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Intelligent Flight Control Systems Evaluation for Loss-of-Control Recovery and Prevention

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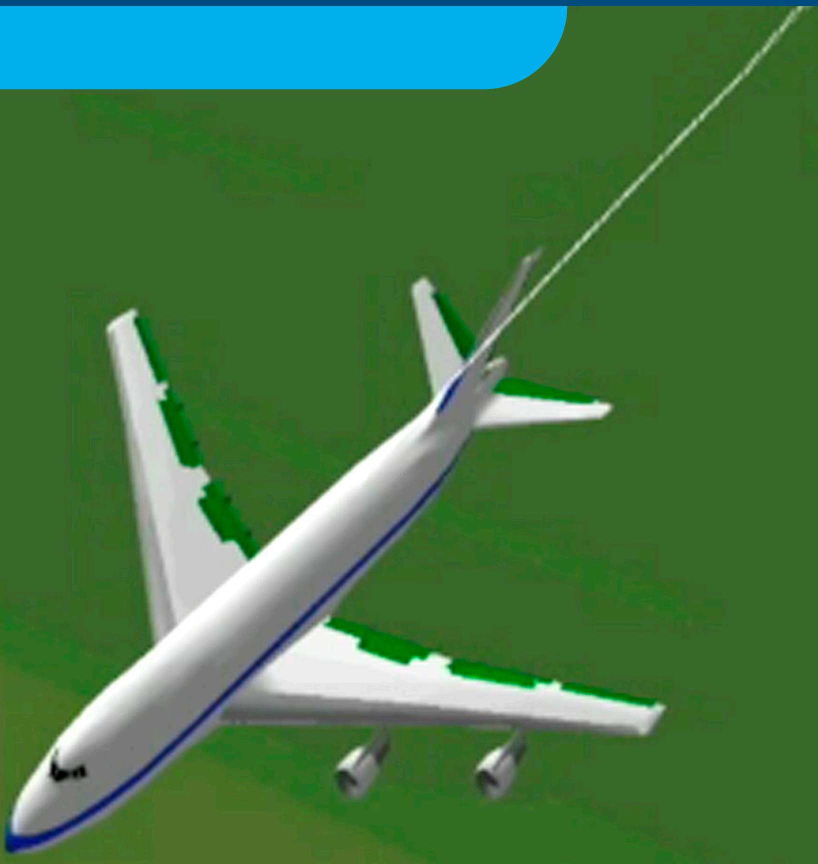

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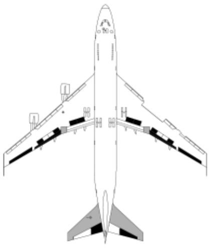
Intelligent Flight Control Systems Evaluation for Loss-of-Control Recovery and Prevention



Problem area

An increasing number of measures are currently being taken by the international aviation community to prevent loss-of-control (LOC) accidents due to in-flight failures, structural damage, and upsets. Fault-tolerant flight control (FTFC), or “intelligent flight control,” is a technology solution aimed to prevent LOC by exploring the remaining physical capabilities of the aircraft to still fly. FTFC leads to improved survivability and ability to recover from adverse flight conditions by intelligent utilization of the control authority of remaining control effectors (including the engines). Reconfigurable control strategies allow us to establish stable equilibrium conditions and required maneuverability for safe approach and landing.

Description of work

The research in this paper was performed within the Flight Mechanics Action Group on Fault-Tolerant Control [FM-AG(16)], which is a collaborative research project conducted within the framework of the Group for Aeronautical Research and Technology in Europe (GARTEUR). The objective was to bring novel intelligent fault-tolerant flight control systems, as conceived within academic and research communities, to a higher technology readiness level. This was achieved by demonstrating the advantages of such systems in a realistic operational context. Within the Action Group, a realistic aircraft simulation benchmark (RECOVER) was

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developed based on data from the digital flight data recorder (DFDR) of the El Al B747 Flight 1862 accident. The benchmark played a crucial role in the Action Group, as it allowed extensive offline design and analysis of new FTFC algorithms by the participants in the Action Group as well as implementation of these algorithms in a full flight research simulator for pilot-in-the-loop evaluation in conditions that would be as realistic as possible. The benchmark, based on actual DFDR data, combined with a piloted simulator campaign in a full flight simulator, provided a unique opportunity for assessment of the merits of novel FTFC techniques in a very realistic scenario and the environment of an actual past failure case.

Results and conclusions

The flight simulator results showed that, after failure, the FTFC algorithm based on online physical model identification was successful in improving handling qualities and pilot performance. For both automatic and manual controlled flights, the reconfigured flight control system was able to cope with potentially catastrophic failures in case of flight critical system failures or if the aircraft configuration changed dramatically due to damage. In most cases, apart from any slight failure transients, the pilots commented that aircraft behavior felt conventional after control reconfiguration following a failure, whereas the control algorithms were successful in recovering the ability to control the damaged aircraft. The pilots demonstrated the ability to fly the damaged aircraft, following control reconfiguration, back to the airport and conduct a survivable approach and landing.

Applicability

For the short term and midterm, aviation authorities recognize the need to improve full flight simulators to become capable of training pilots how to handle LOC. Fault-tolerant flight control is a longer term technology solution that provides redundancy for LOC recovery and prevention by means of new reconfigurable flight control systems.

GENERAL NOTE

This report is based on a paper published in the AIAA Journal of Guidance, Control and Dynamics Special Issue on Aircraft Loss of Control, publication date (online): May 30, 2016, by AIAA.

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Contents

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Intelligent Flight Control Systems Evaluation for Loss-of-Control Recovery and Prevention

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Recent developments in the field of loss-of-control recovery and prevention included improved pilot training, cockpit automation, and fault-tolerant control. The Flight Mechanics Action Group on Fault-Tolerant Control of the Group for Aeronautical Research and Technology in Europe demonstrated the advantages of fault-tolerant "intelligent," flight control systems. The research enabled the improvement of the technology readiness level of these systems by evaluating one of them in realistic operational scenarios. The handling qualities results of a piloted flight simulator assessment with a damaged aircraft model showed that an online physical model identification approach contributed to improved pilot performance following potentially catastrophic structural and flight critical system failures. After the failures and subsequent control reconfiguration by the intelligent flight control system, airline and engineering test pilots experienced no difficulties in conducting a safe approach and landing.

I. Introduction

AN INCREASING number of measures is currently being taken by the international aviation community to prevent loss-of-control (LOC) accidents due to in-flight failures, structural damage, and upsets. Recent airliner accident and incident statistics [1] show that 16 fatal aircraft accidents, resulting in 1526 fatalities, can be attributed to LOC, which is caused by inadequate pilot response (e.g., incorrect stall and recovery procedures), technical malfunctions, or atmospheric upsets. In some cases, clear air turbulence resulted in substantial structural damage and even engine separation. Worldwide civil aviation safety statistics indicate that, today, LOC has become the main cause of aircraft accidents.

Fault-tolerant flight control (FTFC), or "intelligent flight control," is a technology solution aimed to prevent LOC by exploring the remaining physical capability of the aircraft to still fly. Recent research demonstrated that adaptive flight envelope protection should be an integral part of fault-tolerant flight control systems [2–4]. FTFC leads to improved survivability and ability to recover from adverse flight conditions by intelligent utilization of the control authority of remaining control effectors (including the engines). Reconfigurable control strategies allow us to establish stable equilibrium conditions and required maneuverability for safe approach and landing.

Intelligent flight control strategies might have saved two Boeing 737s due to rudder actuator hardovers and a Boeing 767 due to inadvertent asymmetric thrust reverser deployment in flight. The 1989 Sioux City DC-10 incident is an example of the crew performing their own intelligent reconfiguration by just using thrust from the two remaining engines after total hydraulic system failure.

Another example is the case of the Boeing 747 freighter (El Al Flight 1862) in 1992 near Amsterdam in the Netherlands, which suffered from hydraulic failures after separation of the two starboard engines, resulting in a still potentially survivable scenario [5,6]. The aviation community is now faced with new threats such as the surface-to-air missile attack on the Airbus A300B4-203F freighter of DHL at Baghdad International Airport in 2003. This case led to complete hydraulic system failure and severe structural wing damage, after which safe approach and landing still proved to be possible by intelligent use of engine thrust for flight-path control (Fig. 1). The accident cases described here show the potential benefits of intelligent flight control.

Motivated by several aircraft accidents at the end of the 1970s [in particular, the crash of an American Airlines DC-10 (Flight 191) at Chicago in 1979], research on "self-repairing," or reconfigurable fault-tolerant flight control, was initiated to accommodate in-flight failures [7]. A number of new fault detection and isolation methods was proposed in the literature [8–10] together with methods for reconfiguring flight control systems. Several of these reconfigurable control systems have been successfully flight tested and evaluated in piloted simulations [11–15]. In response to the 1989 Sioux City incident, a research program was initiated at the NASA Dryden Flight Research Center on "propulsion-controlled aircraft" (PCA) [12]. The PCA system provided a safe landing capability using just engine thrust. Throughout the 1990s, the system was successfully tested on several commercial and military aircraft.

This paper describes the steps involved in conducting pilot-in-the-loop experiments of new intelligent flight control systems for LOC recovery and prevention, starting from the aircraft simulation model development, validation, and verification to experimental design for handling qualities testing and flight control computational load assessment. This enables us to improve the technology readiness level of new FTFCs by evaluating them in real-time realistic operational scenarios (including representative levels of atmospheric disturbances) and using high-fidelity nonlinear simulation models while relying on detailed failure modeling.

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Fig. 1 Emergency landing sequence and structural damage of DHL A300B4-203F, Baghdad, 2003.

The research in this paper was performed within the Flight Mechanics Action Group on Fault-Tolerant Control [FM-AG(16)], which is a collaborative research project conducted within the framework of the Group for Aeronautical Research and Technology in Europe (GARTEUR). The approach of the GARTEUR research focused on providing redundancy for LOC recovery and prevention by means of new adaptive control law design.

Section II describes the reconfigurable control for vehicle emergency return (RECOVER) aircraft simulation benchmark, based on the Boeing 747-100/200 freighter aircraft, using data from the digital flight data recorder (DFDR) of the El Al Flight 1862 accident flight [5,6].

In Sec. III, the experimental design and piloted assessment of an online physical model identification approach to FTFC is described, which is one of several new FTFC technology solutions developed within the GARTEUR FM-AG(16) project [16]. Handling qualities results in this section show that the new FTFC methodology relieves and assists the pilot in the manual control task to perform a safe approach and landing.

Section IV provides concluding remarks. Appendix A shows the handling qualities evaluation metrics and performance criteria as used for the piloted simulation study. Appendix B presents the results of the handling qualities piloted assessment as described in this paper.

