Taranis and beyond: inspiring aerodynamic capability

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ABSTRACT

In his 1916 book, *Aircraft in Warfare, the Dawn of the Fourth Arm*, F.W. Lanchester wrote:

"The supremacy of British aircraft can only be maintained by the adoption of a thoroughly progressive constructional policy, guided constantly by the most recent scientific discovery and research, and by utilising to the full information and experience gained in the Services."

The recent successful flight trials of the Taranis low-observable unmanned demonstrator aircraft provide the latest evidence of the UK's continued capacity for the entire design, development, manufacture, and flight testing of world-leading combat aircraft, particularly with regard to Aerodynamics. Taranis is both the culmination of many years' research and development in the UK and a starting-point for the next generation of UK combat air systems.

In this lecture, Taranis is reviewed, in such detail as current sensitivities will allow, in the wider context of UK combat aircraft aerodynamic capability, exemplified by the leading roles taken by the UK in the Tornado and Typhoon programmes and the important contribution made to the development of the F-35 Lightning II Joint Strike Fighter.

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The immediate technical challenges associated with the aerodynamic design and qualification of a low-observable air vehicle are considerable. In this instance they have been compounded by the balanced view taken within the project of trade-offs against many parameters. However, the UK aerodynamics community faces equally stringent challenges in terms of the identification and delivery of the most appropriate future systems; increasingly complex and demanding operational and functional requirements; and, perhaps most of all, maintaining an affordable and cost-effective capability in the face of strict budgetary pressures and austere economic conditions.

Nevertheless, those challenges are accompanied by a wide range of opportunities, namely for national and international partnership; radically innovative engineering solutions and approaches; new thinking; and the engagement of the best minds and ideas in the UK academic community.

Taranis represented a big integration task, requiring a particular set of skills to pull together the total package, resting on a bedrock of mastery of the technical issues. It has been an inspirational experience for those of us who have worked on it. It has demonstrated that the UK is capable of achieving the most demanding current and anticipated military aerodynamic requirements and has signposted the way to an exciting and nationally important future.

NOMENCLATURE

G transmitting and receiving gains (assumed equal)
P_r received power
P_t transmitted power
R range
σ Radar Cross-Section (RCS)
λ radar wavelength

1.0 INTRODUCTION

As we approach the centenary of the outbreak of WW1, it is appropriate to consider some of F.W. Lanchester's writings during that conflict and to reflect on the nature and purpose of the military aerospace industry. In 1916 Lanchester published a book entitled *Aircraft in Warfare, the Dawn of the Fourth Arm*. The book is probably chiefly known for its contribution to what is now recognised as the science of operational analysis. In particular it laid out a mathematical approach to the subject of force concentration and propounded the 'N-square Law'. It also reflected Lanchester's wide-ranging interests and opinions, considering topics as diverse as optimum choices for aircraft armament and national strategic aeronautical policy. In connection with the latter, amongst numerous observations and recommendations, Lanchester wrote:

> "*The supremacy of British aircraft can only be maintained by the adoption of a thoroughly progressive constructional policy, guided constantly by the most recent scientific discovery and research, and by utilising to the full information and experience gained in the Services.*"[1]

Here Lanchester raises the subject of what we have come to call UK Combat Air capability. The recent successful flight trials of the Taranis low-observable unmanned demonstrator aircraft have provided the latest visible evidence of that continued capability. The century since the outbreak of WW1 has seen many exceptional and iconic British aircraft, not least in the almost 70 years from the end of WW2. Full consideration of even that constrained period would entail a whole series of lectures. This lecture considers Taranis in the context of the author's own experience, which concentrates on the aerodynamic design team of BAE Systems Military Air & Information (MAI) at Warton and its antecedents.

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2.0 THE JOURNEY TO TARANIS

Taranis is the product of an aviation heritage and organisation which effectively began at the end of WW2. With vision and ambition which would be impressive even today, the then English Electric Company entered upon the field of aerodynamic design with the Canberra, a twin-jet bomber possessing performance characteristics superior to the leading fighters of the day.

The awareness of the threat posed to the UK by high-altitude jet bombers led in turn to the requirement for a supersonic interceptor and to the English Electric Lightning. Growing up not far from Warton during the early 1960s afforded many opportunities to witness the truly awe-inspiring spectacle of a Lightning take-off and routine supersonic operation – at that time still permitted – over the adjacent Lancashire coast. The P1 prototype officially exceeded Mach 1 on its third flight, though later analysis revealed that transonic air data pressure error characteristics indicated that the aircraft was actually supersonic on flight one. The subsequent P1B, which became the Lightning, was the first British aircraft to achieve Mach 2 in level flight.

