FLIGHT SIMULATION IN ACADEMIA
PROGRESS WITH HELIFLIGHT AT THE UNIVERSITY OF LIVERPOOL

Mark D. White Gareth D. Padfield
Flight Science and Technology
Department of Engineering
The University of Liverpool
Liverpool, U.K.

Abstract

Developments in affordable, PC-based simulation technologies have allowed flight simulators to be acquired and operated by academic institutions for both research and teaching. This paper describes the ongoing activities of such a system at the University of Liverpool – HELIFLIGHT - with 6 degrees of freedom motion, wide field of view visuals and programmable force-feel system. Used in combination with the FLIGHTLAB modelling environment, HELIFLIGHT is a high fidelity research tool available to both professional engineers and undergraduates, enabling the examination of handling qualities and pilot-vehicle technology issues. In addition to industry-related applied research activities, the facility has also been utilised as a valuable interactive teaching device in undergraduate degree programmes and encourages the development of new problem-based-learning (PBL) modules. The progress in various research activities is described in this paper, including; the European Commission funded project to develop handling qualities criteria and active control technologies for civil tilt rotor aircraft, the development of simulation fidelity criteria for helicopter real-time simulation, skyguides research as well as a novel approach to the teaching of Flight Handling Qualities to undergraduates using PBL. Examples from undergraduate project work and the 2003 Academy of Engineering HEADSTART Aerospace Focus programme will also be drawn on to describe progress after 4 years of operation with HELIFLIGHT at Liverpool. During this period, the Liverpool Wright Brothers project has included the development of simulations of the Wright brothers' flight vehicles from 1901 to 1905.

Introduction

The early days of flight simulation saw low cost solutions, such as the Sanders Trainer, being applied to the complex problem of providing the sensation or illusion of flight to pilots to *"…enable the novice to obtain a clear conception of the workings of the control of an aeroplane..without any risk personally or otherwise"* (Ref. 1). With advances in aircraft and simulation technology, the relatively high cost of simulation facilities ensured that their development and utilisation was limited mainly to large training organisations and government research agencies. In 2002, CAE and Thales Training & Simulation dominated the market for orders of civil full flight simulators (Ref. 2) and along with Alteon have supplied the majority of civil flight simulators. The cost of such systems are beyond the budgets of academic institutions. Similarly, facilities such as the Large Motion Simulator at QinetiQ (formerly DERA, Ref. 3) and the Vertical Motion Simulator at NASA Ames (Ref. 4) have not normally been accessible to academia.

Over the last twenty years, PC hardware advances in processor power and graphics cards capability have resulted in the price of computing being halved every two years (Ref. 5). This has allowed the level of processing performance and image quality required for high fidelity simulations to be accessible to smaller, less commercially-oriented institutions such as Academia. Such a system, HELIFLIGHT, has been in operation in the Flight Science and Technology Research Group at the University of Liverpool since September 2000.

This paper updates the work presented previously (Ref. 6), reporting the developments in facility hardware upgrades and capabilities as well the expansion of the operational utilisation of the facility.

A significant development of the operational aspect of the facility is the use of HELIFLIGHT in undergraduate teaching programmes. A new problem based learning module on Flight Handing Qualities is detailed as well as the continued growth in the number and scope of undergraduate research projects using HELIFLIGHT, where the value of an integrated modelling and simulation environment is highlighted. In addition, the Royal Academy of Engineering's Headstart Aerospace Focus Programme that took place in Liverpool in the summer of 2003, will show that a facility such as HELFLIGHT has the potential to stimulate interest in

A-level students and attract high calibre students to aerospace engineering and a future career in the industry.

The paper closes with some remarks on the future of simulation in academia and the way in which a more collaborative approach to research between academia and industry will produce more capable aerospace engineers, more fluent in modelling and simulation and concurrent engineering practice, to the benefit of the UK quality of life.

HELIFLIGHT

The flight simulation facility at the University of Liverpool is HELIFLIGHT. It is a relatively low-cost, turnkey and re-configurable flight simulator with five key components (Ref. 6):

- selective fidelity, aircraft-specific, interchangeable flight dynamics modelling software (Ref. 7) with a real time interface (PilotStation)
- 6 degree of freedom motion platform (Maxcue), (Fig. 1)
- four axis dynamic control loading (Loadcue)
- a three channel collimated visual display for forward view, plus two flat panel chin windows, providing a wide field of view visual system (Optivision), each channel running a visual database
- a re-configurable, computer-generated instrument display panel and head up display.

HELIFLIGHT has been upgraded in terms of hardware processing capability and a new visual scene assembly environment. In addition, an eye tracking system has been installed for research use (detailed later).

To allow more complex models to run in real-time, the original dual processor PIII 750 MHz machine was replaced by a dual processor P4 1 GHz system. However, due to ever increasing computational demands in the pursuit of higher fidelity simulations, the system is currently being replaced by a dual P4 3.3 GHz system to allow tilt-rotor models with multiple segment n-bladed prop-rotors, plus horseshoe vortex models, to be run in real-time.

Upgrades to the graphics cards have also been carried out to replace the original 16 MB Voodoo 3 graphics cards with 256 MB GeForce FX5950 cards capable of multisample anti-aliasing and 356 million vertices/sec. The improved graphics capability has reduced the anti-aliasing problems encountered with the previous cards especially in linear image regions such as runway edges. An increase in texture memory and processing power allows more complex macro and micro-texture scene content to be included in visual databases and environmental effects, such as fog, to be displayed.

Figure 1 HELIFLIGHT 6 d.o.f. motion simulator

The basic HELIFLIGHT visual rendering software allowed OpenFlight files to be displayed but had no capability for utilising environmental effects such as fog or time of day and had a fixed Head-Up Display (HUD) symbology. To enable research in degraded visual environments to take place, a new software solution, Landscape (Ref. 8), has been integrated into the HELIFLIGHT visual system. Developed by BAE Systems, Landscape automatically assembles visual databases at run-time and now allows moving models or entities, special effects and user defined HUD symbology to be displayed. Head-up and head-down symbology can be built using the newly acquired VAPS tool suite. This allows users to rapidly design, prototype and test human-machine interfaces.

Previously, HELIFLIGHT was primarily used for handling qualities research, but recently the research focus expanded to include the study of aircraft operations, in particular flight operations in degraded visual environments (DVE). A head mounted eye tracking system has recently been purchased for use in the EPSRC-funded Prospective Skyguides project. The Applied Science Laboratories Model 501 eye tracker (Figure 3) records the pilot's point of regard over time with respect to a calibrated scene plane. This scene can be recorded to video with the point of regard position superimposed for post-trial evaluation using INTERACT video analysis software.

