Manufacturing, Assembly and Integration of a Large Scale Composite Wing Wind Tunnel Model and the Design and Implementation of an associated Measurement System

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Abstract

Building a wind tunnel model with an innovative aerodynamic design including a laminar airfoil concept and morphing parts requires a suitable manufacturing and assembly plan to transfer the virtual model to concrete reality.

The contribution of the INVENT GmbH within the GRETEL consortium is the manufacturing of the main structural components of the Wing and the integration of the Wind Tunnel Model. To realize such a precise projection, the main approach is to implement a high overall accuracy of the later model by realizing a low percentage of geometry deviation already on piece part level. Beginning with a material dedicated tool design concerning cure cycle parameters and induced strain effects, for aspects of geometrical manufacturing accuracy, also suitable inspection techniques, regarding the verification of structural requirements and material conditions are implemented in the integration process at specified steps.

A further part of the integration process of the GRETEL Wind Tunnel Model is the installation of application-related measurement equipment. The Institute of Composite Structures and Adaptive Systems of the German Aerospace Center (DLR) is responsible for the design and realization of such a project customized measurement concept. For the measurement of the pressure distribution along the profile contour with various angles of attack and wing configurations during the testing, the wing is equipped with several pressure taps. Further, the measurement equipment spectrum covers also the registration of acceleration forces and mechanical loads of the inner wing structure components. This concept creates a holistic picture of the coherences between aerodynamical and mechanical dimensions for each tested configuration.

The implementation of all aforementioned aspects into the large-scale model is elucidated and discussed in the light of morphing parts of the model being delivered by another project. The integrated equipment is described and the impact of the integration into the design and assembly of the overall model is illustrated.
1. Introduction

This paper describes the manufacturing of a large scale wind tunnel model with natural laminar flow (NLF) profiles, embedded in the environment of the CleanSky2 founded Project GRETEL - GREen Turboprop Experimental Laminar Flow Wind Tunnel Testing.

The idea to design a more efficient aircraft by reducing especially the profile drag with the realization of NLF capable airfoils is a typical state-of-the-art approach within the ongoing challenge to increase aircraft sustainability. The Wind tunnel experiment of GRETEL marks a preliminary milestone for the surrounding project-frame which has the over-all objective to project the NLF design approach on a twin turboprop mid-range carrier.

According to the preliminarily established requirements and under consideration of the NLF background a manufacturing and assembly concept was worked out and realised. Besides the solutions for manufacturing on detail level also the basics of the associated measurement concept and the dedicated equipment, that is used for surveillance during the preliminary structural tests and the wind tunnel test itself, are presented. [1][2][3][4][5][6]

2. Background

Geometrical accuracy and high surface quality are the main drivers when thinking about requirements for wind tunnel models, even more if natural laminar flow conditions are the central element of the test scope.

2.1. Requirements

To quantify requirements for geometrical tolerances, a CFD analysis for different inflow velocities was performed by Leonardo. Based on this CFD calculations, four different criterions were defined.

| Lifting surfaces / contour tolerances | ≤ 0 mm          |
|-------------------------------------|-----------------|
| Forward facing step                 | ≤ 0.05 mm       |
| Backward facing step                | ≤ 0.3 mm        |
| Gaps                                |                 |
| Surface Roughness                   | < 3.2 µm        |
| Composite parts                     |                 |

Fig.1 surface requirements [7]

These Requirements were relevant and leading for all following activities related to the final manufacturing of every part of the outer surface.
2.2. geometry influencing effects during CFRP parts manufacturing

CFRP specific, geometry influencing effects during manufacturing have to be mentioned, understood and compensated or considered if strict requirements for a complex structure are given. These effects are dividable into intrinsic and extrinsic effects. Intrinsic effects are mainly driven by the internal material behaviour during the cure cycle. Extrinsic effects were understood as those effects which are induced to the manufactured part by outer influences and interactions.

As most influencing effects, the following can be listed:

- Shrinkage
- Forced interaction
- Warpage
- Spring-in

All those effects develop their heaviest impact during the cure phase, in which the cross linking of chemical connections is still incomplete and the material consistence remain formable. Inducing uncontrolled und unobserved forces and tensions to the material results in unforeseeable geometrical discrepancies. [8][9][10]

3. Part manufacturing

With the knowledge about requirements and the heritage regarding manufacturing of CFRP parts, the base for the manufacturing at INVENT is given, starting with the design process leading to a complete tool set and an assembly and measurement concept.

3.1. Tool design and manufacturing

Developing the tool which forms the outer geometry of each part is the most important mechanism to control the geometry of the later resulting part. A huge factor is, besides the material selection and a suitable machinery, the heritage of CFRP manufacturing, whose essence creates a well evaluated database of compensation factors and design details.

