

FLIGHT MECHANICS SIMULATOR FOR ROTORCRAFT DEVELOPMENT

M.L.PREATONI*, A.RAGAZZI*, A.CERUTI**, G.M.SAGGIANI**

*AgustaWestland, Varese, Italy, ** University of Bologna, Italy

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Abstract

This paper describes the design and manufacturing of the AgustaWestland flight mechanics simulator for rotorcraft design.

The aims of the simulator are the design of the handling qualities of any new rotorcraft, the simulation of flight manoeuvres, including those following engine failures and tail rotor loss, the instruments panel lay-out optimisation, etc..

The simulator has no motion capability and it is equipped with a pilot seat plus one assistant seat with no command lines. The pilot's flight controls have four Moog motors for control loading of the feedback force.

The simulator is driven by a home code named SIMENV that interfaces all the off the shelf software packages running in the simulation of rotorcraft flight (MATLAB®, VEGA®, VAPS®, Flightlab®). The out of the window display is provided by three video projectors on an emi-cylindrical screen with 6m of diameter. Two more LCD monitors, placed near the pilot's feet, give the ground view, so that the feeling of being onboard is increased and take-off and landing manoeuvres can be simulated. A cluster of 13 PCs give the computational power for real time simulation and visual generation. The simulator described in the paper is now operational and currently used to improve the factory design chain efficiency. This paper presents also some diagrams explaining the activity of simulation performed to validate this design tool. Results obtained are good and the simulator ongoing work plays an important role in the conceptual phase of AgustaWestland helicopter design process. By this, not only engineers but also the pilot can now be involved

in the helicopter design from the initial phase of the activity process.

1 Introduction

In an aerospace market that is steadily becoming more global and competitive it is of paramount importance to answer promptly the customer's request and customisation with appropriate products.

The quality of the aircrafts delivered to the buyers and the time required to design, develop and produce, are amongst the key factors for a successful rotorcraft manufacturer. To address the above AgustaWestland strategy is to introduce concurrent engineering in the design process, the "lean factory" concepts, and the evolution of aircraft industries from "complete builders" to "final assembly lines".

With respect to these aspects AgustaWestland has recognized, as a strategic approach, the need to bring the test pilots into the design of a new rotorcraft from the preliminary phase of the project, thus creating a strong link between the rotorcraft design and the test phase. AgustaWestland has therefore decided to develop a "Simulator for Design" in which test pilots and engineers can exchange information, comments and judgements of the machine under development before any physical construction.

The name "Simulator for Design" has been selected to emphasize a fundamental difference with the classical flight simulators [1] used for training. In fact while the latter reproduce, with high fidelity, the dynamical behaviour [2], the cabin, the cockpit, and the human/machine interface for a specific type of helicopter, on the contrary the former can be used to simulate a generic rotary wing vehicle, also a tilt rotor

configuration. The advantage of this kind of simulator is to analyse and assess different vehicles or vehicle configurations, even at the preliminary stage of design, whilst no components have yet been designed, only by changing the software.

AgustaWestland Technical Direction approved this project and in particular the Helicopter System Design Department decided to take on the study and development of this new system in collaboration with the University.

AgustaWestland believes strongly in the collaboration between Industry and University. The company has sponsored numerous important activities with many Universities. Amongst them, the collaboration with the University of Bologna-Second Faculty of Engineering has been dated long with very important participation on the European projects like CAPECON, a research project related to Unmanned Air Vehicle. Considering their interest in this field, AgustaWestland decided to involve this University to develop part of the simulator project.

The simulator can really be seen as a tool useful to improve the design cycle, not only in terms of equivalence between the final product performances vs. initial requirements, but also as a device used to detect and solve potential problems at an early stage. In this way different AgustaWestland Departments can be involved at once in the design process, following the philosophy of the "Concurrent Design". This methodology will reduce the manufacturing time of the physical prototype, minimizing the possible defects, with a significant reduction in development costs. It is well known that these costs grow with a quadratic law whenever the necessity to modify the initial design emerges due to incomplete or unsatisfactory initial project assessments. In this case, in fact, the helicopter could be in the advanced phase of the development or, at worst, production, and all changes need a re-manufacturing and related integration on the helicopter system.

A possible strategy to avoid strong modifications when the project is just in an advanced phase, consists in the integration of the final user in the loop of design phase, as early as the development activity. This user can

be represented by the company test pilot. The pilot is familiar with the requirements and needs of the operational pilot in everyday working situations in the different civil and military missions.

