A SIMULATION BENCHMARK FOR AIRCRAFT SURVIVABILITY ASSESSMENT

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Abstract

Reconfigurable flight control, or "Intelligent Flight Control", is aimed to prevent aircraft loss due to multiple failures when the aircraft is still flyable given the available control power. From 2004-2008, a research group on Fault Tolerant Control, comprising a collaboration of thirteen European partners from industry, universities and research institutions, was established within the framework of the Group for Aeronautical Research and Technology in Europe (GARTEUR) co-operation program. The aim of the research group, Flight Mechanics Action Group FM-AG(16), is to demonstrate the capability and potential of innovative reconfigurable flight control algorithms to improve aircraft survivability. A large transport aircraft simulation benchmark (REconfigurable COntrol for Vehicle Emergency Return RECOVER) has been developed within the GARTEUR framework for the integrated evaluation of fault detection and identification (FDI) and reconfigurable flight control strategies. The benchmark includes a suitable set of assessment criteria and failure cases based on reconstructed accident scenarios. The potential of the developed fault tolerant flight control (FTFC) methods to improve aircraft survivability, for both manual and automatic flight, has been demonstrated in 2007 and 2008 during a piloted assessment in the SIMONA research flight simulator of the Delft University of Technology.

1 Introduction

Motivated by several aircraft accidents at the end of the 1970's, in particular the crash of an American Airlines DC-10 at Chicago in 1979, research on 'self-repairing', or reconfigurable fault tolerant flight control (RFTFC), was initiated to accommodate in-flight failures. Today's commercial and military aircraft are being developed with fly-by-wire flight control systems. For military aircraft, the benefits include increased agility and reduced supersonic trim drag (in conjunction with reduced static stability) and carefree handling. For commercial aircraft, the benefits include lower weight (attributed to flight controls) as well as carefree handling. In most cases, there is unlikely to be a mechanical backup and so flight control system integrity is critical. To achieve the required levels of integrity, new aircraft configurations have a degree of redundancy in terms of controls, sensors and computing. Control effector redundancy means that there are more than three control effectors, or motivators, to provide the three moments (pitch, roll and yaw). The full set of controls may be required to satisfy the normal performance requirements but flight is still possible with less control surfaces available. The combination of control effectors provides the opportunity to reconfigure the control system in the event of failures with the aim of increasing the survivability of the aircraft.

A reconfigurable flight control system might have prevented the loss of two Boeing 737s due to a rudder actuator hard-over and of a Boeing 767 due to inadvertent asymmetric thrust reverser deployment. The 1989 Sioux City DC-10 incident is an example of the crew performing their own reconfiguration using asymmetric thrust from the two remaining engines to maintain limited control in the presence of total hydraulic system failure. The crash of a Boeing 747 freighter aircraft (Flight

Fig. 1. Emergency landing sequence using engines only and left wing structural damage due to surface-to-air missile impact, DHL A300B4-203F, Baghdad, 2003.

1862) in 1992 near Amsterdam (the Netherlands), following the separation of the two right-wing engines, was potentially survivable given adequate knowledge about the remaining aerodynamic capabilities of the damaged aircraft [1].

Deliberate hostile attacks on commercial transport aircraft have recently been demonstrated to be survivable. In 2003, the crew of an Airbus A300 freighter performed a successful emergency landing at Baghdad International Airport after suffering from complete hydraulic system failures and severe structural wing damage due to the impact of a surface-to-air missile (SAM) (Figure 1). A reconfigurable flight control system would make this success less dependent on the extreme skill of the pilots.

An increasing number of measures are currently being taken by the international aviation community to prevent loss of flight control accidents. This not only includes improvements in procedures training and human factors, but also finding measures to better mitigate system failures and increase aircraft survivability in case of an accident or degraded flight conditions. Several studies on aircraft accident survivability demonstrated that better situational awareness or guidance would have recovered impaired aircraft if unconventional control strategies were used [1]. In some cases, the crew was able to adapt to the unknown degraded flying qualities by applying control strategies that are not part of any standard airline training curriculum.

2 GARTEUR Action Group

The European Flight Mechanics Action Group FM-AG(16) on Fault Tolerant Control (2004-2008) comprises a collaboration of nine European partners from industry, universities and research establishments (Table 1) as part of the Group for Aeronautical Research and Technology in Europe (GARTEUR) co-operation program. The objective of the group is to demonstrate the capability and viability of new fault detection, isolation and reconfiguration (FDIR) methods when applied to realistic (real-time) operational scenarios to improve aircraft survivability. The research group aims to integrate fault detection and isolation techniques with reconfigurable control strategies to accommodate (unanticipated) fault scenarios where the aircraft configuration has changed dramatically. Furthermore, the group addresses the need for high-fidelity nonlinear simulation models, relying on accurate failure modeling, to improve the prediction of reconfigurable system performance in degraded modes.

