TRAILING EDGE

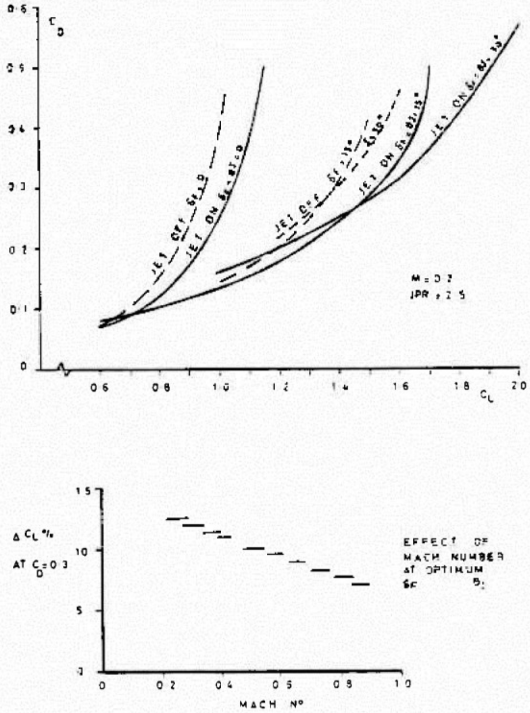
3 ENGINE EXHAUST DUCTED TO WING ROOT T/E

4 REAR ENGINE MOUNTING WITH WING T/E AND NOZZLE EXIT COINCIDENT

Fig.9 shows the effects on the thrust-removed drag polars at low and moderate subsonic speeds based on wind tunnel results. The effects of the presence of the jet and of jet deflection by means of a post-exit deflector flap, mounted behind a conventional, circular nozzle, in conjunction with scheduled trailing edge flap deflection are illustrated. Substantial increases in lift and reductions in drag at high lift are evident. A photograph of the model is shown in Fig.10.

FIG. 9

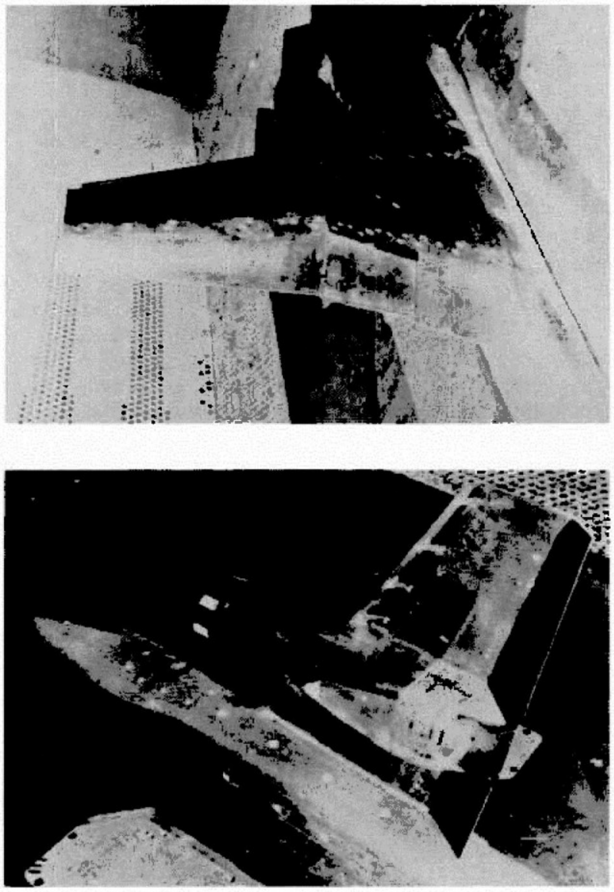
INFLUENCE OF DEFLECTED PROPULSIVE JET AT MID-WING TAILING EDGE ON DRAG POLARS (THRUST REMOVED) (W.T. RESULTS)



The enhanced flap performance and jet deflection at the trailing edge of course gives rise to significant nose down pitching moments and on a tailed layout the benefits would be greatly reduced by the down loads on the tail to trim. The benefits can be realised fully only with a canard configuration where foreplane lift is additive to the effects of jet deflection. Fig.11 shows the effects on attained and sustained turning performance of jet-wing enhancement combined with jet deflection trimmed on the canard configuration. The benefits in low speed manoeuvre performance are substantial and are overwhelming in close combat, as verified by combat simulator results.

