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High Incidence Flight Testing Risk Management

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Throughout recent decades military aircraft have pioneered the development of fly-by-wire (FBW) flight control systems. Headlines proclaim its benefits: 'carefree handling' with 'flight envelope protection,' and many other descriptive headings. These have centred on attaining hitherto unattainable manoeuvrability and we were listening to a speaker who was a flight test engineer with BAE at Warton between 1970-2005.

His presentation was a review of FBW evolution in the military arena. It blended good handling qualities and safety into one picture, the former desirable and the latter essential. There was a strong emphasis on risk during trials, and how potential failures need to be studied, and palliatives put in place before any testing commences. He referred to work with Jaguar, Tornado, FBW Jaguar, EAP and the Eurofighter Typhoon.

There was specific interest on the safety aspects of 'high alpha' flight trials, the presentation charting experience while testing the above aircraft types, all of which could he expected to develop undesirable handling characteristics at 'high alpha' and most notably can enter a 'spin.' The reasons for the outset into a 'spin,' and procedures that will lead to recovery are commonly established in flight testing. Conventional light aircraft spin and recover using well-versed control procedures, but on advanced aircraft the onset and recovery from spins is not always predictable. Newer configurations of high performance aircraft have become more prone to cause the 'unexpected.' He categorised the spin behaviour of these aircraft thus;

- 'oscillatory spin' – the centre of rotation is forward of the aircraft nose and the aircraft oscillates in all three axes (pitch, roll and yaw)
- 'fast flat spin' – the centre of rotation moves towards the aircraft CG and can be "incredibly dangerous" as conventional spin recovery procedures are unlikely to be effective and safe ejection can become impossible
- 'inverted spin' which may be calm or oscillatory
- A 'falling leaf' where the aircraft descended in a highly oscillatory tumble.

He commenced with a review of his own flying experiences in light aircraft, and where 'stall' and 'spin' procedures are a vital part of preliminary training. These are inherently stable aircraft that tend to respond to control inputs in a predictable manner in almost all flight conditions. However, the modern fast-jet has little in common when it reaches high-incidence. Every type (even variants) has to be tested and appropriate handling procedures demonstrated before it can be certified and allowed to enter service.

The speaker's experience in flight-test at Warton coincided with a period when flight-test instrumentation grew from being a largely post-flight review by crew and engineers, to the engineers having real-time access to data through telemetry. This development was, in itself, a significant step in terms of supporting safer test flying. As the

LESSONS FROM THE PAST

- High Incidence Testing is Always <u>High Risk Testing</u>
- Pilot Disorientation is a Significant Risk
- Risk of Engine(s) Flameout is High
- Thorough Trials Preparation Always Pays Off

aircraft became more complex, the testing methods used had to be evolved too, but at the same time the ability to complete flight test programmes with diminishing accident risk was also expected. By reviewing experience with five aircraft types the scope for safety oversight, and the lessons that have led to suitable testing programmes was explained.

Jaguar

This was a 1960s design, relatively conventional with power-augmented flight controls, but high-incidence manoeuvres at high altitude, in some cases, revealed unexpected stability deficiencies. Neither wind-tunnel tests nor computing capabilities had predicted handling deficiencies when high-incidence spinning trials were conducted in France.

He showed a ground camera recording of a single-seat Jaguar that, induced to 'stall' at high altitude, diverged in pitch and became a "falling leaf." It was a more severe event than had been expected. The engines suffered flameouts, and in the film unburnt fuel could be seen streaming from the engine exhaust and intake as the aircraft tumbled. The aircraft did respond to control inputs eventually and the pilot did recover to a stable condition, but this had involved much height loss. An observation quoted was that some 25,000ft could be necessary to recover from such a situation. A more detailed understanding of the cause, and the control movements that would restore controllability was obtained using a vertical wind-tunnel in Lille. A small model was thrown into the flow and induced to spin, and an operator exercised control surfaces. This procedure was adequate to record control effectiveness well enough to ratify suitable crew procedures, although by now computational fluid dynamics (CFD) has matured to the point where action and reaction can be studied with confidence, albeit a theoretical procedure.