The eye tracker will be used to try to understand the pilot's visual information requirements for flight in both good and degraded visual environments for both fixed and rotary wing operations. In doing so, aircraft displays will be developed to recreate the visual cues provided by good visual conditions in the less visually stimulating degraded conditions.

Figure 3 ASL Eye Tacker

Applied Research

In Ref. 6, a number of research activities were in the early stages of development such as the Wright Brothers Project and the Tilt Rotor project investigating Rotorcraft Handling Interactions and Loads Prediction (RHILP). Although the RHILP project has been completed and the centenary of the Wright Brothers first powered controlled flight has passed, research activity in both areas has continued and expanded. The possibility of a future European Civil Tilt-rotor has led to a new research project on Active Control Technologies for Tilt-rotors, ACT-TILT and the Wright Brothers project (Refs. 9 and 10) has been extended to develop high fidelity simulations of the 1905 flyer.

Whereas the majority of previously reported research activities have focussed primarily on the development of high fidelity simulations (RHILP) or fundamental research (Helicopter Ego-Motion Perception – HEMP, Ref. 11), a recent research growth area concentrates on the operational aspect of aircraft. Two new research projects; Prospective Skyguides and OPTIMAL are described, each having their own particular requirements, which will necessitate the continued development of the HELIFLIGHT facility.

In terms of the impact on the academic aspects of aerospace Programmes at Liverpool, high profile projects linked to Industrial endeavours, presented in the following sections, provide opportunities for undergraduates to participate in key applied research activities early in their career and develop sound working practices and skills that would not be possible without access to a facility such as HELIFLIGHT.

Prospective Skyguides

Limited visibility is '*the single most critical factor affecting safety of worldwide aviation operation. Thirty percent of all fatal accidents worldwide are a result of impacts into terrain or obstacles the pilot did not see*' (US Aviation Safety Programme, Ref. 12).

Many natural species rely primarily on optical information to follow a safe path through the cluttered environment near the Earth's surface. In a similar way, pilots use visual perception to create a mental model of where their aircraft will be in the future to fly a safe path through their surroundings. The reliability of this model is particularly critical when flying close to the ground or near to obstacles. In a good visual environment, the pilot is usually able to pick up sufficient information from the available visual scene. As the visual environment degrades, for example due to adverse weather conditions, the available visual information becomes less reliable. To counteract this degradation, the pilot requires some form of guidance vision aid.

To provide a guidance vision aid, a complete reconstruction of the natural world from active/passive sensors coupled with terrain databases can, in principle, be achieved. This would be an arduous and expensive task in the medium term. This begs the question: what is the minimum necessary and sufficient visual information required by a pilot to develop a reliable mental model, rather than a dangerous illusion, that will allow safe flight through the surrounding environment? This research project aims to answer this, and related questions, by:

- Establishing a coherent engineering basis for the design of pilot aids that will support flight in degraded visual conditions, particularly when close to the ground. The intended use of such aids would be for civil fixed and rotary wing aircraft

- Constructing and evaluating synthetic displays that recover the visual cues necessary to allow flight in degraded visual conditions for a range of manoeuvres.

OPTIMAL

The OPTIMAL project is part of the European Commission Framework 6 Programme. It is an Integrated Project (IP) covering a wide range of technical areas through a consortium of 24 partners. The OPTIMAL project is an air-ground cooperative program that is aiming to define and validate innovative approach and landing procedures for fixed and rotary wing aircraft in a pre-operational environment.

The need for these developments is identified by ICAO forecasts of 5% growth per annum of world air traffic. This estimate is likely to be conservative for the European theatre of operations. Taking into account the variations in growth in the types of traffic (i.e. commuter over long-haul), it is a reasonable prediction to expect European air traffic to triple over the 2002-2020 timeframe. The impact of this will be increasing airport congestion and the associated safety, efficiency and environmental effects unless additional measures are taken.

In response, it is required that a re-design of the airspace structure, division, categorisation and the Air Traffic Management (ATM) procedures be proposed that use the improved aircraft performance and new navigation technologies/capabilities.

This will be achieved through the use of a wider range of novel trajectories and new procedures for air traffic controllers as well as new guidance systems. OPTIMAL will develop new tools to support the controller who will deal with fixed-wing and rotorcraft approaching on different (e.g. curved) trajectories simultaneously.

Overall the expected outcomes of the project will be a validated set of approach and landing procedures, support systems and technologies achievable from 2010 as one part of a first step to the Advisory Council for Aeronautical Research in Europe (ACARE) 2020 vision (Ref. 13). These outputs will contribute to the following key objectives in FP6 in the aeronautical domain.

The new innovations from OPTIMAL will include:

- Aircraft continuous descent profiles and curved approaches
- Specific IFR procedures for rotorcraft using augmented GNSS (Global Navigation Satellite Systems)
- Development of all-weather precision approach and landing capabilities
- Aircraft procedures using augmented GNSS and RNP-RNAV (Required Navigation Performance – aRea NAVigation)
- Decision support tools to provide pilots with new ways to safely manage the aircraft approach and landing profiles
- 4 – dimensional trajectory management.

The University of Liverpool is participating in a work package developing rotorcraft procedures, conferring special attention to the context of airports allowing Simultaneous Non Interfering (SNI), Instrument Flight Rules (IFR) rotorcraft operations. The responsibility of the University of Liverpool, in partnership with ONERA the French aerospace government research agency, is a specific rotorcraft flight dynamics study. Within this study a handling qualities assessment of the novel approach trajectories will be made, as well as an analysis of certain emergency scenarios such as vortex-wake encounters (Ref. 14) and one engine inoperative (OEI) occurrences.

ACT-TILT

The ACT-TILT programme aims to define the Flight Control System (FCS) architecture of an advanced European civil tilt-rotor configuration (Figure 4) in order to improve its safety, dispatch reliability and affordability. The work carried out at Liverpool is part of a 5th Framework Programme and the partners include Eurocopter France & Germany, Agusta, Westland, FHL, Liebherr, Teleavio, DLR, NLR, ONERA and Glasgow Caledonian University.

Figure 4 Agusta's ERICA Civil Tilt-Rotor Concept

During normal operations, a tilt-rotor can operate in one of three different modes. In helicopter mode the nacelles are pointed vertically (90°) for low speed manoeuvring before being tilted forward as airspeed increases until they are at 0° in full aeroplane mode. The transformation phase from helicopter mode to aeroplane mode is known as the conversion mode. The University of Liverpool contributes to many aspects of the ACT-TILT programme, particularly the handling qualities assessment and load alleviation functions in the control system. A civil tilt-rotor (CTR) will need to possess excellent handling qualities throughout its Operational Flight Envelope (OFE) and good handling qualities throughout its Safe Flight Envelope (SFE). In addition, any handling qualities degradations caused by failure of flight control system components or loss of functions must be quantified via a safety analysis. Thus the aspect of this work is twofold, to define and validate the Level 1/2 handling qualities boundary for the CTR and to undertake a degraded handling qualities assessment through piloted simulation of the proposed tilt-rotor designs to enable a failure hazard analysis.