Fig.10

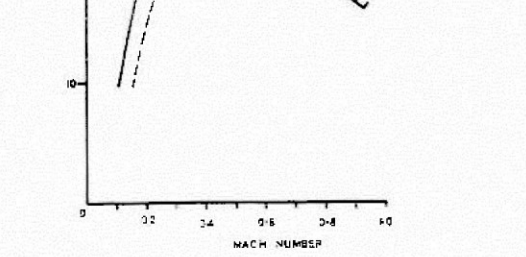
½ MODEL MOUNTED IN TRANSONIC WIND TUNNEL TO INVESTIGATE JET-WING INTERFERENCE WITH POST-EXIT DEFLECTOR NOZZLE



EFFECT OF JET-WING ENHANCEMENT WITH VECTORED THRUST ON TURN RATES

FIG. 11

CANARD CONFIGURATION WITH WING-MOUNTED ENGINES AND P.E.D. NOZZLES



4. Active Controls Technology

The dominant reasons for adopting full-time Fly-by-Wire on the next generation of combat aircraft are, in our view, to permit artificial longitudinal stability to be employed, allowing rearward c.g. location for optimum performance and to enable carefree manoeuvring. With regard to the former, it has already been stated earlier in this paper that the benefits of advanced variable camber wing design cannot be fully exploited without artificial stability. Fig.12 shows the benefits of optimum c.g. location with active controls, compared with c.g. location for natural stability with worst destabilising underwing stores, on the variation of lift/drag ratio with lift coefficient in subsonic flight. The benefits are 10% better loiter performance, that is at maximum lift/drag ratio, and 15% better sustained turning performance. In addition to the benefits in combat performance conferred by artificial stability, the fuel savings are substantial, as indicated in Fig.13.

EFFECT OF ARTIFICIAL STABILITY ON LIFT/DRAG RATIO

FIG.12

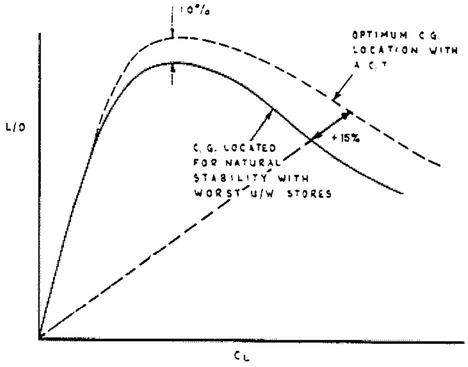


FIG. 13

B.A.S. MISSION - FUEL BREAKDOWN

FLIGHT PHASE	FUEL USED % TOTAL FUEL	 % TAKE OFF MASS
COMBAT	40	10
CRUISES	30	7·5
LOITER (CAP)	20	5
RESERVES E.T.C	10	2.5

FUEL SAVED BY A.C.T. (10% Δ L/D)

	% TOTAL FUEL
COMBAT	4
CRUISES	1·5
LOITER	2
RESERVES	0·5
TOTAL	8% ≡ 2% MISSION TAKE-OFF WEIGHT

PERFORMANCE BENEFITS DUE TO IMPROVED FUEL ECONOMY

- 20% IMPROVEMENT IN COMBAT ENDURANCE
  OR
- 25% IMPROVEMENT IN RADIUS OF ACTION
  OR
- 40% IMPROVEMENT IN CAP TIME

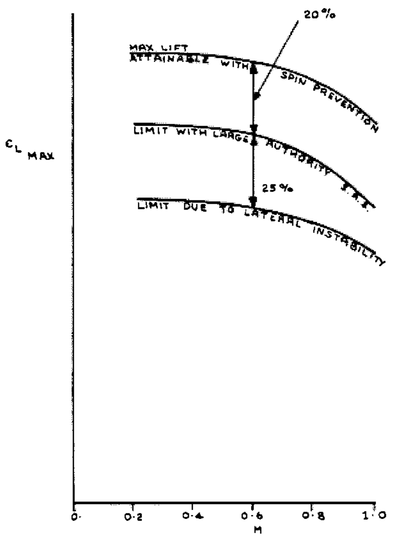
The improved economy in a battlefield air superiority mission is equivalent to either a 20% improvement in combat endurance or 25% improvement in radius of action or 40% improvement in combat air patrol time.

