AW169 Loss of Tail Rotor Effectiveness Simulation

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ABSTRACT

This paper presents the simulation work done to define the rotorcraft flight manual emergency procedure for a loss of tail rotor effectiveness for the AW169 helicopter. The work makes extensive use of both off-line and pilot-in-the-loop simulations.

INTRODUCTION

Tail rotor failures that affect the contribution to stability and control of the tail rotor on the yaw axis of a conventional main-rotor-tail-rotor helicopter go under the name of "loss of tail rotor effectiveness". These failures can be the source of most critical emergency conditions that can prevent continued safe flight or safe landing. Due to the strong effect of such failures on the safety of flight, the design of the tail rotor is guided by requirements (ref. [1]) whose aim is to minimize the likelihood of such failures to occur as well as to provide emergency recovery procedures in the unlikely event that they happen.

The loss of tail rotor effectiveness failures can be grouped into three broad categories: tail rotor control failures (TRCF), tail rotor drive failures (TRDF) and tail rotor loss. A tail rotor control failure is a failure that prevents the control of the tail rotor collective pitch (e.g. disconnection between yaw control and tail rotor). The helicopter will either experience yaw left or right based on the equilibrium position reached by the tail rotor blades free to rotate along the feather axis. A tail rotor drive failure is a failure of the tail rotor drive system, which will cause a rundown of the tail rotor rotational speed, and a loss of tail rotor thrust. Typically, this can occur very quickly, resulting in a rapid yaw right for counter-clockwise main rotors (and vice-versa for clockwise rotors), a loss of control in yaw, pedals free but ineffective and noise and/or vibration at the tail section. A tail rotor loss is a complete loss of the tail rotor system. As in the case of the tail rotor drive failure, the helicopter will experience a rapid yaw right for counter-clockwise main rotors (and vice-versa for clockwise rotors), a loss of control in yaw and pedals free but ineffective.

For all three cases, the severity of the initial yaw rate will be determined by airspeed, altitude, gross weight, centre of gravity and torque settings at the time of the failure. The effectiveness of the vertical fin in limiting the yaw rate will depend mainly on the airspeed at the time of the failure, increasing with airspeed and decreasing with altitude.

Of the three types of failures, the most critical are the second and the third ones, because they compromise both the stability and control characteristics of the helicopter on the yaw axis, while the first, even if necessarily accompanied by the loss of control of the tail rotor pitch, either through pilot

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or Automatic Flight Control System inputs, does not impair the tail rotor passive stabilizing contribution on the helicopter yaw axis.

Loss of tail rotor effectiveness failures can be used as drivers for the sizing of the fin, because the vertical tail surface is the only remaining contributor to directional stability and damping in case of tail rotor drive failure. But this requirement often clashes against the need to provide pedal control margin for low speed lateral flight.

The simulations plotted in Figure 1 (done with the AICAM code, in-house version of the CAMRAD-JA simulation software) explicitly show, for a 100 kts level flight at various angles of sideslip (positive for wind from the right), the importance of the fin and of the tail-rotor along with the main rotor in determining the helicopter equilibrium in yaw.

The simulations refer to a weight of 4800 kg, a speed of 100 kts and have been performed in sea level conditions according to the international standard atmosphere (SL ISA).

Mz is positive nose to the right.

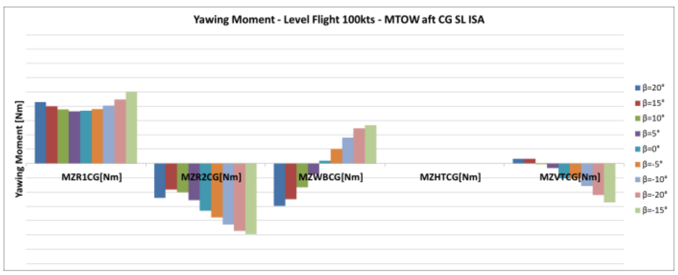


Figure 1 - Yawing Moment Breakdown - Level flight 100kts at 4800 kg, SL ISA

The contributions to yawing moment appearing in Figure 1 are from left to right:

- main rotor (always nose right)
- tail rotor (always nose left)
- fuselage (nose left or right as function of the sideslip angle).
- fin (almost always nose left).

Due to the relative magnitude of the yawing moment generated by tail rotor and fin, it can be inferred that the fin dimensions do not allow to sustain a level flight in case of tail rotor drive failure even at quite high sideslip angles. The only possible solution to find the equilibrium in yaw is to reduce the main rotor contribution to the yawing moment.

Even if for a narrow range of flight conditions some tail rotor failures could be tested in flight (for example mid speed control failures), most of them are too critical for experimental testing and the only feasible approach to quantify their effect on the helicopter handling qualities is simulation.

The main goal of the AW169 tail rotor loss of effectiveness simulation was to provide the Certification Authority, by means of piloted simulations, evidence of the capability of the rotorcraft to be brought to a safe landing after a loss of tail rotor effectiveness failure and possibly to define the best technique to accomplish it.

The simulation task included the development of a simulation model representative of the flight mechanics characteristics of the helicopter both in steady and dynamic conditions; the numerical validation of the simulation model against a broad dataset of experimental flight data; the execution with two test pilots of the tail rotor failures simulations.

