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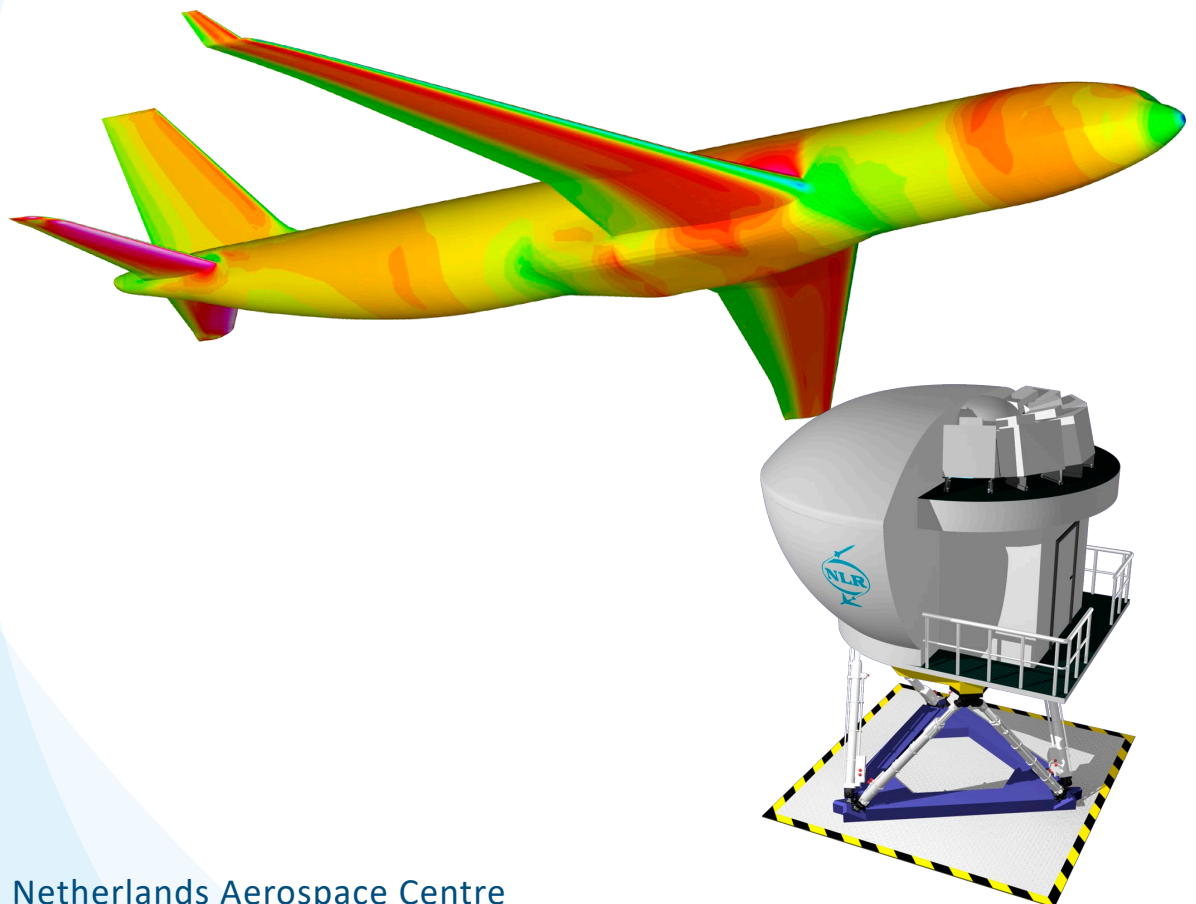Dedicated to innovation in aerospace

New Integrated Modeling and Simulation Techniques for Research and Training Applications

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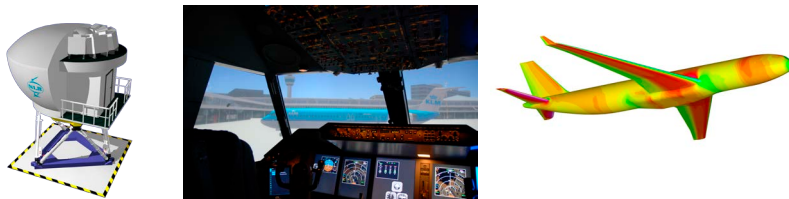
Problem area

Simulation fidelity can be defined as the quality of the simulated vehicle (both equipment and model) to represent the real world vehicle. This includes equipment or hardware fidelity as well as software or model fidelity. For training simulation applications, the emphasis is on adequate transfer of training to the real aircraft. For flight deck research and engineering simulation, the objective is to generate behavior and pilot performance that closely matches the performance in the real environment. For these applications, the representation of the modeled environment through which the aircraft moves, including its motion, plays a major role. To address a wide range of experiment objectives and fidelity requirements, the flexibility and versatility of research and engineering simulators can be utilised in an affordable manner by using integrated modeling and simulation techniques.

Description of work

As a significant part of the costs in the flight simulation development process includes software design, a simulation infrastructure has been developed for the NLR Generic Research Aircraft Cockpit Environment (GRACE) that enables the flexibility to design aircraft specific models or subsystems with different levels of fidelity according to research objectives. As part of the simulation infrastructure, a developed MATLAB/Simulink simulation environment provides the capability to modify submodels for any specific aircraft to be simulated resulting in quick turnaround times for different project experiments. The newly integrated flight

simulation development methods and tools, in conjunction with increased simulation development methods and tools, in conjunction with increased computing power, further improves flexibility and versatility of the NLR simulation facilities to comply with a wide range of research requirements. The integrated modeling and simulation techniques have been used for the development of a modern fly-by-wire transport aircraft conducted for the NLR GRACE reconfigurable simulation facility.

Results and conclusions

With the GRACE, NLR is capable to meet the increasing demands in experimental flight research and flight deck human factors investigations. Affordability in research and engineering simulation is achieved by integrating NLR technology advances in the area of aerodynamic modeling, aircraft system modeling, avionics and HMI development, environmental simulation modeling and motion cueing. To avoid significant costs in simulation software design and testing, a simulation environment has been developed that provides affordable design, auto-coding and testing of specific aircraft models, or submodels, in a modular way according to research and engineering requirements. Validation and tuning methods using operational flight data, in combination with piloted evaluations, have resulted into satisfactory simulation fidelities to meet the requirements for both research and (low-cost) flight training applications.

Applicability

The shown advancements in flight simulation technology and integrated modeling and simulation techniques may benefit the flight training market in providing low-cost simulation solutions.

GENERAL NOTE

This report is based on a presentation held at the AIAA Modeling and Simulation Technologies Conference and Exhibit, San Francisco (CA), August 15 – 18, 2005.

New Integrated Modeling and Simulation Techniques for Research and Training Applications

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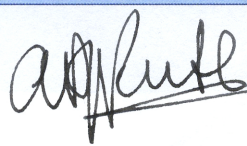
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New Integrated Modeling and Simulation Techniques for Research and Training Applications

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This paper presents new integrated flight simulation development methods and tools to support experimental flight research and training applications. For the modeling and simulation process, as described in this paper, new developed techniques ranging from aerodynamic analysis, avionics display development, aircraft systems modeling, environmental simulation and motion cueing are integrated for the development and implementation of aircraft specific flight simulation models in a generic simulation environment. The integrated simulation methods and tools were applied to the development of a modern fly-by-wire transport aircraft as recently conducted for the NLR Generic Research Aircraft Cockpit Environment (GRACE) reconfigurable flight simulator. The integrated approach for the modeling and simulation process, in combination with increased computing power, results in flexibility, fidelity and quick turn-around times to meet the requirements for both research and the (low-cost) flight training market.

