FLIGHT SIMULATION FOR THE PC-21 PROJECT

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Keywords: *Flight simulation, flight test, turboprop trainer aircraft, aerodata*

Abstract

The new-generation advanced trainer aircraft PC-21 is the first aircraft project for which Pilatus Aircraft Ltd has used flight simulation during the aerodynamic design, development and certification. The Pilatus Engineering Flight Simulator (EFS) was designed and built to provide a cost-effective tool for 6-degrees-of-freedom, pilot-in-the-loop analysis of flight handling characteristics. It has a fixed-base cockpit, electric control loading system, and a triple-channel out-of-the-window view with a HUD.

The PC-21 is a powerful turboprop trainer aircraft with manual flight controls. Special attention was paid to the modelling of the propeller slipstream effects and the flight control forces. Wind tunnel tests on powered and unpowered models have been performed to collect static and dynamic aerodynamic data over a wide range of angles of attack and sideslip. Flight data from a Proof-of-Concept aircraft, on which several new technologies were tested in flight, was used to develop and validate modelling techniques before the first flight of the PC-21.

The PC-21 prototype aircraft has been equipped with a comprehensive flight test instrumentation package. The flight simulator software was used to extract aerodynamic coefficients and derivatives from the flight test data, and compare them directly with the aerodynamic database. The aerodynamic database has been updated regularly to keep the flight simulator abreast of the development of the aircraft. Several modifications to the aircraft have been prepared on the EFS before installation and flight-testing. Some safety-critical flight tests have successfully been supported in near-real time with the simulator software.

1 Introduction

Although flight simulation for engineering purposes has been in use for large aircraft design for many years, only the massive reduction in the cost of computation in the last decade has allowed cost-effective application of 6-DOF flight simulation to the design of small, propeller-driven aircraft. Pilatus Aircraft started development of the fixed-base, pilot-in-the-loop, Engineering Flight Simulator (EFS) in 1999, with the aim to support the PC-21 project throughout its development and certification.

Being a high performance trainer aircraft, the PC-21 was designed to have good flight handling characteristics throughout the flight envelope. One of the challenges in aerodynamic design is to evaluate the handling characteristics from the numbers and graphs generated with empirical methods and wind tunnel tests. The EFS translates and visualizes this numerical data into something that can be communicated to the test pilots – pitch and roll rates, stick forces, accelerations. Early evaluation of the airplane flight mechanics gives the pilot the chance to suggest improvements in terms of flight characteristics. The premature discoveries of possible deficiencies can save valuable time during the design phase of the aircraft and reduce the time for development.

The cost of the development of a new aircraft reflects, among other things, the years needed for its design, prototyping, flight-testing and certification. The diminishing number of prototype aircraft for new projects reflects the increase of the cost to build and operate aircraft, but adds pressure on the flight test department to keep productivity (expressed in for example 'relevant flight test hours per week') high. The EFS can be regarded as a test aircraft, in continuous development in parallel or ahead of the real airplane, which offloads part of the development work from the flying prototypes. The EFS can operate at any hour of the day, in any weather. Test conditions are controlled and repeatable. The aerodynamic characteristics can be easily modified. The EFS can also fulfil other tasks such as the study of the Human Machine Interface (HMI), ergonomic issues, mission software and hardware, the testing of enhanced stability or automatic flight systems or the calculation of structural loads during peculiar manoeuvres.

The market for flight training devices is developing rapidly. Ever more low-cost but capable devices are on offer for use by aeroclubs, private pilots and small aircraft operators. Nowadays, many (potential) customers request from Pilatus a flight training device that is representative of the aircraft model being offered. A previously developed EFS aircraft model provides a developed, detailed and validated aerodynamic database and flight mechanics model that can be readily adapted for commercial purposes.

2 The EFS flight simulator

The Pilatus Engineering Flight Simulator has been developed specifically as an engineering tool to analyse and develop the flight handling characteristics of Pilatus airplanes. The original idea of a tool running on a desktop computer in the Aerodynamics office to check the flight mechanics of an airplane has developed into a full-scale, real-time, "pilot in the loop" facility. The original design and development of the EFS is described in ref. 1. Since then, it has been upgraded in step with the improved capabilities of COTS PC's. Figure 1 shows the present computer schematic, with one Host computer and a CLC computer, complemented by a DeveloperPC.

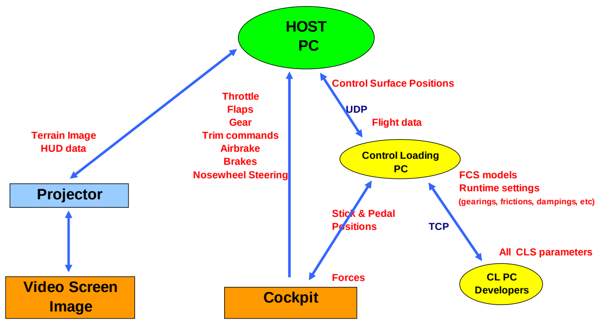

Figure 1: EFS schematic

2.1 The Engineering Flight Simulator

The EFS is located in a dedicated room with a separate control room. This allows the operator to be isolated from the pilot, thus avoiding distraction and adding to the realism. Figure 2 shows the floor plan. Communication is through an intercom system.

During operation the lights in the simulator room are switched off, the only light coming from the visual images and a few cockpit lights.