THE AW169 LIGHT-INTERMEDIATE

The AW169 is a twin-engine helicopter designed to meet the market requests for a versatile and multirole 4-tonne transport rotorcraft. Engineered to satisfy the most demanding para-public and commercial operational requirements, the AW169 features:

- an optimized main rotor, reducing power required and maximizing performance in hover and cruise;
- a large, rapidly-reconfigurable cabin, with constant-height cross section, easy access and adaptability to a variety of missions;
- a 4-axis dual-duplex Automatic Flight Control System;
- an Automated Variable Speed Rotor to optimize performance and fuel consumption as function of flight speed and altitude;
- an improved cockpit to provide excellent external visibility to the pilot.

Figure 2 - The AW169 light-intermediate helicopter with the AW139 and the AW189 in the background

THE CERTIFICATION PROCESS

The main and tail rotors are flight critical components of a helicopter in the sense that a malfunction of either of them may prevent continued safe flight or safe landing. The certification basis (ref. [1]) provides requirements dedicated to the design of these components with the aim of minimizing the likelihood of their failure:

CS 29.547 Main and tail rotor structure

[…]

(b) Each rotor assembly must be designed as prescribed in this paragraph and must function safely for the critical flight load and operating conditions. A design assessment must be performed, including a detailed failure analysis to identify all failures that will prevent continued safe flight or safe landing, and must identify the means to minimise the likelihood of their occurrence. […]

Ref. [2], giving advice on this requirement, specifies the need of the availability of compensating provisions:

A design assessment of the rotors should be carried out in order to substantiate that they are of a safe design and that compensating provisions are made available to prevent failures classified as hazardous and catastrophic […]

Where:

(3) Hazardous. Failure conditions which would reduce the capability of the rotorcraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be --

(i) A large reduction in safety margins or functional capabilities.

(ii) Physical distress or higher workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely.

(iii) Serious or fatal injury to a relatively small number of the occupants.

(iv) Loss of ability to continue safe flight to a suitable landing site.

(4) Catastrophic. Failure conditions which would prevent a safe landing. […]

Ref. [2] continues by listing the compensating provisions that could be used to prevent malfunctions of the main and tail rotor from happening, including in the list emergency procedures:

Compensating provisions may be selected from one or more of those listed below, but not necessarily limited to this list.

(i) Design features; i.e., safety factors, part derating criteria, redundancies, etc.

(ii) A high level of integrity: All parts with catastrophic failure modes and critical characteristics are to be identified as Critical Parts and be subject to a Critical Parts Plan (see AC 29.602). Where a high level of integrity is used as a compensating provision, parts with a hazardous failure mode which would prevent continued safe flight may be included in a Critical Parts Plan or subjected to other enhancements to the normal control procedures for parts.

(iii) Fatigue tolerance evaluation.

(iv) Flight limitation.

(v) Emergency procedures.

(vi) An inspection or check that would detect the failure mode or evidence of conditions that could cause the failure mode.

(vii) A preventive maintenance action to minimize the likelihood of occurrence of the failure mode including replacement actions and verification of serviceability of items which may be subject to a dormant failure mode.

(viii) Special assembly procedures or functional tests for the avoidance of assembly errors which could be safety critical.

(ix) Safety devices or health monitoring means beyond those identified in (vi) and (vii) above. […]

While typically all the compensating provisions listed above are used as compensatory measures for the tail rotor system, it is apparent that the most important in the list are those that prevent a catastrophic failure to occur in the first place. In this sense design procedures and choices are of paramount importance in the process. The emergency procedure is the final possible compensatory measure that the manufacturer can put in place to reduce to a minimum the fatal consequences of a hazardous or catastrophic failure. This procedure has to be included in the emergency procedures section of the rotorcraft flight manual.

Being the loss of tail rotor effectiveness a hazardous /catastrophic condition, certainly a test in flight from the upset of the equilibrium in yaw, through the full development of the yaw dynamics till the final reach of a different equilibrium condition, is not advisable also due to all the other compensating provisions put in place to minimize the probability of occurrence of such failure. For this reason, pilot-in-the-loop simulations were judged the appropriate method to substitute the actual flight test while still retaining adequate representativeness to sufficiently explore the AW169 flight characteristics in this flight condition.

The pilot-in-the-loop simulations were used to understand if after a tail rotor loss of effectiveness failure and the subsequent transient manoeuvre the AW169 can be brought to a steady flight condition and then landed safely, possibly with a repeatable manoeuvre.

This capability was demonstrated for the AW169 in simulation for various operative conditions for values of weight, centre of gravity and ambient conditions chosen in agreement with the Certification Authority.

THE SIMULATION APPROACH

The advantage of simulation can be in general seen from three points of view: safety, economy and effectiveness. This is well known for the training applications and is also valid for the design world.

In fact, during the development of a new rotorcraft, the execution of every manoeuvre has in principle a risk; while this is extremely small and acceptable for operative conditions, it can increase considerably in case of testing of emergency cases, and needs to be mitigated somehow by the flight testing process. With this respect, the simulation can definitely guarantee much more safety, by providing directly an alternative to the specific critical test point and also indirectly, by reducing the number of flight hours for a rotorcraft under development. This is the most important advantage of the simulation and in fact it was the first to be recognized decades ago in the flight training world.

After safety, the attention to cost is perhaps the most important factor to be considered: experimental flights are in general an expensive part of the design process, and this is true in particular for the testing of emergency manoeuvres and failure cases, where the need for special instrumentation, data recording, telemetry, trained specialists etc. can imply significant additional effort. The simulation can of course dramatically reduce this cost, especially thanks to the use of engineering simulators.

