Flight test process for the cooling of a reciprocating engine on a Remotely Piloted Aircraft System

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ABSTRACT

Testing of engine cooling effectiveness, on Tactical Remotely Piloted Aircraft Systems (RPAS), requires addressing peculiar aspects. Reciprocating engines with pushing propeller are typically installed on the rear of the fuselage, while a payload is installed under the aircraft belly. The pusher propeller configuration negatively affects the engine cooling, since the air intakes are not located behind the propeller disk, where the dynamic pressure is higher. Moreover, a payload installed upstream the air inlet may also impair cooling performance, due to the induced aerodynamic perturbation.

Flight testing is then an essential part of engine cooling verification, to ensure that operational use of *tactical RPAS is not limited by the risk of engine overheating. This paper describes the experience of the engineering and flight test team of the Falco Evo Tactical RPAS, for the verification of an engine cooling upgrade, aimed at ensuring higher power delivery in hot climates.*

The flight test process was triggered by engine cooling performance requirements, which had to balance the maximum power available and the aircraft endurance performance, an essential parameter for a Tactical RPAS.

The flight test plan was shaped on requirements and theoretical models to identify the essential set of test points, to maximize the efficiency of data collection and minimize flight campaign costs. Test hazard analysis and specific training at simulator were performed to evaluate potential hazards and identify relevant mitigations with the aim of reducing the risk level. The hazard analysis had to consider both conditions common with manned aircraft and aspects peculiar to the RPAS. Relevant information for test execution were condensed in flight test cards, which represent the driver document for flight test operations.

The flight campaign consisted in the execution of the planned set of test points in a build-up approach. Safety of flight, data gathering efficiency and cost-effectiveness were achieved at the same time. Data analysis and reporting focused on the peculiar test objectives, state of compliance to each relevant cooling requirement was evaluated, including the impact of the under-belly payload installation. Finally, it was possible to collect feedback to tune the engine control algorithms, in the light of the new performance.

1.0 INTRODUCTION

The Falco is a Tactical RPAS which entered in service in the second half of the 2000s. The first operational configuration of the air vehicle (the "Falco XN" version, see Figure 1) has 7.3 meters wingspan and 490 kg maximum take-off weight; it is based on a proven aspirated gasoline engine, delivering 80 HP at sea level.

Figure 1-1: the Falco XN air vehicle

The endurance of the Falco XN well exceeds 10 hours in standard ISA conditions, but is typically around 6 - 8 hours in a realistic mission scenario, in hot climates, with air temperatures on the ground well exceeding ISA conditions. The use of Aviation gasoline in a military environment requires a dedicated logistic effort.

In the light of the above, the Company (Selex ES, former name of what is nowadays a branch of Leonardo) decided to invest into an evolution of the Falco XN platform, in order to cope with the Customers' requirement for a longer endurance and multiple sensors on-board the air vehicle. The Falco Evo was then conceived and developed. While a substantial portion of the original UAS was preserved (overall architecture, avionics, fuselage, Ground Control Station, etc.), modifications were made to the areas where a benefit could be expected, in terms of mission performance and logistics: as main modifications, the wingspan and tail boom were enlarged and, in a second phase, the gasoline engine was replaced by a heavy-fuel turbocharged engine.

The Falco Evo has now 12.7 meters wingspan and 650 kg maximum take-off weight (see Figure 1-2). The payload capability was also incremented, allowing to offer a wide range of mission sensors, including satellite communication. Typical payloads are multi-sensor Electro-Optical turrets, Synthetic Aperture Radars, ELINT, COMINT ad Communication relays.

SATCOM multi-payload configurations of the Falco Evo achieve 20 hours mission endurance in ISA conditions and exceed 15 hours in hot climates. Fuel logistics were also significantly simplified, since the Jet-A1 fuel is readily available on all military and civil airports, without the need for dedicated transportation and storage. The Falco Evo has then become a flexible platform, to be used in a variety of both civil and military scenarios.

