ICAS - von - Kármán - Lecture

Engineering Aspects of International Collaboration on Tornado

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ENGINEERING ASPECTS OF INTERNATIONAL COLLABORATION ON TORNADO

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Abstract

The Tornado is a Multi-Role Combat Aircraft jointly developed into service by Panavia of which Aeritalia, BAe and MBB are the Partner Companies. Operational and Trainer versions of its Interdictor Strike and Air Defence Variants cover a wide range of requirements with high commonality. After reference to pertinent management aspects, the measures adopted by the Engineers in the three companies to accommodate international factors by clear definition, pragmatic action, and good communication are described, with some examples of development arisings.

Introduction

My colleagues and I feel most conscious of the honour afforded by ICAS to us and to the Tornado team in both Engineering and Collaborative contexts. This is particularly so as this award - and indeed ICAS itself - are both associated with the name of Dr. Theodore Von Karman, whose work for international co-operation and exchange of experience is so respected.

It is also a pleasure to submit this paper: part of the satisfaction of Tornado is that it has fostered many friendships and thereby furthered European unity.

A large element of the close cohesion achieved by Panavia in the engineering of Tornado was the cordial association of the System Engineering Directors of the three Partner Companies; for many years the late Helmut Langfelder at MBB; Dr. Ricardo Mautino at Aeritalia, and myself at British Aerospace (to use current company names). Professor Gero Madelung as Managing Director of Panavia, 1969-1977, was no stranger to Engineering issues and achievement on Tornado.

I present this paper on their behalf and of Panavia and its Partner Companies: we all received great support from colleagues above and below us in our own, and associated, organisations.

This paper covers:-

1. What Tornado is
2. Its starting conditions as affecting Engineering
3. Some essential management aspects
4. An account of Engineering, presented broadly in the sequence of the formal Tornado project phases:-

IDS

- Feasibility 1968/9
- Definition 1st May, 1969, to 30th April, 1970
- Development from 1st May, 1970
- Pre-Series, Production Investment and Production from 15th March, 1973

ADV

- Definition November 1973 to 31st December, 1975
- Development from 1st January, 1976
- Production Investment and Production from 29th June, 1977

The IDS and ADV mentioned above are the two main variants of Tornado:-

1. The IDS (Interdictor Strike) Aircraft, with sub-variants:

GAF and GNY operational two-seater and two-pilot variant

IAF operational two-seaters, and two-pilot variant

RAF operational two-seaters, and two-pilot variant

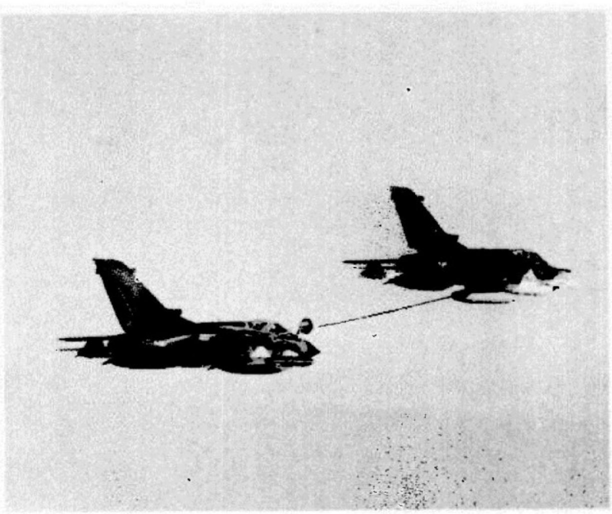

Figure 1. IDS - Tornados

2. The ADV (Air Defence Variant) for the RAF - operational and two-pilot.

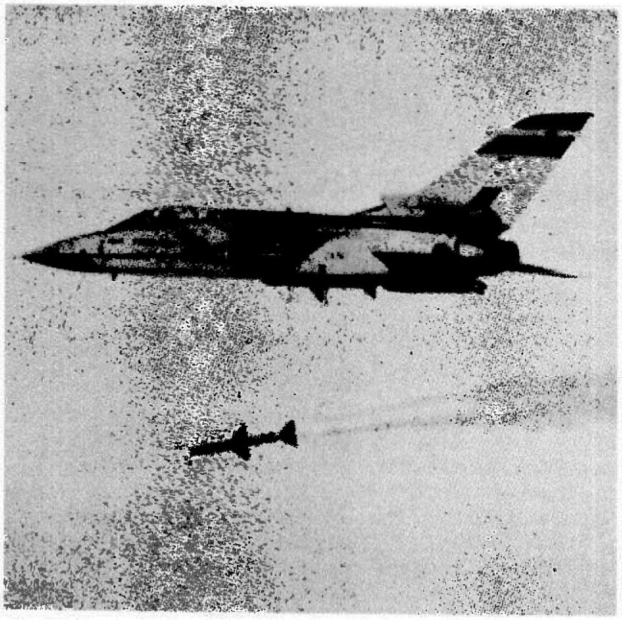

Figure 2. ADV

The notation 'two-pilot' is a better description than 'trainer' because a substantial operational capability is preserved therein. See Annexe 1 for a further description of common and particular IDS and ADV features.

Some Aspects of the Requirement

From the start, a documented requirement existed in some form - initially a bound collection of several national targets. This was progressively refined; it provided a medium - a yardstick - at all stages against which overall or detailed characteristics of the aircraft, or its level of technology could be assessed in terms of return for investment and risk involved.

Tornado has versatility to meet a wide range of roles:-

- Air-to-ground attack
- Interdictor/strike
- Naval Strike
- Reconnaissance
- Air Superiority
- Interception
- Conversion and weapon training

Reference[1] gives an indication as to how these were translated into key aircraft parameters.

Thus, the Tornado and the weapon system of which it is part, does meet, and was always required to meet, full and genuine military requirements from the Air Forces involved - namely of Italy, Germany and Great Britain and the German Navy - a real requirement - a real aeroplane; no-one sought to shelter the product behind political inertia.

Nevertheless, Tornado did represent even more than a weapon system; other features may be termed political, but are real nevertheless. They included:-

- Germany's desire to confirm their industrial capability from project concept to service.
- UK experience made available to Germany and Italy was one element seeking to support UK's admittance to the European Economic Community.
- The United Kingdom wanted to see a strong Rolls-Royce element in the engine, which was the case after a genuine competition in 1969.
- All partners and nations wanted a return commensurate with input - a fair share of work, both design and production but, further, a fair share of the new technology, innovation and expertise. With this they were then willing to undertake the project accepting their share of the risk and investment necessarily involved in a project of this magnitude.

Reference [2] gives an Italian view of this.

The object of the Engineers concerned was to de-couple their activity as far as possible from the novel international elements of a 3-Nation involvement so that they could proceed as normally as possible. The degree of centralisation of functions, particularly Engineering, has been, and will no doubt remain, a source of discussion. There was a rule in the Memorandum of Understanding that all work which could be carried out in the participating nations should be, exploiting existing resources, rather than in a 'central' location. The Official agency, NAMMA, has a System Engineering function, but Panavia met the dual needs of collating engineering between the partners and doing actual work at the partner company sites by having a System Engineering Directorate at each of these: Warton, Munich and Turin, with (existing) teams of Engineers in support. The System Engineers carried a dual, formalised responsibility not only for the excellence of their individual company contributions, but also for the overall compatibility of these with those of their partners in an overall weapon system sense.

Although there were no permanent full-time Engineers in Panavia itself, i.e. in the Munich Arabellastrasse office, the function of a Central Engineering Authority was ensured by the management device that when two or more authorised Partner Company individuals or groups met to make decisions, then these became Panavia decisions: always providing that they did not overdo specialist considerations to the detriment of overall performance, cost, timescale or risk. Similarly a course of action proposed through authoritative paperwork exchanges including telex. Surveillance by the System Engineering Directors was appropriately mounted to ensure all this.

