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VALIDATION OF SCALED FLIGHT TESTING

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Abstract

Today's aeronautical industry has to explore more than ever new technologies and disruptive configurations in order to accelerate the reduction of its environmental footprint. To de-risk new solutions that have an impact on the Overall Aircraft Dynamic Behavior, Scaled Flight Testing features potential interesting assets with respect to existing Ground Test facilities. However, before implementing such a new approach within industry programs, a thorough assessment is needed to quantitatively assessment the benefits. To this end, a consortium made of Airbus, CIRA, NLR and ONERA launched a validation initiative in the frame of the EU Program Clean Sky 2. For several years, the partners concurrently worked on theoretical aspects as well as on the development of the Scaled Flight Demonstrator that is a scaled version of an existing civil transport aircraft with specific design characteristics. Before the successful Qualification Flights, the team completed Wind Tunnel Tests and different series of taxi tests in order to de-risk the system. Also, a step-by-step method has been defined to trace how variations associated to scale affect the aircraft flight dynamics. Last, it must be noted that simulations based on Wind Tunnel data predict similar behavior between the full scale reference airplane and the SFD.

Keywords: Scaled Flight Testing, Scaled Flight Demonstrator, SFD, Froude, Flight tests, Clean Sky 2

1. Introduction

Because of the societal need to reduce the environmental footprint of aviation, research entities and academia, together with industry explore different innovative and disruptive technologies or configurations. As there is no historical data on these new systems, designers have to deal with high level of uncertainties, at component level, systems level and aircraft level. To decrease this uncertainty, numerical simulations based on high fidelity tools can be performed as well as experimental ground tests (e.g. in wind tunnels). For some topics for which free flight is an added value, such as control laws investigations and overall aircraft behavior (flight dynamics) studies, the use of Scaled Flight Demonstrators can add valuable knowledge and thus reduce uncertainty (and decrease risk). However, to accurately identify the potential role of the Scaled Flight Testing approach in industry, it is important to quantify the knowledge that can be gained by flying such smaller vehicles at low altitudes, low speeds and with little payload capabilities when compared to full scale transport airplanes.

Thus, following the NACRE initiative (2006 – 2011), see ref [1] and [2], in the EU Program Clean Sky 2, within the Large Passenger Aircraft (LPA) Innovative Aircraft Demonstration Platforms (IADP), there is the objective to set up and complete a thorough validation process of Scaled Flight Testing as viable means to de-risk disruptive aircraft technologies and aircraft configurations to high TRL (Technology Readiness Level). In order to validate the approach, it has been decided to build a scaled version of a known civil transport aircraft (the Airbus A320) identified as the SFD (Scaled

Flight Demonstrator) and to compare the experimental data obtained through flight tests with full scale aircraft data. In parallel, theoretical analyses on similarity aspects complete the study. In this manner, outcomes of the flight dynamics responses comparison and transposition laws identification would both provide a valuable quantitative assessment of the approach.

The complete SFD system comprises the scaled aircraft as well as a Ground Control Station (GCS). This ground segment includes the Ground Remote Pilot Station (GPRS) that provides a cockpit like environment for the pilot. On the flight vehicle, the On-board Guidance and Navigation and Control system (OGNC) allows automated manoeuvers for parameter identification and the Flight Test Instrumentation (FTI) records more than 150 parameters for accurate post-processing and validation. Datalink and video links are naturally added for communications between the GCS and the SFD.

A presentation of the work carried out by Airbus, CIRA, NLR and ONERA until 2019 in LPA IADP towards the validation of the approach through the development of the SFD and the associated numerical simulations has been given at the Aerospace Europe Conference that took place in February 2020 [1]. For the remainder of that year, the work package dedicated to the SFD development made important progress under the lead of NLR: after the finalization of the detailed design, components have been manufactured and assembled. In some case like for the main wing, parts have been delivered and ground testing started. At the end of the year, the activity mainly consisted of the integration of the numerous subsystems and overall testing including Flight Test Instrumentation. In parallel, CIRA modified the GPRS according to NLR feedback and finalized the OGNC system hardware before delivery to NLR. Regarding the theoretical investigation, ONERA has been able in 2020 to finalize the high fidelity aerodynamic database of the SFD feeding the simulator and enabling preliminary analyses of the overall aircraft behavior differences for both scales. The first period of 2021 enabled to finalize the design of the empennage and the manufacturing of key SFD components. With the airframe completed, extensive work took place concerning the integration of all systems. Concurrently, the GNC followed the planned developments and functionalities have been added to the GRPS according to the latest requests. A first key test of the integrated SFD was the Wind Tunnel Test session in DNW during which sensors, control surfaces, engines and FTI were activated. With the acquired data, the SFD standard Autopilot has been tuned and refined flight performances have been computed. A subsequent test phase led to the Ground Test Readiness Review (GTRR). With this milestone passed in June, taxi tests took place in the Netherlands. After various tests and solution explorations in July and August to solve latency issues, the taxi tests were concluded in September with high speed runs. In the last quarter of 2021, partners worked synchronously to have the full SFD system ready for the first flight. The progress allowed the organization of the Flight Readiness Review (FRR) at the end of October with the participation of an External panel. A FRR closure took place on 26th of November with a positive conclusion considering the extra verifications carried out by the team. In the first quarter of 2022, partners solved that last administrative and technical hurdles in order to successfully complete the first flight of the SFD on 30th March in Deelen (NL).

Figure 1 : Landing of the SFD during the maiden flight (30/03/2022)

The goal this paper is then to provide more details on key systems that have been finalized and important milestones that have been passed in the 2020-2022 period. In a first section, the authors provide details about the Scaled Flight Demonstrator design that is an unmanned aerial vehicle that is designed to meet given scientific objectives. Subsequently, this paper concentrates on two key milestones that enable to decease risk towards the first flight: the wind tunnel tests and the taxi tests. In a third section, information about the successful Qualification Flight Tests carried out by NLR and Orange Aerospace in Deelen (NL) are naturally provided. Concerning the project next steps, the Mission Flight Tests that will close the validation process will take place in Q3 2022 with a specific on-board instrumentation. The next section focuses therefore on the GNC system test method and results. Last, as the activity aims at validating the Scaled Flight Testing approach, an overview of the demonstration steps is presented.

2. The Scaled Flight Demonstrator design

Under the leadership of NLR with the support of Orange Aerospace [4], the design of the Scaled Flight Demonstrator (a 1:8.5 scaled version of the A320-200 with V2500 engines) has been a challenging task. First, many constraints had to be considered such as the limited availability of Commercial Of-The-Shelf components for an unmanned aerial vehicle of such size and weight (4 meters wingspan, 146 kg at takeoff), the limited available internal space to allocate the sub-systems as well as single components, the non-availability of the exact geometry of the full scale aircraft and the overall need to maximize safety. Second, because of the validation purpose of the demonstrator, conflicting requirements had to be managed: the overall geometry, even if not optimized for flight speeds around 50 m/s had to be maintained with an impact on GCS design, operations and pilot training. Also, because of the fast vehicle dynamics to be recorded in flight, the SFD has to embark an advanced Flight Test Instrumentation (FTI) leading to additional weight and system management. Last, it must be noted that the requested autonomous manoeuvers to be completed for parameter identification and overall aircraft behavior analysis necessitated the design and integration of the GNC that adds complexity and risk that goes against safety improvement. Overall, during the conceptual, preliminary and detailed design phases, engineers had to find compromises and defined innovative solutions that resulted in the final version of the SFD shown in Figure 1 (digital mock-up on the left and actual aircraft on the right).

