Upgrade of the Transport Helicopter CH-53G with an Automatic Flight Control System - A Long-Serving Workhorse Gets a New Brain

Konstantin Kampa, Bernhard Stahuber, Manuel Stölzle, Rainer Rebstock
Eurocopter Deutschland GmbH, 81663 München, Germany

Abstract

Flight control systems in modern helicopters are becoming more and more important. Especially at helicopters with military missions, pilots can only cope with multitasking if automatic flight control systems are reducing the work load. The present paper describes the upgrade of the German CH-53G/GS with a modern 4-axis
dual-duplex redundant automatic flight control system. The main challenge was to integrate a fully digital AFCS by keeping the existing mechanical steering system of the HC. The design solutions developed are highlighted in this paper as well as the development of the control laws, built-in test, monitoring functions and pilot interfaces. A qualified hardware-in-the-loop simulation rig, built by Eurocopter in the frame of the CH-53GA upgrade programme, was extensively used to validate the AFCS design.

1. ABBREVIATIONS

ADC	Air Data Computer
AFCAU	Autopilot Flight Control Auxiliary Unit
AFCS	Automatic Flight Control System
AHRS	Attitude Heading Reference Systems
ALT	Altitude
APM	Auto-Pilot Module
BIT	Built-in-test (power-up, continuous)
BWB	Bundesamt für Wehrtechnik und Beschaffung
DCU	Data Concentrator Unit
DPIFR	Dual Pilot Instrument Flight Rules
DVS	Doppler Velocity Sensor
EHA	Electro-Hydraulic Actuator
ESR	Entwicklungs- und Simulations-Rig (Development- and Simulation-Rig)
FCP	Flight Control Panel
FTR	Force Trim Release
GAMS	German Avionics Management System
GPS	Global Positioning System
GSCU	Ground Speed Control Unit
HIL	Hardware-In-the-Loop
IAS	Indicated Airspeed
ISIS	Integrated Standby Indicator System
MFD	Multi Function Display
MR	Main Rotor
PFD	Primary Flight Display
PFT	Automatic Pre-Flight-Test
RAD ALT	Radar Altimeter
RCU	Reconfiguration Unit
SAR	Search And Rescue
SIL	Software-In-the-Loop
SW	Software

2. INTRODUCTION

The Sikorsky Medium Transport Helicopter CH-53G is operated by the German Army. In 1972 the license production started at VFW-Fokker in Speyer, Germany, with 108 CH-53G manufactured until 1975.

In 1992 the first CH-53 was moved to Donauwörth for maintenance. Under the lead of MBB/Eurocopter design improvements were achieved concerning internal/external fuel tanks and self protection means.

By 2012/2013, the fleet will reduce to 82 helicopters accompanied by a life time extension and a comprehensive upgrade program. Since 2007 Eurocopter is under contract to retrofit a total of 40 helicopters to a CH-53GA version. This upgrade includes the repair and overhaul of the air-frame to extend helicopters' design life to 10,000 flight hours, replacement of the entire electrical system and implementation of a new mission and avionic system. The automatic flight control system of the CH-53GA as part of this modernisation campaign will be highlighted in this paper.

Due to these upgrades the weapon system CH-53GA shall be in service until 2030 and fulfil the national as well as current and future NATO requirements. Together with Germany's NH90 TTH and Tiger UHT attack helicopters the CH-53GA will boost the German Army's helicopter force.

3. SHORT DESCRIPTION OF BASIC CH-53G

Table [1] shows the basic technical data of the CH-53G.

Presented at the 36th European Rotorcraft Forum, September 7-9, 2010 in Paris, France

MTOW	19050 kg
Empty weight	10700 kg
Total Length	26,87 m
Engines	2 x GE-T64-100
Main rotor diameter	22,014 m
Number of MR blades	6
MR tip speed (100%)	213,2 m/s
Tail rotor diameter	4,88 m
Number of TR blades	4

Table 1: Basic helicopter data of CH-53G

The original cockpit has a pure analogue design with gyros feeding the attitude and direction indicators (Figure 1). For improved handling characteristics the helicopter is equipped with an automatic flight control system that maintains a desired flight attitude in pitch, roll and yaw. An altitude hold function using the barometric or the radar altimeter information can be engaged on request. Two redundant control amplifiers generate the stabilising command inputs to the hydraulic serial and parallel actuators. The pilot controls the attitude references with the cyclic stick and may select turn coordination or heading hold for the yaw axis. The dual redundant amplifiers and actuators in pitch and roll give him the possibility to reconfigure the system in case of a failure, but only a few automatic failure passivation features are available. Designed for permanent hands-on operation and without higher modes like airspeed hold or navigation coupling, the workload for the pilot is quite high, especially during operation close to the ground or obstacles.

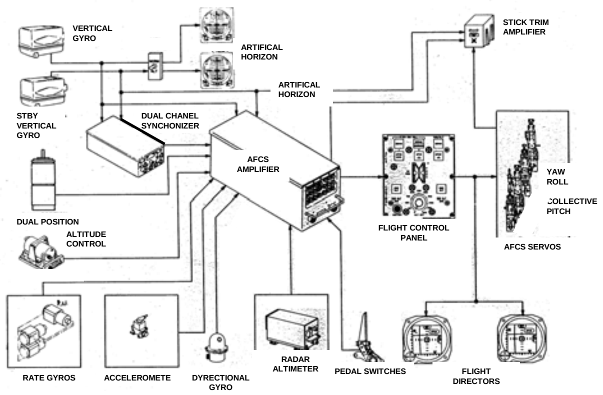

Figure 1: Major AFCS Components of CH-53G

The CH-53G/GS is a back bone of the German Army deployments in domestic and international operations. Main missions of the helicopter are versatile troop and equipment transport. This has been demonstrated during many environmental disasters and political missions under harsh conditions e.g.

- UN mission in IRAK
- Peace implementation Force (IFOR) and Stabilisation Force (SFOR) in Bosnia and Herzegovina under NATO command
- International Security Assistance Force (ISAF) under NATO command in Afghanistan
- Civil fire fighting in Germany (1975) and Peloponnese (2007)
- Rescue operations during floods in Germany (Oder in 1997, Elbe in 2002)
- Rescue operations after earthquakes in Udine (Italy, 1976), Pakistan (2006)

Though during these life-saving operations the existing CH-53G/GS proved its capability with respect to transport, rescue and aero medical evacuation under severe conditions, a need for further improvements turned out to cover future requirements for operative tactical air transport of the German Army.