Three types of function failure have been envisaged:

- Loss – a loss is a frozen value or a default status
- Malfunction – the control surface does not move consistently with the input (hard-over, slow-over or oscillations)
- Degradation – the function is still working but with degraded performance.

A degraded failure caused by a partial loss of power supply or reduced hydraulic pressure can result in a reduction in the power available for the actuators and may result in a reduced actuation rate. This degraded failure was the focus of an initial investigation in degraded handling qualities of CTRs.

Flight simulation trials were carried out where the actuation rate limit was varied until the pilot HQRs identified the Level 2/3 HQ boundary. Two test pilots flew several tasks, including roll-step, bob-up, hover-turn, heave-hop and accel-decel manoeuvres using Liverpool's FLIGHTLAB XV-15 tilt-rotor, the FXV-15 (Ref. 15).

Figure 5 shows the effect of rate limiting on the HQRs given for a 90° hover turn manoeuvre in which the pilot was given a height performance standard of ± 5ft for desired and ± 10 ft for adequate performance, with a desired and adequate heading standard of ± 5° and ± 10°. A critical rate limit of 35°/sec appears to define the Level 2/3 HQ boundary for the FXV-15 and along with results for the other MTEs can be used as the initial guidelines for a failure hazard analysis of the ERICA configuration.

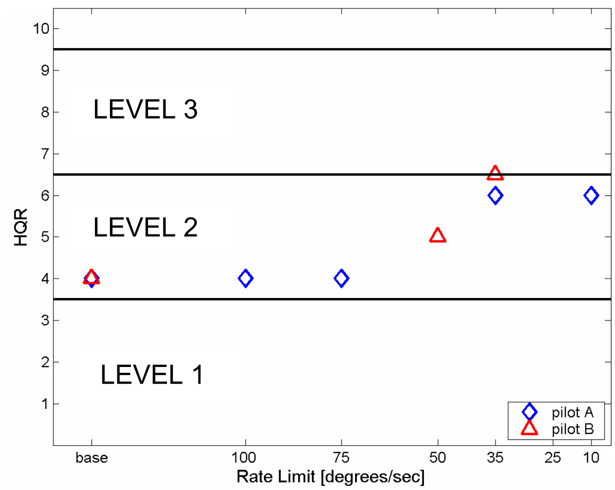

Figure 5 Hover-turn HQRs for rate limited actuation

Further degraded handling qualities work has focused on the effect of a differential nacelle position, the use of helicopter mode controls as a backup to loss of aeroplane mode controls, the effect of failure transients and the definition of Level 1/2 HQs.

Wright Brothers Project

This project was aimed at the construction and evaluation of high-fidelity simulations of the family of Wright brothers' aircraft between 1900 and 1912.

The story of the Wright brothers' aeronautical success provides many lessons for aeronautical engineers today. The Wrights addressed all aspects of construction, aerodynamics design, powerplant and transmission, but it was their ability to grasp the significance of flight control in an aerodynamics context that set them apart from their predecessors. The Wrights were aware that piloted control was more important than intrinsic stability for their low speed flying machines. They had drawn their inspiration for control and manoeuvrability from watching birds fly.

This project approach is to reverse engineer the Wright Flyers from a flight mechanics standpoint. The Liverpool Wright Brothers project included:

- Theoretical aerodynamic analysis using vortex lattice techniques
- Wind tunnel testing of different Wright aircraft types
- Development of a comprehensive real-time simulation models of the aircraft
- Conducting piloted simulation trials using HELIFLIGHT.

One of the Wrights' most innovative solutions for the problem of flight was their patented 'wing-warping' mechanism for control in roll. Inspired by birds, they used a torsional action of their wings to create more lift on one side of the wing than the other. In the Wrights' design the pilot moves his hips in a cradle, moving the cables and thus warping the wings.

A third axis of control in yaw was implemented in order to deal with a secondary effect of the wing-warping, namely adverse yaw. This effect was caused by the wing creating more lift generating increased drag, yawing the aircraft away from the desired turn. The moveable rudder was devised to create yawing moments counteracting the adverse yaw (Figure 6).

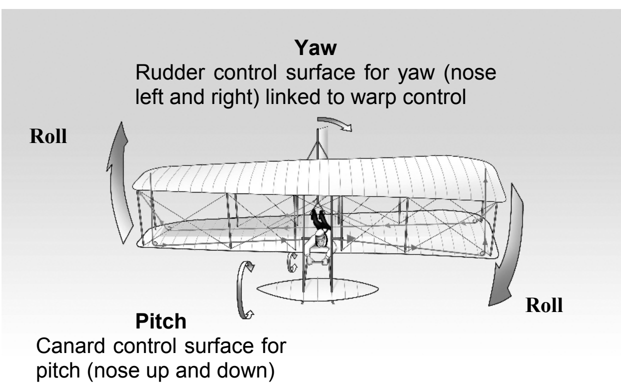

Figure 6 3-axis control system, Wrights' 1902 glider

The Wright brothers' gliders and Flyers were unstable in pitch and roll. Any disturbance, if left unchecked, caused the motion of the aircraft to diverge. The Wrights knew that having sufficient control was more important than stability (Figure 7). The action of pilot as a simple proportional gain in a feedback loop stabilises the pitch divergent mode but reduces the stability of the oscillatory mode. Their unstable aircraft could be flown by a skilled pilot, although the high level of instability of their 1903 Flyer especially, made controlled flight a very demanding task.

A series of simulation trials were conducted using test pilots where manoeuvres such as the roll step (Figure 8) were designed to investigate the flight characteristics. The simulation models were developed using the data acquired from the wind tunnel experiments.

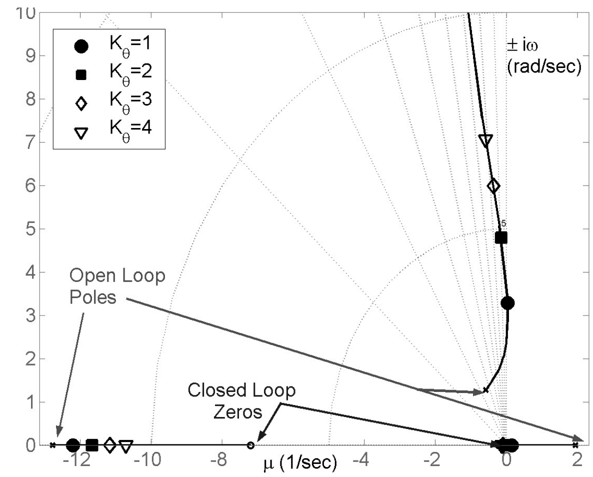

Figure 7 Root loci for 1903 Flyer

The project has revealed much about the handling characteristics of the Wright aircraft, particularly about the high angle of attack aerodynamics and their impact on the flight handling. It has also demonstrated how the 1902 Glider prototyped much of the technology of the 1903 Flyer and was an easier machine to fly because of its reduced instability.

