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Tailoring Flight Test Instrumentation with Additive Manufacturing

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Abstract:
The project “Surface Module Approach for Rapid Testing in Flight Test Instrumentation” (SMART-FTI) is part of the “Clean Sky 2 - Joint Undertaking” (CS2). Innovative aerodynamic measurement technology is being developed and the preliminary results are shown in this paper. With the design freedom of additive manufacturing or “3D-printing”, measurement equipment can be tailored to seamlessly integrate into the loft of any aircraft. Through topology optimization, weight saving measures are applied while keeping strength to allow for flight test applications. The direct integration of the data acquisition (DAQ) into measurement modules supports quick and easy assembly as well as high frequency pneumatic measurements. A fully integrated aerodynamic measurement system approach with PTPv2 – IEEE 1588 is a novelty in FTI.

Key words: additive manufacturing, topology optimization, high frequency measurement, integrated aerodynamic measurement, PTPv2 – IEEE 1588

Introduction

Goal of the project SMART FTI is to develop aerodynamic flight test instrumentation (FTI) for the innovative Airbus Helicopters “RACER”. The RACER is a high-speed helicopter demonstrator developed by Airbus supported within the CS2 frame. With its aerodynamic configuration in service of high speed, aerodynamic flight testing needs are a logical consequence. The aircraft/helicopter hybrid is distinguished by a main rotor and two lateral rotors with additional aerodynamic surfaces. The concept is shown in Fig. 1.

Fig. 1. Rendering model of the RACER concept by Airbus Helicopters [1]

FTI for detailed collection of aerodynamic test data of the complex flow around the new aircraft concept is envisioned. Details on the complex flow can be obtained in Wentrup et al. [2]. For the data collection, several module types and a novel, compact scanner with direct integration into FTI modules are in development. For high frequency measurements, pneumatic links are to be kept to a minimum to avoid lag and damping, a common phenomenon known by pitot systems of aircrafts.

Benefits for Aerodynamic Testing

Although CFD is spreading and generating great guidance for design, the need for validation also rises. In addition, complex configurations, and aerodynamic interaction with structure and rotating elements exhibit a challenge. Consequently, aerodynamic testing in the aircraft industry is performed from concept phase to certification and even beyond. From university research of innovative aerodynamic elements to scaled model testing in the wind-tunnels to flight testing campaigns on prototypes.

In the past advanced aerodynamic flight testing was very complex and limited. Therefore, indirect measurements have been used. For example excessive vibration of a vertical fin has often been tested using strain gauges and accelerometers, although the source of that behavior may come from the propulsion system or aerodynamic interference.

In conclusion, aerodynamic flight test equipment allows for verification of CFD and wind tunnel experiments. It also enhances root cause analysis possibilities for aerodynamic effects that could for example effect engine performance/stability, vibration, handling qualities and aerodynamic performance/stability. Typical aeras of investigation are:

- Engine inlet flow;
- Flow over wings, stabilizers and control surfaces;
- Accelerated flow of the propulsion systems.

Ambition of SMART-FTI

The innovation here is primarily to take known pieces of aerodynamic measurement solutions, puzzle them together and levitate its technology readiness level (TRL) by proving its capabilities in flight testing on the RACER high-speed demonstrator.

Vectoflow, together with Evolution Measurement and Any-shape are forming a strategic partnership bringing in its natural competences and know-how in designing, additive manufacturing, testing, and data acquisition. The resurrection of non-conventional airplanes, helicopters and drones is triggering a demand in aerodynamic testing. The general demands for fuel efficiency and aerodynamic drag reduction can be answered with aerodynamic testing. Also challenges for passenger comfort and noise can be detected with FTI. The consortium is mastering new demands in data communication, new design freedom with additive manufacturing, and recent advances in materials and processes. Finally, the goal is to achieve a one-fits-all concept, that allows easy adoption for future FTI programs.

