ICAS Paper No. 70–57 bis

ENGINEERING SOLUTIONS TO SOME CONFLICTS BETWEEN TRANSONIC FLIGHT AND JET V/STOL

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The Seventh Congress of the International Council of the Aeronautical Sciences

CONSIGLIO NAZIONALE DELLE RICERCHE, ROMA, ITALY / SEPTEMBER 14-18, 1970

Price: 400 Lire

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1. INTRODUCTION

Only one particular type of jet V/STOL aircraft is discussed in this Paper. This is the Hawker Siddeley Harrier family of vectored thrust fighter designs powered by the Rolls-Royce (Bristol) Pegasus engine.

The development period covered is from 1960 to late 1968, during which these aircraft flew over 2,500 hours. This experience included some 10,000 vertical and short take-offs and landings from many types of land surface and from ships at sea. Service Harriers have since carried this total to over 25,000 V/STOL operations.

During this development the flight envelope was extended from the first free hovers at heights of less than 10 ft (3 m) in late 1960, to indicated airspeeds of 630 knots (1,150 km/hr.), Mach numbers of 1.25 and altitudes in excess of 50,000 ft. (15 km) at the present day. Most of this transonic envelope had been attained before the Harrier itself flew in 1966.

This period encompasses aircraft weights from the 10,000 lb. (4,500 kg) of the first P.1127 hovers, to Harrier S.T.O. weights exceeding 22,000 lb. (10,000 kg). The engine has been developed from the first hover flight standard Pegasus 2 (in 1960) of 11,000 lb. (50 kN) thrust, to the 20,000 lb. (91 kN) of the present Pegasus 10 rating.

In order better to appreciate the engineering discussion which is given in later sections of the Paper, it will be useful briefly to recapitulate the historical sequence of development of this family of aircraft.

The design of the first P.1127, and its engine, were defined in 1959. First hovers were made in 1960. First conventional flights, first transitions and first supersonic flights all occurred in 1961. Two of these early prototypes were constructed (Fig.1.1).

A further four P.1127 aircraft were built; they first flew between 1962 and 1964. These aircraft had many detail changes from the first two prototypes (Fig.1.2). The last of this batch of four was more extensively modified during construction, and became the prototype of the first Service-version P.1127, which was named Kestrel (Fig.1.3).

During 1964 and 1965 a total of nine Kestrels were built. They were flown in U.K. during 1965 by the Tripartite (U.K., U.S.A., F.R.G.) V/STOL Evaluation Squadron and were subsequently used for research.

The Harrier design (developed from the Kestrel) was commenced in 1965: the six development-batch aircraft first flew in 1966 and 1967. The first production Harrier flew at the end of 1967. At June 1970, a total of 40 Harrier GR. Mk.1 production aircraft and 5 Harrier Two-Seat (T. Mk.2) aircraft have flown. These 66 aircraft of the Harrier family have accumulated some 6,000 hours flight time – a total which represents well over 90% of the Western World's jet V/STOL flying.

This experience, and the millions of engineering manhours that lie behind the development of the aircraft and its engine and equipment, has provided a large reservoir of knowledge from which further development of the Harrier and its successors is now proceeding. The ability of the vectored thrust V/STOL design to accommodate stretch and development can be attributed to its basic simplicity and flexibility.

The aircraft has predominantly the characteristics of a normal jet fighter. The single basic departure from the conventional equivalent aircraft is the use of four jet nozzles located, two each side, near the centre of gravity. The difficulties that have arisen during development in conventional flight have almost all been associated directly or indirectly with this jet outlet location.

The first part of the Paper deals with the conflicts inherent in the layout of the vectored thrust V/STOL fighter. The constraints imposed by the V/STOL aspects on the designer's freedom to choose those features giving the best transonic flight properties are discussed, to prepare the scene for the more detailed treatment of the two selected areas of conflict which then follow.

The first of these discusses the solutions developed to provide satisfactory flying qualities in the pitching plane in conventional – fully wingborne – flight. The second section concerns the behaviour and handling of the aircraft during take-off and landing. Both the areas chosen have, in common, the feature that a satisfactory technical solution was attained only after considerable redesign. This provides their chief interest to a Paper such as this.

Fig.1.1 Prototype P.1127 in free hover with original wing and flat tailplane.

Fig.1.2 Fifth P.1127 aircraft fitted with anhedral tailplane and streamwise tip version of original wing with vortex generators.

Fig.1.3 Kestrel. Note swept wing and extended span anhedral tailplane.

Fig.1.4 Harrier. GR. Mk.1

2. CONFIGURATION

2.1 Introductory

The conflicts between jet V/STOL and high speed flight arise basically from the aircraft configuration. The layout, which must reconcile the often contradictory demands of the two extremes of the flight envelope, tended (in the past) to have been orientated rather more to the V/STOL end.

The reasons for this were simply that less was known about the detail effects of particular choices of the V/STOL parameters and an ignorant compromise is always risky. The V/STOL fighter designer had everything to lose if he was unsuccessful in this mode of operation. He felt that the transonic end of the flight envelope was a regime of inherently greater engineering certainty. If the aircraft inherited problems at high speed because of an unwillingness to compromise forced by V/STOL considerations, then two decades of experience were available to assist in finding the solution. In the mid/late 1950's, in terms of jet V/STOL, all designers were Wright brothers.

With the vectored thrust approach to jet V/STOL (as with other powerplant arrangements) the characteristics of the powerplant form the foundation upon which the configuration and operation of the entire vehicle are erected.

After a decade of analytical and practical component development, the vectored thrust engine has evolved into the form shown in Fig. 2.1. While the number of compressor and turbine stages has increased and development has mechanically improved many features and simplified others, such as the propulsion nozzles, the Pegasus 10 flying today remains basically the same as the Pegasus 2 which first flew in 1960.

From the aircraft designer's viewpoint, the most important features of this type of engine are: –

(i) the large static air mass flow – needing large intakes with the best possible pressure recovery in V/STOL,

(ii) the large spillage from these intakes during throttled-back cruise flight at low level, where the engine may be operating at less than one fifth of its Sea Level V/STOL thrust,

(iii) the thrust distribution between front and rear nozzles – characteristically about equal front/rear components. This leads to the concept of a *Thrust Centre.* With a 50%/50% thrust split, the Thrust Centre lies longitudinally midway between the nozzles. Over the complete range of nozzle rotation the thrust vector passes through this Thrust Centre, whose position remains approximately constant over the V/STOL operating range.

2.2 Balance and Trim in V/STOL

In the jet V/STOL fighter designs being discussed, control in the V/STOL modes is by a reaction control system which uses engine high pressure bleed air. The engine is designed and developed for V/STOL performance taking into account a mean bleed air demand for the reaction control system (Ref. 1).

This bleed air represents a considerable loss of energy from the powerplant – of the order of one thousand HP (kilowatts) – and so must be used most efficiently in V/STOL by directing the reaction control jets downwards to produce useful lift in steady trim states. Short-term control demands may be permitted to eject reaction air upwards (for roll control) or sideways (for yaw control). Since the aircraft is normally in trim about these axes, these intermittent forces generally have only small effects on the flight path and cause negligible loss to the overall lifting capability.

Most bleed air is used for pitch trim and it is therefore important that the reaction control pitch trim force should always be arranged to provide upward lift.

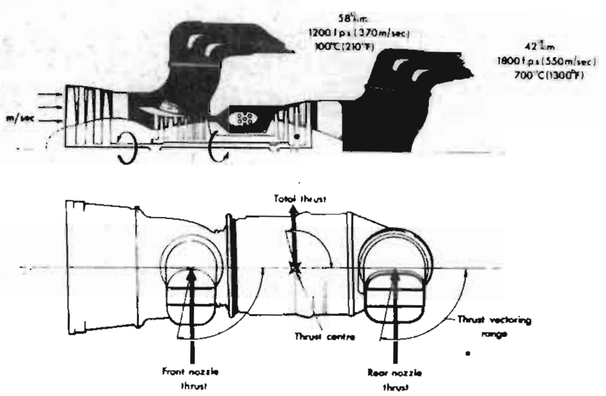
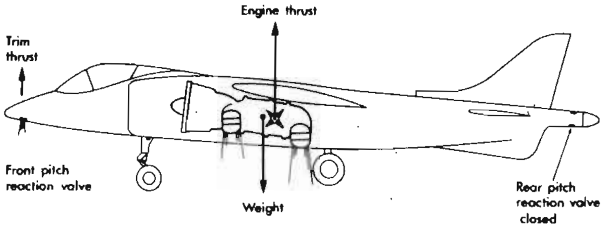


Fig.2.1 The vectored thrust power plant. Concepts and typical quantities.



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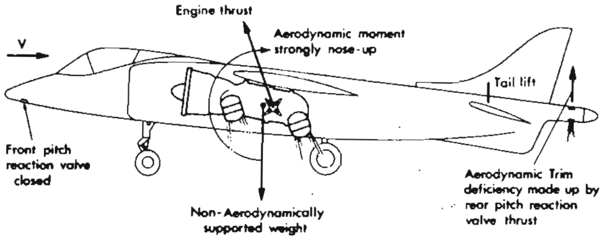
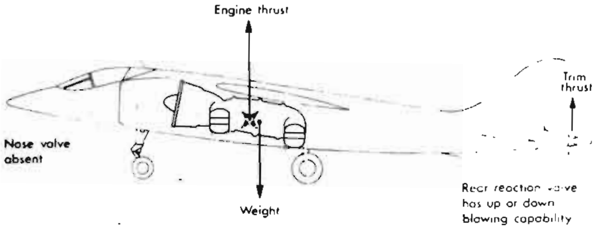


MID-TRANSITION

Fig.2.2 Pitch trim in V/STOL – aft thrust centre.



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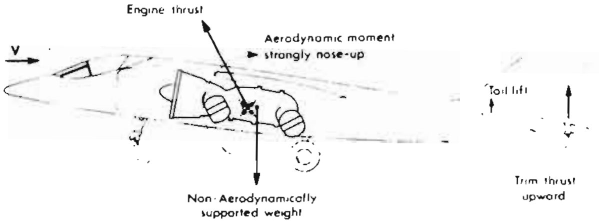

MID-TRANSITION

Fig.2.3 Pitch trim in V/STOL – forward thrust centre.

As the centre of gravity (c.g.) of the loaded aircraft and the engine Thrust Centre cannot always be arranged to coincide exactly, the solution for optimum performance – if the Thrust Centre cannot be located far enough forward always to be in front of the aircraft c.g. range – is to provide a pair of pitch reaction control valves, both downward-blowing, located at nose and tail. Fig.2.2 shows this arrangement. In hover, the aircraft is trimmed on the upward thrust of the front reaction control valve; the rear valve being closed. In transition – where aerodynamic moments tend to be strongly nose-up – a lifting trim force is obtained by opening the rear valve in conjunction with tailplane lift, the front valve then being closed.

If the engine design results in a relatively far forward Thrust Centre (say 30% – 40% of the nozzle spacing aft of the front nozzle thrust line) it is possible to arrange for optimum pitch trimming in V/STOL by a single control valve at the rear which can provide control forces acting either upward or downward, see Fig.2.3.

This is advantageous, since a reaction valve at the extreme tail is generally at a greater moment arm than can be provided in the nose of the aircraft – thus minimising bleed air quantities for a given pitching moment. It has the considerable further merit of removing the ground erosion potential of the relatively high velocity reaction control jet as far away from the engine air intake as possible, and hence also minimising the likelihood of hot gas reingestion into the main air intakes.

Unhappily, this desirable relation between Thrust Centre and aircraft c.g. is not practicable in a conventional aircraft layout except with special versions of the vectored thrust engine where the front nozzle thrust is increased significantly, relative to the rear nozzle thrust, by means of devices such as Plenum Chamber Burning (P.C.B.). This consists of burning fuel in the fan delivery ais so as to provide an energy from the front nozzle exhaust comparable with that from the rear nozzles.