The principle was established that should an external agency (or an internal one for that matter) contact a Panavia partner, it was the responsibility of that partner either to take the direct action required or implied, if the subject lay in his area of authority - or were this not the case to make the appropriate contact within Panavia and ensure that an authoritative response was set in action.

Company internal organisations were not symmetric but, in broad terms, the SE Director in each Partner Company was for many years also Programme Manager or the equivalent. This had advantages of communication, focus and authority, but it could cause conflict between national and international priorities, i.e. whether to give Engineering support to company financial work-sharing deliberations in Rome, or to a Technical consideration of (say) single and two-seater demands in Munich.

As the project developed, these functions have separated in formal terms but there is - and has to be - considerable overlap.

Project arrangements have to interface closely with existing internal Partner Company organisations and great reliance had to be placed on personal good sense and flexibility, always bearing in mind ultimate formal responsibilities. However, once trust had been established, such detailed arrangements followed: as Tornado proceeded, people grew to know each other personally. As initial and separate national and company work was related to joint endeavour, the contentious element of 'committees' decreased: we could battle against common natural laws and old enemies like weight and drag. As the service phase approached, the sheer amount of work for the product support activities caused an upswing of travelling and meetings.

BAe have a separate Flight Operations function which MBB cover within Engineering. An international Flight Test Management Group of Panavia Flight Operations was established at Warton with a Director (finally) in Panavia Munich to satisfy this UK need, based on earlier experience of joint projects.

To accommodate the UK aspects of ADV, the BAe Tornado Project Director holds a Panavia Functional Director-ADV position.

The principle of Engineering lead functions was a valuable one: to avoid a slow bicycle race with each Partner looking over his shoulder to the extent that no-one dared move, the principle was established that within the datum baseline progressively evolved, detailing work would proceed until 'anyone' challenged it: in a sensible interpretation, 'anyone' could contribute to the process of definition but agreements and implementation involving definition itself and funding were necessarily quite formal. Ad hoc content, regular reviews and appropriate paperwork all ensured that this full opportunity was provided: should any point emerge which was not understood or not accepted by one Engineering team from the work of another, then the right of 'check function' was invoked. In some areas such a check function was applied to ensure that a fair balance was given to meet any still discernible national elements in the joint requirement. Performance, being ultimately tied to guarantees, received especially wide surveillance and joint activity. So did stability and control. This was all agreed by the Government agency in their scrutiny for duplication.

Overall Formal Management

With the above introductory remarks a few explanations of overall Management are possibly helpful.

The participating nations - Italy, Germany, UK - administer Tornado through NAMMO (NATO MRCA Development and Production Management Organisation) manifest as a committee of high-level National officials and serving officers based in each country's National Ministry and Services, who meet on a regular basis. Their Agency, NAMMA, is based in Munich and comprises officials seconded from each country.

Panavia, the international company, in the same building as NAMMA, is owned by MBB, Aeritalia and British Aerospace, who are in turn its Partner Companies.

Panavia is vested with Weapon System authority, but NAMMA placed the contracts for the RB.199 engine and Mauser cannon (up to third production batch). Associated Contractor Agreements cover the interfaces and formalised a cordial mode of working between Panavia and TU, Panavia and Mauser.

Turbo-Union is itself an international company, with considerable technical authority vested in Rolls-Royce, in partnership with MTU in Germany and Fiat (Engines) in Italy.

Both Panavia and NAMMA have central directorates in Munich covering the functions of:-

- Finance and Contracts
- Production
- Procurement
- Military Factors and Flight Operations
- Plans and Programmes

but as mentioned there are no permanent central Engineers in Panavia. (However, "PANSEMAMT", the Panavia System Engineering Avionics Management Team which has an international complement, was formally based in MBB and geographically located in Arabellastrasse for some time).

Between Panavia, NAMMA and NAMMO, series of regular meetings and reviews apply, relating achievement and spend, extending or withholding authority and funding as judged appropriate after Company expositions and debate.

Panavia implement a two-tier Board structure: supporting its Board, the executive 'Panavia Staff Meeting' is the forum for defining policy on relations with the customer, review and contributions to submissions, standards, performance, cost and timescale. On many occasions it has contributed to the resolution of specific problems, admitting detail discussion on important technical, costing, equipment selection issues and suchlike. To May 1982, 231 Panavia Staff Meetings have been held over 13 years. All functions are represented there and comment is not confined to the nominal area of personal authority.

Panavia TAMM (Top Avionics Management Meeting) and the Panavia/Turbo-Union Engine Staff Meeting carry out similar functions in their areas to the main Staff Meeting but with more technical emphasis, providing the interface with the National Avionic Systems Companies (EASAMS, ESG and SIA) and Turbo-Union, respectively.

Under varying notations, Panavia Overall Configuration Control Meetings, Flight Test and Flight Operations Meetings have provided valuable international focii for the injection of all partners' views and experience, and to the setting up of standards and programmes. Naturally, modern (but essentially conventional) methods of task definition, budgeting, reporting, discussion and control apply.

Some recollections of Engineering and allied activity are now related to the developing stages of the project.

Pre-Feasibility

Various ruses were adopted by the Officials - themselves just making contact - to introduce the eventual partner teams to each other. One such investigation in 1968 was to address the merits of single and twin-engined aircraft. A study of fleet operating cost showed that the higher initial costs of twin-engined solutions could be reduced by using a short engine and that relative attrition rates gave no overall saving with a single engine. Thus, Industry could confirm the expressed need of the potential users for a twin-engined solution in good conscience in economic terms. This was in the context of a new engine in either application, single or twin.

The Joint Industrial Company - the emergent Panavia - took the lead in 1968/9 in rationalising the OER requirements, weighting them in terms of mass, cost, size and risk (Reference [1]). This experience put a great premium on honesty: to meet the envelope of requirements stipulated by the six nations then involved would have meant an aircraft of nearly double the size finally proposed, with costs far beyond those which the Partner Nations could contemplate. With some considerable courage (since the project at that stage had only an emergent existence) this was told quite directly to the Officials. After more work by the company, a policy of a core SDR requirement and configuration with national appendices appropriate to the needs of individual Customer air forces was endorsed. Subsequently, the national variations were reduced still leading to variants but of a very high commonality.

At that stage (1968) single-seater and two-seater variants existed. These, coupled with the variable geometry concept - which was being very carefully checked (again) against fixed wings - gave a practical basis for defining datum single and two-seat v.g. aircraft of high commonality.

It would be counter-productive to hail the application of variable sweep as a technical innovation: many aircraft use it. Nevertheless, it does provide genuine advantages - without it the Tornado specification could not have been fulfilled. A particular vulnerability of a fixed wing aircraft meeting the STOL requirement was high gust response. As predicted, and promised, Tornado is excellent in this as proven in service.

The project was handled by a single contract placed upon all Partner Companies practically from the start: the last national funding of earlier national projects was terminated at the end of January 1969. This undoubtedly helped the cohesion and common aim of the project.

The activities of these times may be summarised:-

- A joint examination of the initial, essentially national, requirements and activity with the Officials to obtain the best balance between them, formulated finally as a common requirement.
- To translate the emergent requirements into a common airframe and progressively to detail this in some depth with Data Sets outlining the implementation jointly proposed in physical terms. This not only guided the Engineers, but also the Customers. It provided guidance, even at that stage for Product Support and its anticipation.
- Joint team activity over the first quarter of 1969, first in Warton and then in Munich, produced an acceptable proposal for a common aircraft. The teams were then able to disperse geographically to carry on detailing their own allocated sections of the aircraft, with associated lead functions which broadly followed these. Although dispersed geographically, full continuity was maintained through 'specialist' channels and the SE co-ordinating network. Statements of Work had to be derived to define in meaningful terms who would do what and with what responsibility and authority. This was probably the biggest 'chore' of an international nature to which the engineers were called - although some aspects of equipment selection ran it a close second.

