HELICOPTER AUTOPILOT FLY-AWAY MODE AFTER LOSS OF ENGINE

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Abstract

Without doubt, one of the biggest concerns during helicopter Search and Rescue operations is the possibility of engine failure whilst hovering at low height over the sea which can, in extreme cases, lead to the loss of the aircraft and crew. A successful Fly-Away manoeuvre can prevent unnecessary ditching; however, an optimised Fly-Away profile is difficult to manually perform with any degree of consistency. This paper addresses the design and implementation of an Autopilot Automatic Fly-Away Mode (FLYAW) to be used in a multi-engine aircraft following loss of one engine. The target platform is the AW101-612 helicopter and the fundamental objectives of the FLYAW Mode are:

- reduction in the delay time to initiate the Fly-Away in response to the engine failure;
- improved consistency and repeatability in execution of the Fly-Away technique;
- reduced pilot workload;
- to maintain the Fly-Away manoeuvre height loss within the published figures for manual execution of the technique.

A simulation and flight test study has been undertaken to assess the FLYAW Mode in operation at a wide range of initial conditions. The conclusions from these activities are that the fundamental objectives have been accomplished. The mode brings enormous benefits that directly impact aircrew safety and reduce the probability of unnecessary aircraft ditching.

1 INTRODUCTION

Without doubt, one of the biggest concerns during helicopter Search and Rescue (SAR) operations is the possibility of engine failure while hovering at low height. In this scenario, the pilot needs to plan the recovery action in case of engine failure in advance, even before the actual engine failure happens - to ditch in the water or to perform a fly away manoeuvre. This decision is based on the current conditions (height, wind, power margin). If possible, safe recovery of the aircraft is obviously preferable to ditching; however, the Fly-Away manoeuvre is not simple and the outcome (height loss during the manoeuvre) is a direct result of the total reaction time (pilot recognition of the failure plus pilot reaction time) and piloting skills. Even if the aircraft has enough height to perform a safe fly away manoeuvre, a slow recognition of the engine failure, a slow reaction to start the Fly-Away manoeuvre or even flying an incorrect Fly-Away profile may oblige the pilot to ditch the aircraft.

Minimising unnecessary ditching is of paramount importance, as statistics from both the UK and USA indicate that although 88% of controlled ditchings are successful, approximately 50% of the survivors die after safely exiting the aircraft but before rescue arrives [1].

In a scenario of engine failure while hovering at low height, the pilot is in a highly stressful situation and, to perform a correct Fly-Away profile, must adopt a complex control strategy to accelerate immediately and control the rotor speed (Nr) through use of the cyclic and collective controls respectively. The coordination of the two inputs is extremely demanding for the average pilot and an incorrect input in either axis could mean excessive height loss or loss of rotor speed to the point that the aircraft is no longer recoverable and finishes in a scenario worse than a normal controlled ditching.

This paper addresses the design and implementation of a new Automatic Fly-Away Mode (FLYAW) - implemented in an Automatic Flight Control System (AFCS) - to be used in a multi-engine aircraft after the loss of one engine during SAR missions at low height over the sea.

2 AIRCRAFT PLATFORM

The AFCS FLYAW mode has been designed and implemented on the AW101-612 helicopter (Figure 1).

Figure 1 – AW101-612 Helicopter

The AW101-612 is equipped with the AWAC200 AFCS which has been developed by Leonardo Helicopters specifically for this platform. The AWAC200 is a Dual Channel, 4 - axis, Digital Autopilot designed to the highest integrity standards (DAL-A) to improve crew safety and increase operational capability.

The AWAC200 provides stability augmentation, long-term attitude retention and a comprehensive suite of Flight Director modes that extend to Navigation, Approach and SAR modes. These modes, coupled with a number of built-in safety functions to manage power and protect against controlled flight into terrain, serve to reduce pilot workload and permit operation with Dual or Single Pilot in Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) operations.

3 FLY AWAY MANOEUVRE

After the loss of one engine in hover, at normal operating All Up Mass (AUM), the AW101, like most helicopters, no longer has sufficient power available to maintain height. To recover, the pilot must accelerate immediately to an airspeed that will allow the aircraft to hold the height or even to climb. A specific piloting technique, known as a Fly-Away manoeuvre, is manually executed to achieve this objective whilst simultaneously minimising the height lost during the manoeuvre.

The current AW101 Hover Fly-Away Technique from [2] is described below:

1. On recognition of the engine failure, Rotate the aircraft nose down rapidly through 15° from the hover datum, to initiate an acceleration to 45 knots Indicated Airspeed (IAS);
2. Adjust collective as required to minimise height loss and to limit rotor droop to the range 93 to 95% Nr, with a minimum of 90% Nr, whilst observing the 2 minute One Engine Inoperative (OEI) power limits;
3. As soon as the airspeed begins to indicate, raise the nose to minimise height loss and maintain the acceleration to 45 knots IAS.
4. Continue to manage Nr;
5. At 45 knots IAS, adjust attitude to maintain speed, lower collective to obtain Continuous OEI power at a nominal 102% Nr;
6. Climb away as required.