Nomenclature

CAA	=	Civil Aviation Authority
C_L	=	Airplane lift coefficient
C_d	=	Airplane drag coefficient
C_m	=	Airplane pitching moment coefficient
ESDU	=	Engineering Sciences Data Unit
FAA	=	Federal Aviation Administration
FBW	=	Fly-By-Wire
ISA	=	International Standard Atmosphere
JAA	=	Joint Aviation Authorities
NTSB	=	National Transportation Safety Board
ZFT	=	Zero Flight Training

I. Introduction

Since the demonstration of the concept of simulated flight by Edwin A. Link in 1929, simulation technology has improved dramatically providing an accepted means of reducing accidents and increasing safety of aircraft operations. The exploitation of flight simulation technology for air-carrier training and evaluation of operational procedures and system operations dates back to the 1950s. In this period, simulation technology still carried its

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legacy from the early Link Trainer as used during the Second World War. The simulators in these days were characterised mainly by the use of analogue equipment and the typical fashion to paint the outside of the simulator cockpit blue. Training 'in the blue box' soon became more sophisticated when in the 1960s and 1970s simulation technology rapidly advanced. Advancements in computer technology allowed the simulation industry to transfer from analogue to digital computers. Combined with the increase in computing power, enabling the use of more sophisticated modeling of vehicle characteristics, the introduction of visual systems and utilisation of motion cueing devices, resulted into the 'full flight simulator' or FFS by the end of the 1970s.

With the advent of advanced simulator technology, regulatory standards became mandatory. Although flight simulators were used by the air-carriers well into the 1970s for their training purposes, the impact of simulation technology on flight safety was not recognised. During the 1960s and 1970s numerous training related accidents occurred during flights in which hazardous conditions were exercised. Apart from system failures, this included especially simulated engine-failures trained in the real aircraft. This led to the initiative, following a directive by the US National Transportation Safety Board (NTSB), to conduct an investigation into safer methods of performing flight training for hazardous conditions. It was not until the early 1980s that regulatory standards were introduced which enabled the use of flight simulation technology for virtually any training or certification process to be conducted in a properly configured and approved simulator ('Total Simulation Concept'). With the issue of the Advanced Simulator Plan by the FAA in 1980, these regulatory standards would provide a reference for the design and utilisation of flight simulators for training applications. Following the FAA initiative, the UK Civil Aviation Authority (CAA) and European Joint Aviation Authorities (JAA) introduced further standards and rules. Current flight simulator fidelity standards and approval criteria widely used for both general aviation and air carrier training are contained in the FAA Advisory Circular AC-120-40B 'Airplane Simulator Qualification'[1]. These regulations define simulator devices according to four different levels (Level A, B, C and D) each representing a certain amount of fidelity. The FAA Level D standard introduced the so-called 'Zero Flight Training (ZFT)' concept allowing the use of high-end, high quality flight simulators for recurrent training and type conversion, without practicing critical and hazardous maneuvers in the real aircraft.

Figure 1. Edwin A. Link 'Blue Box' (1929).   **Figure 2. Level-D Full Flight Simulator (2005).**

The use of modern simulation technology in aviation is especially useful when dealing with costly or safety critical systems like the airplane. For the Boeing 747 aircraft type, the cost ratio of using a Level D flight simulator for training and using the real aircraft is about 1:40. Part of the cost of using the real aircraft is not only fuel related but mainly due to revenue loss of not using the aircraft for passenger services. In addition, the use of simulation enables flight training to be performed in a safe manner, anywhere, anytime and under any weather circumstances, whereas for the real aircraft this is of course limited. However, despite the technologies available for modern simulation and ever increasing realism encountered in simulation technology, the real aircraft remains indispensable for certain tasks or tests that cannot be sufficiently trained or evaluated in the simulator. This is especially true for research and engineering simulation that is an essential part in the aircraft development process including real flight tests.

A. Trends in Flight Simulation Technology

With the significant increase of computer processing power as seen during the last decade, image generation capabilities and model sophistication initially only available in multimillion dollar flight training simulators have become affordable at 'consumer' level. Additionally, an increase is seen in low-cost simulator hardware vendors providing commercial-off-the-shelve components for low-cost simulation devices. This development has made the use of high-fidelity simulation affordable to a wider audience of flight training providers, flight schools, research establishments and universities.

Within the airline pilot training environment the benefits of flight simulation technology have significantly improved pilot training and increased flight safety. For the situation in Europe, the establishment of a joint JAA Airline Transport Pilot License (ATPL) training syllabus has brought the pilot training requirements of the individual countries up to one common standard. This has lead to a further unification of ab-initio training with type rating training in order to prepare student pilots more adequately for the next generation of advanced technology aircraft. The result is that modern simulation technology is utilised early in ab-initio training programmes introducing the student pilots to required behavior, knowledge and skills necessary for safe operation in a modern airline environment. Within the ab-initio training environment, developments show that single pilot training has become traditional and that more emphasis is made on acquiring multi-crew operational skills and training of airline operational standard procedures. With the introduction of the Multi-crew Pilot's License (MPL) by ICAO[2], which will be implemented for training curricula in 2007, training providers will be able to utilise simulation technologies for training of airline operational procedures in a modern operational cockpit environment. Some flight schools within Europe already provide modern jet training as 'bridge course' for the preparation towards a real airline type rating course. For this initial training, low-cost simulation facilities are employed that prove to be adequate to introduce student pilots with concepts like Crew Resource Management (CRM) and operational procedures in advanced technology cockpits.

The potential of the current state-of-the-art in PC-based simulation has been recognised for integrated flight training applications. It is expected that the utilisation of PC-based simulation, as introduction or briefing tool, may reduce the present time required for training in a full flight simulator by about 20%[3].

As flight simulation technology for training applications progresses, high fidelity simulation for research and engineering applications is applied increasingly during the last 30 years[4]. The use of simulation for research and engineering enables to evaluate new aircraft designs, equipment or concepts in an operational relevant environment. By using high fidelity simulation early in the aircraft development process potential safety implications or human factors problems of new equipment or operational concepts can be identified. This reduces the risk of problems appearing later in the development programme resulting in cost and time reduction. In addition, the simulation can be used to evaluate potentially hazardous situations or failure conditions that would be too dangerous to test in the real aircraft. For experimental flight deck research, the aim of the simulator is to reproduce pilot behavior and performance as experienced during real-life operations.

While for flight training applications the simulator fidelity requirements are clearly specified, for research and engineering simulation the fidelity criteria are highly dependent on the kind of experiment or research objective. As such, no clear fidelity requirements for research and engineering simulation are currently available but initial efforts have been undertaken to provide general guidelines[4].

Simulation fidelity can be defined as the quality of the simulated vehicle (both equipment and model) to represent the real world vehicle. This includes equipment or hardware fidelity as well as software or model fidelity. Depending on the application of the simulator, usually a trade-off is made between both fidelity types[4]. For training simulation applications, the emphasis is on adequate transfer of training to the real aircraft. This necessitates sufficient equipment cues by providing a natural representation of the cockpit environment including instrument layout, control systems, aircraft systems, display configuration etc. For flight deck research and engineering simulation, the objective is to generate behavior and pilot performance that closely matches the performance in the real environment. For these applications, the representation of the modeled environment through which the aircraft moves, including its motion, plays a major role.