Avionics was an activity of particular sensitivity: all nations certainly wanted full involvement preferably within their own individual countries. They saw this rapidly developing area applied to Tornado as an opportunity to develop theory, hardware and software in practical application to a real aircraft of advanced characteristics, with national fall-out benefit. Quite complex management arrangements applied: definition of work and responsibilities was difficult even in technical terms. It was more so when Panavia Partner Companies deeply involved in aircraft activities had to negotiate interfaces in the closest possible and most meaningful manner with system companies also responsible to Panavia, and also having their own interfaces. ADV later provided a further demand with some Government furnished equipment involved. Several levels of overall and detailed responsibility applied and the overall management arrangements were subject to considerable evolution. Nevertheless, a very satisfactory avionics fit was hammered out and performs well in service.

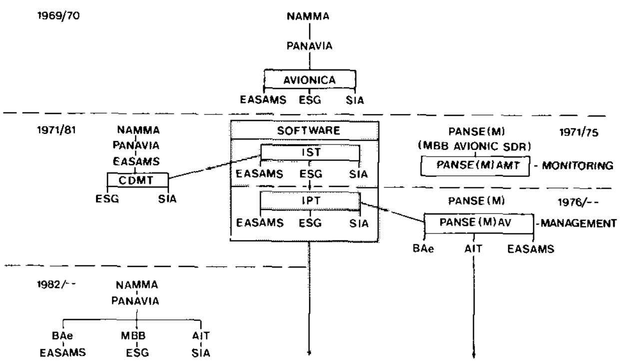

Figure 3. Avionics Management Organisation

Within Panavia full resolution was applied from the start to all aspects, not only engineering: all companies recognised the need to secure willing partners. On issues sufficiently important to reach Board or Staff Meeting status for example, decision had to be by common agreement and discussion - there could be no question of voting on a key engineering feature: all Partners were committing not only their existing and future capital resources, but also their teams to the new project and, therefore, had to be satisfied finally of their own volition that what was being proposed and defined was adequate - in the end there could be no coercion. This has very strongly influenced the engineering approach on Tornado.

Panavia's assault on the MRCA requirement not only embraced the obvious technical factors of sizing and defining the common aircraft: from the very start, partly by the dictate of the requirements laid upon us, but with a great degree of initiative and support from the industrial companies, efforts were devoted to plan and manifest support activities in service, to pursue standardisation and maximum commonality.

In January 1969, key Panavia committees were established to pursue such items, i.e. not always connected with the aircraft itself: specialists would meet to establish policy and plans in such areas as:-

- Work-sharing
- Standards
- Technical programmes (e.g. Wind Tunnel)
- Consistent definitions

and so on.

US-based technical standards and procedures stipulated by the Officials in 1969 have caused occasional disquiet in UK. To British Engineers they lacked the familiarity and the opportunity to comment in their derivation which the UK AvP series enjoyed, but in retrospect it appears that the contribution to standardisation has been worthwhile. On procedures and paperwork Tornado has tended to inherit the highest common factors of participating nations, plus US aspects, with subtleties of interpretation and application. Nevertheless, successful international collaboration has to derive and use a clear definition of what is proposed, what is agreed and what standard is derived and accepted. The Officials have demanded a high standard of visibility throughout and, although this can be overdone, Tornado has been set on a rapidly convergent process as a result.

The use of SI units was also prescribed by the Officials. These, paradoxically, were more familiar to the UK Engineers than their German and Italian colleagues.

The Designers and Engineers had to produce a whole, essentially complete, set of data sheets ranging through normal Design Office usage, Standards, Standard Parts, Material, Stress Allowables, Stress Data Sheets and so on.

The initial recommendation by Panavia for fasteners was for inch standards to be used, but the ruling of the Officials was that metric should be employed. They gave an indication that where a metric standard did not exist, then a concession to use the equivalent inch version would be fairly readily granted. In the event, Panavia seemed reluctant to initiate a double standard and consequently a very extensive range of metric standards was derived for use from the start, with some delay; many of these now enjoy a general usage beyond Tornado (some beyond aircraft applications). A metric range of hydraulic couplings for Tornado was developed suitable for 4,000 lb. per square inch hydraulics (27 MPa).

English was nominated as the language of the project, when MRA75, before the UK joined in. This put a heavy personal load on to many German and Italian partners who had to present their case in a language foreign to them, and to understand the arguments of their British colleagues speaking in their own tongue, often colloquially.

Although minor in comparison, there was a language difficulty even for the UK in that much of the 'English' usage in the early phases of MRCA was American, with many abbreviations to be absorbed. Words were often used in a form of code, for example 'Series Baseline' was readily discernible as 'Production Datum' but, without clues, 'Product Baseline' could not be readily identified as 'Prototype Standard'.

Technical Publications were changed from well-known National formats in varying degrees, finally with a heavy load of translation.

Some compensation was perhaps provided by the UK having somewhat more travelling to do, particularly at senior level, since the company HQ and NAMMA organisations were based in Munich.

Feasibility Studies

Following the receipt of an interim feasibility study judged to be very satisfactory before Christmas 1968, which showed the merits of a variable sweep wing in providing a solution to a core requirement with national variations, the Final Feasibility Study at the end of January 1969 was not welcomed by the Officials: it 'still' contained rival designs based on the similar but not identical backgrounds of the participating companies, BAe (then BAC) and MBB (ex EWR) for example.

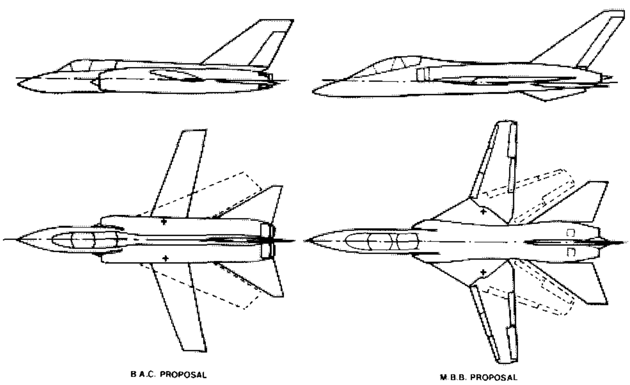

Figure 4. BAC and MBB layouts of January 1969

The Officials left no doubt that were a joint design not produced by the end of March that year then the project would be in jeopardy: further, they required evidence early that month that key points of difference had been resolved. Later, one learned that the Officials saw little chance of such a programme being achieved, but because of the force with which their instructions were registered and the emerging common intent of the Industrial Partners, it was in fact met by a joint design which embodied the best features proposed by the Partners (see Figure 5). Panavia was formed at the same time, March 1969.

The formative technical deliberations themselves were not focused through possibly rather highly-opinionated and dedicated initial project design teams, but through the organisations of the companies in depth. This led to a moderating of individual and initial views and rapidly secured a joint design satisfying the technical conscience of all those concerned.

Protracted trade-off studies were avoided and all partners were drawing on prior national work and experience, so there was much agreement anyway since national laws apply everywhere.

The emergent requirements gave a basis for quantitative judgement and agreement on such items as wing planform, thickness distribution, etc. We certainly did not try to force out a difference between apparently equally attractive solutions; we opted for one and then proceeded to confirm it or perhaps to find out that the real truth of the situation was different to (either) expectation.

On the two aircraft configurations originally presented in the Feasibility Study, many detail differences were apparent but analysis showed that the height of the wing and the spanwise position of the wing pivot were the main items of difference.

The MRCA is smaller than the AFVG or the UKVG which preceded it on the UK route. This meant that the intake ducts, in order to remain clean, increasingly entangled with the wing structure which at the smaller size became inelegant and unduly weighty. Thus, after it was agreed that a range of pivot positions would be studied, a position just outboard of the fuselage side was selected, initially with a retractable in-chord fairing to maintain a clean leading edge. However, a fixed nib was found to have positive advantages when enhanced manoeuvring requirements were specified and this became the definitive layout. The advantages of a high wing location were confirmed in many detailed reactions throughout the fuselage, including weapons and engine installation.