Figure 2 : Detail digital mock-up of the SFD (left) and integrated SFD at the end of the development (right)

In the next paragraph, the authors highlight key elements associated to the SFD design that are considered relevant : the wing aerodynamic design, the engine selection and the nacelle design. To conclude this section, as the purpose of the demonstration is to reproduce the dynamic behavior of the full scale aircraft with the SFD, an overview of the control surfaces is provided.

As the geometry of the reference aircraft was not available for all partners within the activity, NLR used available geometries in the public domain [5] and other sources [6] to generate the 3D outer mold lines of the SFD. The wing being the essential elements regarding aerodynamics, Reynolds Averaged Navier-Stokes (RANS) simulations were carried out by ONERA in order to understand its aerodynamic characteristics and especially the trends concerning the Lift coefficient versus Angle of

Attack curve. It provides indeed an indication of the slope in the linear part and the lift evolution after stall. More important, to increase operation safety with the SFD, the computations identified the location of the initial separation along the swept wing. Unfortunately, the taper ratio of the reference aircraft and the airfoil selection led to a flow degradation around 9° at the wing tip where the ailerons are located. Thus, with the purpose of reducing risk during flight, the wing has been revised with a camber law starting from the kink to the tip. The simulations of the new design showed that the camber solution transferred the separation from the tip to the central part of the wing, avoiding thus any critical control power during stall (see Appendix 1 for the simulations). This is an illustration of the tradeoffs that the design team had to deal with as such change would improve safety but at the same time, the SFD geometry would be less representative of the full scale aircraft. In a later section of the paper, the authors detail the validation process that has been setup in order to take into account such changes of the geometry in the transposition laws between the SFD and full-scale aircraft.

For the propulsion system, considering the size and weight of the SFD, the only solution was to select COTS turbine engines. In order to be similar to the thrust-to-weight ratio of the full scale aircraft, the selection had to be made among products producing at least 230 N. A review of the available solutions pointed out 3 possible engines with their characteristics presented in the next table:

Table 1 : Possible SFD engines

	AMT Titan [7]	**AMT Olympus [7]**	**JetCat P300-PRO-GH [8]**
Thrust	392 N	230N	300 N
SFC @max rpm	0.156 kg/Nh	0.167 kg/Nh	0.157 kg/Nh
Mass	3.645 kg	2.9 kg	2.73 kg
Power Generated	85 W	0	85 W + 900W
Diameter	147 mm	130 mm	132 mm
Price (taxes not included)	10 k€	6.7 k€	5 k€

The decision has been made considering 4 different criteria: Reliability, Service, Cost and Performance. For the first point, there is no data available to back up any reliability arguments and no certificates of conformances provided by the suppliers. There is however a significant amount of data available for the Olympus engine and the model is used by Aachen University on a bench and useful data and parameters could be made available. In addition, it must be known that an exact copy of the Olympus has been certified for a glider aircraft after several tests have been performed. About service, it is again difficult to provide quantitative information but NLR experienced a very reactive AMT team willing to assist. When looking at cost, the difference in the AMT products is not negligible and the JetCat finds itself better positioned. Due to limited resources within the project to be spent on consumable products, this difference has an important weight in the final decision. Regarding performance, the following conditions have been taken into account: Take-off distance, Cruise flight, One Engine Inoperative (OEI) condition, Upset recovery and electrical power. For these aspects, given the weight of the SFD and the planned operations in specific airports, the take-off distance is not an issue as well as the cruise condition for which the engines operates at 50%. For the critical conditions that should not happen, additional thrust would be a benefit as well as the availability of some power generation even if there are back-up solutions available. In the end, the design team decided to go with the AMT Olympus because of the possibility to have additional operational data, a intermediate cost and the sufficient level of performance to complete the standard mission.

The AMT Olympus is a turbojet engine with no by-bass while the SFD has to represent a scaled version of the A320-200, a twin engine civil transport aircraft equipped with turbofan. Thus, it was necessary to design the inner surface of the nacelle in order to have an efficient internal flow in various flight conditions. For this assessment, Computational Fluid Dynamics (CFD) simulations have been performed on an initial geometry in 2 conditions: cruise (with an upwash of 5°) and take-off (Angle of Attack fixed to 30°). From the resulting images (Appendix 2), it can be seen that at an inflow angle of 30°, the flow enters the nacelle nicely for the upper bypass and upper half of the engine inlet. However, for the lower part of the nacelle, an undesired flow behavior can be observed with air being sucked back into the engine inlet. To solve this phenomenon, a nacelle redesign has been proposed with the lower half of the incoming flow guided into the engine inlet. The lower nacelle lip has therefore been thickened considerably, as well as the overall thickness of the lower nacelle half. The illustrations of the flow resulting from CFD simulations of the novel geometry show that the new solution provides much nicer flow conditions within the inlet so that overall performances of the SFD is improved.

As stated earlier, the SFD aims at reproducing the Overall Aircraft Behavior of the full scale aircraft through a thorough analysis of the flight dynamics responses. To trigger the natural movements of the aircraft, specific commands will be given to the different control surfaces enabling movements around the 3 axes. On the SFD, primary flight control results from conventional control surfaces actuated by electrically driven servos: ailerons, elevator and rudder. Roll control is aided by differential outboard flaperon deflection when flaps are extended. The secondary flight controls are flaps (inboard flaps and outboard flaperons) and horizontal stabilizer. Pitch trim is provided by the horizontal stabilizer deflection while roll trim roll is achieved by commanding an offset in servo position. Figure 2 illustrates the locations of the movables while Table 1 provides the deflection ranges.

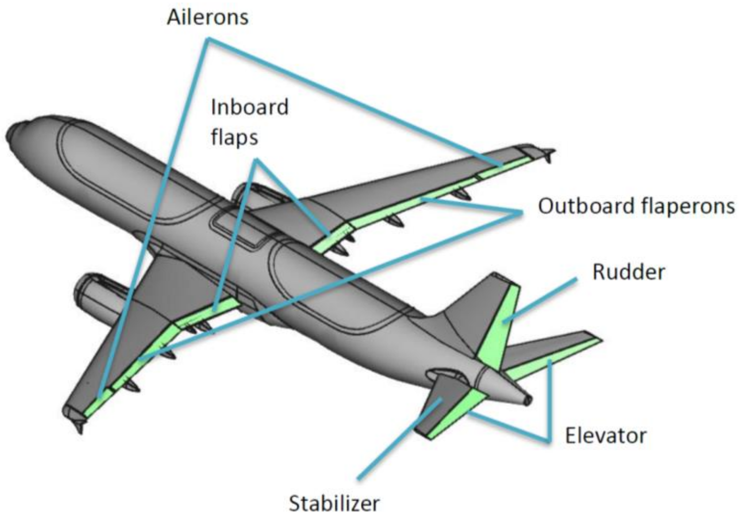

Figure 3 : Flight Control Surfaces of the Scaled Flight Demonstrator

Table 2 : SFD movables and their possible deflection ranges

Rudder		+30° to -30°;
Horizontal stabilizer		-13.5° trailing edge down to 4° trailing edge up
Elevator		-15° trailing edge up to 30° trailing edge down
Ailerons		+25° to -25°
Inboard flap	Flaps up	0°
	Takeoff flaps (half)	15°
	Landing flaps (full)	28°
Outboard flaperons	Flaps up	0°
	Takeoff flaps (half)	-5° to 5° differential flap +15° flap (total 10° to 20°)
	Landing flaps (full)	-5° to 5° differential flap + 20° flap (total 15° to 25°)

Control surfaces have been geometrically scaled from the full-scale aircraft. However, the flaps have been simplified and do not scale with the full-scale aircraft, which limits relevance of low speed condition. In manual mode, the GRPS flight controls drive the associated control surfaces directly and linearly, with the exception of the rudder and nose wheel steering, which has an exponential function.