With non-P.C.B. vectored thrust engines, even of by-pass ratios of 1.4 or more, the work balance in the engine results in a thrust split generally only just acceptable to the aircraft designer, and means providing pitch trim controls for V/STOL as in Fig.2.2. By-pass ratios less than 1.0 which give thrust splits with significantly more than 2/3 total thrust at the rear nozzles, cannot easily be arranged to balance in a conventional airframe whilst retaining a satisfactory payload fraction.

Thus the principal configuration problem is that of obtaining an efficient balance in V/STOL. The further problems that stem from this basic difficulty will become apparent in the following, rather elementary, step-by-step analysis.

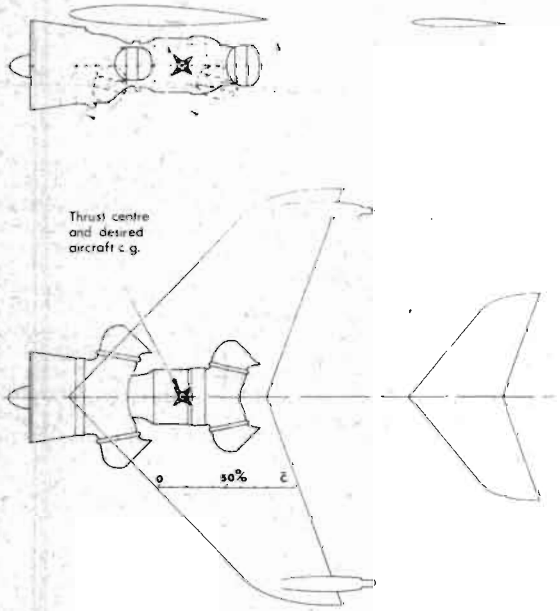

Fig.2.4a Configuration assembly – Stage 1.

2.3 Layout Considerations

To a first approximation it can be taken that the aircraft design c.g. position and the engine Thrust Centre must coincide. In practice, the c.g. can be allowed to displace from the Thrust Centre by only a few percent of the mean chord either way; otherwise large bleed air demands for trim forces in V/STOL can be incurred. Such excessive bleed demands heavily penalise the engine in terms of available thrust and/or useful life.

The wing size and planform having been chosen (after appropriate analysis of the many parameters which affect this crucial selection) and the contribution of the chosen tailplane to pitching stability and control in the presence of the wing having been assessed, it is now possible to place the wing and tailplane in relation to the aircraft c.g. (Fig.2.4a). These locations are determined on the basis of the static and manoeuvre margins required for conventional flight. Having located the wing and tailplane, their own mass contribution to the aircraft c.g. is assigned. Note how the area swept by the jets constrains the vertical position of the tailplane. The designer has many choices – but all of them are confined to positions near or above the wing plane.

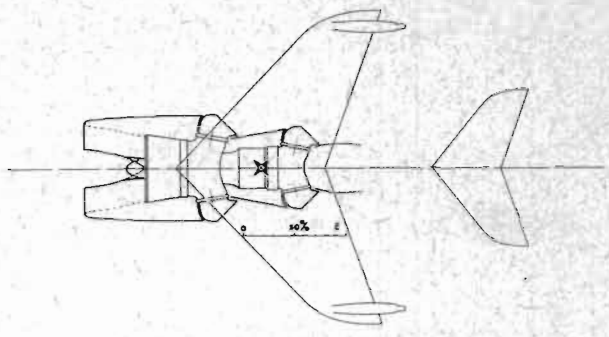

Fig.2.4b Configuration assembly – Stage 2.

Next, a fuselage must be wrapped around the powerplant and the intake geometry decided. The intake must have a layout giving the best V/STOL efficiency, provided that conventional flight operation of the duct is not thereby vitiated. This factor – and the ever-present need to minimise weight – generally compels the adoption of a very short intake duct with all the aerodynamic perils that this can provide. The mass contributions of intake and centre fuselage are thus assigned. (Fig.2.4b).

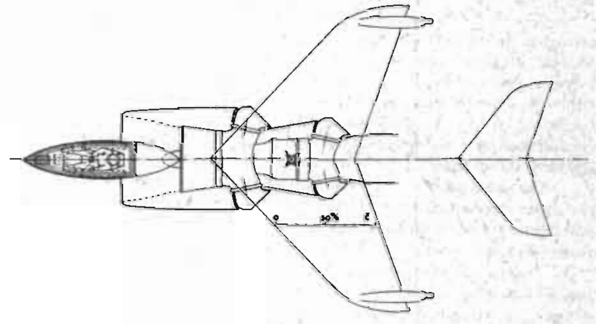

Fig.2.4c Configuration assembly – Stage 3.

The cockpit nacelle can now be positioned ahead of the intakes. With it are located the masses associated with crew escape, cockpit controls, instruments and equipment together with the transparencies and any devices which must have an unobstructed forward view, such as radar, cameras, etc.. This minimum of essential "sharp-end" components still represents a significant fraction of the aircraft mass, and has a most notable contribution to adverse (i.e. forward) movement of the configuration c.g. (Fig.2.4c).

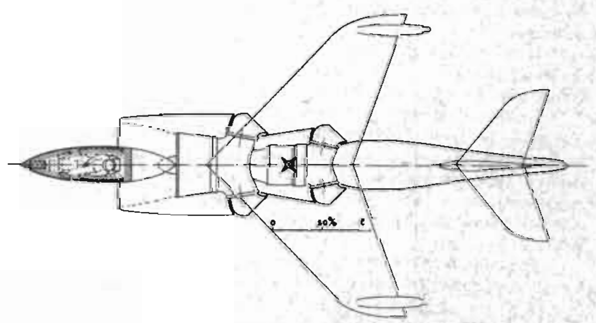

Fig.2.4d Configuration assembly – Stage 4.

Having now assigned the front parts of the fuselage, the fin can be chosen and located, designed to provide adequate directional stability through the speed range. The rear fuselage can then be delineated, supporting the fin and tailplane with adequate strength and stiffness at their assigned stations (Fig.2.4d).

The total fuel load in the aircraft must be arranged so that use of fuel causes the least displacement of the aircraft c.g. The centre of volume of the fuel tankage must therefore be close to the aircraft c.g., and the fuel usage designed to provide a balanced consumption of fuel from the various tanks.

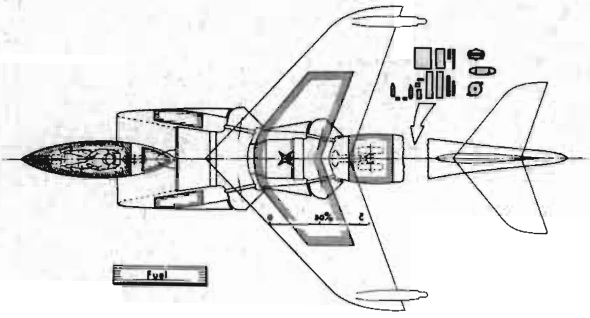

Fig.2.4e Configuration assembly – Stage 5.

Since, with a large vectored thrust engine, fuselage volume is at a considerable premium, the wing must necessarily contribute to fuel stowage. The c.g. of the fuel in a swept wing tends always to be well aft of the aircraft c.g., and thus its contribution to the total fuel c.g. must be offset by the fuselage tanks whose own c.g. is correspondingly ahead of the aircraft c.g. The c.g. of this fuselage fuel is dictated by the volume and location of the tank(s) in the front fuselage, since the appropriate balancing rear fuselage tank is readily accommodated immediately aft of the engine (Fig.2.4e).

It is thus easy to foresee that the total fuel which can usefully be carried in the aircraft is directly limited by the amount that can be stowed *forward* of the engine because of this fundamental balance requirement. Increasing the fuel volume provided in the fuselage ahead of the engine either gives unwelcome increases in the fuselage cross-section (typically a maximum at this location) or pushes further forward the mass of the cockpit nacelle with its associated essential items, thus moving the aircraft c.g. more disadvantageously forward.

The problem of overall balance now becomes plain. With almost all the major masses assigned to positions around the design c.g. which their nature and function dictates, the aircraft has an actual balance point which tends to be unacceptably far forward of the engine Thrust Centre.

The remaining items (comprising mainly equipment) are the only masses which the designer is relatively free to locate so as to achieve the design c.g. position close to the Thrust Centre.

Note that the disposable load (ordnance and stores) must be located so as to minimise aircraft c.g. travel when it is dispensed. Although weapon stations can therefore be disposed laterally, the fore-and-aft location of external stores must be closely related to the aircraft c.g., and ordnance/pylons are not available as an aid to achieving satisfactory aircraft balance.

The various power services (electrics, pneumatics, flying controls, hydraulics, etc.) are generally distributed around the aircraft and, in the main, are not disposable to assist overall balance. Possible exceptions to this rule are the environmental systems which, at the expense of apparently inefficiently long pipe runs, can be housed in the rear fuselage even though the consumer location (for cabin conditioning, pressurisation and oxygen) is in the nose.

In the end the only significant mass available with which the designer can separately control the configuration c.g., is the collection of black boxes (radios, computers, etc.) which comprise the avionics fit of the aircraft.

Because of the inherent tendency of the c.g. of the unequipped empty aircraft to be forward of the desired balance point, the biggest possible proportion of the avionics – together with assignable items from the power services such as batteries, hydraulic accumulators, electrical control equipment, etc. – must necessarily be housed in the rear fuselage. This disposable mass may amount to as little as 5% or 6% of the mass of the empty basic aircraft.

This situation contrasts with the freedom which obtains with the layout of an equivalent non-V/STOL aircraft. Here the engine need not be located at the configuration c.g. The designer therefore has much more freedom in placing the disposable equipments, since the engine itself (representing at least 20% of the mass of the empty aircraft) can be moved fore and aft within quite wide limits in order to achieve satisfactory balance.

The rear fuselage of the V/STOL vectored thrust fighter thus must provide the main equipment stowage space (Fig.2.4e). Consumer location, for very many of the services and functions generated by equipments located in the rear fuselage, is the cockpit. Electrical cables and piperuns must be provided between these two sites, which can be typically 20 to 30 ft. (7 to 10 m) apart. This may appear on first examination to be rather wasteful, but experience in juggling with the balance problems if this type of aircraft quickly shows that housing the maximum possible mass of equipment in the rear fuselage offers the lightest practicable solution.

This fundamental problem cannot be solved simply by re-locating the engine further forward in the airframe so that the Thrust Centre catches up with the c.g.. To do so would mean shortening the intake – already assumed to be the minimum length aerodynamically permissible – and losing fuel volume ahead of the c.g. so that fuel capacity would be reduced or the fuel c.g. would be too far aft of the aircraft c.g.. If the engine is moved forward with intakes unshortened, a large part of the mass of the aircraft (cockpit, intakes, centre fuselage, etc. – some 60% to 70% of the total empty aircraft mass including the engine) is translated with it. The aircraft c.g. thus follows up the engine displacement, severely reducing the desired gain. The resultant c.g. then tends to be too far forward on the wing mean chord, unless it is also a deliberate aim of the change to provide increased stability margins in flight, as was done in the Kestrel redesign (see Fig.3.7 and Section 3.2).

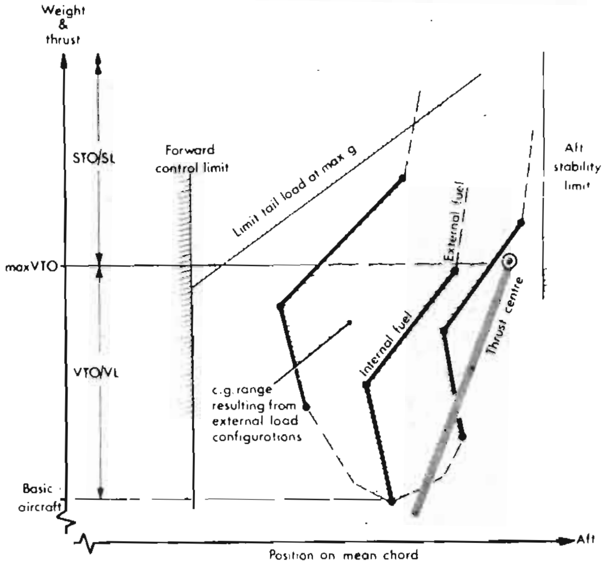

Fig.2.5 Typical c.g. envelope.