When these two key issues were resolved by in-depth examination at the MD/SE Director level, the rest then yielded to a joint team activity in the first three months of 1969. The emergent configuration has been well proven subsequently into Service. Later some of the few overall changes are mentioned.

Definition

The joint (now Panavia) team having defined the basic aircraft with agreed overall lines and in some internal detail, each Partner then proceeded to engineer his section of the aircraft, working to the SOWs, under the overall control of the System Engineering Directors in their dual modes of responsibility (statements of work).

On Tornado, governed by the work division in terms of aircraft major components, technical lead functions were defined and allocated between the System Engineering Teams and their company line management such as avionics, engine and general systems, structures, flight control and so on.

It was known from early 1969 where components of the aircraft would be designed in detail and manufactured. Work-sharing proportions were basically on production quantities with an aim to minimise - or eliminate - the flow of money across national boundaries. Engine, gun and equipment were involved and rules had to be established as to how the several levels of contracting and sub-contracting, purchase of raw materials, use of facilities, etc. could be accounted, as well as Government and National activities outside Panavia. However, Panavia did enjoy a near complete assignment of authority on equipment selection and control, subject to NAMMA endorsement.

An engine competition was held; the selection of Rolls-Royce as a basis for Turbo-Union with MTU and Fiat was welcome to the UK but the invitation to other companies to compete was genuine enough.

Knowing the location of assigned components and the gun and engine selection, several other responsibilities could be defined:-

> SDR - Specification Design Responsibility - for Equipment Specification, Procurement, Testing, all essentially on the basis of where the particular equipment was fitted in the aircraft.

Many cases clearly occurred where important items of equipment were installed in areas of the aircraft allocated to a partner who did not have system SDR. One example: the power controls for the tailerons in the BAe rear fuselage, fed by hydraulic and electric power within BAe system SDR but part of the MBB primary Flying Control SDR. There was no alternative to full communication and discussion, with most careful Specifications.

Like most projects, Tornado has been through the cycle in which it had to demonstrate in its earlier stages a sufficient level of improvement of performance beyond existing and other projected types to even gain existence. (It then passed through a period when cost was under particular scrutiny with many quite positive reviews and equally positive actions to constrain cost, for example reducing prototypes from ten to nine. As production approached, timescale was highlighted).

During the definition of MRCA, there was extreme pressure for minimum cost. This was often interpreted as low weight and small size: it had to be pointed out that, if overdone this could cause cost increase, through R & D interactions and high density, with maintainability penalties in service.

These were avoided. Nevertheless, Tornado must fly and manoeuvre at high speed at low level with minimum response to turbulence. This is already reduced by high wing loading and, when selected, by high wing sweep but the stiffness and strength of a short fuselage are valuable.

Therefore, as high a density as practical was indeed required. Experience confirms the smooth ride and shows that small size renders sighting, let alone counter-attack, most difficult. Shelter operation is also relevant.

In 1970, one further (and transient) advantage of variable sweep was that by appealing to a slightly different forward sweep angle both single-seater (GAF, IAF) aircraft and two-seater (RAF, GNY) aircraft - both current MRCAs at that time - could be stable.

There was a belief that a single-seater aircraft, with a comparatively modest supersonic performance, possible with minimum avionic fit, might meet German Air Force needs and that the two-seater was unnecessarily escalating the cost of the solution. A study was made by Panavia in the spring of 1970 to summarise what in fact was critical in sizing the aircraft in terms of this single-seat and two-seat issue. This study involved the exposition of critical loading cases, what decided the weight of the structure, indeed what dictated the cost.

Some impression of that study is given by the following figures which may be interesting in their own right:-

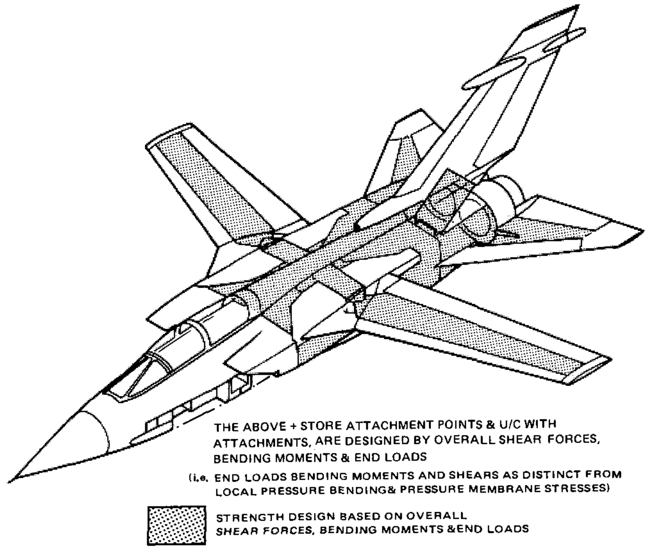

Figure 5. Structure designed by strength

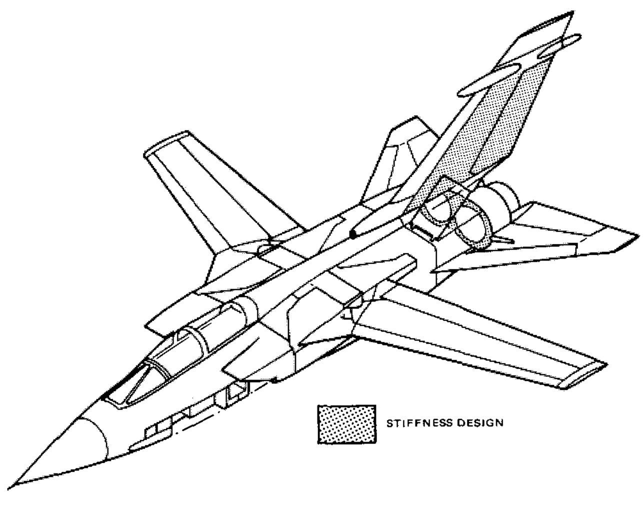

Figure 6. Structure designed by stiffness

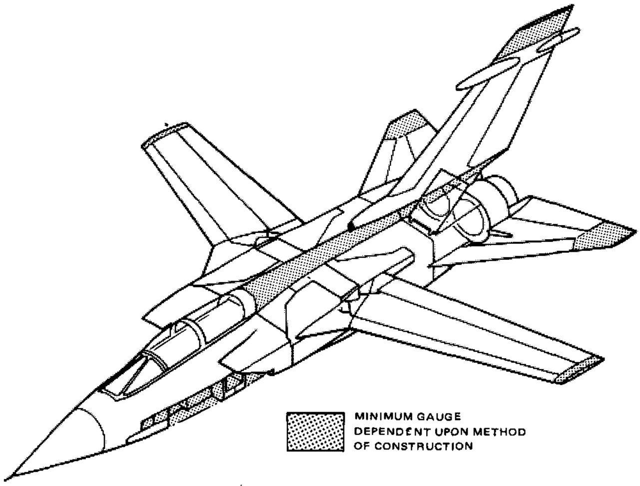

Figure 8. Structure designed by minimum gauge

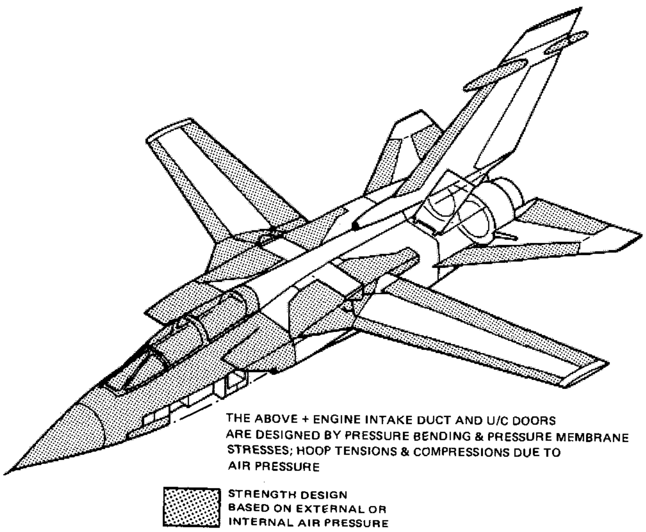

Figure 7. Structure designed by pressure

As a result of these studies and their own appraisals, the German Government and Air Force decided that although it was slightly more costly, the two-seater gave a better overall cost-effectiveness, certainly when allied with commonality with their own Navy version and with that of the Royal Air Force. The Italian Air Force also adopted the two-seater. This episode was one in the train of increasing commonality which has marked Tornado to date. It enabled a common IDS radar to be selected. (Later the commonality between the GAF and GNY variants was further enhanced).