The use of the 'Design Simulator' gives the engineer control of defining the basic characteristics of the vehicle closer to the flight test pilot (the end-user), supporting and implementing the "concurrent collaboration" between them. As the pilot can "flight" an helicopter, even if in the first stage of the development with no a physical prototype yet realized, any change in the machine can be applied without a big effort, both in terms of time and money. Moreover, the pilot can be involved not only in the aircraft performance evaluation and/or flying qualities [3], but also in other aspects like: ergonomics, layout of the instrument panel, operability and easiness of the avionics, vehicle behaviour in case of accidents or partial system failures [4].

Also the designer, seated in the simulator cockpit, can obtain advantages from this methodology: the evaluation of the handling characteristics and flight performances of an helicopter (or a tilt-rotor) can be evaluated not only by analysing tables and diagrams, but also by a more realistic sensation that the Design Simulator can give to the designer: it is well known that the sensation perceived, whilst seated in the cabin and seeing a virtual external view, is more involving than analysing off-line tables and data.

The primary factor to increase the perceived sensation [5] is the virtual environment for the Simulator for Design software programming. For some years the Flight Mechanics Department of AgustaWestland has selected Flightlab® as one of its main software for helicopter simulation. This software is particularly suitable for the simulation of a rotary wing vehicle through a refined mathematical modelling: in fact, it is possible to input all the required parameters that define the dynamic model of a vehicle in a very precise way: aerodynamic, geometrical, inertial characteristics, propulsion, avionics and control system data can be used to define the model. This software can be used for all the

configurations of rotary wing vehicles currently conceived, from the conventional helicopters to the tilt-rotor configurations.

In the following chapters, all the phases of the Simulator for Design development, manufacturing and validation will be described. Chapter 2 will report the list of requirements which have driven the design activity. Chapter 3 will deal with the manufacturing activity of the simulator concerning the mechanical/structural part and the system information/electronic one. Finally, the 4th Chapter will present the simulator validation activity carried out by AgustaWestland. Conclusions and future development will conclude this paper.

2 Simulator requirements

The first phase of the simulator developing was focussed around the definition of the overall requirements and design specimens, defined starting from the know-how and requests coming from the AgustaWestland Department involved in the project.

As this simulator can be considered as a sum of many subsystems mutually interacting, the requirements was grouped in few areas: the mechanical structure, the flights commands, the internal and external view projection devices, the electric and electronics board, the software code and the informatics integration.

In the following section, the main requirements will be analysed.

2.1 Structural requirements

The frame of the simulator has to be designed in order to comply with precise requirements: to support the cabin simulator, to allow the installation of two flanked seats (pilot & co-pilot), to support four digital touch screen displays and to constrain the structure of the cabin in composite fiber. Moreover, the structure has to contain rods and leverages of the flight commands and the entire cinematic chain, so to increase safety, aesthetics, and layout compactness, and to provide space for the installation of force-feedback motors and others accessories like controllers and power

systems. Another requirement was the capability of draining the big heating flux generated by force-feedback motors.

The frame of the structure has to be dimensioned verifying the stiffness so that deformations with dynamic loads of high amplitude can be minimized.

Two other fundamental needs were to move the structure with rubber gear and to keep as low as possible the total height of the simulator. This latter condition faces the problem of interference between the projector beams and the cabin in order not to shadow the view projected on the cylindrical screen.

2.2 Flight Controls requirements

The definition of requirements for flight controls was very critical: the run of the flight commands should simulate all helicopter models which are now in production or in development within AgustaWestland Company and all possible future configurations. But extending the controls run presents the drawback of a reduction in sensibility of the acquisition system and a decrease in ergonomics and pilot comfort. It was so decided to use the ergonomics of the flight commands of a medium helicopter, increasing only a little the total run to cover also other configurations. Another important requirement, considered in the design of the control chain, was to limit the loss of the command run to less than the 1% of the total run itself, also in presence of the maximum operative loads.

The simulator has to be equipped with force-feedback motors, used to simulate the loads encountered during a real flight and to acquire the flight controls. The requirements for the actuators was that at the maximum continuous loads, imposed by the pilot, the motors should provide the 80% of the maximum continuous torque (MCT), while in correspondence of the instantaneous limit loads the engine will provide the 240% of its MCT. The flight controls were also to be linked to the force-feedback motors so to satisfy two other requirements: the maximum run of the commands should generate a rotation of the motor shaft equal to $\pm 40^\circ$,

while not exceeding the requirements related to torque and maximum sustainable loads.