The development of the new RPA propulsion system required addressing many topics: the new engine, indeed, whilst being able to provide a much higher performance with lower fuel consumption (with respect to the gasoline one), also required the development of new control laws and algorithms, to fully exploit its capabilities. Within the integration, engine cooling required a fine tuning, achieved in two steps.

Figure 1-2: the Falco Evo air vehicle

The first version of the engine cooling was based on the experience acquired on the previous gasoline engine and on the data received from the engine manufacturer. Cooling pack was sized and positively bench tested. Subsequent experience, collected during flight tests and operational activities, showed that the peak climb rate was successfully achieved, with engine delivering 100% of its performance, exceeding the vertical velocity requirement. However, in hot climates, with positive off-ISA conditions, a limitation arose: the maximum climb rate could be maintained only for a limited time, due to an increase of the oil and water temperatures. After an initial phase, the climb rate was to be limited and only 80% of the engine power could be delivered.

Such condition was not impairing the mission capabilities, but triggered a further upgrade: the full climb rate allowed by the engine became the requirement to be achieved. A dedicated improvement campaign was then launched: relevant steps were re-assessment of the existing cooling system, tuning of the mathematical models, design, prototyping and bench, ground and flight testing.

The subsequent sections of this paper will describe the whole cooling improvement campaign, with focus on the process followed for the flight tests.

2.0 COOLING DESIGN AND INTEGRATION

2.1 Overview of the aircraft and engine

The Falco Evo aircraft is short-fuselage type with pusher propeller, high gull wing and boom-mounted empennages. The wing, whose airfoil is optimized for flying at low Reynolds, fits 6 flaperon and is divided into three elements: the left and right semi-wings and the central section. The H-shaped empennages are composed of a horizontal stabilizer, which supports two elevators, two vertical fins, which support the rudders, and two booms connecting the fins to the central portion of the wing. The propulsion system is accommodated into the rear compartment of the fuselage, in a pusher configuration. The heavy-fuel four-stroke engine has three-cylinders in line, direct injection and liquid cooling. The following Figure 2-1 shows a 3D representation of the Falco Evo engine, with propeller installed.

Figure 2-1: view of the Falco Evo engine and propeller

2.2 Cooling system characteristics

The Falco Evo engine cooling system has a wider purpose, with respect to the sole extraction of heat from the cooling liquids. Indeed, coolant and oil play their role in keeping the engine core temperature within prescribed limits; however, the boost pressure delivered by the dual stage turbocharger, at high power setting, raises the temperature of the air entering the combustion chamber ("charge air"). If not properly cooled down, such air can lead to severe damages to the engine. Therefore, the Falco Evo engine cooling also includes the charge air temperature reduction.

The study for the upgrade of the engine cooling system did not involve individual sub-systems, but rather encompassed the coolant, oil and turbocharging systems at the same time. Under this point of view, the perfect design would be achieved if oil, coolant and air reached their maximum operating temperature simultaneously, at the maximum engine power, in the desired operating condition.

Of course, reality is far from this scenario. Therefore, a good design needs to achieve a trade-off between cooling performances (achieved separately on oil, water and turbocharging systems) and the absolute maximum performance delivered by the engine. Moreover, key factors to be accounted for by an engine cooling design are the weight of the installation and the cooling drag. Unfortunately, both of them go in the direction of reducing the aircraft endurance.

The cooling system improvement on the Falco Evo took into account all the above considerations.

2.3 The engine cooling improvement

The project phases up to the preparation of the flight campaign can be summarized as design, bench testing on prototype engine and integration on aircraft.

2.3.1 Design

The input for the design phase was the definition of the engine performance, expressed as a limit of off-ISA temperature to be reached at Maximum Take-Off Power.

The design activity included:

- Sizing of the oil and water coolers;
- Sizing of the two stages of the intercooler (low-pressure and high-pressure);
- Installation architecture (location of the radiators, pipes, hoses);
- Sizing of the radiators' ducts (intake and outlet areas), with focus on minimization of the drag;
- CAD modelling;
- Finite element analysis of the mechanical installation;
- Design optimization through CFD analysis.

The output was a prototype installation with new ducted coolers for coolant, oil and charge air.