A typical c.g. diagram is given in Fig.2.5. The Thrust Centre of the engine when installed in the airframe tends to be further aft than the position deduced from bench testing. This arises partly from the effects of intake flow distortion on the relative thrust from the front and rear nozzles, and partly from the pitching moment induced by the jet-induced downwash field which acts on the aircraft in VTOL flight.

A favourable forward shift of engine Thrust Centre is experienced as the hover thrust is reduced. It is possible to take advantage of this and, without exceeding a stipulated c.g./Thrust Centre offset (i.e. a given level of bleed air demand for trim) dispose the internal fuel so that its c.g. is aft of the dry aircraft c.g.. This permits the configuration c.g. to follow the Thrust Centre forward as weight, and hence hover thrust, is reduced. External fuel need not be so closely disposed near the aircraft longitudinal c.g. position as, with worthwhile ordnance loads, the resulting all-up weight is not within the hover flight range.

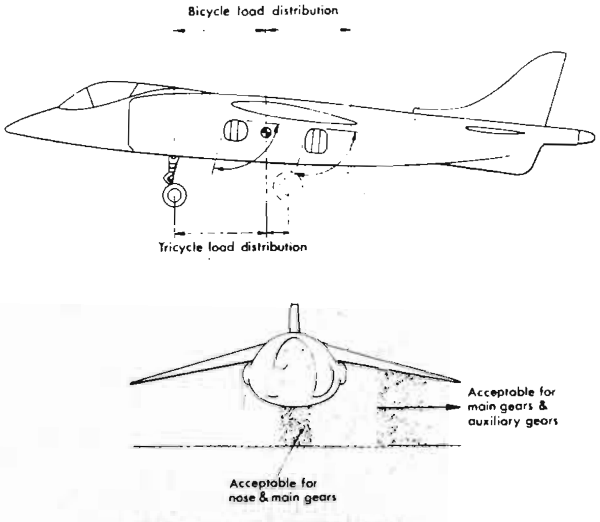

Fig.2.6 Landing gear locations.

A further configuration problem is that of the landing gear. Housing the engine in the centre fuselage with the swivelling jets sweeping a considerable width to each side, denies the use of a conventional tricycle gear housed in the fuselage (Fig.2.6). The high wing position (necessary to provide the clearance for thrust vectoring) plus the fact that it is filled with fuel, and is in any case probably too thin (for aerodynamic reasons) precludes the use of a conventional tricycle gear retracting laterally inwards or outwards, to be housed within the wing box.

Thus the choice lies between a bicycle gear, with the rear main oleo placed on the centreline between the swivelling jets, or a tricycle gear with each main unit outside the jet-swept volumes. The main legs and wheels in this latter configuration must be housed entirely outside the main structural elements of the wing (Fig.2.7).

This tricycle arrangement has not so far been used in the vectored thrust V/STOL fighter chiefly because of:–

(i) The drag penalty of the nacelles which house the low-pressure tyres so necessary to a jet V/STOL aircraft which, by its nature, must be capable of operation away from paved bases.

(ii) Interference with trailing edge controls – particularly flaps, which make an important contribution to the STOL performance parts of the V/STOL operating envelope.

(iii) Conflict with the wing ordnance/stores stations, which is difficult to resolve on the small size of V/STOL fighter, where a particular size of weapon/store occupies a bigger fraction of the available wingspan.

A further factor arising from the V/STOL modes also influences the landing gear configuration. This is the fact that V/STOL implies operational deployment from rough unprepared (or semi-prepared) surfaces. A normal tricycle gear layout with, typically, 10% to 20% of the weight carried on the nosegear gives undesirable – probably unacceptable – ground handling characteristics over rough unprepared surfaces. This predisposes the geometry towards a load distribution which is more nearly equal fore-and-aft than is usual with a conventional tricycle gear.

Such a fore-and-aft weight distribution usually prevents rotation of the aircraft just prior to unstick at take-off. In a conventional aircraft, a fixed ground attitude is normally considered unacceptable. In a V/STOL aircraft, however, the disadvantages are minor and are confined to conventional (i.e. non V/STOL) take-off and landing runs which are (by definition) emergency cases. In V.T.O., rotation is unnecessary; in S.T.O., time is at such a premium that rotation (at normal pitch rates) to higher incidence before unstick would give a significant performance penalty.

Hence the design tends towards a landing gear configuration with an approximately equal front/rear weight distribution, with the ground attitude of the wing arranged to give the best S.T.O. performance.

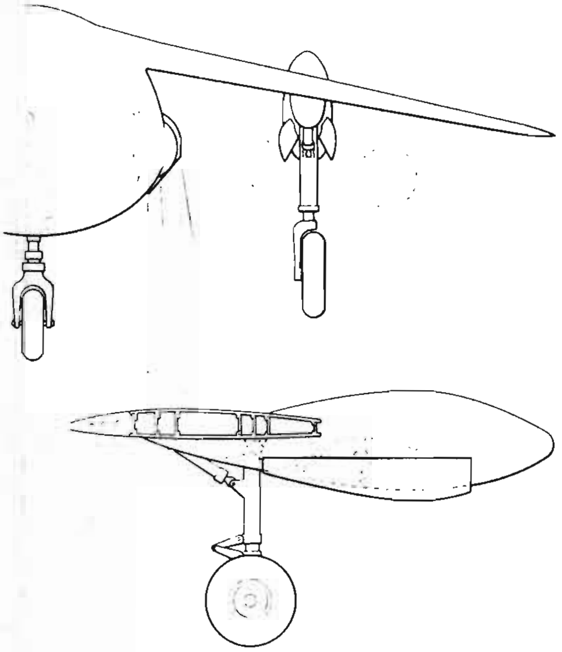

Fig.2.7 Conventional tricycle – possible main gear layout.

Such requirements can be met using either a tricycle configuration as described above, or by a bicycle configuration. The bicycle gear needs additional legs far outboard on the wings to provide lateral restraint in all ground manoeuvre cases, but is the design used in the only operationally-successful jet V/STOL aircraft developed to date. These outrigger units have contributed to the conflicts and difficulties in both the areas chosen for detailed treatment in the Sections which follow.

3. LONGITUDINAL CONTROL AND STABILITY

It has been seen, in Section 2, how the tailplane location on the vectored thrust V/STOL configuration is severely constrained by the practical limitations of the layout.

Pitch-up behaviour at high M was at the forefront of the aerodynamic considerations in the early configuration decisions. So the tailplane was set as low as was considered practicable consistent with being just out of the direct exhaust flow when the jets were aft.

In the very early days of the project, lightness and simplicity were given such high priority that the use of manually operated (i.e. unpowered) elevators was vigorously pursued for some time. However, controllability difficulties in transonic flight with a manual elevator pitch control system were recognised in time as likely to be unsolvable. A weight allowance was found which, in the event, proved acceptably small and, from the original first prototype, pitch control was by an all-moving slab tailplane. This was fully-powered using a tandem cylinder jack fed by independent hydraulic systems. The artifical feel system was a non-linear spring, augmented by a q-feel unit which provided increasing stick forces above V/STOL speeds.

3.1 Early Problems – the P.1127

Evidence of longitudinal stability difficulties was apparent from wind tunnel testing before conventional flight took place. The results of the first explorations of the high speed end of the flight envelope, however, showed that extensive redesign would be required fully to correct these deficiencies.

The P.1127 in conventional flight, jets aft, showed considerably less stability at low incidences than had been expected, and this was coupled with a severe pitch-up behaviour as incidence was increased at the higher Mach numbers. Separated airflow on the outer wings also gave rise to wing drop problems which (initially) proved limiting, even in 1g flight, at high subsonic speeds. Fig.3.1 compares pre-flight tunnel data with some of the early flight measurements of the aerodynamic centre position. Two factors – both arising from the V/STOL-determined aspects of the configuration – were responsible for this pitch misbehaviour.

The lack of pitch stability at *low incidence* was due to the tailplane stability contribution being very small because of its close proximity to the exhaust jet streams. The tailplane on these early aircraft was of small span (to keep down weight) and its local incidence was more a function of jet velocity than aircraft angle of attack. The rate of change of downwash ϵ at the tailplane with wing incidence α was large – the local flow directions being dominated by jet entrainment – and the tailplane contribution to stability therefore minimal.

Pitch instability at *high incidence* and high M originated at the wingtip. The wing was of high taper and only moderate sweep – again in the vital interest of low weight. The local interference provided by the fairing which housed the outrigger undercarriage reduced the effective isobar sweep to zero near the tip and increased local supervelocities considerably on the top surface.

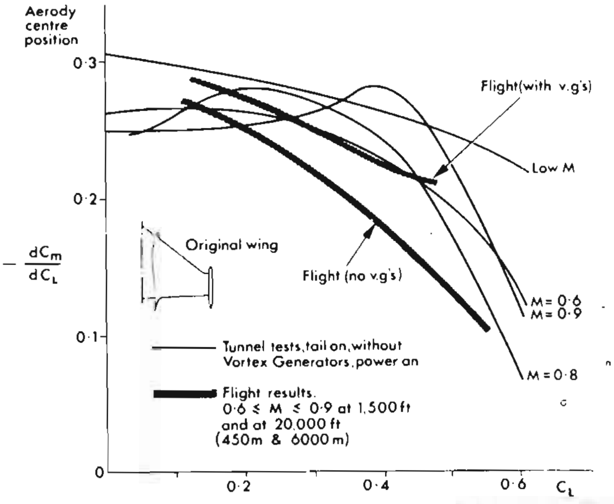

Fig.3.1 Original P.1127. Longitudinal stability on conventional flight.

The net result of these properties was early flow separation on the outer wings as either incidence or Mach number was increased. There was a shedding of lift outboard accompanied by an increase in the downwash aft of the inner portions on the wing. The combination of these adverse factors resulted in severe pitch-up behaviour. The tip-originated separations spread inboard with the strengthening and forward movement of the shock waves as transonic speeds were reached, and were also responsible for the wing drop effects encountered.

These fundamental deficiencies in the design were recognised early and improvements were rapidly engineered into the wing. A new design of wing of a more conventionally swept planform and taper ratio, and having radically different aerofoil sections, was also initiated at this point in the development.

Improvements to the wing ranged from the fitting of vortex generators (v.g's) to a quite extensive rework of the tip portion with the outrigger undercarriage leg housed in a pod which gave the wingtip the best aerodynamic chances of success. This latter change became known as the "Poor Man's Streamwise Tip" as it seemed to offer, at bargain costs, a quick approximation to the more elegant wingtip aerodynamics which were a basic feature of the new swept wing design.

Notwithstanding the high incidence pitch stability deficiencies still being present, the addition of a single row of v.g's to the original wing improved the wing drop behaviour to an extent such that transonic flight was achieved in a dive in December 1961. The P.1127 thus became the first-ever aircraft to combine V/STOL capability with supersonic flight.

The relative geometries of these wing variations are shown in Fig.3.2. The tail-off pitching characteristics obtained from large-scale half-model tunnel tests are shown in Fig.3.3. A steady improvement in the pitching stability is apparent as the aerodynamic refinement is increased progressively in the designs.