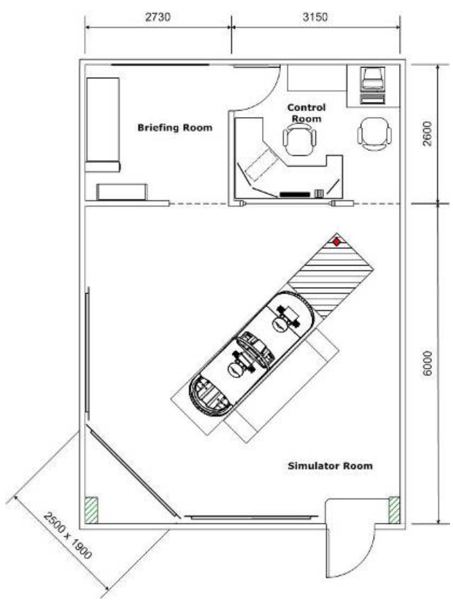

Figure 2: EFS simulator room

The cockpit of the Engineering Flight Simulator consists of a trainer aircraft fuselage, complete with dummy ejection seat and harness (Figure 3). Strapping into the harness again adds to the realism, but also allows the pilot to apply the high control forces required during some simulated manoeuvres. The flight controls (stick and pedals) are real aircraft hardware, as are all switches relevant for simulation of flight mechanics: flap and gear levers, trim switches, etc. Only the front cockpit is completely wired up, the rear seat can be used by an observer. The purpose of some non-relevant switches in the front cockpit has been redefined for specific simulator functions. The flight instruments and all non-relevant aircraft systems are represented only by placards; a Head-up Display is projected on the centre screen to provide flight information to the pilot and additional engineering data to the operator and observers.

Figure 3: EFS simulator room and cockpit

All-electric equipment has been chosen for the EFS for ease of operation and maintenance. During the development time of the PC-21 the EFS has always been available for use when required.

2.2 The Host computer and software

The EFS host computer is an off-the-shelf Pentium-4 PC with the WindowsXP® operating system, which runs the D-Six® software. It has a National Instruments I/O-card for analogue and digital data exchange with the cockpit. Two dual high-end AGP graphics cards provide three channels for out-of-the-cockpit images plus one image for the control screen. The host PC is connected with the computer of the control loading system through a local subnet.

The D-Six® flight simulation environment software was selected to control the EFS. D-Six® is developed by Bihrle Applied Research of Hampton, Va, USA. A D-Six® application fully supports simulation development, analysis and validation activities, as well as real-time, hardware in the loop, simulation deployment.

The term “aeromodel” designates the flight mechanics model, which contains the information on how to assemble the dataset that contains the aerodynamic coefficients. The aeromodel is composed of an aerodynamic database and a flight mechanics model. The aerodynamic database is assembled in D-Six® from tables produced from the data gathered during wind tunnel and/or flight test campaigns or calculated theoretically or with semi-empirical methods.

The flight mechanics model is realized with a code in C++ that generates a Windows dynamic link library (DLL). The main element is the summation of all contributions to the aerodynamic forces and moments that act on the aircraft model. To “fly” an aeromodel D-Six® loads the project and the corresponding DLL.

The C++ code also allows the user to specify and control the functionality of different systems of the aircraft, for example the flight controls, landing gear, flaps, airbrake, etc. D-Six® also contains standardized modules to define for example flight instruments, using Visual Basic functions.

The same D-Six® software can be used to analyze flight test data and validate the aerodynamic models of the EFS. This is discussed in a later chapter.

2.3 The Control Loading System

The PC-21, as well as all other Pilatus aircraft, has been designed with manually operated flight controls. The control forces are an important feed-back to the pilot, and possibly the most significant cue concerning the flight handling characteristics. Correct simulation of the control forces is therefore essential for the EFS.

A major part of the budget was spent on a high-quality electric control loading system (CLS). Original airplane mechanical components have been used for the cockpit controls, and precisely milled parts link this with the Fokker Control Systems Ecol8000 control loading system. The CLS is mounted separately on a trolley behind the cockpit structure that can be disengaged from the cockpit stand. On this trolley are the three electric actuators that generate the forces on the controls, their power supplies and the amplifiers that process the signals from the Control Loading Computer (CLC). The whole Control Loading System (CLS) is removable and can be fitted to other cockpits.

The CLC is a Pentium based computer powered by the real-time operative system VX-Works, with datacards to communicate with the amplifiers. It executes the engines' control loop at 5000 Hz whilst calculating the user's control model at 2500 Hz. The CLC calculates the forces acting on the controls using the data, for example the aerodynamic pressure and the local angles of attack, that it receives from the host simulator computer, to which is linked via an UDP protocol. It returns the values of the relevant parameters, for example the deflection of control surfaces and the control forces

The CLC is connected to the FCS Developer PC that allows real-time monitoring and modification of CLS parameters through a custom software interface. In case of the EFS, this PC also supplies the aircraft control system models that are loaded into the CLC at start-up of the system. These control forces models have been realized in-house, and reflect accurately the behaviour of the real systems of the airplanes. The models of the control system are also written in the C++ language. Apart from simulating the aerodynamic dependent forces (derived from the hinge moments on the control surfaces), they take into account the friction, the stretching, the free play and the inertia of the control systems of the airplane.

2.4 The visual system

D-Six® includes a module that generates the out-of-cockpit views. In case of the EFS, the Host computer generates three adjacent windows of 48° field of view each, providing to the pilot a horizontal view of 144°. The central view contains a configurable Head-Up display that provides the pilot with flight instrumentation. The views are projected by three COTS LCD beamers onto three screens, which are placed at 45° angles. The replacement of the original RGB projector by beamers has significantly reduced the price of acquisition and maintenance.

Originally the EFS used a SGI Octane workstation, connected to the Host PC through the local subnet, to generate a one channel out-of-the-cockpit view. Although the latency was at an acceptable level for flight training devices, it proved to be too large for engineering purposes where often high-gain tasks are performed by the pilot. When the opportunity arose, we changed to using a fairly simple graphic terrain model that is generated by the simulation software D-Six® in step with the aerodynamic simulation. This eliminates the time delay between aircraft motion and visual, at the cost of a slight increase of the time steps to maintain real time.