II. RECOVER Aircraft Simulation Benchmark

A. Benchmark Aircraft Accident Case

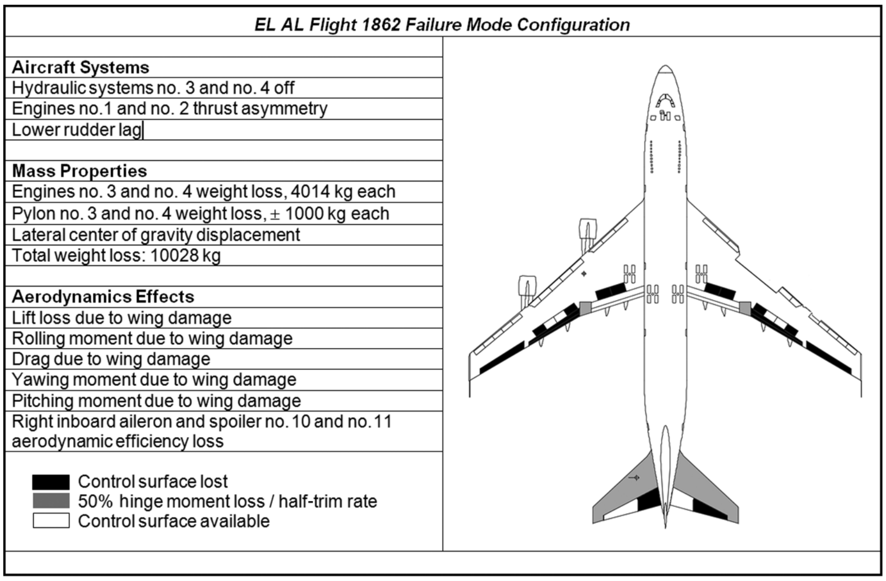
On 4 October 1992, a Boeing 747-200F freighter aircraft [El Al Flight 1862 (Fig. 2)] went down near Amsterdam Schiphol Airport after the separation of both right-wing engines (engine nos. 3 and 4). In an attempt to return to the airport for an emergency landing, the aircraft flew several right-hand circuits in order to lose altitude and to line up with the runway, as intended by the crew. During the second lineup, the crew lost control of the aircraft. As a result, the aircraft crashed, 13 km east of the airport, into an 11-floor apartment building in Bijlmermeer, which is a suburb of Amsterdam. The results of the accident investigation, conducted by several organizations (including the Netherlands Accident Investigation Bureau [17] and the aircraft manufacturer) were hampered by the fact that the actual extent of the structural damage to the right wing, due to the loss of both engines, was unknown. The analysis from this investigation concluded that, given the performance and controllability of the aircraft after the separation of the engines, a successful landing was highly improbable [17]. Figure 2 shows the accident aircraft before takeoff at Amsterdam Schiphol Airport and the reconstructed loss of control trajectory, based on flight data following separation of the right-wing engines.

In 1997, the division of Control and Simulation of the Faculty of Aerospace Engineering of Delft University of Technology (TU Delft), in collaboration with the Netherlands Aerospace Centre/NLR, performed an independent analysis of the accident. In contrast to the analysis performed by the Netherlands Accident Investigation Bureau, the parameters of the DFDR were reconstructed using comprehensive modeling, simulation, and visualization techniques. In this alternative approach, the DFDR pilot control inputs were applied to detailed flight control and aerodynamic models of the accident aircraft. The purpose of the analysis was to acquire an estimate of the actual flying capabilities of the aircraft and to study alternative (unconventional) pilot control strategies for a successful recovery. The application of this technique resulted in a simulation model of the impaired aircraft that could reasonably predict the performance, controllability effects, and control surface deflections as observed on the DFDR. The analysis of the reconstructed model of the aircraft, as used for the GARTEUR FM-AG(16) benchmark, indicated that, from a flight mechanics point of view, the Flight 1862 accident aircraft was recoverable if unconventional control strategies would have been used [5,6].

The El Al Flight 1862 damage configuration to both the aircraft's structure and onboard systems, including partial loss of hydraulics and change in aerodynamics after the separation of both right-wing engines, is illustrated in Fig. 3. An analysis of the engine separation dynamics concluded that the sequence was initiated by the detachment of the right inboard engine and pylon (engine no. 3) from the main wing due to a combination of structural overload and metal fatigue in the pylon–wing joint. Following detachment, the right inboard engine struck the right outboard engine (engine no. 4) in its trajectory, also rupturing the right-wing leading edge up to the front spar. The associated loss of hydraulic systems resulted in limited control capabilities due to unavailable control surfaces aggravated by aerodynamic disturbances, causing a reduction of control effectiveness and an increase of drag and lift loss due to the right-wing structural damage.

A similar incident in 1993, in which a Boeing 747 freighter (flight 46E) lost its left inboard no. 2 engine [18] due to severe or possibly extreme turbulence, provides an estimation of the amount of structural damage incurred by the Flight 1862 accident aircraft (Fig. 4), which was confirmed by wing debris recovered along the Flight 1862 flight path. In the 1993 incident, the flight crew managed to recover the aircraft and conduct an emergency landing, despite the severe performance and controllability problems caused by the separated engine. The Flight 46E control and performance capabilities were representative of those encountered on El Al Flight 1862. Reference [18] shows that the pilot required up to a full right rudder pedal, approximately 60 deg of the right-wing down

Fig. 2 El Al Flight 1862, B747-200F, Amsterdam, 1992 (copyright Werner Fischdick, Netherlands Aerospace Centre/NLR).



EL AL Flight 1862 Failure Mode Configuration

Aircraft Systems	
Hydraulic systems no. 3 and no. 4 off	
Engines no.1 and no. 2 thrust asymmetry	
Lower rudder lag	
Mass Properties	
Engines no. 3 and no. 4 weight loss, 4014 kg each	
Pylon no. 3 and no. 4 weight loss, ± 1000 kg each	
Lateral center of gravity displacement	
Total weight loss: 10028 kg	
Aerodynamics Effects	
Lift loss due to wing damage	
Rolling moment due to wing damage	
Drag due to wing damage	
Yawing moment due to wing damage	
Pitching moment due to wing damage	
Right inboard aileron and spoiler no. 10 and no. 11 aerodynamic efficiency loss	

■ Control surface lost
▨ 50% hinge moment loss / half-trim rate
☐ Control surface available

Fig. 3 Failure modes and structural damage configuration of the El Al Flight 1862 accident aircraft.

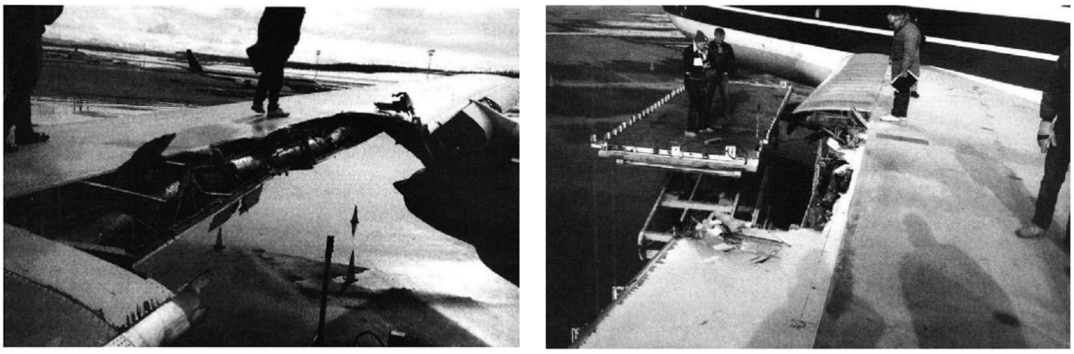


Fig. 4 Wing damage due to separation of engine no. 2, Evergreen Boeing 747-121, Anchorage, 1993 [18].

control wheel deflection, and overboost thrust on left outboard engine no. 1 to control the aircraft toward a survivable landing.

The crew of El Al Flight 1862 was confronted with a flight condition that was very different from what they expected based on training. The Flight 1862 failure mode configuration resulted in degraded flying qualities and performance that required adaptive and unconventional (untrained) control strategies. Additionally, the failure mode configuration caused an unknown degradation of the nominal flight envelope of the aircraft in terms of minimum control speed and maneuverability. For the heavy aircraft configuration at a high speed of around 260 kt indicated airspeed (KIAS), the DFDR indicated that flight control was almost lost, requiring full rudder pedal, 60–70% maximum control wheel deflection, and a high thrust setting on the remaining engines.

B. Aircraft Model Development and Validation

The DFDR of the El Al Flight 1862 accident aircraft was recovered in a highly damaged state, and the tape was broken in four places. The data used for the Flight 1862 reconstruction were obtained from the Netherlands Aerospace Centre/NLR. The quality of the DFDR data, with a sample rate of 1 Hz, was improved by applying several interpolation routines to the original raw data parameters for the estimation of missing or damaged parts. During the reconstruction, several repeated revisions and corrections to these data were made, based on engineering judgment, using the original raw data dump.

The Flight 1862 simulation model reconstruction for the GARTEUR FM-AG(16) benchmark is based on a model validation method using inverse simulation [19] (Fig. 5). The DFDR pilot control inputs Up are directly applied to the nonlinear simulation model of the aircraft and the flight control system. The response error of the simulation output Xc and measured DFDR data Xm are input to a feedback controller. The output of the feedback controller is a measure of the fidelity of the reconstructed model. The reconstruction method has the advantage that the combined effect of structural and flight control system failures can be visualized using the simulation inputs and outputs. The estimation of the aerodynamic effects due to structural damage caused by engine separation can be performed by tuning the parameters of an a priori model structure of the damaged wing (taking into account the additional drag and lift contributions) until the controller output is minimized. An additional advantage of the method is that the DFDR data, with a low sample rate, can be used directly to excite the simulation model and assess the proof of match. A proportional feedback controller is used to feed back the DFDR and calculated pitch and roll state error responses to obtain a reasonable match between DFDR measurements and simulation data.

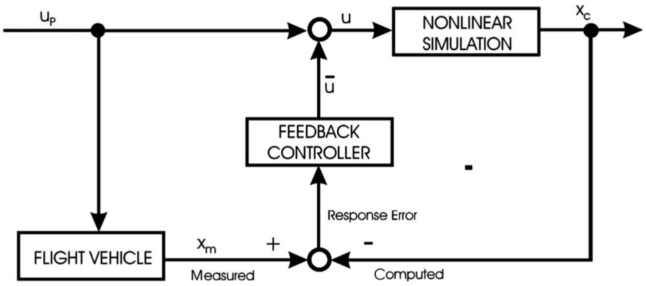


Fig. 5 Inverse simulation principle for the Flight 1862 simulation model validation [19].

Initial model validation was conducted for the departure phase of the undamaged aircraft using the published Flight 1862 weight and balance configuration. This allowed a validation of the undamaged nonlinear baseline aircraft model and reconstruction methodology by means of a proof of match with the DFDR data. The additional effects due to engine separation could then be isolated and identified for the damaged aircraft in the subsequent flight phases using the model reconstruction process. The example flight parameters illustrated in Fig. 6 [altitude above mean sea level (MSL), indicated airspeed, roll angle, and pitch angle] show that the applied reconstruction methodology achieves a close match between the DFDR and undamaged baseline aircraft model before the separation of the right-wing engines at $t = 378$ s for the Flight 1862 departure phase ($t = 47 - 371$ s). The effect of wind conditions on the reconstructed data was taken into account by including a wind model in the simulation using meteorological data recorded at the time of the crash. Gust and turbulence effects were not included in the simulation.