The extra weight, complexity and cost of a full time FBW control system with the required degree of redundancy in its sensors, computing and power supplies has of course to be justified. A recent study by BAe Warton showed that the mass penalty for a full time FBW control system compared with a conventional mechanical control system with autostabilisation added was some 50% of the conventional control system mass. However, if the aircraft with natural stability were rescaled by increasing its wing area to achieve the same subsonic turning performance as the ACT-equipped aircraft, with increased fuel to restore the mission performance, the penalty in take-off mass was seven times as large as that due to the adoption of artificial stability. This and many other similar exercises have amply justified the adoption of full time FBW for the next generation of combat aircraft. To pave the way for this next generation a quadruplex digital full time FBW flight control system, designed to production aircraft standards, has been successfully tested in flight in the Jaguar FBW demonstrator.

The second important reason for the adoption of full time FBW is that it makes carefree manoeuvring possible. Most combat aircraft in current service are limited in their usable lift by lateral instability or deterioration in controllability which can lead to departure into a spin. With effective aerodynamic controls on all three axes and with full authority, full time FBW, the stability of the aeroplane can be augmented and its manoeuvrability restricted as the incidence limit is approached. This should enable the full lift capability of the airframe to be exploited in air combat withour risk of departure. In effect we will have erected a safety barrier in place of the cliff edge. Fig.14 illustrates the potential benefit in usable lift compared with an aircraft of the past generation.

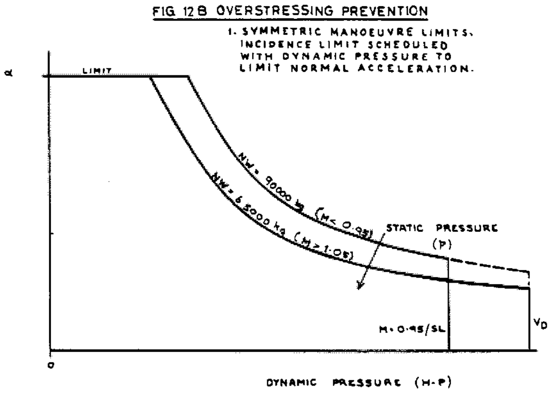
MANOEUVRE LIMITS, EFFECT OF 'FLY-BY-WIRE'

FIG.14



The spin prevention incidence limit may be scheduled with dynamic pressure, in effect airspeed, to provide an overstressing limit, effectively limiting the product of normal acceleration and mass of the aircraft. The limit can additionally be scheduled with altitude to provide separate subsonic and supersonic 'g' limits as illustrated in Fig.15.

FIG. 15



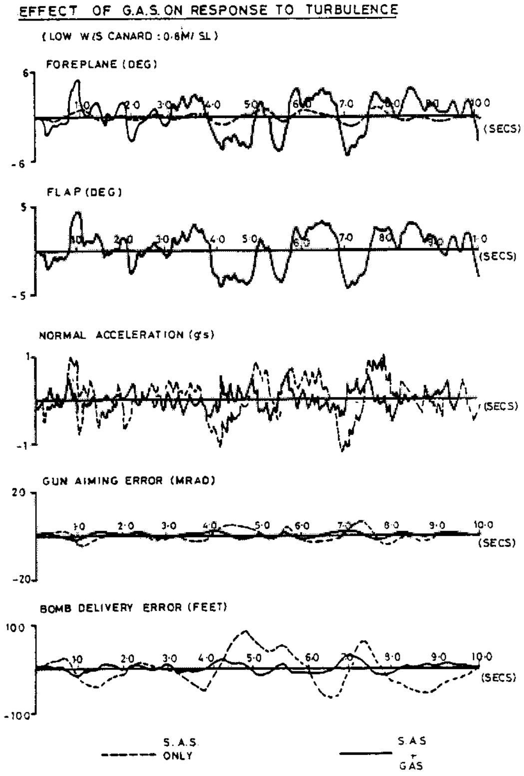
Similarly, although not illustrated, the roll rate limits can be scheduled with incidence and airspeed to prevent lateral overstressing, enabling carefree manoeuvring on all axes.

In addition to the benefits in combat manoeuvrability and consequently combat success, conferred by carefree manoevring, there is a direct economic benefit in aircraft saved due to elimination of spinning accidents. Figures for the loss rate due to spinning accidents in combat training are typically one aircraft lost in 50000 flying hours, representing 15% of total losses. These figures in themselves should justify the cost of a spin prevention system. It should be noted that a spin prevention system conferring carefree manoeuvring in a wide variety of external store configurations has already been demonstrated on the Tornado.