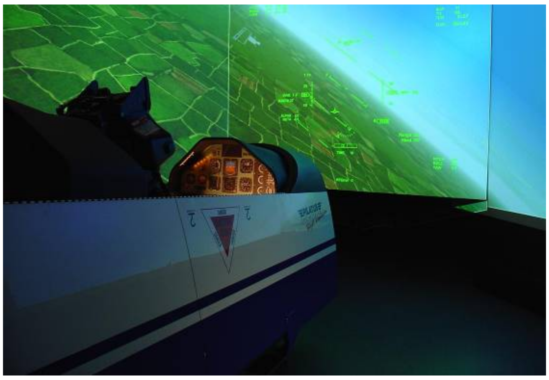

Figure 4: EFS cockpit and out-of-the-cockpit view

With advances in PC computing power and graphic cards, more time becomes available for the terrain image. With the same graphics, the simulation time step can be reduced. Earlier this year, the simple terrain model of D-Six® was replaced with a much more detailed model (based on a computer game program). With the use of modern graphics cards, the host PC now generates three detailed images with the same simulation time step as used to achieve a single, simple image only three years ago.

2.5 Desktop application of D-Six

Apart from controlling the EFS, the simulation environment software D-Six® is also used extensively in the Aerodynamics office ('on the desktop'), and not only in the development of the simulator models. Its replay, visualization and manipulation options have proven very useful to analyse flight test data, extract coefficient data from flight test data, or visualize complex aircraft motions like for example spin entry.

D-Six flight test analysis tools are tightly integrated with the D-Six simulation environment to permit efficient model validation and verification. A comprehensive flight test data editor permits the importation and manipulation of several flight test data formats, with a range of data manipulation tools available. The flight test cross reference interface allows the graphical mapping of the flight test variable names with the associated simulation variable for driving the simulation with stick, surface, or state inputs. The Overdrive feature permits the user to extract coefficient data from flight test data, drive the simulation states with imported flight test or other simulation signals, and to compare the simulation propagated coefficients with those extracted from flight. This permits the user to rapidly identify simulation to flight mismatches.

3 The PC-21 advanced trainer aircraft

Pilatus Aircraft has a long tradition in the design of low-wing, tandem-seat trainer aircraft. The popular PC-7/PC-9 family traces it origins directly back to the P-3 of 1952. The first installation of a turboprop engine in this piston-engine aircraft (P-3B: first flight 1966) led to the development of the PC-7 (1978). An upgraded version was developed as the PC 9 (1984). A complete redesign of the airframe in the early 1990's produced the PC-7MkII and PC-9(M), which are presently in production. More than 850 Pilatus trainer aircraft has been delivered worldwide. The PC-9(M) was further developed by Beech (now Raytheon) into the T-6 Texan II. The good performance and pleasant handling characteristics also made the Pilatus trainers a popular choice for many military and civil aerobatic display teams.

Figure 5: Pilatus PC-21

Pilatus started the design of the new generation training aircraft PC-21 in 1997. The aim of the PC-21 is to offer customers a high-performance aircraft with an up-to-date cockpit that will prepare future pilots for the latest front line aircraft in the most cost effective way. The PC-21 is a fully new developed turboprop aircraft designed for low life-cycle costs. It has a traditional tandem cockpit layout. The cockpits have advanced training system features that allow extensive interaction from the instructor. The open architecture allows easy reconfiguration of the cockpit displays. The engine is from the well-proven PWC PT6 family, but with additional FADEC and a Power Management System (PMS) that limits the engine power as a function of airspeed to generate jet-like thrust characteristics. The engine is mounted with considerable tilt and skew angles that alleviate the use of the yaw trim over a large part of the speed range. An automatic yaw trim system compensates for the remaining torque effects. The PC-21 has the largest flight envelope in its class: low-level cruise speed is more than 300 kTAS, maximum operating speed is 370 kEAS/M0.72, and dive speed is 420 kEAS/M0.77. The PC-21 has been certified to FAR-23 regulations in December 2004. The project is completely financed by Pilatus Aircraft, with no outside capital being attracted. This was an extra incentive to select the most cost-effective tools for design and development.

4 Construction of the PC-21 Aerodynamic Database

From the start of the PC-21 project in 1997 the EFS was intended to be a tool to facilitate communication between the flight mechanics engineers and the test pilots. It was realised that a detailed flight mechanics model was needed to replicate the expected power effects on the handling characteristics. The low speed wind tunnel tests (model scale 1:4) have been arranged to obtain sufficient data at different power settings for each aircraft configuration to allow the construction of an accurate simulator model. The size of the PC-21 aerodynamic database exceeds 8 MByte and 700 files (plus 160 files with propeller engine data).

Aerodynamic data was collected from several sources:

4.1 Wind tunnel tests

An important characteristic of the Pilatus trainer aircraft has always been their good behaviour in a spin. The PC-21 configuration was first tested in the Bihrle Applied Research Large Amplitude Multiple Purpose (LAMP) facility at an early stage to enable prediction of the spinning modes. A small-scale model was used to measure the static and dynamic coefficients over a very large range of angles of attack and sideslip during forced-oscillation and rotary motion. The static results were used as a first check of the aerodynamic characteristics of the configuration. The forced-oscillation data was used in the Aerodynamic Database for the dynamic ('damping') derivatives.

For comparison, the configuration of the PoC aircraft (see §4.2) was also tested, and its spinning modes were predicted. The predicted spin modes were afterwards confirmed in flight.