2.3.2 Bench Testing on prototype engine

The engine fitting the upgraded coolers was extensively run at bench. The tests were carried out in a configuration representative of mission conditions, in order to verify the global effectiveness of the proposed solution in terms of material used, mechanical strength and cooling performance.

The data collected during ground tests were also used by the engine manufacturer to update the engine thermodynamic model. Such tool, once correlated with ground test points, was then adopted to predict the expected oil, coolant and charge air temperatures in pre-defined flight conditions including altitude, outside air temperature and pressure, airspeed and engine load. Those data then represented a set of reference engine temperatures, to monitor the engine behaviour during flight and identify potentially abnormal conditions.

2.3.3 Integration on the aircraft

After completion of the ground tests at bench, a modified engine was installed on the aircraft, to be prepared for the flight campaign. The integration included physical checks of the installation, to ensure the absence of mechanical interferences between newly designed parts and aircraft engine frame. Moreover, adequate match and sealing between the coolers and their respective air ducts was ensured.

Particular attention was paid on the air ducts of the intercooler, where sensitivity tests had showed that small air leaks in the inlet duct caused a relevant drop in the charge air cooling performance.

Following the physical checks, functional engine tests were executed, to clear the aircraft for ground tests and flight.

3.0 PREPARATION OF THE FLIGHT TEST CAMPAIGN

3.1 Objectives and campaign requirements

Clear and sound objectives are essential to perform an effective flight test campaign. In the specific case of the Falco Evo engine cooling verification, objectives were identified well in advance with respect of the beginning of the flight activities. An iterative process was required, to take into account the technical requirements to be verified and proven, the safety aspects related to the test area and the limited budget and time available. Such approach involving engineering, airworthiness, safety and flight test departments, allowed to reach an agreement on the following objectives:

- Verify the air vehicle performances during take-off in TOGA;
- Verify the air vehicle performances during second segment climb at TOGA power;
- Verify the air vehicle performances and rate of climb at maximum continuous power (MCP);
- Verify the air vehicle performances and rate of descent at typical descent power.

The objectives were to be achieved in environmental conditions as hot as possible in the test area, with a RPAS configuration representative of ISR mission activities, including an under-belly 16" EO/IR turret.

Once objectives were clearly defined, the requirements of the flight campaign were developed; with respect to the main objectives stated above, the requirements add the metrics to ensure an alignment between the information required by the engineering department, the purposes of the flight tests and the other constraints. Clear requirements are the key to perform the flight test activities in the most efficient way, by maximizing data collection while keeping costs within budget.

Requirements were classified in two groups. The first group, airworthiness-based, was defined by collecting information from the reference regulation (AEP-4671 - USAR 1043 (Cooling test) and USAR 1047 (Cooling test procedures), see [1]).

The second group, performance-based, was related to the engineering input and to the specific performance to be verified, to be then compared with the data collected during engine bench tests. A summary of the main performance requirements is the following (for the sake of simplicity, only a subset of information is published):

- Take-off power (TOGA) shall be maintained for at least 2 minutes in ISA +30 °C, with 16" under-belly turret installed
- Climb power (MCP) (95%) shall be maintained till service celling in ISA +30 °C, with 16" under-belly turret installed
- Take-off power shall allow to comply with the expected rate-of-climb in ISA+30 °C, in known flight

envelope, with 16" under-belly turret installed.

- Descent power (35%) shall be maintained during continued descent in ISA -10C.

The requirements were reviewed and compared with the time and budget available, until they were considered viable. Where a full demonstration was not possible in flight (due to the high ground temperatures needed) post processing methods were defined, in order to ensure that the experimental activities were significant and allowed to collect usable data.

3.2 Flight Test Instrumentation

Engine cooling performance investigation requires the acquisition of a number of engine parameters, especially temperatures and pressures. As described above, extensive analyses and bench tests were performed before the flight campaign; such activities built a data set, which allowed to almost eliminate the need for dedicated Flight Test Instrumentation during the campaign. Indeed, the standard set of sensors installed on the engine, together with the data collected during the bench tests, provided the flight test personnel the potential of an immediate understanding of relevant temperature and pressure trends, including criticalities.