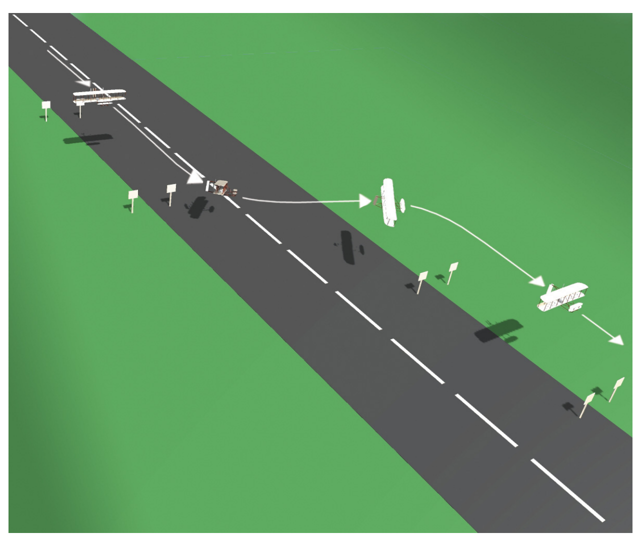

Figure 8 Roll step manoeuvre

Undergraduate Teaching Activities

The role of an Aerospace Engineering degree programme is to produce capable graduates for the Aerospace Industry. Such Programmes also foster within today's school children the desire to study and work in an exciting and varied field such as Aerospace. Once committed to a degree programme, students should be provided with the opportunity and environment to develop their technical and inter-personal skills as fully as possible through challenging modules and exposure to active learning methods. A key part of this learning environment is the tool used to harbour the desire for self-improvement amongst the students.

At Liverpool University, the HELIFLIGHT facility has evolved from a research tool primarily used for Industry and post-graduate projects to a powerful teaching aid for both undergraduate degree programmes as well as a way of providing an insight to A-level students into the attraction of pursuing a career in the Aerospace Industry. The flight dynamics and control systems modelling aspects of industrially based projects have driven the development of high fidelity models, which are then used by undergraduates.

The current simulation environment provides the ability to create models from physics-based components and the assembly of tree-like model structures, to assess trim, stability and handling qualities off-line, and conduct real-time piloted tests.

This section describes two facets of the teaching aspect of HELIFLGHT; used as part of a new PBL module on Flight Handling Qualities and also as the main attraction in the HEADSTART Aerospace Focus Course at Liverpool.

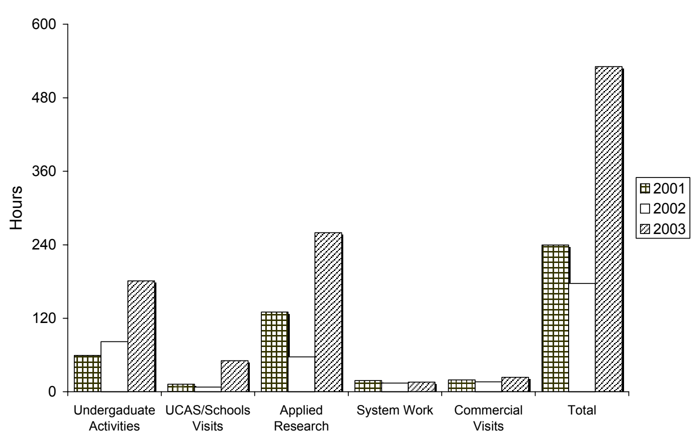

Figure 9 Annual facility utilisation

The growth of facility utilisation in teaching activities is clear in Figure 9, which shows the number of logged piloted simulator hours used each year since commissioning in 2000. The hours shown do not include the more substantial time spent in off-line analysis and model development.

HEADSTART 2003 at Liverpool

Headstart is a summer school programme that aims to provide high quality Year 12 (Scottish Year 5) students, who are interested in science and engineering, an opportunity to spend up to a week at University, exploring appropriate degree courses prior to making their UCAS applications. The courses are designed to demonstrate what science and engineering is about, provide opportunities to meet university lecturers, recent graduates and engineering organisations and to show that engineering is a worthwhile and dynamic career. Headstart is an activity of the Engineering Development Trust and forms part of the Royal Academy of Engineering's *Best* Programme.

30 students attended the Aerospace Focus programme at Liverpool in July 2003, which had a theme celebrating the Wright brothers' achievements. A simulation of the Wright brothers 1903 Flyer had already been developed in the Flight Science and Technology Research Group (Ref. 9) and was used as the baseline model for testing and development. The requirement for the programme was to carry out upgrades to the baseline 1903 Flyer model to produce a vehicle which could be used as a basic observation platform, flying circular flight paths over the ground in winds up to 10kts. The following outline performance requirements were used in the Handling Qualities assessment:

Take-off run	< 300 ft
Climb to 250ft altitude	< 1 minute
Cruise speed	35kts
Maximum speed	45kts
Time to turn through 360 deg	< 30 secs

Typical manoeuvres to be performed included:

- Stall
- 360º turn to left and right
- Power Effects
- Height Tracking
- Take Off and landing
- Straight & Level performance

In order to accomplish this, the students carried out a number of research activities to produce an aircraft with improved performance that was evaluated using the HELIFLIGHT simulator. The students operated in teams of five and worked to tight deadlines in order to produce a solution prior to presentations on the final day. The programme took the form of a number of lectures, laboratory sessions and simulation experiments:

- Planning of flight tests – students split into their teams and using the information packages provided were required to scope out a set of flight simulation tests that would highlight the handling quality deficiencies of the aircraft. A number of geo-specific fight test sites were proposed and students were required to determine which best suited the flight test trials based on relief maps of the area and using real-time weather servers. Each group was required to design a flight test programme and pilot brief detailing the performance standards to be used.

- Control laboratory – although the Wright Brothers did not have access to modern control hardware, the implementation of a simple flight control system for an unstable aircraft was permitted.

- Materials testing – a range of materials were tested (different types of wood, aluminium, steel) to assess their suitability to be included in the aircraft structure (material properties will be determined).

- Wind tunnel tests – each group carried out lift/drag measurements on a Wright aerofoil section compared the results against existing data to determine which wing section will be used on any upgrades.