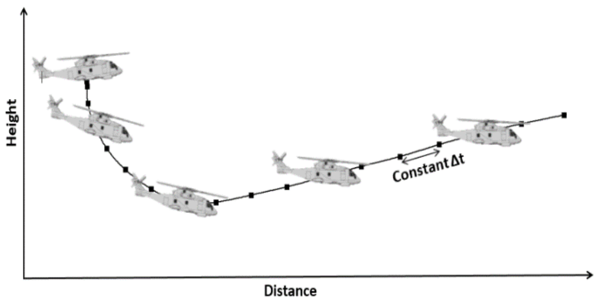


Figure 2 – Fly-Away Diagram

The expected height loss for any given initial condition (aircraft loading, outside air temperature, pressure altitude and airspeed) when adopting this piloting technique is published in the AW101-612 Rotorcraft Flight Manual (RFM) [3] to inform the pilot of the minimum recoverable height that can be maintained in the hover. Nevertheless, in practice, the actual height loss can vary considerably and is profoundly influenced by the recognition and reaction times of the pilot and consistent, repeatable execution of the technique. As shown in Figure 3, the latter is particularly problematic as the technique is highly demanding and, to comply with Civil Certification requirements (CS-29), the technique description is deliberately not over-prescriptive such that the published height loss is determined “with normal piloting skills and without exceptionally favourable conditions” [4].

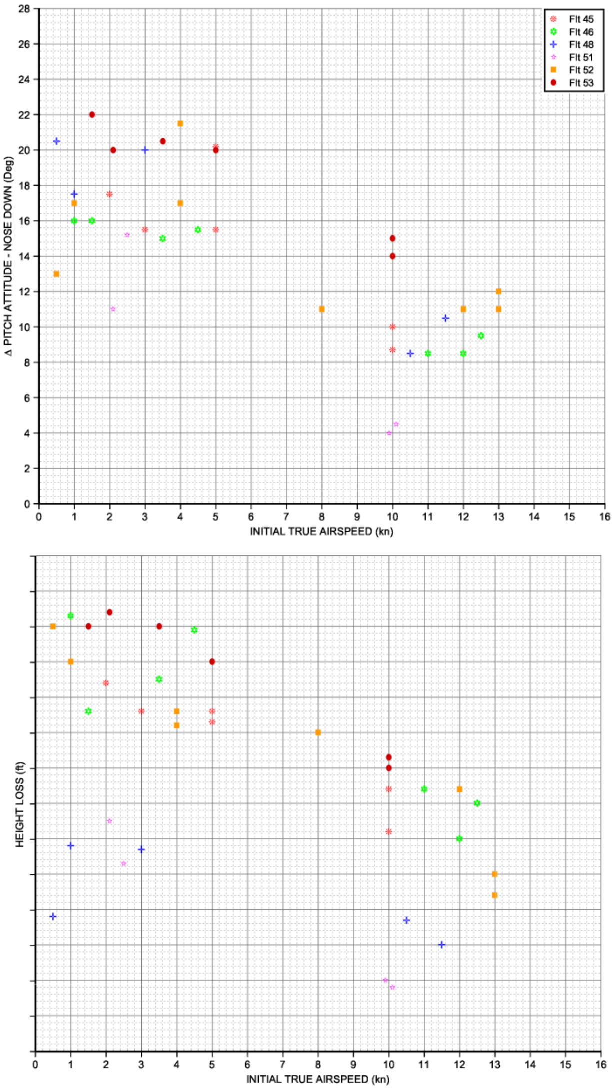


Figure 3 – Fly-Away Manual Manoeuvre Variability

Automatic detection and execution of the Fly-Away technique following an engine failure facilitates a level of consistency and repeatability that is not possible with a pilot in the loop, thereby reducing the inherent variability in height loss during the manoeuvre.

4 AUTOMATIC FLY AWAY MODE

The fundamental FLYAW Mode requirement is to accelerate to safe airspeed while minimising height loss. The design to satisfy this requirement has been implemented in three specific phases.

4.1 Phase 1 - Failure Detection and Fly Away Mode Engagement

The decision to perform a vertical reject (ditching or emergency landing) or a Fly-Away manoeuvre after an engine failure is always a pilot decision, so the engagement of FLYAW mode can never be fully automatic without any pilot intervention. For that reason, two different mode engagement methods have been implemented. The first method consists of a pilot manual engagement, following the loss of an engine, through a single press of a dedicated button (GA/TU pushbutton) on the collective grip. With this approach, even though the Fly-Away manoeuvre is performed automatically by the AFCS the outcome is still highly dependent on the pilot total recognition and reaction time to manually engage the mode. Moreover, there is always the risk that, in this stressful situation, the pilot inadvertently presses the wrong button adding further delay and, consequently, height loss.

Alternatively, to ensure the minimum possible delay time, and to minimise the possibility of pilot error, an automatic engagement of the FLYAW mode in response to an engine failure is possible if previously armed by the pilot. With this method, the mode arming remains the responsibility of the pilot; however, mode engagement becomes independent of pilot recognition and reaction time.

Both FLYAW mode engagement methods rely on the engine failure detection by the AFCS. Typically, the AFCS receives the engine failure information from the avionic systems or directly from the engines (on AW101, the AFCS receives this information from display units).