The PC-21 configuration as initially tested was predicted to be spin resistant in both erect and inverted attitude. Modifications to the aft fuselage and empennage were made to allow the aircraft to spin. Flight tests with the PC-21 prototype have confirmed the good spinning characteristics (see ref. 2 for more details).

After the basic aircraft configuration had been confirmed, the aerodynamic design of the PC-21 went forward with several sessions with a powered model in the low-speed wind tunnel of RUAG at Emmen, Switzerland. Besides collecting data to confirm the performance predictions, much attention was paid to determine the effects of the propeller slipstream on the aerodynamic properties of the aircraft. The geometry of the proposed propeller was reproduced accurately. Sufficient data was collected to generate a detailed aerodynamic database that enabled us to build a flight simulator model for further studies of the flight handling characteristics. However, first a number of corrections had to be applied to the data.

Figure 6: PC-21 wind tunnel models

Reynolds number corrections

The tests in the LAMP facility were conducted at very low Reynolds numbers. This obviously affects the aerodynamic derivatives at angles of attack when the airflow is (largely) attached. Corrections to flight Reynolds numbers had to be made to e.g. the roll-damping derivative.

During powered tests in the large, low-speed wind tunnel most tests were performed at the highest airspeed that allowed a certain thrust coefficient to be achieved. The airspeed had to be reduced to achieve the higher thrust coefficients due to the limited power of the hydraulic engine of the model. The lower maximum lift coefficients that were recorded were first attributed to the propeller slipstream interaction with the wing; after additional tests at the same lower airspeeds without slipstream was it realised that the lower values were in fact caused by the lower Reynolds numbers.

Effects of power

The effect of the propeller slipstream on the lateral and directional coefficients are a function of the thrust coefficient CT and the propeller advance ratio J. Several combinations of CT and J have been tested in the wind tunnel to obtain sufficient coverage of the entire flight envelope.

Comparison with flight test data has shown that the power effect on the longitudinal characteristics was quite well predicted. The effect on the lateral force however was not so good, especially for simulated high-speed conditions. The differences between the model and the real aircraft (engine inlet, propeller flow distortion) are apparently significant enough to spoil the prediction. As a result, the directional trim settings predicted with the EFS (trimmed with slipball centered) match poorly with the flight test results.

Mach number effects

The PC-21 is the fastest aircraft Pilatus has developed to date, both in terms of IAS and Mach number. With a M_{MO} of 0.72, it just enters the transonic regime. Care was taken during the design of the wing, tail and fuselage to delay the onset of transonic effects as much as possible. Although no high-speed wind tunnel tests were conducted, the design was checked extensively with CFD methods (Euler and RANS). Wind tunnel tests at higher mach numbers were not performed.

The aerodynamic database initially contained only Prandtl-Glauert corrections for the lifting surfaces to account for Mach number effects. Near real-time analysis of flight test data, described in §6.2.3, was used during opening of the flight envelope to assure a safe progression into the transonic regime. The change of the aerodynamic characteristics at the higher Mach number was later extracted from further flight test data and incorporated into the aerodynamic database.

4.2 Proof of concept aircraft

An instrumented prototype PC-7MkII aircraft was converted to act as proof-of-concept aircraft for several new technologies. The original PWC PT6-62A engine was replaced with the more powerful PT6A-68 with PMS earmarked for the PC-21. A five-bladed propeller with composite blades replaced the original propeller. After the first series of test flights, the wing was clipped to reduce the aspect ratio to the proposed PC-21 value to assess the ride qualities during low-level, high-speed flight. Several changes were made to the flight control system, the most notable the addition of roll spoilers.

Sufficient data was collected to allow the construction and validation of an ADB for this proof-of-concept (PoC) aircraft. This proved to be a very useful exercise in flight data collection, processing and matching in preparation for the PC-21 program.

4.3 PC-21 prototypes

The PC-21 prototype aircraft made its first flight on July 1st, 2002. It has been built on production tooling, and closely resembles the production standard in structure, systems and avionics.

The PC-21 prototype is equipped with an extensive flight test instrumentation package. More than 500 data channels are recorded in flight. All data is stored onboard and transmitted real-time to the ground via telemetry.

Emphasis was placed on collecting flight test data on control force characteristics early in the PC-21 test program to validate the control surface hinge moment data, and to optimise the flight control system.

The second prototype joined the flight test program in May 2004. Both aircraft were used to collect data for the FAR-23 certification in December 2004.

Right from the first flight of the PC-21 prototype aircraft flight test manoeuvres have been 'replayed' with OverDrive, and corrections have been made to the simulator model to enable continuing support to the Flight Test department during the opening of the flight envelope, see chapter 6.

5 Validation of the EFS

5.1 Validation of hardware

An important issue during validation is the control forces. The EFS being a fixed-base simulator, the pilot does not feel (normal or lateral) acceleration cues. This affects his impression of the forces he exerts on the controls. We handled this problem in two steps: first we carefully compared the EFS control loading system and the PC-21PoC aircraft control system instrumentation, using an independent load transducer to measure the applied forces. This confirmed for us and the pilots that the forces indicated on the EFS were equal to the values recorded by the calibrated aircraft flight test instrumentation. For the second step we went through a 'training exercise' in the EFS where we let the pilots guess what force they were applying. In this way we 'calibrated' the pilot for the EFS. For engineering development it is important to achieve the correct control forces, not to modify them to suit the pilot's impression.

Friction in the control system poses a challenge to the design of a manually controlled aircraft. This is especially true when the control forces in normal flight must be low. Pilatus has paid extra attention in the PC-21 design to achieve low friction even with the pressurized cockpit. The friction forces measured on the PC-21 prototype are significantly lower than those of previous Pilatus aircraft. Aircraft hardware in the cockpit of the EFS ensures that the friction forces in the simulator are lower than in the aircraft. The difference is added mathematically in the control forces models.