Although the benefits of using high-fidelity simulation for research and engineering applications have been demonstrated to be invaluable, the use of advanced technology simulation remains a costly undertaking. To address a wide range of experiment objectives and fidelity requirements, the flexibility and versatility of research and engineering simulators can be utilised in an affordable manner by using integrated modeling and simulation techniques. These advancements may benefit the flight training market in providing low-cost simulation solutions.

This paper presents new integrated modeling and simulation techniques for research and training flight simulation development at the Netherlands National Aerospace Laboratory NLR. The NLR has a long history and experience in developing and operating flight simulation facilities. The NLR Training, Human Factors and Cockpit Operations Department employs both fixed base and motion base flight simulation facilities for civil and military research. For civil applications, the Generic Research Aircraft Cockpit Environment (GRACE) (figure 3) is available with the capability to simulate a range of transport aircraft including Boeing, Airbus and Fokker type of aircraft. As a significant part of the costs in the flight simulation development process includes software design, a simulation infrastructure has been developed that enables the flexibility to design aircraft specific models or subsystems with different levels of fidelity according to research objectives. As part of the simulation infrastructure, a developed MATLAB®/Simulink® simulation environment provides the capability to modify submodels for any specific aircraft to be simulated resulting in quick turn around times for different project experiments.

**Figure 3. NLR Generic Aircraft Cockpit Research Environment (GRACE).**

The newly integrated flight simulation development methods and tools, in conjunction with increased computing power, further improves flexibility and versatility of the NLR simulation facilities to comply with a wide range of research requirements. The integrated modeling and simulation techniques have been used for the development of a modern fly-by-wire transport aircraft recently conducted for the NLR GRACE reconfigurable simulation facility.

II.   History of the GRACE Research Simulator

Flight simulation at the NLR dates back to the early 1960s. In this period, research flight simulation was applied by NLR to investigate low speed handling qualities of experimental Vertical and Short Takeoff and Landing (V/STOL) aircraft. Before the introduction of a moving-base research flight simulator at NLR in 1975, a fixed base simulation facility was used in combination with both fixed base and moving facilities of other organisations. For certain research requirements, modified training simulators were used. The forerunner of the GRACE facility, introduced in 1975 at NLR, was unique in the sense that it featured a four-degrees-of-freedom (4-DOF) motion platform with low acceleration and noise threshold levels and a reconfigurable cockpit (figure 4). The adaptability for a variety of experiments and using digital computer techniques for the simulation of different aircraft types made the facility state-of-the-art in Europe. Up till 2004, this facility has been employed in a wide range of experimental flight research projects, both for national and international contractors, in the field of flying qualities design, operational procedures, ATM concepts and flight simulation technology development for modeling and motion cueing.
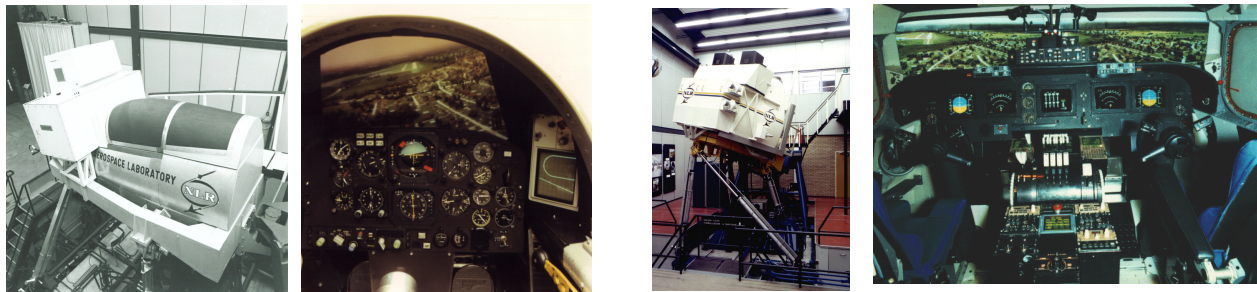
Figure 4. NLR Research Flight Simulator (RFS) with single pilot cockpit (1975-1985) and dual pilot civil transport aircraft cockpit (1985-2004).

III. The GRACE Concept

To meet the increasing demands in experimental flight research projects at NLR, a Dutch consortium of Siemens Netherlands, Dutch Space, Hydraudyne, FCS Simulation Systems, ADSE and NLR developed the Generic Research Aircraft Cockpit Environment (GRACE). The GRACE simulator has been designed based on the concept of providing a full mission capability for experimental flight research while allowing maximum flexibility in both hardware and software at a low-cost.

Depending on experimental requirements, flexibility in equipment cues is obtained by reconfiguring the cockpit according to the type of simulated aircraft (figure 5). The available simulator hardware equipment currently allows fully customizable cockpits for the simulation of Boeing, Airbus, Fokker, business jet or generic advanced flight deck technology aircraft. The forward instrument panel consists of a detachable aluminum overlay that is tailor made according to aircraft type specifications. For each simulated aircraft type, an available instrument panel overlay can be placed in front of a fixed set of 14.1" and 18.1" LCD displays generating a representation of the aircraft's instrument configurations. All instruments on the forward panel are software controlled and, depending on the aircraft type, enable the possibility to simulate both advanced 'glass cockpit' type instruments as well as classic mechanical instruments.

Flight control configurations in the cockpit can be adapted depending on the aircraft type. Both conventional control (column/wheel) and side stick configurations are available for simulation of classic as well a modern fly-by-wire aircraft. For helicopter simulations, a center stick can be installed. Realistic simulation of control forces is provided via a dedicated control loading system consisting of a control loading computer and Actuator Control Units (ACUs) integrated in one PC. Further GRACE simulator components that can be configured for a range of aircraft types include the mid pedestal for simulation of two to four engine aircraft and a reconfigurable automatic flight guidance system including autopilot interface and flight management system (FMS).

Figure 5. The GRACE concept: providing full mission simulation capability of a wide range of aircraft for research and engineering applications.

A. GRACE Integrated Modeling and Simulation Process

The GRACE simulator is an essential part in the integrated modeling and simulation process at NLR for efficient high-fidelity experimental research simulations. For the modeling and simulation process (figure 6), new developed techniques ranging from aerodynamic analysis to avionics and aircraft systems modeling are integrated for the development and implementation of flight simulation models in a generic simulation environment. For the aerodynamics model, Computational Fluid Dynamics (CFD) techniques are used to develop an aerodynamic database of the aircraft instead of applying generic engineering (USAF Stability and Control DATCOM[5], ESDU) and wind tunnel data.