It should be deduced that the Tornado does not appeal to specific or extraordinary gross features of advanced technology - certainly not for their own sake, although what might otherwise have been called development has been fed in from the start by the combined experience and thought of Panavia and its associated companies.

Tornado obtains its balance of cost, performance and timescale through close attention to detail excellence. Key factors are:-

- An advanced technology engine - the Turbo-Union RB.199
- Its aerodynamic configuration, particularly its variable-sweep wing
- Comprehensive avionics
- Comprehensive weapon loads.

Reference[3] illustrated Tornado's attributes in line with modern technologies by comparisons of:

Wing loading, thrust-to-weight ratio
Small size and density
Percentage fuel volume
Weight breakdown

Thrust-to-weight ratio was the major cost driver: compatible with meeting performance, increasing wing-loading gave the greatest saving on unit cost. The Tornado has a high wing loading but exploits high-lift and manoeuvre devices to meet its requirements including landing and take-off speeds and distances.

Particular attention was paid to clean store installations from overall/aerodynamic concepts to details of steadies.

Development

The availability of CAD overall - lines techniques enabled the rapid dissemination to all partners of consistent lines for calculations and wind tunnel testing. This was a very positive contribution to the job, making all the teams feel part of the joint endeavour.

Some illustration of the stability of the Tornado configuration and concept is provided by describing some of the few changes made to the March 1969 datum, but few in Development.

In the early days when the trainers were introduced, some extra 25 cm in the nose was needed to accommodate the second pilot's stick and pedals when fitted, a similar increase in the rear fuselage was needed. Very adequate rear - cockpit forward vision in a trainer mode is given by the canopy. Rearwards vision for the pilot with full aircrew equipment is also excellent. This might not be expected as the cockpit does not have the traditional bubble shape for rear vision, but enjoys a comfortable width in the lee of the radome.

In August 1969 Panavia concluded that another 10% of wing area would meet performance requirements in a better balance and elected to implement this. It was quite a rapid decision and many National Officials were concerned at the sudden, and as they saw it, unilateral industrial move. However, it was accepted and subsequent events have shown its wisdom.

The 1969 concept of store carriage was to utilise the wide fuselage, leaving the wing for overload, but this position was overtaken by increased store-carriage demands as a standard fit.

Wind Tunnel tests in early 1973 with large under-wing tanks showed less stability than expected over a small but operationally important range of subsonic Mach Number. Flow from the intake side, impinging on the tailerons, was sufficiently changed to affect their spanwise loading and, because of sweep, their root torque and jack load. Taileron loading with respect to its own settings symmetric and anti-symmetric were unchanged and adequate. Three degrees less taileron leading edge sweep was found to be an adequate aerodynamic solution not particularly welcome to the tooling area at that stage.

This subject became known as the tailplane problem, although in fact it was the tailplane solution!

On Tornado we exploited wing aeroelasticity to moderate the effects on stability of variable wing sweep and Mach Number range. It was tailored to minimise bending on the fuselage to the extent that wing-structure strengthening embodied during design for fatigue life changed wing stiffness sufficiently to affect wing lift, tail load and fuselage bending moments. We had to strengthen the transport joints, particularly at the rear, but a few kilos extra mass sufficed.

To accommodate the wide range of stores carried on Tornado the Stores Management System (SMS) assists the crew by clearly presenting their loading and release state and managing the sequencing of weapon load release. Initial models of the SMS were comprehensive and to specification, but were seen as too complex and difficult to maintain. Simplification involved one of the few departures from commonality in that the original British supplier continued, after competition, with a simplified version of the initial design for the RAF while the German Air Force and Navy - and finally Italy - opted for an alternative U.S. supplier.

The two Mauser 27 mm cannon in Tornado IDS are a potent weapon: the energy involved when they fire necessitated much effort but finally few changes.

A Lightning was equipped to carry one Mauser cannon beneath it in a pack: it revealed no installation, operating or vibration difficulty. The Rolls-Royce (Vulcan) Flying Test bed carried an RB.199 in a nacelle beneath it (in two positions vertically) which on occasion also had a forebody with a Mauser cannon to anticipate the effects of gun efflux on the RB.199 engine and the effectiveness of its control in such circumstances. No insuperable difficulties were implied.

Rig tests showed fairly high vibration levels. Various measures in the gun and muzzle area then and later did not prove remunerative. The aircraft on the butts showed similar levels. It was therefore decided to embody vibration damping on the mountings of some selected items of equipment. This brought Tornado into conformity fairly literally with emergent Mil. Spec. requirements and a careful development into flight would probably have been possible. The Officials however considered it prudent to apply vibration-table testing to selected equipment over a wider range of sinusoidal and shock spectra. Subsequent changes to equipment were almost entirely at the 'good-housekeeping level' of quality control. Flight experience, has been very satisfactory including the compatibility of the gun with the engine intake.

Selection of Equipment

Selection of equipment design and manufacturing companies is a most important aspect of international collaboration on Tornado lines in which the aspirations (i.e. technical involvement) of the equipment industries of the individual countries concerned need to be respected and balanced: some airframe companies have come rather rapidly to accept that on a collaborative programme they cannot do 100% of the job. Some equipment suppliers viewed that with distaste focussed on the flow of expertise necessarily revealed in submitting detailed tenders required to an agency outside their country, in some cases unsuccessfully.

(The Panavia collaboration agreement to a degree anticipated this: it gave a right of access of partner company information to another against a meaningful need to know, but confined application to Tornado).

Tornado tendering-and-selection procedure with its balancing of technical adequacy, timescale, recurring and non-recurring costs, was modelled on Jaguar, but because of the tri-national nature of Tornado, the size of the project, the concern for involvement and the complexities of introducing 'non-participating nations', it was a much greater task than anticipated. Lengthy deliberations took place on key items: not only worksharing but also expertise-sharing were involved. When the lead sub-contractor had been selected, time was still needed to make arrangements whereby the skill and aspirations of the less successful tenderers, as well as their resources, were induced.

However, these competitive stages (where the national aircraft team often acted as a fierce advocate of their national supplier) forced out many problems which would have normally only been found later. Many partnerships were established - some admittedly under duress - to help later in the product support phase (and hopefully, longer-term, in collaboration on new projects).

Selection still induced a degree of judgement and that cannot help but involve subjective elements: polarising the position, some wished to see the aircraft and its equipment as conventional as possible to minimise risk and thence, to a degree, cost. At the other extreme, some wanted the most advanced technology admitted in order to ensure that expertise was gained by their country and their companies, with benefit to the aircraft through reversed growth factor. (Sometimes the philosophy changed to suit the favourite national proposal!). In the event, a very practical balance has been achieved and a lot of business conferred: the mechanism was joint selection of equipment by industrial recommendation and official endorsement (QCP's Equipment Control Panels). No Panavia equipment recommendation was reversed by NAMMA.

Ground Testing

Reference[4] gives a status survey of MRCA with some particular references to Ground Testing.