GARTEUR

QinetiQ, Bedford, United Kingdom
Airbus, Toulouse, France
National Aerospace Laboratory (NLR), Amsterdam, The Netherlands
Deutsches Zentrum für Luft- und Raumfahrt (DLR), Braunschweig and Oberpfaffenhofen, Germany
Defence Science and Technology Laboratory (DSTL), Bedford, United Kingdom
Centro Italiano Ricerche Aerospaziali (CIRA), Capua, Italy
Delft University of Technology, Delft, The Netherlands
Cambridge University, Cambridge, United Kingdom
Aalborg University, Esbjerg, Denmark
University of Lille, Lille, France
University of Hull, Hull, United Kingdom
University of Bordeaux, Bordeaux, France
University of Leicester, Leicester, United Kingdom

Table 1: GARTEUR FM-AG(16) organisations

3 Flight 1862 Aircraft Accident

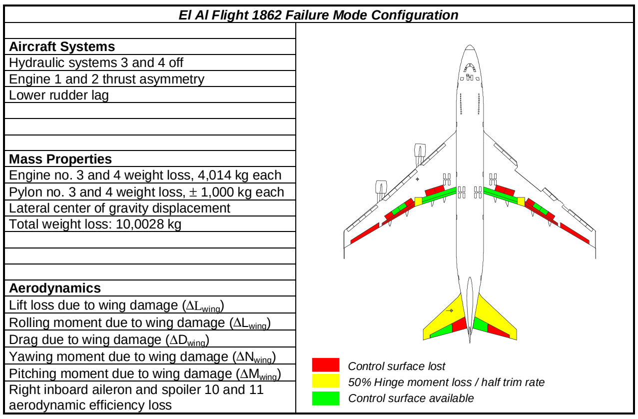
On October 4th, 1992, a Boeing 747-200F freighter aircraft, Flight 1862 (figure 2), went down near Amsterdam Schiphol Airport after the separation of both right-wing engines. In an attempt to return to the airport for an emergency landing, the aircraft flew several right-hand circuits in order to lose altitude and to line up with the runway as intended by the crew. During the second line-up, the crew lost control of the aircraft. As a result, the aircraft crashed, 13 km east of the airport, into an eleven-floor apartment building in the Bijlmermeer, a suburb of Amsterdam. Results of the accident investigation, conducted by several organisations including the Netherlands Accident Investigation Bureau [2] 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 [2].

Fig. 2. The Flight 1862 accident aircraft taxiing and taking off at Amsterdam Schiphol Airport, October 4th, 1992 (copyright Werner Fischdick and LCP Studio).

In 1997, the division of Control and Simulation of the Faculty of Aerospace Engineering of the Delft University of Technology (DUT), in collaboration with the Netherlands National Aerospace Laboratory NLR, performed an independent analysis of the accident [1]. In contrast to the analysis performed by the Netherlands Accident Investigation Bureau, the parameters of the Digital Flight Data Recorder (DFDR) were reconstructed using comprehensive modelling, simulation and visualisation 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 were used [1].

3.1 Failure Mode Configuration

Figure 3 provides an overview of the Flight 1862 failure mode configuration after the separation of both right-wing engines. An analysis of the engine separation dynamics [2] 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 caused



El Al Flight 1862 Failure Mode Configuration
Aircraft Systems
Hydraulic systems 3 and 4 off
Engine 1 and 2 thrust asymmetry
Lower rudder lag
Mass Properties
Engine no. 3 and 4 weight loss, 4,014 kg each
Pylon no. 3 and 4 weight loss, ± 1,000 kg each
Lateral center of gravity displacement
Total weight loss: 10,0028 kg
Aerodynamics
Lift loss due to wing damage (ΔL_{wing})
Rolling moment due to wing damage (ΔL_{wing})
Drag due to wing damage (ΔD_{wing})
Yawing moment due to wing damage (ΔN_{wing})
Pitching moment due to wing damage (ΔM_{wing})
Right inboard aileron and spoiler 10 and 11 aerodynamic efficiency loss

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

by the right-wing structural damage.

The crew of 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 relative low speed of around 260 knots IAS, the DFDR indicated that flight control was almost lost requiring full rudder pedal, 60 to 70 percent maximum control wheel deflection and a high thrust setting on the remaining engines.