Finally, if risk and cost are negative factors that the simulation can successfully eliminate or reduce, there is also a positive dimension to be mentioned: the effectiveness. For sure a proper actual test is 100% realistic and formally provides therefore the best proof, however it has a number of limitations: due to safety and cost the flight tests cannot be easily repeated and it is difficult if not impossible to explore a design space and try what-if scenarios. The simulation can in general be more effective than the real flight: the possible number of repetitions, interruptions, variations of a case of interest increases the insight into the phenomena, and allows the exploration of different parameters and the definition of operative solutions or techniques. Especially by using first principle based models, the simulation can extract and store parameters that in flight are difficult or impossible to make available, offering a greater understanding of the physics.

Of course the reverse of the medal is that these advantages can only be obtained at the cost of the availability of a validated simulation model, an adequate simulation facility and experienced pilots.

To capture the real rotorcraft behaviour as function of the flight conditions, the model will have to heavily rely on an accurate representation of the physical phenomena (physics based modelling), respecting on the other hand the complexity limits imposed by the real-time requirements.

The facility has also important requirements: in particular for complex manoeuvres with pilot in the loop, the level of the cues provided is very important and should be the best compromise between effectiveness and cost. So in most cases a fixed base simulator can provide sufficient cues avoiding the cost and the complexity of a motion base; audio cues provide important awareness to the pilot; attention must be posed to the mechanical characteristics of the inceptors, combining, in case of re-configurable simulators, accuracy with flexibility; the instrumentation plays also an important role and is relatively easy to be implemented using commercial hardware and software.

Finally, also the pilot needs to be compatible with the simulation: piloting experience and professional background are essential for the design activity to be performed through pilot-in-the-loop simulations. Experimental test pilots are typically well trained to for simulator correct usage, understanding modelling principles and characteristics, compensating where acceptable for model and cues limitations and being able at the same time to represent the "normal pilot" scenario.

The above advantages in terms of safety, cost and effectiveness, together with the availability of a validated model, an adequate facility and skilled test pilots, indicated the strong opportunity to use the simulation to define the emergency procedure to cope with a loss of tail rotor effectiveness failure.

THE AWARE SIMULATION FACILITY

AWARE (ref. [3]) is the Leonardo Helicopter Division engineering flight simulation designed for virtual prototyping of rotorcraft for the design and testing of handling qualities behaviour, control systems, inceptors and flight procedures.

Physically, the simulator is made up of: a 3-meter wide cylindrical screen, for the projection of the simulated "out-of-the-window" scene with four projectors; a rotorcraft cockpit mock-up representative of the AgustaWestland product "Family" (AW169, AW139, AW189), equipped with re-configurable touch-screen displays and actively-controlled pilot sticks; a set of PCs, to perform the required computational tasks, including the flight mechanics real-time calculation, the stick force feedback control, the displays and out-of-the-window image generation; an operator station, to control the virtual experiments, display data in real-time and record all the relevant information.

Figure 3 - The AWARE engineering simulator

THE SIMULATION MODEL

The H\C model running in the AWARE simulator features a representation of the AW169 bare aircraft, of the Automatic Flight Control System and of the cockpit displays.

In particular the bare aircraft, modelled with Flightlab commercial modelling piece of software, includes a representation of the fuselage through wind tunnel test data, of the main rotor, represented using a blade element approach, and of the tail modelled as an actuator disk, the engines represented by means of equivalent dynamic model, the landing gear rendered as a series of equivalent stiffness and damping elements.

The AFCS is implemented by means of a compiled Matlab/Simulink model, representing the same logics that, apart from functions and modules not relevant for flight dynamics, are used in the real flight control computers.

The cockpit displays software reproduces the main pages and the functions relevant to the manoeuvres to be simulated.

Figure 4 - The simulated AW169 display

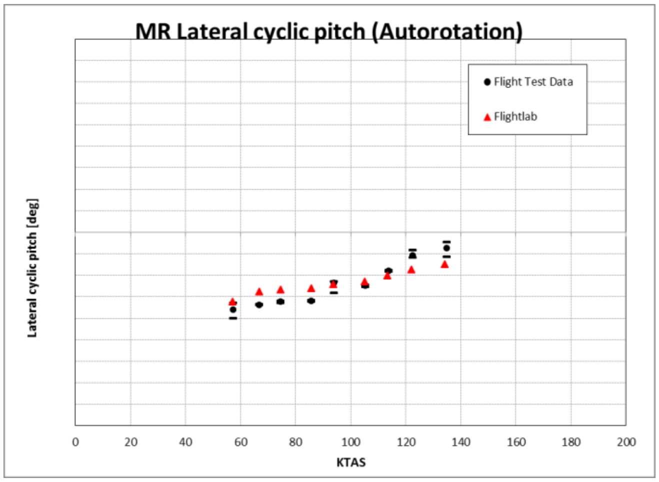
The model was extensively validated for trim as well as dynamic manoeuvres during the whole development cycle of the AW169. Before the first flight, the model was generated based on the best available information, including wind tunnel test data and it was subsequently updated as experimental data became available.