The laboratory exercises were supplemented by seminars on control systems, aircraft performance and the work of the Wright brothers. Throughout the programme the students had access to a test pilot, Roger Bailey, whose experience in flying the Shuttleworth Collection aircraft was invaluable to give the initial piloted assessment to the complete student body as well detailed group assessments based on the test programmes developed by each group. Significant support from members of the academic and research staff was required during the programme, especially with the implementation of model changes using FLIGHTLAB.

Although the students had not yet embarked on an aerospace undergraduate programme, they were very adept at utilising the resources available to correctly identify the major handling deficiencies of the 1903 Flyer, namely sideslip issues due to limited directional lateral control, tendency for PIO in longitudinal axis, asymmetric turning characteristics and adverse yaw problems.

A wide range of solutions were proposed (Figure 10) and implemented by the different groups, who quickly determined that there is no one correct solution for fixing the handling problems presented, rather the solutions tended to be a compromise between the overall operational requirements and the amount of time available to design and test different modifications. Solutions included centring of aircraft engine, engine upgrades to other power plants the groups found on the Internet, relocation of the canard and re-design of the aerofoil sections. Table 1 gives a typical set of results for the original 1903 flyer model and the upgraded flyer.

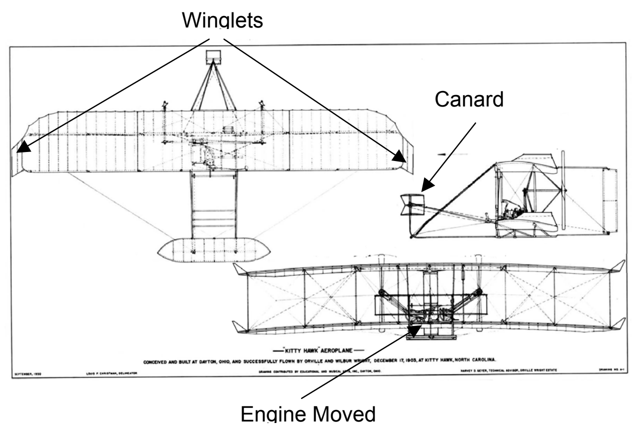

Figure 10 Suggested Modifications to 1903 Flyer

	1903 Flyer	2003 Flyer
Manoeuvre	HQR	HQR
Stall	8	5
Left turn	9	6
Right turn	10	8
Power	9	4
Height Tracking	6	3
Take off	8	5
Landing	6	3

Table 1 Performance Improvements in 1903 Flyer Handling Characteristics

A competitive edge developed between the groups who, at the end of the programme, acted as customers for other groups upgrades. In the role of customer, the groups carried out a critical review of the final presentations on the last day, before giving out scores for technical content of the initial analysis and upgrade performance, quality of presentation and most technically feasible i.e. could the upgrades be achieved in the period of the Wright brothers.

The aim of the programme was not to assess the students' technical knowledge of aerospace problems, but to set a number of challenging problems requiring significant teamwork to develop a solution for which the group as a whole was responsible. The end result of the course was to give an insight into the type of challenges the students will face both as an undergraduate and then latter in their career, with a view to providing a positive experience which would encourage them to choose engineering. An important statistic for the Aerospace Focus Headstart programme at Liverpool is that nearly 90% of those attending indicated that Headstart had confirmed their decision to study engineering and a similar percentage would be including Liverpool in their UCAS choices for their degree. An important facet of the programme was the students enjoyed the considerable technical challenge they encountered and the HELIFLIGHT facility proved to be a valuable teaching and practical tool for the students to try their ideas on. Such facilities appear to be a good advert for attracting students to study engineering at a time when the popularity of engineering courses as a whole appears to be in decline.

Flight Handling Qualities – A Problem Based Learning Module

October 2002 saw the introduction of a new Problem Based Learning (PBL) core module into the M.Eng Aerospace undergraduate programme. The aim of the module is to equip students with the skills and knowledge required to tackle handling qualities and related total system problems that may be experienced in Industry. The problems were examined using a combination of off-line analysis using FLIGHTLAB and piloted simulation trials using HELIFLIGHT.

Four themes underlie PBL:

- Explore problems using background knowledge and experience
- Analyse problems and formulate hypotheses that might explain them
- Design and conduct experiments or perform theoretical analysis to test hypotheses
- Develop new understandings and formulate problem solutions.

Throughout the module the tutor acts as a facilitator rather than a teacher, encouraging useful lines of questioning rather than providing explicit answers and when appropriate provides problem solving structures or methodologies. This encourages the students to take responsibility for their own learning, engaging in active learning through critical self-reflection, self-assessment and collegial learning.

In the Flight Handling Qualities module, the aircraft with its handling deficiency becomes the focus for knowledge acquisition. This method of learning helps the student to garner transferable, technical and interpersonal skills that will serve them for the rest of their lives. The students formed into 5 Teams of 3 or 4 and each team was presented with a task of assessing and quantifying the HQs of a particular aircraft in a particular role and developing fixes to any handling deficiencies.

Test aircraft used in the module were the BO105 (assigned a tactical transport role), the FLIGHTLAB generic rotorcraft similar to UH-60 Blackhawk (to be upgraded for an anti-submarine warfare role), Grob Tutor (required upgrading as an advanced combat trainer), the 1903 Wright Flyer (assigned role as an observation platform) and the XV-15 (to be used for search and rescue missions).

The theory of handling qualities engineering was presented in the first 6 weeks of the first semester and a set of notes was provided to each student to supplement the lectures. The deliverables for each team were an initial assessment report documenting the handling qualities deficiencies and potential solutions to the problems and final report describing the ways in which the HQ problems were fixed, making recommendations concerning the future use of the aircraft and its suitability in the role. Towards the end of the module, the teams presented their work to a 'Customer' (group of staff plus visiting Industrialists) with the objective of demonstrating that the aircraft was now fit for the role. In addition, each individual student was required to maintain a 'Learning Journal', in which they document the development of their understanding of handling qualities from the beginning of the module.

The focus of the Learning Journal is to record the conduct and completion of required tasks. The Journal also aims to encourage self-reflection on what has been learned and how things could be done differently. The Journal provides a rich source of information about a student's self-assessed knowledge and competence in the exercise of skills. The Journal also provides the basis of an external assessment of the student's competence in terms of their technical knowledge and understanding, intellectual skills and ability to apply these skills in practical situations and generally transferable skills, particularly relating to team-work.

The Grob Tutor team was presented with the problem of carrying out design upgrades to allow the basic training aircraft to fulfil a new aircraft role as an advanced combat trainer (ACT), the TutorPlus. An increase in maximum cruise speed at sea level from 135 kts to 200 kts was specified, with a capability of sustaining a 3g turn at 200 kts and the aircraft should be able to track a moving or fixed target at 200 kts. For the expanded operational flight envelope mission task elements (MTEs) were designed to evaluate the effectiveness of the aircraft in different mission phases, the effectiveness being measured in the form of Cooper Harper handling qualities ratings (Ref. 16) using piloted simulation and analysis using MIL SPEC 1797 criteria (Ref. 17).