3. Ground tests of the Scaled Flight Demonstrator

The Scaled Flight Demonstrator is an assembly of many components or subsystems. In order to follow a robust verification and validation plan, these elements had to be tested before their integration within the airframe to assess their functionalities. To facilitate the progress monitoring and the reviews, all the subsystems have been regrouped into 6 categories: Communication

Systems, Propulsion System, Power Distribution System, Landing Gear, Flight Control Systems, Flight Test Instrumentation. With positive outcomes of the tests, the integration phase has been completed and the complete SFD went through a specific vibrating test bench to assess its mass and inertia characteristics. Clearly important from an operation point of view, the outcomes were also key for the Scaled Flight Testing approach validation (verification of the correct Inertia Froude scaling with respect to the reference full-scale aircraft). Among the various ground tests, a key step has been the completion of the Wind Tunnel Tests in DNW of the complete SFD with the propulsion system running. Indeed, this milestone enabled the validation of key subsystems (Structural sizing, Flight control system, Aerodynamic data, Propulsion system, Landing gear and FTI) in almost real flight conditions. Another mandatory phase before the Flight Readiness Review is the taxi tests. The next two paragraphs are thus providing more details about these project milestones.

3.1 Wind tunnel tests

Wind Tunnel Tests were planned since the early stages of the project with the objective of testing directly the SFD in the test section. After a review of the possible test options considering technical, logistics and cost aspects, it has been decided to carry out the tests at DNW [9] in the Large Low-speed Facility (LLF) that can host the 4 meters wingspan demonstrator. In order to minimize the testing time, the SFD was directly connected to control units and electrical power through flexible cables so that the control of the SFD's engines, movables and flaps could be done remotely. For this installation illustrated in the next figure, specific parts were manufactured to install a balance between the wind tunnel sting and the SFD enabling the measurement of forces and moments in the wind tunnel.

Figure 4 : Wind Tunnel Test installation of the SFD (DNW)

The complete series of test has been divided into 2 parts: initial tests on 7th and 8th of April and then on the 19th of May. Regarding the engine set-up, measurements have been made with the engine inlet blocked except for the runs during which the engines were turned on. During the first 2 days of tests, tufts were installed on the wing and on the nacelle to visualize flow patterns in critical areas for different angles of attack. The validation of Scaled Flight Testing requires a reference speed of 46 m/s. Thus, tests in the wind tunnel are carried out at this speed mainly. Other measurements are done at 30 m/s to verify lower-speed aerodynamics.

The wind tunnel test provided a very rich set of data and knowledge about the SFD aerodynamics. First of all, the measurements enable to build a reliable aerodynamic model of the SFD to be used for the Flight Simulator, for the Autopilot tuning and the flight manual performance estimations as well as the flight manual flight envelope. All these elements are key contributions towards the reduction of risk for the first flight. Second, during the tests, the SFD and SFD components such as the landing gear and control surfaces experienced aerodynamic loads associated with airspeeds relevant for the test flights. In some cases, flow separation also induced vibrations and loads. For the duration of the tests, the SFD sustained these loads without damage or aeroelastic issues. Thus, these experimental conditions allowed a verification of the SFD structural integrity at relevant aerodynamic loads. As a third important added value, one can note the stall behavior visualizations. Indeed, because of the observations during the SFD design, it was important to confirm the separation starting point and pattern on the main wing. Thanks to the tuft installation and as shown in Figure 5, the design team could identify the Angle of Attack at which separation starts and confirm that the stall onset occurs on the inboard side of the wing, keeping a clean flow on the ailerons.

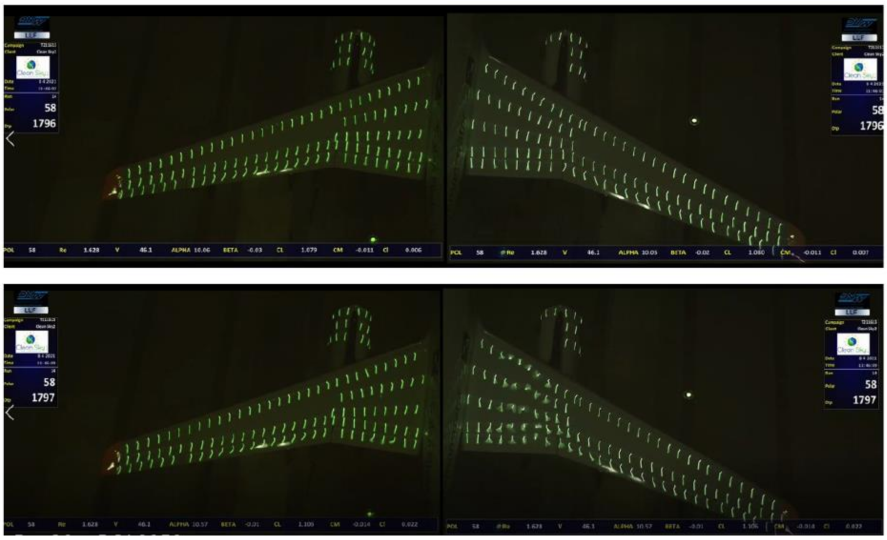

Figure 5 : Tufts visualization on the SFD wing at 46 m/s at 10.06° of Angle of Attack (top) and at 10.57° of Angle of Attack (bottom)

The wind tunnel test provided also a unique opportunity to calibrate the air data system of the SFD. Although the air data boom has been delivered by the manufacturer with a calibration, the presence of the aircraft and its shape generates small deviations that can bias the measurements. Therefore, the measurements of the Angle of Attack, Angle of Sideslip and airspeed have been calibrated at the reference speed of 46 m/s. The acquired data resulted in different polynomial equations that take as input sensor data and return the corrected values. Last, the possibility to test the engines in the wind tunnel (thrust sweep and constant thrust for an angle of attack sweep) gave important information in terms of operations as no nacelle stall nor engine flame-out was observed.

3.2 Taxi tests

Taxi tests are the last stage before the first flight. Thus, they represent a fundamental step in order validate the complete system in an operational environment. For NLR and Orange Aerospace directly involved in this phase, the objectives of the tests were:

- Verification of the GRPS, Datalink and SFD operation;
- Control of the SFD during take-off run taking into account the pilot feedback;
- SFD Performance verification.

In terms of organization and progress tracking, the taxi test campaign has been separated into 2 parts: low-speed taxi tests and high-speed taxi tests that took place at different airports. The opening low-speed taxi tests occurred in March 2021 at Breda Airport (NL). This was the first time that the SFD and GRPS were integrated at system level and that an overall functional testing was performed. Also, it was the first opportunity for the ground crew, including the pilot to experience SFD operations. The ground runs carried out at about 5 m/s allowed an operational check of all systems and a first assessment of ground stability and control as well as braking capabilities. After these tests, different improvements to the SFD system have been implemented and a second series of taxi tests took place in June, also at Breda Airport. The ground runs enabled to test the following characteristics, systems and components:

- Link range test (beyond maximum taxi distance), with transponder on;
- Link loss behaviour (switching primary to secondary, second to primary, both loss);
- Flight control check, with a focus on rudder, nose wheel steering and engine control;
- Engine (Symmetry);

- Indication and display check;
- Electrical system test (voltage, redundancy, temperature, capacity);
- Avionics/payload (temperature monitoring);
- Compass check;
- Low-speed taxi (straight ahead, manoeuvring, braking, 180 degrees turn);
- Braking characteristics (initial indication of braking distance);
- Datalink latency check, and check of update rate of Primary Flight Display (PFD), video versus PFD instruments in turns;
- Weight and balance.