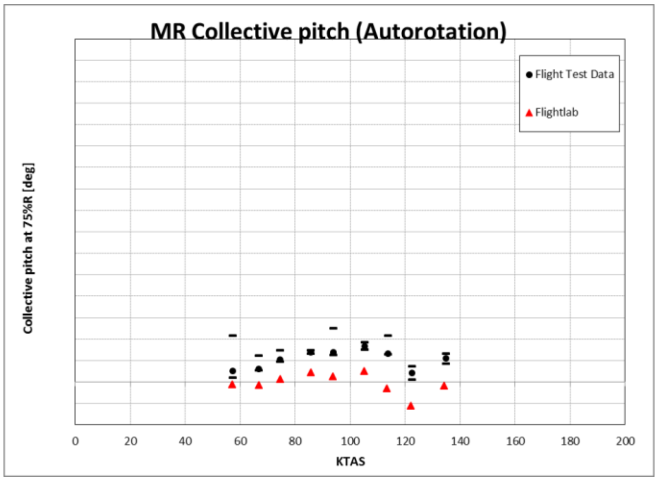
Since no validation data are available for the tail rotor loss of effectiveness conditions, the confidence on the model representativeness is based on the use of first principle modelling and on the general validation process the model underwent during the helicopter development phase.

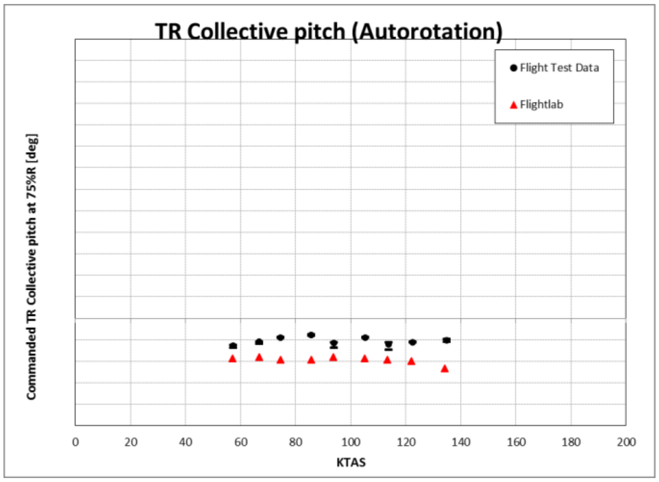
The following figures show an example of the general model correlation level considered acceptable for the tail rotor loss of effectiveness simulation task. In particular the autorotation cases are shown here as reference because considered the most close to the flight condition to be simulated.

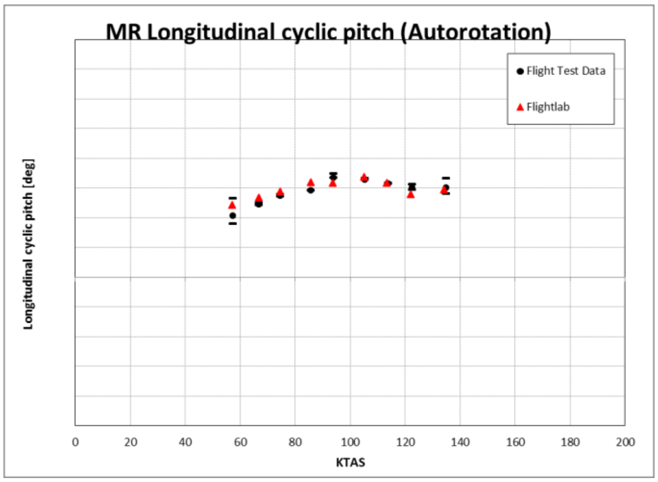
The model results are in good agreement with the flight test data.

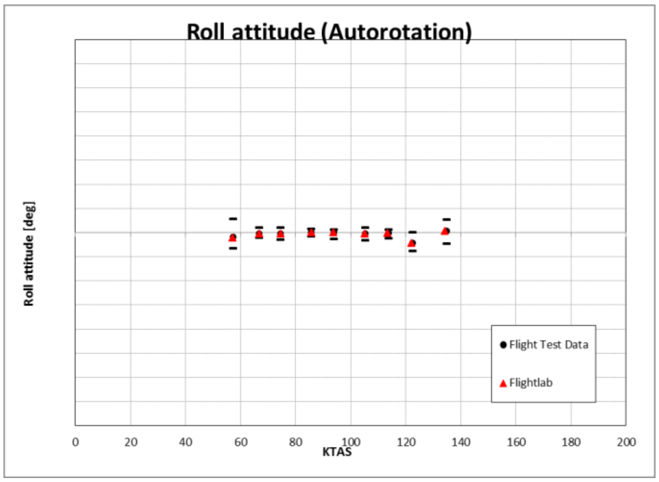
The y axis limits in the figures are set to a typical range of variation for the parameters plotted.