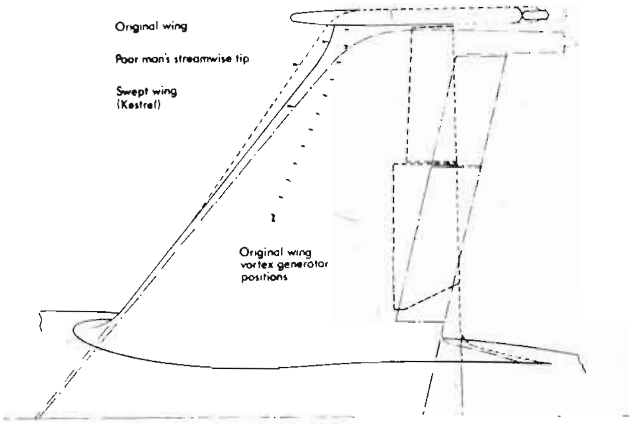

Fig.3.2 P.1127. Wing geometry variations.

At this point it should be remembered that the classic simple cure for level flight pitch stability deficiencies – moving the aircraft c.g. forward to give adequate c.g. margins – was not available in the P.1127. Early flight tests had showed that the engine installed Thrust Centre was further aft than had been predicted. Also, increased thrust was promised only at the expense of a further rearward shift of the Thrust Centre. A c.g. position sufficiently far forward to give acceptable level flight stability margins would have required more than 50% of the reaction control pitch power to trim in the hover – and this from the front control valve, ahead of the intakes. This highly undesirable situation is shown in Fig.3.4, which goes far to explain why further urgent fuselage redesign was implemented, additional to the wing changes mentioned above.

Flight tests of the wing with the Poor Man's Streamwise Tip showed improved aerodynamic behaviour in respect of flow separation outboard, including a less severe transonic wing drop when v.g's were added. However, manoeuvrability was still severely limited at high M by pitch-up and longitudinal instability.

An anhedral tailplane was therefore designed. Tunnel measurements had revealed the existence of favourable sidewash flows outboard of the tip of the flat tailplane. These were exploited by extending the span and incorporating as much anhedral as could be reconciled with possible jet impingement. This tailplane was formed by inserting a 30 in. (762 mm) span flat centre section between the two halves of the original tailplane, which were drooped through 18°. (see Fig.3.8)

Flight with this anhedral tailplane showed a dramatic improvement in high M behaviour – stability was greatly improved at incidence, and pitch-up completely eliminated. Unfortunately the low-incidence c.g. margins were not improved, see Fig.3.5.

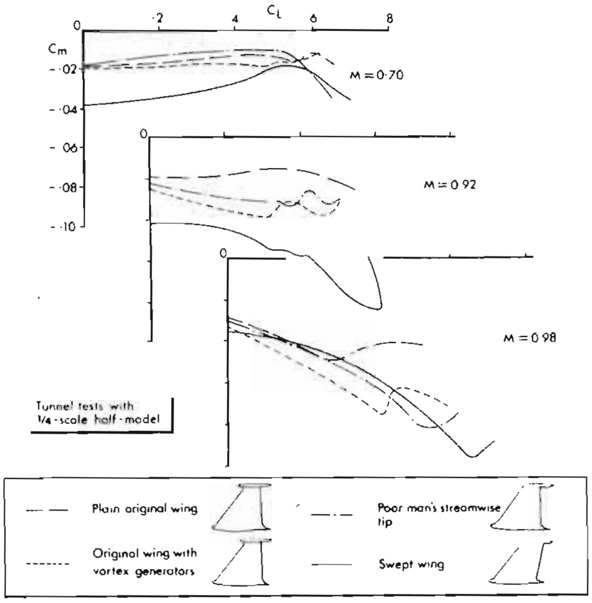

Fig.3.3 P.1127. Pitching characteristics – tail off.

A further factor – already foreshadowed when flying with the flat tailplane – also became apparent at this time. This was a lack of V/STOL pitch trim power in the aircraft nose-down sense in mid-transition at about 120 knots (210 km/hr.). The problem was aggravated by the increased-thrust engines then coming into use, to the extent that transitions were only marginally possible within the available tailplane travel.

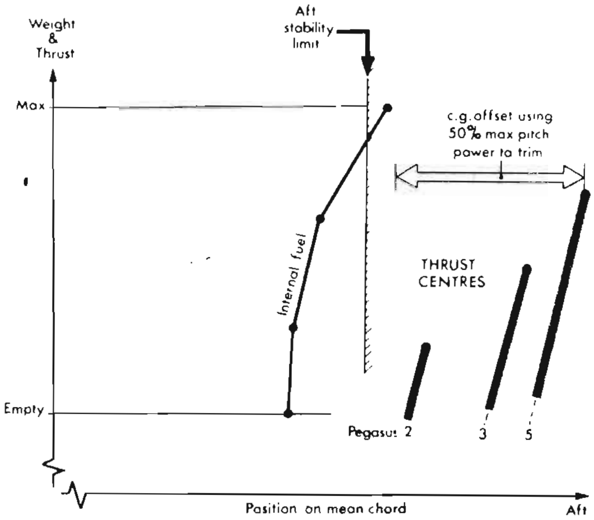

Fig.3.4 P.1127 c.g. diagram.

The extent of the level flight stability problem existing at this date (1962) is shown in the trim curves of Fig.3.6. The grossly destabilising effects of high engine powers, particularly at the lower altitudes, should be noted. The destabilising effects of power continued to bedevil the configuration through to the present Harrier, where it is still a very noticeable handling feature, although in no way limiting as it was in the early aircraft.

3.2 The Kestrel

At this point the U.K., in conjunction with the U.S.A. and the Federal Republic of Germany, agreed to develop a Service version of the P.1127 for V/STOL trials by a Tripartite Evaluation Squadron. This aircraft was named Kestrel (after the British bird of prey which hovers) and was to be fitted with the Pegasus 5 engine of 15,400 lb. (70 kN) V/STOL thrust.

It was decided that this aircraft should be fitted with the new swept wing then under development. Also, since the increased engine thrust was associated with a further aft Thrust Centre (see Fig.3.4), it was essential that the pitch trim bleed requirements should be properly constrained.

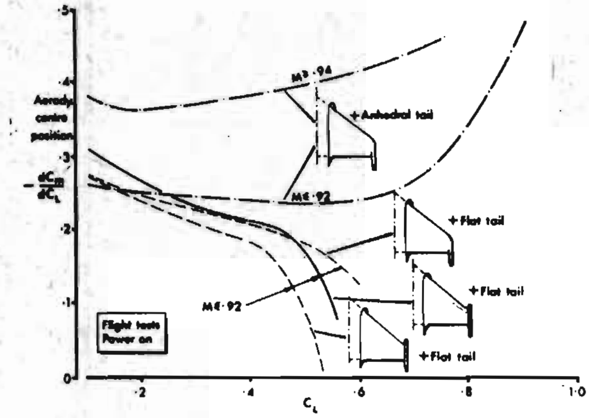

Fig.3.5 P.1127. Pitch stability improvement with anhedral tailplane.

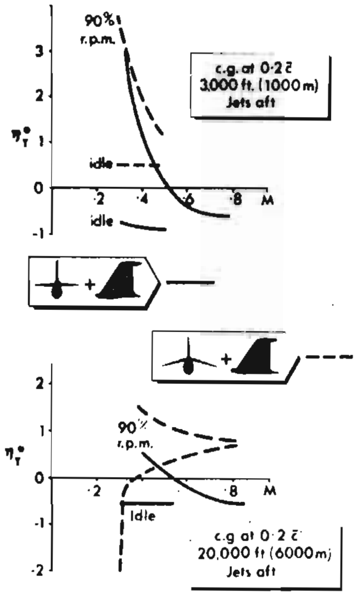

Fig.3.6 P.1127. Longitudinal trim with flat and anhedral tailplanes.

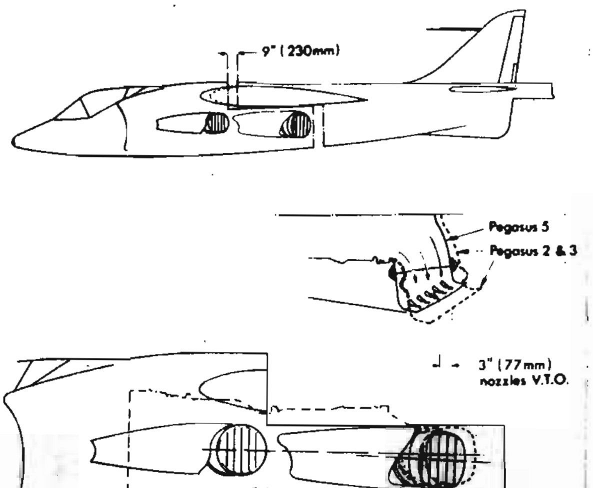

Fig.3.7 Kestrel. Changes to improve longitudinal stability.

Two engineering changes were made in the Kestrel to correct this c.g. – Thrust Centre mismatch. The major change was the insertion of a 9" (230 mm) stepped slice in the fuselage (Fig.3.7). This pulled the aircraft c.g. some 5% further forward on the mean chord to give better low-incidence static margins: it also moved the engine Thrust Centre some 5% c̄ forward relative to the aircraft c.g., reducing the otherwise excessive hover trim bleed air demands.

The second change was to the jet pipe of the Pegasus where, by persuading the turbine discharge to turn outwards round a sharper corner than had been used hitherto, the rear nozzles were moved some 3" (76 mm) further forward with a gain of about half this distance in the position of the Thrust Centre relative to the engine front face (see Fig.3.7). This proved – against all predictions – a triumph of brute practicality over aerodynamic dogma. Not only did the annular discharge from the turbine into the new jet pipe successfully negotiate the sharp forward corner into the nozzle, it did so for less overall pressure loss than in the earlier (supposedly more refined) jet pipe duct.

The remaining item of redesign which requires mention here was the incorporation of a revised anhedral tailplane with more angular travel. The anhedral point was moved in to the side of the fuselage, the tips being in the same vertical position as the original anhedral tail (Fig.3.8). The maximum reaction capability of the rear (nose-down) pitch valve was also substantially increased and its gearing changed in relation to tailplane angle in order better to cope with the trim deficiency in mid-transition.

The Kestrel prototype with these major changes flew in February 1964. Despite the enormous effort to provide an adequate c.g. margin for level flight it was quickly apparent that, at low incidences and moderate Mach numbers, the Kestrel was only marginally statically stable, particularly at high power settings. The Thrust Centre – c.g. relation, however, appeared to have been correctly arranged, in that bleed air demands in hover were acceptable, and nose-down trim power in mid-transition was satisfactory.

At high M, pitch stability became strongly positive, particularly at high incidence. The aircraft showed no sign of pitch-up.

The new swept wing had been designed with the peaky-type pressure distribution which had been pioneered in the early 1960's by H. Pearcey and others at the National Physical Laboratory in the U.K. H.S.A. adapted this type of distribution for the first time to blunt-nosed thin aerofoils in order to retain good low-speed handling qualities. Flow breakdown at incidence at high M on this wing in flight mainfested itself by sharp wing rocking through as much as ± 30° roll amplitude at a frequency of about 1 Hz. Vortex generators failed to alleviate this problem which remains with the Kestrel to this day.

Carriage of the first external stores on aircraft of this family (100 gallon – 450 lit. – drop tanks) produced further deterioration of the level flight pitch stability.

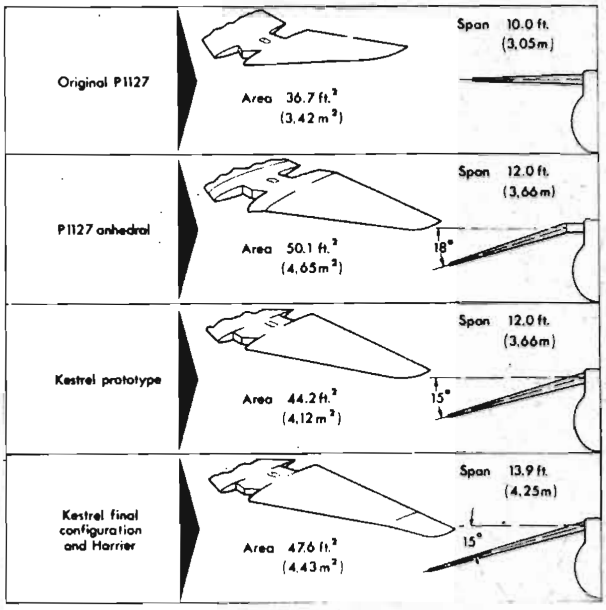

Fig.3.8 Tailplane variations.