In later trials, the longer fuselage two-seat Jaguar revealed even more undesirable high-incidence handling qualities – much of the extra mass being further from the CG. This led to the variant being limited to a reduced flight envelope.

Tornado

Before Tornado flight testing commenced, around the early-70s, the first comprehensive real-time telemetry system was installed at Warton. Prior to that, a simple analogue and very limited telemetry system (only about 12 parameters) had been used for the Lightning spinning trials. This was a major step forward as ground staff could now be fully aware of circumstances throughout a test flight. With regard to the testing of a technology-filled aircraft, and with a variable-configuration wing, it was likely that high-incidence trials would be demanding. This certainly warranted the advent of real-time instrumentation data being available to the observer team on the ground.

A ‘safety pilot’ position was added in the flight-test telemetry room for high incidence trials so a monitoring pilot could communicate directly with their airborne colleague throughout a trial. Traditional time-based graphs were no longer awaited for post-flight, but were presented in real-time on pen recorders. There was the opportunity to make decisions on behalf of a crew, and with more observers aware of real-time issues. Training programmes were conducted to ensure that every member of the telemetry tear was familiar with every type of spin and possible failure cases. It was essential to co-ordinate a team-ethos. If the circumstances arose to call for a ‘STOP’ in a trial, there was to be a ‘no blame’ philosophy so that vital decisions were handled promptly. The telemetry ground station team needed a ‘big-picture’ that would guide everyone present, and Trevor Saunders, then leader of the team, addressed this by developing a table on which there were eight potentiometers, each related to a major flight parameter. With practice, the operators were able generate telemetry pen recorder traces that replicated all types of spin. Three different warning lights would illuminate if pre-determined limits were reached (2 low height and one longitudinal g at the pilot warnings). Essential parameters for spin identification were incidence, sideslip, yaw rate and roll rate, altitude, and pilots control positions. In this way, the members of the telemetry team could practice the range of calls defined in recovery drills. This ensured that all ream members knew exactly what to do for all possible scenarios

We were talked through a set of telemetry charts from the deliberate spinning trials in the Tornado programme. A number of different spins were described which illustrated the difficulties experienced in recovering the aircraft from the different spins experienced in certain wing configurations. This led to the early termination of the deliberate spinning programme due to the need to rely the spin recovery parachute to recover the aircraft. In the final deliberate spinning test, multiple spin entries occurred as the pilot tried to recover the aircraft and the spin parachute had to be deployed to achieve recovery. The height loss was considerable with spin entry at 40,000 ft and final recovery to level flight with the first engine re-lit at 8,500ft.

IMPACT OF TORNADO FULL AUTHORITY FLIGHT CONTROL SYSTEM

- If Aircraft Departs, CSAS will Oppose Aircraft Response at up to Maximum Actuator Rate.
- Oscillatory Post Departure/Spin Characteristics will result in Large Hydraulic System Demands
- Emergency Hydraulic System Must be Capable of Supporting CSAS Actuator Demands
- CSAS will apply OUTSPIN roll control which can be PRO SPIN
- Pilot Control Inputs Must be Able to Over-Ride Adverse CSAS Control Surface Demands
- Must provide Emergency Disconnect Capability for CSAS

As a result of this experience, the high incidence flight trials changed to boundary definition for the planned Spin Prevention and Incidence Limiting System (SPILS) using wing configurations with good spin recovery characteristics. From the flight test engineer’s perspective, the probability of losing an aircraft in trials was minimised, and the right lessons were learned in the development programme. This was the right time to do it, not after the aircraft had entered service.