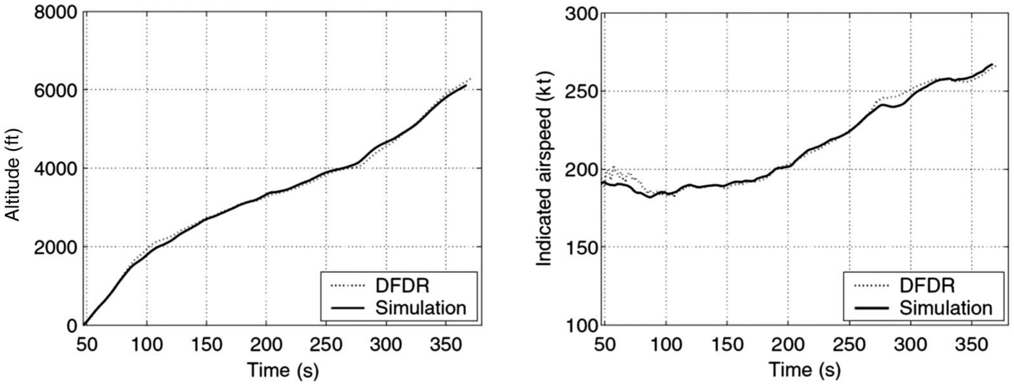
The objective of the simulation tuning process was to closely match the Flight 1862 trends in performance and control capabilities as provided by the DFDR throughout the different flight phases. Figure 7 illustrates the effects of the estimated right-wing damage aerodynamic contributions on example simulation model inputs and outputs for the lateral control characteristics (control wheel deflection and roll angle) for the flight stage between $t = 378$ s and $t = 647$ s. It can be seen that, under the prevailing flight conditions where both right-wing engines no. 3 and no. 4 are separated, a reasonable match between the DFDR and simulated control wheel deflection and roll angle can be achieved.

Figure 8 illustrates the DFDR and simulated flight parameters of the El Al Flight 1862 final stage of flight up to the loss of control (inboard trailing edge flaps 1, $t = 648 - 874$ s). Figure 8a shows the estimated amount of aerodynamic drag increase, due to the loss of the right-wing engines, obtained by reconstruction of the Flight 1862 DFDR aircraft performance capabilities. The figure indicates that a drag increase of about 10% at a low angle of attack may be expected, as compared to the unfailed case, for the damage configuration as shown in Fig. 3. At a higher angle of attack, local flow separation at the right-wing damaged section (midspan) occurs, resulting in a rapid increase of drag of about 20 to 30%. This effect results in a significant reduction of the aircraft's maximum climb capability down to approximately minus $1500 - 2000$ ft/min, as observed on the DFDR, and can be predicted well by the reconstructed model as shown in Fig. 8b. The reduced control authority of the damaged aircraft is insufficient to recover from the significant performance degradation using the remaining engines as shown in Figs. 8c and 8d.

Figure 9 presents the performance and lateral control capabilities of the reconstructed Flight 1862 accident aircraft model, after separation of both right-wing engines, as a function of thrust and aircraft weight. Figure 9a shows the estimated effect of engine thrust and weight on maximum climb performance for straight flight at 260 KIAS. The reconstructed model indicates that, in these conditions and at heavy weight (700,000 lb/317,460 kg), level flight capability was available between maximum continuous thrust (MCT) and takeoff/go-around thrust (TOGA). At or above approximately TOGA thrust, the aircraft had limited climb capability.

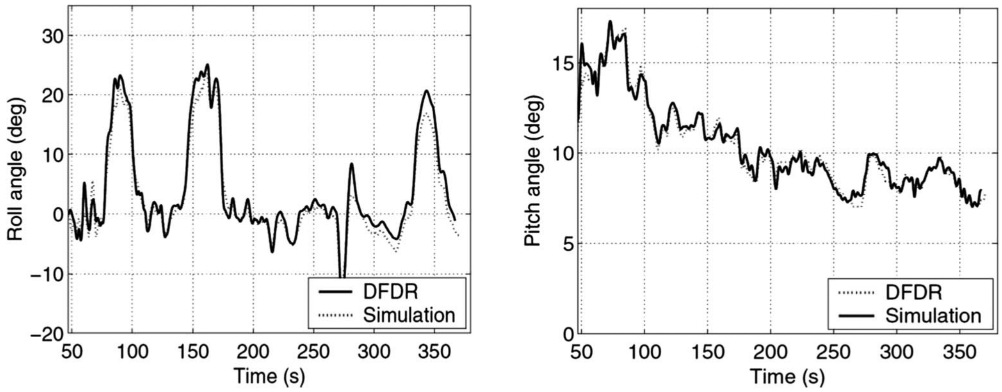
The estimated effect of engine thrust and weight on control wheel position for straight flight at 260 KIAS is illustrated in Fig. 9b. Analysis shows that adequate lateral control capabilities remained available to achieve the estimated performance capabilities. Figure 9 indicates a significant improvement in available performance and controllability at a lower weight (577,648 lb/261,972 kg) if more fuel had been jettisoned.

A simulation analysis of the accident flight using the reconstructed model predicts sufficient performance and controllability, after the separation of the engines, to fly a low-drag approach profile at a 3.5 deg glideslope angle for a high-speed landing or ditch at 200–210 KIAS and at a lower weight (577,648 lb/261,972 kg). Note again that this lower weight could have been obtained by jettisoning more fuel. The lower thrust requirement for this approach profile results in a significant improvement in lateral control margins that are adequate to compensate for additional thrust variations. The aforementioned



a) DFDR and simulated altitude

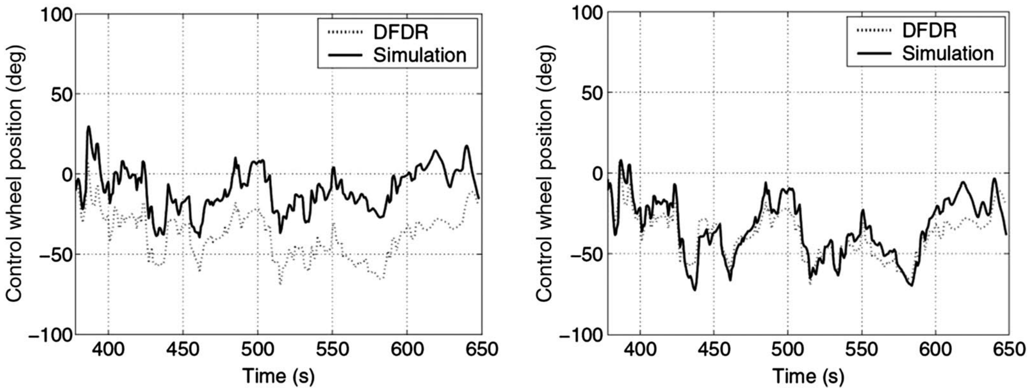
b) DFDR and simulated indicated airspeed



c) DFDR and simulated roll angle

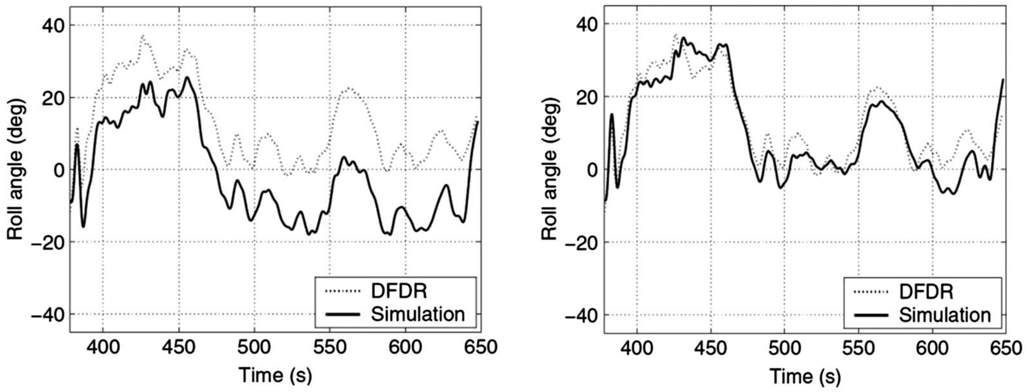
d) DFDR and simulated pitch angle

Fig. 6 Validation of the undamaged El Al Flight 1862 nonlinear baseline aircraft model.



a) Aerodynamic estimates not included

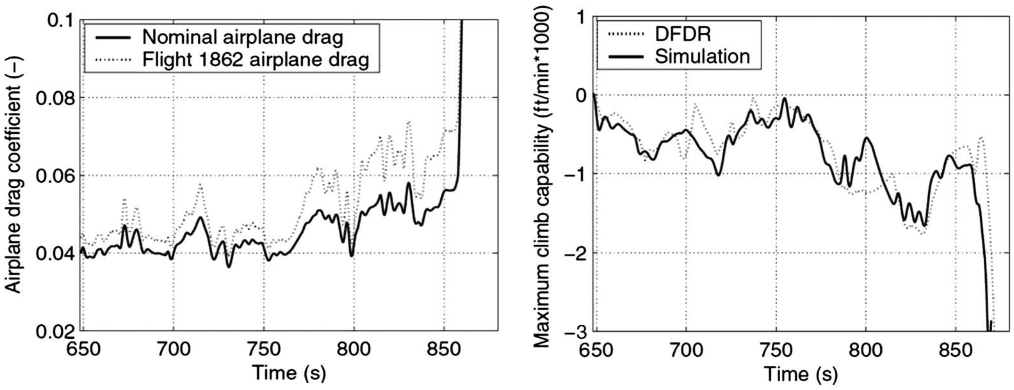
b) Aerodynamic estimates included



c) Aerodynamic estimates not included

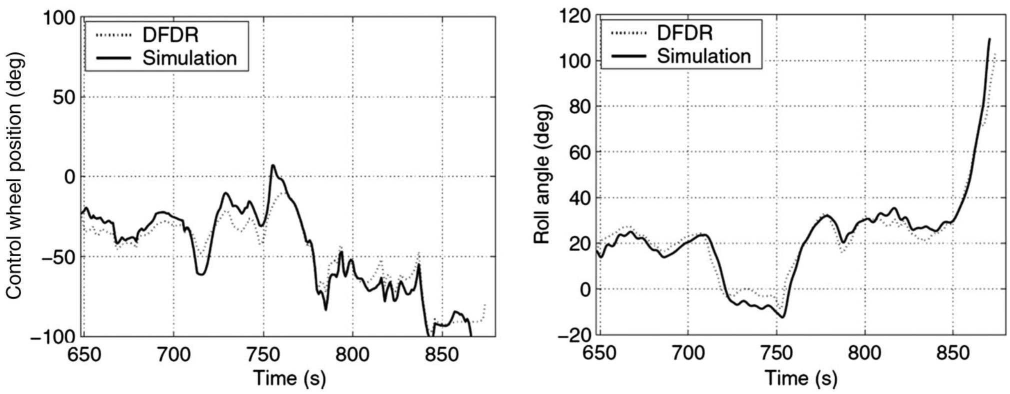
d) Aerodynamic estimates included

Fig. 7 Effect of estimated aerodynamic contributions due to right-wing engines no. 3 and no. 4 separation.