In a late attempt to correct the lack of low-incidence pitch stability – particularly with external tanks carried – before the Kestrel went into Service, an extension was added to the tailplane tip increasing the span by some 12" (300 mm) each side (Fig. 3.8). This addition to the tailplane area was in the best position to pick up the favourable sidewash and downwash flows outboard of the jet exhausts. It enlarged the tailplane span to 60% of the wingspan, and, although successful in its primary aim of generating more positive pitch stability margins, it was the cause of a further major problem – this time structural.

When running at high power on the ground with jets aft, the large-span anhedral tailplane exhibited "flapping"-type motions (chiefly anti-symmetric in mode) of large amplitude, excited by the shear at the edges of the jet exhaust. This gave rise to concern for structural safety and dampers were introduced for all high power, jets aft, ground engine running for checkout purposes. The reader should note here that, for high-power engine test running, all aircraft of this vectored thrust family had always required to be tethered to ground strong points, as the full throttle thrust/weight ratio was beyond the capability of the tyre-to-ground friction force to hold with all wheels locked, or even chocked. If the aircraft were not restrained, the cockpit occupant (pilot or engineer) had to be prepared for flight if he applied high power, jets aft, whether the brakes were on or off.

Thus, since restraining gear strong points were in any case required on the ground (Fig.3.9) it was not too onerous to call up further attachment points for the tailplane friction dampers, Fig.3.10.

It was established that the fatigue damage was greatest due to motions in the anti-symmetric vertical oscillation mode of the tailplane at 13 Hz. The fin was also excited laterally at this frequency. Although running time in this condition at high power was only a small fraction of total engine time on the ground, the stresses induced in the tailplane centre-section were such that it was worthwhile – even for the limited life to which the Kestrel was designed (1,000 hours) – to damp this motion. The dampers reduced the root bending moment by 75% and this was shown to give a life extension satisfactory for the Kestrel.

Nine aircraft were built and delivered to the Tripartite Evaluation Squadron. The Kestrel was the first jet V/STOL aircraft to be granted a release for flying by Service Pilots. A total of about 600 hours flying was conducted during the V/STOL field evaluation trials in U.K. by the Squadron during 1965. Subsequently the Kestrels were used for research in the U.K. and (under the designation XV–6A) in the U.S.A. for further trials by the three U.S. Services and for research by N.A.S.A.

"Crown Copyright"

Fig.3.9 Engine ground running restraining gear.

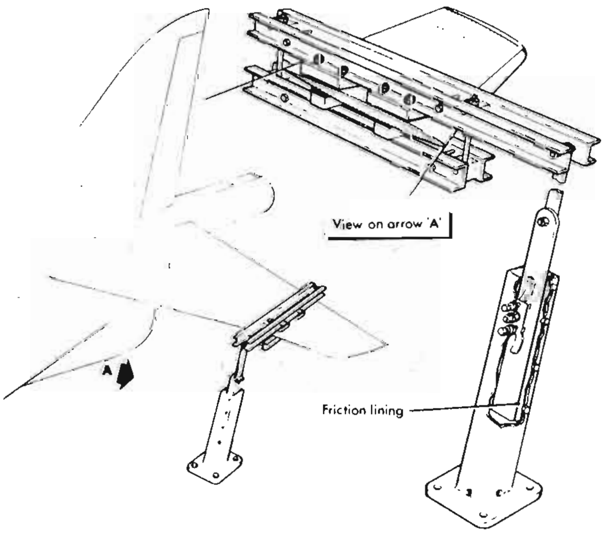

Fig.3.10 Kestrel. Tailplane vibration dampers.

3.3 The Harrier*

The plateau of development represented by the Kestrel was considered to be a satisfactory level of attainment for a limited-purpose Service V/STOL Evaluation aircraft. Indeed, in 1965, it was unapproached by any other aircraft in the World. Nevertheless, when the go-ahead for the development of the Harrier was given in 1965, the designers appreciated better than anyone that much higher standards yet would need to be realised for an operational jet V/STOL aircraft to be built in large numbers.

The main areas of improvement in longitudinal stability and control still concerned the time-honoured deficiencies which had so strongly resisted all our efforts completely to remove during the preceding 5 years. In the Harrier, plans to eliminate these shortcomings completely were further threatened by the consequential effects of a 25% increase in engine thrust. Attention was therefore directed to:–

(i) Maintaining the correct relation between c.g. and Thrust Centre in V/STOL.

(ii) Providing adequate pitch stability, static and manoeuvring, over the complete flight envelope – this time menaced by the requirement to carry extensive arrays of external stores.

(iii) Ensuring good handling qualities over a speed range of –50 knots to +635 knots/Mach 1.25 with the widest possible c.g. range.

(iv) Removing all concern for the structural integrity and life of the tailplane.

The terms of reference under which the design of the Harrier proceeded included the usual homily on minimising the extent of the changes from the Kestrel. This was acceptable as a Design Aim, but the practical appreciation that the fewer the configuration changes made, the less likely would be the risk of new unknown problems appearing, was a far greater stimulus to the Design Team.

With the larger thrust of the Pegasus 6 engine, the Thrust Centre had (inevitably) moved further aft compared with the Pegasus 5 in the Kestrel. Since the changes involved in producing the Kestrel had sufficiently compensated the earlier Thrust Centre – c.g. mismatch, it was not necessary in the Harrier to relocate the engine in the fuselage. The c.g. could not be allowed to move back on the mean chord, however, because of concern over attaining adequate stability in conventional flight, and the main aerodynamic problem was therefore that of ensuring adequate c.g. margins with adverse store loads by providing a more rearward aerodynamic centre.

Maintaining the geometry of the interspar structural box, the Kestrel wing leading edge was redesigned and additional span and area added outboard of the wing tip undercarriage legs (Fig.3.11). The leading edge redesign retained the use of large nose radius aerofoils with a "peaky" pressure

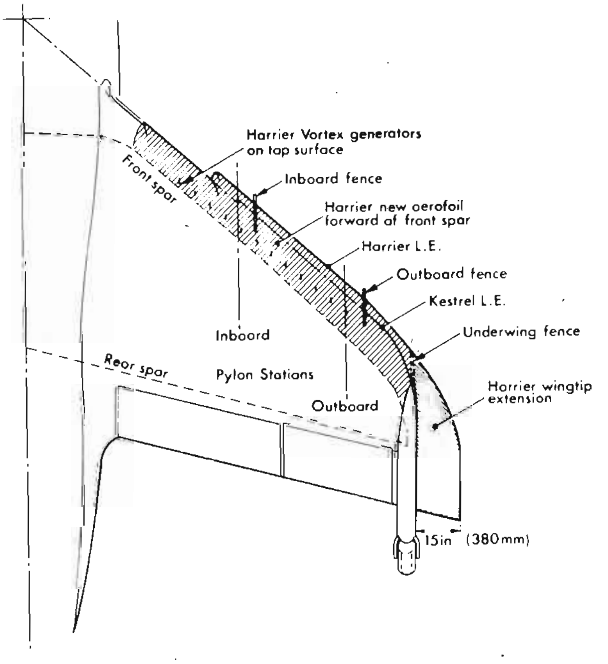

Fig.3.11 Planform of Harrier wing showing Kestrel basis.

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* *Named after a species of bird of prey widespread through the Northern Hemisphere (U.S.A.: Marsh Hawk). Notable for its agility and grace in low level flight from which it seeks and strikes its prey with great violence.*

distribution, but great care was taken to grade the spanwise loadings to ensure a progressive lateral flow breakdown under transonic flow conditions on the upper surface (Ref.2, Dec. 1969).

The tailplane design was unchanged aerodynamically from the Kestrel, except that the trim range occupied a larger fraction of total tailplane movement. A light bobweight was added to the pitch control system.

After some ad hoc development in wind tunnel and flight, this new wing with its array of fences, L.E. sawteeth and v.g's proved to have completely satisfactory handling qualities allied to excellent lifting capabilities.

Pitching behaviour over the complete Mach number range, through incidences up to 20 deg., is unexceptionable, with adequate static and dynamic stability even with the worst destabilising arrays of external stores.

This standard of behaviour would be noteworthy even in a conventional aircraft, and has led an Official U.K. Testing Authority to comment that – "the almost imperceptible effect on the handling characteristics throughout the flight envelope of the numerous combinations of differing underwing stores makes (the Harrier) a remarkable aircraft".

Evidence can still be found of the handling problems which dominated what might now be termed the Late Bronze Age of the vectored thrust V/STOL fighter. For example, Fig.3.12 shows the trim curves for the Harrier carrying a moderately severe array of external stores with the c.g. near the mid-point of the very wide c.g. range. The destabilising effects of 20,000 to 30,000 jet horsepower passing closely beneath the tailplane are still in evidence, although they are of little practical import.

The remaining outstanding problem in the pitching plane, arising from this V/STOL configuration, was that of tailplane vibration.

It was clear that, for a Service aircraft to be built in large numbers for world-wide use, a requirement to fit tailplane dampers during engine ground testing would impose an unacceptable penalty on the operator. The first steps, therefore, in finding a solution, were to quantify our knowledge of the problem more securely than had been possible with the Kestrel.

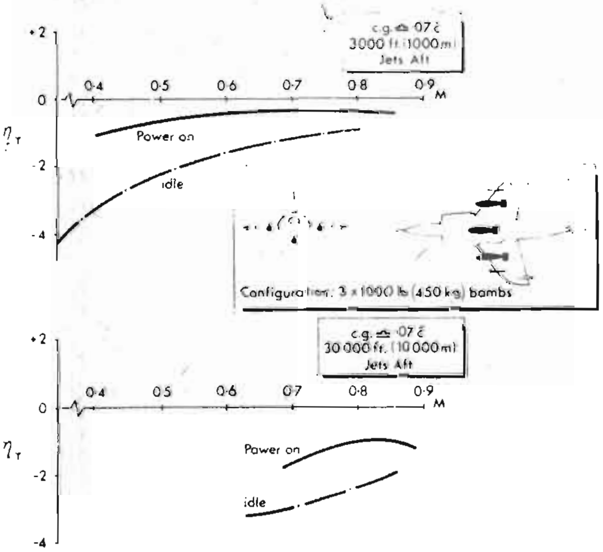

Fig.3.12 Harrier. Flight trim curves.

Fig.3.13 shows the measurements made, on an early Harrier development aircraft, of the maximum values of alternating root bending moment in the tailplane. The reduced excitation arising from jet deflection and the effects of forward speed should be noted.

The value of the max. alternating moment at max. engine speed under static conditions approaches 25% of the moment imposed by the design flight tail load. The rather drastic effects of such large-amplitude fluctuating stresses on the fatigue life of an aluminium alloy structure can be appreciated.

Accordingly, steps were taken to strengthen the Harrier tailplane for the production aircraft. The development aircraft had been fitted with tailplanes considerably improved over the standards provided in the Kestrel, but which were clearly inadequate for 3,000 hours of Service flying in the light of the measurements made on examples of these strengthened structures.

Fortunately the problems were concentrated near the tailplane root. While efficient load diffusion was quite essential, the stress levels due to engine excitation on ground test fell away rapidly beyond 20% semi-span outboard. The frequency of the alternating stress was about 13 Hz so that an overall utilisation of 30 sec. of high power application under near-static conditions per hour of flying time (including ground testing) would impose over one million damage cycles during the expected life of the aircraft from this cause alone.

It was therefore quite clear that a material such as steel – having an infinite life below a certain level of stress – would require to be used, and the design would need to ensure that this infinite-life stress would not be exceeded anywhere in the root structure under these rapid damage-accumulating ground running conditions at high power.