3.2 Controllability and Performance

The aircraft design and certification requirements state that there should be enough controllability to handle a multiple engine failure on one side in order to continue flight. For the case of Flight 1862 (Figure 4), the wing damage caused an additional lift loss and drag increase on the right wing. Because these effects are a function of angle of attack, an increase in angle of attack will create an additional rolling moment (*Δ Lwing*) and yawing moment (*Δ Nwing*) into the direction of the dead engines. This in turn will require more opposite control wheel deflection, especially to counteract bank steepening during maneuvering. Banking into the dead engines will increase the minimum control speed and therefore reduce the available controllability.

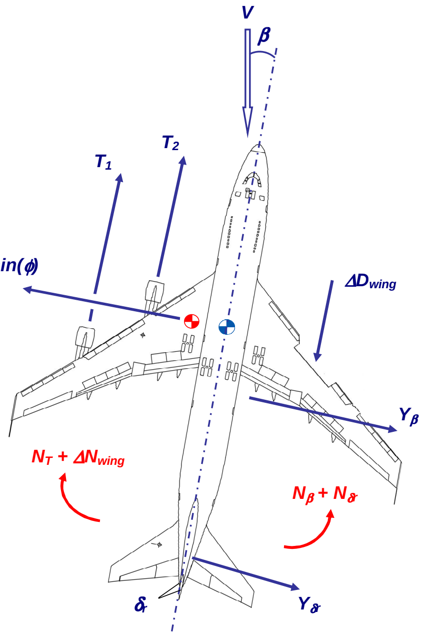


Fig. 4. Top view of the Flight 1862 aircraft forces and moments for equilibrium flight with separated engines and wing damage.

The Flight 1862 accident aircraft was designed to have enough rudder authority to keep the control wheel almost neutral with two engines inoperative on one side. However, in the case of Flight 1862, the DFDR indicated that control wheel deflections between 20 to 60 degrees to the left were needed for lateral control and straight flight. The aerodynamic effects due to the wing damage and degraded effectiveness of the right-wing inboard aileron required larger left wing down control wheel deflections than in the nominal case. The largest deflection of approximately 60 degrees was required for straight and almost level flight at full pedal and high thrust.

An energy analysis of the flight using the DFDR data [2] indicated that after the separation of the engines, the aircraft had level flight capability at go-around thrust and at an indicated airspeed of approximately 270 knots. Maneuvering capabilities were marginal and resulted in a loss of altitude. A normal load of approximately 1.1 g, equivalent to 25 degrees of bank, reduced the maximum climb capability to approximately minus 400 feet/min. At Maximum Continuous Thrust (MCT) and at approximately 270 knots IAS, maximum climb performance was about minus 350 feet/min. Below 260 knots IAS, a normal load of 1.15 g and an angle of attack above approximately 8 degrees, resulted in significant performance degradation. At 256 knots IAS, a normal load of 1.2 g and MCT thrust, maximum climb performance was reduced to minus 2000 feet/min.

3.3 Recovery Capabilities

Figure 5 presents the performance capabilities of the Flight 1862 accident aircraft after separation of both right-wing engines, reconstructed via the methods described in reference [1], as a function of thrust and aircraft weight. The reconstructed model indicates that in these conditions and at heavy weight (700,000 lbs/ 317,460 kg), level flight capability was available between MCT and Take-Off/Go Around thrust (TOGA). At or above approximately TOGA thrust, the aircraft had limited climb capability. Analysis shows that adequate control capabilities remained available to achieve the estimated performance capabilities [1]. Figure 5 indicates a significant improvement in available performance and controllability at a lower weight if more fuel had been jettisoned.

Simulation analysis of the accident flight using the reconstructed model [1] predicts sufficient performance and controllability, after the separation of the engines, to fly a *low-drag* approach profile at a 3.5 degrees glide slope angle for a high-speed landing or ditch at 200/210 KIAS and at a lower weight. 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 [1]. The above predictions have been confirmed during the piloted simulator campaign later in the FM-AG(16) program [6].

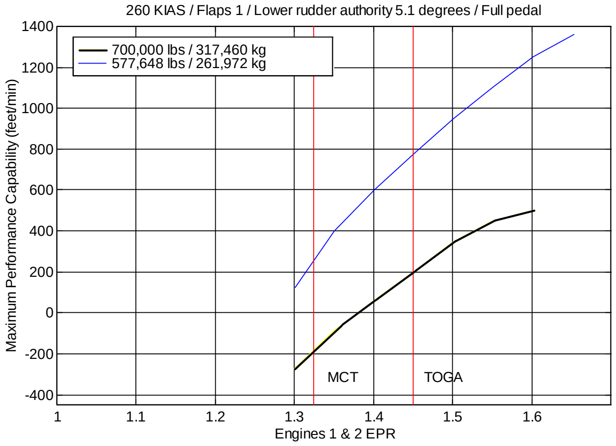


Fig. 5. Flight 1862: Effect of engine thrust and weight on maximum climb performance for straight flight at 260 KIAS.