Figure 6 : First ground runs test of the SFD at Breda Airport

These low-speed taxi tests allowed to gain confidence and experience on the SFD system as a whole and its behavior has been evaluated as acceptable. Thus, the milestone has been considered as validated. However, different issues have been identified (especially the analogue video quality considered as insufficient), mostly related to the GRPS. For this reason, the consortium decided during the Ground Test Readiness Review to start high-speed taxi tests only after the resolution of the open points and also a positive pilot feedback to increase ground test speed.

The objective of the high-speed taxi tests is a further check of ground stability and control up to high taxi speeds (braking, engines), in preparation of the first flight. Naturally, several integrated system tests are checked one more time (for example datalink range check, control checks,…). The main purpose is an evaluation of high-speed taxi characteristics (especially lateral control). In terms of speed, the goal is to reach 80% of the stall speed for 3 configurations: (i) 55 kts in a clean configuration, (ii) 50 kts with the takeoff flaps, (iii) 45 kts with the landing flaps (Stall speeds have been calculated from wind tunnel tests).

After the implementation of new solutions, the SFD test team started the high-speed taxi tests in July. Unfortunately, with the ground speed increasing, it became quickly clear that latency was a significant issue. The pilot was exposed to Pilot Induced Oscillation (PIO) and reached a maximum speed of only 20 knots in safe conditions. Following the discovery of the latency issue, other solutions have been implemented: the analog video option was further assessed to improve the quality and in addition, the nose wheel steering control loop was optimized to reduce its latency as well. Nevertheless, these experimental tests have been characterized by several new issues:

- Latency: the improvement made through the revised nosewheel steering was noticeable but there was still too much latency on the entire system as a whole;
- Following these tests the analog system was concluded to be unacceptable and a digital video solution was proposed;
- A critical datalink issue occurred: Both the primary- and secondary datalink failed which resulted in the emergency command. Following this command the engines are turned off and the brakes are activated. If this would happen in flight, the parachute would be automatically deployed ending the data acquisition and putting the project at risk.

In September after additional runs using a temporary digital video solution, a speed of 31 kts has been reached with PIO effects becoming too significant at higher speed. Then from 7th of September, the SFD taxi tests were performed at Deelen Airport (EHDE) where the crew had larger test time windows and a larger runway to operate. With an improved digital video system and an optimized rudder / nosewheel steering gain scheduling, the target speed for the clean configuration of 55 knots was reached. PIO susceptibility was still present but several acceptable high-speeds ground runs were performed. After these successful high-speed taxi runs, the other flap configurations have been tested and validated. Although the goals of the high-speed taxi test were achieved and the pilot considered the SFD behavior as acceptable, NLR decided to implement a ground assisted mode to further improve the performance and almost fully eliminate PIO effects at higher speeds. With this implemented mode, the high-speed test program was completed and all speeds were achieved in November with final tests dedicated to the rotation maneuver. This positive outcome enabled the closure of the Flight Readiness Review.

Figure 7 : Rotation Manoeuvers made with the SFD during the Taxi tests

4. Qualification Flight Tests

On the 26th of November, NLR presented the latest changes to the SFD system requested during the initial review as well as the status of the team preparation towards the first flight. The consortium came to a positive conclusion associated to a list of final actions to be considered prior to the first flight. This translated into an evaluation of the project risk that has been completed at the end of December with a confirmation that SFD testing and preparation towards the First Flight would continue with no changes to the ground segment and the allocation of specific systems analysis after the first flight. With the objective of reducing risk, the SFD pilot carried out extensive practices sessions on the simulator but also with other flying vehicles in order to get used to latency. This training was completed with additional taxi tests to increase confidence. During the tests, the operational team noted an unexpected wearing of the control surfaces actuators (due to the important number of ground cycles). Thus, always to minimize possible issues during the flight campaigns, new actuators have been ordered and installed. With the insurance and frequencies licenses available, the operational team transported the complete system in Deelen in week 12 to start the Qualification Flight Tests. This initial series of flights aims at verifying the safe and efficient operability of the Scaled Flight Demonstrator and all associated subsystems. On the the 30th of March, after different ground runs and good weather conditions, the SFD took off for the first time at 16h32. The pilot made 2 circuits and completed a smooth landing. An extract of the first flight video [10] is shown in Figure 8. In April, the operational team made 5 additional flights in order to qualify the system:

- Wednesday 13/04 : 2nd flight with a takeoff at 09:27 hrs (6 circuits);
- Thursday 14/04 : 3rd flight with a takeoff at 16:34 (3 circuits);
- Thursday 26/04 : 4th flight with a takeoff at 10:23 (6 circuits);
- Thursday 26/04 : 5th flight with a takeoff at 13:17 (flight Beyond Visual Line of Sight);
- Thursday 28/04 : 6th flight with a takeoff at 15:00 (6 circuits);

The flight paths recorded during all 6 flights can be found in Appendix 3.

Figure 8 : SFD maiden flight on 30th of March 2022 [10]

During these Qualification Flight Tests, different functions and flight conditions have been verified and the feedback from the pilot taken into account to assess the outcome and prepare the next flight. In terms of performances, the altitude of 2000 ft Above Ground Level (AGL) has been reached (2 steps) at speeds below 100 kts with different flap settings. The acquired data during level flights as well as climb segments enabled the safe expansion of the flight envelope. In terms of SFD control, direct as well as assisted modes were tested with iterations on the different gains of the laws to achieve a more comfortable behavior. For these flights, the On-board Guidance Navigation and Control system developed by CIRA was installed but not active. An analysis of the recorded measurements showed that the OGNC and the SFD systems were synchronized with little variations. The review by the operational team of the flight data, together with debriefing sessions with the pilot, led to the conclusion that the SFD system as a whole is considered safe and efficient to proceed to the Mission Flight Tests. For the specific manoeuvers to be achieved during these future tests, the On-board GNC system will be activated.

5. The On-board Guidance, Navigation & Control system

As presented in [3], the GNC system under the responsibility of CIRA is decomposed into two parts: the On-board Guide, Navigation and Control (OGNC) system and the Ground Remote Pilot Station (GRPS). During Taxi tests and the initial Flight Tests, the GRPS has been successfully used resulting in a qualification of the overall Scaled Flight Demonstrator system. In order to fully validate the Scaled Flight Testing approach, Mission Flight Tests dedicated to parameter identification must be completed so that the characteristics of the SFD can be compared to the reference aircraft. To this end, the operational team will activate the OGNC, a complementary system allowing an automated flight of the SFD including manoeuvers to initiate specific aircraft responses. In this section, details are provided about the test method implemented by CIRA to verify and validate the OGNC.