A further application of active controls technology envisaged for the next generation of combat aircraft is gust alleviation. In recent years there have been many published studies claiming extravagent benefits for gust alleviation systems. However, many of these studies have been somewhat idealised and have ignored lags introduced by the sensing, computing, filtering and actuation in the real hardware of a gust alleviation system. Nevertheless, taking account of such effects, it is still believed that a substantial improvement in ride qualities can be achieved. The phrase "ride qualities" is used here in preference to "ride comfort" because it is believed that the pilot will tolerate the physical discomfort of severe bumps in low altitude high speed flight if this results in reduced vulnerability, but on reaching his target he must be able to deliver his weapons accurately; this is believed to be the most important consideration in providing good ride qualities.

Fig.16 shows the time history of 10 seconds flight through a patch of severe turbulence at low altitude, high speed on a low wing loading canard with and without a gust alleviation system. The system drives active flaps to suppress the normal acceleration disturbances and the all-moving foreplane to counteract the residual pitching moments. The increased foreplane activity and flap motions with gust alleviation engaged are evident and it is shown that the larger normal acceleration effects are suppressed although the smaller higher frequency bumps are little effected. The most striking effects (literally) are the improvements in gun aiming and bomb delivery errors, particularly the latter, where peak errors of nearly 100 ft are reduced to less than 20 ft with the gust alleviation system operative.

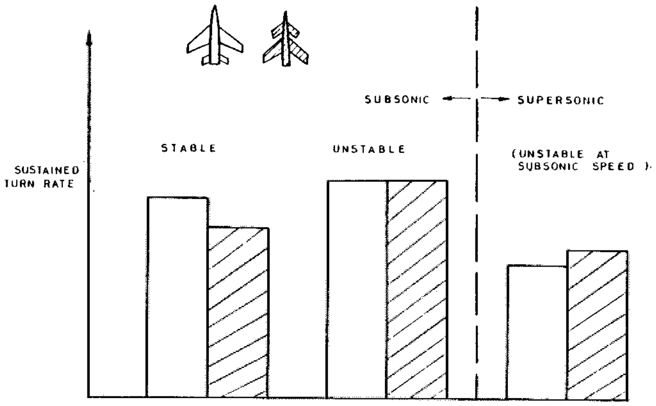
FIG.16



A further application of artificial stability is to canard configurations. A naturally stable canard is not competitive as an air superiority fighter because the enforced forward c.g. location and associated highly loaded foreplane generate high drag and impair wing performance in subsonic manoeuvring flight. With artificial stability the c.g. can be located close to the wing/body aerodynamic centre, with a lightly loaded foreplane, yielding lift/drag ratios similar to those of a tailed configuration (Fig.17). In supersonic flight, with the aerodynamic centre aft, positive foreplane lift to trim yields a higher lift/drag ratio in manoeuvre than that of a conventional aircraft with a down-loaded tailplane.

FIG. 17

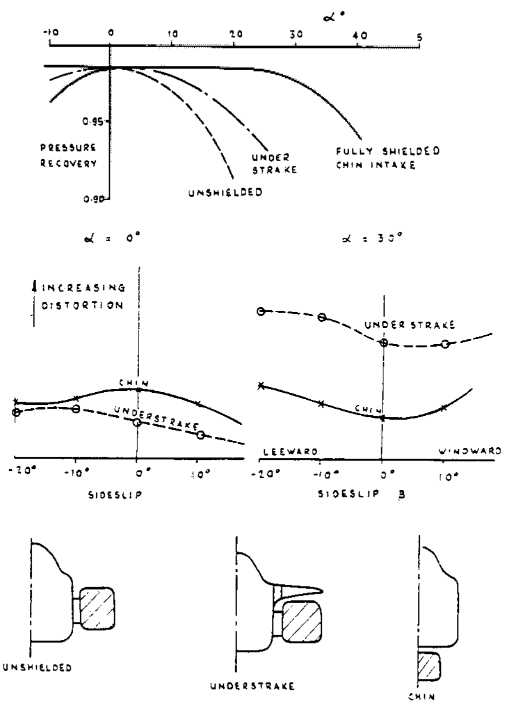
CANARD VS TAIL WITH ARTIFICIAL STABILITY



ARTIFICAL STABILITY MAKES CANARD COMPETITIVE SUBSONIC SUPERIOR SUBSONICALLY

FIG. 18

EFFECT OF INCIDENCE ON INTAKE PERFORMANCE
COMPARISON OF ALTERNATIVE LOCATIONS



Other points in favour of the canard are:

- Favourable trimmed lift interference at high incidence subsonically.