4. DESIGN OBJECTIVES OF CH-53GA

4.1. Overview of CH-53 GA Avionics Architecture

To meet the new operational requirements, upgrades of the avionics system, tactical communication and mission equipment became necessary. Especially the following features have been embodied into the CH-53GA:

- A new communication and data transmission system that will allow joint missions with NH90 transport and Tiger attack helicopters, e.g. using satellite communication capabilities with crypto features.
- An improved navigation and high level civil-standard (IFR) flight management system.
- A mission system with forward-looking infrared camera to improve night mission capabilities, a new electronic warfare system for self-protection (EloKa) and a Digital Map Generator.
- The German Avionic Management System (GAMS), developed by Rockwell Collins. It is composed of 5 Multi-Function Displays, 2 Control Display Units with alphanumeric input/output control and 2 Integrated Processing Centers for equipment and system control. For data storing, retrieving and converting a Data Transfer Unit (DTU) and 2 Data Concentrator Units (DCU) are implemented.
- A new automatic flight control system with a 4-axis autopilot (AFCS) and automatic hovering capabilities.

The complex avionics system upgrade is described in more detail in [1].

The AFCS development is presented in this paper.

4.2. General Requirements for the AFCS

The AFCS for the governmental helicopter CH-53GA is based on the Eurocopter “Avionique Nouvelle” AFCS family [2]. This AFCS standard contains a flexible AFCS architecture, which can be adjusted according to safety and redundancy requirements. A basic versatile AFCS software including all functions and modes, configured and adapted in detail to several helicopter types (e.g. 4-Axes Autopilot with SAR Modes on EC725) simplifies the software life cycle process. Being completely developed and qualified by EUROCOPTER, compatibility within the different helicopter types and short modification periods are guaranteed. The family concept keeps similarities in system design, functional and operational aspects.

The AFCS is designed to provide full automatic stabilization in pitch, roll and yaw axes. The pilot perceives increased handling and flying qualities when compared with the standard helicopter CH-53G/GS flying qualities. It is designed to satisfy the FAR29 requirements for DPIFR operation.

With the AFCS "hands-off" functionality in all modes the pilots' workload is considerably decreased.

Beside the basic attitude hold mode, the AFCS offers several sets of upper modes:

- Barometric modes like airspeed hold or altitude acquisition and hold,
- 3D-hover or groundspeed hold with hover acquisition from any speed,
- Navigation modes coupled to the flight management system.

Because of the high safety requirements the architecture is designed to be dual redundant with duplex Autopilot-Modules. All functions of the implemented system are designed fail-safe. The flight state sensors and the pitch/roll actuators are dual redundant. Together with a third flight state back-up sensor, the system performs an automatic reconfiguration in case of a sensor failure. With this architecture, the monitoring is designed to perform fail-operative after the first failure and fail-passive after the second failure condition.

5. HARDWARE-IN-THE-LOOP DEVELOPMENT SIMULATOR

A hardware-in-the-loop development and simulation rig (ESR) was built by Eurocopter in the frame of the CH-53GA upgrade programme.

Figure 2: CH-53GA Avionics Simulator

The mechanical control system is represented up to the mixing unit (control rods are shortened to save space). Original EHAs from Sikorsky are used in all four axes, supplied by a duplex hydraulic system identical to the helicopter system.

The Control and Display System is genuine GAMS (Rockwell Collins) equipment as installed in the CH-53GA cockpit.

All original AFCS components are integrated conform to the HC in order to perform hardware-in-the-loop development and certification verification tests.

A patch panel is used to switch within minutes between different configurations depending on the supplied helicopter configuration or simulated components.

Figure 3: Cockpit of the CH-53GA Avionics Simulator

With the combined configuration management for helicopter and ESR, the ESR provides a qualified development, support and test facility. Its main benefits for the AFCS are:

- Evaluation of the control law design and modelling in a HC realistic environment
- Development and test of the actuator/hydraulic monitoring based on the real HW
- Comprehensive failure simulations including assessment of the reconfiguration logic, pilot indications and warnings as well as flight path deviations of the HC
- Functional tests and qualification of the AFCS SW to achieve flight clearance by German Airworthiness Department
- Support of flight test, e.g. preparation of test procedures, investigation of HW and SW problems (trouble-shooting)
- Support of HMI, Avionics and AFCS Certification
- Pilot assessment of handling and HMI

More details are given in [1].

The effort spent on this test facility paid off during the flight testing phases. The enormous reduction of flight time has been a big saving in this project, especially with a helicopter of that size. Without this rig most failure tests, a major part of the functional design verifications, flight test preparation or trouble shooting would have taken place on a prototype helicopter, either on ground or during expensive flight hours. Besides these savings a strong improvement concerning safety during development flight test was attained, that was contributing as an advantageous factor to the permit to fly procedure together with the military qualification authorities.

6. ARCHITECTURE OF THE AFCS

6.1. Architecture Overview for the AFCS of CH-53GA

Figure 4 shows the overall architecture of the final AFCS design. Especially the interaction with the helicopter systems and AFCS environmental components are included, depicting also different interface types as ARINC 429, analogue and discrete.