Other requirements can be summarized in:

- Maximum loads as defined in the ADS 33 regulation, also in case of failures like loss of power in the hydraulic systems.
- Capability of defining the dynamic behaviour of the feel system in terms of pulsation (angular velocity), damping, and gradients.
- Angular velocity as high as necessary to realize the stick control dynamic required.
- Complete re-configurability of the system.
- Capability to growth.

2.3 Electric, Electronics, Software and Information requirements

The electric components of the simulator have the function of acquiring the movements of the brake leverages in the pedal controls and the state of the numerous sensors and push-buttons embodied on the command: grip, trim, switch at 2 ways or 3 ways. The acquisition system has to be connected to a set of potentiometers and connectors for push-buttons. It also has to provide signal conditioning because it is expected that the PC stations would probably be distant from the sensors providing flight commands data sampling. Moreover, the simulator has to be equipped with a safety current cut-off system to stop the simulation and the feed-back motors in case of emergency.

All the subsystems of the Design Simulator have to be connected through a net to allow data and information exchange. A cluster of PCs would be necessary to manage the exchange and in particular: the acquisition of flight controls rotation, the force feed-back generation, the dynamic simulation, the buttons and switches position detection, the external view projection, the instrument and motors panel display, and finally the whole simulation system management and configuration. Furthermore, the simulator has to have the capability of growth in order to allow the interfacing of other computers and devices as possible future expansion.

It has been preferred to use Software packages which are familiar within AgustaWestland in order to minimise the acquisition and training costs for the operation of the simulator. In addition, it has to be re-configurable, easy to program and generated code should be expandable at the same time. Another requirement was to manage all the software parameters using only one main graphic interface window, running on a single PC. In this way, only one operator can manage all of the simulation parameters (as helicopter dynamic model, initial attitude and position, failures simulation management, force feed-back motors settings, external view and instruments view, signal acquisition) in real-time, even whilst the simulation is running.

2.4 Visual requirements

The main requirement for the visual was to project the external view over a large panoramic screen of 180°. Image warping and overlapping have to be corrected to gain a realistic panoramic view. The flight instruments have to be reproduced over touch screen displays to allow the complete re-configurability of the cockpit in short time. The digital cockpit, in fact, enables the reproduction of different analogue instruments and glass cockpits by simply selecting instruments in a predefined library of layouts (database).

It was also necessary to predispose the frame of the simulator for the installation of another two monitors in the lower zone of the cabin to simulate the view under the pilot's feet: this view is considered particularly important during take-off and landing because pilots compute the distance from the ground looking at these openings.

3. Simulator layout

Following the definition of the requirements listed above, it has been possible to define the simulator layout (Fig. 1).

First, it was decided that the cabin would be as generic as possible, with the overall dimensions of a medium size helicopter. The cockpit instrument panel includes four LCD touch-screen monitors, for instruments panels and for

engine parameters display, while the frame of simulator has two cut-outs for the installation of two screens to simulate the chin windows for the ground view.

A cluster of 13 PCs allows the elaboration of helicopter dynamics behaviour, the acquisition of flight controls in “real-time” and the management of the environment in which the vehicle moves. The PCs operative system is a mix of Windows® and Linux®. The net is isolated from the external world to increase the data security and safety and to avoid the outside interferences. A main PC station manages the entire simulator, providing the capability to modify the flight parameters not only off-line but also during the flight tests without stopping the simulation. The SIMENV is an in house code able to manage all the software developed as a mixed FLIGHTLAB® [6] and MATLAB® [7] environment. While the FLIGHTLAB® well defines the helicopter flight dynamics, the last was chosen for managing the overall simulation of the systems involved in the flight dynamics like actuators, flight control computers, sensors, motors. This software environment shares also information with all the other software packages of the simulator like the one for the external views or for the instrument panels representation.