Both Canberra and Lightning were required to achieve ground-breaking levels of aerodynamic performance and pioneering research into aerodynamic phenomena. The resulting capability found its next expression in the ill-fated TSR2, which first flew in 1964 but was cancelled in 1965. Although the UK was still capable of world class aerodynamic design, the demise of TSR2 finally signalled that the UK faced practical limits of project affordability. Henceforth, it would be essential to provide evidence of the control of both cost and risk before securing commitment to such large programmes. Even the VSTOL research and development which led to the iconic Harrier depended ultimately on external interest and funding, particular from the United States Marine Corps. Those constrained financial and political circumstances ushered in the present era of international co-operation and collaboration.

Initial collaborative activities involved the UK and France, echoing the civil Concorde project. A tangible outcome was the SEPECAT Jaguar light attack and trainer aircraft. Discussions also took place about more complex systems, with similar levels of capability to those envisaged for TSR2, typified by the so-called Anglo-French Variable Geometry (AFVG) study. The underlying concept used variable geometry (i.e. wing sweep and a high lift system, which might nowadays be considered examples of 'morphing') to address the conflicting requirements of different parts of the flight envelope. In particular, high-speed low-level attack capability had to be reconciled with the ability to operate from what were expected to be damaged and artificially shortened airfields. With a change of participants along the way, the concept evolved into the Multi-Role Combat Aircraft (MRCA), and ultimately the UK/German/Italian Panavia Tornado. Tornado still forms the mainstay of the UK strike capability.

The MRCA/Tornado programme entailed significant aerodynamic development. It also afforded many lessons in practical international collaboration. Whilst it might be tempting to wish that the need for such collaboration would simply 'go away', the experience of the last five decades shows that will not happen. Realistic and honest assessments must be made of the partners' respective capabilities, for example in aerodynamics, which are then balanced with national and business aspirations in arriving at programme workshare. Such is the importance and long-term impact of such assessments that they must be based on systematic evidence and not on over-simplified snap judgments. The nature of aeronautical science renders it equally unlikely that partner nations are either 'years behind' or 'years ahead'. The ability to form efficient international teams and work effectively in collaboration is itself important. It has specific lessons which take time to learn and which cannot be ignored. There is ample evidence from both the civil and military aerospace industries of the success of European collaboration and of the UK's effective role within it.

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As Tornado entered service at the end of the 1970s, attention turned to prospective concepts for a next major combat aircraft programme. International discussions led through various potential concepts and collaborative arrangements. In the early 1980s those manifested as a fighter concept, the UK/German/Italian Agile Combat Aircraft (ACA) and its UK contract element, the Experimental Aircraft Programme (EAP) demonstrator. Funding pressures within the other partner nations resulted in the aerodynamic aspects of EAP being largely, though by no means entirely, discharged by the UK.

In terms of aerodynamics, EAP was a highly capable aircraft. In particular, it built on the experience in Flight Control Systems (FCS) of the then British Aerospace (BAe). Throughout the post-war development of the Canberra, Lightning, TSR2, Jaguar, and Tornado BAe had progressively developed FCS of increasing complexity and sophistication. The application of emergent fly-by-wire (FBW) technology to the stabilisation and control of unstable airframes was de-risked through the FBW Jaguar programme. The resulting capability allowed the exploitation of longitudinal instability to optimise both subsonic and supersonic manoeuvring performance. EAP combined a full-authority quadruplex digital FCS, featuring no mechanical backup, with a longitudinally unstable configuration. It demonstrated the supersonic acceleration and manoeuvre necessary for beyond-visual-range (BVR) combat, exceeding Mach 1 on its first flight and achieving Mach 2 during its flight test programme. It also pioneered the sub- and transonic performance and agility required for close-in combat, including the demonstration of incidence and 'g' protection and an extent of what was then termed 'carefree handling' (see, for example, Ref. 2).

By the later stages of the EAP programme, further international discussions and agreements had led to the establishment of the four-nation European Fighter Aircraft (EFA) programme. EFA brought together the UK, Germany, Italy, and Spain and eventually became the Eurofighter Typhoon. Typhoon is now successfully in service with the Royal Air Force, the air forces of the partner nations, and a number of export customers. It is the direct descendant of EAP in terms of airframe performance and agility.

As international partnerships mature, there must of necessity be an increasing degree of mutual interdependence in order to realise the financial benefits of collaboration. In those circumstances, although individual nations may have overall design responsibility for particular systems (known as SDR), typically no single nation has sole responsibility. It is therefore easy to lose sight, for example, of the extent of the involvement of the UK in Typhoon aerodynamics. The UK continues to play a role which is both central and fundamental to the development of the design and the evolution of the overall weapon system. Detailed illustrations can be found, for example, in Refs 3 and 4. Participation in the Typhoon programme has enabled the sustainment of a strong UK capability at the forefront of combat aircraft aerodynamics.