Figure 7: calibration of the control forces

Another practical aspect is elastic deformation of the control system. In the initial EFS model this was not included, but as the design progressed estimated values were inserted. When the first prototype was ready, experimental values for the stiffness of the control systems obtained from the limit load tests were used to update the EFS model.

5.2 Pilot assessment

Although most pilots at Pilatus were familiar with flight simulators used for training, flying and evaluating an aircraft model in the EFS for engineering purposes proved to be quite different. First is the fact that the EFS has a fixed base. The large flight envelope of the Pilatus aerobatic trainer aircraft makes the application of a motion platform impractical. However, this type of aircraft is mainly assessed in manoeuvring flight. Many cues for the pilots are missing; the pilots had to learn to accurately assess the aircraft reaction from the image on the screen and through the flight controls.

With a powerful aircraft like the PC-21 the rudder trim must be used with change of power or speed, unless the automatic rudder trim system is installed. In the EFS inexperienced pilots often forgot to trim directionally or to apply sufficient rudder to avoid significant sideslip due to the lack of lateral acceleration feedback. This can lead to errors in the assessment of manoeuvres (for example stalls and dive manoeuvres). EFS pilots had to learn to visually check the slipball all the time.

The realistic cockpit with a replica ejection seat and seat harness, the dark simulator room with separate control room and the use of intercom for communication all contribute to the realism of the EFS. Over the years this was further improved by adding side screens (extending the visual system to more than 140° horizontal view) and aircraft sounds (mainly engine and airflow).

Acceptance of the EFS was initially hampered by the fact that it was evaluated together with the model of a new aircraft. The test pilots had a lot of experience on Pilatus PC-7 and PC-9 trainer aircraft. However, this proved to be a drawback when the new aircraft design was first flown in the EFS. The pilot's first comments on the model were based on their experiences with existing aircraft, and several aspects of the handling were described as 'unrealistic'. But the PC-21 possesses a completely new airframe, as it is designed for significantly higher performance than the previous Pilatus aircraft. The changes that had to be made to the PC-21PoC validation model (which was based on predicted PC-21 data) only encouraged the concern of the pilots. However, later flight test data has shown that the PC 21 has indeed many of the different characteristics that the simulator model displayed.

Despite these comments, the test pilots adapt quickly to the conditions in the EFS, and can provide consistent feed-back. However, for validation it proves to be an advantage if a pilot can perform the same manoeuvre on the simulator and the aircraft within a short time. Some pilots will actually close their eyes while flying well-rehearsed manoeuvres in the EFS to see how the simulator model performs to a series of well-known control inputs.

6 Use of EFS in the PC-21 development

6.1 Support of design activities

6.1.1 Design phase

During the detail development of the PC-21 the EFS has been used to evaluate the design for manoeuvrability and controllability in the design envelope with the proposed control system design concepts. The control forces were balanced between the high-speed and the low-speed end of the speed range.

In support of the certification of the flight control system, failures of the flight control system have been simulated on the EFS. Tests have been performed with disconnected control surfaces, balance tabs or trim tabs. Also jamming of controls has been investigated. Some interesting results were obtained; the following example was observed with the mechanically operated roll control system.

The roll control system comprises ailerons and (hydraulically operated) roll spoilers. A disconnection can occur either between the control stick and the roll spoiler actuator, or between this actuator and the aileron. In the first case all roll control is lost on one side, in the second case the roll spoiler still operates when the control stick moves. Perhaps surprisingly the second case is initially the worst, although in both cases the aircraft remains controllable. After disconnection at moderate airspeeds both ailerons float to full up deflection; this happens so fast that the pilot usually cannot stop the control stick from moving fully away from the side of the disconnected aileron. In the first case, the aircraft now flies with both ailerons fully up and both roll spoilers fully deflected, with hardly any upset in along the roll axis! Bank angle must be controlled with rudder.

In the second case however, the ailerons also float up, but the roll spoiler on the side of the disconnected aileron is not activated. The aircraft now flies with both ailerons fully up but only one roll spoiler fully deflected, and rolls quickly away from the disconnected aileron. The pilot instinctively stops the rolling motion by moving the control stick back towards the centre; some roll control is left to bring the wings back to level. By the way, Pilatus is not aware of a flight control system failure ever happening on a Pilatus aircraft in flight.

Safety analyses have also been performed in support of the structural design for birdstrike. The controllability of the aircraft after structural failure of the horizontal and vertical tail was evaluated, and recommendations for continued safe flight have been issued. To improve safety after a large birdstrike on the horizontal stabilizer, the pitch control system is designed to disengage the two elevator halves when one half is jammed or lost due to structural damage. The pitch control forces are reduced with geared balance tabs. Each elevator half has its own balance tab after simulator tests demonstrated the catastrophic effects of an aerodynamically overbalanced elevator.

The PC-21 has a Fowler flap with three settings: up, take-off and land. Thanks to the powerful lateral control system, EFS tests have shown that asymmetric flap deflection is controllable even when one flap is a full setting different from the other.

6.1.2 Preparation for first flight

The control surfaces of the PC-21 are all quite delicately balanced to achieve the required control forces over the speed range. All hinge moments had been theoretically predicted, although supported by in-house experience. There was a concern that the accuracy of the predictions might result in overbalance of some of the controls. To alleviate the concerns, the error margins for each of the hinge moment contributions were estimated, and tests were conducted on the EFS to investigate the 'worst case' combinations. The gearing ratios of the control balance tabs for the first series of test flights were chosen such that overbalanced controls would be avoided without the control forces increasing to potentially unacceptably high values. Flight tests confirmed later that most hinge moment predictions had been quite accurate, and the gearing ratios could be adjusted accordingly.