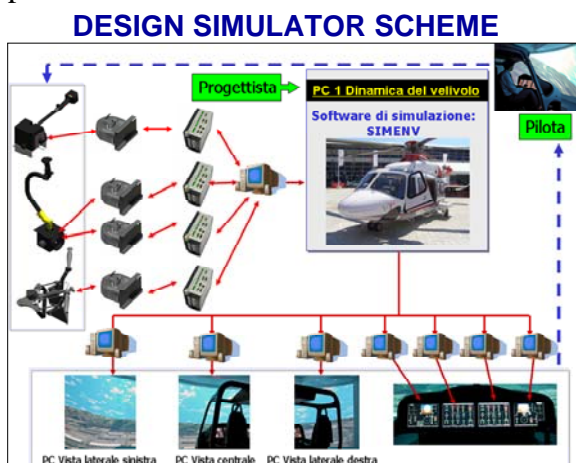


Fig. 1 – Simulator General Layout

The Flight controls are linked to force feed-back motors by a cinematic chain. The chain of the command supports has been dimensioned by considering three kinds of loads. The first represents the mean continuous load that the pilot can act during the flight, load characterised

by a high value of frequency. The second presents the maximum continuous load imposed by the pilot and it is applied with low frequency. The last represents the limit load imposed by the pilot and can be sustained only for a very short time in emergency situation. All these values of loads have been defined considering civil and military requirements. An inspection door permits an easy access to the chain. The controls chain is connected with four force-feedback motors, and the simulator software can manage the force-feedback motors behaviour and to change it in order to simulate different kinds of helicopters. The motors are off the shelf systems and comply with the requirements reported in chapter 2.2. The force-feedback actuators are installed in the rear zone with another inspection door for quick access. In order to drain the heat generated by the motors, several cuts were made around the simulator base so to generate a flux of air. Moreover, it was decided to locate the simulator in a room provided with an air conditioning system.

For inputs acquisition, the flight controls are acquired directly by the control boards of the feed-back motors, while all other kinds of signals are acquired by a dedicated board. This panel allows the acquisition of the position of buttons, switches, and selectors present on the flight controls and the rotation of brakes command. The board has been designed to manage: 8 potentiometers (analogical signals), 2 keys with 5 ways (centre, up, down, right, left, 4x2 digital channels), 2 keys with 3 ways (right, left, centre, 2x2 digital channels), 6 keys on-off (6x1 digital channels). In total 8 analogical and 18 digital channels are available on the board. The data acquired are then sent to the PC where the helicopter dynamics is computed. The output consists of the helicopter attitude (pitch, roll yaw angles), its position in the space (in terms of latitude, longitude and height), the feedback force on the commands and other complementary data required by instrument panel indicators.

Three projectors, mounted with an angle of 60° each one, provide the external view [8]. The projectors manage the correction and compensation of image deformation (warping)

and the overlapping of the lateral views. They are capable to assembly a unique image from the three projectors. The panoramic image is projected over a large semi-cylindrical white screen of wood, with an height of 2.7m (≈ 9 ft) and a diameter of 6m (≈ 20 ft).

About the visual it was decided to use an off-the-shelf software simple as possible, to be easily interfaced with Flightlab and open as to guarantee the flexibility need to simulate all the products of AgustaWestland Company: from conventional vertical flight vehicles to tilt rotor ones.

3.1 Building the Simulator hardware

The structural design deals with the project of the simulator base, the command chain, the flight commands, and the integration of instruments panels and pilots seats. The design has been deployed with the CAD Software Solid Works®. Although simple and user friendly, it provides an efficient management of complex three-dimensional drawings, with the capability of converting a 3D model into a 2D constructive drawing in a short time.

The first phase of the structural study was focused on the design of all the parts currently available at the stage: flight controls, pilot seats, and instrument panels. These part models have been positioned in a 3D assembly drawing, each mounted respecting the relative distance as in the AgustaWestland medium helicopter class: it has to be noticed that this is a simple controls chain positioning in the space, without the simulator main base structure that will be designed only in the following.

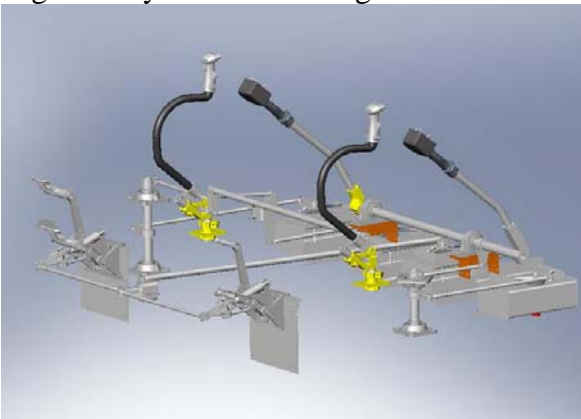


Fig. 2 – Pilots Controls line

Then, the cinematic chain, the leverages and the rods required, were defined (Fig. 2). The design guidelines, followed in this phase, have been with respect to transmission ratios defined in the requirements, the definition of a transmission with as low non-linearity as possible, the use of guide of motion based on rolling bearings mounted over high quality supports to guarantee the lowest clearance and the maximum stiffness possible.