SMART-FTI Process

Secondary FTI is developed in the SMART-FTI project, under the premise: no permission of modification of the aircraft structure. The following work packages have been formulated forming the process of the SMART-FTI project:

- Region of Interest (ROI) definition and Requirements:
  Definition of measurement points and data to obtain; Requirements engineering.
- Conception of Scanner:
  Development of scanner and concept for direct integration into the FTI modules.
- Conception of FTI modules:
  Development of measurement concepts for surface modules and conception of Vectoflow's conventional rakes and probes for measurement tasks; validation of additive manufacturability.
- Design/Integration:
  Detailed design on specified ROIs including the minimal invasive integration into the RACER helicopter and fast/easy installation to the airframe.
- Substantiation of loads:
  Simulations to obtain Permit to Fly (PtF)
- Manufacturing:
  Additive Manufacturing of the polymer and metallic modules.
- Flight Testing:
  Data acquisition and post processing.

Currently, the design and integration stage are being concluded and a PtF is targeted.

Additive Manufacturing

Additive manufacturing is an umbrella term for manufacturing technologies, which build parts by adding increments to a build platform totaling up to the final part. [3] Recent advances in these technologies and its qualification for flight applications lead to a broader use in aerospace as demonstrated in Blakey-Milner et al. [4]. While there are several technologies available, the present article will focus on the laser powder bed fusion (LPBF) process for metals and organic polymers, used to produce the FTI.

The LPBF process of building parts is a continuous repetition of the following steps: powder deposition, laser exposure, lowering the build platform. [3] A detailed graph of the LPBF setup is given in Fig. 2.

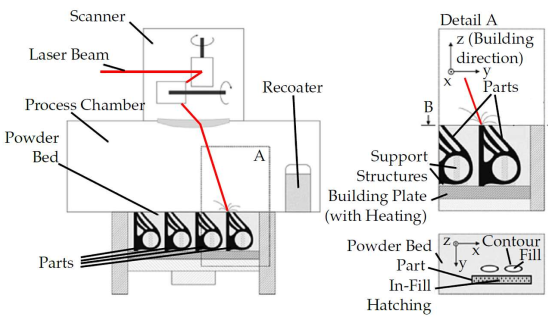

Fig. 2. Graph of LPBF Process (laser powder bed fusion), modified from [5]

The layer-wise process allows for a high design freedom, which can be used to introduce lightweight structures e.g., lattices or honeycombs, or internal channels. [6] These features make the process predestined for the manufacturing of flow probes and FTI with internal channels. With AM, lightweight parts with integral internal channels for pressure measurements can be manufactured in one piece using a single process.

As the process does not require any tooling, short lead times of several hours to days can be realized, making the process suitable for rapid prototyping. [3]

Surface Modules

The main topic of the SMART FTI project is the development of surface modules to measure pressure gradients. While, in this project, the ROIs follow curves in 2D-planes around profiles, the pressure mapping can be placed nearly arbitrarily across a module.

The module concept is a local thickening of 10mm of the aerodynamic surface at the ROI. This value is derived from the maximum scanner thickness of 10mm and to ensure smoothness for the added profile thickness. The scanner is integrated into the modules. The scanner specification is detailed in a later section. An overview for the surface module prototype is given in Fig. 3.

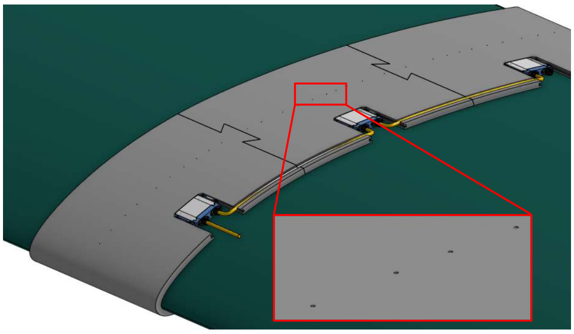

Fig. 3. Placeholder surface module – general layout of plastic module with integrated scanners on a generic airfoil – isometric view

A side view on the profile is given in Fig. 4. The overall thickness of $t_{max} = 10mm$ is kept around the profile.