The flight test schedule for the first flight was rehearsed and refined on the EFS. For the first flight it was important to stay within gliding distance of the airfield. Both project pilots also trained for a number of emergencies, for example engine failure and failure of the electronic flight displays.

6.1.3 Support of flight test activities

During the development of the aircraft and its systems, the EFS has often been used to evaluate in more detail than can be done with the aircraft, characteristics observed in flight. Flight test procedures and manoeuvres have been developed and rehearsed on the EFS. The effects of configuration, mass and CG on the outcome of a test were often predicted with the EFS.

6.2 Comparison with flight test data

6.2.1 Calibration

The PC-21 P01 is equipped with a wing tip mounted flight test boom that measures static and total pressures, and has vanes to measure the angles of attack and sideslip. The vanes were calibrated to the aircraft angle of attack and sideslip using VSaero panel method computations. Longitudinal, lateral and directional aerodynamic coefficients were extracted from the first flight test points; however, they did not match well with the predicted values. It was realised that a more accurate calibration of the angle of attack was needed to improve the matching of the flight test data with the prediction.

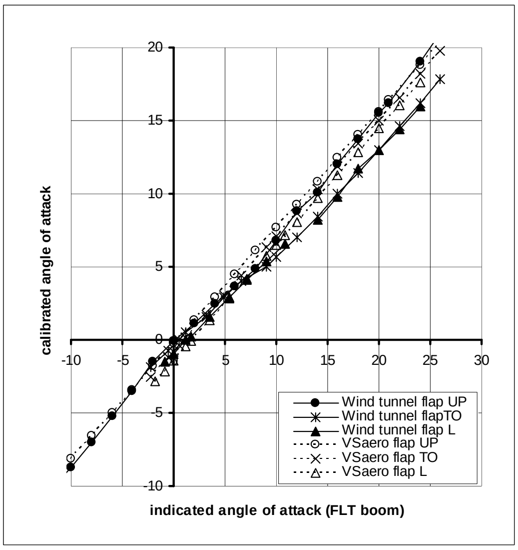

Figure 8: Calibration of the aircraft AoA

After the first series of stall tests the maximum lift coefficient was found to agree well with prediction. It was decided to perform the calibration of the angle of attack by matching the lift curves of the wind tunnel and flight test. Although the resulting calibration curves of vane alpha versus aircraft angle of attack are much less linear than predicted by the panel method (see Figure 8), all aerodynamic force and moment coefficients match much better. This example shows the importance of correct calibration of the flight test instrumentation.

6.2.2 Aerodynamic model development and validation

The D-Six® module OverDrive provides the capability to extract the aerodynamic coefficients from flight test data. Figure 9 shows the schematic.

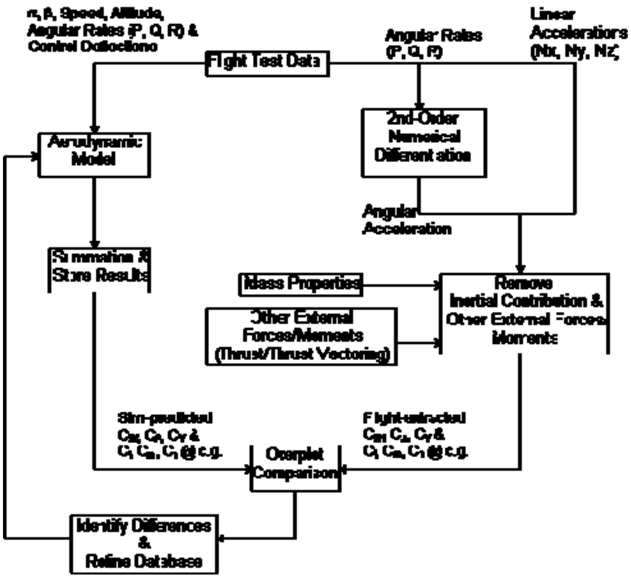

Figure 10: D-Six® Overdrive schematic

The flight test instrumentation in the aircraft records aircraft attitude, speed, linear accelerations and angular rates. Using the linear and angular accelerations (differentiated from the rates) and the known mass properties of the aircraft, the module calculates the total forces and moments acting on the aircraft for each test point. The module subtracts the measured external forces and moments (for example engine torque). It calls the aircraft model to determine the predicted external forces and moments that are not measured on the aircraft (for example mass, propeller direct forces), and subtracts those as well. What is left represents the aerodynamic forces and moments. These are reduced to the total aerodynamic coefficients valid for the particular aircraft configuration and

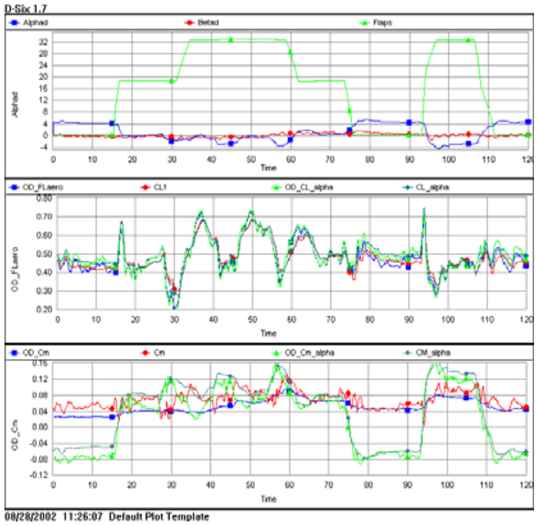

Figure 9: D-Six® Overdrive comparison plot

to baseline data by subtracting the contributions due to for example control surface deflections or extended landing gear. These contributions are again taken from the aircraft model, interpolated with the actual flight conditions. Finally, the baseline data from flight is compared with the simulator model data.