First, tests have been classified into four distinct categories:

- Functional: the aim of these tests is to verify that the functions defined in the requirements are correctly implemented in the algorithms.
- Performance: These tests aim to evaluate the GNC performance with respect to the requirements. To perform this test, it is necessary to use a simulation model based on the actual SFD aerodynamic and inertia model available after the wind tunnel tests.
- Real-time Hardware-In-the-Loop: These tests are performed using a Hardware/Software in the loop facility that integrates the OGNC and GRPS Hardware and Software with a simulator of the others SFD systems. The aim of these tests is to verify the correct integration with the input and output from actual interfaces.
- Integrated: These tests are performed with the OGNC and GRPS integrate with the others SFD systems. The aim of these tests is to verify the full integration (Hardware and Software) of the complete SFD facility.

To carry out these different tests, different benches (offline and real-time) have been developed. The

Matlab/Simulink [11] test environment is dedicated to functional and performance tests. It includes a model of the OGNC as well as the aircraft model so that GNC logics and algorithms can be tested. Figure 9 provides a view of the environment highlighting in blue the elements that are verified including the On Ground Computer (OGC).

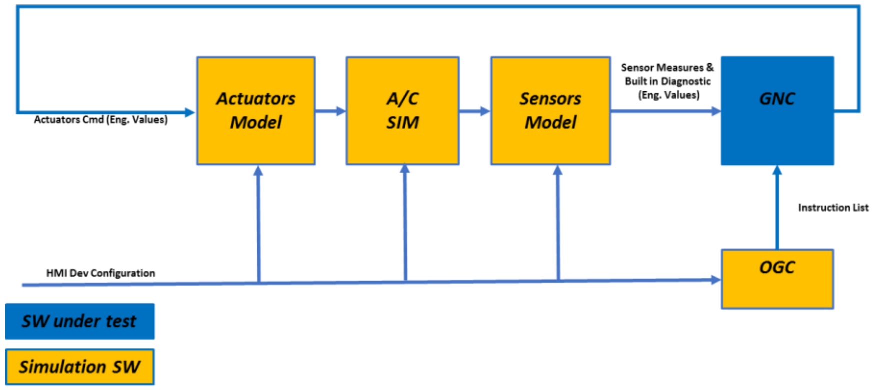

Figure 9 : Offline simulation environment

In addition, CIRA developed a Hardware-in-the-Loop test environment for real time verification and validation that integrates the OGNC and GRPS Hardware / Software. It includes also a real time simulator that reproduces the aircraft dynamics and emulates all the SFD systems. Illustrated in Figure 10, the capability includes the Flight Control Computer (FCC) that commands depending on the algorithms the movables and throttle inputs of the simulator (in orange in Figure 10) and the OuT of Window (OTW) Monitor.

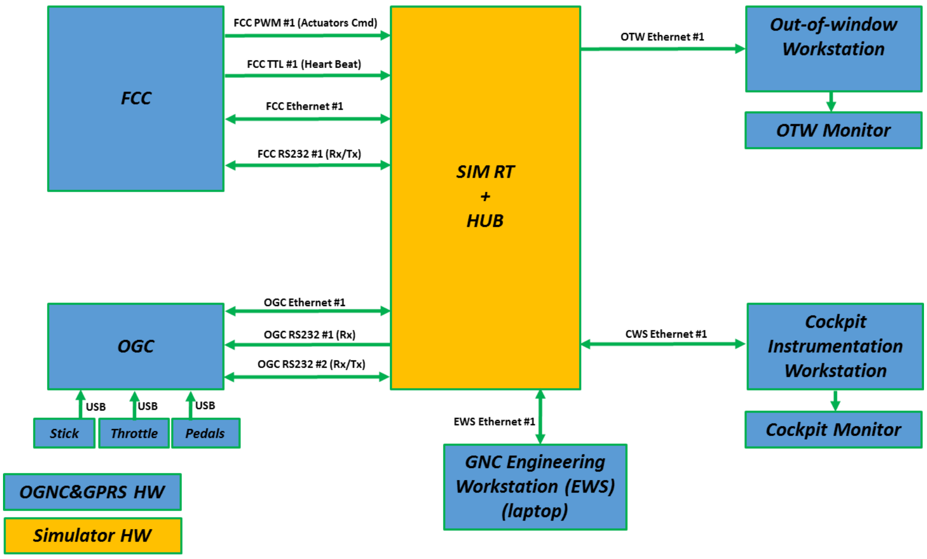

Figure 10 : Overall architecture of the Hardware-in-the-Loop test environment

Last, CIRA and NLR put in place and Hardware / Pilot in the loop test environment designed to complete tests for pilot training purposes. In this configuration, the GNC Hardware and Software are directly interacting with the Ground Control Station and the SFD systems. This facility uses the NLR aircraft simulator with the standard Autopilot control loop to provide simulated data to the OGNC and to the GPRS through an ethernet bus (see Figure 11). In this way the pilot and flight crew can simulate a complete mission: in particular, for each phase of the mission the pilot selects the control laws of the standard Autopilot (to simulate the take off, climb, approach and landing) or the control laws of the OGNC (to simulate the mission flight test manoeuvres execution). Before the each flight, the flight test card will be executed through simulation using this facility in the actual test conditions (weather, mass and balance) to mitigate the risk of failures during the experimental flight.

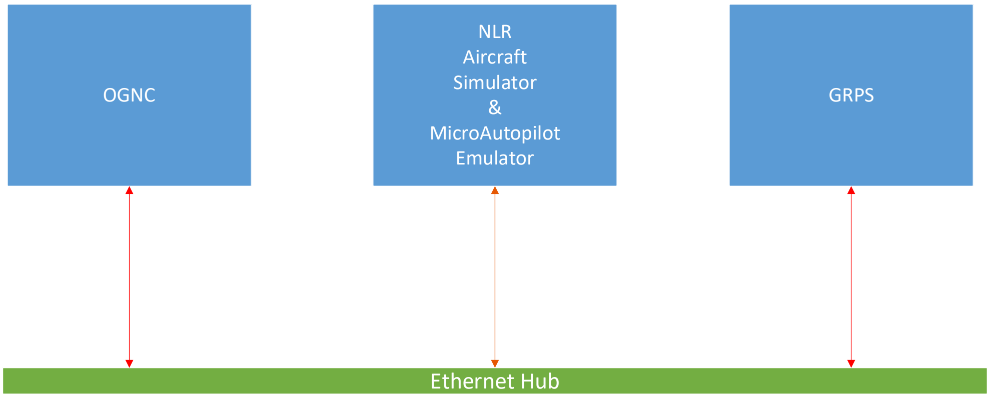

Figure 11 : Architecture of the HW and Pilot in the loop test environment

For each test performed that has been performed, CIRA specialists reported the following information in deliverables:

- Scope: the aim of the test is given as well as the list of requirements to be verified;
- Test description: the description of the test (including conditions) and the test rig details are provided;
- Expected Results: the specialists report in this section the expected results that are required to pass the test;
- Actual Results: the test responsible reports if the test is successfully passed or not;
- Note: Additional information about the test that is considered relevant is added to the test report.

Regarding the OGNC, this approach has been followed in order to validate the Way-Point Follower mode, the Diagnostic and Emergency logics, the Maneuver Execution mode, the associated control laws, the Mission Logic and the Test Automation Instruction Management. With successful results, the OGNC has been transferred to NLR for an integration within the SFD. In the next Mission Flight Tests, specific flights dedicated to the OGNC fine tuning are planned.