Using CFD techniques, geometric data of specific aircraft configurations is required to establish a flow domain discretisation. By subsequently solving the Navier Stokes equations using a network of computers, the aircraft aerodynamic flow characteristics for different configurations are determined. The resulting aerodynamic database includes a first estimate of aircraft performance and controllability derivatives.
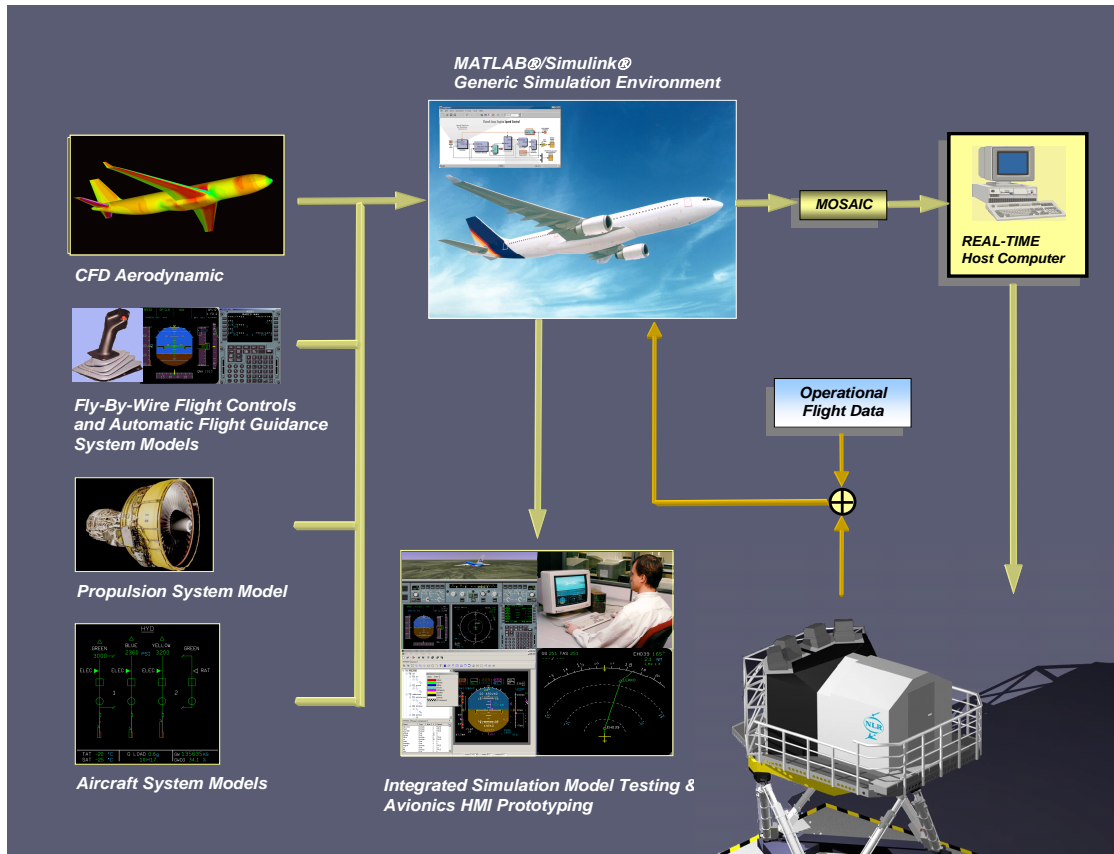
Generic gasturbine modeling and simulation tools are used to obtain a first estimate of engine performance characteristics that can be further tuned using available data of the specific aircraft engine and aerodynamics.

For the simulation of modern transport aircraft, a generic automatic flight guidance system, including fly-by-wire flight control system technology, has been developed that can be tuned and modified to obtain aircraft specific flying qualities, or control methods, and flight envelope protection features. A research flight management system (RFMS), which provides a full interface with the generic automatic flight control systems, can be adapted to represent different types of Control Display Unit (CDU) interfaces and FMS features.

Avionics and systems Human-Machine Interface (HMI) prototyping is performed using a developed tool (*Vincent)* to design and implement aircraft specific displays providing smooth graphical representations of, for instance, Electronic Flight Instrument System (EFIS) or aircraft system displays according to manufacturer specifications for any type of aircraft. The developed avionics displays, as used in the GRACE generic cockpit environment, can be made fully interactive with the software simulation environment for real-time representation of flight parameters and system functionalities. This capability is utilised for testing and evaluation of new aircraft submodels or integrated models early in the modeling and simulation process to ensure smooth transfer to the GRACE real-time simulation (RTS) environment. To this end, the Avionics Integration Research Simulator (AIRSIM) has been developed at NLR providing a desktop simulation capability representative of the GRACE environment using the full avionics suite including avionics software models, EFIS configurations, FMS, automatic flight guidance systems and environment simulation (visual database, air traffic etc.). Developed aircraft system models, including hydraulic, electric and pneumatic systems including their aircraft-specific HMI interfaces and display characteristics, can be made fully interactive in the simulation environment.

Configuring the simulator for quick testing or rapid prototyping of developed MATLAB®/Simulink® simulation models is performed by the NLR software tool MOSAIC (Model-Oriented Software Automatic Interface Converter). The MOSAIC tool performs automated model transfer of the MATLAB®/Simulink® simulation environment, including its aircraft specific submodels, to the GRACE RTS environment. The tool takes as input model source code that has been generated by the Real-Time Workshop (RTW) of Simulink® and delivers as output model source code that can run in the RTS environment.

Following preliminary aerodynamic and aircraft systems model development and evaluation, fine-tuning of performance and control characteristics is applied as part of the integrated modeling and simulation process to meet available aircraft specifications. Where flight test data of the aircraft-specific manufacturer is either not available or restricted, other sources of aircraft data (e.g. open source data, flight manuals etc.) is used as much as possible.

Figure 6. GRACE integrated modeling and simulation process for the development of a modern fly-by-wire transport aircraft simulation.

IV.   Generic Simulation Environment

The generic simulation environment, as part of the modeling and simulation process, provides the capability to design aircraft specific models or submodels in an integrated and affordable way. The simulation environment comprises modular submodels including environmental and flight mechanics models and aircraft specific models ranging from aerodynamics, propulsion, mass properties, (fly-by-wire) flight controls, flight management and on-board systems.

B. Model Architecture

The generic simulation environment has been developed in the MATLAB®/Simulink® and Stateflow® visual programming environment. The defined interfaces between the various submodels enable the integration of aircraft-specific models of any structure. The model architecture of the generic simulation environment is illustrated in figure 7. Within the architecture, a high level division is made between the *Forces and Moments Model*, the *Systems Model* and the *Mass Properties Model*. The *Forces and Moments Model* is further comprised of the *Aerodynamic Forces and Moments* of the bare airframe, *Propulsion Forces and Moments* and *Undercarriage Forces and Moments*. The clearly defined interfaces between these submodels enable the bare airframe to be composed of different aircraft components such as customised engines, landing gear, flight controls and aircraft systems. Due to its modularity, aircraft specific submodels, such as aircraft systems, can be designed and tested independently before integration in the complete aircraft. Clearly specified interfaces and trimming tools provide full non-linear standalone aircraft simulations in a desktop setup for preliminary performance evaluation or flying qualities tuning.

Figure 7. GRACE generic simulation environment model architecture.

C. Aerodynamic Modeling

Aircraft motions are characterised by six degrees-of-freedom, i.e. translations and rotations in three directions. Flight simulation requires a model of the aerodynamic forces and moments that induce such motions. The aerodynamic model describes the functional relationships between the forces and moments and a number of relevant parameters describing the aircraft state and control surface deflections. These relations can be given in either tables or in polynomial expressions. Tables are particularly suitable means to describe non-linear relations (e.g. drag, lift and pitching moment as function of angle-of-attack and Mach number) whereas polynomial expansions (Taylor series) may be used for relations featuring linear relationships.