Engine sensors were then acquired through the standard engine monitoring unit of the Falco Evo, to be then routed to the GCS via the aircraft avionics and the RPAS Data Link, without the need for dedicated equipment.

Even if CFD had been performed during the design phase, the impact of the turret on the oil and coolant radiators was to be confirmed in flight. For this purpose, tufts were properly positioned in the coolant and oil inlet duct; the use of the turret IR sensor could be used to monitor the relevant areas, ensuring that air flow was mainly laminar and turbulence was reduced at minimum (see Figure 3-1).

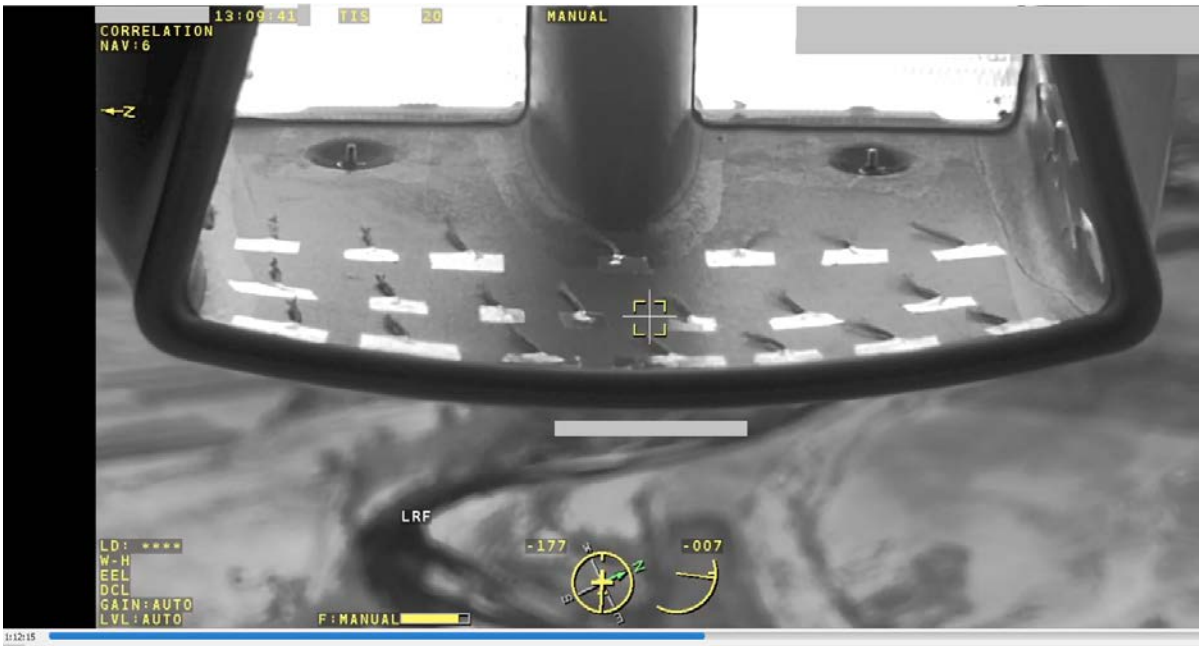

Figure 3-1: tuft image acquired by IR sensor in the air and oil inlet duct

The Ground Control Station disseminated the data collected to a Control Room (see below), for real-time monitoring.

In order to increase the awareness and reaction to relevant events, real-time parameter trends were displayed in the Control Room: engineering specialists could rely on such tools, also allowing the prediction of possible out-of-limit conditions.

3.3 Safety assessment and risk reduction

As required by the internal flight test process, a comprehensive safety case was prepared. The main specific hazard identified for the flight campaign was the engine overheat during takeoffs and climbs, due to engine cooling system ineffectiveness at high power settings and low speed. Engine overheat would possibly cause an engine partial power (possibly due to a failure of the turbocharger) or a flameout, leading to aircraft loss and damages on ground. Moreover, excessive engine cooling during descents was also identified as a possible hazard: since the Falco EVO features a Diesel engine, exceeding exhaust gas temperature (EGT) lower limits might lead to an engine flameout.