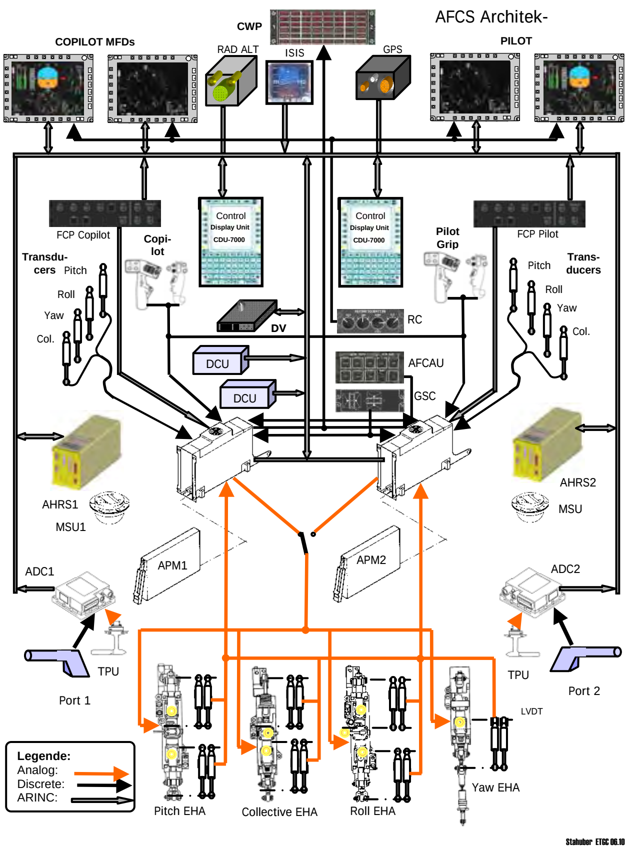

Figure 4: Architecture of the AFCS

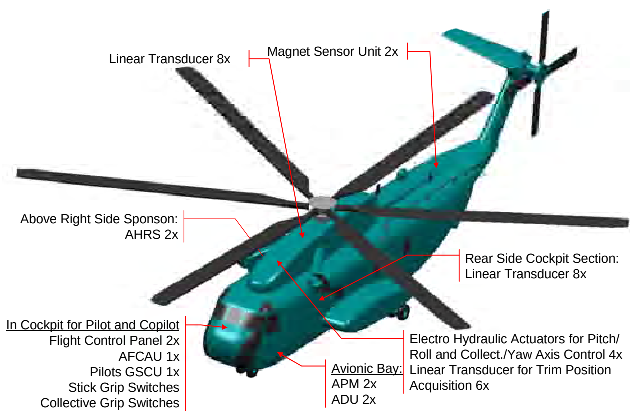

Figure 5: Location of the AFCS components

Only a few components have been kept from the former installations. The mechanical control linkages including sticks, pedals, actuators and boosters have not been touched. On top of this block diagram the components of the avionics system interacting with the AFCS computer for display, navigation or sensor information are shown. In the centre the AFCS components with the duplex APM, the control panels, the flight state sensors (AHRS) and the air data sensors (ADC) are displayed. At the bottom of this figure the electro hydraulic actuators, equipped with the motion transducers are indicated.

To give an idea about the components localisation Figure 5 shows the different installation areas. The widely distributed arrangement of the components is required for operational and safety reasons like channel separation, vibration, cooling or EMC aspects.

6.2. AFCS Components

6.2.1. Actuators

The electro-hydraulic serial actuators are closed loop control servo actuators with low-current signal inputs. For the longitudinal and lateral axes duplex control valves for the output piston are installed (see Figure 6).

The parallel trim pistons and control valves of the pitch, roll and collective axes are integrated in the actuator units.

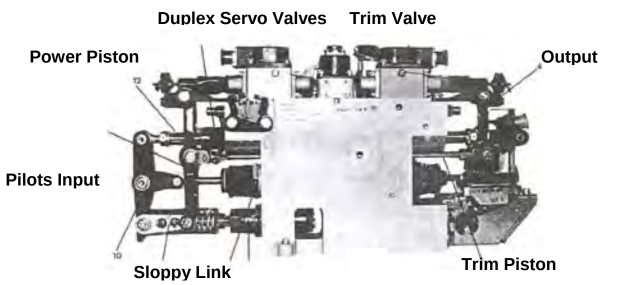

Figure 6: Electric-Hydraulic Actuator of the CH-53G

The digital commands of the AFCS computer are converted into dual analogue commands to drive both coils of each actuator valve.

The serial stroke of the actuators is limited to ± 10% of the total output travel, but is executed with maximum speed. No force is fed back to the pilots input.

The parallel trim position is limited in speed with full authority and can be released on pilot request (force-free stick). For the yaw axis, the automatic trim actuator is replaced by a damped piston. The connection to a damped sloppy link moves the trim position with a constant serial command for automatic trim re-centering. This specific actuator in yaw is used to inhibit large and high dynamic inputs which could stress the tail structure.

6.2.2. Motion Transducers

The system is equipped with the following motion transducers:

- Duplex sensors at all four control axes to measure pilot inputs.
- Duplex sensors at all four actuator outputs.
- Duplex sensors at longitudinal, lateral and collective trim piston outputs for the closed loop control of the trim position.

The transducers are linear variable differential transducers, supplied by high frequency AC signal.

This sensor information is used for system monitoring, pilots' intervention detection and command decoupling control.

6.2.3. Autopilot Modules APM2020

Each one of the two Autopilot Modules is separately installed in a single slot rack with dual ventilation. Being the core component of the AFCS, they provide the main functionality.

Figure 7: Autopilot Module APM2020 (Sagem)

The APM2020 is a fail-passive digital computer. To fulfil safety requirements, the internal architecture is of "dual" type. The critical functions are performed by two separate processing units. In active redundancy, both processing units are participating in the function generation, communicating with each other and operating synchronously.

Each processing unit is fitted with its own service circuits like power supply, processor, memory, input and output interface. The output interfaces have been adapted to match the existing electro-hydraulic actuator specifications.

The two processing units transmit signals to a failure deactivation device made up of a voter and limiters. These analogue voter/limiters, are designed to counter instantaneously any active failures of hard-over type on one output command independently of the other output.

For safety purposes, wired logic is combined with various software monitoring features that allow the proper operation of the computer. This wired logic comprises:

- logic for connection and disconnection of the APM,
- logic for hands-on control (alarm of request for reversion to manual piloting),
- logic for information validity check to the display system.

6.2.4. Control Panels and Control Switches

With four control panels the pilot can select and adjust all AFCS functions.

Control panels are:

Figure 8: AFCAU

Figure 9: FCP

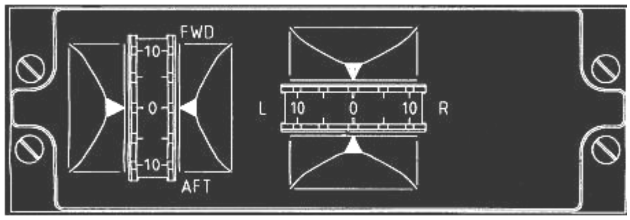

Figure 10: GSCU

Figure 11: RCU

- Autopilot Flight Control Auxiliary Unit (AFCAU).

  The basic control panel includes the ON/OFF push buttons for both APMs, the Auto-Trim engagement for all 3 trim axes, a push button to deactivate the basic stability augmentation, the hydraulic servos switch ON/OFF function for the redundant hydraulic supplies and the Pre-Flight-Test engagement.
- Flight Control Panels (FCP)

  The two FCPs include the push buttons for the upper mode engagement and rotary buttons for pre-selection of all references. They also provide inputs for course, upper limit, lower limit and baro selections.
- Hover Ground Speed Control Unit (GSCU)

  The GSCU is active only in combination with the hover mode and provides limited drift selections in lateral and longitudinal axes.

- Reconfiguration Unit (RCU)

  The RCU is a reconfiguration selector. By default the rotary switches are in upright position. In case of sensor discrepancies, the pilots have to select the correct inertial (AHRS and ISIS), barometric (ADC) or engine data (DCU) sensor after identification. A fourth selector is used to deselect one of the two FCPs in case of malfunction.

The AFCAU, RCU and the GSCU are located at the centre panel and can be used by both pilots. The co-pilot and pilots FCP are located underneath the displays. The FCP selections are displayed on the AFCS strip at the multi-function displays (see Figure 13, Figure 17).