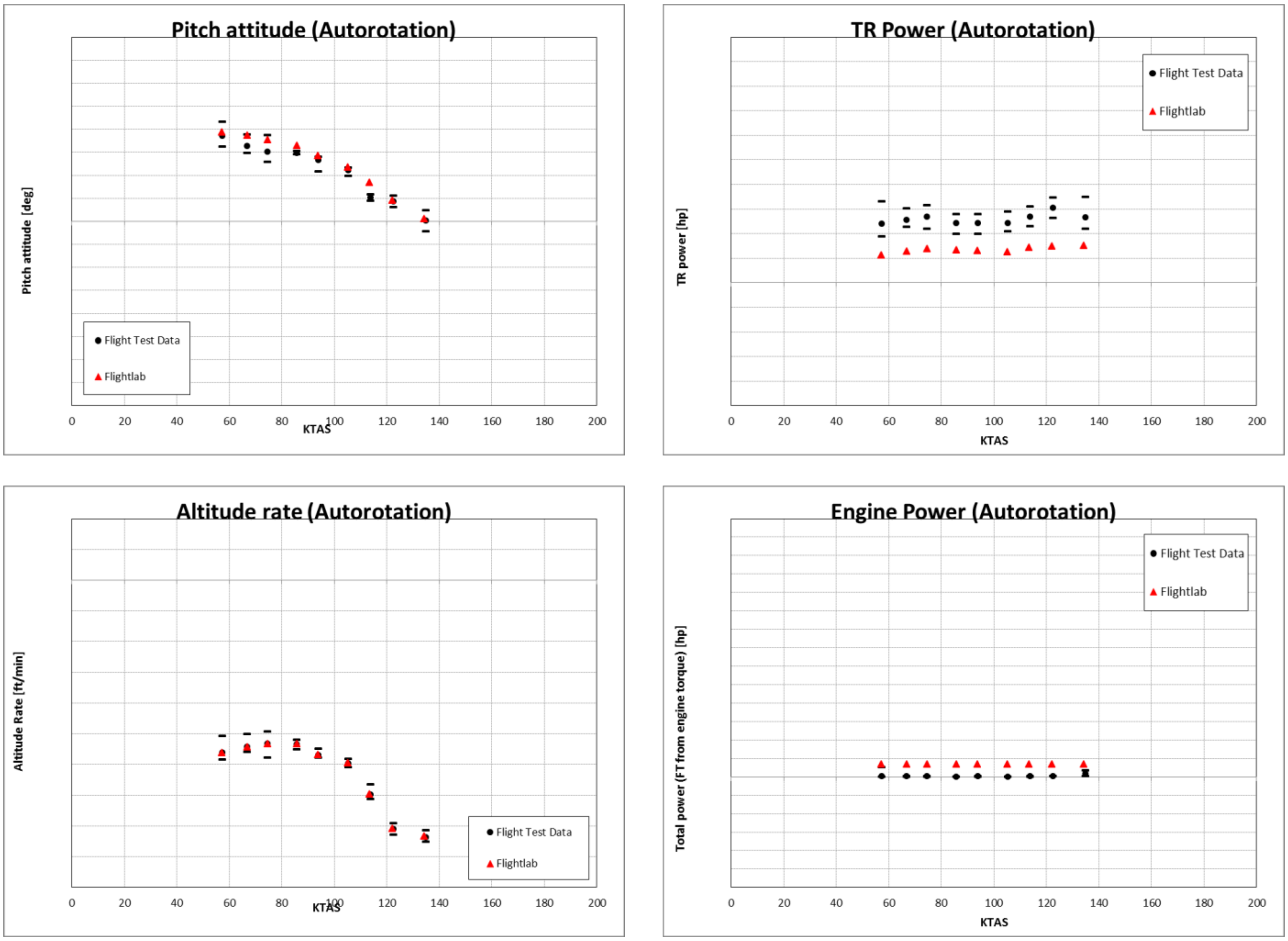












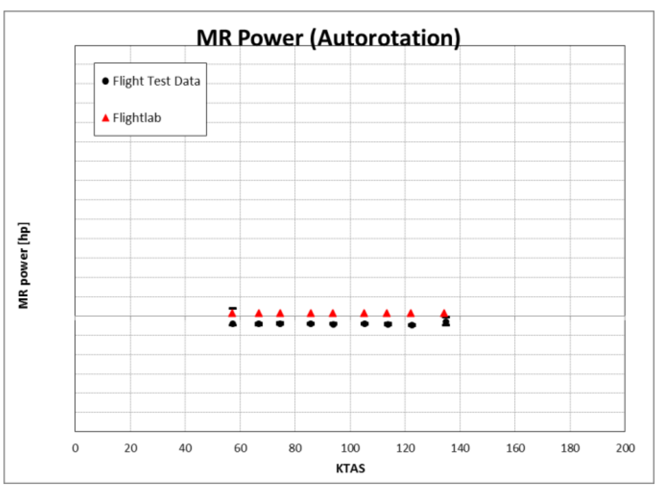


Figure 5 - Examples of the AW169 FLIGHTLAB model validation in autorotation trim

The model was also validated in the frequency domain for various flight speeds and altitudes. An example of the correlation level reached is shown in the following figures in terms of frequency response of body angular rates to controls at mid speed, low altitude. The frequency responses were available for two prototypes: AC1 and AC2. The simulation results are presented both with and without actuators and sensors models.

The validation on the yaw axis is poorer than that on pitch and roll probably do to the simplified modelling approach used for the tail rotor.

