Four Decades of Transonic Fighter Design

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A sizeable market potentially exists for aircraft in the light combat aircraft category. A review of progress in some aspects of the design of transonic fighters over four decades is presented by comparing the Hawker Hunter and British Aerospace Hawk 200. The genesis and development of each aircraft is briefly traced, whereupon the main areas of comparison, i.e., aerodynamics, propulsion, structure, performance, avionics, and cost are addressed, including reference to contemporary aircraft. It is not only clear that significant advances have been made but also that the future holds promise of even more.

Nomenclature

AOA	= angle of attack
BAe	= British Aerospace PLc
BPR	= bypass ratio
b	= wing span
c.g.	= center of gravity
CRT	= cathode ray tube
EFA	= European Fighter Aircraft
FLIR	= forward-looking infrared
FOD	= foreign object damage
HOTAS	= hands-on-throttle-and-stick
HUD/WAC	= heads up display/weapon aiming computer
INS	= inertial navigation system
ISA	= International Standard Atmosphere
LCC	= life cycle cost
psf	= pounds per square foot
RAT	= ram air turbine
RTD & E	= research, test, development, and evaluation
RWR	= radar warning receiver
rpg	= rounds per gun
S	= wing area
SLS	= sea level static
SWR	= specific warload range
TBO	= time before overhaul
TET	= turbine entry temperature
TSFC	= thrust specific fuel consumption
T/W	= thrust/weight ratio
W/b^2	= span loading
W/S	= wing loading

Introduction

TRANSONIC fighter design is arguably not at the leading edge of aeronautical research and development in these days of the advanced tactical fighter (ATF) and EFA. Nevertheless, aircraft manufacturers are in the business of making money by making airplanes, and a sizeable market (1500 plus) potentially exists for aircraft in the LCA category. Indeed, the future may see the world's air forces no longer able to maintain their existing force structures due to the fact that they will simply be unable to afford the necessary equipment. The many current examples of upgrading/retrofitting existing aircraft with more capable and reliable avionics and engines bear testimony to this. To examine the progress in transonic fighter design, this paper makes specific reference to two well-known aircraft: the Hawker Hunter and the smaller British Aerospace Hawk 200 (Fig. 1). Both were designed at the same Hawker Aircraft Ltd. (now British Aerospace Kingston) facility, which gives added validity to the comparison.

Hawker Hunter

The Hunter arose from the design studies carried out in 1947 et seq. to fulfill a United Kingdom requirement for a replacement for the then current Gloster Meteor, which had seen limited service during WWII. In essence, a single-seat interceptor was required for the destruction in daylight of high-speed high-altitude bombers. The desired aircraft could be regarded as a slightly improved North American F-86 (which had first flown in 1947) but with more emphasis placed on fast-climbing high-altitude interception rather than on long-range air superiority. Armament was to consist of two 30-mm cannons with 200 rpg, and the aircraft was to be equipped with a gyro-stabilized gunsight and nose-mounted scanner, VHF and IFF. Maximum speed was to be 550 kt at 45,000 ft but, since the swept wing was still relatively novel, the Royal Air Force (RAF) was prepared to consider a top speed of 500 kt, on the understanding that the aircraft could be rewinged. The operating altitude was to be reached in not more than 6 min from brakes release. Airbrakes were to operate within 4 s across the entire flight spectrum, without a large trim change. The structural limit load was specified as 4 g. Field length was limited to 3600 ft. Fuel tanks, though not necessarily self-sealing, had not to lose more than 50% of remaining fuel after one hit.

Hawker Aircraft regarded these requirements as falling short of producing the right type of aeroplane, and in 1947 a

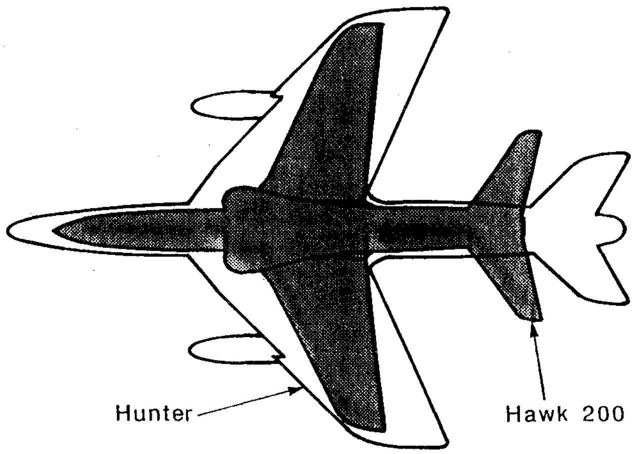

Fig. 1 Size comparison.