a) Estimated drag increase due to engine separation

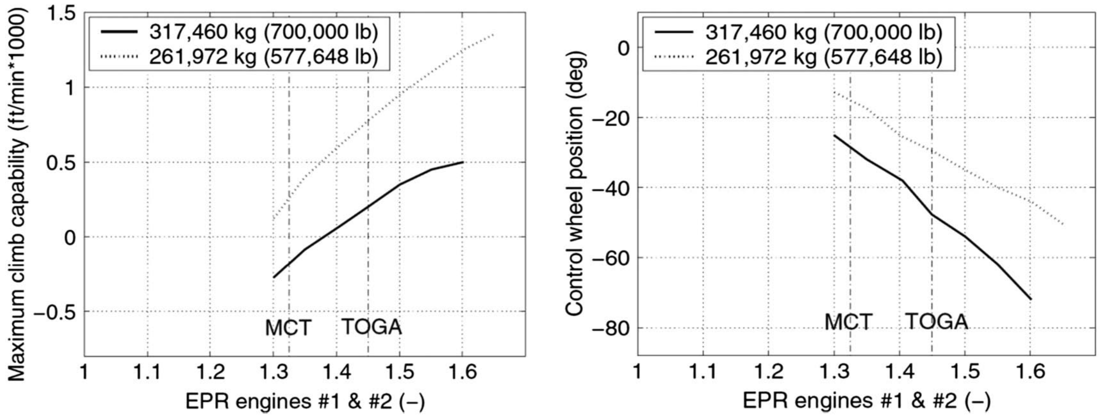
b) DFDR and simulated maximum climb capability



c) DFDR and simulated control wheel position

d) DFDR and simulated roll angle

Fig. 8 DFDR and simulated flight parameters of the El Al Flight 1862 final stage of flight.



a) EL AL Flight 1862 performance capabilities **b) EL AL Flight 1862 lateral control capabilities**

Fig. 9 El Al Flight 1862 performance and control capabilities.

predictions were confirmed during a real-time piloted model validation in the Simulation, Motion, and Navigation (SIMONA) Research Simulator of the Delft University of Technology later in the GARTEUR FM-AG(16) program.

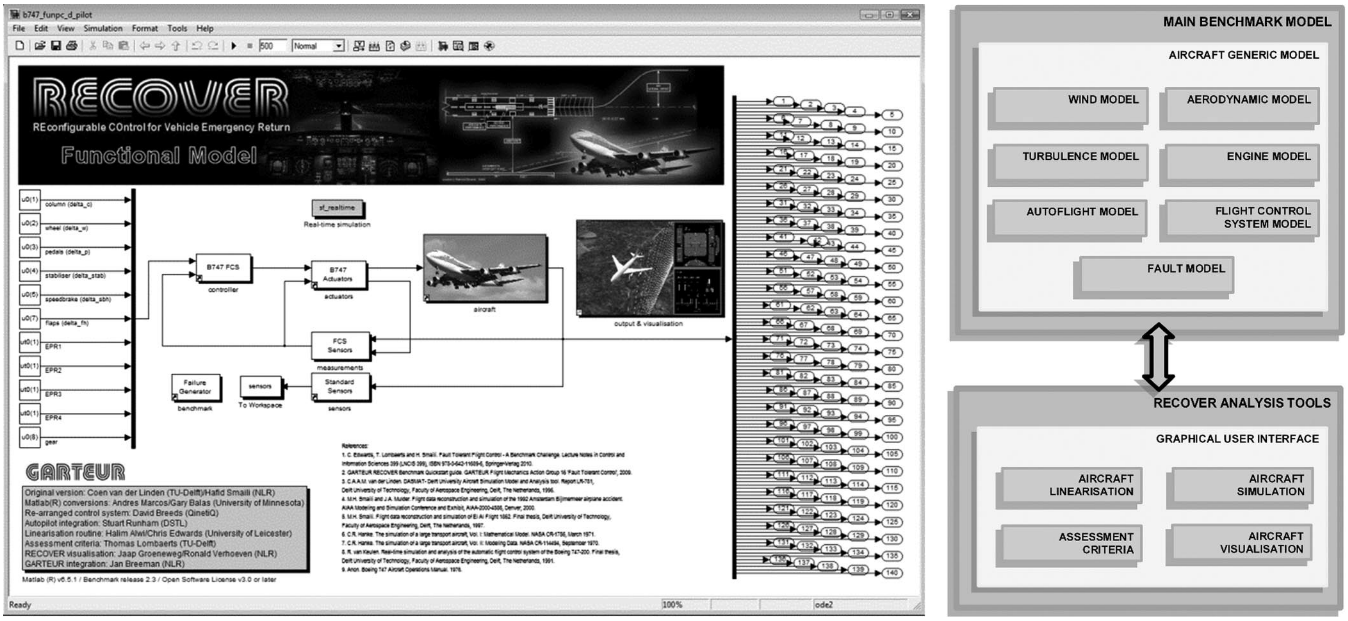
C. Aircraft Benchmark Model

For the assessment of novel fault-tolerant flight control techniques, the GARTEUR FM-AG(16) research group developed an aircraft simulation benchmark, based on the reconstructed El Al Flight 1862 aircraft model [16]. The benchmark simulation environment (RECOVER) was based on the Delft University Aircraft Simulation and Analysis Tool (DASMAT) [20]. The DASMAT was further enhanced with a full nonlinear simulation of the Boeing 747-100/200 aircraft (Flightlab747/FTLAB747), including flight control system architecture, for the Flight 1862 accident study as conducted by TU Delft. The simulation environment was subsequently used and further enhanced as a realistic tool for evaluation of fault detection and fault-tolerant control schemes within other research programs [21].

The GARTEUR RECOVER benchmark has been developed as a MATLAB®/Simulink® platform for the design and integrated (real-time) evaluation of new fault-tolerant control techniques. The benchmark consists of a set of high-fidelity simulation and flight control design tools, including aircraft fault scenarios. For a representative simulation of damaged aircraft handling qualities and performances, the benchmark aircraft model has been validated against data from the digital flight data recorder of the El Al Flight 1862 Boeing 747-200 accident aircraft.

The GARTEUR RECOVER benchmark software package is equipped with several simulation and analysis tools, all centered around a generic nonlinear aircraft model for six-degree-of-freedom nonlinear aircraft simulations. Figure 10 shows the benchmark functional model operating shell for open-loop nonlinear offline (interactive) simulations and software architecture. For high-performance computation and visualization capabilities, the package has been integrated as a toolbox in the computing environment MATLAB/Simulink. The benchmark is operated via a MATLAB graphical user interface from which the different benchmark tools may be selected. The user options in the main menu are divided into three main sections, allowing initializing the benchmark, running the simulations, and selecting the analysis tools. The tools of the GARTEUR RECOVER benchmark include trimming and linearization for (fault-tolerant) flight control law design, nonlinear offline (interactive) simulations, simulation data analysis, and high-resolution three-dimensional flight trajectory and pilot interface visualizations for interactive (real-time) simulations (Fig. 11). The modularity of the benchmark makes it customizable to address research goals in terms of aircraft type, flight control system configuration, failure scenarios, and flight control law assessment criteria.

Figure 12 illustrates a detailed schematic overview of the GARTEUR RECOVER benchmark showing model component



Original version: Coen van der Linden (TU-Delft)/Hafid Smaili (NLR)
Matlab(R) conversions: Andres Marcos/Gary Balas (University of Minnesota)
Re-arranged control system: David Breeds (QinetiQ)
Autopilot integration: Stuart Runham (DSTL)
Linearisation routine: Halim Alwi/Chris Edwards (University of Leicester)
Assessment criteria: Thomas Lombaerts (TU-Delft)
RECOVER visualisation: Jaap Groeneweg/Ronald Verhoeven (NLR)
GARTEUR integration: Jan Breeman (NLR)

Matlab (R) v6.5.1 / Benchmark release 2.3 / Open Software License v3.0 or later

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Fig. 10 GARTEUR RECOVER benchmark functional model and software architecture.

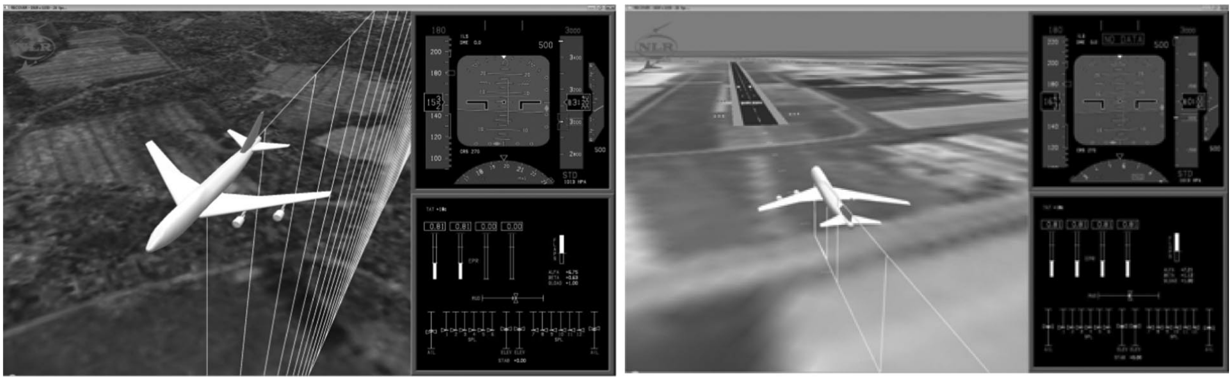


Fig. 11 GARTEUR RECOVER benchmark high-resolution aircraft visualization tool.

