

SCALED FLIGHT TESTING SUPPORTING THE DEVELOPMENT OF RADICAL NEW AIRCRAFT

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Abstract

Scaled flight testing can contribute to valuable reduction of risk and cost in the development of a radical new aircraft. The role of scaled flight testing in the aircraft development process is described, where it is essential that the relationships between the small-scale and full-scale results are properly defined. The validity of results of scaled flight testing for predicting the full-scale aircraft properties is addressed next. A 1:8.5 scaled version of a typical large passenger aircraft was built, tested in the wind tunnel and flight tested. During the flight tests an accurate flight test instrumentation system measured the scaled aircraft flight parameters. Results of the scaled flight testing have been compared with full-scale test results which validates the value of the scaled flight testing methodology. In a next step the scaled flight testing methodology is applied to investigate and demonstrated the benefits of distributed electric propulsion. The scaled aircraft has been re-built in the same shape but the jet propulsion is replaced by propulsion with six propellers. The development, manufacturing, wind tunnel test and taxi tests are described, flight tests still have to be performed. Finally the role of the flight test engineer in the scaled flight test campaigns has been compared with the role of a flight test engineer in a typical full-scale flight test campaign. The roles were chosen very similar and that worked out very well in these scaled flight test campaigns.

Abbreviations

BVLOS	Beyond Visual Line Of Sight	IEP	Innovative Evaluation Platform
CFD	Computational Fluid Dynamics	IMU	Inertial Measurement Unit
DEP	Distributed Electric Propulsion	JU	Joint Undertaking
ESC	Electronic Speed Controller	LLF	Large Low-speed Facility
FTE	Flight Test Engineer	LPA	Large Passenger Aircraft
FTI	Flight Test Instrumentation	MEMS	Micro Electro-Mechanical System
GAM	Grant Agreement for Members	PiC	Pilot in Command
GCS	Ground Control Station	SFD	Scaled Flight Demonstrator
GNC	Guidance, Navigation and Control	TP	Technical Publication
GNSS	Global Navigation Satellite System	USA	United States of America

1 INTRODUCTION

The request for sustainable aviation initiates developments of new aircraft technology to be integrated in new aircraft configurations. To harvest the benefits of these new aircraft configurations a large development effort is deployed. Such a development is costly and faces risks in what aircraft has the best design, market potential and flight characteristics. Reductions of risks in a phase as early as possible in the development process are welcome because development changes in later phases are increasingly expensive and time consuming. It has been recognized that testing the technology and configurations on scale can reduce risks and costs, ref. [1], [2], [3], [4] and [5]. Several aspects of the testing on scale are addressed in this paper:

- The role of scaled flight testing is explained.
- The validation of the scaled flight testing methodology for flight dynamics and control requires a well-known aircraft configuration and advanced means for accurate measurements on scaled flight tests. Specific attention is for the flight test instrumentation generating the measurement results.
- The methodology is applied to an aircraft for investigating and demonstrating a novel technology, the distributed electric propulsion. First results are presented and the approach is explained.
- The roles of the crew and in particular the Flight Test Engineer in these flight campaigns are compared with the roles in typical conventional aircraft flight test campaigns.

The activities described are performed in a collaborate effort by Airbus, ONERA, CIRA, TU Delft, Orange Aerospace and NLR.

2 THE ROLE OF SCALED FLIGHT TESTING IN THE AIRCRAFT DEVELOPMENT PROCESS

In the development process of an aircraft different phases can be distinguished, see Figure 1. Evaluating the design in the consecutive phases may result in design changes and the evaluation is an iterative process. Changes have a larger impact and cost if a change has to be made in a later phase and therefore risk reduction for changes is required during the development process. Generating a good design is the basis, after which a thorough calculation phase is performed, including aerodynamic verification of the design in Computational Fluid Dynamics (CFD). The next phase is normally a phase in which a scale model is tested in the wind tunnel. Aerodynamics is further validated for the aircraft shape and control surfaces. Dynamics and controllability of the aircraft is tested only to a limited extend in the wind tunnel. Testing a scale model in free-flight adds to the information obtained with the static wind tunnel model and as such to the risk reduction of modifying the design in the more expensive full-scale prototype flight test phase. The dynamics and controllability information is not really needed if a derivative of an already existing configuration is evaluated, but adds valuable information if a radical new aircraft configuration is developed. The risk of developing the wrong or not optimized configuration is reduced in the scale model testing phase instead of the later full-scale prototype flight testing phase or, even worse, the series production.