To increase redundancy and minimise the possibility of non-detection or even delayed detection of the engine failure due to a problem in the avionics system, the AFCS uses the engine failure detection from the display units but also runs an independent algorithm to detect the engine problem directly based in the engines NG and torque. The AFCS algorithm is presented in Figure 4

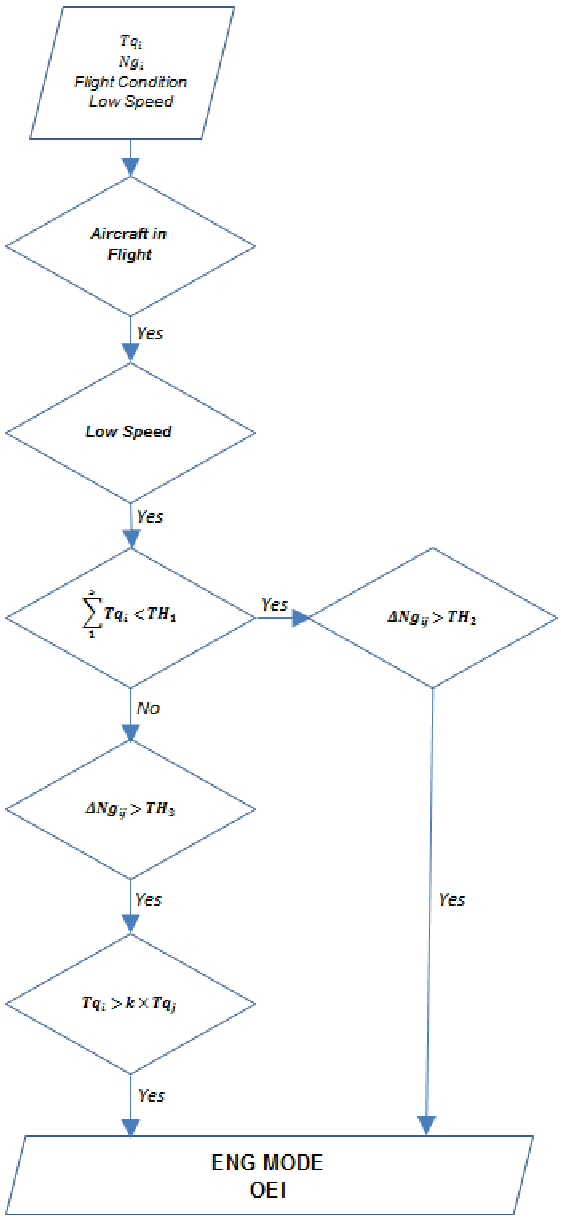


Figure 4 – AFCS Engine OEI Algorithm

4.2 Phase 2 - Pitch Down and Low NR Control

Immediately after engagement, the FLYAW mode commands a rapid pitch down to accelerate the aircraft longitudinally. Simultaneously, in the collective axis, all the power limitation protections are lifted and replaced by an Nr control law that manages a controlled reduction of Nr while the remaining engines operate with maximum torque (on AW101 the engines limit the torque at 136% to prevent aircraft transmission damage).

The end of this phase is achieved as soon as a pre-defined airspeed threshold is reached. Typically this phase lasts only 5s to 10s if starting from hover condition, however, it is the most critical phase in terms of aircraft control for the Fly-Away manoeuvre.

4.2.1 Initial Rapid Pitch Down

The magnitude of the initial, rapid, pitch down manoeuvre is key – too small and the aircraft will operate for too long at high induced power and lose height, too large and the aircraft will sacrifice height to sustain the acceleration.

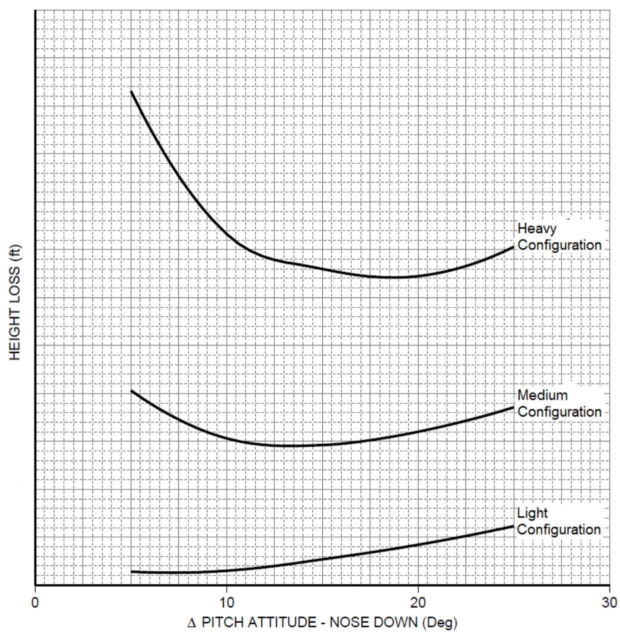


Figure 5 - Height Loss vs Initial Pitch Attitude Delta

Figure 5 shows the Fly-Away height loss variation with different pitch attitude deltas in different weight configurations– information gained from previous, in-house, simulation studies. A pitch attitude delta of 15-20° is the optimum pitch change for minimal height loss. Consequently, upon engagement of the FLYAW mode, the AFCS will immediately command the aircraft to perform a pitch down manoeuvre that targets a precise pitch attitude delta of 15° at approximately 10 °/s.