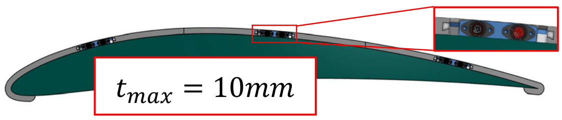

Fig. 4. Side view of the module concept on a generic airfoil

A 2D-simulation yielded an acceptable alteration of aerodynamic profile characteristics with the constant thickness increase. The influence on performance sank with having only a partial chord length instrumented with the module. Hence, in the first prototype shown in Fig. 6 only the first two thirds of chord length are equipped with the module.

Within the thickness, the developed EvoScann scanners sit on an intermediate piece, which is glued into the surface module. The concept is shown in Fig. 5. Airtightness is ensured with sealings, which are not shown in the presented CAD-model.

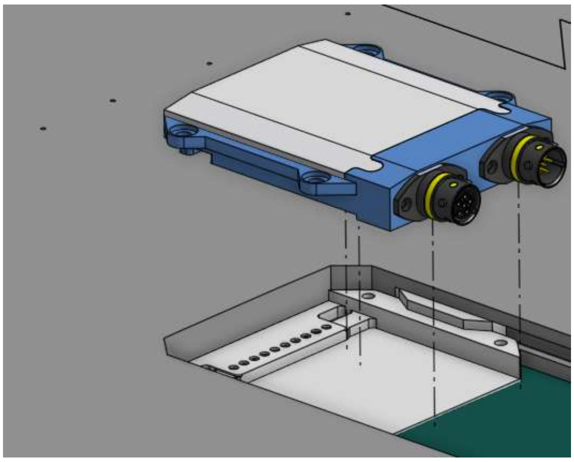

Fig. 5. Integration concept of scanner into the plastic module

In the final prototype, the connection to the aircraft is modelled in detail. Threaded inserts, so called Clickbonds, are glued to the aerodynamic surfaces. The surface modules can then be fixated with screws. Gaps and cable slots are sealed with aluminum tape. The concept is shown in Fig. 6.

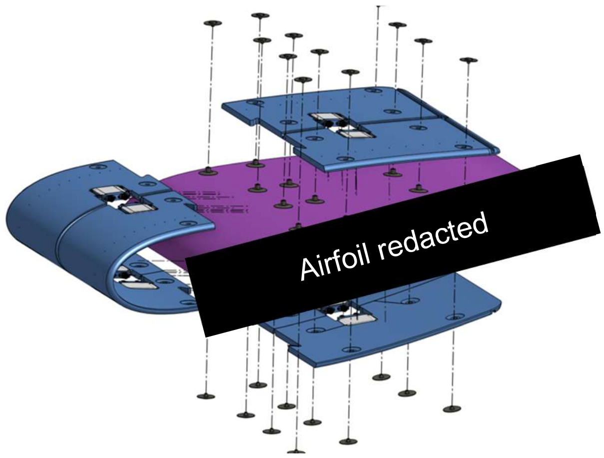

Fig. 6. Integration concept onto airfoils with clickbonds, airfoil redacted due to NDA

For the surface modules, an organic material (polyamide) has been chosen. The choice has been made according to the following requirements:

- Low density, due to weight constraints on the tail empennage;
- Manufacturability by LPBF;
- Thermal stability at elevated ambient temperature;
- Material flexibility for adaption to manufacturing tolerances of the aerodynamic surfaces.