4 GARTEUR RECOVER Benchmark

For the assessment of novel fault tolerant flight control techniques, the GARTEUR FM-AG(16) research group developed a simulation benchmark, based on the reconstructed Flight 1862 aircraft model (REconfigurable COntrol for Vehicle Emergency Return RECOVER). The benchmark simulation environment is based on the Delft University Aircraft Simulation and Analysis Tool DASMAT. The DASMAT tool 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 Delft University. The simulation environment was subsequently utilised and further enhanced as a realistic platform for evaluation of fault detection and fault tolerant control schemes within other research programmes [3].

The test scenarios that are an integral part of the GARTEUR RECOVER benchmark were selected to provide challenging assessment criteria, as specifications for reconfigurable control, to evaluate the effectiveness and potential of the fault tolerant flight control methods under investigation. Validated against data from the Digital Flight Data Recorder (DFDR), the benchmark provides accurate failure models, realistic scenarios and assessment criteria for a civil large transport aircraft with fault conditions ranging in severity from major to catastrophic.

The geometry of the GARTEUR RECOVER benchmark flight scenario (Figure 6) is roughly modeled after the Flight 1862 accident profile. 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. Hopefully, 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, localizer intercept, 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.

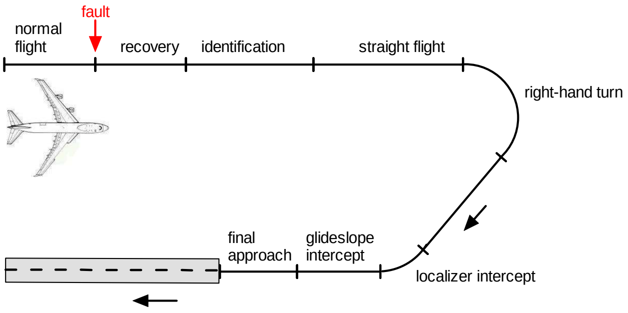


Fig. 6. GARTEUR FM-AG(16) RECOVER benchmark flight scenario for qualification of fault tolerant flight control techniques.

4.1 Benchmark Overview

The original Boeing 747-100/200 benchmark model [1] was based on the use of the classical (hydro-mechanical) flight control system for the B747-100/200 with the pilot cockpit controls as inputs. However, it was felt that the use of only the classic control capabilities would be too limiting for the purpose of the GARTEUR FM-AG(16) research. Therefore, it was decided to create a "fly-by-wire" version of the Boeing 747 aircraft, where all 30 aerodynamic control surfaces can be controlled individually. This allows the modern controllers, developed by the Action Group, to have the capability to completely reconfigure the flight controls.

Figure 7 illustrates a schematic overview of the GARTEUR FM-AG(16) RECOVER benchmark including relationships between the different model components of the benchmark.

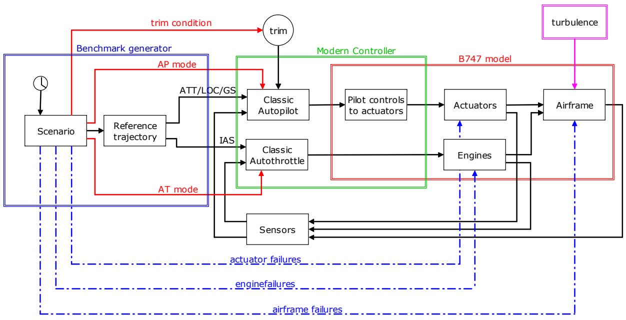


Fig. 7. Detailed schematic of the GARTEUR FM-AG(16) RECOVER benchmark model showing the relationships with test maneuver and failure scenario generation.

The basic aircraft model of the benchmark contains airframe, actuator, engines and turbulence models and is represented by the red outline in the diagram. It was also desired to have a basic classical controller available in the benchmark, based on the Boeing 747 classic Sperry autopilot including autothrottle, to serve as a reference for the new FTFC controller developments. Any new FTFC controller designs are meant to replace the classic autopilot and autothrottle and should drive the separate control surface deflections directly. This is indicated in the diagram by the green outline. In order to operate the benchmark, a scenario and failure generator was added. The scenario consists of commands fed into the autopilot and autothrottle, while the failures are directly introduced into the airframe and system models as indicated by the broken lines.