The rich heritage of the Harrier and its predecessors established and sustained a unique capability in Vertical/Short Take-Off and Landing (VSTOL) aerodynamics. From the early stages of those programmes there was an aspiration to expand the flight envelope to higher speed, range, payload, and manoeuvrability. The financial constraints affecting the industry in general also led to the exploration of opportunities for international collaboration on VSTOL. By the late 1980s a Memorandum of Understanding (MoU) was signed for a joint US/UK Advanced Short Take-Off and Vertical Landing (ASTOVL) research and study programme (see Ref. 5). Supplemented by further national research activities, the existing UK experience and capability in VSTOL contributed directly to the developments which led to the Joint Strike Fighter (JSF) programme. JSF is a chiefly US-led programme, but the UK continues to play a key part in its aerodynamic development, particularly with regard to flight control laws, ASTOVL propulsion integration, and other niche ASTOVL skills. BAE Systems MAI aerodynamicists are an active and important part of the F-35 Lightning II team.

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3.0 THE SCOPE OF AERODYNAMICS WITHIN BAE SYSTEMS MAI

Most organisations involved in aerodynamics have different interpretations of its scope and all of them are correct. In the particular case of BAE Systems MAI, the aerodynamic capability is wide-ranging. It is customarily regarded as sixteen distinct skill streams, organised into three principal skill groups:

- Flight dynamics, comprising:
  - Flight mechanics, including stability and control and handling qualities
  - FCS flight control law design and development
  - Guidance control law design and development
  - Air data
- Aerostructures, comprising:
  - Static (i.e. quasi-steady-state) loads
  - Dynamics (i.e. unsteady/time-variant loads)
  - Aeroelastics (quasi-steady and flutter)
  - Aeroservoelastics, also known as structural coupling
  - Acoustics
  - Store release
- Configuration aerodynamics, comprising:
  - Configuration design, including wing design and drag estimation
  - Performance
  - Propulsion integration
  - ASTOVL
  - Propeller modelling
  - Icing analysis

These basic skill streams are supplemented by integration-level skills in:

- Aerodynamic integration and
- Concept engineering

and supported by modelling and analysis, including:

- Computational Fluid Dynamics (CFD) and
- Wind tunnel, ground, and flight test data

4.0 TARANIS: REVOLUTION AND EVOLUTION

Throughout the post-war combat aircraft heritage described above, aerodynamicists enjoyed an almost unchallenged degree of influence on the external shape of aircraft. It was limited principally by constraints of overall size and the local accommodation of structures and systems, chiefly the main radar sensors and powerplant. The need to ensure survivability against the most capable threat systems requires a rigorous adoption of the disciplines of Low Observability (LO), or stealth.

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An unfamiliar equation has come to dominate the aircraft design process, namely the radar range equation (see Ref. 6):

$$P_r = P_t G^2 \sigma \lambda^2 / (4\pi)^3 R^4 \quad \ldots (1)$$

The principal implication of the equation for aircraft engineers in general and aerodynamicists in particular is that, in order to reduce the detection range by a given factor, the RCS must be reduced by the fourth power of that factor. Thus, in order to achieve a significant reduction in the range for detection or successful engagement, the required reduction in RCS sets a severe engineering challenge.

The anticipated impact of the challenge of LO on aerodynamics in the UK was assessed several years ago and is discussed, for example, in Ref. 7. Based upon that assessment, various plans and programmes were put in place to mitigate the perceived aerodynamic risks and acquire the necessary data to inform design decisions. As ever, affordability and cost-effectiveness exerted a controlling influence. Research and demonstration activities were funded by both Government (MoD) and Industry.

Concurrent studies into operational system concepts increasingly concentrated on Remotely Piloted Air Systems (RPAS). However, LO requirements have continued to be the dominant influence on aerodynamics.

In parallel with more customary and established research routes to risk mitigation, it also became clear that only innovative approaches to technology and system demonstration could meet the challenges of affordability in the UK. In particular, BAE Systems MAI undertook a series of affordable flying demonstrations. Some of those demonstrations were chiefly concerned with mission and vehicle management systems. Others addressed the aerodynamic challenges associated with LO configurations, particularly through the Raven and Corax demonstrators.

The combined approach to risk mitigation through established and innovative research and demonstration created the conditions in which a large-scale LO flight demonstration by the UK became feasible. A project charter was signed between DE&S, BAE Systems, Rolls-Royce, QinetiQ and GE Aviation to work together to design, manufacture, test and fly an experimental 'mission representative' UAV system. With BAE Systems as prime contractor to DE&S, the Team Taranis partners have worked closely with the customer and Industry to develop and demonstrate new technologies on a flying demonstrator.