Although the density of the used material is relatively low, the constant profile thickness yielded in a significant weight. Due to the large lever to the center of gravity of the aircraft, the weight needed to be reduced. Here, the high flexibility of the LPBF process comes in handy. Topology optimization by integration of a honeycomb or Voronoi structure comes with no penalty on the manufacturing side. A printed prototype is shown in Fig. 7. It is even beneficial for the manufacturing time as less material needs to be molten. The effort is on the design side. With the application of the weight saving measure, up to 55% of weight could be saved compared to the full material. In the future, topology can be further optimized by tailoring the honeycomb/Voronoi structure to the loads.

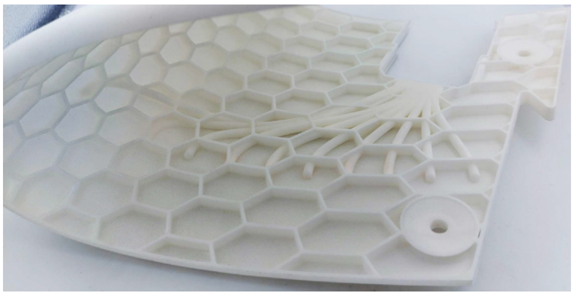

Fig. 7. Printed Prototype with honeycomb structure

An overview of the instrumented tail section of the RACER helicopter is given in Fig. 8.

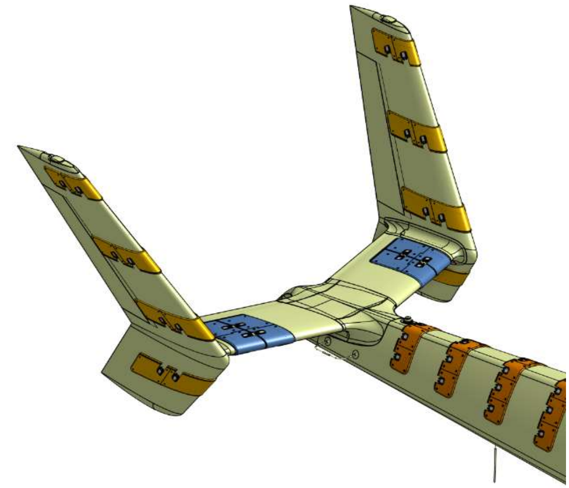

Fig. 8. Overview of the FTI installation on the tail-section of the RACER (aspect ratio modified)

The polymer PA-12 with a melting point of merely 187°C is used in colder areas. For higher temperatures, metallic modules are in use. Further, while the obtained data from the surface modules is valuable, sometimes more spatial resolution is required. The rakes and flow probes described in the next section can deliver the higher spatial resolution of measurements.

Rakes and Flow Probes

In higher temperature regions close to the main rotor and engines, plastic modules cannot fulfill the requirements. For installation on the RACER, metallic modules are envisioned. These consist of metallic flow probes, or rakes, which allow for higher temperature acceptance. The basic principle is a nearly unrestricted placement of measurement points, e.g., 5-hole probes or Kiel probes (Fig. 10). The probes are held by an aerodynamic profile, which contains internal pressure pneumatic channels as pressure tubes. Using the advantages of LPBF, these rakes can be manufactured in a single piece.

While metallic rakes are a standard product at Vectoflow with a high TRL, the innovation in this project lies in the mount of the scanners directly to the rakes. The latter eliminates the need for extensive plastic tubing to centralized, analog DAQs leading to fast frequency responses. An overview of the concept is given in Fig. 9.