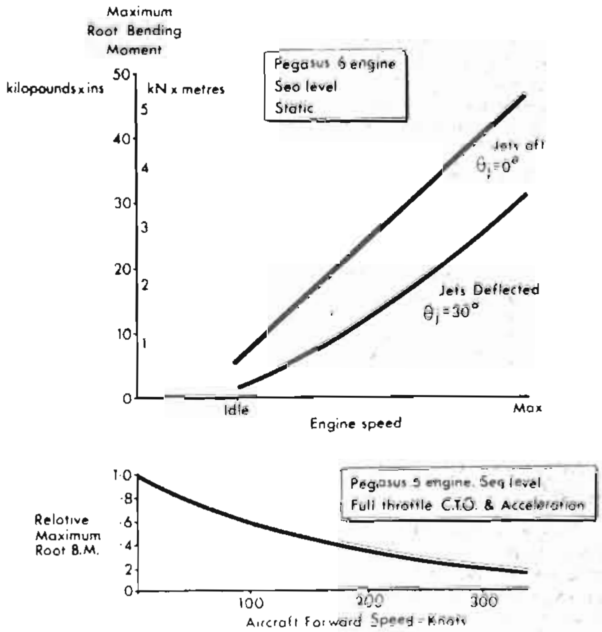

Fig.3.13 Harrier. Tailplane vibration loading at root.

This final production version of the Harrier tailplane is shown in Fig.3.14. Steel channels are used to box in the fin spar cutout. The steel booms capping these channels are continued outboard of the root rib. The top and bottom skins of the carry-through box are etched from .19" (4.8 mm) aluminium alloy plate. These covers are double-curvature formed at the root rib and extend spanwise a considerable distance outboard underneath the basic aluminium alloy tailplane outer skins. These outer skins have a complex pattern of chemical etching from their basic 0.19" (4.8 mm) thickness to give the lowest stresses along rivet lines without the weight penalty of excessively thick basic panels.

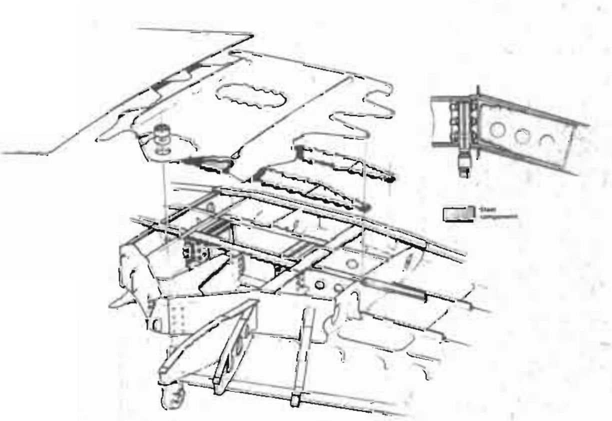

Fig.3.14 Harrier. Tailplane root structure.

Redesign of the Kestrel tailplane to produce the early Harrier unit of the same external geometry increased the weight by 24 lb. (11 kg) to a total of 203 lb. (92 kg). This had resulted in a less-than-adequate life improvement in the light of the data acquired by full-scale test. The second stage of redesign, resulting in the construction shown in Fig.3.14, increased the weight only by a further 8 lb. (26 kg) but added sufficient strength to enable the unit successfully to complete fatigue testing to the equivalent of 15,000 flight hours. The weight increase would have been considerably greater if weight economy in the less critical parts of the structure had not been prosecuted with the utmost vigour.

4. GROUND HANDLING

As has been noted in Section 2, the landing gear configuration arises directly from the layout of the aircraft – the choice being influenced chiefly by the V/STOL end of the envelope but with high speed flight having important secondary influences; e.g. the aerodynamic interference arising from housing the main legs and low pressure tyres of a tricycle layout at mid-span on a low aspect ratio wing of small size.

Thus, from the start of drawing issue on the first P.1127 prototype, a bicycle landing gear was chosen as the least unacceptable of the known evils and because if gave promise of contributing the least weight. The fact that the *unknown* evils gave rise to some of the toughest nuts to crack in perfecting the operational V/STOL vectored thrust fighter provides a rationale for this section of the paper.

Whilst the landing gear *per se* clearly plays no part in transonic flight, the transonic capability of the vectored thrust fighter influences its configuration and this configuration dictates the undercarriage layout.

4.1 Early Problems – the P.1127

In 1959/60 no previous military aircraft had been designed in the U.K. with a bicycle landing gear. The P.1127 designers therefore sought any information from all sources. This was painfully sparse, so the original undercarriage design was created partly by applying what could be construed as applicable from the U.K. Military Design Manual (Av.P.970), and partly by constructing new criteria from "self-evident" engineering considerations.

Basic to this original design philosophy was the intention that the lateral support struts – the outriggers – should not be lowered until the main gear had absorbed the initial landing impact. This arose chiefly from apprehension about the likely weight penalties if the outriggers were locked down for landing and had to be stressed, therefore, as impact energy-absorbing devices.

These original outriggers were provided in essence only to prop up the aircraft laterally in the ground-supported cases – static, taxying, take-off and the low-speed phase of horizontal landing. As a consequence of this, the outrigger emerged as a slender and somewhat fragile design of commendably low weight. The geometry of this arrangement allowed rather light contact between the outrigger wheels and the ground under static conditions only when the aircraft was loaded.

In the event, the original design concept of the outriggers being signalled DOWN by the main oleo closure on landing was never employed. All four legs were used on all occasions and it was here, on the very first hovers, that the first major difficulty with the bicycle gear was experienced.

With the aircraft weight partially supported by the engine, the main and nose legs extended and the outriggers came off the ground leaving the aircraft to be balanced laterally by what was, in these early trials, an inadequate roll control system. Sprung extensions were quickly fitted to the outrigger legs and hover flight was thus accomplished (Fig.4.1).

Fig.4.1 P.1127. Outrigger extensions fitted for first hovers.

The trailing skid extensions could not be carried for conventional flight, however, and the same problems of lack of lateral support with the aircraft only partially ground-borne were evident in the first conventional take-offs and landings. At this stage of the design the outrigger wheels were fully castoring (again to minimise lateral loads and the concomitant weight penalty) and a shimmy problem promptly appeared. This was suppressed by fitting shear pins to lock out the castor freedom.

But the worst aspect of the lack of roll constraint from the outriggers in conventional landing was the heel (angle of bank) that the aircraft developed, particularly in cross-wind conditions. This produced a sideways component of the considerable wing lift – the wing being set at about 8° incidence to the ground, as the aircraft could not be rotated for unstick in S.T.O. This lateral component of lift was resisted weakly by the stabilising sideforce obtained from the fixed mainwheels behind the c.g. If the pilot did not make fast and furious use of the sideforces generated by the nosewheel and the fin and rudder, the situation quickly got out of hand and the aircraft would run off the runway. The imprecision of the then-current nosewheel steering system contributed significantly to this potentially hazardous situation.

Later P.1127 aircraft had a nosewheel steering system with better precision and two ranges of authority, ±35° for low speed taxying and ±5° for high speed steering. This eased the problems of the conventional landing run slightly – provided the pilot remembered to select the correct steering authority beforehand – but the manoeuvre was still highly precarious. A further factor added to this insecurity. To avoid weight penalty on the main leg arising from pivot turns, the twin main wheels rotated independently on stub axles. With the considerable heel that occurred, only one main wheel had substantial ground contact, and the anti-skid system was too crude to prevent the other wheel locking – with consequent tyre burst. This then left the aircraft with only half its design brake capacity.

The availability of reverse thrust (the engine nozzles could be rotated to about 10 deg. forward of the vertical) proved to be a dubious asset. Use of nozzle braking at the high engine thrusts reduced still further the ground load carried by the fuselage-mounted oleos, which thus extended. This increased the heel angle, the lateral component of wing lift was further increased and the aircraft showed even stronger proclivity to depart from the runway in crosswinds. To quote Ref.3 "About this time the number of 'see me about the undercarriage' notes sent by the pilots to the designers was, understandably, showing a definite upward trend".

4.2 Basic Design Changes

In the economy-size redesign of the P.1127 which produced the Kestrel, none of the major adverse features of the original landing gear were eliminated, even allowing that the outrigger design loads were increased, that the nosewheel steering was made a little more powerful and that the brake energy capacity was augmented.

However, design work on the P.1154 supersonic V/STOL project at this same period was not being conducted under the same FIBDATD rules*. This work resulted in a number of improvements including:–

(i) Better outrigger design to ensure that the aircraft was properly supported laterally in all ground manoeuvres. A target was set to provide the aircraft (during all taxying cases at high or low weights) with the same order of roll stiffness as a quality sports car – about 1 deg. of bank per unit lateral g.

(ii) The main leg twin wheels were mounted on a live axle – to avoid carrying extra brake capacity against one tyre bursting, and to ensure the best anti-shimmy and judder properties.

(iii) New rationalised stressing cases for landing with the outriggers locked down were devised, including proof vertical velocity touchdowns with forward, rearward, and sideways velocity, with favourable and adverse bank angles and roll rates.

(iv) Radically improved nosewheel steering. Since this system is virtually the only means of steering on the ground, it needed to be engineered to the precision and reliability standards of a powered flying control.

When the Harrier project was initiated in 1965, immediately after cancellation of the P.1154, there were many fewer restrictions on the extent of the redesign by which the Kestrel was transformed into the Harrier, than had been imposed on the Kestrel-out-of-P.1127 progression.

Forthwith, the benefits of the P.1154 work were applied to the new aircraft but with a number of restrictions on freedom of choice still applying, chiefly those of retaining the overall aircraft shape and configuration.

4.3 The Early Harrier

The Harrier Specification laid down requirements for greatly increased energy-absorbing capacity in the landing gear. This was provided by increasing the strokes of the oleos whilst maintaining the peak reaction loads substantially the same as in the earlier aircraft, otherwise a more extensive structural redesign would have been necessary. Because, at full compression, the main and nosewheels were close against the underfuselage, the extra oleo travel was provided at the full extension end of the stroke.

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* *Fix It – But Don't Alter The Drawings*

The geometry was designed to permit the outriggers to give the appropriate roll support at all weights from empty aircraft to maximum loaded. But when the aircraft was just off the ground – all legs fully extended – there was more roll freedom from main wheels to outrigger wheels than with the Kestrel (Fig.4.2) becuase of the longer oleo travels.

At the time of the Harrier first flight in 1966 there seemed no solution to this dilemma within the constraints imposed by the various requirements of gear performance, stowage volume on retraction, etc.

The first 100 hours or so of Harrier flying completely vindicated all these landing gear improvements. The revised nosewheel steering system (Ref.1) proved un-faultable. The roll stiffness during taxying – even over rough ground – provided the security associated with a conventional wide-track tricycle gear. There were no problems arising from outrigger fragility, and the increased energy capacity of the oleos allowed optimum non-flared short landings (i.e. partially jet-borne) to be made with a clear conscience.

However, with the aircraft only partly ground-supported in VTO or STO, or in conventional landing, the bogey of heel remained. With jets down in VTO and STO, as the thrust supported progressively more of the weight before lift-off, the main oleo extended and the wings had to be deliberately levelled using the roll controls, to ensure a clean unstick. At the high-speed end of a conventional landing run, the small fraction of the weight unsupported by aerodynamics was insufficient to overcome the full extension pre-load in the main oleo. The aircraft therefore heeled onto an outrigger and the pilot had to practice his anti-ground-loop skills very vigorously.

Fig.4.3 shows the relative spring curves of the three oleos supporting the rear of the aircraft. It can be seen that a load of 4,000 lb. (18 kN) is needed on the main leg before an outrigger can even contact the ground at zero bank, much less provide lateral restraint. With the wing operating at an effective angle of attack (flaps down) of some 10 deg., and with weight transfer onto the nosewheel due to the aircraft's deceleration, main leg reactions of this magnitude were not attained until the airspeed had fallen to a value approaching half the touchdown speed.