4.2 Aircraft Fault Models

The DFDR of the 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, as part of the study conducted by Delft University [1], was obtained from the Netherlands National

Aerospace Laboratory 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 this data were made, based on engineering judgment, using the original raw data dump.

The Flight 1862 right-wing configuration after the separation of the engines is presented in Figure 8. The damage indicated in this figure was estimated by examination of wing debris recovered along the flight path of the accident aircraft [2]. For an estimation of the aerodynamic contributions of the damaged right wing, the reconstruction method as described in reference [1] enables an iterative adjustment of initial aerodynamic estimates due to wing damage to obtain a match with the DFDR performance and control capabilities. 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. For the wing configuration, as shown in figure 8, the Flight 1862 model reconstruction shows a drag increase of about 20 to 30 percent at higher angle-of-attack [1]. All fault scenarios, selected for the GARTEUR FM-AG(16) benchmark, have proven to be critical in recent aircraft accident and incident cases. The benchmark failure scenarios are listed in table 2.

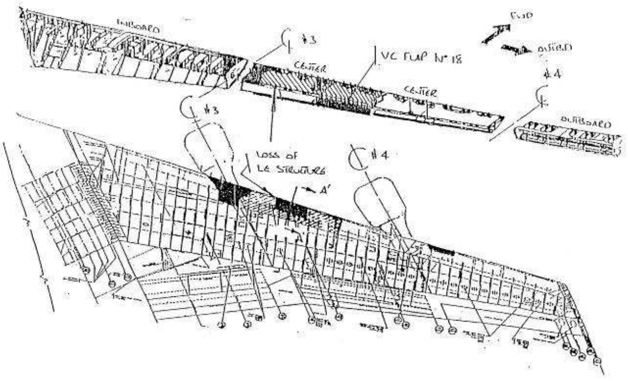


Fig. 8. Flight 1862 estimated right-wing structural damage configuration.

Failure mode	**Reconfiguration**	**Criticality**
No failure	N/A	None
Stuck or erroneous elevator	Stabiliser Ailerons (symmetric) Differential thrust	Major
Stuck or erroneous aileron	Ailerons (other) Spoilers	Major
Elevator/stabiliser runaway	Elevator Ailerons Flaps Thrust Use of static stability	Catastrophic
Stuck, erroneous or rudder runaway	Remaining surfaces Asymmetric thrust	Catastrophic
Loss of vertical tail surface	Differential thrust Differential Speedbrakes	Catastrophic
Engine separation & structural damage	Remaining surfaces Remaining engines Remaining sensors	Catastrophic

Table 2. GARTEUR FM-AG(16) RECOVER benchmark fault scenarios.

Although the first four failure cases are serious, it might be expected that continued flight to the original destination would 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 degrees). It is similar to aircraft accident cases in which a loss of the vertical tail occurred (e.g. JAL 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 emphasising end conditions in the specifications.

5 Piloted Assessment

As part of the project, the developed reconfiguration schemes have been demonstrated in the SIMONA motion-base research flight simulator of the Delft University of Technology. The aim of the piloted evaluation was to demonstrate the potential of the developed FTFC methods under real-time constraints and operational conditions while confronting the crew with realistic aircraft failure conditions. The fault cases were based on the GARTEUR FM-AG(16) benchmark scenarios, ranging in severity from major to catastrophic. This included the replication of the reconstructed Flight 1862 aircraft dynamics. The simulator results are substantiated by data on handling qualities and pilot workload in the degraded flight conditions.

Two piloted evaluation sessions were performed in November 2007 and April 2008. A demonstration of the feasibility of the novel reconfiguration techniques for the reconstructed Flight 1862 scenario was performed during the group's final workshop in November 2007.

The evaluation of the new fault tolerant control algorithms was performed by experienced test pilots from Delft University and the National Aerospace Laboratory (NLR). The scenario and data measurements were designed to excite the aircraft in all axes and assess its flying qualities during piloted control of both the conventional and reconfigured (failed) aircraft. After the failure was introduced, a number of maneuvers were performed and the pilots were asked to rate the aircraft's performance in both degraded and reconfigured mode. The pilot's control activity was recorded to obtain a quantitative measure of workload to be correlated with the qualitative (subjective) pilot handling qualities ratings. In addition, the computational load of all control algorithms was measured to assess the applicability in actual aircraft hardware.