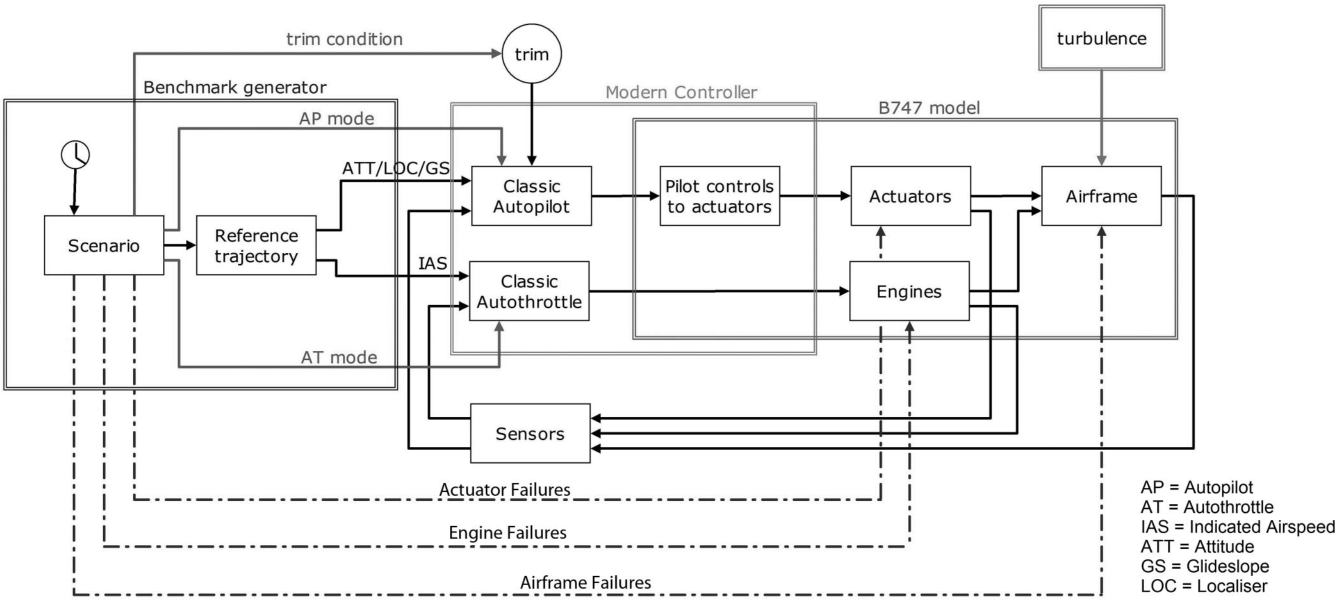


Fig. 12 Detailed schematic and model components of the GARTEUR RECOVER benchmark.

relationships, including test maneuver and failure scenario generation and fault injection. The basic aircraft model contains airframe, actuator, engine, and turbulence models, and it is represented by the outline in the diagram designated as the B747 model. As described previously, the input of this model was initially based on the pilot's control inputs, which have a fixed linkage to the control surfaces. To control the surfaces separately, as required for the reconfigurable control algorithms, the "pilot controls to actuators" block is separated from the baseline aircraft model. A basic classical controller is available in the benchmark, based on the Boeing 747 classic autopilot including autothrottle, to serve as a reference for new adaptive control algorithm designs. Any newly designed FTFC controller, to be evaluated with the benchmark model, is meant to replace the classic autopilot and autothrottle, and it should drive the individual control surfaces directly. This is indicated in the diagram by the outline titled "modern controller." To operate the benchmark, a scenario and failure mode generator are added. The scenario consists of commands fed into the autopilot and autothrottle, whereas the failures are directly introduced into the airframe, flight control system, and propulsion models via MATLAB/Simulink Goto/From blocks, as indicated by the broken lines.

The test scenarios that are an integral part of the GARTEUR RECOVER benchmark were selected to provide challenging (operational) assessment criteria as specifications for reconfigurable control to evaluate the effectiveness and potential of the FTFC methods being investigated in the GARTEUR program. The RECOVER benchmark fault scenarios, control reconfiguration method, and severity classifications are summarized in Table 1. The selected fault scenarios in Table 1 for the benchmark model are representative of recent accident and incident cases, and they consist of a combination of structural damage and stuck or erroneous control surfaces. Note that, in this paper, we use the terms "fault" and "failure" for the same scenarios and degraded modes. An additional requirement for the selection of the fault scenarios was the availability of sufficient information or flight-test data for the modeling and validation of the failure modes.

The first four failure cases in Table 1 are not serious, and it might be expected that continued flight to the original destination will be possible. That is not true for the last two fault cases, which are extremely serious and where a landing at the nearest airport is all that can be hoped for. The next-to-last case is directionally very unstable due to the loss of the vertical tail and rudder controls (rudder stuck at 0 deg). It is similar to aircraft accident cases in which a loss of the vertical tail occurred (e.g., Japan Airlines Flight 123), although it is not intended to be an accurate representation. The last fault case is a very accurate representation of the Flight 1862 accident as described in this paper. In this case, the aircraft is not unstable, but the flight envelope is severely limited. In the last two cases, it cannot be expected that the aircraft will be able to follow the reference trajectory closely. The benchmark assessment criteria have been designed to take this into account by emphasizing end conditions in the specifications [22].

The geometry of the GARTEUR RECOVER benchmark flight scenario (Fig. 13) is roughly modeled after the Flight 1862 accident

Table 1 GARTEUR FM-AG(16) RECOVER benchmark fault scenarios

Failure mode	Reconfiguration	Criticality
No failure	N/A[a]	None
Stuck elevator	Stabilizer Ailerons (symmetric) Differential thrust	Major
Stuck aileron	Ailerons (other) Spoilers	Major
Stabilizer runaway	Elevator (bad stabilizer) Ailerons (symmetric) Flaps Differential thrust	Critical
Rudder runaway	Remaining surfaces Differential thrust	Critical
Loss of vertical tail surface	Remaining surfaces Differential thrust	Catastrophic
Engine separation and structural damage	Remaining surfaces Remaining engines Remaining sensors	Catastrophic

[a] N/A denotes "not applicable."

profile for the qualification of new fault-tolerant flight control systems to safely land a damaged large transport aircraft. The scenario consists of a number of phases. First, it starts with a short section of normal flight, after which a fault occurs, which is in turn followed by a recovery phase. If this recovery is successful, the aircraft should again be in a stable flight condition, although not necessarily at the original altitude and heading. After recovery, an optional identification phase is introduced, during which the flying capabilities of the aircraft can be assessed. This allows for a complete parameter identification of the model for the damaged aircraft, as well as the identification of the safe flight envelope. The knowledge gained during this identification phase can be used by the controller to improve the chances of a safe landing. In principle, the flight control system is now reconfigured to allow safe flight. The performance of the reconfigured aircraft is subsequently assessed in a series of five flight phases. These consist of straight and level flight, a right-hand turn to a course intercepting the localizer, a localizer intercept, a glideslope intercept, and the final approach. During the final approach phase, the aircraft is subjected to a sudden lateral displacement just before the threshold, which simulates the effect of a low-altitude windshear. The landing itself is not part of the benchmark, because a realistic aerodynamic model of the damaged aircraft in ground effect is not available. However, it is believed that, if the aircraft is brought to the threshold in a stable condition, the pilot will certainly be able to take care of the final flare and landing.

III. Flight Simulator Integration and Piloted Assessment

A. Motivation and Goals

An online piloted moving-base simulator evaluation of fault-tolerant flight control systems can give new insights into real-time performance issues, applicability in an operational environment and, if applicable, handling qualities of different aircraft configurations. It can serve as a proof of concept and allows the assessment of the benefits of the controllers in terms of compensation for impaired aircraft control, performance improvements in failed configurations, and lowering of pilot workload. For this purpose, the GARTEUR FM-AG(16) benchmark aircraft model and the fault-tolerant controllers were implemented in a pilot-in-the-loop flight simulator. Pilots with operational experience on the aircraft in question were used to assess the efficiency of the controllers and their influence on the handling of the aircraft. Ideally, the pilot would not be aware of any differences in aircraft handling with the controller engaged for the normal fault-free and damaged aircraft, and the pilot would be able to perform normal flying tasks with satisfactory performance in both cases.

Within the GARTEUR FM-AG(16), a number of fault-tolerant flight control algorithms were developed (Table 2). Their underlying principles ranged from FTFC with guaranteed nominal performance $H\infty$, sliding-mode control allocation, and model-predictive control to parameter estimation and nonlinear dynamic inversion [16]. As part of the action group's work, a real-time assessment and piloted evaluation were performed for several of these algorithms.

The objectives of this evaluation can be summarized as follows: 1) analyzing real-time performance and integration issues of the reconfigurable fault-tolerant flight control algorithms by integrating them in the complete aircraft environment, 2) qualitative assessment of the FTFC algorithms in terms of aircraft handling qualities in both nominal and failed conditions, 3) quantitative assessment of the FTFC algorithms benefits in terms of pilot workload to substantiate the handling qualities ratings, and 4) providing an additional control design challenge to raise the technology readiness level of the FTFC control designs by demonstrating the capability in ensuring a survivable recovery of a damaged aircraft in real-time operational conditions and procedures.

B. Flight Simulator Configuration

The GARTEUR FM-AG(16) piloted evaluation was performed on the SIMONA Research Simulator (Fig. 14) at the Delft University of Technology. SIMONA is a six-degree-of-freedom research flight simulator, with configurable flight-deck instrumentation systems, a wide-view outside visual display system, hydraulic control loading, and a motion system.

The flight deck of the SIMONA resembles a generic two-person side-by-side cockpit, as found in many modern airliners. For the

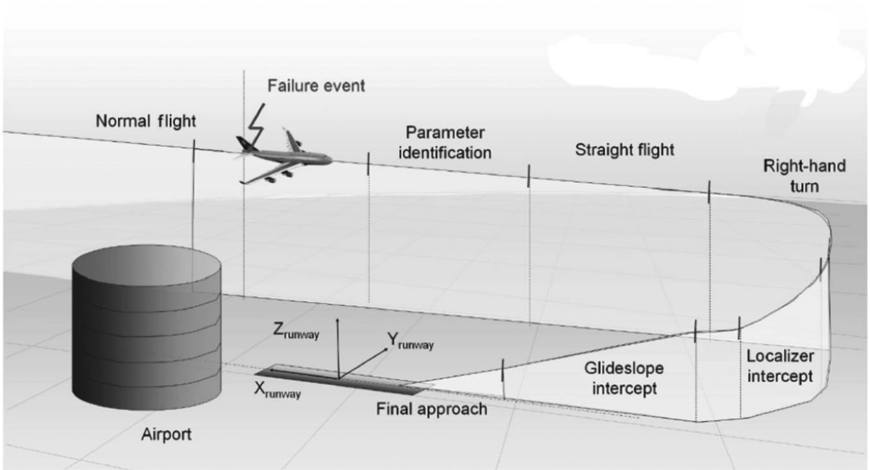


Fig. 13 GARTEUR RECOVER benchmark flight scenario and phases.

Table 2 GARTEUR FM-AG(16) fault-tolerant flight control algorithms

No.	FTFC algorithm	Control type
0[a]	Classic flight control system	Manual (classic)
1[a]	Model reference adaptive sliding modes control with control allocation	Autoflight
2[a]	Integral action control	Autoflight
3[a]	Fault tolerant control with guaranteed nominal performance $H\infty$	Manual (classic) and altitude hold
4	Fault detection, identification, and reconfiguration system based around optimal control allocation	Manual and autoflight
5[a]	Subspace predictive control	Autoflight
6	Real-time model identification and model predictive control	Manual (FBW)
7[a]	Real-time model identification and nonlinear dynamic inversion	Manual (FBW)
8	Adaptive model following control	Autoflight

[a] Evaluated in piloted simulation.