In current practice, aircraft aerodynamic models are constructed on the basis of information from three complementary sources:

1. *Semi-empirical methods*. ESDU and the USAF-DATCOM sheets are valuable sources of information for building flight simulator aerodynamic models. These datasheets require a limited set of geometric input data and deliver reliable results as long as the configuration at hand does not depart too far from the configurations that were used to build the datasheets.

2. *Wind Tunnel test data*. During an aircraft development program, a comprehensive wind tunnel test campaign at low-speed as well as high-speed will be performed. Such test campaigns deliver highly accurate data which is a useful source to enhance the flight simulator aerodynamic model. In specific cases, special dynamic wind tunnel tests are performed using a test rig capable to performing dynamic (oscillatory) motions.

3. *Flight test data*. When the prototype aircraft is taken to flight, its flight path trajectory and control surface deflections are recorded continuously. These recordings provide means to validate (and to certify) the flight simulator aerodynamic model. At the same time, this source of information is used to fine-tune the a-priori aerodynamic models obtained from data gathered in Steps 1 and 2. To maximise the data content in the recordings, special maneuvers are conducted during the flight test program.

With the advancement of Computational Fluid Dynamics (CFD) technology, which goes hand in hand with the increase in computational power, this technique is emerging as an alternative source of information for flight simulation model development. Computational Fluid Dynamics techniques emerged as early as the 1970s in the form of so-called panel codes. As computing power further increased in the 1990s, Euler and Reynolds-Averaged

Navier-Stokes methods are now operational to capture the flow around complete aircraft configurations. As such, these methods are becoming established tools in use during the aircraft detailed design phase delivering aerodynamic performance data. In principle, flow solutions based on the Reynolds-Averaged Navier-Stokes equations should be able to capture all the needs for flight simulation purposes. They can be applied to arbitrary configurations, can provide data in all flight regimes (from low-speed, high-lift flow up to high-speed transonic and supersonic flow), and are able to compute up to (and even slightly into) conditions featuring detached flow (e.g. stall and buffet).

At NLR, modern CFD-based methods are now being used for flight simulation aerodynamic model development.

1. *CFD Aerodynamic Model Composition*

The geometry used for aerodynamic flight simulation model development retains the fuselage, wing, horizontal and vertical tailplanes and is based on open literature sources. Details concerning the nacelles and flap track fairings are currently not included. An aircraft structure deforms when subjected to aerodynamic loading and this deformation in its turn affects the flow around it. These deformations significantly affect lift, drag and pitching moment of the configuration and therefore need to be incorporated in a realistic simulation environment.

The aerodynamic model must represent free travel of each individual control surface even though, during normal operation, the control surface deflections are synchronised by the flight control system. This requirement originates from the desire to model system failure modes in the simulation environment. Deflections of elevators, ailerons and rudders are enforced as perturbations on the baseline airframe geometry. Deflections of the spoilers are modeled as triangular "bumbs" on the wing of which the rear-ward facing step is large enough to enforce flow separation. Stabiliser deflections are modeled by rotating the complete stabiliser and remodeling the fuselage/stabiliser intersection.

The flow domain is decomposed using the NLR proprietary ENDOMO tool. The domain decomposition process proceeds in a semi-automatic way[6], starting from manually determined face distribution on the configuration surface (figure 8 left). A thin first layer of blocks is created following surface. Additional layers of blocks are grown until the far-field boundary is reached. Manual fine tuning of the resulting block shapes is needed at several locations. The flow domain is decomposed in a total of 184 blocks for a semi-span configuration and 368 blocks for a full-span configuration (figure 8 mid).

For the airframe model configuration without deflected control surfaces, a spatial grid is created with the NLR proprietary ENGRID tool. Careful grid tuning is performed for the baseline aircraft in order to minimize the numerical errors in the flow domain. Figure 8 (right) illustrates the established numerical grid on the configuration surface following the domain decomposition process. The boundary layer blocks feature 32 cells in surface normal direction and the first cell height is tuned for a proper resolution of the boundary layers. The total number of grid cells is limited to 2.5 million for a semi-span configuration and 5.0 million for a full-span configuration. The resulting block topology of the aircraft without deflected control surfaces morphs to all subsequent aircraft variants featuring deflected control surfaces using volume spline techniques. A spatial grid for each individual aircraft variant (i.e. aircraft with deflected control surfaces) is subsequently generated using the ENGRID tool.
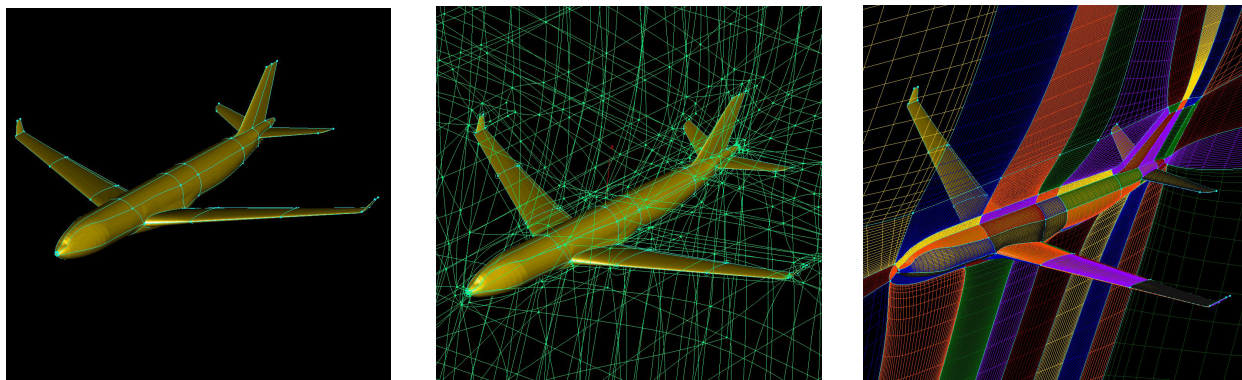
Figure 8. ENDOMO domain decomposition process (left and mid) and ENGRID numerical grid on the configuration surface of the airframe model (right).

The CFD aerodynamic analysis tool in use at NLR is the ENSOLV code[7]. ENSOLV solves the Navier-Stokes and Euler equations in a multi-block domain. The Navier Stokes equations are solved in the viscous flow dominated regions in the immediate vicinity of the configuration, while the Euler equations are solved in the outer-flow domain. The ENSOLV CFD code is coupled to a NASTRAN structural model to support aero-elastic computations[8].

2. *CFD Aerodynamic Model Database Generation*

The CFD results obtained at certain discrete points in the flight envelope form the basis for constructing the flight simulator aerodynamic models. These aerodynamic models take the shape of tabulated data, representing the steady-state symmetric aerodynamic force and moment coefficients as function of Mach number and angle of attack, extended with polynomial expressions representing the additional effects due to control surface deflection, rotation rates, and unsteady aerodynamic effects.

The tabulated data represents the aircraft lift (C_L), drag (C_d) and pitching moment (C_m) coefficients as function of Mach number and angle of attack at a fixed Reynolds number, fixed dynamic pressure, control surfaces in neutral position, flaps up, gear up and steady rectilinear flight. This relationship is based on CFD computations for various Mach-angle of attack combinations using the semi-span configuration. A flow solution for a single Mach-alpha entry takes 1.5 hours computing time on a NEC-SX5 super computer (figure 9 left). Representative base functions are fitted to this data to cover the range between Mach 0 and Mach 1 and -20° to 20° angle of attack. The shape of the selected base functions is mainly based on experience. The base functions cover extensive zones where no information is present from CFD computations. Next, the fitted base functions are tabulated for use as simulator aerodynamic database. Figure 9 (right) shows an illustration of the tabulated values of the lift coefficient C_L versus Mach number and angle-of-attack. The white dots on the lift coefficient surface in the figure indicate the individual CFD results while the wire frame surface represents the data table as used for the simulator aerodynamic database. Empirical relations are used to correct the CFD-based steady state model for Reynolds number departures from the reference value, ground effect, effect of landing gear extension and the extension of a ram air turbine.