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Table 1 Revised U.K. government specifications

Single-seat day interceptor
Limit load: 7.5 g
Limit EAS: 620 kt
Max speed at 45,000 ft: 547 kt
Time to 45,000 ft: < 6 min
Service ceiling: 50,000 ft
Endurance: >1 h
Combat at 45,000 ft: 10 min
Field length: 3600 ft
Cockpit altitude: 25,000 ft at 50,000 ft

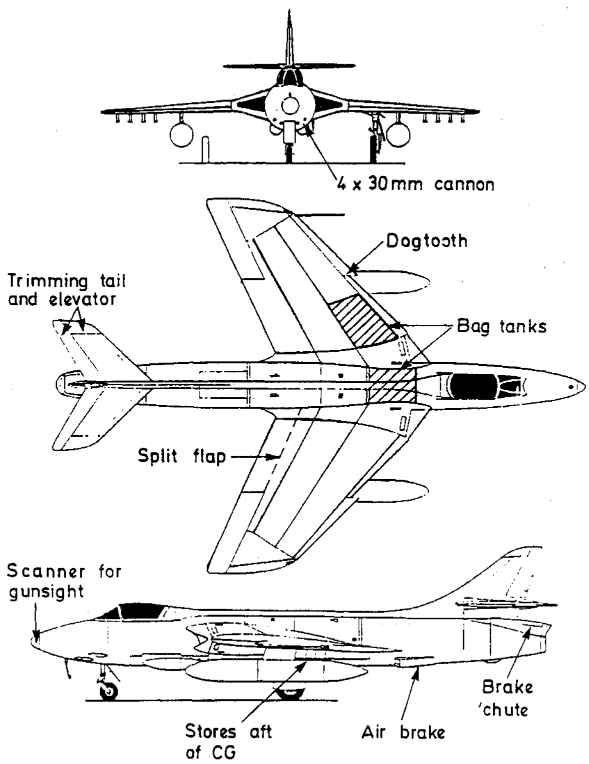

Fig. 2 Hawker Hunter FGA.9.

private-venture fighter, based on the Rolls-Royce AJ.65 axial turbojet, was started, culminating in the Hawker P.1067. Many texts[1-4] describe the origins of the Hunter; suffice it to say here that, when the prototype appeared and flew in July 1951, it bore the traditional Hawker hallmarks: smallest possible airframe, largest possible engine, and a reasonable military load. It was designed to revised U.K. Government specification F3.48 (subsequently, Operational Requirement OR.228), as shown in Table 1.

Subsequent experience with the Hunter showed that only the F.Mk 3 with afterburner could meet the 6-min climb requirement. The initial F.Mk 1 took over 11 min, having a service ceiling of 46,000 ft, a maximum endurance of 80 min, and only 33 min if combat was included. The F-86A with two drop tanks had 90 min endurance, including 20 min combat. The Hunter F.1 required a takeoff distance of 4900 ft, and landed within 5800 ft when it was given limited service release in mid-1954. Nevertheless, the Hunter was the first RAF fighter with an axial engine, the first to have a swept wing, and the first to use four of the new 30-mm Aden cannons. It thus represented a great advance over the aircraft it superseded. When the F.6 version entered service in 1956, with the vastly improved R-R Avon 200 of 10,000-lb thrust, the RAF had got the aircraft it really needed. In terms of aerospace business, the Hunter was the most successful of postwar U.K. fighters, 2000 having been sold. It was operated by 31 air forces around the world and still remains in service. The main design features of the Hunter are shown in Fig. 2.

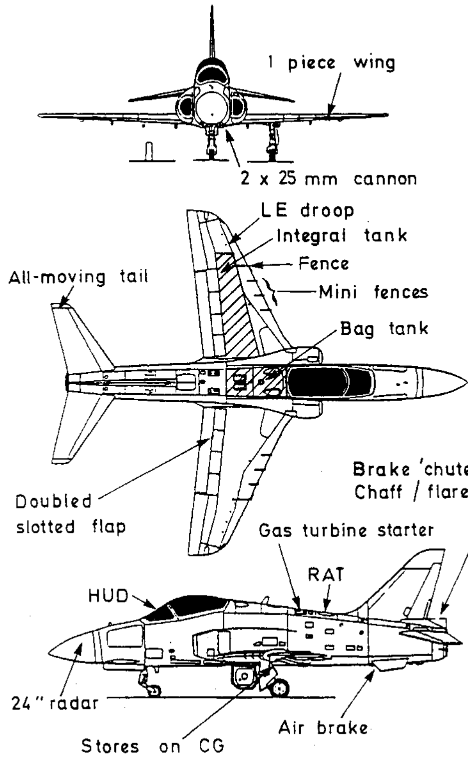

Fig. 3 British Aerospace Hawk 200.

British Aerospace Hawk

The Hawk was designed specifically to an RAF requirement for a two-seat all-through jet trainer. Initially, 175 aircraft were ordered under a fixed-price contract to replace Hunter, Gnat, and Jet Provost trainers. Student pilots were to be taken from an early stage in flying training and prepared for high-performance aircraft, such as Jaguar, Harrier, Phantom, Tornado, and, in the future, EFA. Training tasks included general handling; aerobatics, stalling, and spinning; instrument and procedural training; night flying, formation and tactical work; and weapons training. Economy of operation figured largely in the overall equation.[5] First flight was in 1974, and the Mk.1 entered service in 1976. To date, approximately 700 aircraft of the various versions have been ordered, including those T-45s for the U.S. Navy. British Aerospace expects to be producing Hawks at least up to the end of the century.