Fly by Wire (FBW) Jaguar

This was a considerably modified Jaguar with a quadruplex digital flight control system (FCS), and no manual back-up. Initial flying was conducted with the centre of gravity (CG) in the regime certified on the basic aircraft. The control laws had been designed to provide carefree handling so it should not be possible to provoke a spin entry. However, high incidence trials would be necessary to verify this. The design of the flight control system had therefore to include a “spin recovery mode” to enable spin recovery if a departure and spin entry occurred.

It was considered essential that this mode be tested in the air prior to the start of the hi carefree handling trials. When the spin recovery mode was engaged for the first time in flight, there was a tendency for the pilot to enter pilot induced oscillation (PIO), attributed to interaction of differential tailplane deflections affecting the roll and yaw response of the aircraft. This had not been observed in the simulator due to the lack of cues in the early standard of simulators used at the time A simple control law modification solved the problem.

A spin-recovery chute had also been installed, although tests were not intended to include spinning trials, but safety considerations dictated that a recovery capability was provided. Deployment of the chute on the first chute proving flight resulted in unexpected loss of the parachute. The test flight had been conducted with a chase aircraft alongside and a cameraman to film the deployment, but a camera problem meant there was no record. It was known that the parachute deployment had been correctly initiated, but the chute detached from the aircraft and there was no evidence as to why it separated. Several days later, a trawler captain from Fleetwood telephoned Warton to say he had 'fished' a parachute out of the Irish Sea and did it belong to the company. He was content to deliver the 'chute' and it was in a condition still good enough to reveal that a weak link had failed because of a design error. A redesigned weak link was installed, the aircraft was returned to trials, and subsequent test deployments were completely successful.

Carefree handling trials commenced soon after and were completely successful with no departures experienced.

In later flights, the aircraft was destabilised (CG was moved aft with ballast in the rear, and wing root strakes added ahead of the inboard wing leading-edge moved the centre of lift forward). Trials thereafter provided data that confirmed the integrity of the all-digital FBW system and provided design guidance for future crew/system relationships. There was little more that the speaker could say about this invaluable proof of concept programme. It was to be fundamental to the development of the next two aircraft that were soon to undergo trials at Warton.

Experimental Aircraft Programme (EAP)

It was pointed out in the presentation that the growing complexity of aircraft was reflected too in the expansion of flight test facility capabilities. By now the flight test team could handle a much expanded range of parameters.

The EAP was a prototype design with a configuration new to everyone involved, and again it had a full fly-by-wire system. The flight control system (FCS) used the same processing architecture as the FBW Jaguar but served many more flight control surfaces. This time the aircraft was unstable, and it had very non-linear aerodynamic characteristics. Essential safety criteria had been addressed with provisions for recovery in place that included an auxiliary power source to support hydraulic supply in the event of an engine flame-out. In addition, there was a spin-recovery parachute that could be deployed in the event of the aircraft entering a spin. The chute would stabilise the aircraft and the FCS would resume normal flight control behaviour. Trials were planned to prove that the aircraft should not 'depart' in manoeuvres, and safety assessments had instilled confidence that the design process had identified and addressed management of significant failures.

Initial 'carefree' handling trials were successfully completed within a limited flight envelope, and without having to use any safety systems. There was confidence therefore to conduct a further series of tests that required the EAP to conduct a series of clinical combat manoeuvres with a target Hawker Hunter. It flew combat manoeuvres that involved manoeuvres in all 3 axes. All seemed well at first, but on one occasion, as the EAP closed to within about 1,200 metres of the target, the EAP penetrated the Hunter's wake aircraft and pitched up, rolled and yawed sharply. These events were accompanied by FCS and hydraulics warnings and so the pilot relaxed to 1g and opposed the roll response. The wake traverse and subsequent aircraft response lasted for 2.5 secs. The pilot reset the failures and Telemetry called to terminate the trial and return to base.