The scaled flight testing methodology can also be applied for other aspects than dynamics and controllability, such as noise emission assessments, system development, recovery procedures from hazardous flight conditions and aeroelasticity, see ref. [3], [4], [5], but that is not the focus in this paper.

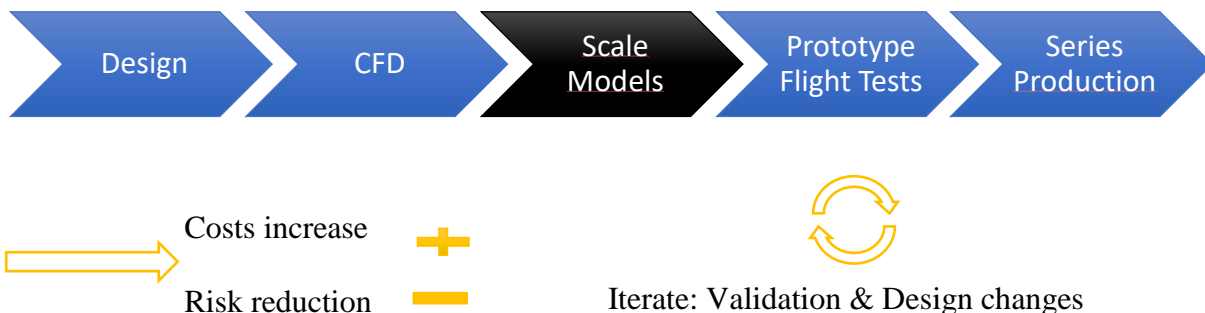


Figure 1 Different phases in the development process of a new aircraft associated with increasing cost and, if successful, with reduced developments risks and reduced iterations and design changes.

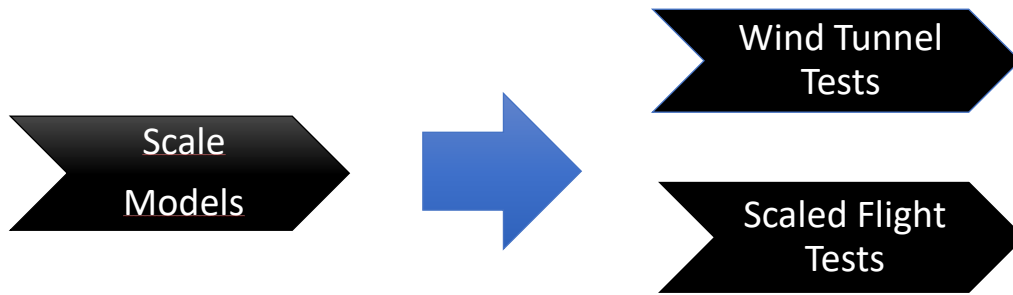


Figure 2 Scale model testing in the wind tunnel and in free-flight for radical new aircraft configurations

3 VALIDATION OF THE SCALED FLIGHT TESTING APPROACH

3.1 Development and manufacturing

A scaled version of a Large Passenger Aircraft was developed for the validation of the scaled flight testing methodology. A scale 1:8.5 was chosen for the demonstrator which results in a wing span of 4 meters. The mass of the aircraft is 140 kg. In this, Froude scaling is applied to obtain a good similarity for the dynamic characteristics. Jet engines, two AMT type Olympus HP engines with a maximum thrust of each 230 N, see ref. [7], provide the propulsion of the aircraft. The aircraft, the wind tunnel test and the lowspeed taxi tests have been described in more detail in ref. [1] and [2].