Ever since the Hawk trainer first flew, there had been great interest in a single-seat ground-attack version, since, with its ability to sustain 6 g at low level, the trainer had shown distinct fighter-like qualities. One of the aircraft's notable features is the wing's modest quarter-chord sweep of 21.5 deg, combined with a nominal 10% thickness ratio. The Hawk's main rival, the Alpha Jet, has figures of 28 deg and 9%, respectively, but is slightly slower. The low sweep angle places underwing stores in line with the Hawk's center of gravity. The result is a high tolerance to bulky, heavy external stores that can be released with little trim change. Thus, the trainer's combination of high subsonic speed, maneuverability, stores tolerance, fighter-like handling with an excellent warload/-radius performance provided by its economical turbofan, generous fuel volume, large external tanks, and very strong structure gave it considerable potential for operational roles. Indeed, the Hawk trainers used by the RAF's tactical weapons units are specially configured and have an operational wartime role of secondary air defense.

Although a single-seat variant was under examination in the late 1970s, it would appear that the impact of announcing a future one-place airplane on early export sales of the two-seater was a strong argument in delaying development. In essence, the aims behind the single-seat Hawk 200 were to provide a true combat aircraft with improved rear vision, via a bubble canopy like that of the F-86, and to generally refine the airframe to take best advantage of the systems it was to carry. This was achieved by placing the single seat in a position, relative to the trainer, between the two crew positions. This gave extra equipment space in the nose, and full night/bad weather and electronic warfare capability (referred to later), together with increased firepower via two 25-mm Aden cannons. The nose of the aircraft can accommodate a 24-in.-diam antenna with just one cannon. External changes include the nose landing gear leg moved slightly aft to increase space in the nose, an increase in fin height, and provision of a combat wing (discussed later). The main features of the Hawk 200 are shown in Fig. 3.

Aerodynamic Design

By today's standards, the Hunter has a low wing loading (46 psf), as shown in Fig. 4, and a high quarter-chord sweep (40 deg). To compensate for the weight penalty of a swept wing, the aerodynamic benefits of sweep had to be maximized. By the end of the 1940s, the adverse effects of loss of isobar sweep at wing root and tip were appreciated. On the P.1067, this was compensated for by taking the airfoil section's thickness forward at the root via the root air intake and aft at the tip by a streamwise fairing. In comparison with the F-86, the Hunter's wing was a significant aerodynamic advance. The clean streamwise tip, which became known in the United Kingdom as a Kuchemann tip, is characteristic of both the British Aerospace Harrier and Hawk. The Hawk, additionally, has locally increased sweep at the wing root and, with its thicker wing and only half the sweep of the Hunter, achieves the same limiting Mach number.

The problem of pitch-up, a characteristic of many first-generation swept-wing fighters, was eventually overcome on the Hunter by use of a dogtooth cambered leading-edge extension. This reduced the local lift coefficients at high speeds and weakened the embedded shockwaves (due to the smaller thickness ratio), whereas at high angle of attack (AOA) the dogtooth discontinuity reduced the outboard boundary-layer flow and delayed tip stalling. It has been observed, with the benefit of hindsight, that putting the tail above the wing plane would inevitably exacerbate pitch-up tendencies, though there were many contemporary aircraft with this configuration. The Hunter lies within the band, on an aspect ratio vs sweep plot, of configurations likely to experience pitch-up, whereas the Hawk, with its higher aspect ratio/lower sweep, does not.[6] A side issue, related to the tail/fin junction, was the very severe buffeting experienced as a result of flow separation at high speed. This was cured by a bullet-shaped fairing towards the rear of the junction.

The high-lift devices on the Hunter, namely its split flaps, were originally designed to operate also as airbrakes, though flight tests quickly showed them to give quite unacceptable nose-down trim changes. Side-mounted airbrakes were tried but also gave excessive pitch trim changes due to alterations in the downwash at the tail as well as buffet and directional control problems. The resulting ventral airbrake required considerable design and development effort, because it came late in the program and had to be mounted externally. It never quite gave the deceleration that pilots wanted and could not be used on landing due to inadequate ground clearance. This latter restriction is also applied, via an interlock in the landing gear system, to the Hawk — apart from the T-45, which has large side-mounted airbrakes. However, the fact the the Hunter's flaps had been stressed to 7.5 g (corresponding to 80-deg deflection at maximum speed) meant that they could be used as combat flaps, not only conferring a higher lift coefficient, but also a better lift/drag ratio, due to a reduction in aircraft AOA in a turn or pull-out.

In an endeavor to optimize the basic Hawk wing for combat, British Aerospace removed the trainer's existing stall strips and fence and concentrated on improving the lift at low speeds through the double-slotted flap system and wing flow control, which resulted in a 15% improvement in usable lift. At higher speeds, even more significant improvements were obtained via the better handling at high AOA arising from flow separation control devices (the three minifences and single large fence shown in Fig. 3). Further improvements were obtained by increased leading-edge camber, movable leading-edge devices having been ruled out due to weight, complexity, and cost. Additional benefits have accrued via modifications to the rear airfoil section, to improve aft loading, and the use of rear camber by use of partial combat flap deflection (Fig. 5).[7]

All these changes have consistently and very significantly improved sustained turn rate, which was already very good due to the relatively high aspect ratio ($A = 5.3$) and consequent low span loading (Fig. 6).[8] Together with the engine improvements referred to below and on-going combat flap development, the sustained turn rate has been increased across the whole Mach number spectrum.[9]