The basis for MRCA Tornado was a full and progressive development programme, with minimised flight risk and innovation at that stage.

Relevant Wind Tunnel experience of the Partners was drawn upon: over 40 major models were tested, one third were complete models. At Warton alone some 30,000 hours of tunnel occupation, involved the 1.2 m transonic/supersonic blow-down tunnel and the 2.7 x 2.1 m and 5.5 m low speed tunnels.

Development rigs were allocated between partner companies in line with lead responsibilities avoiding duplication of effort and expense. After being used for basic development, they contributed to qualification and supported the flight programme. There was very close scrutiny by NAMMA of the Panavia Statements of Work to expose any duplication particularly rigorously applied to rigs and testing.

Warton reproduced flying controls on their hydraulic rig and, on occasion, embodied them: in Ottobrun hydraulic load was represented on MBB's flying control rig, not the hydraulics themselves.

The fuel system rig was at Turin, there were environmental control and electric generation rigs at Warton.

Extensive tests of the canopy and sequenced crew and seat ejection were carried out on sleds: some development of limb restraint was needed. There were extensive Bird impact and ingestion tests on the windscreen, canopy and engine.

'Stage 2' avionic software activities were carried out essentially in Munich.

'Stage 3', two Hack Buccaneers were based at Warton. The Tornado itself made good progress and several times this caused the hack contribution to be reviewed. They provided a valuable insurance against delays on Tornado, introduced a lead in development particularly in the early phases and when some displays were updated: they provided valuable inputs to service usage and training (videos).

The stage 4 Avionic rig at Warton although reproducing representative wiring lengths reasonably well, was more reminiscent of filing cabinets in installation terms, permitting ready change and its exploration. At Ottoburn the MBB stage 4 rig more nearly represented the actual aircraft, with the object to cover features including EMC, which depend on installation realism.

Partner companies' flight simulators were designed and/or used for distinct areas of investigation and computation including handling, manoeuvre and attack, target tracking, both air-to-air and against ground targets.

A great deal of work was done to rationalise the workload of the crew from the earliest stages of the programme. This embraced a variety of exercises in mock-ups of increasing realism and eventually simulation, in which ergonomic studies were made and applied. These activities were formalised in international terms by an Official Cockpit Control Committee: this very much involved the Officials, the Engineers and flying personnel of all the Services and Partner Companies. Despite initial misgivings that a proliferation of inputs (each necessarily having a subjective element based on different human characteristics and experience) this process although quite formal did succeed in giving the two cockpits of Tornado high commonality between variants. These are highly regarded by everyone who flies in them.

The particularly subjective area of lighting was assisted by a comprehensive lighting simulator with representative cockpits and displays.

Flight Test

The Tornado first flew on 14th August, 1974. The Flight Test Programme - itself derived by joint Panavia activity and endorsed by the Officials - assigned work and testing to the Partner Companies and prototypes in a sequence and to an integrated concept so as to avoid duplication. It sought to exploit national facilities and airspace capabilities, also being related as far as possible to the engineering functions of the partners. Ref.[5] gives an authoritative account.

Comprehensive instrumentation and efficient flight test procedures were needed to cover the data required in over 5,000 hours development flying to date (including ADV). Instrumentation policy was that each prototype would be capable of undertaking a back-up role for the primary role of the others in various degrees of expedient mixing. Some contingency wiring was also built in.

Telemetry ground stations at Caselle, Manching and Warton were essentially identical, certainly compatible: up to 200 parameters are displayed in real time.

BAe's four prototypes were devoted to flight envelope expansion (flutter, handling and stability): to engine and air intake testing - their envelope expansion and development: rapid rolling, stalling and spinning, gun-firing, measurement of flight loads; in-flight refuelling and dual control assessment.

Most recently the development of SPILS (Spin Prevention and Incidence Limiting System) has been cleared at Warton in line with its derivation there, but in close liaison with MBB.

MBB's three prototypes were mainly responsible for flight performance including take-off, landing, debris and hot-gas ingestion/ thrust reverser and undercarriage aspects; optimisation of the control system particularly auto-pilot and terrain following and integration of avionic systems. MBB undertook a substantial part of the engine flying, gun-firing and covered particular German Navy features.

Aeritalia's particular responsibility for external stores was reflected in their flight envelope clearance for flutter and handling, dropping and firing, flight-load measurements and performance including high ambients.

All partners were, and are involved with Avionics, Navigation and Weapons Systems, including national weapon fits.

Detailed expositions were compiled progressively in anticipation of how each phase of the flight test programme was to develop at each site. In addition, day-by-day telex exchanges between sites, Panavia central and NAMMA, (on occasion hour-by-hour by telephone) on actual progress were found invaluable in matching progress on complementary and mutually dependent programmes, expanding capability and removing limits safely. This was also expressed in formal airworthiness release documentation specific to programme phases, blocks of flying or individual flights.

Aircraft flight clearance was covered by Systems Engineering Directors' validation for their companies' components and, with the M.D., the aircraft overall, with full discussion with aircrew, and the international version of equipment certification and allied procedures defining standard.

Special measures - essentially carefully defined detailed procedures, personal nominations and twenty-four-hour contact arrangements were taken to ensure that any serious unexpected arisings would be quickly and authoritatively communicated between sites with progressive detailing of diagnosis, actions initiated or required including the appropriate constraint of, or release for, further flying. Fortunately the use of these procedures was limited.

Flight testing generally confirmed expectations for the aircraft, its avionics and weapon systems. See Reference[5]. Control in primary and reversionary modes of the CSAS well received by pilots from the start. Detail attention to mechanical friction and increased break-out forces (after considerable discussion) with corresponding gain changes were needed.

Wing sweep, flap and slat operation including sweeping under 'g' has been reliable with very small trim changes, clean or with full loads. Handling qualities with stores are very similar to clean aircraft. Low-speed flight envelope clearance, including spins, involved fitting (and one deployment) of a spin-recovery tail parachute and gantry and an EPU to assist engine restarting and regain of control.

Minor changes to slat-sealing postponed mild wing-rock and subsequent recoverable wing-drop to adequate incidences.

One of the few problems is described in Reference[5]: a reduction in directional stability between about 0.9 M and 0.95 M at low altitude was due to flow breakaway: thrust reverser sealing and local changes to the rear spine and gully resolved this. Autopilot and Terrain following have been well proven essentially to expectations.

One flying aircraft was completely suspended in a ground frame for resonance tests. Flight flutter testing by frequency sweeps and pyrotechnic impulse generators covering CSAS states and stores configurations was guided by theory, and confirmed it: despite the many moving surfaces on the aircraft, such buffeting as does occur is at small levels of intensity. The smooth ride characteristics in rough air have been fully demonstrated.

Panavia were instructed to measure Tornado loads in flight and with modern techniques good results have been obtained. These involved calibration of flying aircraft up to 40% of ultimate load initially clean at Warton, later with stores at Turin.

A full circle of flight-load and strength verification by many proof and 95% ultimate ground static tests has been achieved. Fatigue testing of tail attachments, quite extensive but nominally local testing of the wing pivot area and a full scale aircraft test may be mentioned.

The thrust reversers are an interesting feature of Tornado, involving close integration with the engine and several potential areas of interaction with the overall aircraft. Their development is described rather fully in Reference (6) from a Flight Operations viewpoint.

Engine

The Tornado's two Turbo-Union RB.199-34R three-spool reheated turbofans Reference (7) are required to give economic fuel consumption for cruise and transonic interdiction with high thrust for take-off, manoeuvre and acceleration up to Mach 2 plus. Advanced technology gives a short, light engine with a thrust-to-weight ratio greater than eight, contributing to economy in the overall size of the aeroplane.

Reference (5) gives an account of some of the development activities on the engine and its control gear. It anticipated satisfactory performance now achieved in service: as in development, the advantages of modular engine construction are confirmed.

Early high-pressure turbine blade failures, were always contained, have never impared engine functioning, being only detected by ground inspection.