6. Scaled Flight Testing validation process

As stated in the introduction, the objective of the project is to validate the Scaled Flight Testing approach. To achieve this goal, it is important to set up a thorough approach that enables a clear comparison of the overall aircraft behavior associated to the full scale and the one related to the Scaled Flight Demonstrator. However, it was clear from the beginning that there would be differences between the reference aircraft and the vehicle to be flown. Among other, one can point out the geometry, the flight domain and the structure flexibility. Therefore the idea is not to try at any cost to have the exact similarity but to master all the different effects that will modify the flight dynamics responses between the scales. In Figure 12, the authors illustrate all the different intermediate steps that have been identified and analyzed in order to quantitatively assess Scaled Flight Testing.

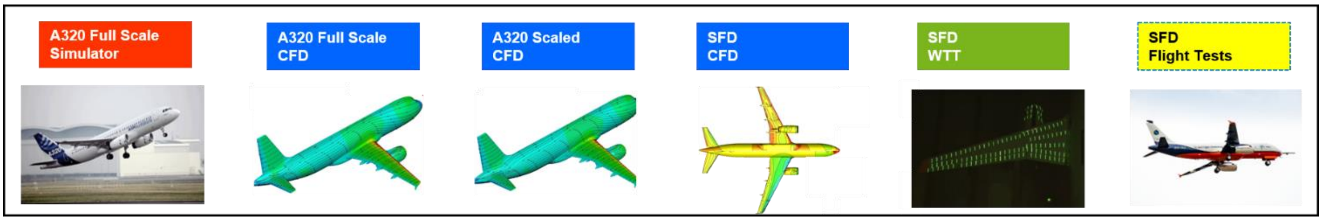

Figure 12 : All different intermediate steps to assess from a technical point of view the Scaled Flight Testing approach

On the left side of Figure 11, there is the full scale reference aircraft, the A320-200. In the frame of the project, in order to complete the validation, Airbus provides the dynamic responses of this aircraft for a given set of conditions (altitude, speed, weight, throttle level, control surfaces deflections) computed with the industrial simulator that is based on flight dynamics principles. As the software takes into account inputs from flight data, effects associated to structure deflection are also taken into account. A first step towards the numerical representation of the SFD in terms of dynamic simulations is to build a simulation model based on the aerodynamics database generated through high-fidelity RANS simulations on the exact A320-200 geometry considering the flight condition of reference for the full scale. Then, the database is recomputed considering the scaled geometry of the A320-200: during this step, it is possible to assess the impact of the Reynolds number of the aircraft responses. However, as stated earlier in the paper, the SFD is not the exact geometry of the A320. Thus, it is important that the simulator model takes into account the geometry differences by integrating the aerodata set associated to the exact SFD shape. The problem is that there can be numerical uncertainties and for this reason, the penultimate step is the generation of the SFD flight dynamic model based on the Wind Tunnel Tests data. An example of the resulting dynamic response of the SFD is presented in Appendix 4 with simulation results associated to a rudder doublet. With the completion of the SFD Mission Flight Tests, it will be possible to calibrate accurately this last simulation model. Experts are then capable to identify all the effects that affect the Overall Aircraft Behavior and subsequently define transposition laws between the two scales.

At this stage of the project, as only the last step is missing, there is already a good understanding of the overall transposition process thanks to the various CFD analyses. Besides, the behavior of the SFD can be represented with low uncertainty because of the experimental data obtained at DNW (see section 3.1). During comparisons between the flight simulations of the SFD and the full scale aircraft, the scaling impacts marginally change the control surface efficiencies and does not change substantially the dynamic responses. Therefore, the work carried out confirms the interest of scaled flight testing to represent full scale aircraft behavior.

7. Conclusion

In the last two years, the consortium made of Airbus, CIRA, NLR (and Orange Aerospace) and ONERA made important efforts to deliver visible results towards the validation of Scaled Flight Testing. Through wind tunnel tests at DNW, the partners gained at first confidence with the aircraft, its systems and its operations including the jet-engines. In addition, a reliable aerodynamic database has been generated to both verify the performance level and populate an accurate simulation model of the Scaled Flight Demonstrator and its responses. Through the various taxi tests in different airports, NLR carried out also a systemic de-risking of the complete system. During ground runs, issues were identified, reported and solved with solutions that were compromises between risk level, performance and impact at planning level. This continuous improvement of the SFD system led a to robust version that after its first flight on 30th of March has been able to complete 5 other flights (even 2 during the same day) showing promising productivity. The end of the Qualification Flight Tests has been a great achievement paving the way for the final step of the demonstration. For this last stage, CIRA has been largely involved not only to validate the On-board Guidance, Navigation and Control system that will allow automated measurement sequences during flight but also to organize the experimental flight campaign at Aeroporti di Puglia. Last, ONERA set up in collaboration with Airbus a validation process for the Scaled Flight Testing approach that will result in quantitative information to better assess the possible industrial use of this new European capability. Regarding the next steps, with the Mission Flight Tests in Italy planned in Q3 2022, the consortium aims at presenting the results of the validation process at the end of the year. With a longer view on the calendar, it is important to note that within LPA IADP, activities have been organized so that the SFD will be modified to de-risk distributed electric propulsion in 2023.

8. Acknowledgments

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10. Copyright Statement

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Appendix 1 – Simulation of the wing aerodynamics at high angles of attack before and after the redesign