Propulsion

The striking advances made in the field of engine technology are far beyond the scope of a mere paper. Table 2 draws attention to progress made in the narrower field of engines for transonic combat aircraft.[10,11]

The Hunter first flew with a Rolls-Royce Avon of 7500-lb thrust, though the third prototype had an Armstrong Siddeley Sapphire. This latter engine was consistently able to avoid the surge problem that afflicted the Avon for over 5 years, until Rolls-Royce proved the adoption of a compressor like that in the Sapphire. It appears that the first four stages of the Sap-

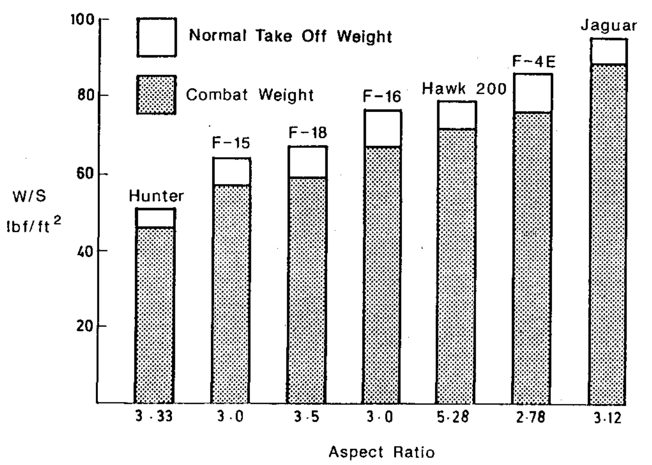

Fig. 4 Wing loading comparison.

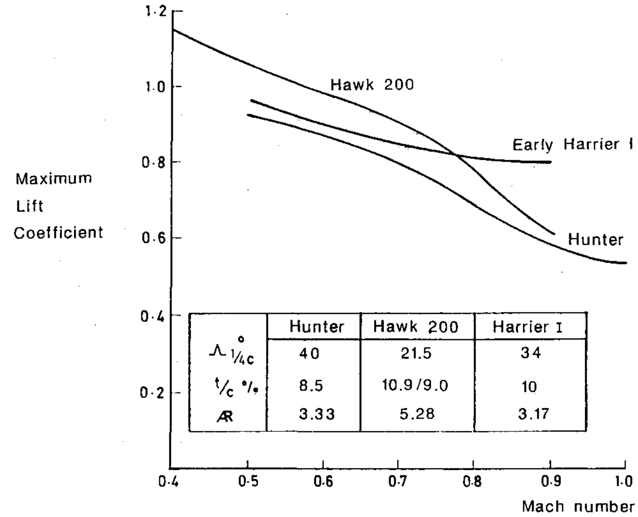

Fig. 5 High-speed lift characteristics.

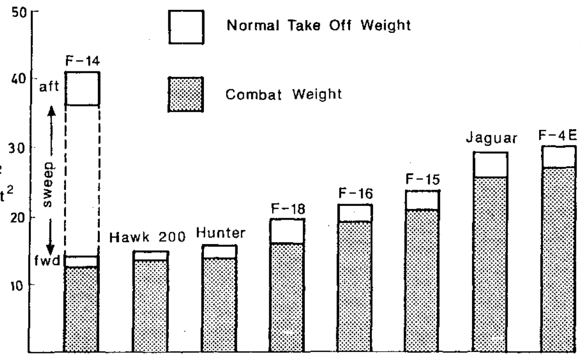

Fig. 6 Span loading comparison.

Table 2 Characteristics of Avon and Adour engines

ISA SLS Max	AVON Mk 207 turbojet	ADOUR Mk871 turbofan BPR = 0.79
Thrust, kN (lb)	45 (10,150)	26 (5845)
Pressure ratio	7.8:1	11.2:1
Weight (basic), kg (lb)	1282 (2852)	598 (1330)
Airflow, kg/s (lb/s)	68 (152)	43.6 (96.9)
Diameter (casing), m (in.)	0.99 (39)	0.74 (29)
Length, m (in.)	3.12 (123)	1.96 (77.2)
Thrust/weight	3.6:1	4.4:1
Specific thrust, Ns/kg (lb/lb/s)	663 (67)	596 (60)
TSFC, kg/kN h (lb/h/lb)	89 (0.88)	77 (0.76)
TET, K (°F)	1200 (1700)	≈ 1500 (2240)
	Configuration	
Compressor	15	2/5 LP/HP
Combustion chamber	Cannular	Annular
Turbine	2	1/1 HP/LP
Thrust/intake area, kN/m² (lb/ft²)	53 (1100)	106 (2200)
TBO, h	700	1200

phire's compressor carried only half the load of those in the early Avons and, thus, ran much further from the stall line, allowing the Sapphire to tolerate greater inlet flow distortion.[1] Thus, it was not until the 200 Series Avon, with a sophisticated fuel system, flew in the Hunter F.6 in 1954 that the aircraft was truly regarded as anything other than interim. It has to be recalled that only after axial flow compressors had replaced centrifugal flow designs in the late 1940s did pressure ratios start to climb to 7:1. In the 1950s, single rotor compressors with variable stators and dual rotor designs were both capable of 12:1. Cartridge starters were originally used on the Avon, but were later replaced by liquid fuel types.