A joint activity between Panavia and Turbo-Union identified and detailed all flight and ground problems and their solution relevant to either side of the interface which was fully documented from geometry through to mutual deliveries of hardware.

A smooth intake duct was a feature of the aircraft and no special dynamic instrumentation was called up. Aims for distortion level and its accommodation overlapped and were broadly achieved. It was however, agreed that were difficulties encountered the economic solution would be persued even if on the side of the "innocent party". As the flight envelope expanded, the incidence of surging increased and it was (paradoxically the non-development flying of the 1978 SBAC Farnborough Show which confirmed the susceptability of the left hand engine - intake combination to surge. For reasons which are doubtless outlined in Reference (8), swirl was finally identified as a major element and a solution determined.

ADV

A fuller introduction of the Air Defence Version in this narrative is now overdue.

The ADV Version of Tornado is required by the United Kingdom to fulfil NATO tasks including the defence of the UK and its sea approaches. It is a full part of Panavia's activity, although the majority, but not all, of the changes occur in the avionics and front fuselage, thereby mostly involving the Warton team, but by no means entirely.

Purchase of ADV aircraft was always part of the UK buy, and definition proceeded in parallel with the early IDS Definition Phase, but it was intensified from 1973 onwards. This variant was required to have a minimum change from the IDS version, and in pursuit of this several of the original studies assessed air-to-air weapons carried on under-wing pylons. With reasonable estimates of installation drag, performance would not have been adequate in terms of agility and radius. Extra engine development to rectify this would have meant further cost of development of the RB.199 engine which was itself still at that time emergent in its first form. Thus a cleaner missile installation was sought. The weapon involved, Skyflash, is a British development of Sparrow. To fit four of these quite large weapons to what was, by that time, a defined Tornado in a clean installation using existing E.R.U.'s demanded considerable ingenuity. The fins and wings were ingeniously accommodated internally with minimum change. About half a metre length was added at the forward transport joint for the front pair. A balanced increment of fuel in this extension and in the large fin is embodied. Forward movement of the centre of gravity is compensated by higher sweep on the inner section of the wing, with the resulting lower thickness-chord ratio root also reducing drag: so does the slimmer radome for the intercept radar with its look-down mode.

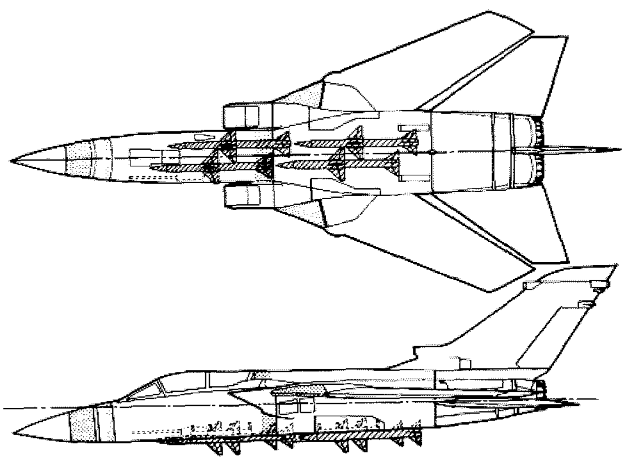

Figure 9. ADV Illustrating Changes from IDS

To carry four Skyflash with the minimum change described, it was necessary to dispense with one Mauser cannon. This enabled further improvements in maintainability to be secured.

Thus, the ADV has a multiple strike capability: four Skyflash, short range missiles and a gun. The Foxhunter radar represents the major avionic change: a major part of the IDS avionics is retained.

A fuller description of ADV is in the Annex.

Detailed design of the ADV has followed existing IDS assignments, but with a particular lead function at Warton.

Flight testing began on 27th October, 1979 and embraces three development aircraft. The qualities of the IDS version are in no way diminished in aircraft terms, this leaving the main task as the proving of the radar and weapon system in its avionics and mechanical and armament senses.

The majority of IDS armament positions are retained.

Production Investment and Production

(Back to IDS!)

The deliberations of 1969 determined which parts of the aircraft would be built by the partners:-

- BAe: front fuselage, rear fuselage, tailerons, fin and rudder
- MBB: centre fuselage
- Aeritalia: wing and attachments

Inside each country there is considerable sub-contracting inside and outside the partner companies. Some transfer of wing fittings from Italy to U.K. was necessary for work sharing and investment balance as production began.

The measures taken to ensure physical continuity were typical of those for any aircraft to be built in several places:-

- provision of appropriate physical joints, avoiding artificiality of location
- establishment of geometric continuity including external lines by overlapping lofting and mock-ups in joint areas
- interchangeability media, and so on.

Since the problem was recognised, no difficulty was experienced in the physical marry-up of Tornado at any stage and the requirements for interchangeability in service were thereby assisted from the start and proven in the P.I. phase.

It was in the action and documentation supporting the production 'split' that the main engineering challenge arose, focussed in the Design area.

In 1969 a drawing system was jointly derived which was new to all the partners, but compatible with their differing internal procedures: not solely the face of the drawing, but supporting bills of materials, schedules and the overall collation of Design and Build Standards were all important. Applicability and effectivity measures were of course particularly so to ensure compatibility.

The many variants of Tornado have been described and while it is true to claim a high degree of commonality overall, local areas such as nose electrical wiring did present a considerable task in terms of precise definition required for actual built. Although the increasing commonality of the Tornado with time was welcome in terms of overall economy, it added to the task of detailed (re) definition particularly on electrical wiring.

Up to the signing of the first production contract 1976, alterations were embodied with a scrutiny by Panavia and partners and with general oversight by NAMMA to the general level which applied during development. Considerable care had to be taken to ensure that changes having "referred effects in other partner's areas were defined and the appropriate "complementary alts." raised. The first prescription of new variants and equipment updates could immediately be recognised for overall content.

Again, careful communication , discussions, scrutiny and record could alone provide the cohesive approach required.

With the signing of the production contract, the formality of Modification Procedure was introduced. The presentation of the case for Mods. has been a demanding and continuing task, involving four users whose priorities could differ but who were all involved in payment.

The coverage of change of ADV, itself at a Development stage with alt. procedure applying contemporary with, and using major components of IDS itself on a formal production status has revealed many subtleties. It should be restated that this all had to be conducted through a period of increasing financial stringency, continuing to date. The Engineers have had to enhance their already keen understanding of cost issues.

Value Engineering was a formal requirement from the development stage and fortunately very often confirmed the adequacy of the datum solution (within the sensible allowance of estimating tolerances). However, some changes were admitted and later merged with productionising modifications - always foreseen in principle and intended to help manifest the production learning law Changes went both ways in "sophistication" terms: some fabricated items were replaced by castings, forgings and machined items, some by S.P.F. Titanium or Carbon Fibre Composite; some components went "back" to fabrication.

Despite some financial posers as to who pays the non-recurring cost of such changes and who draws the benefit, this activity has been fruitful and the production learning law obtained.

SERVICE ASPECTS

The aircraft is now delivered as from 1980 and is giving good service, to programme, in the partner countries and in their joint TTTE activity (Tornado Tri-national Training Establishment, Cottesmore).

Thus, arrangements made for the product support of Tornado are giving encouraging results. Ground equipment, spares and technical publications have all had their problems, but none which have not been covered by prompt and expedient support action. Reference [9] gives an independent witness of service satisfaction: some few local exceedences of failure rate are more than compensated by ease of rapid rectification exceeding expectation.

Maintainability was kept very much in mind from the start on Tornado - it is part of the formal numerical requirements laid upon Panavia. Many features of the aircraft contribute to a good service reputation: many access panels, a doubly-hinged radome for access to both front and rear of the radar: a windscreen hinging forward to give access to the rear of the instrument panel, and engine access via hinged/rapid-removal doors. The engine has a minimum connection to the aircraft and its services.