For hands-on control of AFCS and avionic functions the cyclic and collective grips have been modified. The buttons of the collective grip have been reassigned, the cyclic grip has been taken from the EC135 design with customised button layout including the emergency cut-off, groundspeed mode engagement and four-way reference beep switches.

6.2.5. Sensors

For the basic flight state references two Attitude Heading Reference Systems (AHRS LCR-100 by Northrop Grumman/LITEF) are installed providing

- Translational accelerations,
- Body angular rates,
- Pitch and roll attitude as well as platform azimuth magnetic and true heading,
- Position, Ground speed and vertical speed (inertial reference with GPS speed and position hybridization).

Figure 12: Smith 341 MFD ISIS

Connected to the original dynamic and static pressure system the two Air Data Computers (ADC) acquire and compute

- total barometric pressure, differential pressure, air temperature
- barometric altitude, indicated airspeed and vertical speed.

Together with a third flight state and barometric sensor, which is provided by the Integrated Standby Indicator System ISIS, (see Figure 12), a monitoring for separation of a failed unit and automatic reconfiguration is possible. ISIS also serves as a backup display for the attitude and barometric indications.

Engine and vehicle relevant data inputs are received and distributed by the Data Concentrator Unit (DCU).

The radar altimeter system output is used for the cruise height mode (CRHT) and ground proximity protection.

The global positioning system is providing earth related coordinates for determination of geographic position and course calculation for automatic flight path following.

Navigational sensor information and direct steering commands from the Flight Management System are used by the AFCS for automatic approach, flight pass following or long-term navigation.

The Doppler velocity sensor (DVS) provides ground speed data as a second source beside the AHRS/GPS hybrid platform for redundancy reasons in case of loss of GPS signal. With the vertical speed signal measured by the Doppler sensor a distance to ground can be derived and used to monitor the radar altimeter sensor.

6.2.6. Displays

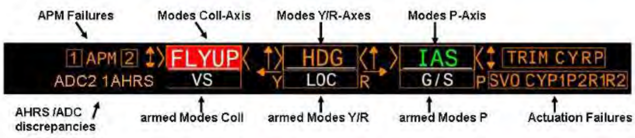

Figure 13: MFD AFCS Strip

The AFCS information is displayed on the primary flight display page of the four outboard multi-function displays (see Figure 17). A major part of the advisory and caution annunciations are displayed on the AFCS strip (see Figure 13), like

Advisories

- Upper mode engagement, armament and capture state,
- Override of the controls by the pilot,
- Reference change,
- PFT Information.

Cautions

- Degradation of upper modes,
- Axis degradation,
- Loss of actuation,
- Loss of control with immediate recovery alarm (hands-on alarm),
- Disengagement of the AFCS,
- Manual re-centering,

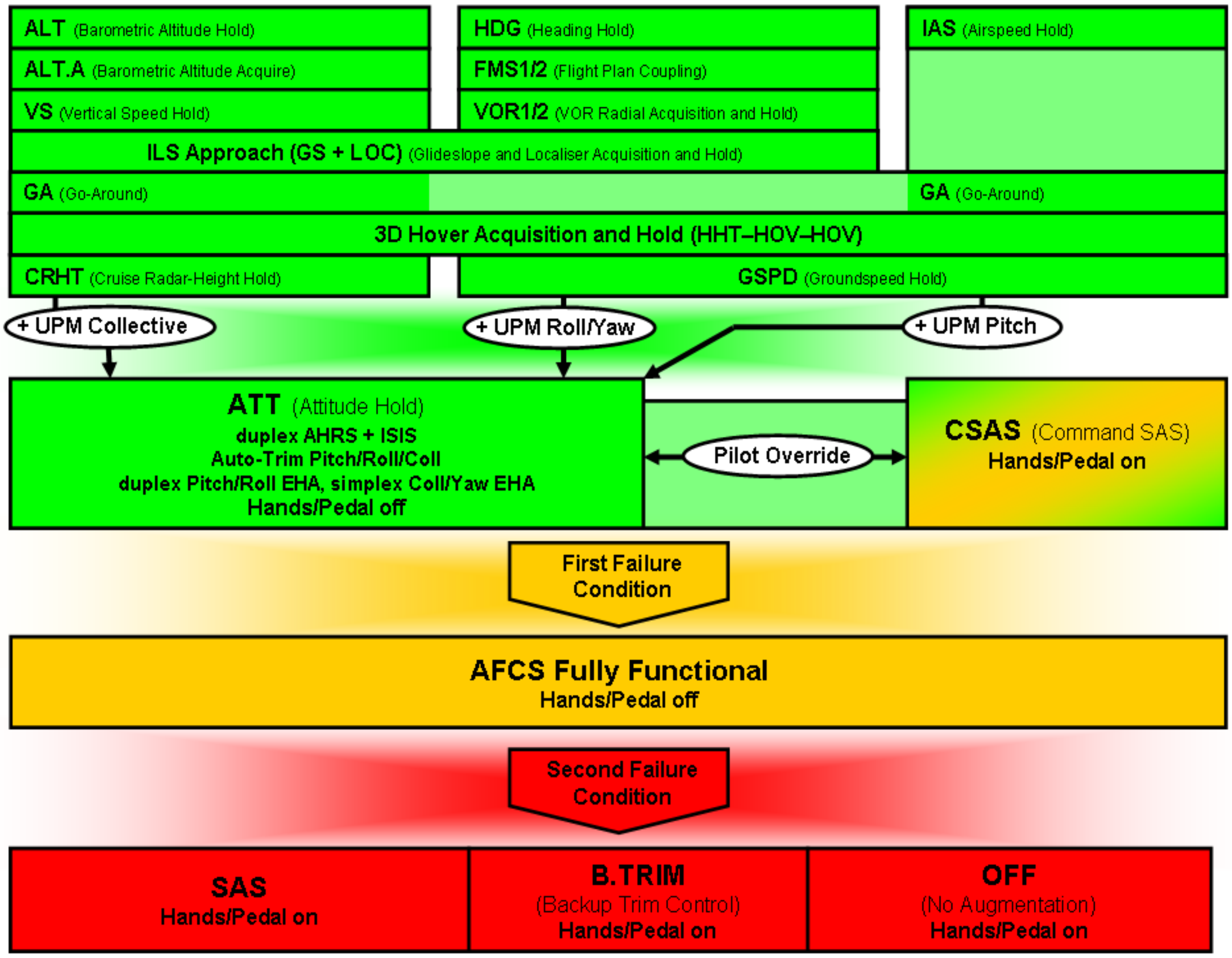

Figure 14: AFCS Normal and Failure Modes

- AFCS Display Anomalies

Beyond this AFCS dedicated annunciation area additional autopilot information is integrated into other areas of the flight display, like

- Sensor discrepancy annunciations,
- Upper modes references for barometric mode, airspeed modes, groundspeed modes, heading mode and radar altitude modes,
- Hover velocity and track

For maintenance and troubleshooting purposes dedicated AFCS information is displayed on a MFD sub-page providing

- Dedicated messages to identify failed components and functions,
- Signals and data used for system ground tests.