The Rolls-Royce Turbomeca Adour Mk 871 two-shaft turbofan in the Hawk 200 is the product of a long process of development and flight experience. The original Adour first ran in 1967 as an afterburning engine for the Anglo-French Jaguar, which flew in 1968 and entered service in 1973. The unreheated version was eventually chosen in 1971 for the definitive Hawker Siddeley HS 1182, as the Hawk was originally known, and had 96% commonality with the Adour Mk 101, for the Jaguar, which was already in large-scale production. The Adour in its various forms is currently flying in over 1000 aircraft of four different types around the world, with experience exceeding over 2.5 million h. The modular construction, with all rotating assemblies balanced, means that rebalancing after module change is unnecessary. Compared with the Avon, Fig. 7 is much more reliable not having inlet guide vanes or variable stators, has a robust compressor with low aspect ratio blades highly resistant to FOD and operates at moderate pressures and temperatures with a single and proven hydromechanical control system. The Adour in the Hawk uses

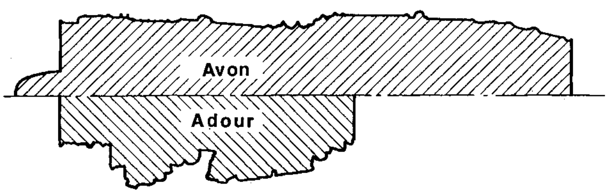

Fig. 7 Engine comparison.

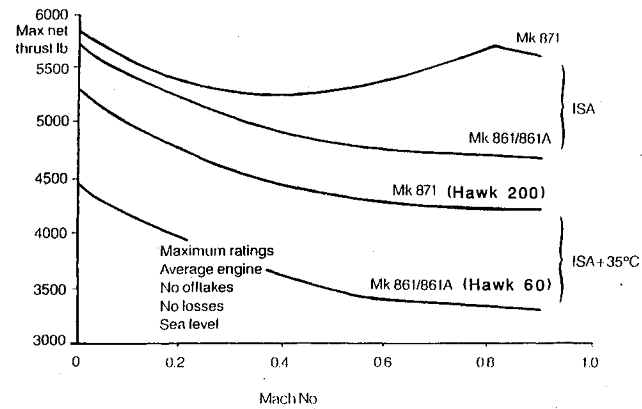

Fig. 8 Adour Mk.871 — enhanced thrust at high ambient temperature and speed.

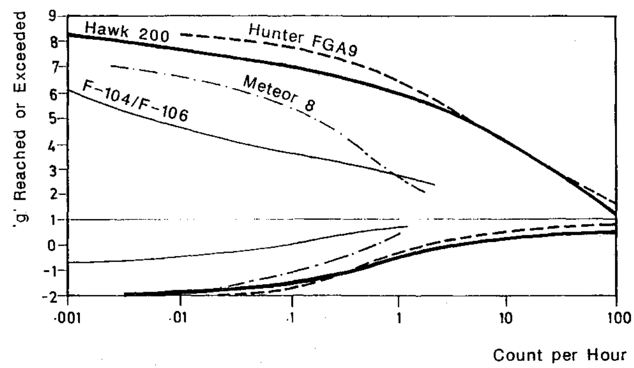

Fig. 9 Normal acceleration spectrum.

a very compact gas turbine starter operating on aircraft fuel located forward of the ram air turbine in the upper fuselage. The Mk 871 Adour for Hawk 100/200 was designed to provide increased thrust, particularly in hot ambient conditions and at high forward speeds. It has demonstrated improvements of over 26% at Mach 0.8 sea level, ISA plus 35°C, and 20% at Mach 0.8 SL, ISA relative to the Mk 861 in the Hawk Mk 60, while retaining the same cruise TSFC (Fig. 8).[11] These improvements have been achieved by increasing the LP shaft speed, fuel flow, combustion, and turbine operating temperatures, and reducing turbine blade tip leakage.

Structural Design

Having been designed for a limit load of 7.5 *g*, the Hunter had a strong structure for its day, though was of contemporary fabricated construction. Figure 9[12,13] compares normal acceleration spectra for Hunter FGA.9 (fighter ground attack), Hawk, and others. One case was recorded of a Hunter experiencing an estimated 14 *g* in a turn that bent the pitot-static tube, though the aircraft remained in one piece despite its 11.25 *g*-designed ultimate load factor.