In order to reach a high level of accuracy of geometry and surface related values, the use of CNC milled, open moulds made from aluminium was chosen. All tools are designed with temperature expansion, shrinkage and spring in compensating factors.

![CNC milled tools for spar and skin parts](image)

Fig.2 CNC milled tools for spar and skin parts

All parts whose outer surfaces are forming the outer shape of the later assembled wing are manufactured with their outer surface orientated in tool direction.
For this reason, the tool surface of these parts was further polished after the milling process to reach an even higher quality. The surface of each tool was measured regarding the surface roughness in comparison to the earlier defined requirements.

3.2. Material selection and manufacturing

The complete structure of the main wing of the model was manufactured from CFRP material. During the material selection two different groups of structural components were identified. Associated to this differentiation suitable materials for each group were chosen. For the spar parts, an unidirectional, non woven material was foreseen. The skin parts were manufactured using a fabric material. Both selected materials are prepregs for reasons of handling simplifications.

Using prepregs for manufacturing applications, some process steps are directly implicated. The major steps for all parts could be summarized as the following ones:

- Tool preparation
- Layup
- Vacuum build-up
- Autoclave process
- Demoulding and rework of outer edges

Besides the high effort to produce very accurate tools, special attention was given to the rework of the raw parts after the cure process and demoulding. For the skin parts, divided into upper and lower parts, specialized jigs were designed and milled to create a vacuum assisted fixation for an additional milling process. With this preparation, the outer shape and also part-related individual borehole patterns were applied to the parts to realise the highest grade of accuracy.

Fig.3 Lower Skin parts after shaping process
4. Assembly

With the described preliminary steps of manufacturing leading to parts with a low deviation regarding geometry, the base for an assembly of a highly accurate over-all structure is created. To reach this foreseen level of accuracy a suited assembly concept was worked out. The most important technical device during assembly is a reliable reference for each part which is added to the structure during the assembly. In case of GRETEL, as reference a special mounting-table was used. This table not only worked as a reference but also as base for several adjustable jigs. These jigs were the second major part of the concept. They allowed to not only to fix the parts during the mounting process but also are equipped with stopping points so the adjustment in dry condition of every part related to the reference was possible.

![Fig. 4 Assembly desk with bonding jig](image)

The required measurement according to the CAD model correlated with the reference was performed with an optical measurement system. Each additional part in the mounting sequence was directed into the measured target-position with adjusting the associated jig, to enable a repositioning of the part for the following bonding step.

![Fig. 5 adjustable mounting jigs for spar bonding process](image)
The first steps during the assembly procedure were the bonding of the front and rear spar to the upper skin and the installation of the dedicated ribs. With these steps, the center wingbox was established. The following steps are mainly characterized by the manual work which has to be performed to reach the best fit of the parts. These steps could be summarized as the following:

- Installation of detachable leading edges
  - Shimming process
  - Drilling of boreholes for fixation devices
- Installation of detachable lower wing skins
  - Shimming process
  - Drilling of boreholes for fixation devices
- Installation of Nacelle
  - Shimming process
  - Drilling of boreholes for fixation devices
- Installation of Root Rib
  - Adhesive bonding between aluminium part and CFRP main structure
  - Drilling of boreholes for HI-Loks

All these manual work steps were also accompanied with the optical measurement system and the use of several adjustable mounting aids.
The root rib part forms the connection between the inner load transferring structure of the wing, mainly the two spars, and the wind tunnel. This part was designed and manufactured as an aluminium construction, splitted into two halves for better handling. The two parts of the root rib were milled by using a CNC device. After the combination of these two parts, the root rib was mounted to the wing with a combination of adhesive bonding and mechanical connections established by Hi-Locks as last step of the assembly procedure.

5. Measurement concept

During the assembly process, not only structural components were added to the wing. In parallel, also parts of the dedicated measurement system for the observation of the wing during the static load tests and the wind tunnel test itself were installed. A passive component of the measurement equipment is the dot pattern on the surface of the wing skins. Those spots, made from neon, UV-light-reflective foil were directly integrated during the manufacturing phase of the piece parts to avoid any interference with the laminar boundary layer on the outer surface. The main measurement concept is established by a system of several different devices on selected areas of the wing.
The pressure distribution over the chord of the wing is measured by a system of pressure tubes. To get a complete picture of the flow conditions, the pressure tubes were aligned along three cross sections of the wing orientated in flow direction. To cover the whole wing, the positions of the three cross sections are evenly divided along the wingspan.

![Fig.9 Installation of Pressure taps](image)

These three positions in span direction were also used for the devices which are used for the observation of mechanical loads of the structure. For this purpose, on each station, a triple of strain gauges is applied on front and rear spar webs. With those devices a complete detection of bending-, and torsional moments at each cross section is covered. In addition to that, three accelerometers were mounted to the wing structure to detect vibrations during the wind tunnel testing.[11]

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