The participants' specific roles were:

- **BAE Systems** – Design, final assembly and test, flight systems, flight control system, ground station, system performance measurements, integration, qualification and trials, airframe and aerodynamics, communications integration, LO, intake system, sensors and mission avionics and autonomy
- **Rolls-Royce** – Engine and exhaust systems plus systems performance measurements,
- **GE Aviation and Triumph Group** – Flight systems
- **QinetiQ** – Communications and high level mission autonomy
- **Cobham** – Communications antennas.
- **APPH** – Undercarriage
- **Claverham** – Flight control systems (Actuation)
- **DSTL** – System performance measurement, MoD technical advisors
- **GE Intelligent Platforms** – mission avionics hardware

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Figure 1. Taranis in flight.

Although the national sensitivity around the LO configuration and demonstration demanded a UK national approach, it should be acknowledged that an important contribution was made by BAE Systems Australia, based on their experience of guidance and control systems for unmanned vehicles.

5.0 TARANIS: THE STEALTH CHALLENGE

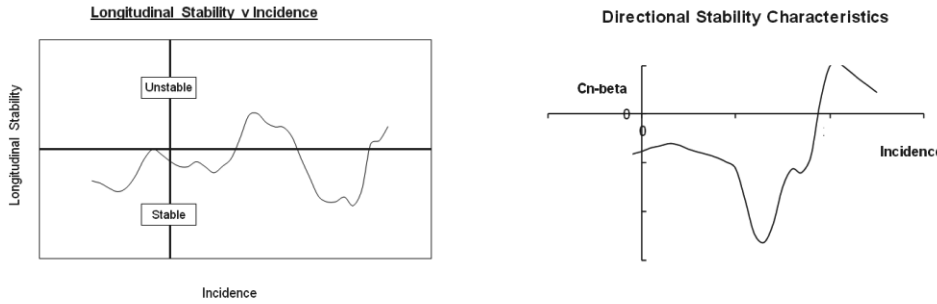
As anticipated, the aerodynamic challenges of LO on Taranis affected every aspect of the configuration, chiefly:

- The huge challenge of flying and controlling an inherently aerodynamically unstable aircraft, possessing a compromised configuration with non-linear aerodynamic characteristics and severely constrained stabilisation and control surfaces
- Intake and exhaust systems which push the boundaries of engineering in order to provide a satisfactory supply of air to the engine while meeting the signature requirements
- Aerodynamic effects of and on materials and treatments
- State-of-the-art sensors, including air data
- A configuration allowing usable real estate for mission sensors, antennas and payload without compromising the signature requirements

5.1 Stability and control

Based on preceding UK research and demonstration programmes, an innovative approach to stabilisation and control was developed (see, for example, see Ref. 8). The class of configurations represented by Taranis typically feature a number of adverse external aerodynamic flow features, leading to challenging non-linear stability and control characteristics. Typical examples are illustrated in the following figure, showing variations with incidence of longitudinal stability, dC_m/dC_N, and directional stability, $C_{n\beta}$.

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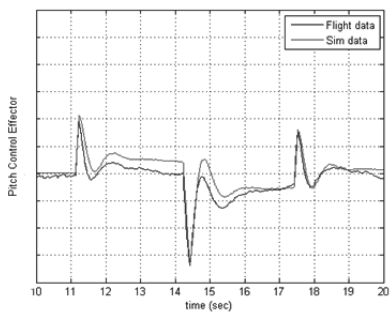


(a) (b)

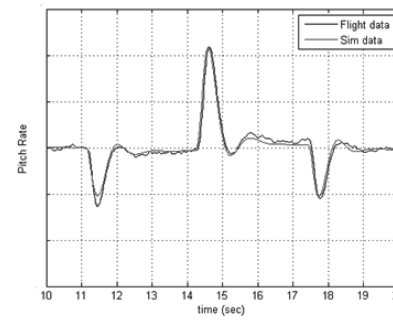
Figure 2. (a) Longitudinal stability *vs* incidence (b) Directional stability *vs* incidence.

Longitudinal stability displays an unstable pitch non-linearity ('pitch-up'). The directional stability shows an example of a rapid-onset unstable non-linearity, colloquially known as a 'Cn-beta bucket'. The onset of both pitch and yaw non-linearities arises from the onset of initial flow breakdown. During the process of design development, detailed assessment is necessary of the effects of such non-linearities, together with the effectiveness of available controls. The assessment of controllability and resulting stability margins influences design decisions about which aerodynamic features can be accommodated and which must be ameliorated by changing the configuration design.