6.2.7. Central Warning Panel

The class A alarm “AFCS Hands-on” is displayed together with the “MASTER” light and an acoustic warning.

7. SOFTWARE FUNCTIONALITY

7.1. Modes and Functions

How to match state-of-the-art digital functionality with an old, but highly sophisticated mechanical design?

The major challenge was the correct interfacing with the actuation system. Detailed re-engineering of the integrated trim and serial actuators with duplex hydraulic supply, of the wiring with interlocks and automatic reconfiguration, and of the interaction with the pilot controls has been performed with intensive and beneficial use of the HIL simulator.

Some undocumented characteristics of the prior system which were identified to be safety critical have been found with the HIL simulator and could be addressed in an early phase of the development process. For example, the necessity of the permanent function to steadily hold the trim actuator in position and counteract an inherent trim drift caused by tolerances and ageing of the components, has been defined long before the first flight of the prototype; but it is not apparent from the documentation.

The multiple redundant system design used together with specifically introduced software functionality achieves the required safety to prevent unintended and unnoticed motions of the trim system.

Beside of the shown examples, many of the existent functions have been adapted to fit the CH-53G design, but also to keep the AFCS family concept of the EC fleet in mind for high HMI compatibility between different helicopter types.

Structurally, the system is divided into basic functionality and higher modes of operation. The interfacing, sensor conditioning, monitoring and control law calculation form the important basic functionality. Mode management, visualisation, higher control modes and maintenance functions complete the system usability.

Mechanically, the CH-53G offers all necessary possibilities to integrate a modern control system. As common practice for helicopter control systems, all four axes, meaning longitudinal, lateral, yaw and vertical, are equipped with fast and precise hydraulic actuators which can be controlled with limited authority at a bandwidth of 4 Hz. This enables to integrate a fast inner loop control for stabilisation, closed by the AHRS rate sensors.

The basic mode of the implemented AFCS is a long term attitude retention mode (ATT) for pitch and roll axes with turn coordination or heading hold function in hover for the yaw axis. Via trim release or beep action the attitude references can be set or altered. Because of the mechanical controls coupling, the pilot can override the automatic control any time and "fly-through", always supported by command-SAS control from the AFCS (see Figure 14 central row). Important for that, to give the pilot the right feeling of being in control, is the sensitive but robust detection of the state if the pilot overrides the automatism or if he is hands-off. Sensitiveness is necessary for a good interaction between pilot and flight control system, robustness because of adjustment tolerances or mechanical variations of the position transducers which have been introduced for this function.

Figure 15: CH-53G brown-out landing

The activation of the collective control, also referred as 4-axis control, includes automatic power management which gives the AFCS possibilities to limit the required power and prioritise concurrent control targets, respecting safety constraints like 'height before speed'.

On top of this basic stabilising mode the pilot can choose between several control intents like barometric modes (e.g. airspeed hold or altitude acquisition), navigational modes (e.g. coupling to the FMS), or hover modes which comprise groundspeed and radar height settings, especially designed for operational application. Figure 14 also gives an overview of available modes per axis, from left to right for collective, roll/yaw and pitch.

Figure 16: CH-53GS fast roping operation

Typical mission elements of the CH-53 helicopter are positioning of heavy structures at predefined areas, tracking of moving ships during fast roping operation or approaching unknown landing sites where the pilots may encounter heavy and high-risk brown-out conditions (see Figure 15, Figure 16). The groundspeed modes using high-accurate hybrid data from the inertial platform augmented by GPS data and monitored by Doppler velocity sensor data were adapted to the specific operational conditions of the CH-53. The track-hold control of the groundspeed hold mode enables the pilot to track the movement of a ship while he can rotate the helicopter around the z-axis to get clearance from obstacles or improve his field of view.

Figure 17: GAMS Primary Flight Display with Hover Page below the Attitude Direction Indicator

The 3-dimensional hover mode will highly improve the safety in areas with dusty grounds. Once in brownout condition without proper augmentation the pilot will loose orientation within seconds and tends to drift. The high accurate position hold function together with the radar height control gives the pilot the necessary time to land or depart safely without hitting any structures nearby. The hover display which is integrated into the PFD (see Figure 17) shows the current groundspeed and acceleration, the selected reference ground speed and a marked position for precise position hold improvement in poor visual conditions.

The one-button go-around activation in any flight condition has been intentionally developed for approach abortion. The mode immediately pulls power and climbs away with high vertical speed, always respecting power limitation. In hover condition the mode acts as an emergency start by additionally accelerating to the speed for best climb performance. Therefore, the go-around mode will be beneficial in sudden brown-out condition in case the crew decides to abort landing.

Many design decisions were focused on a simple and intuitive handling. The major part of the CH-53 flying crew have no or only little experience with glass cockpits and digital equipment. Therefore, they need an adequate design which increases operational safety and reduces training effort. The fail-safe philosophy with auto-reconfiguration functions helps in case of a malfunction. Mechanisms for care-free handling are included to isolate the consequences in given limits or at least inform the pilot by several warning mechanisms.

7.2. Control Law development

The actual control loops were designed according to the family control concept of Eurocopter. The good control performance has often been confirmed by customer pilots, and has been achieved within a wide range of the EC fleet, from the small EC135 to the large EC225. With the CH-53GA, a further step in HC size has been performed.

While most of the interfacing, monitoring and management functions can be designed and tested in simulation, either SIL or HIL, the detailed tuning of the control loops, especially the basic stabilisation loops, require extremely high accurate models.

In a first step a system identification campaign of a CH-53G was performed to get the baseline of performance, data for tuning the nonlinear flight mechanical model and information about critical envelope areas, structural modes and the barometric sensors.

In cooperation with the German Aerospace Center (DLR), a linear dynamical 6-DOF model in forward flight has been identified with data from this campaign. The basic helicopter with no stability augmentation has been excited by sinusoidal pilot inputs in all axes with increasing frequency. The model showed good results in the higher frequency range, but could not meet the accuracy levels required at lower frequencies due to the difficult manual excitation of the not augmented helicopter. During further investigations the DLR identified a state-space model of the lateral-directional motion at high speed where the dutch-roll mode and roll-yaw coupling is easily excited and arise in high amplitudes. When a classical model structure with vertical velocity, roll and yaw rate as states and roll and pedal command as input was used, deficiencies in the responses due to pedal input remained for higher frequencies (above 0.6Hz). These deficiencies could be corrected by adding the pedal input rate as an additional model input.