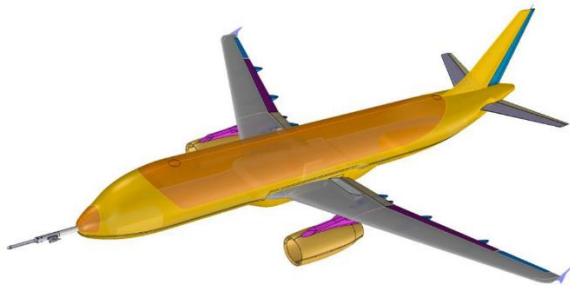


Figure 3 Scaled Flight Demonstrator for the validation of the scaled flight testing methodology

3.2 Wind tunnel testing

The scaled aircraft was first installed in a large wind tunnel, the Large Low-Speed Facility of DNW in Marknesse in the Netherlands, to acquire aerodynamic data and to test the aircraft and the aircraft systems, see Figure 4. Aerodynamic data was input for the reduction of the risk for the first flight, for developing a simulator to train the pilots and to develop control laws. The jet engines were also operated in the wind tunnel to acquire thrust effects.



Figure 4 Scaled aircraft with jet engines in the wind tunnel

3.3 Taxi and flight testing

After the wind tunnel test the same scaled aircraft performed taxi test and flight test campaigns. Low speed taxi tests on Breda International Airport, high speed taxi tests and aircraft qualification flights on Deelen Airbase in the Netherlands and measurement flights at Aeroporti di Puglia in Grottaglie, Italy. The aircraft was operated from a ground control station in which pilots and test engineers controlled the aircraft Beyond Visual Line Of Sight (BVLOS). See Figure 5 and Figure 6.



Figure 5 Scaled aircraft with jet engines during the landing of a test flight



Figure 6 Pilots in the ground control station during the flight test with the scaled aircraft with jet engines

The test flights were initially attributed to qualify the aircraft for the flight envelope foreseen for the test objectives and in a second phase dynamic manoeuvres were executed applying a dedicated autopilot, the Guidance, Navigation and Control computer (GNC). The GNC, developed by CIRA, commands the dynamic manoeuvres and flight parts between these manoeuvres. Advantage of this automatic input generation is that the input is better defined than a human pilot steering the aircraft. Dynamic inputs were generated with an increasing amplitude during which the pilot monitors the adequate behaviour of the aircraft and in between the steps the behaviour is analysed and verified on the ground.

Handing over the control from the autopilot assisting the pilot in normal operation to the autopilot dedicated for the measurement sections appeared a delicate part of the operations. Although well prepared, the aircraft showed quite an upset manoeuvre when the handing over was tested in flight. The robustness of the aircraft design and the pilot in command limited the impact and the 6 qualification flights and 19 measurement flights with 69 dynamic manoeuvres were flown successfully.

3.4 Flight test instrumentation

Accurate instrumentation was developed and installed in the aircraft that measures amongst others air data, inertial data, angular position of surfaces and engine parameters. High accuracy was requested in order not to jeopardize the quality of results and as such the validation of the methodology due to measurement errors. Small and accurate instrumentation appeared to be available on the market, which led to measurement uncertainties in the same range as normally applied as for a full-scale prototype aircraft. In this, it was taken into account that the dynamics is different. The velocity of the scaled aircraft is smaller, but the rotations are faster. A short description of the major components of the FTI selected is provided below, complying to the power, weight and budget constraints set by the SFD. Table 1 provides an overview of the components and Table 2 gives according to the argumentation above the typical ranges and accuracies for FTI for dynamic full-scale aircraft measurements, the Froude scaling factor applicable for the parameter and the derived goals for SFD sensor ranges and accuracies.

3.4.1 Air Data

A Simtec ADP55 air data system was installed which has the pressure and temperature sensors integrated in a nose boom. The pressure sensors installed in the boom provide high temporal resolution for the measurements. As the dynamics of the aircraft is an important aim for the validation of scaled flight testing high temporal resolution is important.