The problem was plainly due to the greater extended length of the main oleo (Fig.4.2) and its relatively high initial closure load (Fig.4.3). It could be overcome by reducing the oleo travel (not acceptable since this would have reduced the energy capability) or by reducing the pre-load (again reducing energy capacity since the oleo compression ratio could not be correspondingly increased) or by extending the outrigger legs. This latter was not possible as their oleos could not accommodate increased extension without a correspondingly extended fully-closed length. This would have increased unacceptably the loads on the leg and local wing structure in the critical stressing cases.

Many potential solutions were studied: a two-stage compression main leg oleo; double telescopic outriggers with the second extension initiated by wheel spin-up signals; hydraulic shortening of the main oleo – also initiated by wheel spin-up signals. All suffered from those classic engineering demerits: – expense and complication. All required considerable time to effect.

The solution finally chosen arose out of the studies of the hydraulically-shortening main leg. This scheme was intended to pull in the main oleo by application of hydraulic pressure to the rod annulus side of the main piston, signalled by wheel spin-up on ground contact.

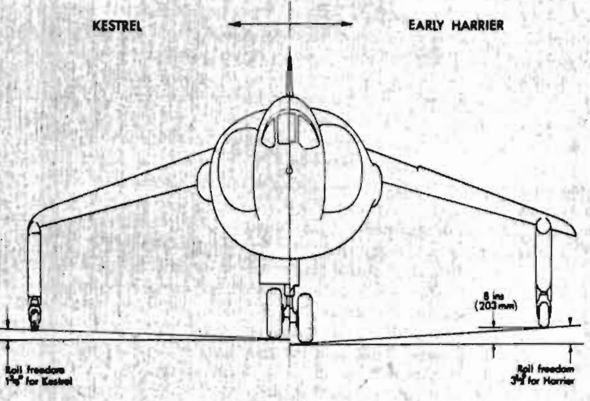

Fig.4.2 Harrier and Kestrel. Roll freedom with oleos at full extension.

The *self-shortening* main oleo (as it has been termed) offers precisely this feature of contracting the oleo under the very light loads applied after ground contact, but without the complexity of hydraulics and wheel speed signalling.

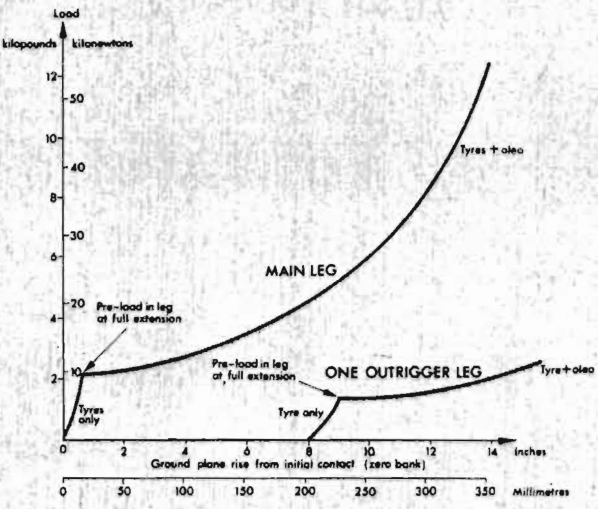

Fig.4.3 Harrier landing gear. Static spring curves (original design).

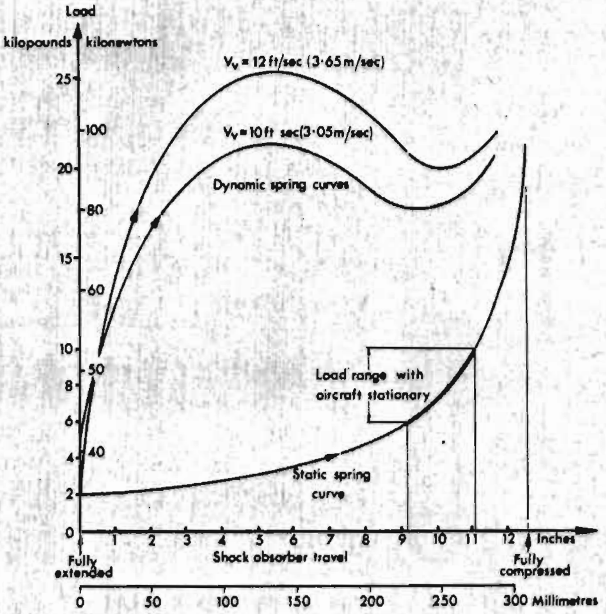

Fig.4.4 Harrier. Main oleo spring curves (original design).

Its function is to allow a rapid sink of the central element of the three struts behind the aircraft c.g. in all landings, so as to permit the outriggers to carry as large a fraction of the available (i.e. non-aerodynamically or jet-supported) weight as possible. This ensures that the aircraft remains level laterally.

4.4 The Current Harrier

As with many engineering achievements when viewed with hindsight, the principles are absurdly simple. All that was needed was a spacer tube inside the main oleo sliding member, and a container external to the leg to carry excess oil at full compression.

Fig.4.5 shows the operating principle of the telescopic oleo-pneumatic shock absorber. As the sliding member moves inwards the separator piston is forced downwards, compressing the gas (usually nitrogen) stored in the sliding member. On recoil – with external load removed – the energy stored in the fully compressed gas extends the leg, the separator piston travelling back up the sliding member as it extends.

If a stop tube is now placed towards the top of the sliding member (Fig.4.6) the separator piston, on contacting this stop, can exert no pressure

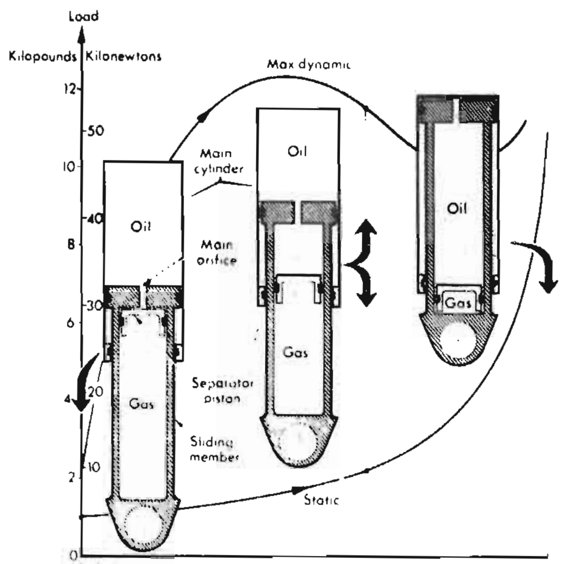

Fig.4.5 Principles of oleo-pneumatic strut.

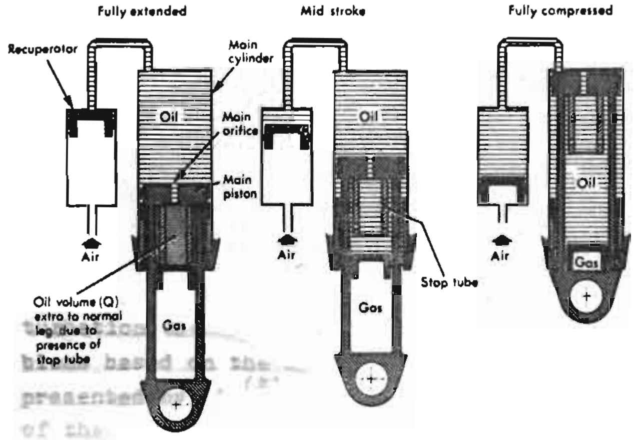

Fig.4.6 Principles of self-shortening oleo.

on the oil above. The leg thus has no static "spring" once this condition is achieved, and the remaining outward motion of the leg is resisted only by the friction of the various seals and bearings.

Fig.4.7 shows the spring curve resulting from this modification. Under static or quasi-static conditions (i.e. very low closure rates) the oleo will close (i.e. the leg will "sink") from the fully extended postion with the application of a force of a hundred or two pounds (0.5 to 1 kN). The position of the step in the main oleo spring curve (7" – 178 mm – in from full extension) was selected so that the outriggers could just touch the ground before the main leg commenced to offer appreciable resistance to further inward motion.

The volume Q shown in Fig.4.6, corresponding to the length of the stop tube introduced, is filled with oil instead of with gas at the outward extremes of oleo travel. At full compression this oil must be spilled or the separator piston will "bottom" prematurely, the leg will suffer a hydraulic lock, and will probably burst.

A separate container or recuperator is therefore provided, outside the oleo, which accommodates this extra quantity of oil. To prevent cavitation on recoil, the piston in this recuperator is lightly pressurised with air.

Now, on dynamic closure, oil in the main cylinder can flow two ways: upwards into the recuperator and downwards into the sliding member. The main orifice in the main piston must have characteristics which are matched with the new orifice provided by the oil path between the main cylinder and the recuperator. There must be no possibility of the main piston arriving at the top of the main cylinder (full compression) whatever the rate of closure, with any portion of the extra oil volume Q still remaining within the leg.

This second orifice between cylinder and recuperator must, however, offer very low flow resistance at very low rates of closure or the leg will be prevented from "sinking".

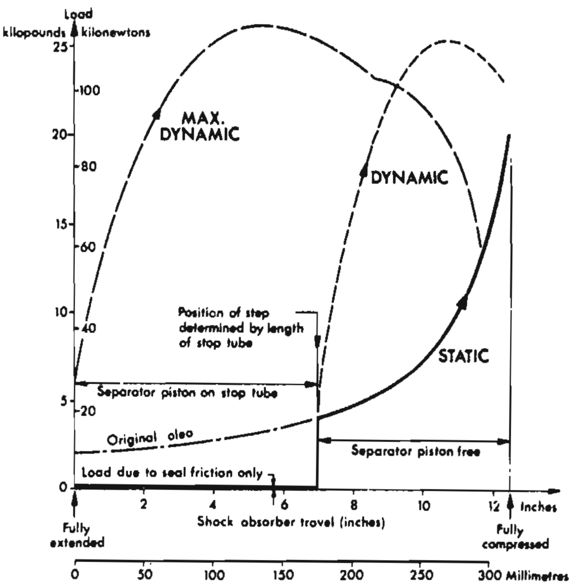

Fig.4.7 Harrier. Main oleo spring curves (self-shortening leg).

The balancing of these parallel oil flow paths under these contradictory operation conditions was very satisfactorily achieved by the undercarriage contractor – Dowty Rotol Limited.

Specification design conditions the same as for the original leg are met by the modified oleo: 12 fps (3.7 m/sec.) proof vertical velocity with the aircraft fully airborne or jet-borne (i.e. no aircraft vertical acceleration just prior to oleo closure) and 10 fps (3.05 m/sec.) with one third of the aircraft weight unsupported during oleo closure (i.e. accelerating at 1/3 g).

In the earlier stages of design it was feared that, in the absence of an internal extending force derived from the gas pressure, the leg would not re-extend below the step in the spring curve after inward movement. In practice, the general environment (weight of the unsprung mass of wheels plus brakes, vibration, aircraft normal acceleration, etc.) proved sufficient for the leg to overcome its internal frictions and "fall" out to full extension within a second or so of the sprung recoil achieving the extension corresponding to the step in the spring curve.

Since the leg could not be guaranteed to return to full extension before each touchdown in landings consisting of a series of bounces, the design was also required to provide an energy capability of 9 fps (2.75 m/sec.) fully airborne, when closure commenced from the step in the spring curve, Fig.4.7. The modified leg satisfactorily complied with this additional requirement.

As the geometry will not permit the wheels to enter the stowage bay correctly on gear retraction unless the oleo is fully extended, hydraulic extension of the modified leg to full travel was originally considered as a prerequisite of retraction. However, this problem was solved simply and satisfactorily by fitting a pair of ramps (one opposite each wheel) at the forward end of the wheel bay (Fig.4.8). Their shape ensures that the leg is fully extended when locked up, and hence is always fully extended for the first landing contact when the gear is subsequently lowered.