The correspondence of the cinematic chain behaviour respect to its requirements, defined in chapter 2.2 and relative to loads acting on the flight controls and on the moments on force-feedback motors, has been studied using energetic conservative approach, based on the Virtual Works principle. Once the cinematic line of the commands and positions of the force-feedback motors have been sketched, it has been possible to draw the structural base of the simulator (frame) made of steel.

The frame has been designed using structural tubes with a square section of 50x50 mm: this dimension is a compromise between the need of high stiffness (as a consequence of chain low deformation requirement) and a moderate obstruction to allow the movement of leverages and rods in the space. Once defined the frame of the simulator base, an analysis with Finite Element Methods has been carried out. The results of the analysis have shown small deformations of the frame, also in the worse load condition. It was also verified that the loss of the controls run, due to the frame deformation, was less than the 1% of the total run as required. The leverages and rods of the command chain were verified by Euler axial load as they support working cycle made of compression and traction loads. It must be kept in mind, that the over-dimensioning of these rods can be disadvantageous because it increases the inertia controls, while an under-dimensioning could lead to chain failure.

After these checks, the complete structure of the simulator base could be sketched, as seen in Fig. 3. Care has been considered about possible interference in commands rods and leverages runs.

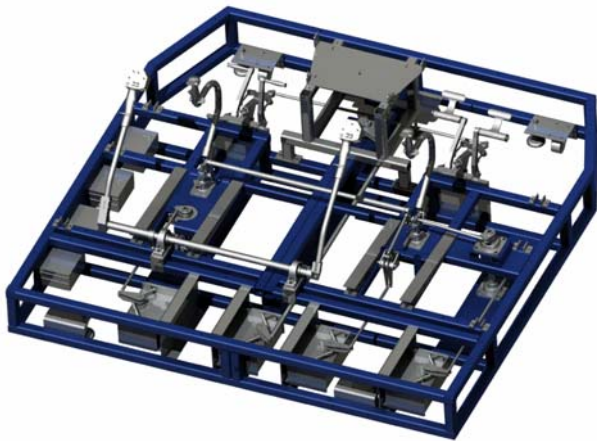


Fig. 3 – Simulator mechanical structure

All movements of flight commands have been simulated in order to avoid any possible combination of movements that could generate collisions in the chain.

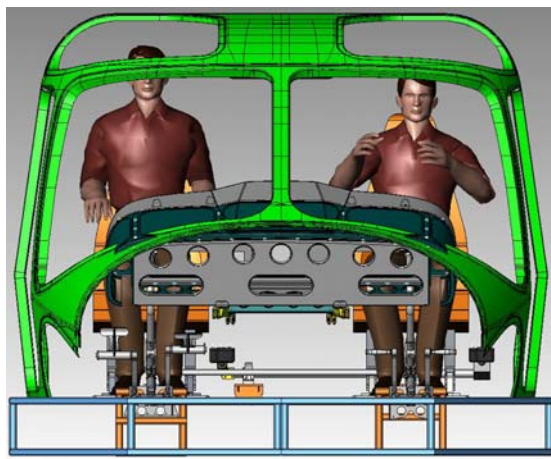


Fig. 4 – Ergonomics study of cabin

In a similar way, all the other parts of the simulator were modelled into the 3D CAD program. Before freezing the design, ergonomics studies were carried out with the use of two virtual dummies, one small (1.65 m) and one tall (1.95 m), representing the pilots (Fig. 4), so to verify the flight commands positioning, the placement of the seats, the visibility of the cockpit screens, etc. As the entire simulator has been modelled in 3D (Fig. 5), it was quite easy to plot the drawing for the manufacturing (Fig. 6). Hundreds of constructive 2D drawings were necessary for the production.