A unique opportunity was provided for the calibration of the boom during the wind tunnel test of the SFD. The boom, installed on the aircraft, could be calibrated at different air velocities, angle of attacks and angle of side slip, which are all accurately measured with the wind tunnel instrumentation.

3.4.2 Aircraft position, acceleration and attitude

Aircraft acceleration and attitude is measured with an Inertial Measurement Unit (IMU). Aircraft position is not a parameter to be measured for the validation of scaled flight testing, but inertial measurement units deliver the information anyhow and require satellite navigation inputs to correct the drift of their internal sensors. For

the range and accuracy demands we selected and applied the iMAR iNAT-M200/SLN-DA IMU. Heading information is enhanced through inputs two Global Navigation Satellite System (GNSS) antenna's installed at 2.6 meter distance from each other on the SFD.

3.4.3 Control surface angular position

The challenge for selecting a control surface position sensor was to find a small sensor that can be integrated in the small spaces around the actuator and control surface in combination with high accuracy. For the control surface position as well as the flap position Contelec Vert-X rotary sensors were selected.

On the rudder also a torque sensor was installed to investigate the feasibility to measure this parameter on scale. It appeared a challenge to install the sensor such that only the torque is measured in the very small space. With an uncertainty of 10% of full-scale in the current installation it needs improvements.

3.4.4 Propulsion

Many of the engine parameters, such as fan speed and exhaust gas temperature, are generated by the sensors integrated in the AMT type Olympus HP engine or by processing these parameters. Fuel flow is measured with a small turbine rotating as function of the fuel flow in the Tecflow type IR-OPFLOW 100-11/H flow meter.

3.4.5 Aircraft systems and avionics

Aircraft systems and avionics also produce a lot of data that is all recorded on the FTI for later analysis and system performance monitoring.

3.4.6 Data acquisition and recording

A large stream of digital and analog data of more than 150 parameters is generated in the aircraft and supplied to the data acquisition and recording units. Analog data is filtered and digitized before recording. Zodiac XMA and MDR units were selected and applied for the filtering, digitizing and on-board recording of data. The units do not significantly affect the signal quality. All parameters are time stamped with GNSS time and recorded on-board the aircraft. A selection of the data is telemetered to the ground for real-time monitoring parameters and FTI performance.

Parameter	Manufacturer	Type	Characteristics
Air data	Simtec	ADP55	5-hole probe, sensors integrated in the boom
Inertial and position	iMAR	iNAT-M200/SLN	MEMS accelerometers and gyros and satellite navigation, also for heading inputs
Control surface position	Contelec	Vert-X	Hall sensor
Propulsion	AMT	Olympus HP	Rotation and exhaust gas temperature measured in the gas turbine
Fuel flow	Tecflow Zodiac	IR-OPFLOW 100-11/H XMA and MDR	Data acquisition and recording system tailored for flight test applications

Table 1 Main FTI components

			Full Scale		Scaled Aircraft		Scaled Aircraft	
Parameter	Froude Scale factor	Unit	Range	Accuracy (σ)	Range	Accuracy (σ)	Range	Accuracy (σ)
Typical sensor Range/Accuracy for Full-Scale FTI Parameters							Realised	
Linear Accelerations	1	$m \cdot s^{-2}$	+/- 40	0.01	+/- 40	0.01	✓	✓
Angular rates	$n^{-0.5}$	$deg \cdot s^{-1}$	+/- 200	0.1	+/- 600	0.3	✓	✓
Attitude Angles	1	deg	+/- 180	0.01	+/- 180	0.01	✓	✓
Control surface / flap position	1	deg	+/- 35	0.1	+/- 35	0.1	✓	0.1 to 0.3
Angle of Attack and Sideslip	1	deg	+/- 30	0.1	+/- 30	0.1	✓	✓
Absolute Pressure (for altitude and needed for air density)	n	Pa	110000	20	110000	2.4	✓	25
Differential Pressure (for airspeed)	$n^{0.5}$	Pa	10000	2	3500	0.7	✓	✓

Table 2 Key parameters measured, typical full-scale ranges and accuracies and derived goals (geometric scaling factor n) for ranges and accuracies for the SFD FTI.