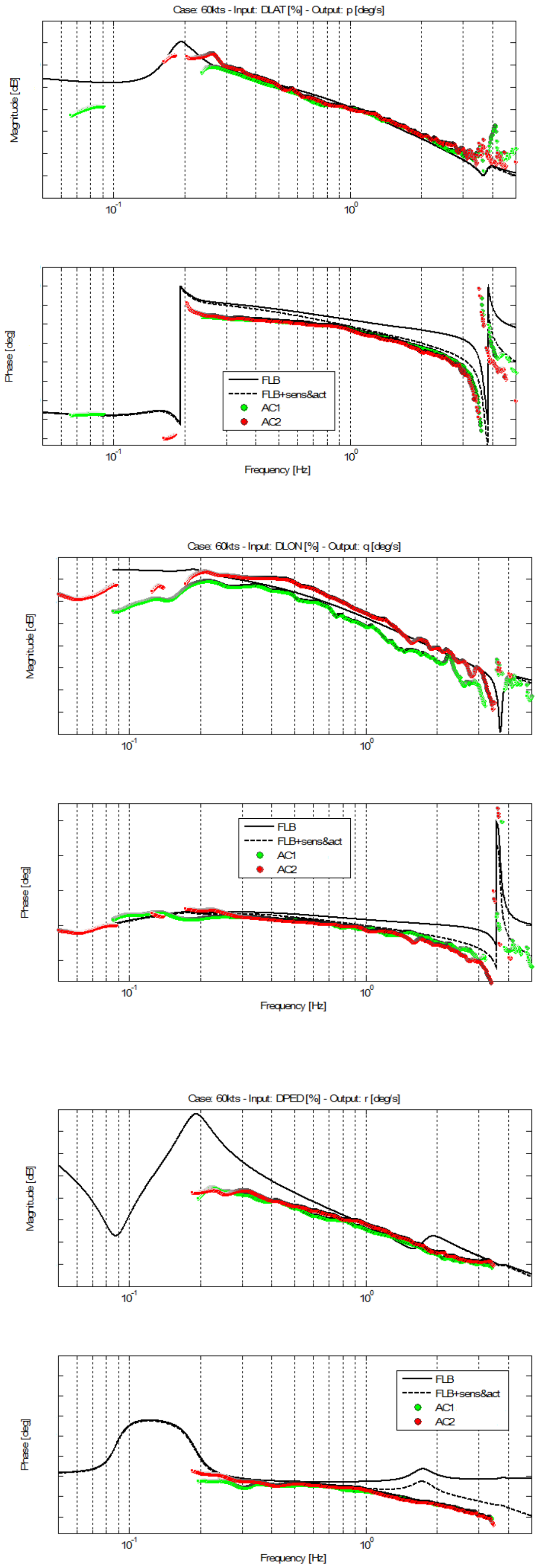


Figure 6 - Examples of the AW169 FLIGHTLAB model dynamic validation

THE MANOEUVER SIMULATION

Due to the satisfactory comparison between simulated and flight test data shown in the previous section and to the physics-based nature of the model, the simulator was considered to possess predictive capabilities adequate to simulate the recovery manoeuvre from a loss of tail rotor effectiveness failure.

The tail rotor control failures were simulated as conditions of tail rotor collective pitch stuck at the value (7.5 deg) estimated to guarantee equilibrium along the blade feathering axis without the contribution provided by the servo. Using a conservative approach, the tail rotor drive failures and tail rotor loss failures were merged and simulated as instantaneous loss of the tail rotor.

The simulated conditions were:

1) TRDF: 4000 kg, mid CG, ISA 3000 ft, straight and level flight at 80 kts (IAS);
2) TRDF: 4000 kg, mid CG, ISA 3000 ft, straight and level flight at VH (>140 kts, IAS);
3) TRDF: 4000 kg, mid CG, ISA 3000 ft, 80 kts (IAS) climb at 1500-1800 ft/min;
4) TRCF: 4000 kg, mid CG, ISA 300 ft, hover;
5) TRCF: 4000 kg, mid CG, ISA 3000 ft, straight and level flight at 80 kts (IAS).

These test points were considered representative of the take-off and landing envelope both in terms of configuration (weight and CG position) and ambient conditions.

To increase the level of confidence in the simulation results, the test campaign was performed by two pilots.

The next three figures show for cases 1), 4) and 5) the time histories of the most relevant parameters recorded during the simulation sessions. The dotted vertical line marks the failure injection, while the dashed line the time of touch down.

As shown in Figure 7 the tail rotor drive failure at 80 kts is followed by a strong yaw nose right (negative beta)/roll left angular motion produced by the loss of the tail rotor. The yaw motion, by affecting the aerodynamic environment of the horizontal tail plane, induces a pitch down motion of the helicopter.

The pilot is able to bring and maintain the helicopter back to a steady flight condition with 75 kts ground speed, 2750 ft/min descent speed, roll equal to -20 deg (left wing down) and beta equal to -40 deg (nose right). Before the touch down the engines are turned off in order to prevent collective to yaw coupling. The touch down, cushioned by the collective pull, happens at -1000 ft/min, well within the fuselage crashworthy limits of 8 m/s (=1575 ft/min).

In general, for tail rotor drive failures pilot-in-the loop simulations have highlighted that suitable steady conditions can be reached although the accomplishment of entire entry-steady-recovery manoeuvre is a complex task.