GARTEUR FM-AG(16) piloted experiment, the SIMONA cockpit was configured to represent the Boeing 747 aircraft type with a glass cockpit layout. The cockpit displays were based on the Boeing 747-400 electronic flight instrumentation system (EFIS; Fig. 15). To help the pilots assess the reconfigurable controller's actions, the surface deflections of the elevators (referred to as ELEV), the inner and outer ailerons (referred to as AIL), and upper and lower rudders (referred to as RUD) were shown in the upper right-hand corner of the engine indication and crew alerting system display (EICAS; Fig. 15b). Engine performance was also monitored via the EICAS engine parameters, consisting of low-pressure compressor rotation speed (referred to as N1) and engine pressure ratio (EPR). The EICAS display also shows the current total air temperature (TAT) and exhaust gas temperature (EGT) during the simulation. Further technical characteristics of the SIMONA, including the control loading feel system and motion platform, can be found in [23].

C. Aircraft Configuration and Validation

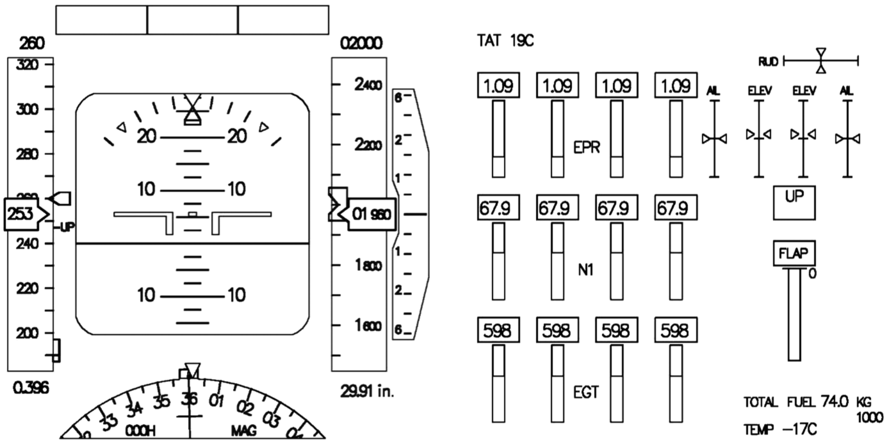
For the piloted experiment, the benchmark model and the designed fault-tolerant control algorithms were converted from Simulink to the real-time environment. Several validation steps were performed to assure the benchmark model was implemented correctly. This included proof-of-match validation and piloted checkout of the baseline aircraft, control feel system, and Flight 1862 controllability and performance characteristics. The aircraft model could be flown in the manual classical (hydromechanical) flight control system mode and in the manual fly-by-wire mode, where flight control was performed via the subsequent FTFC module (design dependent). In the first configuration, aircraft control was via the mechanical and hydraulic system architecture modeled after the B747-100/200 aircraft. In the second case, all control surfaces were commanded via the respective FTFC module. Some modules were driven by manual control, and others were driven by the mode control panel for full automatic failure recovery, stabilization, and approach and landing. Operational characteristics of the benchmark aircraft model for the piloted simulation can be found in Table 3. Aircraft configurations and flight conditions as used for the piloted experiment are shown in Table 4.

D. Test Method

The test method of the piloted evaluation within the GARTEUR FM-AG(16) program was designed to assess the FTFC failure mode accommodation capabilities in terms of aircraft upset recovery and stabilization, controllability, and pilot workload to restore handling qualities up to levels that at least allowed a survivable landing. To obtain a good comparison, the aircraft was flown in both the conventional (classical) control mode and in the fly-by-wire FTFC mode. Fault detection and isolation capabilities were tested on their

a) Outside view **b) Cockpit view**

Fig. 14 SIMONA Research Simulator (photo credit: Joost Ellerbroek).



a) Primary flight display **b) Engine indicating and crew alerting system**

Fig. 15 SIMONA flight-deck displays representing the Boeing 747-400 EFIS.

Table 3 Boeing 747-100/200 series aircraft data and three-view

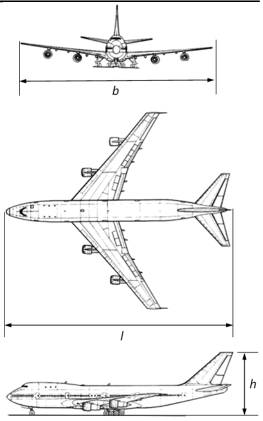
Parameter	Value	Views
Wing area	511 m^2	
Wing mean aerodynamic chord	8.324 m	
Wingspan (b)	59.65 m	
Length overall (l)	70.66 m	
Height overall (h)	19.33 m	
Maximum taxi weight	713,000 lb/ 323,411 kg	
Maximum takeoff weight	710,000 lb/ 322,051 kg	
Maximum landing weight	564,000 lb/ 255,826 kg	
Maximum zero fuel weight	526,500 lb/ 238,816 kg	
Load factor range flaps up	−1.0/ + 2.5	
Load factor range flaps down	0/2	

Table 4 Aircraft configurations and flight conditions

Flight phase	Aircraft mass, kg × 1000	Altitude, ft (MSL)	Airspeed, KIAS	Center of gravity, % mean aerodynamic chord	Flaps, deg	Gear
Failure and parameter identification phase	317/327[a]	2000	270	25	1	Up
Straight flight	317	2000	270	25	1	Up
Localizer intercept	317	2000	174/270[a]	25	20/1[a]	Up
Glideslope intercept	317	2000	162/220[a]	25	25/1[a]	Down/ up[a]

[a] El Al Flight 1862 accident scenario.

Table 5 Evaluation pilots in the GARTEUR FM-AG(16) experiment campaign

Pilot	Age	Flight hours	Type ratings
1	64	13,000	Cessna Citation II, DC-3, DC-8, Boeing 747-200/300/400
2	51	14,000	Boeing 747-400
3	43	15,000	Boeing 747-300, Boeing 767
4	54	18,000	Boeing 747-400, Boeing 737, DC-10, DC-9, Fokker F-28
5	40	12,000	Boeing 747-400, Boeing 737
6	41	8,000	Cessna Citation II, Boeing 767, Airbus A330

robustness under real-time environmental conditions, including continuous aircraft maneuvering. The FTFC modules were tested using the same flight scenario and failure modes.

For each flight phase, appropriate exercises were defined with performance criteria (displayed after each run to the pilot and experiment leader) to rate the handling qualities of both the undamaged and damaged aircraft. Each pilot performed one run of each configuration. After each run, the pilots gave a handling qualities rating for each flight phase using the Cooper–Harper (CH) rating scale [24]. Workload was obtained for each scenario phase by measuring the combined pilot control force activities for the wheel, column, and pedal.

The emphasis of the piloted assessment was on manual pilot-in-the-loop control of the impaired aircraft. FTFC modules that only allowed flying the recovered aircraft in autopilot mode were compared in terms of pilot acceptability of automatic recovery maneuvers and commanded flight-path behavior.

The pilots were made aware of the failed aircraft configurations and characteristics during the preflight briefing. This prevented any distraction caused by the unknown damaged aircraft configuration and assured that they reverted to the primary task of conducting the handling qualities tasks.

E. Participants

Familiarity with the flown aircraft is one of the main requirements for the participants in a piloted evaluation. Some flight-test or evaluation experience is also beneficial, especially when using standard rating scales. In the GARTEUR FM-AG(16) simulator campaign, six professional airline pilots with an average experience of about 14,000 flight hours participated in the evaluation. Five pilots, who conducted the handling qualities evaluation, were type rated for the Boeing 747 aircraft, whereas one pilot was rated for the Boeing 767 and Airbus A330 aircraft. Some of the pilots had engineering flight-testing experience. Table 5 shows information on the individual background and experience of the evaluation pilots.

F. Test Procedure

To accurately replicate the operational conditions of the reconstructed Flight 1862 accident aircraft in the simulator, the experiment scenario was aimed at a landing on Runway 27 of Amsterdam Schiphol Airport (Fig. 16). The SIMONA airport scenery was representative of Amsterdam Schiphol Airport and its surroundings for flight under the visual flight rules.

Each pilot started to fly the classical control mode in an unfailed condition to familiarize with the baseline aircraft handling qualities. This procedure was repeated several times until the pilot felt confident to proceed. The pilot would rate if the unfailed baseline aircraft model exhibited at least level-1 handling qualities (CH 1–3). The same procedure was conducted to familiarize with the baseline fly-by-wire configuration.

The procedure starts at 2000 ft MSL at a high speed of 260 KIAS and a northerly heading of 360 deg. The pilot is asked to accelerate to 270 KIAS to allow a minimum control speed margin (El Al Flight 1862 scenario). When stabilized on a heading of 90 deg, a failure is injected. The pilot is then required to recover the aircraft from any upset and stabilize at 2000 ft and 270 KIAS while selecting flaps 1. The pilot is now allowed to familiarize himself and adapt to the degraded handling qualities and required control strategies to compensate for the failure mode.

After a climb and altitude capture task to 2500 ft, a lateral gross acquisition task is performed by capturing −20 and 20 deg bank angles. Following descent to 2000 ft at 270 KIAS, the pilot is given a heading of 240 deg for the approach to Amsterdam Schiphol Runway 27. When stabilized on a heading of 240 deg, speed is reduced to the landing reference speed for flaps 20 (V_{Ref} 20, 174 KIAS). For the Flight 1862 scenario, airspeed remains at 270 KIAS to allow enough stall margin for the damaged right wing. The first run is paused to enable the pilot to rate the climb to 2500 ft and the lateral gross acquisition task using the Cooper–Harper scale.

The second run starts after a reposition to a predetermined point at 2000 ft, a heading of 240 deg, and speed at V_{Ref} 20 (174 KIAS) or 270 KIAS (El Al Flight 1862 scenario) for the approach to Schiphol Runway 27. The pilot's task is to capture the localizer in the failure mode configuration. When the aircraft intercepts the glideslope, speed is reduced to V_{Ref} 25 (169 KIAS) or 220 KIAS (El Al Flight 1862 scenario). The run is aborted at 500 ft. A Cooper–Harper rating is given for the localizer and glideslope capture task. The applied performance criteria for each FTFC handling qualities evaluation maneuver, as conducted in the experiment, can be found in Appendix A.