With the data from the identification campaign the flight mechanical model used for HIL simulation could be improved, but the model can still not yet meet the accuracy necessary for precise control loop tuning.

Before the first flight, the preliminary design of the control loops has been performed using the described identification results for a quite conservative approach. With this basic stabilising control of the first prototype helicopter, computer generated frequency sweeps could be performed to identify on- and off-axis responses in several flight states. Figure 18 and Figure 19 show the flight data and identification results of the roll and the pitch axis attitude response of the CH-53GA at 130kts level flight.

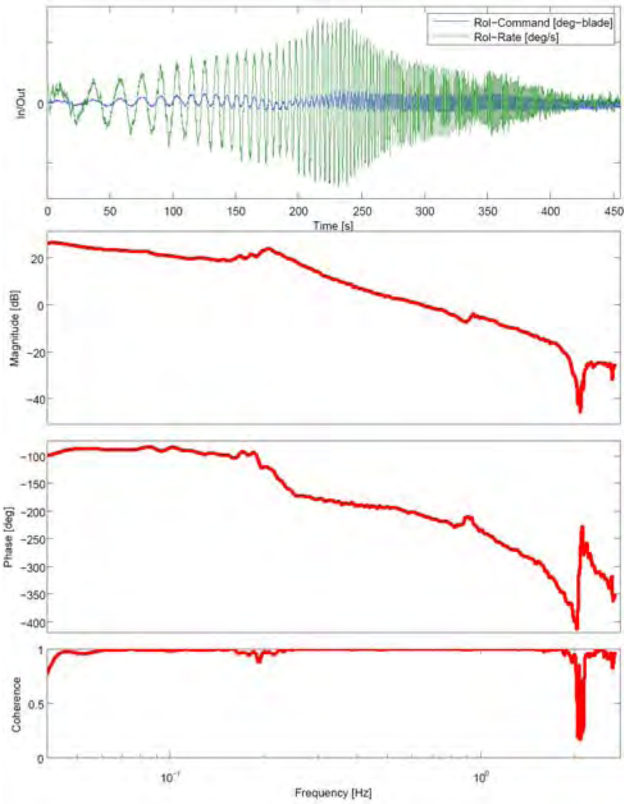

Figure 18: Roll reference frequency sweep flight data and identification of the on-axis roll response roll command => roll angle

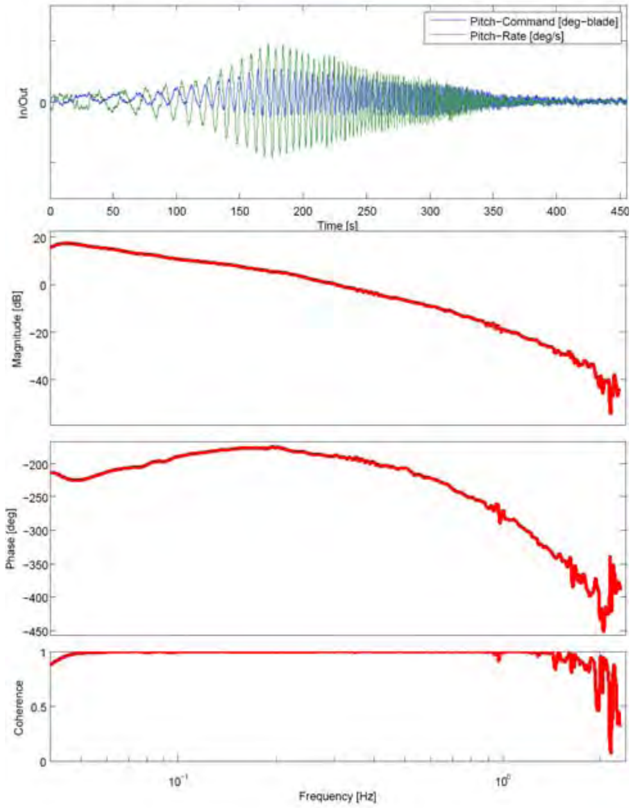

Figure 19: Pitch reference frequency sweep flight data and identification of the on-axis pitch response pitch command => pitch angle

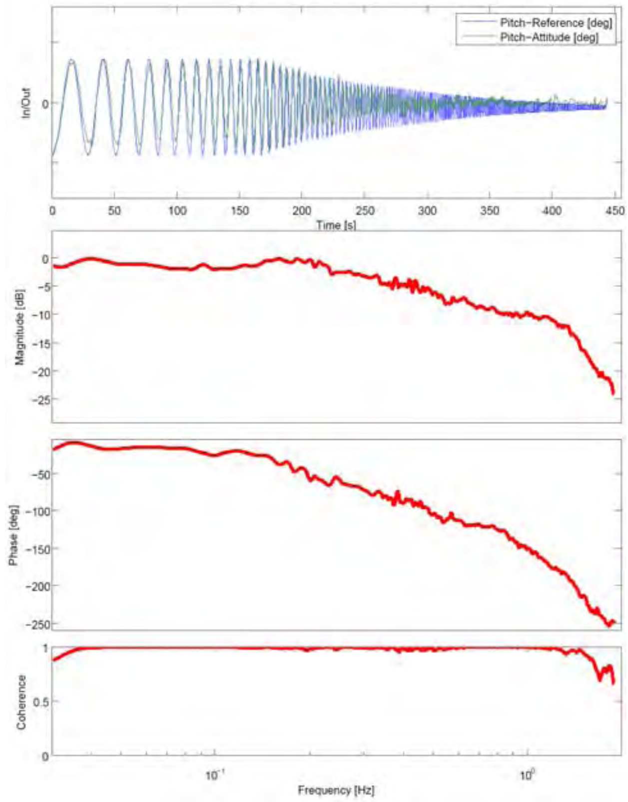

Figure 20: Pitch reference frequency sweep flight data and identification of the closed-loop pitch response pitch angle reference => pitch angle

The command to the actuator and the measurement of the rate sensor is shown at the top of the figures. Below, magnitude, phase and coherence of the non-parametric identification of the helicopter attitude response are given. The high coherence throughout the wide range of frequency shows the advantage of the computer generated frequency sweep with the full augmented helicopter. The roll response clearly shows the dutch-roll mode at 0.2Hz, the lead-lag mode of the main rotor at 2.1Hz and a small inhomogeneity at 0.9Hz, where some kind of structural mode appears.

Using a process of loop-shaping control design the high-gain controllers including the basic stabilisation, attitude hold, axes decoupling and outer control loops could be tuned in rather short time. Figure 20 shows the closed-loop response pitch-reference to pitch-angle of the final pitch control loop, which has been shaped to gives a smooth feeling to the pilot but also the necessary agility for manoeuvres.