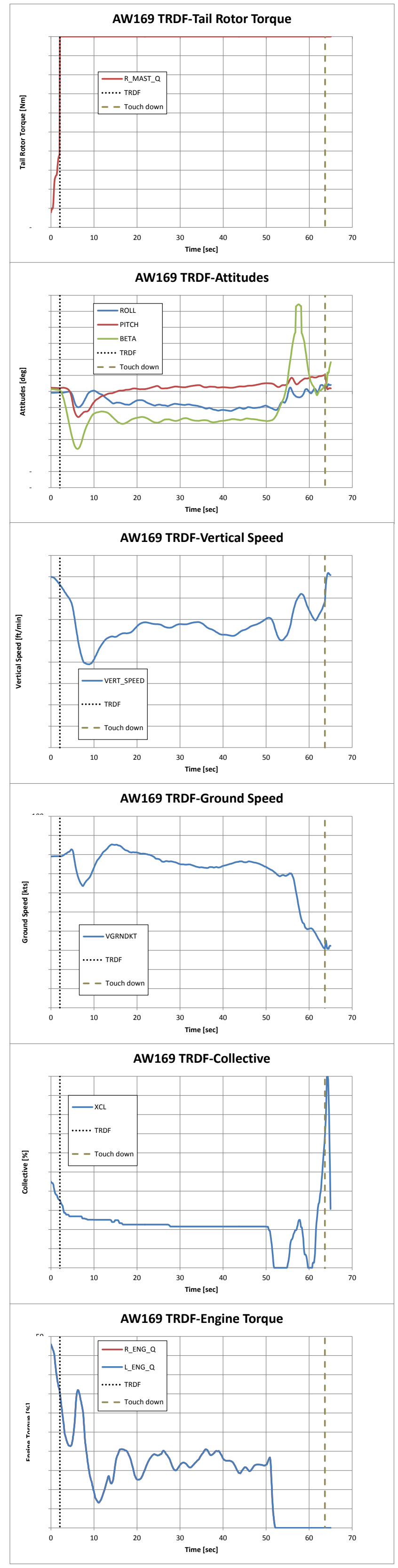


Figure 7 - AW169 tail rotor drive failure at mid speed

Figure 8 shows that the tail rotor control failure from a 300 ft hover condition is followed by a strong yaw right angular motion produced by the reduction in the tail rotor thrust. The pilot intervenes by lowering the collective to reduce the yaw motion and to bring the helicopter to the ground. The rate of descent is reduced close to the ground by the collective pull and the landing is finalized at a vertical speed below 430 ft/min. It is worth noticing that the touch down speed is less than the sinking speed for limit landing (=492 ft/min).