- Better afterbody lines, yielding lower supersonic drag, due to absence of tailplane and spigot supporting structure.

- Better potential for gust alleviation because foreplane lift to cancel flap pitching moment is additive to flap lift in opposing gust effects.

- Inherent potential for direct force manoeuvring by:

  Flaps + foreplane - direct lift

  Flaps + foreplane with incidence change - drag modulation

  Differential foreplane + rudders - direct side force.

5. Intake Design

Aerodynamic stability, controllability and performance at high incidence are worthless unless satisfactory operation of the engine under the same conditions can be generated. The enemies of satisfactory engine operation are distortion, turbulence and swirl of the flow at the engine face, and modern high by-pass ratio engines tend to be more "fussy" in this respect than their pure jet predecessors. Fig.18 illustrates some of the effects of intake location on pressure recovery and distortion. A fully shielded chin intake position is shown to be superior over the tested range of incidence and sideslip. However, the full benefits of the chin location are realised only if it is fully shielded i.e. its width is significantly less than that of the fuselage at the intake station. The chin location can severely restrict underfuselage store carriage and the final choice for the designer is not so clear cut when all the practical considerations are taken into account. Considerable improvements are possible on a side intake. For instance Fig.19 illustrates the improvements that can be obtained on a conventional side intake layout by means of scarfing the intake face, i.e. cutting back the lower lip behind the upper lip, by drooping the lower cowl and by a duct fence. Compared with a conventional unscarfed side intake, these measures result in a 40° improvement in the incidence capability for a given level of instantaneous distortion. Such an intake should give satisfactory operation up to and beyond the usable lift limits of any configuration of fighter envisaged. A variable lower cowl lip also permits adjustment of intake area to reduce spillage drag, with significant benefits in supersonic acceleration and in subsonic cruise and loiter performance as indicated in Fig.20.

Intake design in the future may be influenced by the need to suppress radar echo in design for stealth. Intake ducts are quite the largest contribution to the important frontal aspect echo. Some form of shielding by other parts of the aircraft's structure does seem attractive but all-round protection is not feasible and any significant shielding involves major compromises on aircraft layout.

It may prove sufficient to rely upon suitable tailoring of ducts and on the incorporation of radar absorbent material which has a powerful effect.

FIG.19

EFFECT OF INTAKE SCARFING, COWL DROOP AND DUCT FENCES

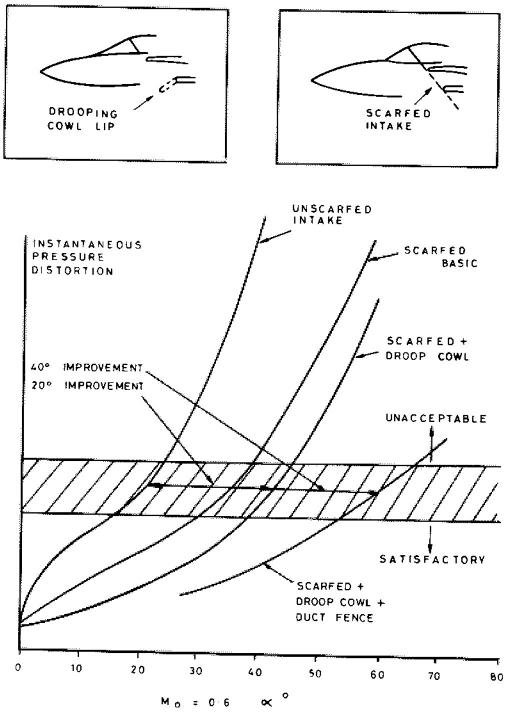
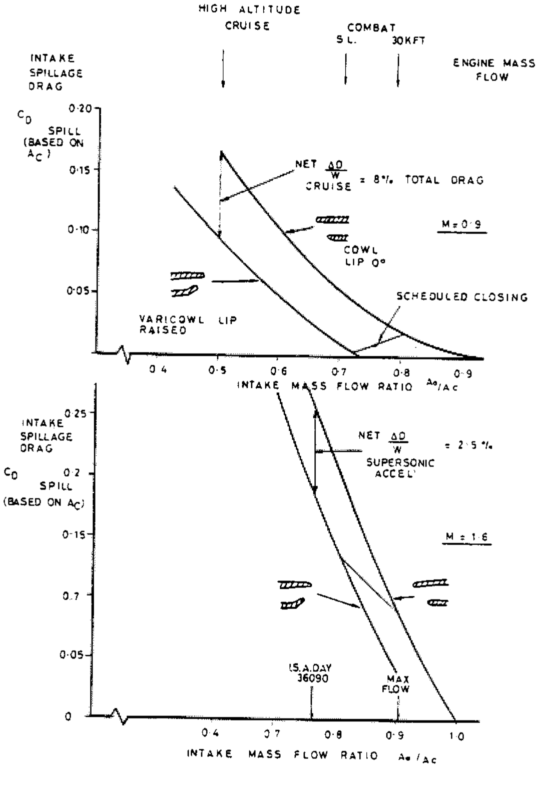