Fig. 5 – Simulator CAD photo realistic view

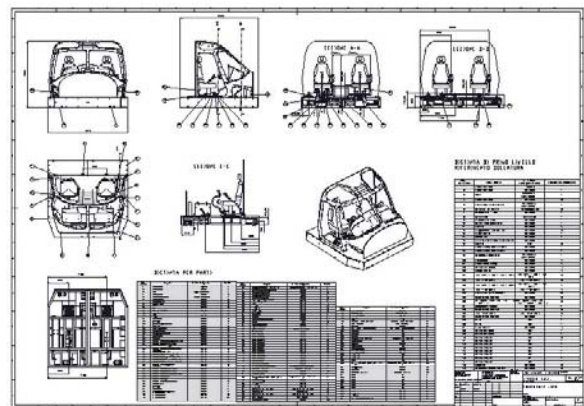


Fig. 6 – Simulator assembly drawing

To cope with the force feedback motors requirements, the ECoL-8000 Q-Line of the Moog FCS® series were selected and integrated into the simulator (Fig. 7).



Fig. 7 – Force feedback motors and controllers

These motors have been adopted for other similar configurations in the training simulators of AgustaWestland Company: it was very simple and easy to integrate them into the simulator, and the calibration phase was quite short.

3.2 The Simulator codes

The Software has to manage many tasks of the simulator like the helicopter flight dynamics behaviour, the data input/output, the external view, the instrument panel in the cockpit and other systems.

As much as possible the software packages selected has to be in use inside the AgustaWestland group, so that internal experience gained will guarantee the reduction of the time required for training the personnel working on the simulator. The dynamic behaviour of the helicopter, as stated above, is simulated using the FLIGHTLAB® code. It is a multi-body software designed for simulation, both off-line and real-time, with complete models of helicopters.

Other parts of the code, like the ones for the actuation management, the data logging, the interface with feedback motors and control loading and the cockpit displays views have been developed in Matlab-Simulink® environment, using the real time module Real-Time Workshop® for the generation of real-time code. All software codes are connected by a program called SIMENV (Fig. 8), written using the Matlab® GUI (Graphic User Interface), that allows the complete management of the simulation, both off-line and in real-time, by desktop.

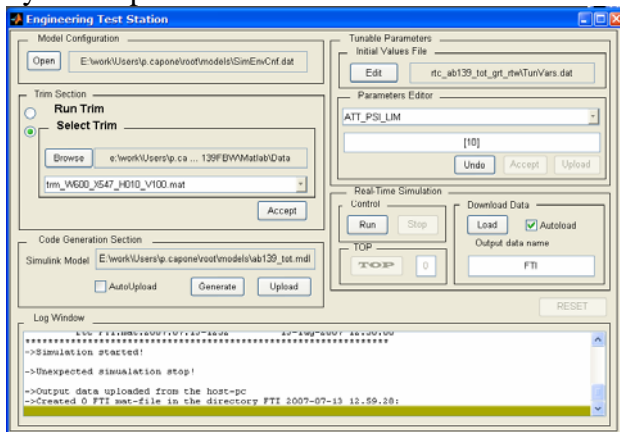


Fig. 8 – Simenv

SIMENV allows the operator to:

- Define the model for simulation
- Decide to run the simulation in real-time or off-line

- Design the flight control laws.
- Modify simulation parameters even in real-time mode.
- Log of the results, directly in Matlab® coding.

Moreover, SIMENV can be integrated with other toolbox like flying qualities evaluation tool (HQ&C).

CREATOR® and VEGA® have been chosen as the main software to simulate the external virtual views. The first package allows the building of 3D models (houses, buildings, etc...) in which the helicopter will fly during the simulation. The second is used to project these models, managing the corrections for warping, perspective deformation, and overlapping of central and lateral views. Also the effect due to the atmospheric conditions can be simulated on the scene with VEGA. Figure 9 presents a view obtained with CREATOR® and VEGA®.



Fig. 9 – VEGA Software

The image generation systems provide the pilots with a very realistic feel of the flight, very close to the real flight, being immersed in a virtual environment similar to the real panorama (Fig. 10).



Fig. 10 – The final simulator configuration

The final cockpit layout is very up-to-date simulating a modern digital cockpit (Fig. 11).



Fig. 11 – Instrument Panel detail

4 Validation of the flight mechanics models

The fidelity of a simulator depends on the level of detail of the image generated by the visual system, on the accuracy of the acceleration and vibration cues provided by the mounting platform, and above all on the simulation capabilities of the flight mechanics code used as simulation driver.

The aim of the validation procedure of a flight mechanics model to be used in a flight simulator is the generation of a mathematical model validated in the whole helicopter flight envelope.

This paragraph presents some of the results of the validation process of the FLIGHTLAB® model of the medium twin engine helicopter class.