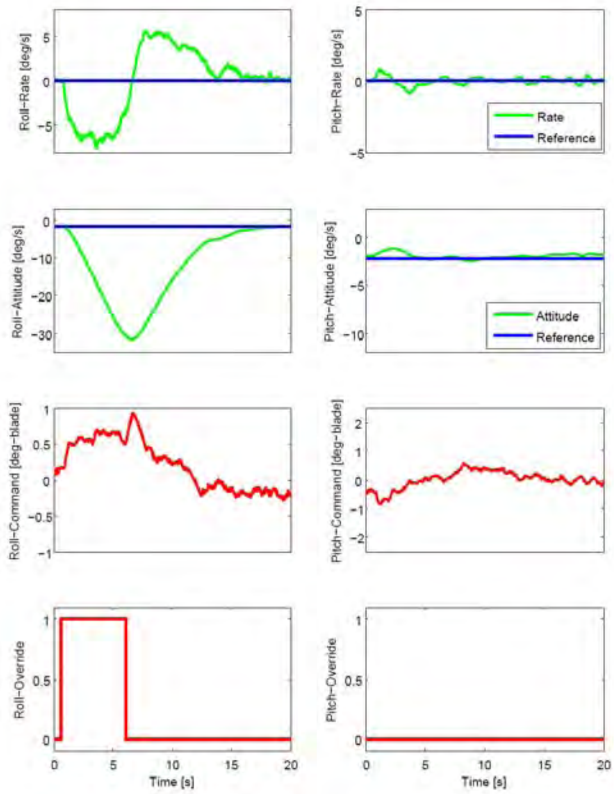

Figure 21: CH-53G S/N65053 flight test data – AFCS attitude mode, pilot roll override and release

Another verification result of the control performance is shown in Figure 21 and Figure 22. A defined input to the pitch or the roll axis by overriding the spring of the trim actuator (see fourth row) excites a defined attitude deviation from the reference (see second row). Upon release the linear control loop returns the helicopter to the reference values in a smoothly damped manner. The off-axis reaction is small during the whole manoeuvre, especially during the recovery, and shows the performance of the decoupling. The strong axis couplings like command coupling as well as state coupling, especially in the lateral and directional axes, has been a major challenge for the detailed control design. For example in forward flight the off axis response of a yaw input to the roll axis is similar in magnitude at certain frequencies to the on-axis response to the yaw axis itself.

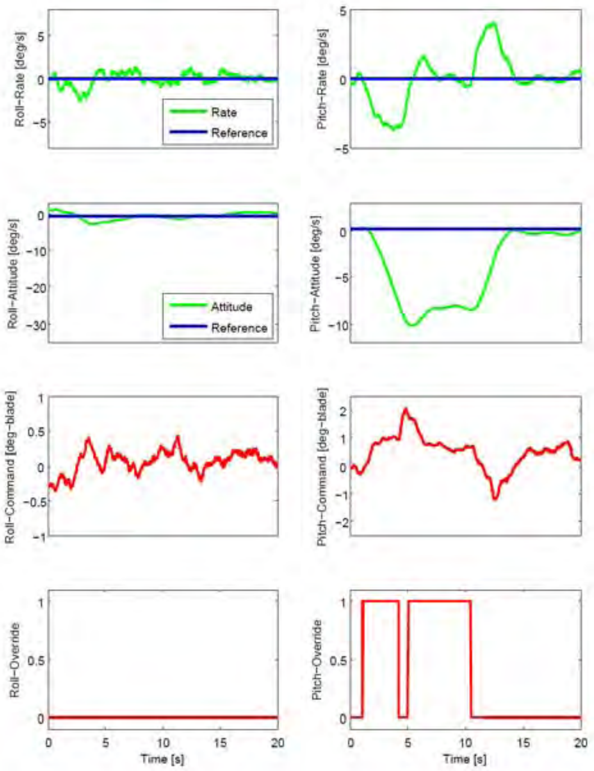

Figure 22: CH-53G S/N65053 flight test data – AFCS attitude mode, pilot pitch override and release

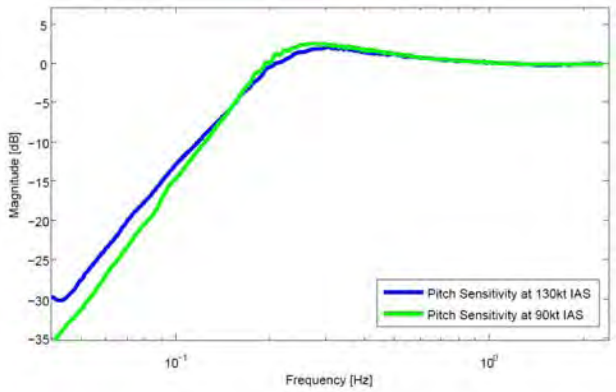

Figure 23: Pitch axis attitude sensitivity function as indicator for the disturbance rejection performance.

The sensitivity to external disturbance like turbulence can be analysed by the direct identification of the closed loop sensitivity function. Figure 23 shows the identified magnitude of the pitch attitude sensitivity at 130kts and 90kts level flight. For both airspeeds, oscillations with a period longer than 6 seconds are damped out very well, as the sensitivity function is below -3dB (bandwidth 0.17Hz). The trade-off between good disturbance rejection and limited noise amplification has been found with a maximum magnitude of 2.5dB.

The obtained identifications were not only used for control law tuning but also for detailed adjustment of other functions like power management and to have a baseline for a later comparison of the performance improvement.

7.3. Safety Features

To meet the required functional safety criteria, several mechanisms are used to locate and possibly passivate system failures. These functions have been adapted considerably for the CH-53GA design to fit the specific interfacing and functionality.

Self-Testing

The localisation of failures is performed by an automatic Pre-Flight-Test and a continuous Built-in-Test. Automatic reconfiguration functions use the available redundancies to passivate detected failures or switch to degraded modes or back-up modes to ensure maximum availability of functionality and safety.

The Pre-Flight-Test is performed prior to each flight not only to look for hidden failures of redundant or backup functions. All basic hardware resources like actuation, hydraulics, interfaces to sensors or communication with the display system is checked to ensure a fully functional system. In case of a detected malfunction, the failed part of the system is inhibited and the pilot is informed and can proceed according to the minimum equipment list.

The continuous Built-in-Test permanently checks for malfunctions of the computational hardware, the actuation interfacing, the actuation response of the EHAs and TRIMs, the hydraulic pressure, the basic sensors (AHRS), the barometric and hover sensors and the display system. In case of a detected and localised malfunction, the system automatically disables the failed component and reconfigures to the best available state.