Departures from the steady flight condition are represented using Taylor series expansions that take the additional effects due to surface deflections and gear extension into account. The values of the aerodynamic derivatives are based on series of CFD computations in which one variable at a time is given an offset and the effect on the forces and moments is observed. The semi-span numerical grid is used for all symmetric effects while the full-span numerical grid for all asymmetric effects. The additional aerodynamic unsteady effects computed by CFD comprise:

1. Curvature of the free-stream flow due to the aircraft roll, pitch and yaw velocity components. This is computed by solving the Navier-Stokes equations in a rotating frame of reference.
2. Instationary effects due to accelerations in body-y and body-z direction give rise to beta-dot and alpha-dot derivatives. This requires time accurate solution of the Navier-Stokes equations.
3. Effect of control surface deflections. This is computed by perturbing the aircraft geometry and morphing the computational grid on to the perturbed geometry. Some effects show a strong dependency on Mach number and/or angle of attack, which give rise to Taylor series expansions featuring cross terms with Mach and alpha.
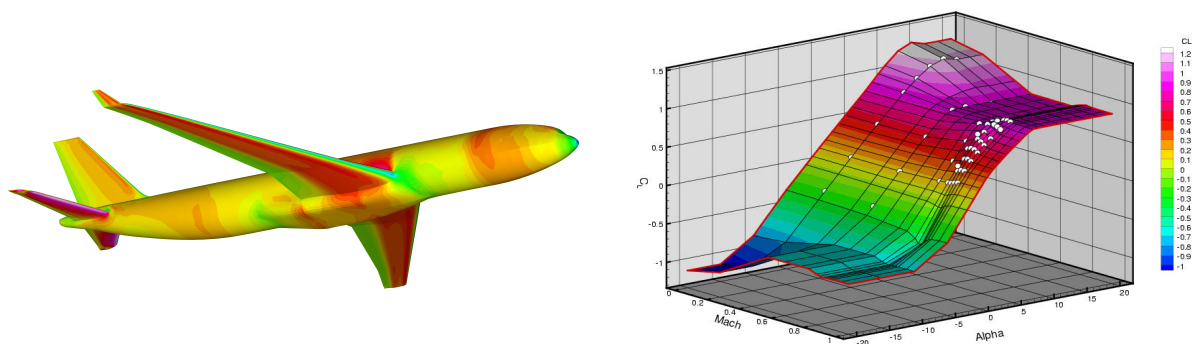
Figure 9. CFD pressure distribution for the calculation of aerodynamic force and moment coefficients (left) and calculated lift coefficient *(C_L)* as function of Mach number and angle of attack (right).
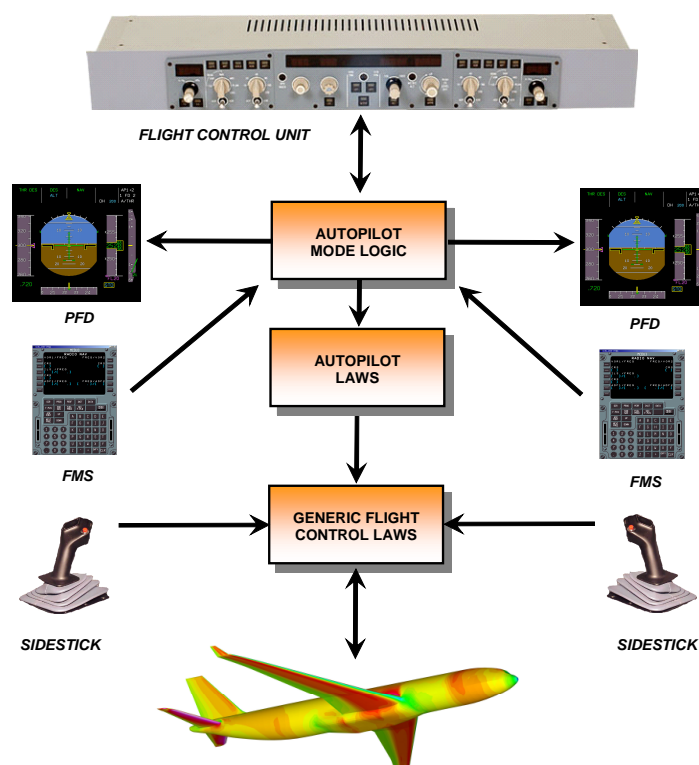
D. Generic Automatic Flight Guidance System Simulation

The generic automatic flight guidance system model enables the simulation of advanced flight control and flight management systems. Figure 10 illustrates the model architecture for the simulation of a modern fly-by-wire (FBW) transport aircraft.

The fly-by-wire system provides full automatic stabilisation and trim throughout the flight envelope and is designed to improve handling qualities. To obtain maximum maneuverability and performance within the aircraft operational limits, a flight envelope protection system is included. The envelop protection system provides bank angle limitation up to certain degrees and overspeed and stall protection. The current FBW system is a rate command attitude hold system that maintains the demanded attitude by the pilot when the stick is released. A set of generic flight control laws can be tuned using parameter datafiles enabling the FBW system to be adapted for a wide range of transport or business jet type of aircraft.

The autopilot mode logic provides the switching of the autopilot laws depending on the phase of flight which is displayed on the Flight Mode Annunciator (FMA) in the Primary Flight Display (PFD). The autopilot mode logic has been developed as a Stateflow® module. Stateflow® is an interactive design tool integrated in the MATLAB®Simulink® environment and is very suited for modeling and simulation of event-driven systems. The autopilot mode logic module can be reconfigured depending on the simulated aircraft.

The flight management system, which closely interacts with the flight control system, is based on the Research Flight Management System (RFMS) developed at NLR. The RFMS provides a full FMS functionality for a specific type of aircraft using a generic core program. In-house developed FMS pages are built on top of this core providing a realistic representation of the aircraft specific Control Display Unit (CDU).

Figure 10. GRACE generic automatic flight guidance system simulation for a modern fly-by-wire transport aircraft.

E. Generic Propulsion Systems Simulation

Modeling and simulation of aircraft specific propulsion systems is performed using a combination of available operational flight data or performance scaling of a similar engine model available. When no performance data of the particular engine can be obtained, in-house developed gasturbine simulation tools are used. NLR's Gas turbine Simulation Program (GSP) is a component-based object-oriented modeling environment for gasturbines. With GSP, both steady-state and transient simulation of a specific gas turbine configuration can be performed using a selection of engine component models. GSP provides the capability to analyse of effects of ambient and flight conditions, installation losses, deterioration and malfunctions of engine systems on performance. The performance data generated by GSP can subsequently be used for the aircraft integrated propulsion system simulations. Figure 11 shows a GSP engine model arrangement for generation of propulsion system performance data.
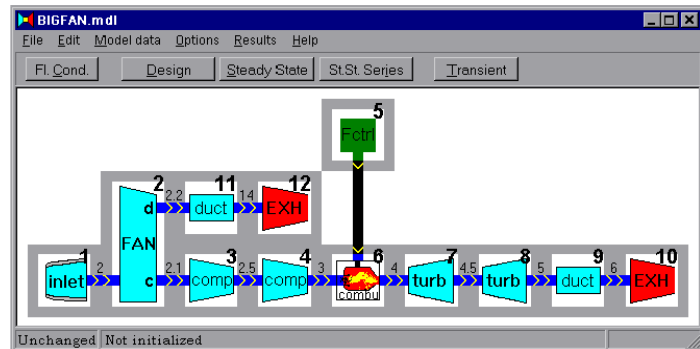

Figure 11. GSP model arrangements for the simulation of a simple turbofan engine.