4.2.2 Minimum Rotor Speed

Nr management during the Fly-Away manoeuvre is a balancing exercise between two factors that both affect the final height loss.

Whilst the engines are supplying maximum torque, any increase in collective pitch will produce an increase in drag resulting in a reduction of Nr. However, during this process the rotational energy of the rotor is converted to aircraft potential energy resulting in a temporary, beneficial increase of lift that can be used to arrest the aircraft initial sink and accelerate the aircraft away from the high power hover condition.

On the other hand, due to the engine torque limit, any reduction of Nr also results in a corresponding reduction of engine power that manifests itself in the long term as an increase of height loss.

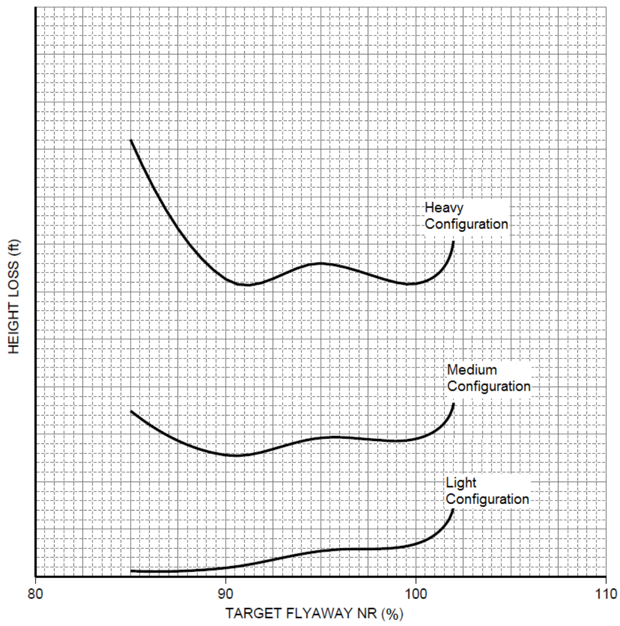


Figure 6 – Height Loss vs Nr

Figure 6 shows the Fly-Away height loss variation with different target Nr – information gained from previous, in-house, simulation studies. An Nr target of 92-96% is the optimum for minimal height loss. Consequently, upon engagement of the FLYAW mode, the AFCS will immediately command a controlled reduction of Nr to 95%. A dedicated control law has been designed to manage the Nr profile.

4.3 Phase 3 - Speed Control and Nr Recovery

As soon as the phase 2 airspeed threshold has been reached, the AFCS automatically reverts from pitch attitude control to airspeed control in which the final target speed is the aircraft Minimum Power Speed, Vy (on AW101, the Vy is 80kt). During this final phase the nose of the aircraft is typically raised to control a constant acceleration of approximately 1.5kt/s. If FLYAW mode is engaged above the phase 2 airspeed threshold, FLYAW mode starts immediately in phase 3 and directly controls the acceleration to Vy without the initial rapid pitch down.

In this phase, the Nr reference is increased to a value close to the nominal Nr (the new Nr reference used is 99.5%). The remaining engines will continue to operate at maximum torque; however, the engine power produced is increased as the Nr increases. The Nr will only fully recover the nominal value when the maximum torque from the remaining engines is no longer required to acquire and hold the FLYAW mode rate of climb target.

5 METHODOLOGY

Following completion of the FLYAW mode design phase, the test phase was commenced. The methodology of test was to initially verify the results of the FLYAW mode design in a Hardware-in-the-Loop (HIL) test rig environment prior to progression to flight test. The HIL facility incorporates a high fidelity flight model that is representative in terms of aircraft dynamics, engine performance and sensor performance.

The HIL facility was used to:

- Demonstrate compliance to the pertinent system requirements and aforementioned performance objectives

- Provide an efficient means to tune the FLYAW mode prior to the flight test activity

Following completion of the rig test phase, the FLYAW mode was tested in flight on a AW101 development aircraft (designated CIV01) with representative aerodynamic and engine performance as well as mass properties.

In order to protect the aircraft transmission from the high torque that can be supplied by the engines following an engine failure, all tests were performed in an engine Training Mode that limits the operative engines torque to 112% during the OEI condition. This limit results in greater height loss than a real engine failure (where the engines are permitted to go to 136% torque); however, this is accounted for in the data analysis by validating the observed height loss for any particular Fly-Away test against height loss charts specific to the Training Mode configuration. Furthermore, testing of the FLYAW mode in the HIL rig environment was performed with the true OEI engine torque limits.

Flight tests were conducted at the Leonardo Helicopters facility in Yeovil, England, and the results are presented in the following section.

6 RESULTS

6.1 HIL Rig Test Results

Figure 7 shows the HIL Fly-Away Rig Test result of a simulated aircraft at 15000kg, Pressure Altitude of 500ft and Outside Air Temperature (OAT) of 15°C for a true engine failure case (without engine Training Mode) where the engines limit to 136% torque.