G. Piloted Handling Qualities Evaluation Results

1. Handling Qualities Ratings

If the fault-tolerant flight control system takes the form of a manual fly-by-wire flight control algorithm, as opposed to a fully automatic system, the requirements on the (degraded) handling qualities need to be taken into account. The system must provide the pilot with good handling qualities in normal flight conditions and acceptable handling qualities in failed conditions. Piloted simulator handling qualities results were obtained for an FTFC algorithm that consisted

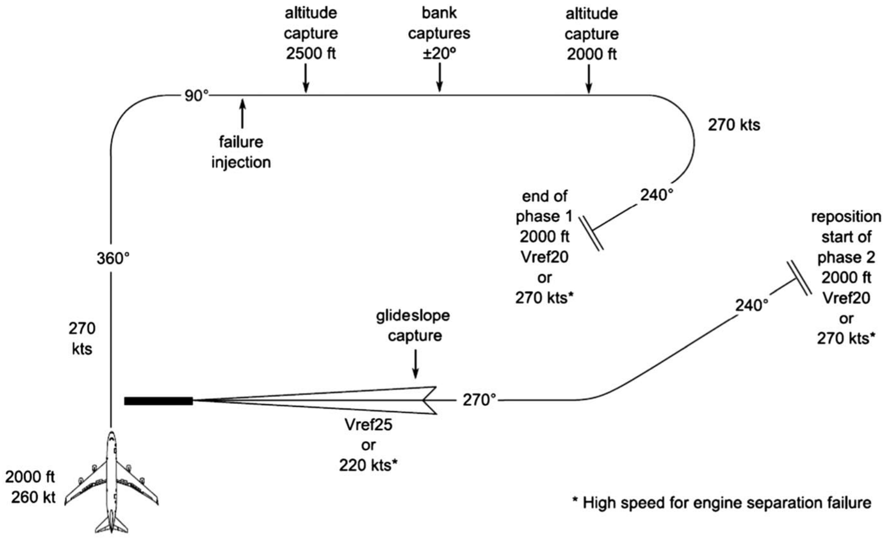
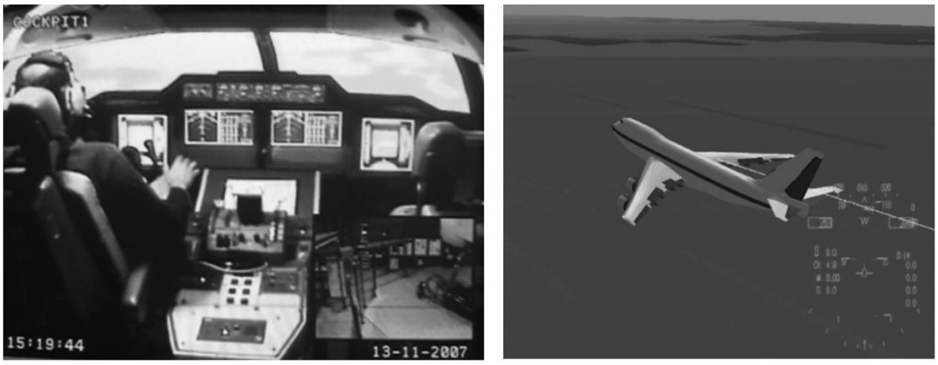


Fig. 16 Experiment scenario and handling qualities tasks.

of a combination of real-time aerodynamic model identification (in case of structural damage) and adaptive nonlinear dynamic inversion (ANDI) for control allocation and reconfiguration [25] (FTFC algorithm design no. 7 in Table 2).

Manual controlled flight, for both the baseline aircraft and under fault reconfiguration, was assessed for a left rudder hardover to the blowdown limit (Fig. 17) and a separation of both right-wing engines (Fig. 18). Figure 17 shows the evaluation sequence and recovery techniques as applied by the test pilot encountering a sudden left rudder hardover failure without the ANDI FTFC system for compensation. Figures 17a and 17b show the start of the test run where the aircraft is stabilized before failure insertion. The altitude is 2000 ft, airspeed is 260 KIAS, sideslip is 0 deg, and bank angle is 0 deg. The aircraft dynamics and applied pilot recovery techniques, when the failure is inserted, are depicted in Figs. 17c and 17d. The aircraft enters an upset of about 30 deg left bank and achieves a maximum sideslip excursion of about 11.8 deg. To recover from the failure, the pilot applies full right wing down control wheel deflection and differential thrust. Figure 18b shows the simulated aircraft configuration for the right-wing engine nos. 3 and 4 separation failure mode (El Al Flight 1862 scenario). To compensate for the failure, the pilot (left seated) applies the left control wheel deflection and full left rudder pedal to counteract the roll and yaw tendency. During the test run, it was observed that, in this particular failure case, without control reconfiguration, the large control wheel deflection obstructed the view of the primary flight instruments (Fig. 18a).

The GARTEUR FM-AG(16) experiment pilots were asked to rate both the baseline aircraft with the hydromechanical control system configuration and the fly-by-wire ANDI reconfigurable control laws using the Cooper–Harper handling qualities rating scale. To allow a meaningful comparison to be made, the pilots were instructed to rate the failed and/or augmented aircraft as a fully operational vehicle, and



a) Pilot seated left before failure

b) Aircraft straight and level before failure

c) Pilot applying recovery technique

d) Aircraft attitude after failure insertion

Fig. 17 Rudder hardover failure and recovery.

a) Pilot (left seated) compensating for failure **b) Aircraft simulation model configuration**

Fig. 18 Right-wing engines no. 3 and no. 4 separation failure mode.

no allowances for the failure were to be taken into account. Both the rudder runaway scenario and the Flight 1862 engine separation scenario were rated. As a comparison basis, the classical flight control system and fly-by-wire ANDI control algorithms were rated for the nominal flight conditions (no failure modes). This also provided the opportunity to familiarize the pilots with the different baseline control strategies.

The handling qualities analysis results are illustrated in Appendix B. For all evaluation tasks, pilot handling qualities ratings were provided for both longitudinal and lateral task performance. For the evaluated control algorithm, the piloted evaluation tasks included altitude capture, bank angle acquisition, and localizer capture up to the intercept of the glideslope. The bank angle capture task was subdivided into an evaluation of left- and right-bank acquisition capabilities to account for asymmetric failure modes. Appendix B shows the individual ratings, horizontally separated for the classical flight control system (left) and fault-tolerant fly-by-wire control system (right), as well as from top to bottom showing the altitude capture task, the left-bank capture task, the right-bank capture task, and the localizer intercept task. The ratings presented are for the unfailed aircraft (no fail), rudder hardover (rudder) and right wing engine separation (engine) failure scenarios.

The experiment results show that both the baseline (classical) and fly-by-wire (FBW) ANDI (FBW-ANDI) aircraft configuration were rated level 1 (rating of 1–3) by most pilots for the unfailed condition. This provides a comparison basis when analyzing pilot performance in degraded conditions for the different flight control system configurations. The trends of the pilot ratings for the ANDI reconfigurable control algorithm show that, especially for the El Al Flight 1862 engine separation scenario, conventional flight control was restored up to acceptable handling qualities levels (upper level 1) following a failure. In these conditions, no significant task performance degradations occurred as compared to the unfailed fly-by-wire aircraft, whereas the physical and mental workloads were reduced as indicated by an analysis of the aggregated control forces and pilot comments [26]. After incurring significant damage due to the separation of the right-wing engines, the pilot ratings for the conventional aircraft with a classical control system clearly show that, in all conditions, above the minimum control speed, level 2 (ratings of 4–6) handling qualities existed. The reconfigured aircraft (FBW-ANDI) was able to improve the handling qualities back toward the upper level 1 region. This was substantiated by the measured pilot control activities, representative of workload, indicating no sustained pilot compensation after control reconfiguration [26].

The rudder hardover scenario appeared to be more critical from a handling qualities perspective. As with the Flight 1862 case, level 2 handling qualities were obtained in most conditions for the classical control system. However, the lateral control tasks were observed to induce severely coupled longitudinal and lateral dynamics resulting in further degradation of the handling qualities to level 3 (ratings of 7–9). For the reconfigured aircraft, the handling qualities ratings remain about level 2 after control reconfiguration, despite no required sustained control inputs by the pilot. Most likely, the main reason for the inferior rating was caused by the fact that the fault-tolerant controller was a rate controller that minimized disturbances in angular rates but not the disturbed angle itself. As a consequence, rudder hardover resulted in a yaw rate to the left, which was eliminated by the controller, but the heading angle change was not eliminated automatically, and it was left to the pilot to compensate. As a consequence, a constant nonzero roll or sideslip angle was needed in order to reestablish equilibrium. This attitude was disturbing, especially since no corresponding pilot actions were needed. A possible solution for this was the implementation of a rate control attitude hold algorithm that included automatic differential thrust application as a reconfiguration strategy to compensate for the yawing moment.

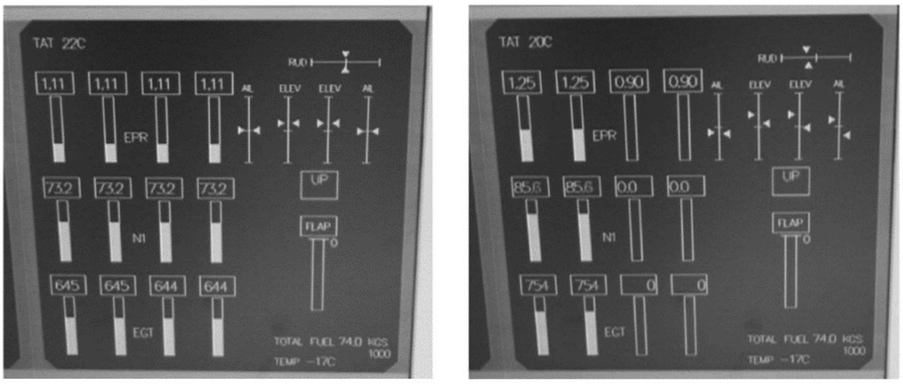
2. *Pilot–Cockpit Interface*

Information regarding flight control reconfiguration status by the ANDI algorithm was available to the pilot via the EICAS display in the cockpit. Figures 19a and 19b illustrate the EICAS display before and after the separation of the no. 3 and no. 4 right-wing engines. The EICAS display in Fig. 19b shows the loss of thrust (left: EPR, N1, EGT) and control surface reconfiguration (upper right: RUD, ELEV, AIL). As shown in the figures, the asymmetric physical loss of the engines is recovered and compensated by allocation of control to the remaining surfaces. For this scenario, the inboard ailerons are only half-operational, supported by the remaining spoilers, as indicated by the aircraft damage configuration in Fig. 3. The EICAS display shows that the FTFC algorithm exploits the full control authority of the rudder, where the human pilot relies less on rudder control input to compensate for the loss of the right-wing engines. As a consequence, slightly less aileron deflections are needed in the FTFC case compared to classic control.

The reconfiguration status of the ANDI algorithm for a sudden left rudder hardover to the aerodynamic blowdown limit, as presented to the pilot, is illustrated in Figs. 19c and 19d. Figure 19d shows the control surface reconfiguration after the failure has been inserted and detected. Following the failure, lateral and directional control is allocated to the ailerons and spoilers providing roll and yaw compensation, whereas any longitudinal trim offsets, due to the failure, are compensated by the elevators.