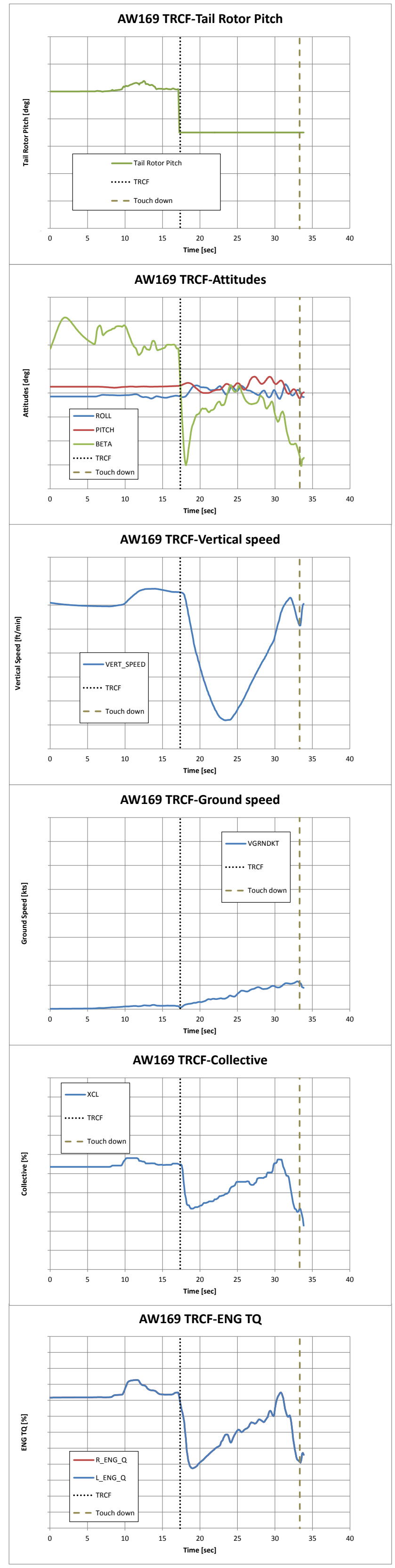


Figure 8 - AW169 tail rotor control failure in hover

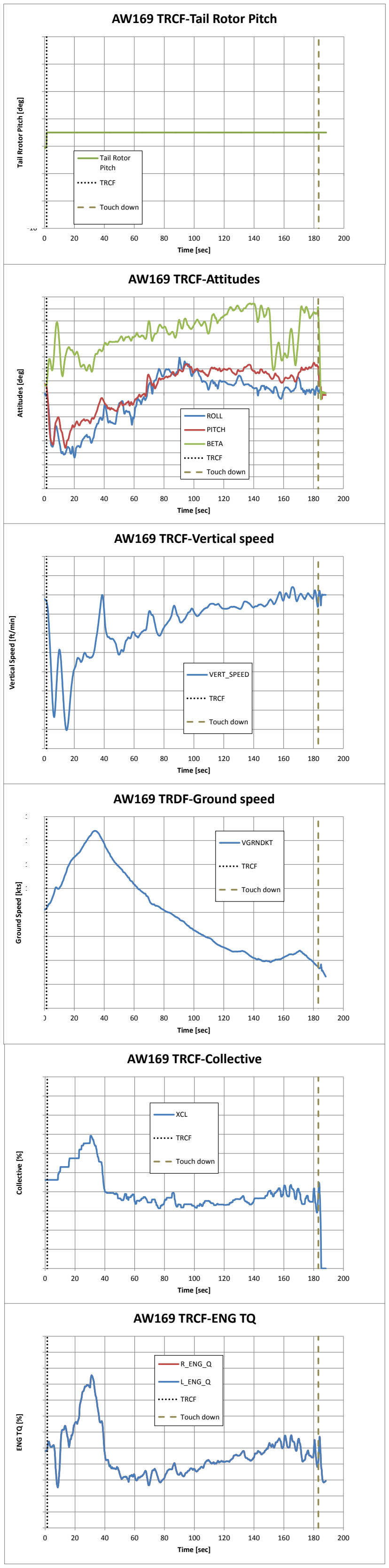


Figure 9 - AW169 tail rotor control failure at mid speed

In Figure 9 the management of the entry phase after a tail rotor control failure from a straight and level flight at 80 kts is accomplished by the pilot without difficulty. The failure is in fact followed by a mild yaw left angular motion produced by the increase in tail rotor thrust.

The pilot first accelerate and then decelerate the helicopter to assess the controllability of the helicopter over a broad range of flight speed and finally perform a run-on landing at 20-30 kts ground speed, with acceptable landing parameters.

§

This piloted simulation campaign demonstrated the capabilities of the AW169 helicopter to be brought to the ground within the limits of safe landing. The manoeuvre was confirmed to be complex, with high expected pilot workload.

Although several successful landing simulations have been performed, it was not possible to highlight a precise piloting technique to properly handle the helicopter in the middle section of the manoeuvres between the entry and the final touchdown.

In the following are reproduced the pages of the Rotorcraft Flight Manual the Emergency procedure written in the Rotorcraft Flight Manual:

AW169 — AW169 - RFM Document N° 169F0290X001 — Section 3 Emergency and Malfunction Procedures

LOSS OF TAIL ROTOR EFFECTIVENESS

Loss of tail rotor effectiveness will result in a rapid yaw to the right and a loss of yaw control, possibly accompanied by noise or vibration in the tail section. The severity of the initial yaw rate will be determined by the airspeed, altitude, gross weight, center of gravity and torque settings at the time that the failure occurs. The effectiveness of the vertical fin in limiting the yaw rate and yaw angle will depend on the airspeed at the time of the failure, fin effectiveness increasing at higher airspeeds.

The following cues will be present:

- Aircraft increase of yaw rate;
- Loss of yaw control, pedals free but ineffective;
- Possible noise and vibration from the aft fuselage area.

Severe yaw rates will result in large yaw angles within a very short period of time and, depending on the flight conditions at the time of failure, it is possible that yaw angles in excess of 30° will be experienced.

Additionally, very high yaw rates will produce aircraft pitching and rolling making retention of control difficult without the use of large cyclic inputs, which are structurally undesirable. Finally, very high yaw rates will produce disorienting effects on the pilots. Therefore, it is vital that corrective action, as outlined in the following procedures, be taken quickly to prevent post-failure yaw rates from reaching unacceptable high levels.

In Hover

- **Lower collective to LAND IMMEDIATELY while maintaining attitude and minimizing lateral translation with the cyclic control;**
- **Select both ENG MODE knobs to OFF if time available.**

In Forward Flight

- **Move collective immediately to minimize yaw rate (lowering the collective to reduce yaw right / increasing the collective to reduce yaw left);**
- **Establish a suitable airspeed/rate of descent/attitude combination to reach a stable condition;**
- **At landing site assess running landing capability;**

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Section 3 Emergency and Malfunction Procedures — AW169 - RFM Document N° 169F0290X001 — AW169

- **If a running landing cannot be carried out with a suitable power and speed, shutdown engines;**
- **Carry Out AUTOROTATIVE LANDING PROCEDURE ON LAND** page 3-26 **or AUTOROTATIVE LANDING PROCEDURE ON WATER** page 3-28.

Note

- Land into wind;
- Raising or Lowering the collective while maintaining NR within limits may be effective in helping control sideslip. (Increasing collective, nose left).

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CONCLUSIONS AND WAY FORWARD

The tail rotor loss of efficiency failures can produce hazardous-catastrophic flight conditions for helicopters and require specific attention during the development and the certification of the product. Being the not testable in flight it was decided, in accordance with the Certification Authority to use a simulation approach instead.

The AW169 simulation model was demonstrated, through a validation process against flight test data (both steady and dynamic), to be adequate to be used in the AWARE simulator to perform pilot-in-the-loop simulations of the recovery manoeuvres from a loss of tail rotor effectiveness failure.

The simulations demonstrated the capability of the helicopter to be brought to a safe landing, with several successful repetitions; the tests confirmed the high workload level of the manoeuvre and provided elements for the definition of the recommendations for a recovery.

The results collected during the simulation sessions were used along with in-house experience and best practices to write the recovery procedure from a tail rotor loss of effectiveness failure as reported in the AW169 Rotorcraft Flight Manual.

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REFERENCES

[1] CS-29 – Certification Specification for Large Rotorcraft, Amendment 2 dated 17/11/2008

[2] AC – 29-2C Advisory Circular, Certification of Transport Category Rotorcraft - Change 3

[3] Preatoni, Ragazzi, Ceruti, Saggiani - Flight Mechanics Simulator For Rotorcraft Development – ICAS 2008

[3] Bianco-Mengotti, Del Grande, Ragazzi, La Barbera, Lo Coco, "AW139 SHIP INTERFACE: EXPERIMENTAL TRIALS AND SIMULATIONS" AHS 69th Annual Forum, Phoenix, Arizona, May 2013