FIG. 20

VARICOWL EFFECTS ON INTAKE SPILLAGE DRAG

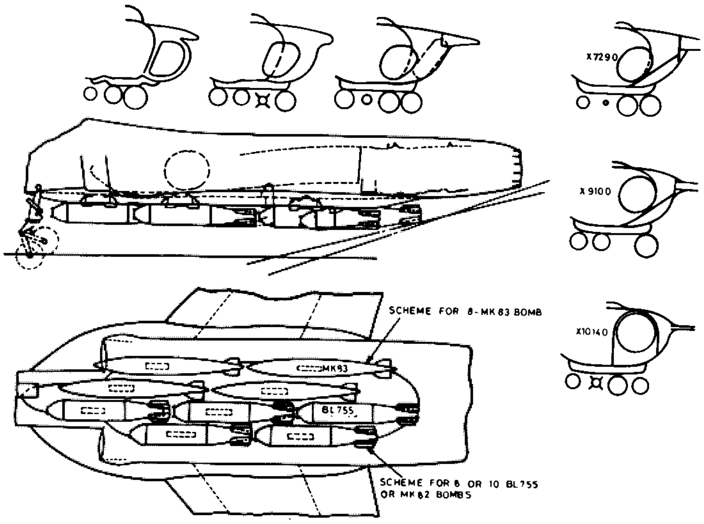


6. Low Drag Store Carriage

The subject of intake location discussed in the previous paragraph is inevitably coupled with the question of external store carriage. The desire for high penetration speeds in dry combat thrust for ground attack aircraft carrying a large number of close support weapons favours an underfuselage carriage scheme such as illustrated in Fig.21, taken from Ref.3.

SCHEME FOR UNDERFUSELAGE PALLET

FIG.21



By means of tandem shielding and staggered columns of bombs, interference drag is greatly reduced compared with conventional underwing carriage.

EFFECT OF LOW DRAG WEAPON CARRIAGE FIG. 22

(8 BOMBS LOW ALTITUDE)