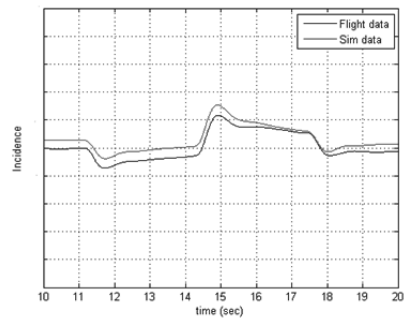
In order to support the design and flight clearance of the Taranis flight control laws, a detailed aerodynamic description of the aircraft's stability and control characteristics was compiled,



(a) Pitch control effector



(b) Pitch rate



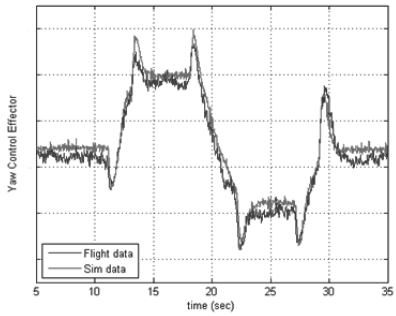
(c) Incidence

Figure 3. Pitch manoeuvre.

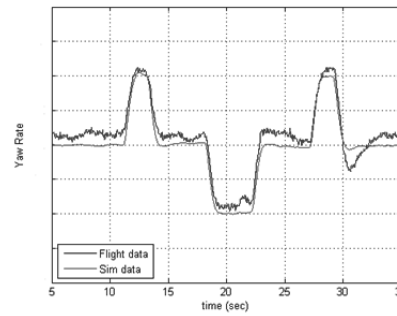
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also known as an S&C dataset. The dataset was chiefly based on wind-tunnel data, supplemented with CFD analysis and the use of empirically-derived datasheets. The flight control laws team used the dataset as input to their suite of six-degree-of-freedom simulation models.

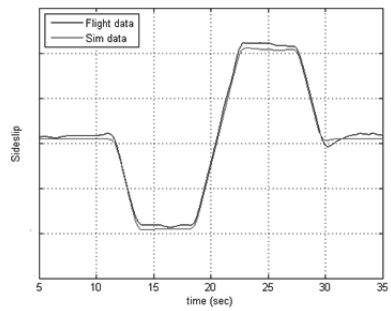
Figures 3, 4, 5 and 6 show examples of comparisons between simulated and flight measured parameter time histories for a sample of flight test manoeuvres in pitch, yaw, roll, acceleration and deceleration.



(a) Yaw control effector

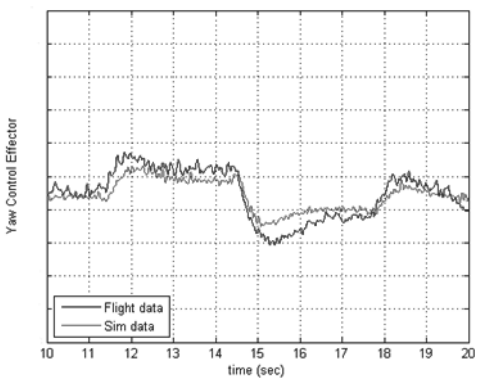


(b) Yaw rate

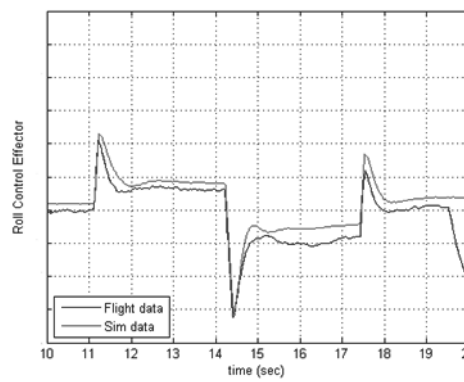


(b) Sideslip

Figure 4. Steady heading sideslip manoeuvre.

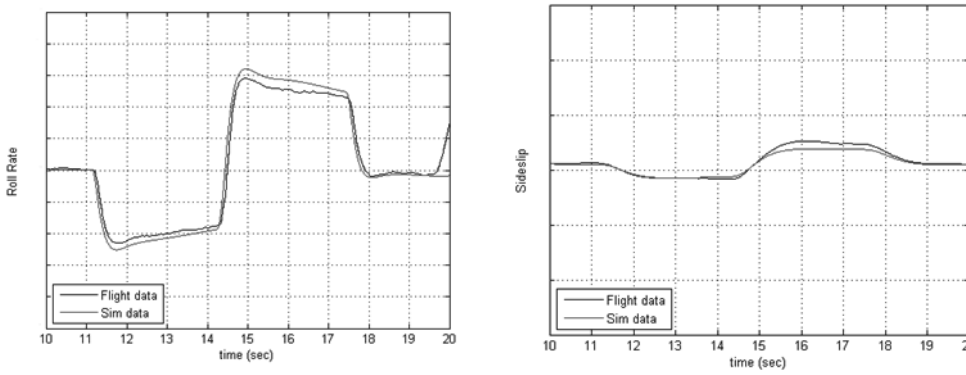


(a) Yaw control effector



(b) Roll control effector

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(c) Roll rate (d) Sideslip

Figure 5. Roll manoeuvre.