✓ means that the performance goal for the scaled parameter in the SFD FTI is achieved or exceeded

The FTI for the SFD complies with the goals set, except for the control surface / flap position and the absolute pressure. Solutions were searched for and found in the analysis to deal with these limitations.

3.5 Analysis

The results of the flight tests were analysed and have been compared with full-scale aircraft data. The scaling and reduced inertia lead to faster responses as reflected in the Froude scaling and these known relationships have been compensated for. Differences between the shape and aerodynamics of the SFD and the full-scale aircraft were taken into account in the analysis as is described in ref. [2]. The scaled flight testing methodology provides good results with a good similarity to full-scale aircraft data for the SFD built and the manoeuvres flown.

4 APPLICATION OF THE SCALED FLIGHT TESTING FOR DEMONSTRATION OF DISTRIBUTED ELECTRIC PROPULSION

4.1 Development and manufacturing

A new scaled aircraft has been manufactured with the same fuselage shape, wing shape and tail shape as the SFD, but with propulsion through six electrically driven propellers instead of the two jet engines. This distributed electric propulsion (DEP) was chosen as a next subject for demonstration and test as this configuration needs considerably less energy for the propulsion, ref. [8], [9], [10], [11], [12]. Allocation of thrust to the propellers depending on the flight phase and manoeuvres enhances the propulsion efficiency further, see ref. [13] and [14]. This both for full-scale and on scale. Objective of the scaled testing is to

reduce the development risk of the distributed propulsion technology and to enable the optimization of the technology for efficient and safe aviation. Again a wind tunnel campaign has been performed to acquire the aerodynamic data of the configuration, see Figure 7. A programme for taxi and flight tests is ongoing.

4.2 Wind tunnel

The DEP-SFD was like the SFD tested in the DNW LLF with the following objectives:

- Generation of data for the evaluation of the Distributed Electric Propulsion technology
 - Measure installed thrust for the inner, middle and tip propellers individually and combined
 - Measure effectiveness of differential thrust (left, right)
 - Input for performance and / or stability and control as a function of DEP thrust investigations
- Reduction of risk for the first flight by:
 - Supporting Flight Simulator development
 - Supporting AutoPilot tuning
 - Supporting flight performance determination
 - Supporting flight envelope determination
 - Verifying structural integrity of the SFD at relevant aerodynamic loads
 - Verifying performance of the Electronic Speed Controller (ESC), the motors and the propellers at relevant operating points.

The DEP-SFD was installed in the wind tunnel, see Figure 7, and a large test program with 178 measurement conditions was run. A large advantage was that the DEP-SFD systems could be controlled remotely (as was the case for the SFD). This allowed, similar to the SFD, for fast operations and in two days the measurements were performed. Runs were performed without the propellers installed and with the propellers installed, both at equal throttle level and with differential throttle settings between the propellers.