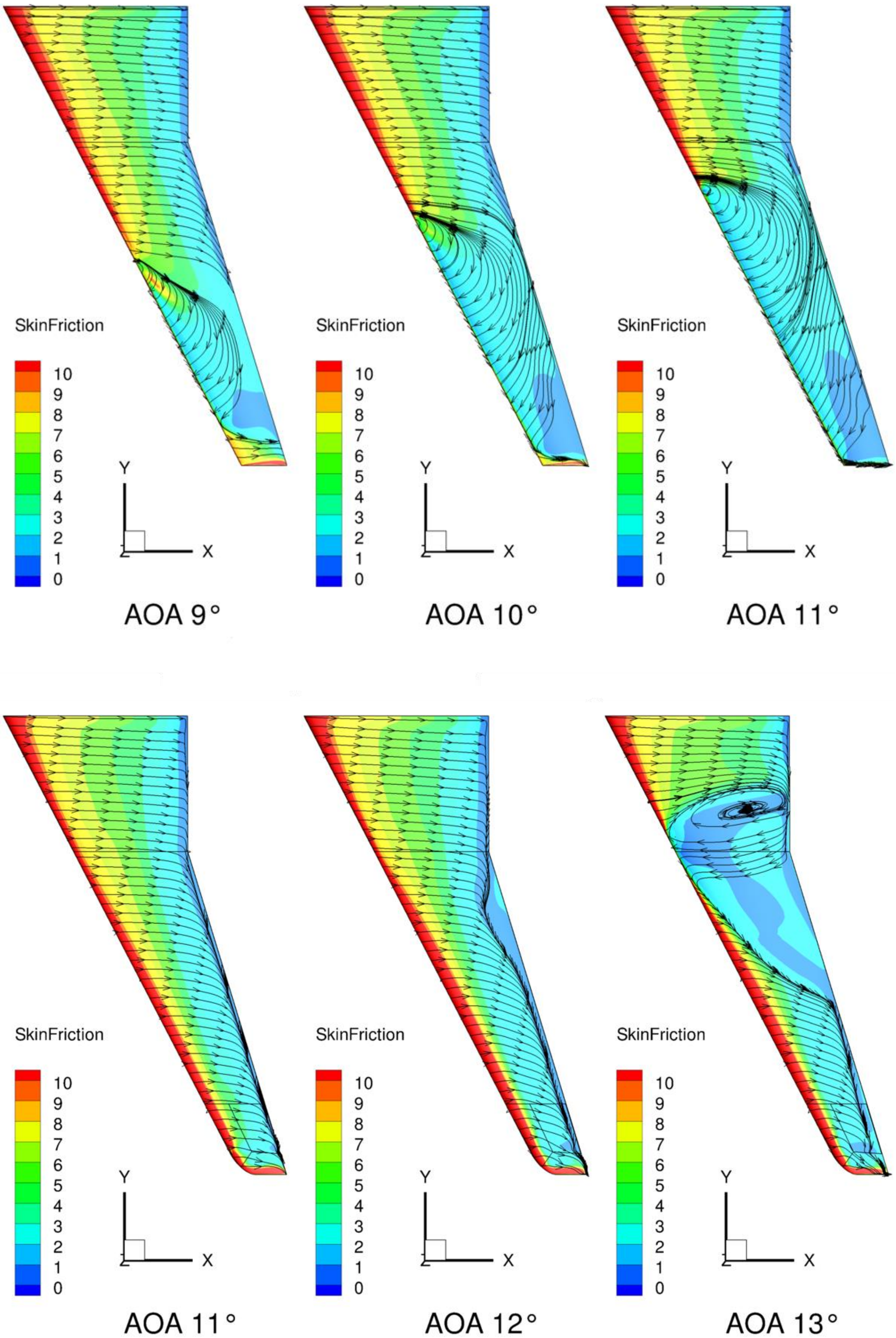

Figure 13 : Wing aerodynamics simulations for the original wing (top) and the redesigned one (bottom)

Appendix 2 – Simulation of nacelle aerodynamics before and after the redesign

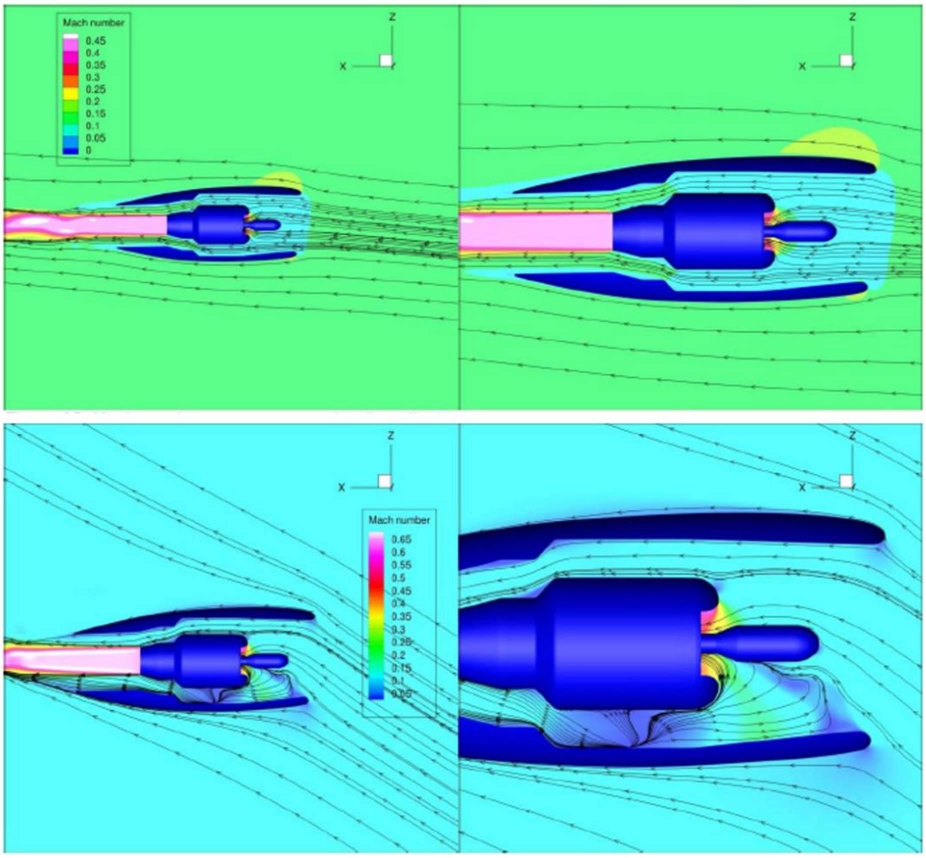

Figure 14 : First design of the nacelle (cruise condition on top with 5° upwash and take-off condition at the bottom with 30° AOA)

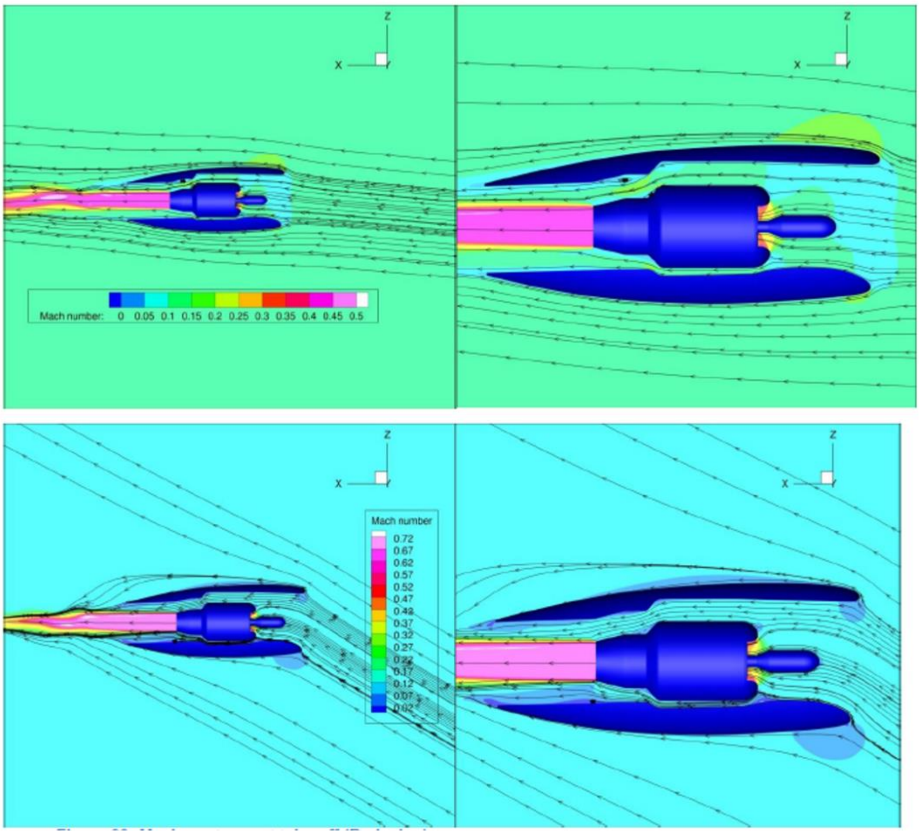

Figure 15 : Revised and final design of the nacelle (cruise condition on top with 5° upwash and take-off condition at the bottom with 30° AOA)