The Hawk is made of conventional aerospace materials by contemporary manufacturing methods, i.e., integral machining. It is designed for a fatigue life of 6000 h (i.e., 300 h/yr for 20 yr) and +8/−4 *g* clean, +7/−4 *g* with 3000-lb warload plus 60% internal fuel, and +6/−3 *g* with 5000-lb warload plus 60% internal fuel. It has been flown to beyond 9 *g*; during ground testing, 15.5 *g* was applied before any failure occurred. Particular attention was paid in the Hawk's design to ensuring good access for structural inspection, and a high percentage of the fuselage external surface consists of panels and doors. Whereas the Hawk's engine is removed downwards without the need to raise the aircraft off its wheels, the Hunter's rear fuselage needed removing with twice as many bolts attaching it as on the F-86. Despite the apparent large difference in appearance, the structure of the Mk 200 single-seater is identical to the Mk 60 and Mk 100 two-seaters aft of the cockpit. The scaled weight breakdowns for Hunter FGA.9 and Hawk 200 in the clean takeoff condition are shown in Fig. 10.[12,14] The much larger equipment (i.e., avionics) load, higher fuel fraction, and lower powerplant fraction of the lighter Hawk 200 are amply illustrated.

Integral Wing Tanks

The use of integral wing tanks was considered for the Hunter, and tests were carried out in 1948 on a representative design, though a decision was made in 1949 against the concept on the grounds that insufficient experience existed relevant to a 7.5 *g* structure. This left the Hunter with a wing that was a very inefficient fuel container. (The early Hunters had only 1530 liters of fuel, all in the fuselage.) Figure 11 shows the evolution of integral tanks, demonstrating that the Hunter suffered from a chronic lack of fuel volume, particularly when compared to the F-86, and was a consequence of the U.K. Government's doctrine requiring very limited flight endurance. Provision for two 455-liter drop tanks was made and flown in 1954, after several incidents involving aircraft landing with insufficient fuel to taxi from the runway, and worse![1,2] The Hunter F.4 had internal fuel increased to 2000 liters by the addition of eight small bag tanks in the wings, and then two more drop tanks on outboard pylons, giving a total of 3700 liters. The outboard stations were only ever used for the ferry configuration. Later, a Hunter F.6 was flown with tip tanks, though these caused so much buffet at very modest lift coefficients that they were abandoned.

Wing Structure

The use of side-mounted air inlets on the Hunter, rather than the pitot intakes on the F-86 and MiG-15, gave a minimum wetted area to the forebody, maximized useful volume (radar-equipped Hunters were projected), and gave good accessibility. The intakes, like those on the contemporary Republic RF-84F, had little depth, so that the boundary-layer diverter drag was small. What depth existed thickened up the wing root, thereby reducing the weight of the spar booms and providing room for the main wheels in the wings. This allowed a much wider undercarriage track than the F-86, whose wheels

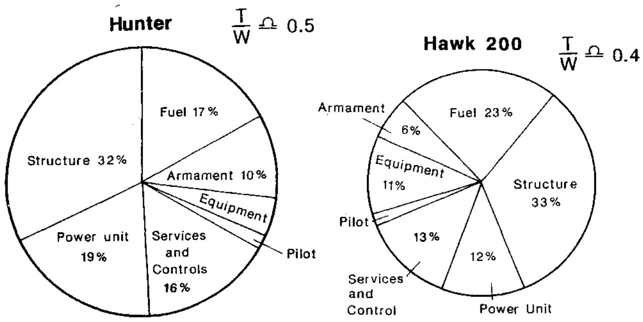

Fig. 10 Comparative weight breakdown (clean).

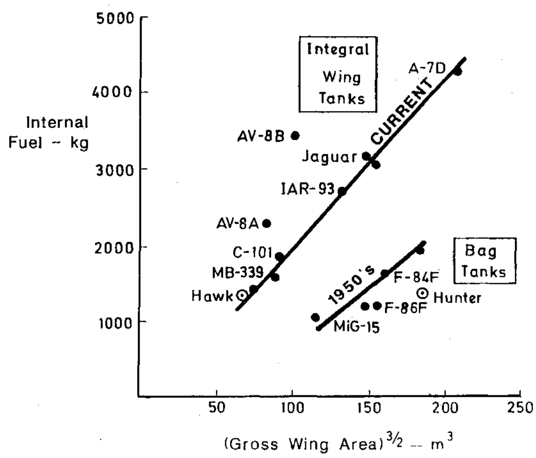

Fig. 11 Evolution of integral tanks.

Table 3 Representative performance comparison between Hunter and Hawk aircraft

	Hunter FGA.9/F.6	Hawk 200
Max speed (dive), M	1.2	1.2
Max level speed, M	0.93	0.85
Max speed (loaded) SL, M	0.88 (4 tanks)	0.78 (5×Mk83 bombs)
Service ceiling, ft	47,000	47,000
Max rate of climb, fpm	16,500	11,800
Time to 40,000 ft, min	5.5	10
Ferry miles, nm/lb fuel	0.17	0.31
Stalling speeds, kt	86–101	90–125
Turn rates: STR, deg/s	14	19
(60% fuel): ITR, deg/s	23	22
Takeoff ground run, ft (ISA SL, full fuel, clean)	1750	1800
Landing ground run, ft (ISA SL, 5% fuel braking parachute)	2200	1820
Combat air patrol @ 100 nm, internal Fuel only	4×30-mm, 135 rpg 25 min loiter —	2×30 mm, 100 rpg 2×AIM-9 130 min loiter
Ground attack role	2×1046 l tanks	2×860 l tanks
Hi-Lo-Hi	4×30 mm; 135 rpg Radius 545 nm —	3×Mk83 bombs 2×30 mm, 100 rpg Radius 580 nm