5.1 Test Objectives

The objectives of the FM-AG(16) piloted simulator evaluation can be summarised as follows:

- Identifying real-time performance and integration issues of the FTFC designs by simulating integration in the complete aircraft environment.
- Qualitative assessment of FTFC strategy benefits in terms of aircraft handling qualities.
- Quantitative assessment of FTFC strategy benefits in terms of pilot workload to substantiate the qualitative data.
- Demonstrate new FTFC strategies that show the capability and potential to ensure a survivable recovery of a severely damaged aircraft under realistic operational conditions.

5.2 FTFC Concepts

Table 3 presents the FM-AG(16) FTFC strategies and methods, as developed by the design teams. The concepts that have been evaluated during the piloted simulator evaluation are highlighted.

FTFC Strategy	**Organisation**
Model Reference Adaptive Sliding Modes Control with Control Allocation (MRAC)	University of Leicester
Integral Action Control (INTAC)	University of Leicester
FTC with Guaranteed Nominal Performance	University of Bordeaux
Fault Detection, Identification and Reconfiguration System Based Around Optimal Control Allocation	QinetiQ
Subspace Predictive Control	Delft University of Technology - Delft Center for Systems and Control (DCSC)
Real-Time Model Identification and Robust Model Predictive Control	Delft University of Technology - Aerospace Engineering (AE -DCSC)
Real-Time Model Identification and Nonlinear Dynamic Inversion Control	Delft University of Technology - Aerospace Engineering (AE)
FTC with Adaptive Control	CIRA

Table 3. GARTEUR FM-AG(16) developed FDI and flight control reconfiguration concepts (yellow: FTFC concepts evaluated in piloted simulation).

The aircraft model can be flown in the manual classical (hydro-mechanical) flight control system mode and in manual fly-by-wire mode where flight control is performed via the subsequent FTFC module (design dependent). In the first configuration, aircraft control is via the mechanical and hydraulic system architecture modeled after the B747-100/200 aircraft. In the second case, all control surfaces are commanded via the respective FTFC module. Some modules are driven by manual control, others by the Mode Control Panel (MCP) for full automatic failure recovery, stabilisation and approach and landing.

5.3 SIMONA Research Simulator

The SIMONA research simulator (SRS) is part of the International Research Institute for Simulation, Motion and Navigation (SIMONA) of the Faculty of Aerospace Engineering of the Delft University of Technology. SIMONA, built by the Delft University, is a full research flight simulator with a high performance motion system, wide field of view (collimated) outside visual system, programmable glass cockpit, hydraulically loaded flight controls and a flexible computer and software architecture. For the piloted FTFC performance assessment, the SIMONA cockpit was configured to represent the B747 aircraft type with glass cockpit lay-out (Figure 9). As the scope of the project did not include an assessment of cockpit human factors interfacing (HMI) issues, no additional information regarding the flight control system status and aircraft configuration was presented. For pilot workload measurements, the cockpit control wheel, column and pedal forces were recorded as a measure of pilot workload.

Fig. 9. SIMONA cockpit configuration for the GARTEUR FM-AG(16) piloted simulator campaign.

The benchmark model was used for the offline design and evaluation of the fault tolerant control algorithms and subsequently converted to C-code through the MATLAB/SIMULINK© Real Time Workshop. The SRS uses an object-oriented, modular software architecture (Delft University Environment for Communication and Activation DUECA), which was well suited to integrate the model and different fault-tolerant control algorithms. The generated code was then integrated in the SIMONA research simulator. 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 SIMONA simulator was fitted with a 6 Degrees-of-Freedom (DoF) motion system tuned to the aircraft in nominal and failed conditions to provide the pilot with information on the aircraft motions through inertial motion cues. The cockpit flight displays were augmented with control surface animations to monitor the FTFC controller's actions.

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

5.4 Test Method

The test method of the piloted FTFC evaluation was designed to assess the FTFC failure mode accommodation capabilities in terms of aircraft stabilisation, controllability and pilot workload to restore handling qualities up to levels that at least recover aircraft controllability for 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. FDI capabilities were tested on their robustness under real-time environmental conditions including continuous aircraft maneuvering. The FTFC modules were tested using the same flight scenario and failure modes.

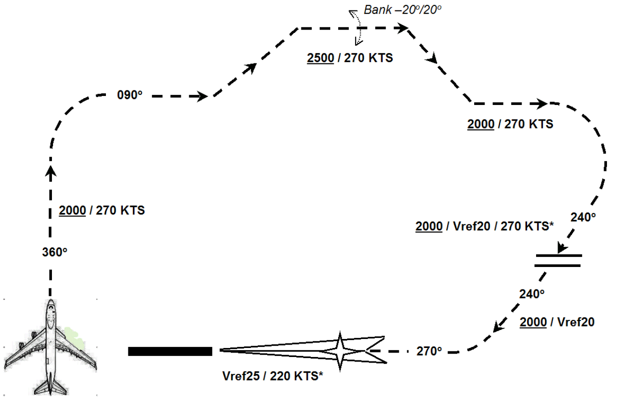
For each flight phase, appropriate exercises were defined with performance criteria (displayed after each run to the pilot and experiment leader) to rate the handling qualities of both the undamaged and damaged aircraft. Each pilot performed one run of each configuration. After each run, the pilots gave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

5.5 Test Procedure

The test procedure for the FM-AG(16) SIMONA piloted assessment is shown in figure 10.