The Fly-Away phases described in Section 4 can be clearly seen in the figure which presents the rapid pitch down, control of Nr, and controlled acceleration to Vy.

The simulated height loss for the test configuration is 128ft - an improvement over the manual manoeuvre in the RFM [3] which predicts a Height Loss of 170ft.

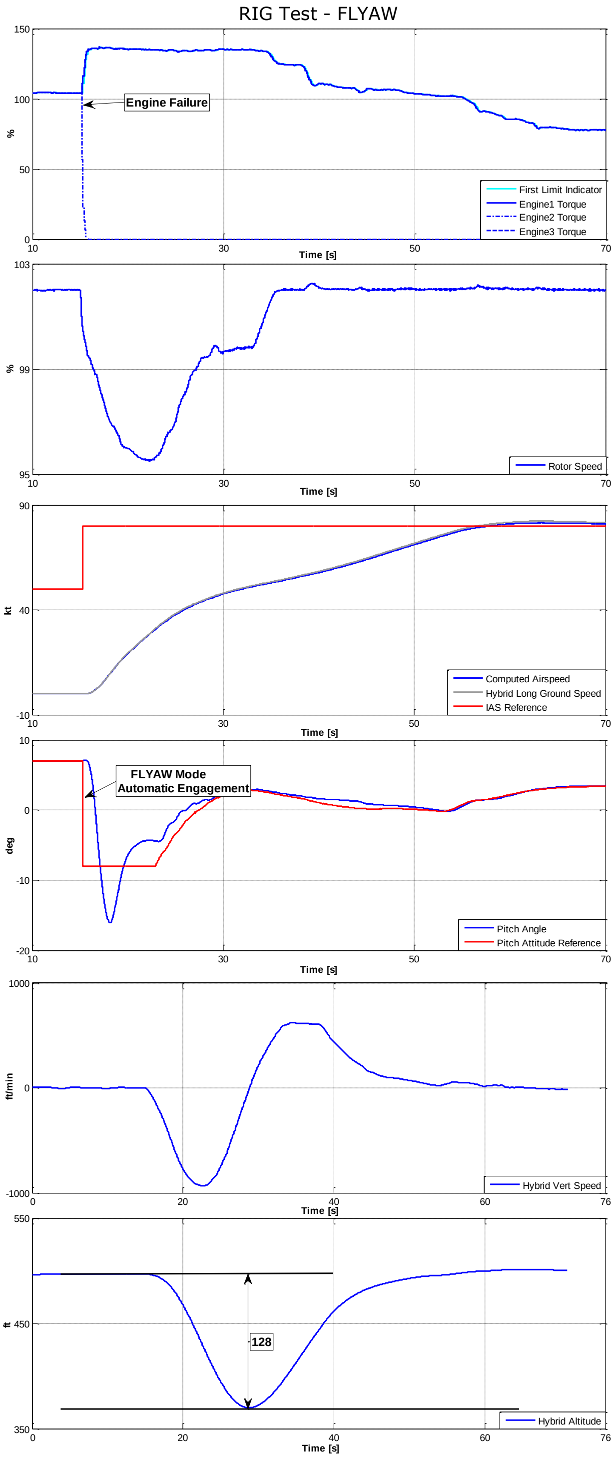


Figure 7 – FLYAW Mode HIL Rig Test Results

6.2 Flight Test Results

Figure 8 presents the time histories of the key variables recorded during a FLYAW mode test on the development aircraft at mid weight (13860kg) and low speed (12kts) condition. As described in Section 5, the engines were limited by the Training Mode to 112% torque as can be seen in the figure. The similarity of the aircraft response to that of the HIL rig tests, presented in Figure 7, is evident.