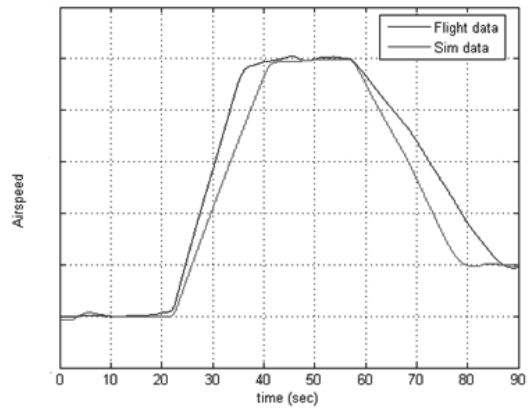


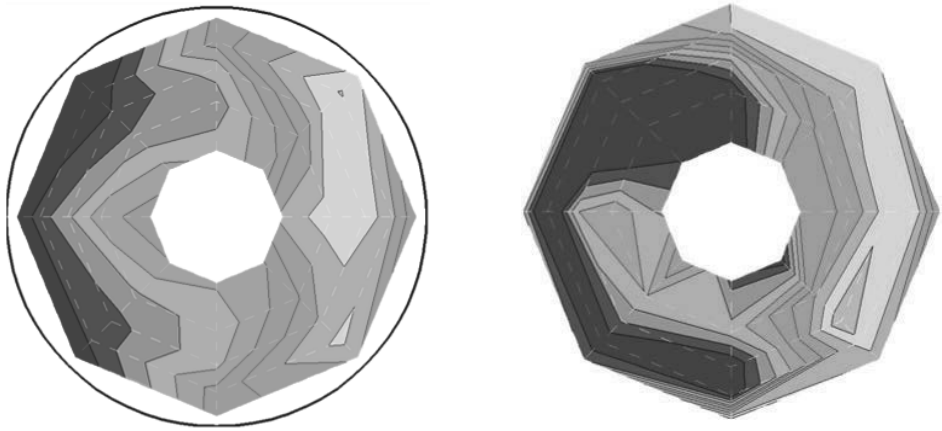
Figure 6. Acceleration and deceleration.

In general, the flight measured data show excellent agreement with the simulation model results. However, the results for acceleration and deceleration suggest that the modelled value of aircraft drag might be pessimistic. Overall, the comparisons are a very encouraging confirmation of the validity of the flight control philosophy and the supporting aerodynamic data.

5.2 Propulsion integration

The achievement of an LO solution for the engine air induction system transgresses all the established principles of good intake aerodynamic design. For Taranis, therefore, a radically new approach was necessary, starting from the point of identifying design solution options with the required signature characteristics. The aerodynamic task thus became one of mitigating the resulting adverse behaviours. LO intakes typically feature local flow swirls, embedded separations, and associated unsteady (time-variant) flow phenomena. Significant intake risk reduction was carried out through government- and industry-funded research programmes, involving both airframe and powerplant contractors as well as research organisations. The most

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(a) Wind-tunnel rake measurement (b) CFD at wind-tunnel rake locations

Figure 7. Intake total pressure contours at aerodynamic interface plane.

cost-effective use was made of both CFD and wind-tunnel testing, both in the risk reduction programmes and in the Taranis design and development programme itself. As the engine itself is, as always, the final arbiter of intake flow quality, the qualification and flight clearance activities for Taranis included static test of a full-sized and fully representative intake together with the engine.

Figure 7 provides a typical comparison of CFD predicted and wind-tunnel measured intake flow characteristics, at a consistent engine face Mach number. The contour plots illustrate total pressure at the Aerodynamic Interface Plane (AIP), which is the established location for the mutual assessment of engine/intake aerodynamic compatibility. Areas coloured blue and yellow denote relatively high and low total pressure respectively. The CFD prediction displays reasonable agreement with the wind-tunnel measurement, particularly for the overall total pressure pattern.

The novel and innovative engine exhaust solution developed for Taranis set further challenges for propulsion integration aerodynamics. In some respects, the relatively high aspect ratio rectangular exit was easier to integrate into the 'flying wing' Taranis configuration. However, the interactions between the exhaust jet and the airframe required careful assessment and evaluation. A dedicated and novel afterbody wind-tunnel model was tested in order to quantify the effects of the jet on the aircraft's overall stability and control characteristics and provide throttle-dependent terms for the S&C dataset.