Piloted simulation and offline analysis indicated that the basic aircraft had insufficient engine power and roll control power and was poorly damped in pitch. To meet the requirements the span and chord of the ailerons were increased, a power plant upgrade was implemented and control surface mixing and a longitudinal state feedback control system was included (feeding back downward velocity, *w*, and pitch rate, *q*) and the technical and economic viability of each modification was assessed.

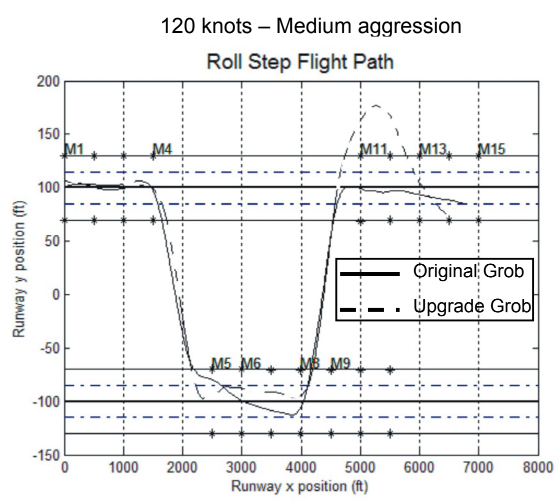

Figure 11 Improvements in Grob roll performance

The basic trainer was found to have level 3 handling qualities in the MTEs designed to assess is capability as a combat trainer. Following the design changes, the TutorPlus was found to have level 1 handling qualities in all areas except for roll control power where it was level 2 (Figure 11). The modifications to aircraft were costed at £450,000 raising the cost of the basic aircraft to almost £1,000,000 which was reasoned to be competitive by the students compared with buying an existing ACT.

Undergraduate Research

HELIFLIGHT is extensively utilised as a research tool in a large number of undergraduate projects for both fixed wing and rotary wing studies. In a typical project students are required to research the problem, use the FLIGHTLAB modelling and simulation tools, design and conduct experiments and present their results to an assessment panel. The project work complements the teaching and learning activities that take place in the taught modules. The following sections highlight some of the undergraduate projects that have been undertaken recently.

Centaur Seaplane

In the current seaboard aircraft market, there is an expected increase in demand for a commercial seaplane. Most conventional seaplanes have a number of operating limitations that restrict their deployment in the commercial area. Suffering corrosion problems with aluminium hulls in saltwater, heavily constrained by wave height and limited ability to operate in most harbours due to their wing-spans, the commercial attractiveness of seaplanes is reduced. Traditional designs must overcome the large drag hump created by the bow wave produced during takeoff, which necessitates a strong heavy hull to withstand the hydrodynamic forces and large oversized engines to overcome the initial drag during takeoff. Subsequently there is a reduction in payload and efficiency during flight with increased fuel consumption.

Figure 12 Proposed design of the Centaur Seaplane

A new project, Warrior Aero Marine's Centaur Seaplane (Figure 12), is focussed around an innovative slender hull design and using modern manufacturing techniques, aims to overcome these problems. An undergraduate project was established to provide initial data on the aircraft's performance. This was achieved by constructing a high fidelity simulation model of the seaplane using aerodynamic data obtained from wind tunnel tests on a 1/25th scale fuselage model, engine data supplied by Avco Lycoming and Warrior's aerodynamic database for the main lifting surfaces. Analysis to date has shown that the fuselage is directionally stable and the offline flight simulation predictions match the calculated takeoff distances reasonably well. Further work will be carried out to generate a more complete set of wind tunnel data and examine the interaction of propeller downwash on the performance of the tail with a view to producing a simulation model that can be used for handling qualities studies. This project has given the student the opportunity to combine flight simulation analysis techniques with traditional experimental and theoretical methods to an industrially relevant problem and as such could be considered to be the template that undergraduate aerospace engineering research projects could follow.

Simulation fidelity research

As part of the ongoing applied research in the area of rotary wing simulation fidelity (Ref.18) a number of undergraduate projects have been initiated to expand the knowledge base of the current simulation environment.

A handling qualities assessment of an existing FLIGHTLAB Bo105 simulation model (Ref.18), designated F-Bo105, was carried out using the US Army's ADS-33E-PRF standard (Ref. 19) and both offline and piloted simulation data was compared to actual flight test obtained by DLR (Ref. 20). A number of ADS-33 parameters such as attitude quickness, bandwidth and control power criteria were determined for the F-Bo105 in roll, pitch and yaw axis. The response of the F-Bo105 in each of these axes was further investigated using piloted simulation of ADS-33 mission task elements (MTEs); the accel-decel and roll step manoeuvre.

In the pitch axis, the attitude quickness is defined as the ratio of the maximum pitch rate P_{pk} to the peak pitch angle change $\Delta\theta_{pk}$. From the closed loop pitch attitude quickness results, the F-Bo105 achieved Level 1 handling qualities for general manoeuvring tasks, similar to the DLR Bo105 in flight (Figure 13). Qualitative results in the form of pilot's HQRs for the accel-decel MTE for both the simulation trial and actual flight test suggest that the F-Bo105 has flight characteristics that are comparable to the actual aircraft. Further improvements in model fidelity may be obtained by producing a hingeless rotor model rather than the articulated hinge model with an equivalent hinge offset as currently used.

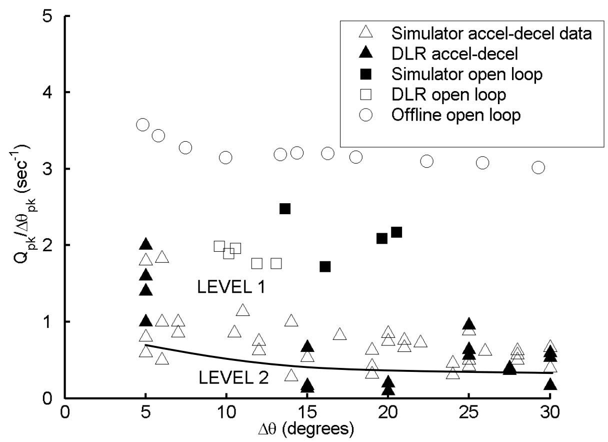

Figure 13 Pitch attitude quickness results

The above analysis provides a baseline of the F-Bo105 and allows students to use the model as a research aircraft in other activities. One such project aimed to use an adaptive pilot model to determine fidelity criteria for yaw axis manoeuvres. This work develops existing research (Ref. 18) in an attempt to quantify overall simulation fidelity criteria. Heffley, (Ref. 21) recognised that the guidance portrait for an accel-decel MTE, in this study a hover turn moving through angle ψ, could be modelled as a 2nd order system (Fig. 14) where the model parameters, ζ and ω of equation (1) are allowed to vary according to pilot adaption due to changing cue and task demands.

$$\ddot{\psi} + 2\zeta\omega\dot{\psi} + \omega^2\psi = 0 \qquad (1)$$

In order to assess the validity of this concept, a number of flight simulation trials were conducted investigating the effect of both visual cueing and motion cueing on a pilot's control strategy when flying 180° hover turns.