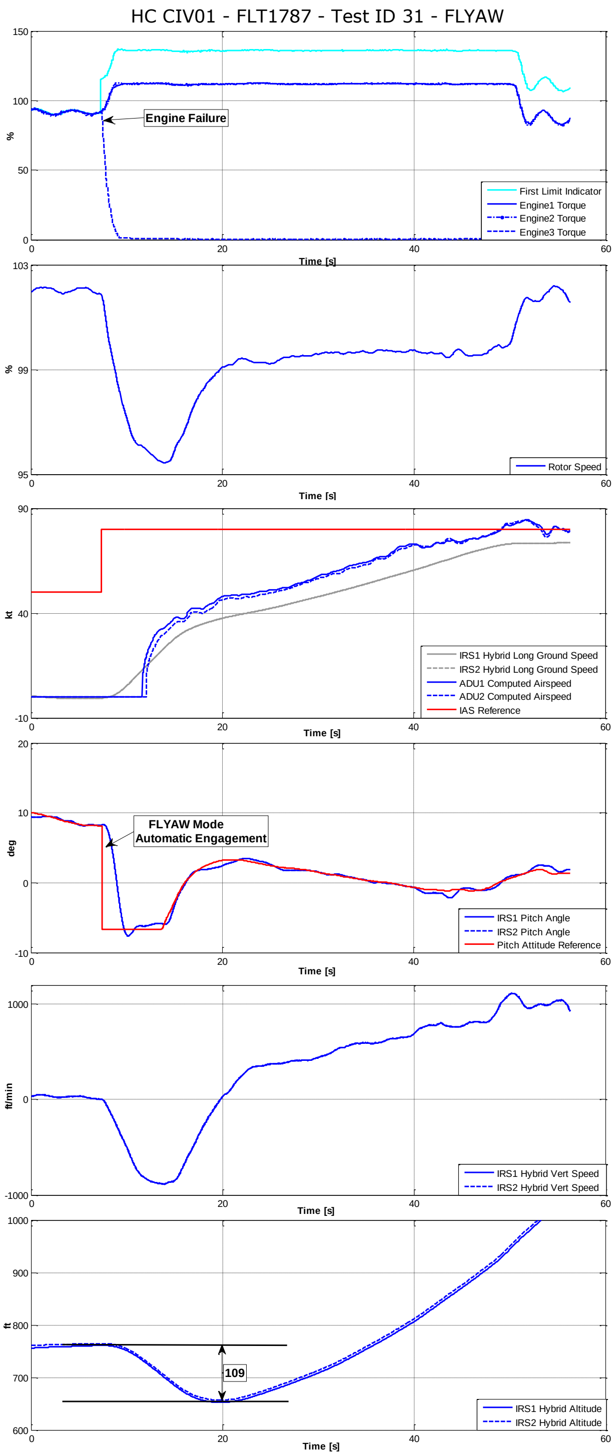


Figure 8 – FLYAW Mode Flight Test Results

The complete results of the FLYAW Mode flight test activity are presented in Figure 9. In total, 31 Automatic Fly-Aways were performed in both light and heavy configurations and at varying initial airspeeds.

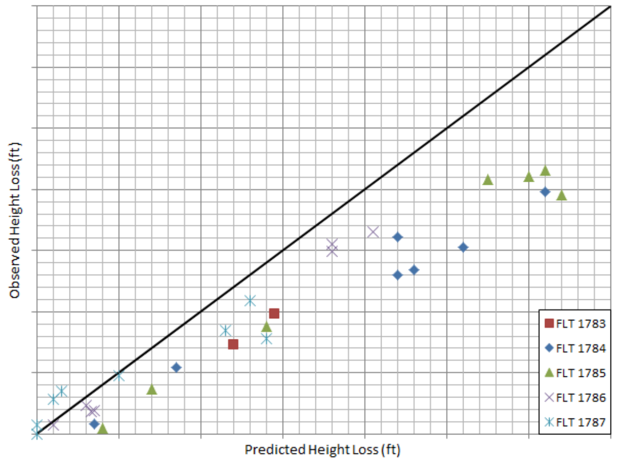


Figure 9 - Flight Test Activity Observed Height Loss Vs Predicted Height Loss

In all but the lightest aircraft configurations (less than 12,000kg AUM), the automatic Fly-Away manoeuvre demonstrated a reduced height loss than that predicted. The most marked improvement is for the heavy configurations at low speed.

6.3 Manual Manoeuvre Vs FLYAW mode

Comparisons between manually executed Fly-Away manoeuvres - performed by Leonardo Helicopters Test Pilots - and AFCS automatic Fly-Aways have been conducted under the same test configuration and are reported in Figure 10

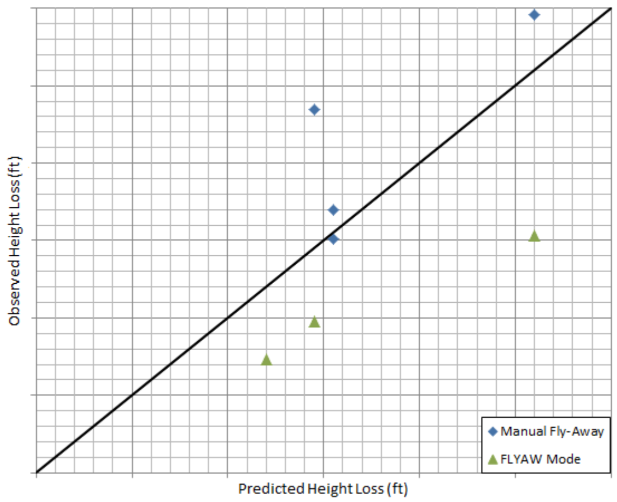
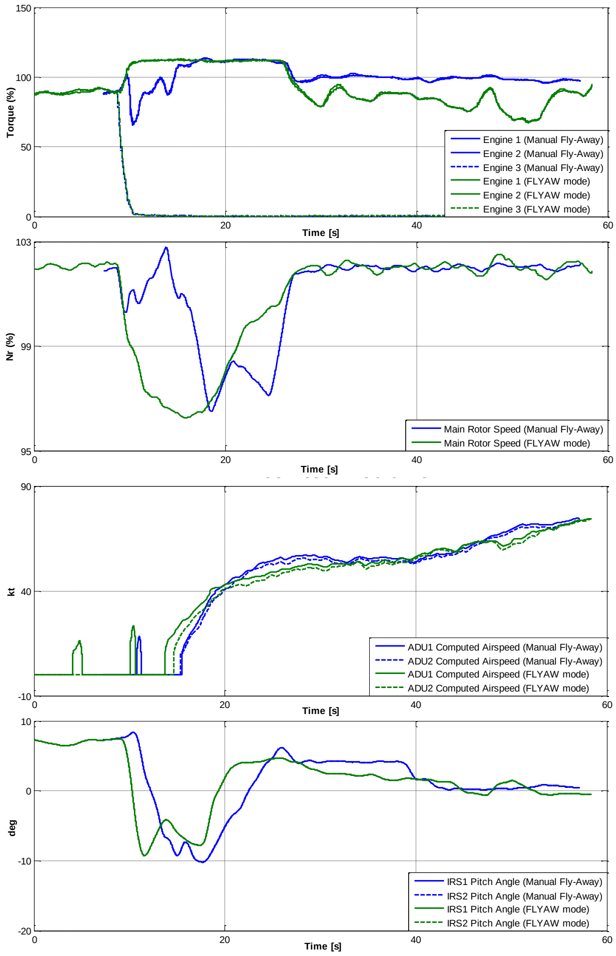