In addition to ground tests and theoretical predictions, the following procedures were applied to mitigate the risks and reduce their probability to an acceptable level:

- Climb test point sequence was conceived to guarantee a build-up approach, starting from higher airspeed and therefore higher values of inlet airflow available, down to best rate of climb speed. Build-up approach was also applied for descent trials, reducing step by step the power settings, preventing the lower limits from being exceeded.
- Distance from the airbase and flight test altitude were selected in order to guarantee a glide back.
- Knock-it-Off (KIO) were properly defined for parameters featuring dynamic and fast variations (especially EGT), in order to interrupt an ongoing test without exceeding the relevant limits.
- Engine telemetry live monitoring was available in the Control Room, with the possibility of a real-time prediction of variation for the critical parameters and their gradients.
- Flight area selection and safety analysis were performed, guaranteeing a segregated air space with no other traffic, adequate runway length, areas on finals to manage takeoff abort and emergency landing.

A list of corrective actions was also prepared to mitigate the risk severity, including:

- Definition of takeoff abort modes and escape maneuver after takeoff, consisting in an anticipated power reduction and consequent teardrop landing.
- Definition of the power reduction procedure and relevant power and altitude settings to be performed during the climb phase.
- Use of the parachute recovery procedure in case of an unsafe aircraft behavior.

The Flight Crew exercised at simulator on possible failures, both in calm air and with light wind and turbulence. Dedicated simulation sessions were also carried out, for takeoff abort maneuver and for the identification of the best procedure to manage the engine out pattern.

4.0 EXECUTION OF THE FLIGHT TEST CAMPAIGN

4.1 Personnel involved

Being the Falco Evo a consolidated platform, the resources for the flight test campaign could be tailored on the specific modification to be tested, thus allowing an efficient use of personnel. Besides a project manager, in charge of the logistic aspects of the activity, eight people were indeed necessary to execute the flight tests and process the data collected: the flight crew, the ground crew and the test personnel:

- the Flight Crew, operating in the Ground Control Station, was composed by three people:
  - Test Pilot;

  - Lead Flight Test Engineer, also acting as co-pilot, test conductor and electro-optical turret operator;
  - Data Link / GCS technician.
- the Ground Crew, responsible for the maintenance and pre/post-flight ramp activities. This crew, a standard also required by the Falco Evo during routine operations, includes two resources:
  - mechanic technician, in charge of the propulsion system and the air vehicle structure, and
  - avionics technician, responsible for the electrical distribution and electronic equipment.
- the Test Personnel, operating in the Control Room, included three resources:
  - the Test Director, in charge of clearing test points within the build-up approach, managing go/nogo decisions and communicating with the Flight Crew.
  - two specialists, to monitor the air vehicle and engine performance. A specialist was from the Leonardo engineering, the second specialist came from the engine manufacturer design organization.

Post-flight data processing and analysis was performed by the Lead Flight Test Engineer and by the two specialists.

4.2 Overview of the flight tests

Engine cooling was tested by performing takeoffs, climbs and descents (C&D) with two aircraft configurations: clean and ISR (the latter with belly-mounted EO/IR turret). Both configurations were tested at minimum and maximum take-off weight, with forward center-of-gravity position.

Worst test conditions in terms of outside air temperature (OAT) and altitude were considered; tests were performed at low altitude and ISA + 25 °C (highest available in summer at the test site). Such conditions were adequate, to allow the post-processing verification of compliance, in the entire temperature range of interest. For time and cost optimization purposes, test points were arranged in four flights, one for each configuration (i.e. clean and ISR, minimum and maximum takeoff weight). Test points were selected to limit each flight to a maximum of 90 minutes, allowing the collection of significant data and, between each session, an adequate inspection of critical components and a preliminary processing, to understand if all data were usable or some test points had to be repeated.