Table 4 Specific warload range comparison

	Hunter FGA.9	Hawk 200
Warload, lb bombs	2×1000	3×1000
RoA, nm	215	580
TOW, lb	22,000	19,500
SWR, nm	≈20	≈90

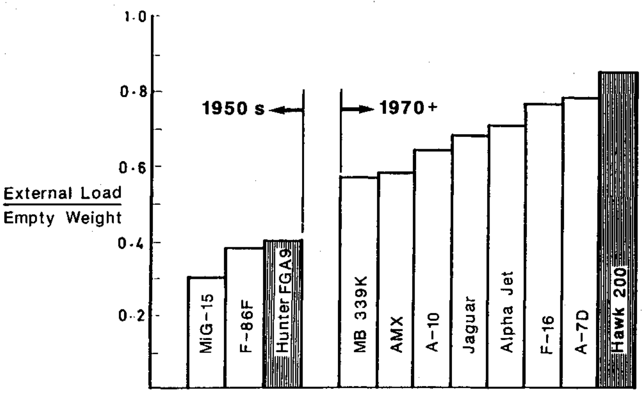

Fig. 12 External store carriage.

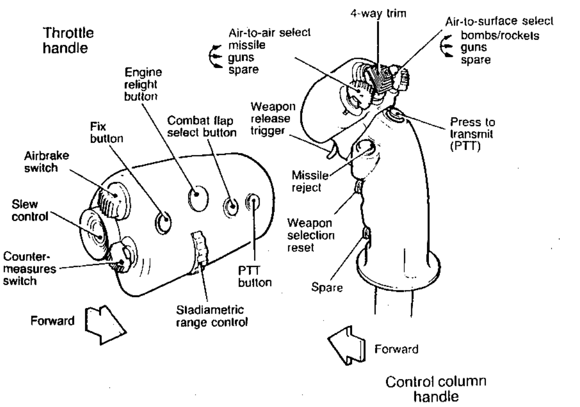

Fig. 13 HOTAS controls.

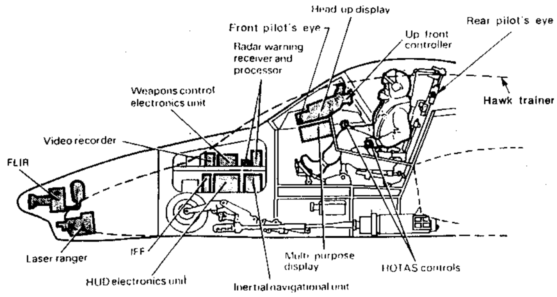

Fig. 14 Cockpit comparison.

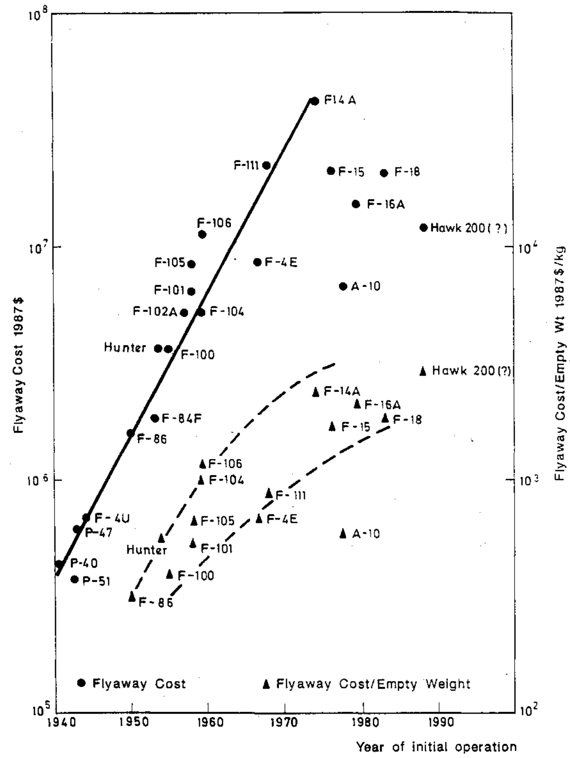

Fig. 15 Fighter cost trend.

retracted into the fuselage. Cutting a hole for the landing gear in the lower wing surface between front and rear spars is a penalty paid on many current low-winged aircraft. On the Hawk, however, the main undercarriage is mounted on the front spar and retracts forward of the main wing box, so that the wheels are located under the intake ducting with slight bulges on the wing lower surface. This reduces the problems of a major stress-raising cutout and load diffusion around it. The Hawk's wing is a one-piece structure attached by six bolts; the main wing box, of integral construction, forms a fuel tank contributing to a total internal capacity equal to that of the much larger Hunter. The fuel fraction, here defined as internal fuel load/empty weight, is 21% for the Hunter and 33% for the Hawk, i.e., a 50% improvement.

Performance

Table 3 gives a representative performance comparison between the Hunter FGA.9/F.6 and the Hawk 200.

The author knows of no single figure of merit or criterion by which the relative worth of a combat aircraft can be fairly judged. However, for the purposes of comparing progress over a not inconsiderable period of time, the following parameter is offered:

$$\mathrm{SWR} = \frac{\text{warload} \times \text{radius of action}}{\text{takeoff weight}}$$

The result of applying this criterion to the Hunter and Hawk 200 in two roughly comparable configurations is shown in Table 4.