Figure 10 - Comparison between Manual and Automatic Fly-Aways

One such comparison is presented in Figure 11: in blue, the data of a manual Fly-Away (CIV01 Flight 1783 Test ID50); in green, the data of the automatic FLYAW mode (CIV01 Flight 1783 Test ID48). The dramatic improvement in height loss shown for the automatic Fly-Away results from an improved Nr control together with a reduced delay time to initiate the pitch down manoeuvre, accelerating faster out of the dangerous low speed domain.

FLT1783 Test ID 50 & 48



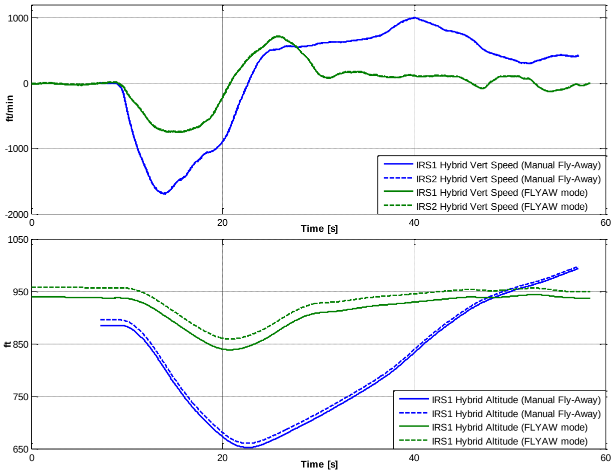


Figure 11 – Example Comparison between Manual and Automatic Fly-Away

6.4 Engine Failure Detection

Comparison of the OEI detection time between the algorithm within the AFCS and that produced by the Cockpit Display Units is presented in Table 1. The results were obtained on the production aircraft (NOR01) and confirm that the algorithm, presented in Figure 4, is capable not only of detecting the OEI state but also of detecting it with a reduced delay time of up 1.1 seconds with respect to the external avionics equipment detection time which is crucial to minimise the height loss.

Flight (Production Aircraft NOR01)	Test ID	Weight Configuration	Engine Failure Detection Time (s)	
			Display Units	DAFCS Algorithm
91	11	Heavy	**1.97**	**0.83**
107	21	Light	**2.11**	**1.59**

Table 1 – Engine Failure Detection Results

The impact of increased delay time on height loss has been investigated via simulation in the HIL rig test environment and the results are presented in Table 2 and Figure 12. The simulations have been performed with no wind at a pressure altitude of 500ft and OAT of 15°C.

Weight Configuration	Head Wind (kt)	Predicted Height Loss* (ft)	Delay Time of FLYAW mode Engagement	Observed Height Loss (ft)
Heavy	0	170	0s (Auto Engagement)	128
			1s	151
			2s	169
			3s	194
Light	0	55	0s (Auto Engagement)	11
			1.6	28
			2.7	41

Table 2 – Impact of Engine Failure Detection Delay Time on Height Loss

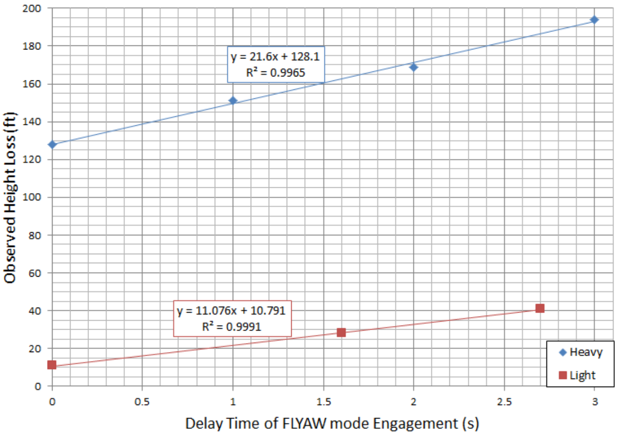


Figure 12 - Impact of Engine Failure Detection Delay Time on Height Loss

For a light weight configuration, approximately 11ft of additional height loss is observed for every second of delay. Repeating the same tests with using a heavy weight configuration, the rate at which the total height loss is increased per second of delay time is double (+21.6ft per each second of engine failure detection delay time).