The mathematical model features:

1. blade element theory for the main rotor with lookup tables for non-linear lift, drag and pitching moment, as function of incidence and Mach number, used in a quasi-unsteady aerodynamic model;
2. five rigid blades with offset flap and hinges;
3. Peters-He 3-state main rotor inflow model;
4. actuator disk model of the tail rotor;
5. rigid fuselage;

6. lookup tables of fuselage and empennage forces as function of angle of attack and sideslip;
7. Peters-He 3-state interference on empennage;
8. ideal engine;
9. automatic flight control system (AFCS).

The validation of the mathematical model has been performed against flight test data recorded in these flight conditions:

1. trimmed flights;
2. control inputs with AFCS off;
3. control inputs with AFCS on.

The figures from 12 to 19 show the results of the comparison between simulation (blue lines) and flight test (red points) for three test cases representing the flight conditions listed above.

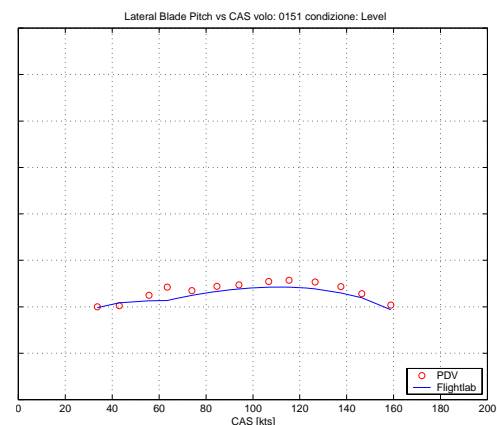


Fig. 12 – Lateral Cyclic

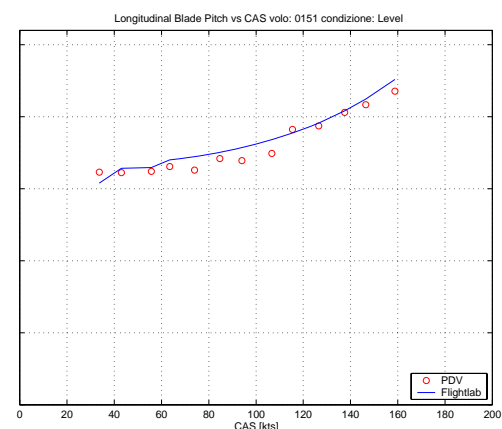


Fig. 13 – Longitudinal cyclic

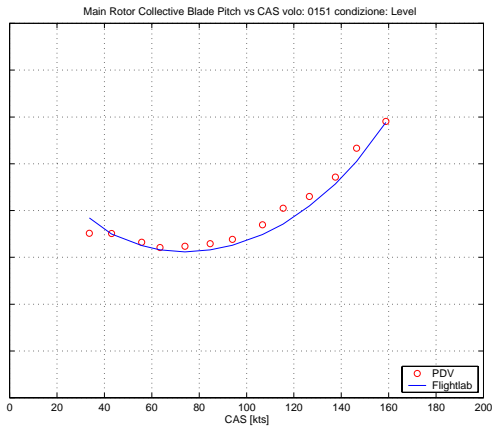


Fig. 14 – Main rotor collective pitch

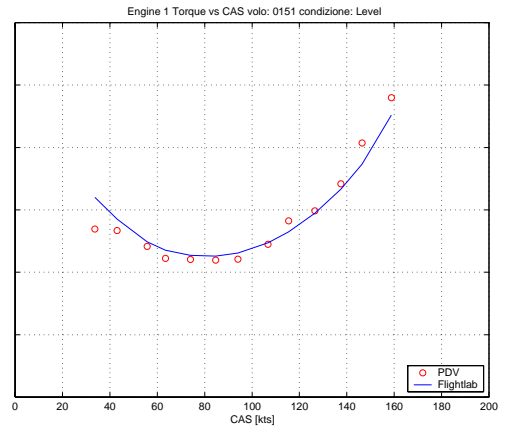


Fig. 17 – Engine 1 torque

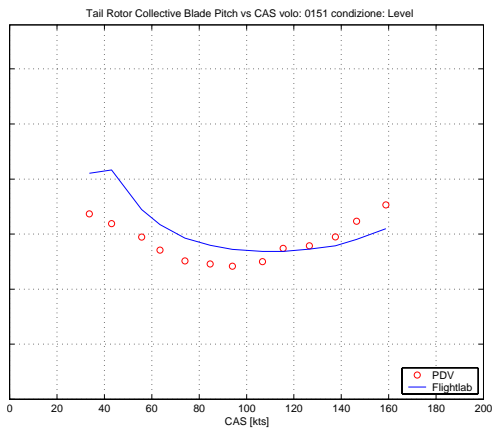


Fig. 15 – Tail rotor collective pitch

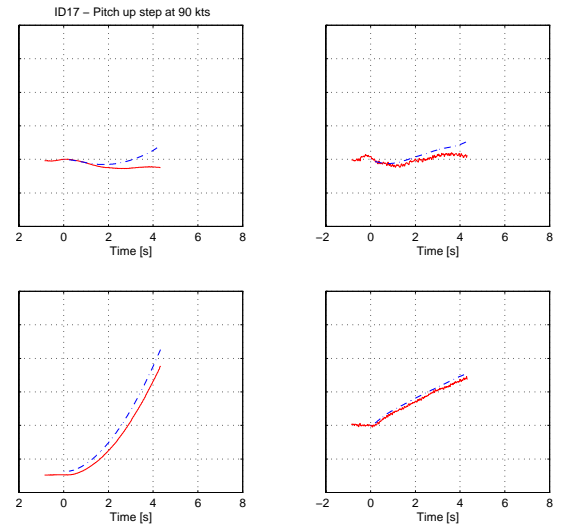


Fig. 18 – Pitch up step at 90 kts, AFCS off

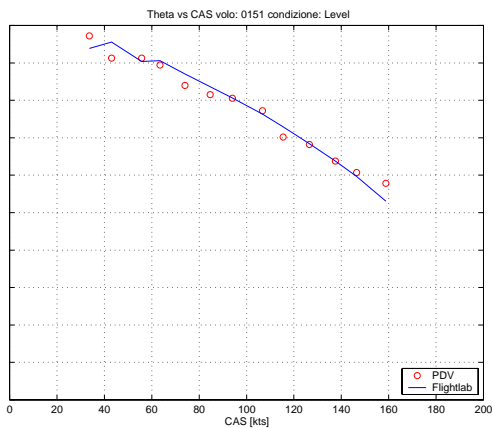


Fig. 16 – Theta

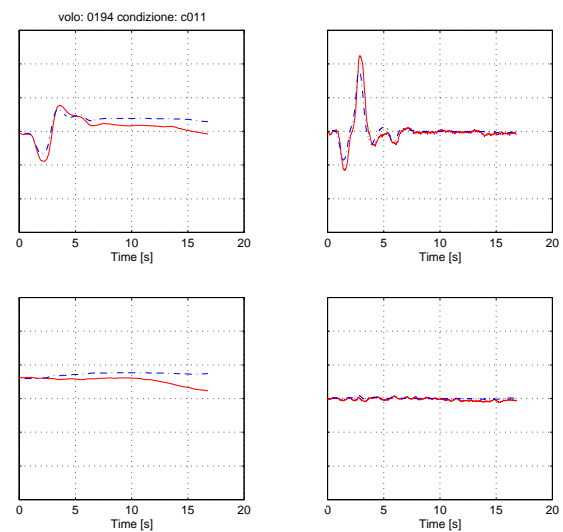


Fig. 19 – Doublet of lateral cyclic, AFCS on

As can be seen from the figures above, the results show a good correlation between simulation and experimental data. If necessary, the results could be also improved by increasing the level of complexity of the mathematical model used.

5 Conclusions

The present paper reports the main concepts and requirements that drove the development of a simulator for the preliminary design phase in AgustaWestland. Starting from the necessity of having a new tool to perform more sophisticated flight mechanics analyses for the old and new AgustaWestland products, this system has been expanded to include other aspects of the preliminary design phase like: Man Machine Interface (MMI) issues and the definition of the control panel lay-out. This tool will permit to perform all the required analyses for the normal operations but, most important, also for emergency conditions and to evaluate the handling qualities of the different rotorcrafts even in the case of failure of subsystems like: engines, flight controls, avionics systems, etc. before the design phase is completed. Of course this is part of the Concurrent Design Process strategy required to improve the design phase and then reduce both “Design Costs” and “Time to Market” of the Agusta Westland products.

All the validation tests like those reported in section 4 of this paper show a very good correlation of simulated flight conditions with the flight tests.

For all the above listed reasons this simulator is now used in the Helicopter System Design and Avionics Department as a very important tool to develop the new AgustaWestland products, or to improve the existing ones.

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