Visual databases of the Manching aerodrome were created by the student with different levels of micro and macro texture representing high, medium and low resolution visual models which were flown with and without the aid of instruments. Motion cueing was varied during the simulation flight tests to provide conditions ranging from 6 degree of freedom motion cueing, state limited cueing (e.g. locking height or translation) to no motion cueing (fixed base).

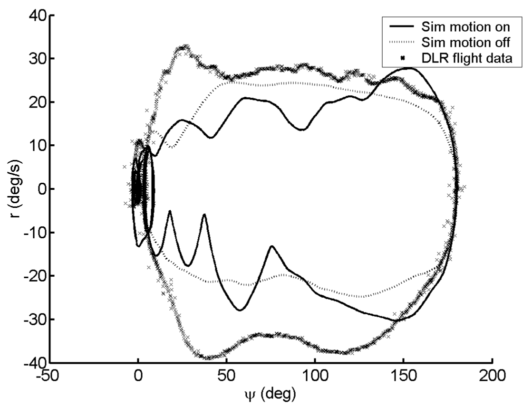

Figure 14 Hover turn phase-plane portraits

As may be expected, a pilot with instrumentation had a better task performance and was able to compensate for any drift in height or plan position during the manoeuvre than when the instrumentation was removed. Reducing the resolution of the visual databases produced a reduction in task performance and a reduction in control activity – the pilot was not aware of any excursions from the performance standards and therefore made fewer, smaller amplitude control inputs. Similarly, the task performance without any motion cueing was poor compared with 6 degree of freedom cueing. Although the 6 d.o.f. cueing does not reproduce the full motion of the actual aircraft, there appears to be sufficient motion cues available to allow a pilot to complete the manoeuvre within the desired performance parameters and more importantly adopt a control strategy similar to that used in the actual aircraft.

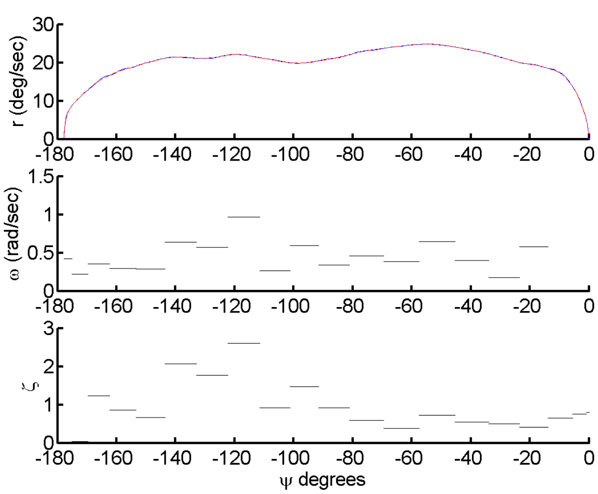

Figure 15 Determination of APM parameters and phase-plane portrait reconstruction for hover turn

From the phase-plane portraits in Figure 14, it is possible to determine ζ and ω for windows during the manoeuvre using a least squares fit. Once these values are obtained, variations throughout manoeuvre can be assessed and the phase-plane portrait re-constructed (Figure 15). It is anticipated that these variations may provide a metric by which the fidelity of the overall simulation may be quantified and is the focus of ongoing work.

In a related project, the effect of motion cueing on pilot performance and workload for helicopter flight simulation was assessed in a heave axis manoeuvre, a bob-up. The student identified that one of the main roles of flight simulation is to enable pilots to develop and maintain the skills and techniques that are required in real flight and that there is an ongoing debate regarding the importance of motion bases in flight simulation. The objectives of the project were to:

- Identify the degree to which pilot control is affected by motion cueing in simulated helicopter flight
- Investigate the effectiveness of fixed base simulators in promoting a positive transfer of flight training
- Determine to what extent motion cues affect pilot perception of workload
- Examine the difference of effects of motion cueing on experienced and non-experienced pilots.

This simulation trial was conducted with 12 student pilots plus an experienced test pilot who were required to stabilise a helicopter aircraft in hover aligned with a reference marker, perform a bob-up to a higher marker (approximately a 40ft vertical re-position) and stabilise the aircraft for 5 seconds. The manoeuvre was repeated for three bob-up and bob-downs. During the manoeuvre the control activity, manoeuvre and stabilisation times and workload in terms of the 70% cut-off frequency were recorded and a post-trial subjective rating of pilot workload was given using the Bedford Workload Scale (Ref. 22). Student pilots were split into two groups, one group received training with motion and one without motion. Figure 16 shows the results from the transfer session on two performance parameters, stabilisation time and maximum overshoot.

It was found the vertical translation and stabilisation tasks performed with motion produced superior performance and reduced control activity compared to that of those trained without motion. Although motion cues had little effect on subjective workload during training for inexperienced pilots, on transfer, those trained with motion experienced a significant reduction in subjective workload whereas the workload of those trained without motion increased on transfer. During training, control patterns are adopted by those without motion cues which were significantly different to that normally represented by real flight, with much larger control input amplitudes being used and at a less frequent rate. Interestingly, the experienced test pilot achieved acceptable levels of performance using the simulator without motion, suggesting that although motion platforms may be necessary for initial student pilot training, fixed-base simulators may suffice for recurrent training of already experienced pilots.