5.3 Aerodynamic performance

The demonstration of aerodynamic performance was not a primary objective of the Taranis programme. Design choices were made and design development influenced in order to ensure that the aircraft performance was adequate to enable achievement of the primary demonstrations. As usual, aircraft performance datasets were generated, using a combination of prediction and test measurement, and a comprehensive performance Operating Data Manual (ODM) compiled for the use of the operating team. Actual performance was monitored throughout the flight trials. Airfield performance agreed well with prediction and in-flight performance showed reasonable agreement, subject to the possibly pessimistic predicted drag, noted above.

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5.4 Air data

Throughout the era of fast jet combat aircraft, flight control systems have progressively increased in sophistication and capability. From initially providing powered assistance to the human pilot, they have been used to optimise, augment, and ultimately artificially provide stabilisation characteristics. They have also provided departure prevention, safe manoeuvre limitation, and optimal scheduling of aircraft handling with varying flight condition. In order to provide this increasingly capable functionality detailed, accurate, and robust knowledge of the aircraft's flight condition has been essential. Thus, air data systems have evolved from relatively basic sources of altitude and airspeed information to complex, high-integrity systems fully integrated into the FCS. Historically-established methods of providing high-integrity air data to the FCS have made extensive use of a range of multiple external probes.

LO requirements preclude the use of conventional air data measurement techniques, and for Taranis a novel air data system was developed. Initial flight trials with a conventional air data noseboom gave confidence in the behaviour of the novel system, and flight trials to date have been completed with the noseboom removed. Measured air data values and aircraft manoeuvring characteristics have been almost indistinguishable from the initial boom-on flights.

6.0 TARANIS: THE TEAM CHALLENGE

In addition to the evident technical challenges entailed in demonstrating an unmanned low observable vehicle, the most significant challenge to the Taranis project lay in achieving an affordable programme. From the outset, all the teams engaged in the various sub-systems were fully aware that, in the words of one of the project's senior management team, 'everything is tradable except affordability'.

In the case of aerodynamics (including flight control laws), deliberate choices and recommendations were made at the earliest stages of programme planning with the specific intention of minimising programme cost. Those choices and recommendations included:

- Careful selection of the flight envelope, to enable achievement of the primary demonstration objectives while avoiding as far as possible regions of high risk and high complexity.
- Maximising the read-across of experience from the preceding demonstration programmes, particularly Raven.
- As a result, it was possible to minimise the requirement for wind-tunnel data and the size of the wind-tunnel programme. The Taranis wind-tunnel programme consisted of six main models. 1,576 individual test runs were carried out, comprising about 43,100 data points. An additional benefit of the relatively small size of the wind-tunnel programme was the resulting size of the task of creating the S&C dataset.
- Minimising the size of the aerodynamics team. Growing from the small organisation which had carried out the preceding demonstrations, it was relatively easy to control the growth of the team size to the capability and capacity which was absolutely essential to achieving the programme, with maximum use of skill specialists on an as-required basis from neighbouring project teams. Although a large number of individuals contributed to Taranis aerodynamics, at any one time the maximum team size was 12, including the flight control laws and air data team. Conventional wisdom based on past experience suggests a project aerodynamics team size typically three to four times larger. A member of the project management team once memorably remarked, in a particular context, that aerodynamics was 'a small team that doesn't do much'. Of course, we like to think that was his way of recognising the high cost-effectiveness of the aerodynamics contribution.

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- Maximum use of state-of-the-art tools, methods, modelling, and simulation, including aggressive and proportionate use of CFD. Approximately 300 complex CFD solutions were performed on wing and general aerodynamic design, and approximately 100 on propulsion integration.
- A philosophy to minimise loads and Aeroelastics work:
  - Minimised structural optimisation
  - No traditional envelope-expansion flutter testing
  - No in-flight loads measurement apart from specific control surface actuators.

The achievement of a technically and intellectually demanding programme with a small team depends critically upon the performance of the team members both as individuals and as a team. The Taranis aerodynamics team has consisted of a group of extraordinarily talented and motivated people, whom it has been a privilege to lead.

An aggressive use of new toolsets and processes inevitably carries a degree of risk that they might not prove to be as capable as wished. Some of the toolset choices and assumptions made during the planning of the Taranis programme were not fully achieved. However, the impact of shortfalls in toolset capability was manageable within the flexibility of the programme, and in some instances was offset by advances and innovations in capability.

At the core of any successful project aerodynamics programme is a philosophy of qualification. In general, the overall process of qualification progresses through distinct, though related, stages:

- Capture and decomposition of requirements
- Input to design development
- Evaluation of definitive design
- Generation of evidence for flight clearance

It is common for flight clearance to proceed through a process of flight envelope expansion. That process must be anticipated in the initial requirements capture and reflected in design development by designing the system with test requirements in view.