* El Al Flight 1862 case

Fig. 10. GARTEUR FM-AG(16) piloted simulation test procedure.

Each pilot started to fly the classical control mode in unfailed condition to familiarise with the baseline aircraft handling qualities. This procedure was repeated several times until the pilot felt convenient 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 familiarise with the baseline fly-by-wire configuration.

The procedure starts at 2000 feet at a high speed of 260 KIAS and a northerly heading of 360 degrees. The pilot is asked to accelerate to 270 KIAS to allow a minimum control speed margin (Flight 1862 scenario). When stabilised on a heading of 90 degrees, a failure is injected. The pilot is then required to recover the aircraft and stabilise at 2000 feet and 270 KIAS while selecting flaps 1. The pilot is now allowed to familiarise himself and adapt to the degraded handling qualities and required control strategies to compensate for the failure mode.

After a climb task to 2500 feet, a lateral gross acquisition task is performed by capturing -20 and 20 degrees bank angles. Following descent to 2000 feet at 270 KIAS, the pilot is given a heading of 240 degrees for the approach to Amsterdam Schiphol runway 27. When stabilised on a heading of 240 degrees, speed is reduced to Vref20 (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 stopped to enable the pilot to rate the climb to 2500 feet and lateral gross acquisition task using the Cooper-Harper scale.

The second run starts at 2000 feet, a heading of 240 degrees and speed at Vref20 (174 KIAS) or 270 KIAS (Flight 1862 scenario) for the approach to Schiphol runway 27. The pilot's task is to capture the localiser in the failure mode configuration. When the aircraft intercepts the glideslope, speed is reduced to Vref25 (169 KIAS) or 220 KIAS (Flight 1862 scenario). The run is aborted at 500 feet before touchdown. A Cooper-Harper rating is given for the localiser and glideslope capture task.

5.6 Simulator Results

The GARTEUR FM-AG(16) piloted simulator campaign provided a unique opportunity to assess pilot performance under flight validated accident scenarios and operational conditions. Six professional airline pilots, with an average experience of about 15.000 flight hours, participated in the piloted simulations. Five pilots were type rated for the Boeing 747 aircraft while one pilot was rated for the Boeing 767 and Airbus A330 aircraft.

In general, the results show, for both automatic and manual controlled flight, that the developed FTFC strategies were able to cope with potentially catastrophic failures in case the aircraft configuration has changed dramatically. The FTFC algorithms that were based on full automatic flight control, demonstrated the capability to satisfactorily recover from a failure, reconfigure and stabilise the aircraft (figure 11). In most cases, apart from any slight failure transients, the pilots commented that aircraft behavior felt conventional after a failure. Further results can be found in references [4, 6].

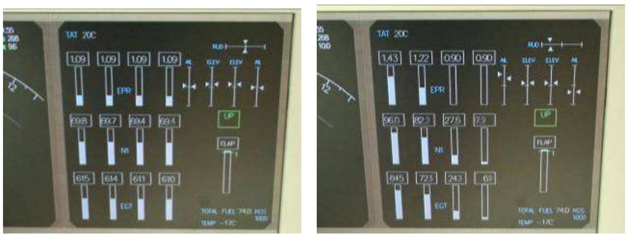


Fig. 11. Flight control and engine display showing controls and engine reconfiguration (autopilot mode) after a rudder runaway failure (Left: before failure. Right: after failure).