F. Avionics Software and HMI Prototyping

For the evaluation of avionics display formats, the NLR developed a rapid prototyping environment (*Vincent*) that facilitates efficient design of cockpit display applications (figure 12 left) using a component based design strategy. In particular, *Vincent* enables prototyping of advanced interactive 2-D or 3-D avionics display concepts, including their logic, for evaluation in both simulation or in real flight test. For flight simulation based applications, *Vincent* is able to design a realistic set of avionics display formats closely resembling the graphical format and configuration as found in the cockpit of various aircraft. Both glass cockpit type of displays or classical mechanical instrument representations can be designed graphically. *Vincent* includes a high-performance interpreter, built on top of the OpenGL advanced graphics library to render display prototypes. A fully modeled primary flight display renders at about 120 frames per second on moderate PC hardware. This graphical performance makes the displays very suitable for application in a real-time simulation environment ranging from desktop simulations up to the integration in full flight simulators. *Vincent* generated avionics are applied in the GRACE simulation environment including all glass cockpit flight instrumentation and aircraft specific systems displays. The *AIRSIM* desktop simulation (figure 12 right) provides a representation of the GRACE simulator environment enabling the integrated testing of developed simulation models and display concepts or facilitating accident or incident investigations.

Figure 12. *Vincent* **avionics display development environment (left) and** *AIRSIM* **desktop flight simulator.**

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V. Environment Modeling and Simulation

To address a wide range of environmental cue fidelities for research and engineering simulation applications, visual database and motion cueing optimisation techniques are applied in the modeling and simulation process.

A. Visual database generation

The visual image projection system of the GRACE simulator consists of four Wide-Angle Collimated (WAC) displays having an SXGA resolution of 1280×1024. For image generation, three PC-based image generators are used each providing a channel of the visual system. The visual database is read from PC runtime software for projection through the three image generator channels.

For a natural representation of the aircraft's surroundings, several visual database development techniques are used. Depending on research requirements, detailed airports or geographical environments are modeled utilising COTS graphical modeling tools (e.g. Vega). Recently, NLR applied visual database design techniques using the latest developments in low-cost PC-based graphics technology for full mission simulation applications. Using these low-cost techniques, a natural representation of the Amsterdam Schiphol area, including a detailed rendition of the airport, was created using the OpenFlight graphics format (figure 13 left). The surroundings include the simulation of realistic air traffic creating a complete ATC environment using in-house developed aircraft models (figure 13 right).

Advanced weather simulation is integrated in the environment simulation enabling the generation of cloud layers, wind profiles, windshear including various microburst models and turbulence.


Figure 13. GRACE image generation of Amsterdam Schiphol airport and surroundings (left) including air traffic (right) using low-cost PC-based graphics technology in OpenFlight format.

B. High-fidelity motion cueing

The GRACE cockpit and visual display system are mounted on top of an electrically driven synergistic motion system consisting of a triangular shaped moving platform (figure 14). The platform is mounted on top of three pairs of servo-actuators. The design of the motion platform is based on electric servo technology, which results in a system with high dynamic response. Motion cueing optimisation of the platform, for a natural reproduction of the aircraft's motion through its environment, is initially performed relying on the many years of in-house NLR experience in this field.

Advancements in motion cueing technology for flight simulation applications have been lagging behind as compared to developments in simulator techniques and image generation. The tuning of simulator motion systems is currently performed on a subjective basis relying on the perception of the pilot. The lack of adequate guidelines and

standards for aircraft specific, or task specific, motion cueing requirements results into a time consuming and costly optimisation process. Current guidelines on motion systems by the regulatory authorities (FAA/JAA) are restricted to the physical design properties of the motion platform (e.g. platform dimensions, actuator characteristics, etc.). Novel motion cue optimisation studies have recently been conducted at the NLR, in cooperation with the Netherlands Organisation for Applied Scientific Research (TNO), taking benefit of promising advances in the field of human perception and psychophysiology[9]. For this study, the application of model-predicted human motion perception for the assessment of simulator motion fidelity was evaluated. This development will address the shortcomings in the current simulator motion cueing requirements by providing objective evaluation criteria for aircraft and training dependent motion cue optimisation.
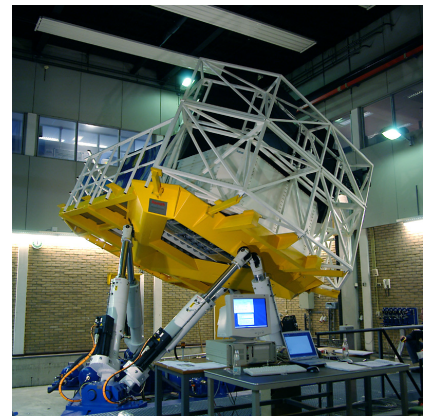
Figure 14. GRACE motion system for generation high-fidelity environmental cues.

VI. Simulation Model Tuning and Validation Techniques

Generally, the evaluation of a flight simulator requires two types of validation tests to ensure the simulator performs according to the fidelity requirements for the intended use[10]. These tests include performance tests and functional tests. The performance tests are objective tests that include the use of any available flight test data, operational flight data (e.g. flight manual or aircraft operating manual) or other data sources of the specific aircraft. The performance test is conducted in order to demonstrate that the simulated aircraft represents the real aircraft both from aerodynamic (performance) and handling qualities (controllability) point of view. The functional test is a subjective test performed by a type-rated test pilot to evaluate that critical flight training tasks can be performed in the simulator within the type rating pilot performance standards. For research and engineering simulators, where the aim is not to provide transfer of training to the real aircraft, the piloted checkout will especially enable a qualitative assessment of the natural representation of the aircraft environment and motion cues. Both simulator validation types are conducted at NLR for simulation model tuning and validation in cooperation with experienced airline and test pilots.

A. Performance Validation Tests: Operational Flight Data Techniques

Over the years, the NLR has employed several methods to match its simulation models with aircraft performance data, which is available from various sources, without relying on extensive and costly flight test data packages. Depending on the aircraft type under consideration, this information can be obtained from open sources, from references such as aircraft operating manuals, or from more specialised sources.

Performance matching and validation techniques are applied at NLR for both research and training flight simulations depending on available operational flight data. To match the aircraft performance with that of a developed simulation model, use is made of the performance data contained in the aircraft-operating manual provided either by the customer or available from the NLR operated research aircraft. The operating manual contains large amounts of performance data for various flight phases, such as takeoff, climb, cruise, descent and landing. This data is used to improve the existing aerodynamic model of the aircraft and to derive modifications to the engine thrust model.