Takeoffs were performed with TOGA power setting (100% throttle), cleared by a number of high speed taxi sessions, up to rotation speed. Climb and cooling performances were investigated for several speeds with Wide-Open Throttle (WOT) power setting. The Flight Test Technique (FTT) for climbs foresaw trimming the aircraft in leveled flight at the desired airspeed; once engine temperatures were stable, the climb was performed at the trim speed, full throttle until the asymptotic values of engine temperatures were reached (i.e. 1°C/min, as required by the reference [1]). Descents were performed at different throttle settings.

Oil, coolant, exhaust and charge air temperatures were recorded together with all the telemetries, to be then processed and compared with the expected design values.

4.3 Flight test process

In accordance with the Company procedures, the flight test process was composed of the following sequence, where iteration between steps was accepted:

- A Request for Flight Test (RFT) was provided by the engineering department to the flight test department. The RFT represents the state of the art of objectives and requirements to be met; an initial raw set of test point was also included.
- A Test Plan (TP) was drawn up by the flight test department. The TP included mid-level details about

test area, test points, test technique, hazard analysis, etc. This document allowed providing a comprehensive overview of the campaign, while allowing an efficient distribution of the essential information to all resources involved.

- A Short Test Plan (STP) with high-level of details was then drawn up by the flight test department. The STP detailed the individual portions of the test plan, including all data required to issue the test cards and conduct the test.
- An Experimental Flight Test Order (EFTO) was then prepared by the flight test department. The EFTO contained all information about the main configuration parameters, crew, test limitations, normal procedures, exceptions and the test card. Each test card included one or more test points.
- On the basis of the information above, flight tests were executed by flight test department, jointly with specialists from the engineering department (see § 4.1 above).
- A typical test day started with a crew brief, based on a master briefing guide. The brief covered the last weather info, RPAS maintenance status, airworthiness, emergency procedures recall etc. Flight was then conducted by the flight crew, in contact with the Test Director. After each flight, a debrief was performed, in accordance with the master briefing guide. Main points of debriefing were safety, test points result (acceptability) and remarks on the activity.
- Post flight report (PFR) and, when required, a quick data analysis were prepared by the Lead FTE. The PFR included a description of the activity actually performed, including deviations from the test card; preliminary qualitative results were also included in the PFR. The PFR information was based on personnel's first impressions, test card remarks and pilot's briefing notes. Some more complex cases required a quick data overview.
- At the end of the flight campaign, the data collected were further processed and included in two main test reports (each traced to specific requirements):
  - The engine cooling report, prepared by the Leonardo engineering specialist, focused on the effectiveness of the updated cooling system. Engine temperatures and pressure data were elaborated and correlated with ambient temperature and altitude. Post processing was performed, in order to verify that cooling was ensured at the required off-ISA. Videos from IR sensor were also processed, to confirm the results of the CFD analysis on the coolant and oil duct (see § 2.3.1 above).
  - The air vehicle performance report, instead, was prepared by the Lead FTE. Such report focused on the performances guaranteed by the air vehicle in the new configuration, since the new cooling pack modified the aerodynamics of the air vehicle, due to larger radiators and different cowlings.
- The compliance matrixes of the propulsion system and of the air vehicle were then updated, on the basis of the two test reports. Data were also supplied to the engine manufacturer, for modelling purposes and to issue the Declaration of Design and Performance for the new engine configuration.

4.4 The test card

The test card was the tool to conduct each test flight: detailed test data, during preparation and execution, were reported there together with immediate remarks. Therefore, the filled test card represented a main input for the debriefing and PFR.
Even if telemetry recording was available, the practice of collecting handwritten data on the test card was useful, especially to record aspect not immediately detectable through routine post processing. Moreover, the test card provided the timing of relevant events, facilitating the subsequent data analysis.
The test cards included both preparatory information and areas to record the actual execution.
The preparatory information was the following:

- Traceability of test points to requirements.

- Initial flight parameters.
- Aircraft Configuration (i.e. flap, landing gear, power setting, etc.).
- Test Procedures (quick recall on main points and flight test technique).
- Priority of the test point (some points could be skipped in case time was not available).
- Data band (parameter values, including tolerance, to consider a test as valid).
- Test limits (limitations related to the test point and knock-it-off criteria).