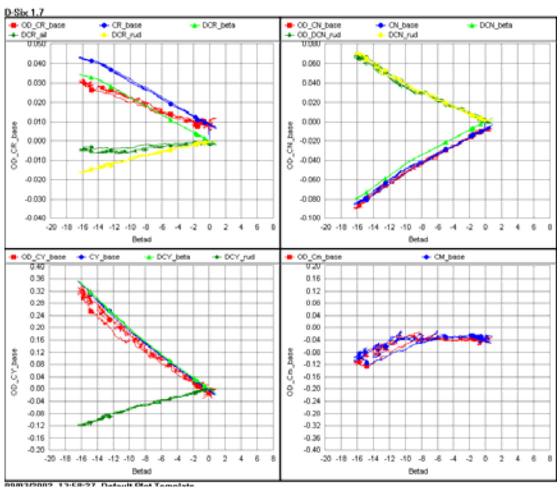

Figure 11: D-Six® Overdrive cross-plot

Figure 10 shows a typical example of the changes to the longitudinal coefficients during flap extension and retraction. Figure 11 shows the results of a sideslip manoeuvre in a cross-plot: the prediction of the lateral and directional stability can be assessed directly by comparing the gradients.

Obviously, the accuracy of the validation depends on the quality of the input data. Not only must the flight test instrumentation be properly calibrated, but also the aircraft mass properties must be known. The vertical position of the centre of gravity, for example, turned out to be much more difficult to obtain then you would expect, but it is vital for matching the lateral stability derivative Cl_{β}.

With the new PC-21 we were fortunate to have state-of-the-art AHRS on board, which gives reliable and repeatable readings. The PoC aircraft had an older generation AHRS which produced especially acceleration data with much more offsets and drifts. This made matching between flights sometimes very difficult.

The EFS model of the PC-21 was found to agree well with data from flight test. Some differences can be expected, like an offset of the zero-lift pitching moment. Longitudinal and directional stability and controllability agree well with the low-speed wind tunnel results. However, at high airspeeds, elastic deformation of the airframe can become significant. For example, bending of the fuselage under horizontal tail loads at high speed reduces the apparent longitudinal static stability. But deformation can also be used intentionally: stretch in the rudder system helps to limit the load on the vertical tail and aft fuselage by reducing the rudder deflection at full pedal deflection at high airspeeds. Modelling these effects is complicated by their often non-linear behaviour.

6.2.3 Near real-time flight test analysis

The D-Six® replay module OverDrive also gives us the capability to check the aircraft characteristics in almost real-time. This was used during a number of test flights, for example during the high-speed flutter tests. After the conclusion of each test point, the test data that was received with telemetry was converted and loaded into D-Six®. The aerodynamic force and moment coefficients of the aircraft were calculated, and the results were immediately compared with the prediction for the same flight conditions. This procedure took just over one minute for each test point. A decision to proceed with the next point (from the aerodynamics point of view) could be given before the aircraft had climbed back to its initial altitude. This helped us to complete the first series of flutter tests to V_D and M_D (at low and high altitude) in only two flights.

6.3 Support during development

Several improvements concerning performance and flight handling were made to the PC-21 prototype during the development. Three examples where the EFS was involved are presented here.

6.3.1 Lateral stability

Soon after we started to analyse flight test data, it was realised that the lateral stability (dihedral effect) was significantly lower than what had been measured in the wind tunnel. Subsequent investigations showed that this is caused by model support interference. The support has a streamlined fairing that encloses the hydraulic lines to the engine. This fairing is fixed to the strut, and rotates with the model in sideslip. Therefore with sideslip the strut produces lift, and it generates an asymmetric pressure field on the model lower surface that induces an additional rolling moment with sideslip. This was confirmed with VSaero panel calculations. Ironically, after a first series of tests the wing dihedral of the wind tunnel model had been reduced from the original estimation.

Investigations were performed with the EFS to determine the required amount of dihedral, taking into account the aerodynamic characteristics of the aircraft and the flight control system as derived from flight tests. Subsequently new up-swept wing tips were designed (see Figure 12) and successfully flight-tested that restored the lateral stability to the required level.

Figure 12: Original and up-swept wingtips

6.3.2 Powered roll control system

During the development flight-testing it was realised that the requirements for roll performance throughout the speed envelope could not be met with a manual roll control system. The control forces increased with airspeeds to a level where the pilot could not achieve full stick deflection, and the high forces caused elastic deformation in the control circuit with significant blowback of the ailerons. This caused also a reduction of the roll spoilers' deflection, reducing roll performance even more. As a solution, a hydraulic actuator was introduced into the system. Many concepts were evaluated on the EFS to optimise the design of the single actuator without major changes to the roll control mechanism, while maintaining sufficient manual roll control in case of failure of the hydraulic system.

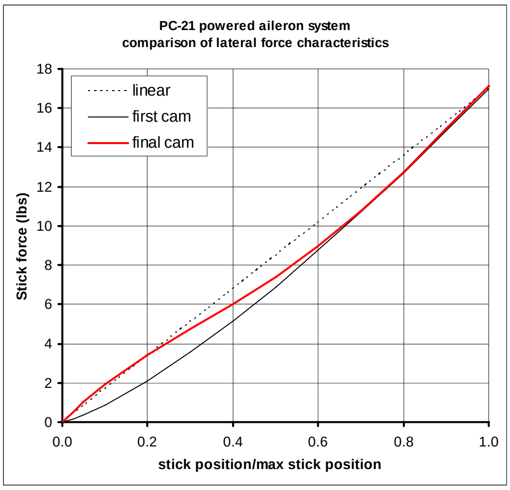

Figure 13: Roll control force characteristics

An artificial feel unit was added, which if possible should only have a mechanical spring. However, to maintain the pleasantly harmonised control forces at low airspeeds, non-linear spring characteristics were required. Thanks to the thorough preparation on the simulator, only one adjustment was made to the initial installation on the aircraft. Figure 13 shows the characteristic of the initial spring, developed in the EFS and flight-tested, and of the final spring that is now implemented in the aircraft. The adjustment was needed because the lack of perception of the roll acceleration in the EFS made it difficult for the pilots to precisely determine the required roll control inputs, and therefore the roll forces. In the end, dedicated flight test time on the aircraft for this program was limited to less than one hour of evaluation.