Real time and post flight analysis of the instrumentation data showed that the four Airstream Direction Detector (ADD) units on the front fuselage (used by the FCS to determine incidence and sideslip for use by the control laws) had been severely affected by penetration of the vortex core and produced sharp conflicting and erroneous signals which had been fed though to all 7 primary actuators The sensors signals caused all seven primary control surfaces to respond at their maximum rate (60 degrees/sec), and to return to their trimmed positions as soon as the aircraft left the wake. This was a short period event and the aircraft was stable and fully controllable immediately. The seriousness of the short upset was that the actuator demand exceeded the maximum capabilities of the adopted Tornado hydraulic pumps. A similar upset of double the duration would have seen hydraulic pressure falling to a critical value, and that would have led to a loss of control and have jeopardised the safety of aircraft and pilot.

In the flight test context, the lesson was that safety analysis on this occasion had not identified this possibility. The pump delivery rate should have been almost three times that available for an aircraft intended for production, but demonstrator programme costs had necessitated the use of existing Tornado pumps. A significant risk had been identified and appropriate limitations were imposed. A control fix which introduced additional inertially derived incidence and sideslip signals into the computation process solved the problem and flight trials were then performed with a series of deliberate wake penetrations which were problem free. New pilot procedures and cockpit warnings were introduced to address the limited hydraulic capability of the Tornado hydraulic pumps and all subsequent carefree handling trials were problem free and completely successful. Very valuable lessons had been learned.

Eurofighter (Typhoon)

The Eurofighter – RAF 'Typhoon' – was the successor to Tornado, but by now digital FBW system, and configuration, were well understood from experience with the FBW Jaguar and EAP. The aircraft systems configuration embodied lessons learned from earlier experience, and the full flight envelope performance had been well mapped using knowledge from CFD programs and both wind-tunnel and flight test data. The latter was used to program the in-house simulators and was able to replicate handling aspects thoroughly. Simulator sessions that pre-empted flight tests could be shared as real-time data with the flight-test team. It was the ultimate realism possible to deliver equivalent readiness for the ground-based and flying crews even before the flight test programme commenced.

EUROFIGHTER TYPHOON CAREFREE HANDLING FLIGHT TRIALS PREPARATION

- Simulation Facility Used to Assess Aircraft Post Departure Behaviour and Prove EPU Auto Start • and Hydraulic Protection Functions
- High AoA Drills Defined from Spinning Tunnel and Aerodynamic Modelling/Simulation.
- All Possible Failure Scenarios Considered in Trials Preparation and Drills Preparation
- Telemetry Team Fully Trained for all Foreseen Situations using Spinning Table
- Simulation Facility Used to Train Aircrew in Conjunction with Telemetry Team for all Normal and Failure Cases (Simulator Linked to Telemetry Room)
- Full Flight Test Safety Review Performed to Generate Clearance to Commence Flight Trials

There was little that could be said about the current front-line aircraft, but the chronological review had described the way that flight testing did change over some 35 years, and bolstered confidence that when Eurofighter was flown and tested, the handling qualities and flight envelope protection capability was a splendid example of 'carefree' handling.

Future generation aircraft

The speaker concluded with a reflection that in the 35 years he worked as a flight test engineer he saw a lot of progress, and with not a single aircraft lost in the flight trial programmes. That is a statement in itself that there had been lessons learned. Success was attributed to team effort and his final observation that the especially capable 'Tempest' stealth aircraft, expected to be flown in the near future, has a configuration considerably different to previous aircraft designed, built and tested at Warton. The challenges will continue to task the up and coming engineers.

IN CONCLUSION

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Questions and answers were indicative of much overall interest, and reflected that those present, until hearing this presentation, were generally unaware of much of the work that goes on behind the scenes in the testing of modern aircraft. The 100-strong audience expressed satisfaction with wide applause, and the sight of a Jaguar in a 'falling leaf' spin streaming fuel from the intakes was the centre of conversation amongst many attendees.

Lecture notes by Mike Hirst