7 DATA ANALYSIS

Results obtained through both simulation and flight test of the FLYAW Mode have been extremely positive. Simulations, using a true engine failure, demonstrated a reduced height loss in all the scenarios tested including those with a 2s delay time from the engine failure.

In all flight tests performed except those with the lightest aircraft configurations (less than 12,000kg AUM), the automatic Fly-Away manoeuvre demonstrated a smaller height loss than that predicted. The most marked improvement is for the heavy configurations at low speed. This improvement is due to optimum Nr control together with a reduced delay time to initiate the pitch down manoeuvre, accelerating faster out of the dangerous low speed domain. Both of these factors can be seen directly in the comparison against the manual manoeuvre presented in Figure 11. Immediately after engine failure detection, as a first reaction, the pilot lowers the collective to avoid the excessive Nr droop and only then performs the pitch down. Even though the pilot was expecting the engine failure to happen and reacted almost immediately (observed pilot reaction times between 0.52s and 0.84s - lower than the required 1.5s for aircraft certification), the pitch down manoeuvre was initiated with a delay time 1.1s to 2s greater than the FLYAW mode. Also, the pilot's first reaction tends to lower the collective excessively (in anticipation of an Nr droop) and keep it low for the first 2-5s when compared to FLYAW mode.

For the cases where the aircraft has a power margin large enough to permit the aircraft to maintain height at the trim condition in OEI (for example, the cases with light weights below 12,000kg AUM), the height loss has been observed to be marginally increased with respect to that predicted. This is because the magnitude of the initial pitch down is not modified based upon power margin and results in a pitch down which is too extreme for these cases. Notwithstanding this, the height loss observed in these cases is below the Minimum Usage Height defined for the AFCS modes and as such a margin of safety is always preserved.

All flight test points have been performed with the engines operating in Training Mode and, as such, the engines limit the torque to 112% as opposed to the 136% that is available in a true OEI condition. Consequently the height loss observed is greater for all test points than that which would be expected in a real scenario due to the extra power available. Notwithstanding this, all predicted height loss figures have been generated from charts which take Training Mode into consideration and as such provide a representative comparison value.

8 FUTURE WORK AND POSSIBLE IMPROVEMENTS

Although the results obtained in testing the FLYAW Mode are positive, some areas of qualification testing remain outstanding.

Due to time and environmental constraints, only a narrow set of ambient conditions were tested during flight and simulation tests - nominally 15-23°C and between 500-1000ft Above Sea Level (ASL). More flight and/or simulation tests need be performed to confirm FLYAW mode performance in the complete aircraft flight envelope.

In all FLYAW mode tests, an approximation of the head wind condition is reported so the predicted height loss can be obtained from the charts. However, the charts are based in a zero cross wind condition - typically the Height/Velocity (H/V) trials are performed with wind speeds lower than 5kt - which was not always verified in the reported flights and may have some impact on the results obtained (in some cases the cross wind reached 10kts). Proper H/V trials performed with low wind speeds will be performed in the future for the full qualification and certification of the FLYAW mode.

All manual Fly-Aways used to compare with FLYAW mode in Section 6.3 have been performed by the same flight test pilot. Allowing additional pilots to manually conduct the manoeuvre would give more statistical evidence to conclude the true benefits the FLYAW mode can give in comparison to an operator pilot.

It is recognised from the flight test results that when the aircraft has power margin large enough to maintain height at the trim condition in OEI, the FLYAW mode does not show an improvement in height loss over that predicted. Further development could ensure optimised pitch down profiles based upon power margin. For the conditions described, the pitch down profile could be updated to demand a reduced pitch down delta at mode engagement, thus reducing the initial aircraft acceleration in favour of maintaining height.

Even with the new FLYAW mode, the decision to Fly-Away or ditch the aircraft is ultimately left to the pilot. The evaluation of the Fly-Away performance data to automate this decision goes beyond the concept of an AFCS mode. Nevertheless, in the future this delicate decision could be guided by an algorithm based upon the RFM height loss charts [3] (resident in an Avionic System) that could give the Go/No-go signal to the pilot, removing the risk of pilot misjudgement in a stressful environment.

9 CONCLUSIONS

An AFCS mode to perform an automatic Fly-Away manoeuvre in response to an engine failure during SAR missions at low height over the sea has been designed, implemented, and tested on the AW101-612 platform.

In total, the flight test of 31 Automatic Fly-Aways has been performed over a wide range of test conditions. The results have been extremely positive and evidence the following benefits over the manual technique:

- Reduction in height loss;
- Implicit reduction in pilot workload (due to the manoeuvre being initiated automatically and being performed hands-off);
- Reduced variability in height loss figures for consistent test conditions and aircraft configuration.

The overall, combined effect of these benefits is the introduction of a highly desirable AFCS mode that has a profound impact on aircrew safety. It significantly reduces the probability of unnecessary aircraft ditching, particularly in scenarios where the pilot experiences high workload that can delay detection and reaction to the failure.

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