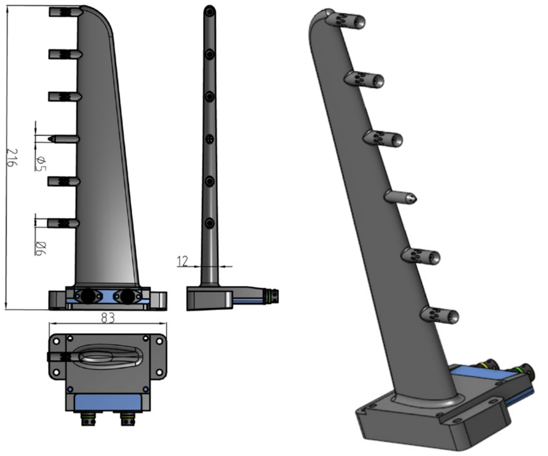

Fig. 9. Metallic rake concept with integrated scanner

Another novelty is the choice of material for this project. Due to low-weight requirements, rakes are printed in Scalmalloy®. It is a lightweight aluminum alloy with exceptional strength and ductility [7], exclusively developed for AM [8]. While AM of Scalmalloy® has been proven successful in aerospace [9], it has not yet been applied to LPBF of flow probes. Due to the larger extent of melt-pools for aluminum-alloys, resolution is lower. This was overcome by adaption of Vectoflow's standard geometry to the new requirements. The printed probes are shown in Fig. 10.

Fig. 10. Kiel-probe manufactured by LPBF from Scalmalloy®

First calibrations of the Kiel-probes show a recovery of 99% of the total pressure over an angle range of ±53° for yaw and pitch. Pitch-angle results are shown in Fig. 11.

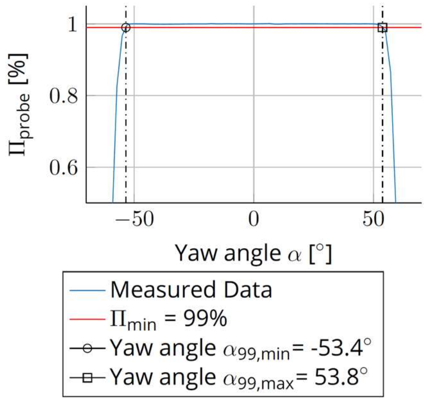

Fig. 11. Total pressure recovery over yaw-angle for calibration of developed Scalmalloy Kiel-probes at Ma=0.3

The rake geometry can be adapted to suit any measurement grid. For example, rakes can be curved to be fitted to freeform surfaces, as shown in Fig. 13. This allows for a 2D-mapping of external flow conditions in the plane of interest. For the integration of the scanner, the base can get bulky. To prevent aerodynamic perturbations, an aerodynamic cover, which is additively manufactured as well, might be added.

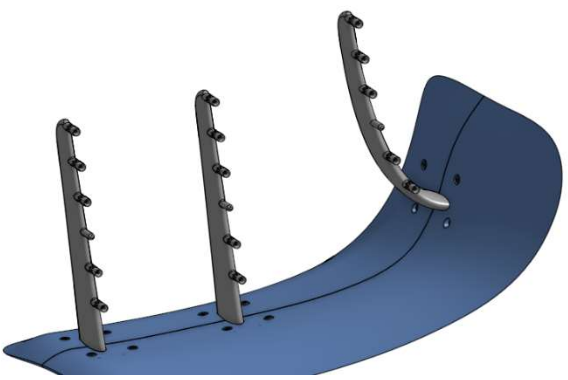

Fig. 13. Rake assembly adapted to freeform surface with aerodynamic cover

Scanner Features and Measurement Topology

Specifically for this project, a scanner is developed by Evolution Measurement using its experience from the EvoScann standard product as a base. A top-level requirement is the ease of installation without the need for extensive wiring, which is met with the measurement topology in Fig. 12: the potential to daisy-chain the scanners. This means only one cable between each scanner is required for data and power transmission. In the following, key-features of the novel scanner are listed.

Mechanical features:

- Low profile form factor <10mm to suit embedding into aerodynamic surfaces with minimum intrusion.
- IP67 Rating to allow uses in outdoor and varying environmental conditions.

Sensor features:

- 10 True-differential pressure measurement – ranges from +/-20mBar to +/-1Bar.
- Typical accuracy of measurement <0.1% FS
- Measurement resolution to 0.0006mbar
- Electronic resolution 24bit
- 1 Additional Absolute pressure channel to detect for local static pressure measurement deviations.
- High frequency synchronous measurement up to 4kHz across all channels.
- Wide Operating Temperature -40˚C to +110˚C.