Manual controlled flight under fault reconfiguration was assessed for both a runaway of the rudder to the blow-down limit (figure 12) and a separation of both right-wing engines. The FTFC strategy that was evaluated here consisted of a combination of real-time aerodynamic model identification and adaptive nonlinear dynamic inversion for control allocation and reconfiguration [5]. The results show that, especially for the Flight 1862 scenario, conventional flight control was restored to acceptable levels while physical and mental workload was reduced significantly. This is illustrated in figure 13 where an example is given of lateral handling qualities pilot ratings for the localiser capture task. It can be seen that, for this task, both the baseline and fly-by-wire (FBW) aircraft were rated Level 1 (Rating 1-3). After separation of the right-wing engines, lateral handling qualities degraded to Level 2 for the conventional aircraft with classical control system. The reconfigured aircraft (FBW) shows about Level 1 handling qualities after incurring significant damage due to the loss of the right-wing engines. This was substantiated by measured pilot control activities, representative of workload, indicating no pilot compensation after reconfiguration. For the rudder runaway failure, however, Level 2 handling qualities remain after reconfiguration despite no required pilot compensation (figure 14). The difference is most probably caused by not utilizing differential thrust for reconfiguration to compensate for the yawing moment. As a consequence, a constant non-zero roll or sideslip angle is needed in order to re-establish equilibrium. This attitude is disturbing, especially since no corresponding pilot actions are needed as can be seen in figure 14. The incorporation of differential thrust in the control allocation part of the fault tolerant controller will be the subject of a later study.

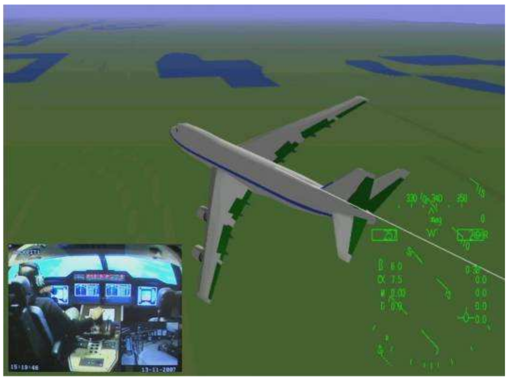


Fig. 12. FM-AG(16) piloted simulation showing a large roll transient after a runaway of the rudder without reconfiguration.

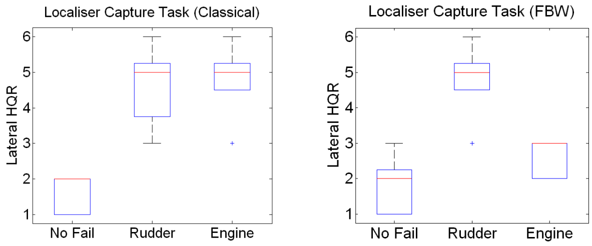


Fig. 13. Lateral handling qualities pilot ratings for localiser capture task (Left: baseline aircraft. Right: fly-by-wire aircraft).

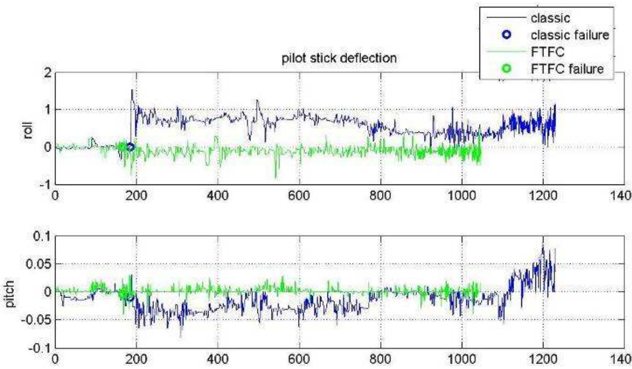


Fig. 14. Measured pilot control activities for rudder runaway failure mode.

Fig. 15. FM-AG(16) piloted simulation showing aircraft with separated right-wing engines (Flight 1862 scenario).

The results of the GARTEUR FM-AG(16) piloted simulator campaign were successfully demonstrated (figure 15) during the project's final workshop in November 2007 to the general public and Dutch press.

6 Conclusions

Reconfigurable flight control aims to improve the survivability of both commercial and military aircraft in failure cases where the aircraft is still flyable given the available control power. A benchmark for the integrated evaluation of new fault detection, isolation and reconfigurable control techniques has been developed within the framework of the European GARTEUR Flight Mechanics Action Group FM-AG(16) on Fault Tolerant Control. Validated against data from the Digital Flight Data Recorder (DFDR), the benchmark addresses the need for high-fidelity nonlinear simulation models to improve the prediction of reconfigurable system performance in degraded modes.

The piloted evaluation of new fault tolerant flight control algorithms, developed within FM-AG(16), showed that several of the approaches to fault tolerant control can be used in a realistic real-time (simulation) environment. Both auto-flight and manually controlled algorithms were shown to be able to cope with a number of potentially catastrophic failures. In most cases, the reconfiguration algorithms significantly enhanced handling qualities and lowered pilot workload. Computational load was mostly within the performance limits of current PC-type hardware, although it is probably still too high for application in today's aircraft hardware.

The GARTEUR partners hope that the results of this work will eventually contribute to safer air travel.

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