This is, however approximate a comparison, a significant reflection of the Hawk's ability. Of course, SWR will generally increase with aircraft size; e.g., the Canberra light bomber of Hunter vintage exceeds an SWR of 120 but is more than twice as heavy as a Hawk and was designed as a bomber. What is particularly notable for the Hawk is the high SWR (4.5 times that of the Hunter) achieved by such a small and, hence, low-observable, airframe. The large improvement in load-carrying ability from 1950s aircraft to more recent types is shown in Fig. 12, with the Hawk 200 being able to lift an external load equal to 85% of its empty weight.

Avionics

Unlike the previous generation of RAF fighters, the Hunter's cockpit originally tended to follow the U.S. practice of arranging the instruments and secondary controls in tidy consoles that no longer gave the impression that many items had been included as afterthoughts. This became less true, however, as the various marks of Hunter entered service. The cockpit layout and visibility were praised, apart from reservations about the view aft, which was certainly inferior to that of the F-86. The main avionics fit to the Hunter included VHF multichannel transceiver, gyro-stabilized gunsight, and compass. The avionics suite in the Hawk 200 is extensive, having a high-performance INS, a new generation head-up display/weapon aiming computer (HUD/WAC), and a new high-accuracy air data sensor. These components are interconnected via a MIL-STD-1553B dual redundant multiplex digital databus that, apart from providing a high-integrity and reliable data link, also ensures growth of future systems. There is also a stores management system and comprehensive communication package.

With the Hawk 200 cockpit designed for high-speed low-level attack roles, all of the time-critical weapons, navigation, and countermeasures controls have been located on the throttle or control column using the HOTAS principle (Fig. 13). The electronic warfare system comprises an RWR that detects, identifies, and displays in rank order of threat. A chaff and flare dispenser is mounted on the extreme rear fuselage (Fig. 2), and release of decoys can be controlled either by a throttle switch or automatically by the RWR.[15]

The aircraft is offered with optional sensors. For night attack missions, an FLIR system matched with night vision goggles and a steerable laser rangefinder is offered. This is the variant shown in Fig. 14, which also compares the cockpit positions of the Hawk trainer (shown dotted) and the single-seat aircraft. For bad-weather operations, a multimode pulse-Doppler radar with antenna diameter up to 24 in. is possible. BAe has reportedly purchased Westinghouse APG-66s (the F-16 radar) for an undisclosed Hawk 200 customer.[16] The radar would have a dedicated CRT display, in addition to the color multipurpose CRT display.

Costs

The growth in acquisition (flyaway) cost and flyaway cost/weight (empty) of combat aircraft can be seen in Fig. 15 to have been enormous over the last four decades. The original graph[17] has been added to and updated from 1975 USD to 1987 USD, making an allowance for inflation. However, Fig. 15 does not pretend to be precise nor wholly accurate; it merely illustrates the trend. On the basis of the early 1970s' trends in flyaway cost and U.S. gross national product (GNP), it was predicted[18] that by A.D. 2150 an entire year's GNP would be required just to buy one fighter. Furthermore, by A.D. 2080 it would take a whole year's GNP to develop one fighter. An even more bizarre situation was foreseen for LCC: whereas, in the 1950s, the RTD & E plus acquisition cost was approximately 70% of an aircraft fleet's LCC, and operation and support cost the remaining 30%, by the mid-1970s the two contributions to LCC had been approximately reversed, largely due to the explosion in the cost of fuel. Thus it was that all procurement agencies insisted that cost be given equal weighting with aircraft performance and that preliminary design effort must show the tradeoffs between cost and performance. The divergence, from the unit cost line connecting the P-40 to the F-14 (Fig. 15), of more recent aircraft may be a demonstration that cost awareness has paid dividends. However, that is a long way from arguing that the military benefits afforded by the modern combat aircraft are three or four times those of their 1950s' predecessors.

Conclusion

The progress in the design, development, and operation of transonic fighters over the past four decades has been profound. Due to inadequate foresight by the authors of the requirement from which the Hunter evolved, the aircraft suffered throughout its career from a lack of internal fuel. Longitudinal control at high speed was another of the Hunter's drawbacks, it never having benefited from an all-flying tail, one of the excellent features of the F-86. Delays during the development of the Avon engine and its airframe integration together with a revised airbrake prevented the delivery of a really combat-capable aircraft for over 5 years. But the Hunter, despite these shortcomings, represented a milestone in fighter development, and is regarded as one of the most beautiful, useful, and popular combat aircraft ever built. Its principal virtues are its great firepower, robust structure, and operational flexibility. Indeed, it is destined to remain in service in parts of the world 40 years after its first flight. The Hawk, originally conceived as a trainer in the late 1960s, has since its early days shown virtues equally applicable to a fighter. The advent of the single-seater in the late 1980s promises, with the adoption of state-of-the-art avionics, to extend the role of the transonic fighter into the next century. The lessons to be learned can, thus, be summarized: get the requirement right or, better still, let industry have a relatively free hand, and then develop a good design so that its full potential can be realized.

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