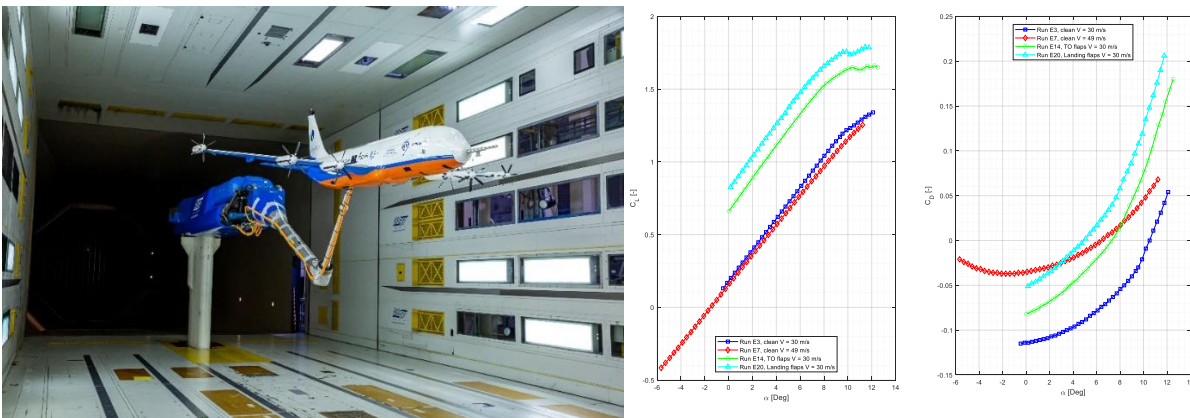


Figure 7 Scaled aircraft with distributed electric propulsion in the wind tunnel and some results, lift and drag coefficients as a function of flap setting and air speed

4.3 Taxi testing

Taxi tests, lowspeed taxi tests on Breda International Airport and highspeed taxi tests on Deelen Airbase in the Netherlands, have been performed successfully. The aircraft taxied at speeds up to 60 knots. Aircraft qualification and measurement flights are foreseen for summer 2023 on Aeroporte di Puglia in Grottaglie, Italy again.

4.4 Flight test instrumentation

The same FTI has been installed in the DEP-SFD. Modifications have been made to monitor the electric propulsion system instead of the fuel and gas turbine propulsion.

5 ROLE OF THE FLIGHT TEST ENGINEER IN SCALED FLIGHT TESTING

Flight testing the SFD and DEP-SFD was and is performed by a team located in a Ground Control Station (GCS). When developing the operations with the SFD it was considered to put a pilot next to the runway to land the aircraft and in less urgency to take off. It was decided to control the aircraft from the GCS in all flight phases. Reasons were:

- More accurate approach and runway alignment due to the quite high velocity of the aircraft (49 m/s airspeed) and the distance covered
- The complexity and additional risks introduced by taking over the aircraft from the Beyond Visual Line Of Sight (BVLOS) pilot.

The pilot training phase in the simulator before the first flight also validated this approach. The pilots had the SFD well in control in all phases of the flight. This resulted in operations from the GCS by:

- The Pilot in Command (PiC)
- The Pilot Monitoring reducing the workload of the PiC monitoring essential systems and flight test program progress
- The Flight Control Specialist monitoring autopilot and telemetry
- The Flight Test Instrumentation Engineer monitoring the FTI performance and selected parameters
- For the measurement phases, the Flight Test Engineer monitoring the GNC.

Next to the runway and in a chase car following the SFD and DEP-SFD are at least 2 observers that are in contact with the Pilot Monitoring.

The tasks of the crew were based on manned flight test operations and did not differ much from typical flight test operations. Being centred in the GCS allowed for direct communication between pilots and flight test engineers and the communication with observers worked out well. Therefore the roles and tasks of the flight test engineer were very similar to roles and tasks in conventional flight test operations.

6 CONCLUSIONS

The interest for scaled flight testing is generated by the development efforts of radical new aircraft enabling sustainable aviation. New aircraft configurations and new technologies are to be introduced to achieve this. The role of scaled flight testing in the aircraft development process has been described.

Scaled flight testing has been validated as a useful method to investigate the dynamics of an aircraft. For this purpose a 1:8.5 scaled Large Passenger Aircraft was developed, manufactured and flight tested. Dynamics of the scaled version has been measured accurately and compared with the full-scale aircraft dynamics. The relationship between results from the scaled flight tests and full-scale aircraft being governed by scaling laws has been validated.

The validated scaled flight testing methodology is being applied for demonstrating and investigating DEP technology. A DEP-SFD has been manufactured for that. The wind tunnel test and taxi tests with the DEP-SFD were successfully performed. The DEP-SFD will be flight tested soon.

The roles of the crew and in particular of the FTE have been addressed. The unconventional scaled flight testing operations with an aircraft quite different from a conventional aircraft does not lead to an unconventional flight testing approach for the crew and FTE.

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