BITE (Built-In Test Equipment) provides in-flight and ground check on equipment serviceability either continuously or on demand. This reduces ground-test equipment and enhances flexibility of operation.

A great contribution to NATO standardisation has been made by Tornado: at an engineering level, this has meant specifications not only for the aircraft but for its equipment and ground equipment, down to a very fine level.

Good support and co-operation analogous to that of CSDE (Central Servicing and Development Establishment of the RAF) has been extended to the other partners.

As described, it was - and is - the duty of all 'Panavia' Engineers when contacted by NAMMA or Service Officials to refer the matter to the appropriate SDR Companies or to initiate any action or discussion required. Similar arrangements apply in the service support phase, but through familiar Product Support organisations. Panavia equipment purchases for spares extrapolate earlier development stage management arrangements, but for technical publications some re-arrangements of task have been needed.

Conclusion

Increasing pressures on the defence budgets of the countries concerned made it unlikely that any one of them in isolation could finance a demanding and, therefore, comprehensive product such as Tornado. Collaboration offered an attractive route to the procurement of this very advanced weapon system for which there was a clear military need. The greater production quantity brought learning laws into prominence which would otherwise have been denied: sharing of R & D costs and the release of funds enabled a new engine to be embarked upon. This in turn enabled the aircraft to be made smaller and more effective than it would have been by the application of existing engines.

Verbal requests on the content of this paper asked for Engineering rather than Management aspects to be addressed: this was difficult since a description of international effects could not avoid some management element. Natural laws must always apply to Engineering processes and in their final implementation Tornado, like any other aircraft must respect these. Thus, it is at the interfaces where the innovation lies. These also apply to any aircraft: it has to be defined, made controllable, stressed, equipped, built, tested and supported and many people and areas are involved even in a single-company project: these are well known. It is hoped, therefore, that some insight into the special means of international discussion, proposal, agreement, definition has been given. Clear and consistent presentation, excellent communication are most important but paramount by far is the achievement of trust and goodwill in the common venture.

Annex 1

Tornado Characteristics

(See Reference [10] for a fuller description).

All Tornados are two-seat, twin-engined aircraft. A large, doubly-hinged, radome leads back to generously-sized cockpits with zero-zero rocket seats under a single-piece canopy.

The three-position variable-sweep wing, has extensive leading-edge slats, trailing-edge flaps and electrically-signalled spoilers which also act as lift dumpers - all controlled through a central Wing Sweep Control Unit.

Flight control is by the low-set tailerons, moving symmetrically to pitch the aircraft, anti-symmetrically to roll it. The rudder on the large single fin is conventional.

Two Turbo Union RB.199-B4R engines in the rear fuselage carry thrust reversers of target type. The intakes have variable horizontal wedges and auxiliary doors. Engine connections are fuel, control electrics, double-purpose (starting and power take-off) shafts and air tappings. An APU starts the first engine and can run the aircraft systems on the ground.

Thrust 9000 lb dry, 16000 lb re-heat, for each engine. Mauser 27 mm cannon are fixed in the forward fuselage.

The strength and geometry of the tricycle undercarriage are designed to maximise the armament load. A wide variety of weapons, overload tanks, pods, etc., are carried under the fuselage, and under the wings on swivelling pylons.

Access to equipment and guns is provided by many access panels: a forward-hinging windscreen and large engine doors aid installation and inspection.

A large proportion of the aircraft volume in wing and fuselage (and fin where specified) is occupied by fuel tanks, with self-sealing matched to sequence and location.

To the brevity of this paper, the aircraft systems are unremarkable: 4000 psi hydraulics: 115/200 V, Hz main electrics. They provide safety appropriate to the twin-engine level:

No single equipment failure shall hazard the aircraft.

No single failure shall cause the mission to be aborted.

They have extensive built-in-test and on-board check facilities, as does the avionics.

Attention to survivability and electromagnetic capability has received balanced attention throughout and in the physical layout of equipment and systems.

The command Stability and Augmentation Control System (CSAS) is electrically signalled triplex; quadruplex into the taileron controls. After several levels of reversion, mechanical back-up is available (but not on the rudder).

The basic structural material is light alloy, some honeycomb through rivetted structure to NC machined. Taileron spigots, undercarriage areas are steel. Titanium is principally used in the E.B.W. centre wing box and associated lugs, the wing pivot pin, flap tracks and rear fuselage keel.

The span is 46 ft. at 25° sweep
28 ft. at 68° sweep

The length is 55 ft.
Weights up to 55,000 lb. have been mentioned.

The IDS avionics are remarkable for their comprehensive nature and detailed excellence and include a doppler-monitored inertia-navigation system; the navigation system can be updated by visual fixes, by using the ground mapping radar. This system is capable of very high navigation accuracy and enables Tornado to locate a target in almost any weather condition for low-level first-pass attack without alteration of altitude. Accurate range is provided by laser.

The terrain-following radar and radar altimeter feed the HUD and TF display in manual mode, but automatic TF at high subsonic speed at 'sea level' is the normal operation.

The displays indicate the path that the aircraft will fly over the terrain ahead, enabling the pilot to monitor the system; he can revert to manual at any time. Various automatic safety features are incorporated.

Ballistic weapon characteristics are stored in the central computer which determines accurate release points, in conjunction with the SMS.

ADV Avionics

(See Reference (11) for a fuller description).

A "Foxhunter" Air Interception and Interrogation fire-control Radar in the nose of ADV operates in track-while-scan or range-while-scan modes. It uses pulse-doppler techniques (frequency-modulated interrupted continuous wave) to track about 10 targets simultaneously; a typical target range being up to 100 nautical miles.

A radar warning receiver is connected to a computer which analyses detected emitters and provides a read-out on a target and its direction of approach.

The Navigator has two TV displays which can operature in a number of modes, basically a range/azimuth display incorporating track-while-scan data. An alternative is a Tactical Planning format. In addition to its air-to-air operation, and air-to-ground ranging and mapping facility (VAS) is also featured on ADV.

List of References

1. "The MRCA Project" A paper by B.O. Heath published in "The Aeronautical Journal" of the Royal Aeronautical Society - Volume 74 No. 714 dated June 1970.
2. "The MRCA Programme - Research Development and Production Activities" Aeritalia and Italian Contribution - An Aeritalia paper Ref. PM 79161.
3. "MRCA Tornado: Achievement by International Collaboration" by B.O. Heath. Published in "The Aeronautical Journal" of the Royal Aeronautical Society dated September, 1979 Volume 6 No. 9.
4. "A Status Summary of the MRCA Project" by G. Madelung published in "The Aeronautical Journal" of the Royal Aeronautical Society dated December, 1973.
5. "Europe's Tornado - Flight Development of the MRCA" by R.P. Beamont published in "Aerospace - The Journal of the Royal Aeronautical Society dated April 1976 Volume 3 No. 4.
6. "Development of the Tornado Thrust Reverser" by J.D. Eagles (Chief Test Pilot at BAe Warton) A paper given at the 13th Annual Symposium of the Society of Experimental Test Pilots, European Section - 4th to 6th May, 1981.
7. "Power Plant for Tornado - The RB.199" by J.C. Allan published in "Aerospace" - The Journal of the Royal Aeronautical Society dated April 1976 Volume 3 No. 4.
8. "Intake Swirl - A Major Disturbance Parameter in Engine/Intake Compatibility" A paper by F. Aulehla of MBB to be given at 13th Congress of the International Council of the Aeronautical Sciences, Seattle on 26th August, 1982.
9. Report on the Entry of the Tornado into Service by the Luftwaffe Tornado Introduction Team given to General Oblesser (German Airforce Chief of Staff) and representatives of the Press on 2nd December, 1981. (Summarised in "Flight International" 23rd January, 1982).
10. "Tornado Takes-off" An Article in "Air International" dated September, 1976.
11. "The Tornado Two Takesoff" An Article in "Air International" dated November, 1979.