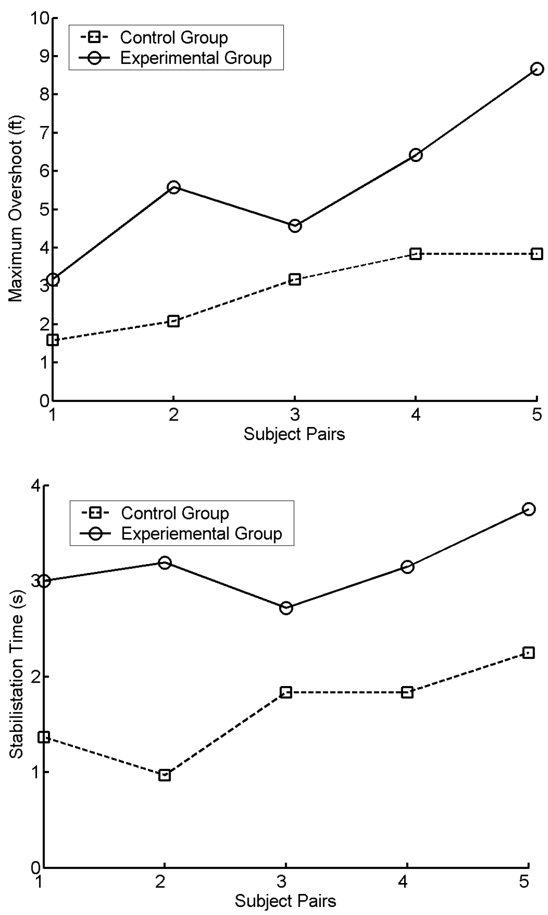

Figure 16 Key performance results for bob-up tests

A perspective on the Future of Flight Simulation in Academia

As has been highlighted in the previous sections, the use of flight simulation at the University of Liverpool is becoming more widespread both for applied research and as an undergraduate teaching and research tool. The PBL approach to learning appears to be a positive step forward in producing capable graduates with the skills that are required by the aerospace industry and who can easily integrate into that environment. It is anticipated that additional teaching modules will be developed having a simulation component.

Existing collaborations between Liverpool and the Aerospace industry are important and a closer partnership between the two groups will be desirable to both parties. Cheaper and faster simulation hardware will mean that the simulation technology gap that exists between industry and academia will continue to close and it will become more economical to use academia for research with their large resource pool and expertise. In return, academia will gain access to information and tools that will strengthen their simulation capabilities.

With increasing financial demands being placed on academia, new revenue streams will have to be developed. Flight simulation expertise will provide opportunities to develop new undergraduate aerospace engineering programmes such as the MEng Aerospace Engineering with Pilot Studies programme planned at Liverpool. Offering successful candidates a pathway to obtaining both a PPL and ATPL in conjunction with an Aerospace Engineering degree, this new degree aims to produce a new generation of pilots with enhanced technical skills to meet future demands for pilots in the commercial civil aviation industry.

Academia is faced with a number of interesting challenges and opportunities in the field of fight simulation and it is hoped that this will inspire more students to consider a career in aerospace engineering.

Acknowledgements

The ACT-TILT project is funded by the EU 5th Framework Growth programme and the results presented in this section were obtained during a HQ simulation trial run by Dr Neil Cameron; the contribution from partners at ONERA and CAA and DGA test pilots is acknowledged. The authors would also like to acknowledge undergraduate researchers Pamela Forsythe, Steven Kendrick, Jonathan Miller and Andrew Moon for their enthusiasm and professionalism during the research activities reported in this paper. Finally the commitment of the numerous technical, clerical and research staff who are involved in day-to-day operation of HELIFLIGHT is appreciated.

References

1. Harward, D. M. The Sanders Teacher, Flight, vol. 2, pp 1006-1007, December 1910.
2. Walker, K. New for Old – Civil Simulators, Flight International, pp 29 – 30, March 2003.
3. Padfield G. D., Charlton, M. K. and Kimberly, A. M. Helicopter Flying Qualities in Critical Mission Task Elements, 18th European Rotorcraft Forum, Avignon, September 1992.
4. VMS Overview, NASA Document EB-2000-07/2-AF-ARC, October 2000.
5. Sage, A. P. Information Technology and Civil Engineering in the 21st Century, ASCE Talk, September 2002.
6. Padfield, G. D. and White, M. D., Flight Simulation in Academia – HELIFLIGHT in its First Year of Operation, The Aeronautical Journal, Vol. 107, No. 1075, pp 529-538, September 2003.
7. DuVal, R. W. A real-time multi-body dynamics architecture for rotorcraft simulation, The challenge of realistic rotorcraft simulation, RAeS Conference, November 2001, London.
8. Bickerstaffe, I. H. Portrait of Landscape: a visualisation solution for military aircraft development, presented at 1998 IMAGE Conference, Scottsdale, Arizona, 2-7 August 1998.
9. Lawrence, B. and Padfield, G.D, Flight Testing Simulations of the Wright 1902 Glider and 1903 Flyer, 34th Annual Society of Flight Test Engineers Symposium, Portsmouth, Virginia, U. S. September 15-19, 2003.
10. Padfield, G. D. and Lawrence, B. The birth of flight control: An engineering analysis of the Wright brothers' 1902 glider, The Aeronautical Journal, pp. 697-718, Vol. 107, No. 1078, December 2003.
11. Padfield, G. D., Lee, D. N. and Bradley, R. How do helicopter pilots know when to stop, turn or pull up? (Developing guidelines for vision aids), American Helicopter Society 57th Annual Forum, Washington, DC, May 9-11, 2001.
12. Prinzel L. J. III, Hughes M. F., Kramer, L. J. and Arthur, J. J. Aviation Safety Benefits of NASA Synthetic Vision: Low Visibility Loss-of-Control, Runway Incursion Detection, and CFIT Experiments http://avsp.larc.nasa.gov/pdfs/csrp50.pdf
13. European Aeronautics: A vision for 2020, ACARE report, January 2001.
14. Padfield, G.D, Manimala, B. and Turner, G.P. A Severity Analysis for Rotorcraft Encounters with Vortex Wakes, 28th European Rotorcraft Forum, Bristol, UK, Sept, 2002.
15. Meyer, M. A. and Padfield. G. D. First steps in the development of handling qualities criteria for a civil tiltrotor, American Helicopter Society 58th Annual Forum, Montreal Canada, June 11-13, 2002.
16. Cooper, G. E. and Harper, P. J. The use of pilot rating in the evaluation of aircraft handling qualities, NASA TN-D-5153, 1969.
17. Anon. MIL-HDBK-1797, Flying qualities of piloted aircraft, U.S. Department of Defense, 1997.
18. Padfield, G. D and White, M. D. Measuring simulation fidelity through an adaptive pilot model, Paper 59, 29th European Rotorcraft Forum, Friedrichshafen, Germany, September 2003.
19. Anon. Aeronautical Design Standard ADS-33E-PRF, Handling qualities requirements for military rotorcraft, United States Army, 2000.
20. Ockier, C. J. Evaluation of ADS-33D handling qualities criteria using the BO 105 helicopter, DLR pub? 1998.
21. Heffley, R. K., A pilot-in-the-loop analysis of several kinds of helicopter acceleration and deceleration manoeuvres, NASA CP 2216, Helicopter Handling Qualities. 1982.
22. Roscoe, A., and Ellis, G., A subjective rating scale for assessing pilot workload in flight, RAE report TR90019. Farnborough, UK 1990.