The areas to record the actual execution included the following:

- Initial and final time of each test point (useful in the post processing phase).
- Fuel and weather.
- Peculiar test point data as, heading, altitude, vertical speed, etc.
- Remarks.

5.0 ACHIEVEMENTS OF THE CAMPAIGN

The engine cooling flights took one week of a larger activity, mainly devoted to new payload integration.

A clear definition of the campaign objectives and limits, together with an extensive preparatory phase, allowed a good exploitation of the time and resources available.

A first result of the flight campaign, instrumental to the achievement of the objectives, was the confirmation of the new cooling system effectiveness. Indeed, the sizing of cooling plants was proven to be adequate for the purpose. The correlation between the predicted fluid temperatures in the different flight conditions was close to the expectation, including the cases with 16" under-belly turret.

The above achievement allowed to substantially remove the rate-of-climb limitation in hot climates: the Falco Evo engine can now be used in mission at full power in a wider range of temperatures. However, as predicted by the design phase, the charge air temperature is a parameter to be carefully managed on the ground, at low speed: indeed, the air entering the combustion chamber after turbo compression heats quickly, in response to a throttle increase.

The air vehicle climb performance, at TOGA power, at take-off and during second segment climb, exceeded the predicted values in the test conditions. The same is true for the rate of climb at maximum continuous power. The rate of descent was in line with the predicted values, while the fluid temperatures were always kept in green arc. The slight reduction of endurance due to the new cooling pack was in line with the estimations.

The post processing of data confirmed that the climb performance was in line with the expectations in hot climatic conditions and that the cooling was acceptable even in cold conditions (Northern climates and high altitude).

During cooling flights, the engine showed a responsiveness higher than expected, when a throttle change was applied. This unexpected benefit of the new cooling system, not fully understood during the bench tests, was indeed part of the pilot's feedback in the PFRs. The engineering department then tuned the engine control laws, which were successfully flight tested after the end of the cooling campaign. The air vehicle performance model was also updated with the feedback from the flights; the new performance diagrams and the residual limitations for hot climates were included in the flight manual.

6.0 CONCLUSIONS

The flight campaign for the updated Falco Evo engine cooling allowed to collect a number of best practices, which may help getting the most from future RPAS flight testing.

For an existing RPAS, a flight test campaign is typically the final step of a new development. In such a context, extensive modelling and bench testing helps in reducing the number of test points needed in flight. In the specific case of the Falco Evo engine cooling, Leonardo and the engine manufacturer collaborated on the analyses and tests that would have better predicted the behaviour of the engine in flight and, on the other side, the behaviour of the air vehicle with the modified engine.

The first step of a flight campaign with a RPAS should be the clarification and the agreement of the objectives, which shall drive the entire subsequent action. Definition of the objectives should take into account the resources available (including budget and time), in order to align stakeholders on realistic expectations.

The use of a "waterfall-like" approach in the definition and execution of the flight campaign, from general planning to more granular definition of tests, allows to keep track of the requirements along the way and not to lose the focus on the objectives. With this approach, each test point in each test card is linked with the requirement(s) it will contribute to prove and is coherent with the objectives of the flight campaign. This allows to use the airborne time and the available resources in an efficient way.

When a modification on an existing RPAS is flight tested, the direct involvement of a limited and motivated team in the flight campaign may further help in the effective achievement of the objectives. Collaboration and cohesion between the team members facilitates the execution of the activities.

The key lesson, however, is that an effective RPAS flight campaign begins from the development phase, followed by accurate planning and tracking of the relevant information throughout the campaign preparation and execution.

Accurate preparation and planning is the key to reach the campaign objectives with an efficient use of resources.

7.0 REFERENCED DOCUMENTATION

[1] AEP-4671 - UNMANNED AIRCRAFT SYSTEMS AIRWORTHINESS REQUIREMENTS (USAR) - EDITION B VERSION 1