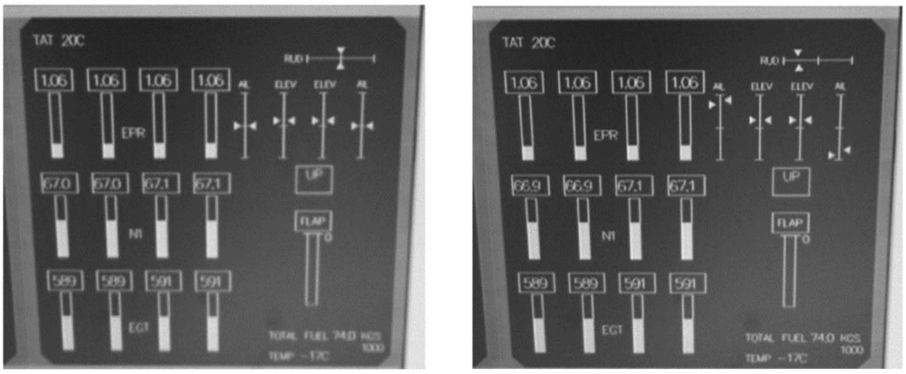
3. *Flight Control Computer Computational Load*

A measure of a controller's practical applicability is the computational load it places on the flight control computer. The amount of additional calculations necessary for fault-tolerant flight control must be sufficiently low to enable actual introduction within the foreseeable future. This will be determined largely on the structure of the algorithm. The computational loads of the GARTEUR FM-AG(16) algorithms were measured in the simulator software environment without a pilot in the loop. For comparison purposes, a standard desktop PC (AMD Athlon TM X2 5600+ processor) is used to measure the time needed by each algorithm to perform a single integration step. The ANDI control algorithm, for which the handling qualities are assessed in piloted simulation as described in this paper, employs real-time state reconstruction using an iterated extended Kalman filter at every time step, leading to a much larger demand on the processor. For this algorithm, a frame



a) EICAS display before failure

b) EICAS display after failure reconfiguration



c) EICAS display before failure

d) EICAS display after failure reconfiguration

Fig. 19 EICAS display providing control reconfiguration status of ANDI control algorithm.

time of 2.6 ms is measured as compared to a frame time of 0.02 ms for the baseline (hydromechanical) flight control system. In general, the computational load of the algorithms is mostly within the performance limits of current PC-type hardware, although it is probably still too high for application in today's aircraft hardware.

4. *Summary*

In general, the results show, for both automatic and manual controlled flights, that the developed GARTEUR FM-AG(16) FTFC strategies were able to cope with potentially catastrophic failures in case of flight critical system failures or if the aircraft configuration changed dramatically due to damage. In most cases, apart from any slight failure transients, the pilots commented that aircraft behavior felt conventional after control reconfiguration following a failure, whereas the control algorithms were successful in recovering the ability to control the damaged aircraft.

Due to the automatic failure recovery and stabilization capabilities of reconfigurable flight control, it is expected that the pilot is able to land the aircraft sooner due to the reduction of the time-consuming learning phase for the pilot to understand the new basic principles of the damaged aircraft's flying characteristics. Although control reconfiguration can use the control effectors in an optimal manner for failure recovery and stabilization from the associated upset, the physical constraints on the flight envelope (e.g., maximum aileron deflections) still exist. The experiment showed that control surface saturation can still occur and cause a clifflike deterioration of handling qualities, and possibly loss of control. To restore the flight envelope awareness that was lost due to the handling qualities being seamlessly recovered by the controller and to prevent the pilot from inadvertently leaving the safe flight envelope, information regarding the flight envelope should be an integral part of a fault-tolerant flight control scheme.

For both the El Al Flight 1862 and rudder hardover case, as part of the scenarios surveyed in this experimental research, the pilots demonstrated the ability to fly the damaged aircraft, following control reconfiguration, back to the airport and conduct a survivable approach and landing.

IV. Conclusions

The primary objective of the Group for Aeronautical Research and Technology in Europe Flight Mechanics Action Group on Fault-Tolerant Control was to bring novel intelligent fault-tolerant flight control systems, as conceived within academic and research communities, to a higher technology readiness level. This was achieved by demonstrating the advantages of such systems in a realistic operational context.

Within the action group, a realistic aircraft simulation benchmark (RECOVER) was developed based on data from the digital flight data recorder of the El Al B747 Flight 1862 accident. The benchmark played a crucial role in the action group, as it allowed extensive offline design and analysis of new FTFC algorithms by the participants in the action group as well as implementation of these algorithms in the Simulation, Motion, and Navigation full flight research simulator for pilot-in-the-loop evaluation in conditions that would be as realistic as possible.

The benchmark, based on actual DFDR data, combined with a piloted simulator campaign in a full flight simulator, provided a unique opportunity for assessment of the merits of novel FTFC techniques in a very realistic scenario and the environment of an actual past failure case. The flight simulator results showed that, after failure, the FTFC based on online physical model identification was successful in improving handling qualities and pilot performance.

The GARTEUR FM-AG(16) flight simulator evaluations also demonstrated that future work in the area of FTFC should not only be focused on handling qualities but also on strategies to keep the aircraft after failures within its now possibly much smaller safe flight envelope, i.e., the set of flight conditions for which the equilibrium of external moments and forces is possible and flight performance allows a safe approach and landing [2–4]. For the short term and midterm, aviation authorities now recognize the need to improve full flight simulators to become capable of training pilots how to handle LOC.

Appendix A: GARTEUR FM-AG(16) Handling Qualities Evaluation Maneuvers and Performance Criteria

Table A1 FTFC evaluation maneuvers and performance criteria

		Lateral performance		Longitudinal performance	
Maneuver	Description	Required	Adequate	Required	Adequate
Altitude capture	Intercept new altitude with a climb or sink rate of at least 1000 ft/min and without over- or undershoots outside the required performance band. Maintain heading and airspeed within the required performance bands.	Heading: ±2 deg	Heading: ±4 deg	Altitude: ±50 ft, Speed: ±5 kt	Altitude: ±100 ft, Speed: ±10 kt
Bank angle capture	Attain a 20 deg bank angle as quickly and precisely as possible and hold it stable. Maintain altitude and airspeed within the required performance bands.	Bank: 20 deg ±1 deg	Bank: 20 deg ±2 deg	Altitude: ±50 ft, Speed: ±5 kt	Altitude: ±100 ft, Speed: ±10 kt
Localizer intercept	Intercept and follow the localizer. Maintain altitude and airspeed within the required performance bands.	Localizer offset: ±0.5 dot	Localizer offset: ±1 dot	Altitude: ±50 ft, Speed: ±5 kt	Altitude: ±100 ft, Speed: ±10 kt
Glideslope intercept	Intercept and follow the glideslope and localizer. Maintain airspeed within the required performance bands.	Localizer offset: ±0.5 dot	Localizer offset: ±1 dot	Glideslope offset: ±0.5 dot, Speed: ±5 kt	Glideslope offset: ±1 dot, Speed: ±10 kt

Appendix B: Classical and FTFC Longitudinal and Lateral Handling Qualities Ratings

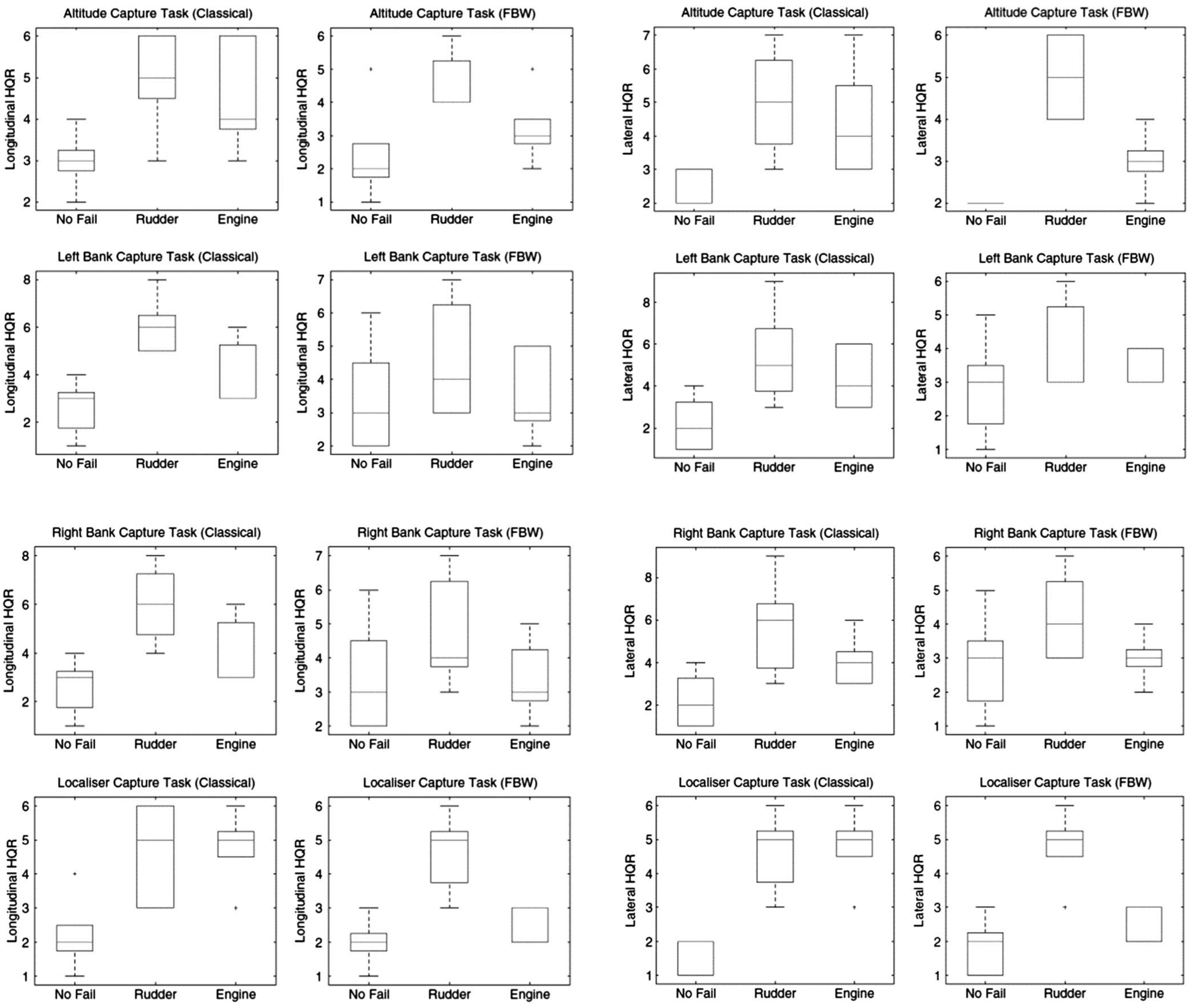


Fig. B1 Pilot longitudinal and lateral handling qualities ratings.

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