The introduction of this single straightforward change to the main leg of the bicycle landing gear of the Harrier has completely transformed its ground handling qualities during V/STOL and in conventional take-off and landing. The cost of the modification was under 18 lb. (8 kg.) of weight at less than a thousand dollars per aircraft. Rarely can the designers gain so much for so little in contemporary aircraft engineering.

In VTO the aircraft rides laterally level until thrust exceeds weight, when it unsticks cleanly without abnormal use of roll control, even in crosswinds. Ships' decks rolling at up to 5 or 6 deg. cause the pilot no problems.

In the manoeuvre previously known as the "hairy horizontal" (i.e. conventional, fully wingborne) landing, the aircraft settles down squarely immediately on first ground contact and runs straight and true with no assistance from the pilot. Crosswinds exceeding 23 knots (43 km/hr) make no difference to the handling, and there appears no need to kick off drift

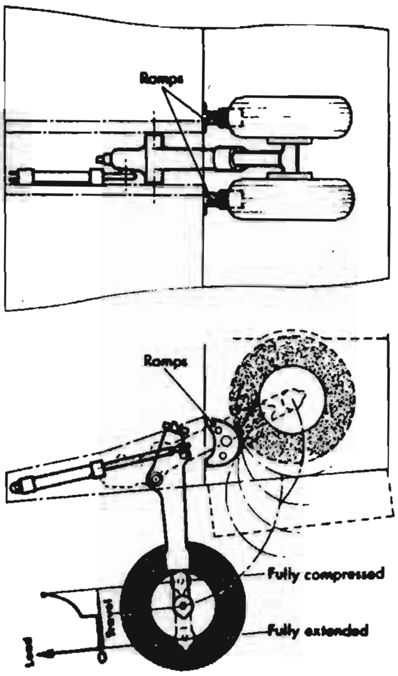

Fig.4.8 Harrier. Oleo extension ramps in main gear bay.

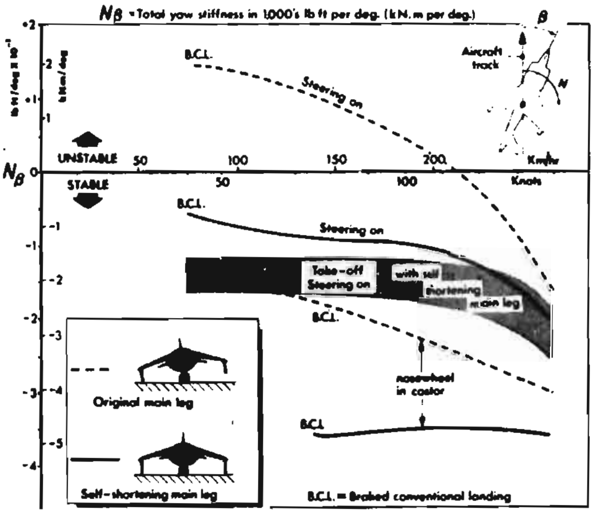

Fig.4.9 Harrier. Small-angle directional stability on wet or dry runways.

just before touchdown. The aircraft straightens up immediately on ground contact and tracks true in azimuth down the touchdown velocity vector.

The reasons for this greatly improved ground vehicle stability are worth touching on. In the Kestrel design, nosewheel steering control was not available until a weight-on-wheels switch on the main oleo was closed after touchdown. Until this weight switch was made, the Kestrel nosewheel was locked to centre. With the switch made, steer was available in either the ±5° or ±35° range on pilot selection.

With the aircraft heeled, the contribution of the lee-side main wheel (the only wheel aft of the c.g. carrying any substantial load) to directional stability was less than the destabilising effect of the directionally-restrained nosewheel. The aircraft was thus directionally unstable in this mode. If the nosewheel was allowed to castor, the sideways lift component due to heel would run the aircraft off the runway even though the aircraft was then directionally stable.

The early Harrier flying, as has been noted, suffered from this same directional misbehaviour, which verged on the unacceptable in crosswinds.

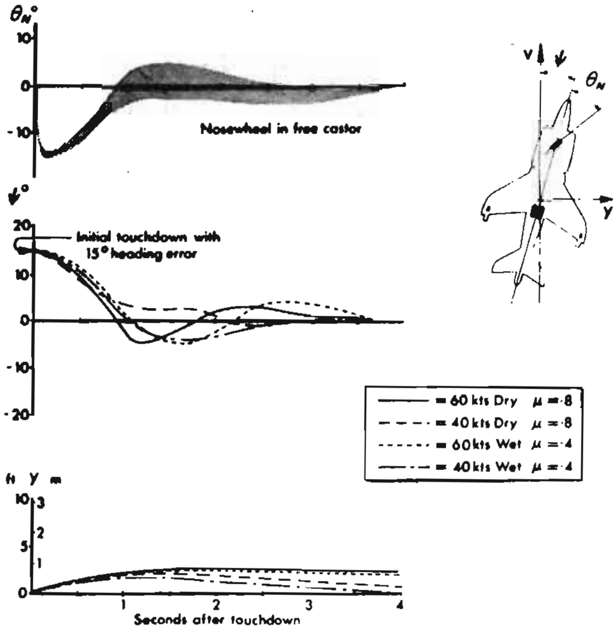

Fig.4.10 Harrier with self-shortening main leg. Directional self-correction after touchdown (nosewheel in castor).

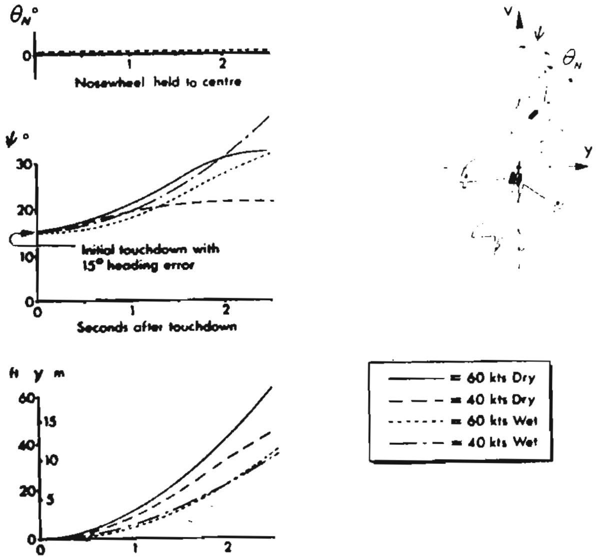

Fig.4.11 Harrier with self-shortening main leg. Initial divergence after touchdown (nosewheel held to centre).

At the same time as the self-shortening main leg was adopted, therefore, the nosewheel steering system was modified to give free castor with gear locked down, unless steer was selected by the pilot.

The directional stability characteristics are shown in Fig.4.9. The values computed for the total yaw stiffness N_β include the contributions from aerodynamics as well as the tyres. An optimum value for N_β for aircraft of Harrier weight and size appears to be about minus 1,000 lb. ft. per degree (1.3 kN.m/deg.). Experience has shown, however, that pilots can cope with values up to about plus 1,000 lb. ft. per degree – i.e. moderately unstable.

Fig.4.9 shows the effect of allowing the nosewheel to castor on the original Harrier configuration, which generated considerable heel. With steer engaged, the aircraft was directionally stable, at speeds in excess of 120 knots (220 km/hr), only by virtue of the aerodynamic contribution. It will be appreciated that this was not very helpful in crosswind conditions.

With the self-shortening main leg (i.e. no appreciable heel) Fig.4.9 shows the aircraft to have substantial directional stability in all the ground manoeuvres indicated, including those with the steering engaged.

One further aspect concerns the ability of the present configuration rapidly to align itself with the runway after touchdown with large heading errors. Fig.4.10 shows the computed time-history of landings with a 15^0 heading error at touchdown with the nosewheel in castor. The aircraft is tracking to within a few degrees of the velocity vector within a second after touchdown with no action on the part of the pilot.

Even with steering inadvertently engaged at touchdown and the nosewheel held to centre, the time to diverge is relatively long (Fig.4.11) and can be easily corrected by the pilot. At touchdown speeds higher than those in Fig.4.11 the divergence would not occur, nosewheel held to centre, because of the aerodynamic stiffness in yaw.

In summary, therefore, the conflicts between transonic requirements and V/STOL compatibility originally forced the adoption of an unusual undercarriage configuration. Because this bicycle configuration was new and less perfectly understood (owing to lack of experience) than a conventional tricycle gear, severe problems arose in ground handling with the earlier designs.

The engineering attention directed to the solution of these problems has now provided a landing gear design that is probably better suited to the special needs of V/STOL from unprepared sites than a conventional tricycle, and which almost certainly gives better handling than many tricycle gears in operation from runways.

5. CONCLUDING REMARKS

This Paper has dwelt at some length on the technical struggle which has been waged over the best part of a decade to provide unexceptionable performance in two areas of the design.

There are of course, many other aspects of an aircraft which need simultaneously to be developed to correspondingly satisfactory standards. Solutions to problems arising in one area often lead to deterioration (sometimes completely unanticipated) in other areas. The only measure of overall success is the standard of performance – using the word in its widest sense – of the complete aircraft or weapons system.

In Europe and North America there have been many attempts in the past 15 years to produce a satisfactory jet V/STOL fighter. The aircraft designer can resist almost anything but a challenge. Thus motivated, armed with the best that advanced technology can provide and spurred by the very appreciable military and commercial benefits that will arise from producing a completely satisfactory V/STOL aircraft, designers have tackled a wide range of vehicles.

Alone amongst a dozen or more examples of the small military jet V/STOL type, the vectored thrust fighter has survived and succeeded. It is appropriate here briefly to discuss – with hind-sight – the main reasons for this success. In doing this it is well to remember that what now appears as crystal-clear history was, in its time, the murky future.

Above all else it is the basic simplicity of the vectored thrust V/STOL concept that, from the beginning, carried the seeds of success. One engine providing both lift and thrust had that elementary logic which all concerned with design and development recognised and held to, almost as a Article of Faith. This feature tended to be regarded with rather less enthusiasm and conviction by those who were more distantly connected with the project. It was easy in the early days for those who opposed the concept to demonstrate by parametric studies that this form of V/STOL was both uneconomic and unsafe.

This basic simplicity, however, led to early success in demonstrating undramatic V/STOL flight. Correctly, all problems encountered in the early days which were extraneous to this essential first objective were by-passed. Without success in V/STOL, ultimate failure was unavoidable.

Much of the later development was therefore concerned with upgrading the conventional flight qualities of the V/STOL vehicle to provide a satisfactory transonic fighter capability. A major lesson of the P.1127/Kestrel/Harrier programmes is that V/STOL capability in itself is not particularly difficult to provide in a vehicle. Furthermore, there are few problems involved in designing an equivalent conventional vehicle giving satisfactory transonic capabilities. The real problems are met only when a single vehicle must combine V/STOL with transonic performance and be militarily competitive.

At every stage of the conventional-flight improvement programme, check-back to V/STOL performance was required, as the struggle even to maintain parity in – much more to improve – performance and handling in these modes was and remains unceasing.

The Harrier is a notable example of what a dedicated and determined Design and Development Team can provide, starting from a fundamentally correct basic concept. It has reconciled the conflicts between jet V/STOL and transonic flight to an extent so far unequalled in world aviation.

ACKNOWLEDGEMENTS

The author expresses his appreciation to those many colleagues who have contributed – directly or indirectly – to the compilation of this Paper, and to the Directors of Hawker Siddeley Aviation Limited with whose permission it has been prepared and published.

Views and opinions expressed in the Paper are entirely personal. The engineering features described have resulted from the efforts and application of the Design Team and Test Pilots. The credit for the high standards achieved by the Harrier V/STOL fighter is theirs.

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