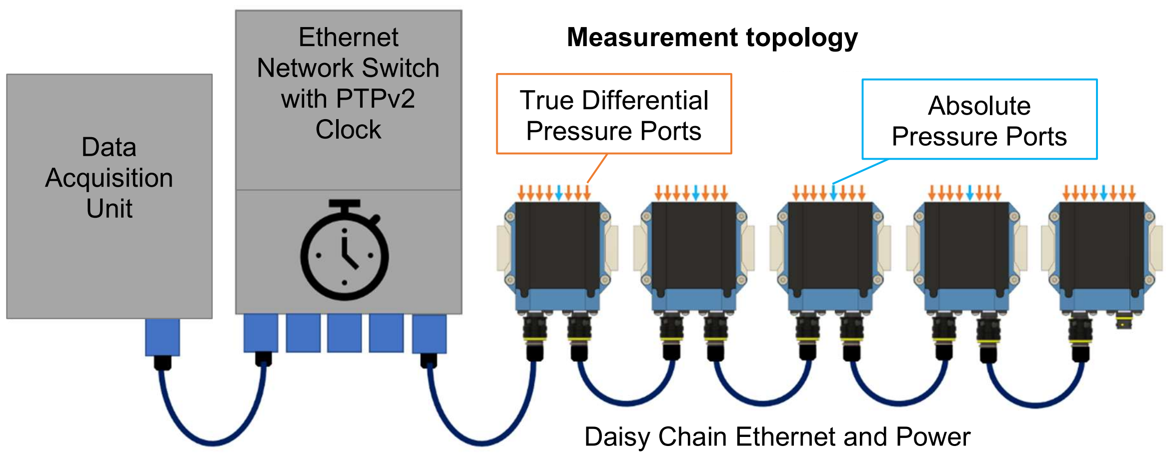

Fig. 12. Topology of data acquisition

- Direct coupling of scanner to test article maximizes frequency response to provide best measurement fidelity

Electrical features:

- Low Power consumption <1W per scanner.
- Power over Ethernet (PoE) compatible for ease of use and reduction in cabling to the scanners, whilst also proving full electrical isolation of the measurement.
- Embedded Ethernet Switch enabling multiple scanners to be daisy-chained reducing the complexity of the electrical Installation.
- IEEE 1588 PTPv2 compliant – accurate time stamping of data packets, allowing all scanners on the network scanners to be synchronized.
- Possible future software integration of flow probe and surface characteristics to provide direct velocity and angular information output

Impact for Future Programs

Within the SMART-FTI projects materials and processes for additive manufacturing of modules that are safe for flight are being developed. Probes and scanner technology are merged into modules which form a useful product with state-of-the-art connectivity. Future programs will benefit from the ability to go above and beyond in aerodynamic testing by generating larger sets of aerodynamic data in one test campaign. SMART-FTI modules are driving efficiency and usefulness of these campaigns.

These modules may have the number of measurement points that are typical for wool threads but with quantitative figures. They can also be used to get quantitative data for external flow, to generate the full aerodynamic data set. At high frequency rates this data allows to investigate more thoroughly the root cause and unsteady effects of the aerodynamic and propulsion elements of the aircraft configuration.

This innovative technology will help addressing key issues and unknowns with novel distributed propulsion systems, and aerodynamic optimization designs, just like the RACER, but in electrical vertical take-off and landing aircraft (eVTOL) businesses.

The modules with contributions from many different companies, in contrast to a self-assembled system, will reduce the complexity for the end-user: The consortium provides an all-in-one solution with a simple plug and play interface allowing to connect to modern FTI developments, e.g., in eVTOL developments shown in da Motta [10]. In addition, the rapid prototyping of FTI can take place early and in parallel to the prototype development. This saves costly development/improvement time and leverages the OEM into a better market situation.

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