1. Airplane simulator performance matching an validation techniques

An example of applying operational flight data techniques for performance matching and validation has been conducted for the simulation of a small business jet type of aircraft. For this aircraft simulation, deviations from the expected climb performance and thrust settings were identified. The analysis resulted in a reliable model of the

induced drag of the aircraft as well as the thrust of the engine in certain conditions using operational data on the climb and cruise performances. The only aircraft specific data which had to be known *a-priori* to conduct this analysis (apart from the cruise climb performance data from the manual) was the zero-lift drag coefficient. This data was obtained from the aerodynamic model after careful scaling, but other methods can be employed if such information is lacking.

Engine thrust data for the propulsion modeling is commonly stored in a table which returns the corrected thrust as a function of Mach number. From the analysis of the cruise climb data, a drag model was obtained, as well as some data points of corrected thrust at certain values of

Mach and corrected engine speed. With this realistic drag model, it is relatively simple to obtain additional data points for the maximum rate of climb and the cruise condition. For a condition specified in the operating manual, it is possible to calculate the required thrust using the obtained drag.

With the information obtained from analysing the airplane performance at 65 representative conditions for cruise, cruise climb and maximum rate of climb a thrust matrix was constructed. One data point is added to the matrix, this being the static thrust at maximum takeoff power at 0 m ISA, quoted by the engine manufacturer. The distribution of the points in the matrix is shown in figure 15. The symbols in figure 15 illustrate at which combination of Mach number and the corrected engine speed a value of corrected thrust is known. It is noted that it should not be

Figure 15. Overview of the data points used in the performance analysis.

Figure 16. Simulated and quoted cruise performance at FL100, FL250 and FL350.

difficult to add more points to the thrust matrix than the 66 which are shown now, but these points will all lie within the areas already covered with points. Based on the existing simulation model, an *a-priori* engine model is defined, which is a table containing values of corrected thrust as a function of Mach number and corrected engine speed. A tool has been developed that determines for all data points shown in figure 15 the error made between their real value of corrected thrust and the value obtained by two-dimensional linear interpolation from the table.

The developed thrust and drag model was subsequently implemented in the flight simulator. Offline simulations were performed to validate the newly developed model and to compare it with the performance as quoted in the operations manual. Figure 16 illustrates the results of these offline simulations for cruise conditions at FL100, FL250 and FL350. Similar encouraging results were obtained for climb conditions. The performance matching and validation technique as illustrated above can be applied to other aircraft for which similar data is available.

B. Functional Validation Tests: Piloted Evaluation

Aerodynamic models developed at the NLR using CFD techniques are integrated in the GRACE flight simulation environment together with the flight control and aircraft systems models, the mass properties model, the propulsion system model and the undercarriage model. Piloted evaluations are performed for a qualitative assessment of aircraft performances and handling qualities which are compared to published operational data such as stall speeds, engine speeds and fuel flows for given flight conditions, engine-idle decent rates, climb performances and flight control characteristics.

For the evaluation of low speed characteristics, 1-g stall speed tests are performed as they are mostly specified in the available operational airplane data. The 1-g stall speed is defined as the lowest speed at which the lift force, normal to the flight path, is equal to the airplane weight at the critical angle of attack and in the most unfavorable center-of-gravity position. The aim of the low speed test in the simulator is to determine whether the established a-priori aerodynamic model (bare airframe) exhibits the required stall characteristics for the type of aircraft simulated. For fly-by-wire aircraft simulations, the low speed protection system is initially disabled in order to test if the bare airframe angle of attack is lower than the protection threshold. For the required airplane configuration, the test
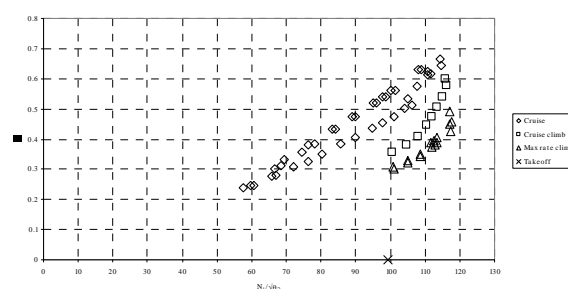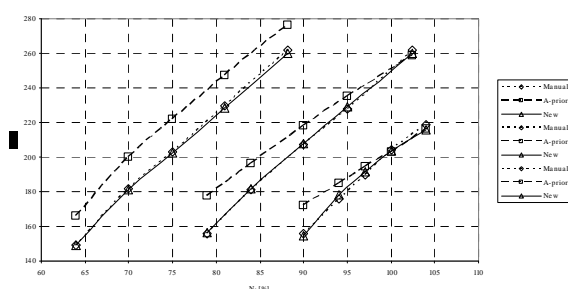
procedure is conducted by closing the throttles to idle from a stabilised trim condition to obtain a deceleration rate of about 1 knot per second. Stall speeds at the 'g-break' are then compared to published operational data. The simulation is subsequently flown throughout the flight envelope to evaluate engine and aircraft performance characteristics in climb, cruise and descent conditions.

Qualitative assessment of the airplane handling qualities is performed to evaluate whether the simulation is representative of the real aircraft. Handling qualities in both roll and pitch axis are evaluated for the bare airframe and with the FBW system engaged.

Following the qualitative assessment of performance and handling qualities in the simulator, the CFD-computed drag polars are corrected to reduce the discrepancies between the published and observed performances. The CFD-computed maximum lift

Figure 17. GRACE piloted simulator evaluation.

coefficient is corrected in the tabulated data to meet the published aircraft stall speeds. Handing qualities discrepancies are further tuned offline, based on the pilots comments, preceding simulator evaluation.

VII.   Conclusions

With the increasing demands in experimental flight research and engineering, high-fidelity flight simulation has become a major part of the aircraft design process and evaluation of new equipment or operational concepts. Flight simulation technology significantly benefited from the advances in computing power as seen during the last decade. The increased processing power is now available at 'consumer' cost and enables the capability for highly sophisticated modeling of vehicle characteristics, its dynamics and its natural surroundings. Although the benefit of using high-fidelity full mission simulation for research and training applications have been demonstrated to be invaluable, advanced simulation technology can be utilised in an affordable manner using integrate modeling and simulation techniques.

As simulator fidelity requirements for research and engineering applications are highly dependent on a wide range of experimental objectives, while for training applications fidelity requirements are clearly defined, research simulators need to be flexible and versatile to address the experimental requirements. With the introduction of the Generic Research Aircraft Cockpit Environment (GRACE) at NLR in 2003, NLR is capable to meet the increasing demands in experimental flight research and flight deck human factors investigations. The GRACE concept is based on providing an affordable high-fidelity full mission capability for both research and engineering applications while allowing maximum flexibility in both hardware and software.

Affordability in research and engineering simulation at NLR is further achieved by integrating NLR technology advances in the area of aerodynamic modeling, aircraft system modeling, avionics and HMI development, environmental simulation modeling and motion cueing. To avoid significant costs in simulation software design and testing, a simulation environment has been developed that provides affordable design, auto-coding and testing of specific aircraft models, or sub models, in a modular way according to research and engineering requirements. Validation and tuning methods using operational flight data, in combination with piloted evaluations, have resulted into satisfactory simulation fidelities to meet the requirements for both research and (low-cost) flight training applications.

As flight simulation technology advances, at NLR innovation has found its way outside the simulator cabin; Edwin A. Link's blue paint has evolved into Vincent van Gogh's Starry-Night.

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