6.3.3 Autopilot system development

The latest large project for the EFS is the support of the development of an autopilot system. For this program however, only the software and flight model are used, not the actual cockpit. The Pilatus Avionics Rig is used for risk mitigation to resolve integration issues before installation of the autopilot on the aircraft, and to develop autopilot servo speeds and gain settings for initial flight testing. A copy of the simulation software D-Six® was re-hosted on a PC that is connected to the avionics development rig. Models of the autopilot servos serve as interface between the aircraft model and the actual autopilot computer. After solving initial problems in the avionics interfaces, the inner and outer loop gain parameters of the digital autopilot computer were determined that are used to start the flight test campaign. Autopilot and servo failures were also extensively evaluated. This work allowed Pilatus to enter the flight test campaign with confidence. After flight testing started, the servo models have been expanded to analyse and resolve a few 'non-linear' characteristics that were observed in flight. The Avionics Rig installation has contributed significantly to the successful start of the autopilot flight-test campaign.

6.4 Support of certification

The EFS has played only a small direct role in the certification process of the PC-21. Because both the EFS and the aircraft models were new to Pilatus and the certification authorities, and there was no time in the program to perform a full validation of the model, it was never intended to submit data generated on the EFS for certification of flight handling characteristics.

However, the EFS was used to demonstrate the characteristics of the aircraft in some extreme situations that are considered too dangerous to actually fly. These include systematic tests of flight control system failures to determine the severity of single and combined failures (disconnected or jammed controls), engine failure just after lift-off and flight with extreme fuel unbalance. Without the EFS, only data from analysis on paper could have been submitted, with much larger room for interpretation.

7 The future of the EFS

The main customer of the EFS, the PC-21 trainer aircraft, has finished its initial development and certification. The open architecture of the mission software, however, allows extensive customization. At the moment the EFS cockpit is (finally) being equipped with a complete set of PC-21 cockpit avionics, which is connected to the avionics development rig. Together with recent significant improvements to the D-Six® out-of-the-window graphics, this will allow Pilatus engineers to evaluate and capture the customers' requirements by evaluating modifications to the mission system and cockpit display symbology during simulated missions.

The modular design of the EFS allows replacement of the cockpit structure with relatively little effort, while retaining all other hardware. In this way the EFS can support a new aircraft project in the company with a relatively low investment. Within the engineering department and among the pilots, the advantages of the EFS are by now well established, as is evidenced by the regular question: "Can't we have a quick look with the simulator?"

8 Concluding remarks

Aircraft cockpit hardware relevant to the foreseen tasks, a high-quality control loading system, and COTS PC components can be combined into a very cost-effective flight simulator for engineering purposes. The large increase in the performance of COTS PC's and graphic cards allows increasingly realistic flight simulation at an affordable price. Detailed aircraft models running at high speed can be combined with graphic displays using a single COTS PC, reducing latency to a minimum. Simulation update speed can be traded against visual detail depending on the task, which allows the simulator to be used for both engineering- and mission-oriented tasks.

The choice of all-electric components for the EFS has been a wise one. The EFS has demonstrated a very high reliability. The start-up time of only a few minutes is much appreciated by the users. The parts that require most attention and maintenance are the mechanical flight controls, which are original aircraft parts. In the EFS the usage is much more intense than in the aircraft, high control forces are applied much more regularly, and free-play develops much faster in the EFS than on the aircraft.

D-Six® has proven to be an excellent tool to support an engineering flight simulator. It provides a stable simulation environment both for the EFS and on the desktop, with all tools required to run a simulation and record and analyse the results integrated in one package. Aircraft specific details can be easily included in the flight model. Aircraft flight models can conveniently be transferred from the desktop in the office to the EFS. The same model can be used for comparison with flight test data.

The EFS provides the design engineers and the pilots of Pilatus with a tool to evaluate the characteristics of a new design at an early stage. The EFS has helped to evaluate risks in the preparation of the first flight of the PC-21 prototype, to assist with the definition of the test schedule and to prepare the pilots for emergencies.

There is a distinct difference between flight simulators for training and for engineering purposes. On the EFS the pilots have to make adjustments to their perceptions to fit the limitations of the (fixed-base) simulator with physically correct aircraft models. When developed into training simulator models, it is advisable to keep as close as possible to the correct physical model.

Testing of flight handling characteristics in the EFS is a fast and efficient way to find ‘unexpected’ behaviour. Care must be taken to model each system correctly, as incorrect modelling can hide problems, or indicate problems that do not exist in the real aircraft. A well-prepared and sufficiently detailed ab-initio aerodynamic model is required. In the flight test phase the EFS was very useful to evaluate characteristics observed in flight, e.g. to eliminate the influence of certain variables, and to determine which variables do contribute significantly.

During validation of an aerodynamic model, one must be prepared to discover unexpected or neglegted aspects. Proper analysis of relevant data usually results in the discovery of the missing piece. Aerodynamics, flight mechanics and structural dynamics follow the laws of physics, even though it sometimes doesn’t look that way!

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