Appendix 3 – Overview of the six Qualification Flight Tests

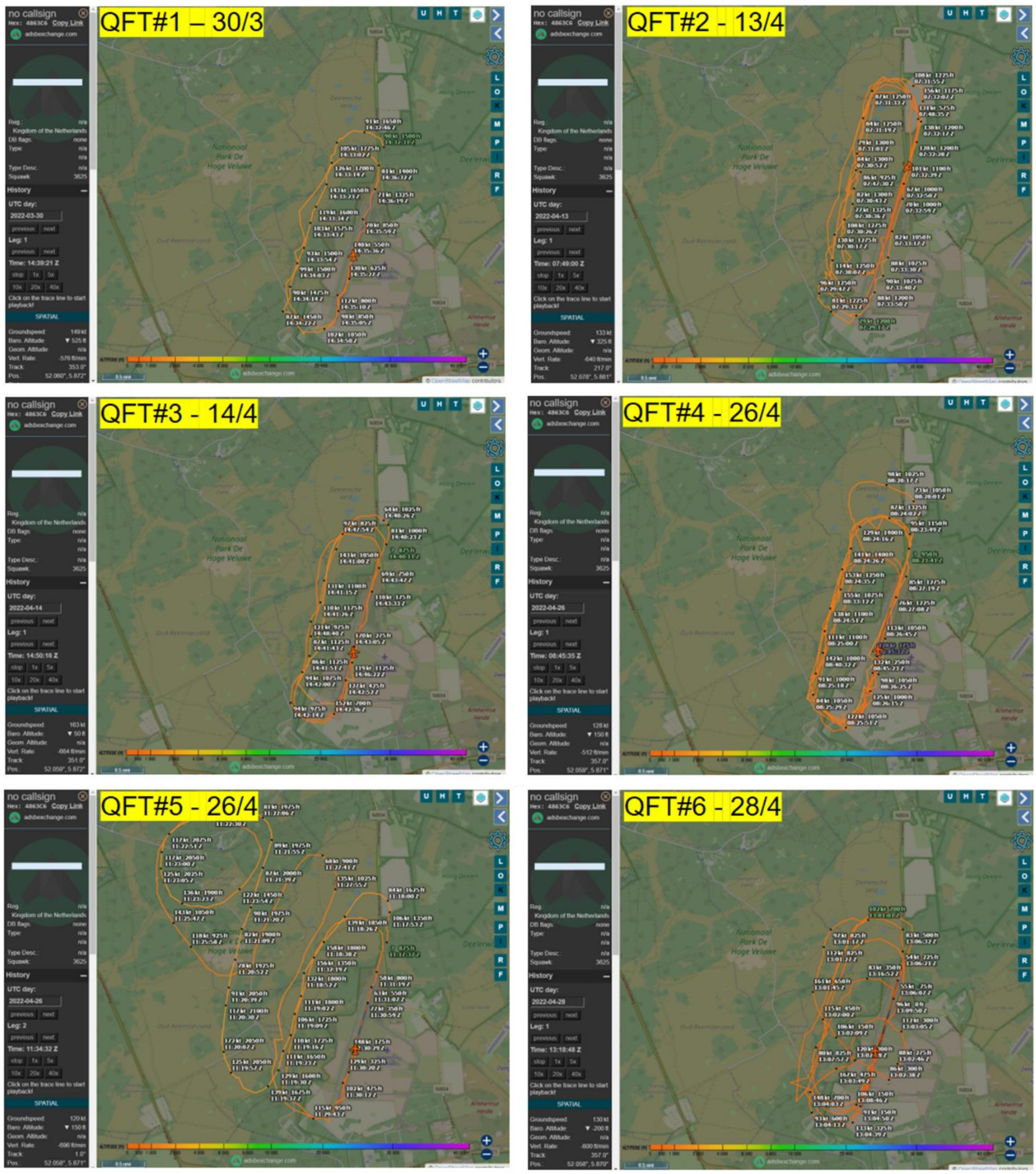

Figure 16 : Flight path of the SFD around Deelen Airport for the six Qualification Flights

Appendix 4 – Simulations results for the SFD (Aerodynamic model from Wind Tunnel Tests)

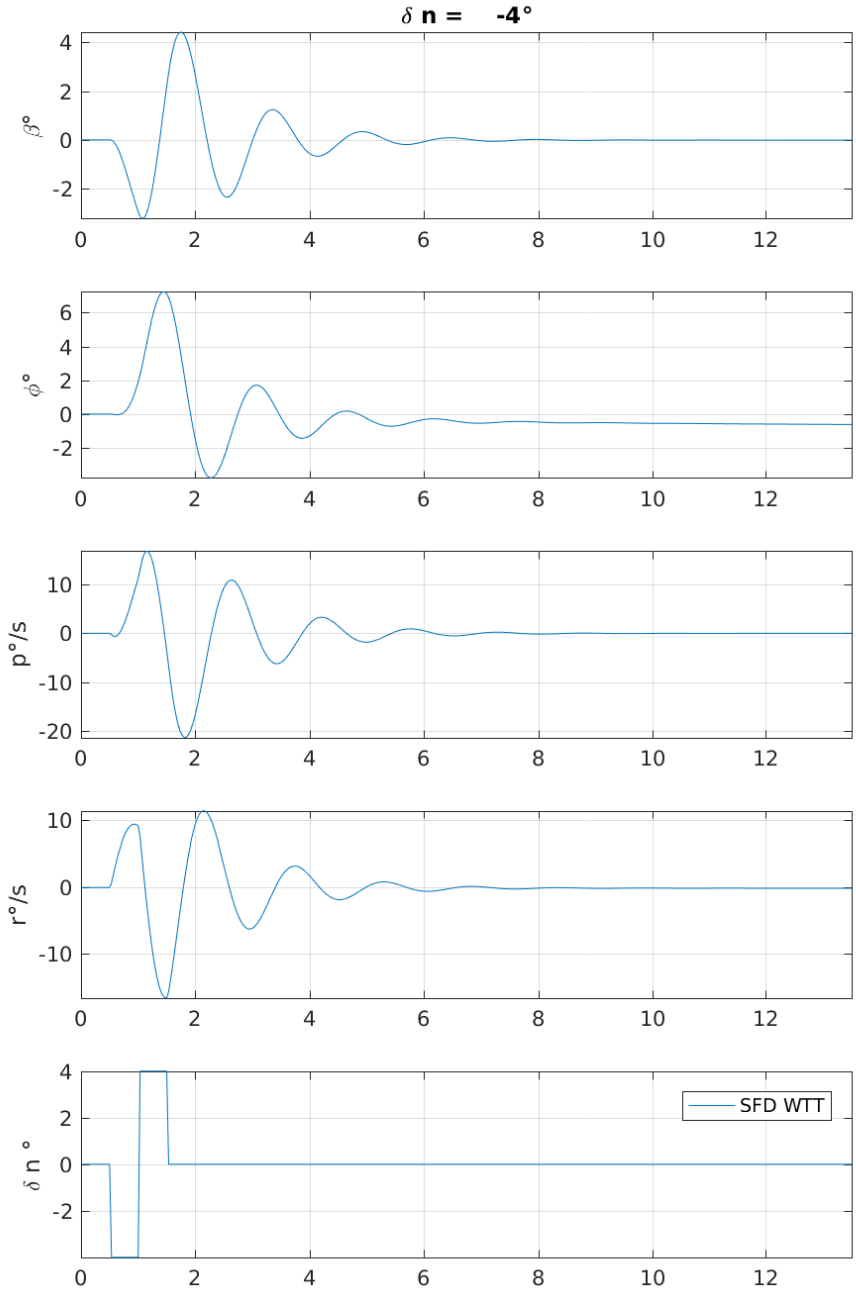

Figure 17 : Responses of the SFD model based on Wind Tunnel Data to a rudder doublet