7.0 BEYOND TARANIS

Taranis now has a significant place in the UK's heritage of innovation and excellence in the fast jet era. It has built on the experience of many years and multiple projects and marks a culmination of over 20 years of dedicated research in the UK into the challenges of stealth aircraft. Of course, it is not an operational system and therefore it is also a starting-point. Numerous challenges remain for the UK combat aircraft community.

Probably the most significant single challenge is how to turn the technological progress of Taranis into operational military capability in the hands of the UK's armed services. In addition to the achievement of stringent LO requirements, from an aerodynamic perspective an operational system will require – relative to Taranis – demanding payload/range/endurance capability and a wider flight envelope in terms of speed, altitude, and manoeuvre. Taranis has demonstrated that the UK has the necessary aerodynamic capability to meet those challenges.

Defence budgets, particularly in the UK and for combat aircraft weapon systems, will continue to be severely constrained for the foreseeable future. The UK combat aircraft aerodynamics community faces the twin pressures of sustaining its capability in austere financial conditions whilst continuing to offer cost-effective programme performance against demanding technical requirements. The important contribution to the UK economy of the civil aerospace sector has recently been recognised in the establishment of the UK Aerodynamics Centre, with significant public investment which is

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targeted exclusively on the civil sector. It is appropriate to consider the economic contribution of the defence aerospace sector and apply similar considerations to the case for investment in combat aircraft aerodynamics.

An important lesson from the history of combat aircraft weapon system programmes is the time taken from the development of initial concepts to the deployment of operational systems. Considering, for example, the development of an agile fighter from initial discussions in about 1978/79, and that of an ASTOVL system from around 1988 (as noted above), the typical gestation period is about 25 years. Clearly, such lengthy development programmes are vulnerable to advances in technology and changes in circumstances rendering them obsolete long before entry into service. Similarly, over such long periods they are susceptible to escalation of requirements, complexity, and costs.

It is therefore important to consider the need for, and feasibility of, faster turn-round times from concept to operational system. The pressures of budgets and timescales lead to an obvious interest in aerodynamic processes and approaches which are cheaper and faster than current capabilities. However, the relative cost of the aerodynamic aspect of a typical complex combat aircraft weapon system programme is a small proportion of the total cost. Meanwhile, the decisions made on the basis of early-lifecycle aerodynamic activities have a disproportionate and long-reaching effect on the overall programme. It is therefore essential to balance the attraction of cheaper and faster aerodynamic programmes with the benefits of a more considered approach and adequate early investment in aerodynamic risk mitigation and concept maturation.

It is unlikely that the sustainment or further enhancement of UK combat aircraft aerodynamic capability will happen through the 'traditional' method of large-scale investment in research and development programmes in industry. However, if the capability is allowed to lapse, it will cost considerably more to recover it later than to sustain it through the 'lean years'. Recent examples of academic innovation, for example in the FLAVIIR consortium, have indicated a potential way forward by enabling closer co-operation between academic institutions, government, and industry. Clearly, development and demonstration programmes, such as Taranis, involving the integration of sensitive technologies, will continue to require a controlled development environment. Fundamental enabling science and technologies may be more cost-effectively pursued by co-ordinated engagement with academic institutions.

Put crudely, we know that the world does not owe us a living, but the success of programmes such as Taranis demonstrates that the UK possesses the capability to create and add value and to provide a sovereign capability alternative to dependence on offshore acquisitions.

To return to Lanchester's 1916 writings:

> "*The maintenance of the present superiority of the British reconnaissance machine and the development of different types, and, in short, the building up and consolidation of the Aeronautical arm, both as to quality and quantity,in order to ensure our capacity to hold our own with the other great Powers, is a task of national importance, and, as such, one of the first magnitude.*"[9]

It is also important to add a cautionary note: the continued perception of the superiority of British (indeed, Allied) aircraft during WW1 was based to some extent on an ignorance of the advances made in thick aerofoil aerodynamic design in Germany. One possible source of that ignorance lay in the low Reynolds number capability of British test facilities at the time. Thus, the higher performance of German aircraft such as the Fokker DVII came as a particularly nasty surprise. (See, for example, Ref. 10)). It is essential to guard against complacency and to be continually prepared to challenge cherished assumptions.

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7.1 Concluding remarks

The successful flight trials of the Taranis unmanned low-observable demonstrator aircraft have provided the latest evidence of the UK's continued capacity for the entire design, development, manufacture, and flight testing of world-leading combat aircraft, particularly with regard to Aerodynamics.

In the words of Nigel Whitehead, Group Managing Director – Programmes and Support, BAE Systems, in a message to members of the Taranis flight controls and air data team following successful demonstration of the Taranis novel air data system:

"You have turned the 'theoretically possible' into the 'practically achievable'. Very few people have made such a contribution to the world of aviation over the decades. I hope that we will be allowed to tell the world about it at some stage."

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