Redundant Components

As mentioned before, important functions are linked to the position transducer signals from the actuators. The six motion transducers attached to each control axis (four for the yaw axis) are used for detecting pilot interventions, determining feed-forward, decoupling commands and monitor the actuator behaviour. The reliable detection of pilot interventions is achieved by the exchange of information between the duplex APMs. Together with implemented actuator models a first failure of any component can be exactly localised and mostly instant passivated by automatic reconfiguration of the system. Figure 24 shows the attitude disturbance of the pitch axis in case of a pitch down EHA runaway during 4-axis upper mode operation with airspeed and altitude hold engaged at 130kt. Without automatic passivation this failure would lead to a large attitude change and altitude loss. The passivation feature not only for this failure condition can be demonstrated and verified with the HIL simulator, which is qualified representative for most failure analysis and tests.

Only 0.4 seconds after the servo output position has run down (at time 12.7s), what relates to the maximum negative command position of the EHA, the failure is detected and localised by the monitor. Another 0.2 seconds later the hydraulic circuit has been switched to the second circuit, activating the backup pitch and roll EHAs, and the AFCS counteracts with maximum command upwards. 3 seconds later the disturbance from the runaway has dissolved. 5 Seconds after the runaway the airspeed and altitude references have been regained (not shown in the plot). There is only a small attitude disturbance (± 3°) for a short time. The pilot is informed about the reduced redundancy by annunciations at the PFD, but there is no direct impact on safety or operational aspects.

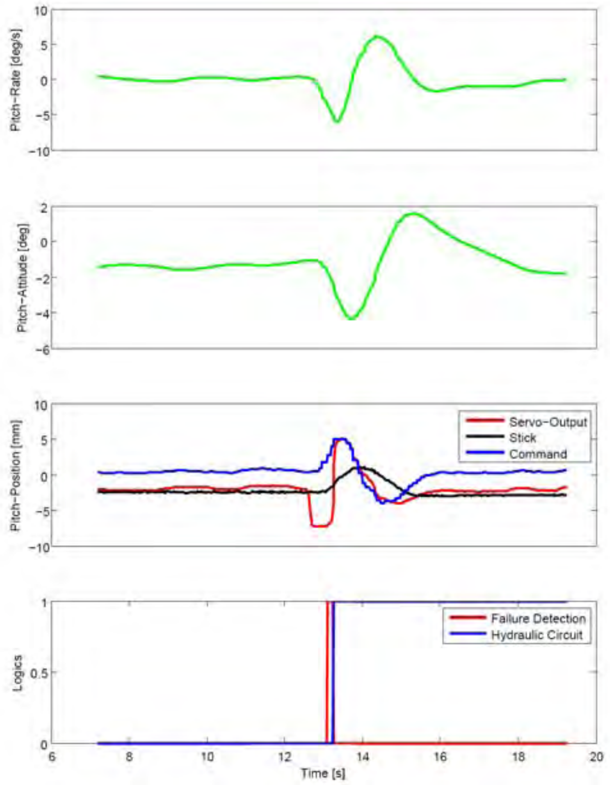

Figure 24: Pitch EHA runaway failure demonstration at the ESR (HIL test rig)

Simplex Components

The lower part of Figure 14 shows the main first and second failure conditions, and the resulting system degradation. Most first failure conditions are covered by the redundant architecture and result in a degraded state with full functionality. An example for a functional degradation with a first failure condition is a trim defect. Upon that failure the automatic trim function is disengaged and the affected axis is degraded to a pure SAS-mode control law. The mechanical controls and trim system was not changed, so no improvement for that failure condition could be implemented. Nevertheless the pilot is informed by a caution and annunciations at the PFD to get hands-on, because the long-term retention function has been de-activated. An example where the new system offers large improvement in functional availability is the redundant usage of the two collective actuators, the trim and the EHA. In nominal condition both actuators are used for best control performance. In case of EHA failure, the complete functionality is mastered only by the trim actuator with slightly decreased performance.

Depending on the failed component, the mission or the flight can be continued or has to be aborted within a certain time.

Safety Functions for Normal Operation

Beside the detection and localisation of malfunctions, some safety features have been implemented for normal operation. One is the robust ground detection, which uses different sensors depending on the operational state. The ground detection is a critical function for the AFCS to avoid large inputs on ground and loss of stability in flight. The ground switches can fail and the radar altimeter can be deactivated by the pilot or output misleading information when operated above certain surfaces. A combination of many parameters is used to get a robust mechanism.

Care-free handling features like speed protection or ground proximity protection are provided for increased flight safety. The airspeed is limited to V_{NE} as long as an upper mode is engaged. During operation of a barometric vertical mode the Level-Off function protects against dangerous reference selection. If radar altimeter information is available the helicopter automatically levels-off when approaching the terrain and keeps a safety distance in case of raising terrain. For close-to-ground operation, the height hold modes with radar altimeter feedback have been equipped with a ground proximity protection feature that leads to a fly-up alarm and immediate collective increase command in case the helicopter to ground approach speed and distance is assessed to be critical.

The already mentioned power management functions help the pilot to respect the limits of the engines or the transmission system. In hands-off operation the autopilot will not exceed any power limits except for the emergency fly-up mode. An engine loss is immediately detected and respected by adapted limits of power and acceleration.

Maintenance

For keeping the helicopter in operation the maintenance mode helps the service team to troubleshoot occurred malfunctions. Any detected failure is memorized in a non-volatile memory and can be read-out anytime after flight by using the maintenance page of the PFD with no use of any ground test tool.

8. SUMMARY AND CONCLUSION

This paper describes the design and implementation of an advanced 4 axes automatic flight control system for the CH-53G.

In order to overcome the particular challenge in using the existing hydro-mechanic control system of the CH-53G dedicated integration tests and also identification flights were performed.

Obtained models were used in the complex development simulation tool (HIL). Thus, prior flight testing control loops, interfacing and SW logic features could be verified saving many flight hours and increasing flight safety.

In order to improve HQ for dedicated missions like landing under brown-out conditions or fast roping operation, dedicated AFCS functions as ground-speed mode or a 3-D hover mode are implemented.

Some examples are presented with respect to control performance of attitude hold, pilot override and failure passivation.

Finally safety functions were addressed like self testing features, redundant architecture, automatic reconfiguration aspects and Care Free Handling.

The CH-53GA is being equipped with the most advanced AFCS and Avionics system of the Eurocopter Avionique Nouvelle family. Looking to future transport helicopter, design innovations for guidance and control will be in favour for enhanced All Weather Mission systems, fly by wire/light control systems, new active inceptor concepts and guidance/control law software for autonomous flight. Eurocopter has already launched wide spread research and development programs on these areas.

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