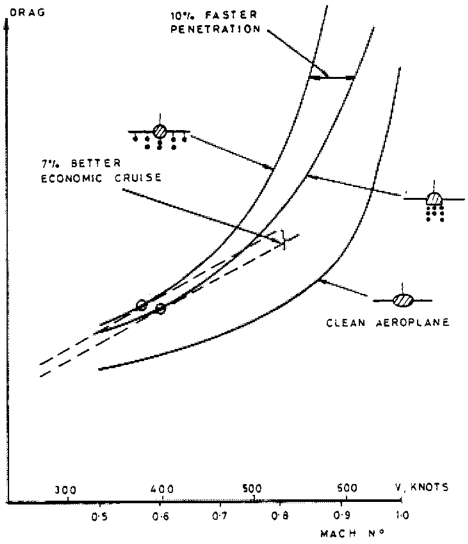


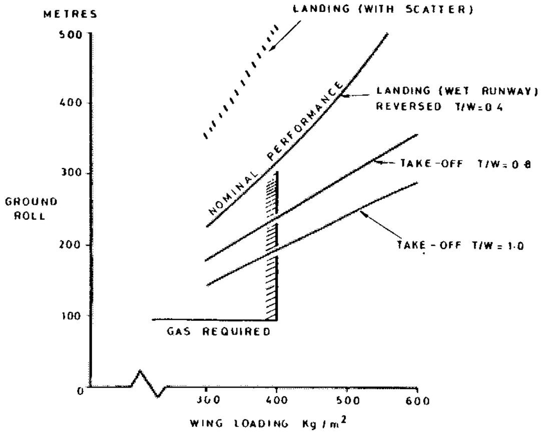
Fig.22 illustrates the relative drags of such a carriage scheme with 8 bombs underfuselage, compared with a more conventional carriage layout of 2 tandem bombs underfuselage, twin tandem underwing inboard and singles outboard. Low drag underfuselage carriage results in 10% faster penetration speeds and 7% better economic cruise with obvious benefits in reduced vulnerability and improved radius of action.

7. Short Take Off and Landing

Fig.23 from Ref.3, shows the variation of take-off and landing ground rolls with wing loading, assuming maximum lift capability and thrust/weight ratios typical of current and future fighters. With wing loadings likely to be in the 300 - 400 kg/m^2 (60 - 80lb/sq ft) range and a thrust/weight ratio of about 1 there is little difficulty in achieving a take-off ground roll below 300m. The nominal landing performance on a wet runway however, with a thrust reverser or with a parachute of equivalent deceleration capability is some 50% longer than the take-off run. Further, if account is taken of the scatter in pilot performance on landing the 99% probability figure of landing within a given distance is between 2 and 3 times the nominal take-off distance.

FIG .23

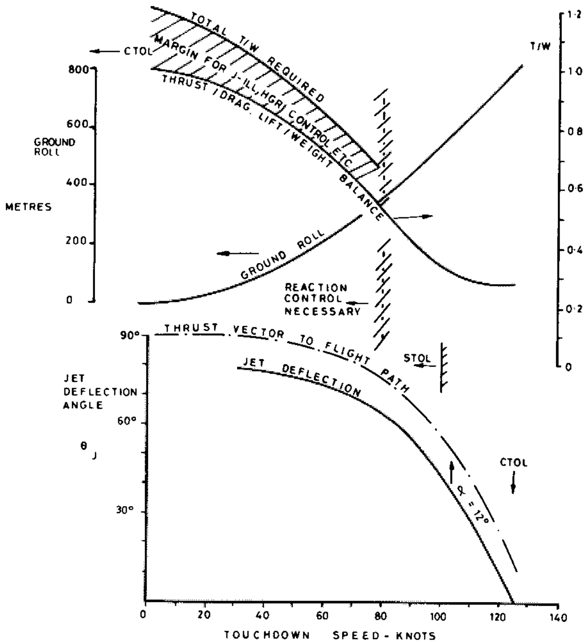
TAKE OFF AND LANDING FIXED WING FIGHTER



Although some of the scatter in landing performance can be reduced by improved pilot aids and particularly by elimination of the landing flare, it is still landing performance which dictates the airfield lengths required, either for dispersed operation or from operation from repaired runways. The message is clear - if ultra short airfield distances are required for such conditions, then some form of powered lift or vectored thrust must be employed and it is the ultra short landing performance that largely rules the configuration design. Fig.24 illustrates the variation in ground roll with available vectored thrust to weight ratio and thrust vector angle.

FIG. 24

USTOL APPROACH. VARIATION OF APPROACH SPEED AND LANDING DISTANCE WITH AVAILABLE THRUST / WEIGHT RATIO AND JET DEFLECTION



BASED ON C_L = 1 1 AT 12°, L/D = 3, 3° GLIDE PATH

The figure, which is typical, but not unique, shows clearly that small thrust vector angles are of little benefit because they do not permit large thrust values to be used from considerations of the out of balance longitudinal forces. Only when the thrust vector gets past 50 or 60° is the benefit significant and if true vertical operation is required or is feasible, a thrust/weight ratio in excess of 1.2 at landing weight is probably required, taking account of jet-induced lift losses, hot gas ingestion, reaction control allowances and thrust margins for acceleration and manoeuvre.

Whether ultra short or true vertical operation is required it is clear that the thrust is there for combat and the lift is there for combat, so it is up to the ingenuity of the designers and aerodynamicists to configure the design so that vectored thrust can be used with minimum penalties in airframe performance, weight and cost in the future. This is undoubtedly the way ahead, in the long term if not the short term.

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