Italian Association of Aeronautics and Astronautics
XXVII AIDAA Congress
4-7 September 2023, Padova, Italy

DEVELOPMENT OF AN FBG-BASED HINGE MOMENT MEASURING SYSTEM FOR WIND TUNNEL TESTING

A. Taraborrelli[1,a], A. Gurioli[2,b], P. De Fidelibus[2,c], E. Casciaro[1,d], M. Boffadossi[1,e], P. Bettini[1,f]

[1]Department of Aerospace Science and Technologies, Politecnico di Milano,

via La Masa 34, 20156, Milano (MI), Italy

[2]Air Vehicle Technologies, Wind Tunnel Testing, Leonardo Aircraft Division,

via ing. Paolo Foresio 1, 21040, Venegono Superiore (VA), Italy

[a]alessandro.taraborrelli@mail.polimi.it [b]alessandro.gurioli@leonardocompany.com
[c]paride.defidelibus@leonardocompany.com [d]emanuele.casciaro@polimi.it
[e]maurizio.boffadossi@polimi.it [f]paolo.bettini@polimi.it

Keywords: Additive Manufacturing, Fiber Bragg Gratings, Wind Tunnel Testing, Hinge Moment.

Abstract

This paper presents the development and implementation of a hinge moment measuring system for wind tunnel tests based on Fiber Bragg Grating (FBG) sensors. These sensors, which are drawn directly into optical fibers, are capable of measuring strain and temperature variations and represent a precious addition to the aeronautical industry thanks to their peculiar characteristics, including high accuracy, low invasivity, embeddability and electromagnetic immunity. In detail, the development of the system exploits a combination of Fused Deposition Modeling technology and FemtoSecond® Gratings to design and create an independent, deformable structure in which a set of FBGs could be embedded within internal curved channels obtained during the 3D-printing process. This involved a complete re-design of the interface between the stabilizer and the elevator of a horizontal tail model. The material used for producing the structure is ULTEM 9085™, which made the development of the system particularly cost-effective and efficient. The paper also describes the installation of the FBGs, including the design of the channels, the selection of a glue, its injection technique and the following calibration procedure. Finally, the component is tested in the wind tunnel facility of Leonardo Aircraft Division in Venegono (VA, Italy), and the obtained results for some elevator's deflections are presented.

Introduction

Wind tunnel testing is a well-established discipline in Engineering, which, side-by-side with modern computational fluid dynamics, is used for the analysis of the behaviour and performance of aircrafts, cars, buildings and more during their design phase. In wind tunnel activities, the main focus is on measuring forces and moments, and for static measurements, this is typically done by relying on strain gauges. However, strain gauges still show many disadvantages, including inertial effects, high invasivity and susceptibility to electromagnetic interference among the others [1]. Optical fiber sensors represent a promising alternative to strain gauges, thank to their peculiar characteristics such as high sensitivity, faster response time, low invasivity and immunity to electromagnetic interference [2]. Furthermore, these sensors can be directly integrated into structures both during and after their manufacturing process, as demonstrated by S. Pinto [3], who successfully installed them in a component through internal, straight channels directly created during a 3D printing sequence. This paper describes the design and testing of an optical fiber-based hinge moment measuring system for the elevator of a wind tunnel aircraft model's horizontal tail. Since these measurements are highly critical and challenging to obtain by using traditional strain gauges sensors, especially because of the size constraints imposed by the component, the activity presented in this work focused on developing a system based on a minimally invasive technology. To do this, a complete re-design of the interface between the stabilizer and the elevator of the model was carried out, in order to integrate between them an independent, deformable structure capable of hosting several Fiber Bragg Gratings (FBGs) within internal curved passages obtained through the Fused Deposition Modeling (FDM) technique. The making of this work was made possible thank to Leonardo Company's Aircraft Division in Venegono (VA, Italy), with special recognition to the Wind Tunnel Department. The Company's printer, specifically the Stratasys Fortus® 400mc, was used to build the component with the ULTEM™ 9085 material, which guarantees excellent physical and mechanical properties for high-demand and special applications.

Design

The design of the intermediate deformable structure, shown in Fig. 1 and 2, is the result of an accurate trade-off between the overall structural stiffness of the assembly and the deformability of the sensitive sections. This was achieved by performing several Finite Element Analysis on the component, which were carried out by imposing a set of hinge moments corresponding to the expected loads for the experimental conditions under exam. The final design presents two deformable trusses per each measuring station (4 in total), since the idea was to keep a back-up channel which could have been useful in case of problems related to the adjacent one.

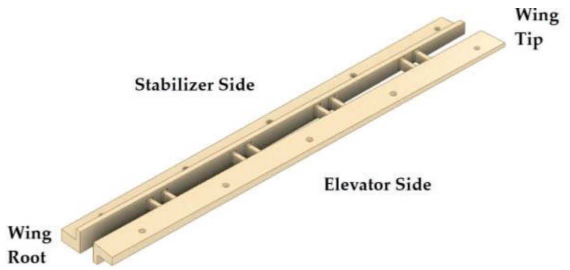

Figure 1: 3D-view of the deformable structure's design (without channels)

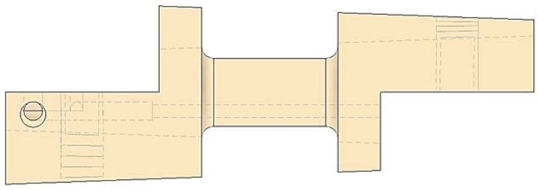

Figure 2: View from the wing root with detail of the system of channels

Manufacturing of the Internal Channels and Sensors' Installation

The design of the internal channels in the structure had to meet several requirements, including the presence of turns, conjunction points and areas with varying radius, as well as the compatibility with the size constraints of the structure and the printing resolution of the Fortus® 400mc. Several tests were conducted until finding out an optimum pattern and diameter for the passages. Small sinks were included in the design at the conjunction areas between the channels, to prevent the printer from depositing excessive material that could potentially obstruct the passages. Fig. 3 shows the intended position of five polyimide-coated Femto-Second gratings (in blue) inside the channels. To fix and secure the sensors in each measuring station, M-Bond 600 Adhesive by Micro Measurements was chosen and used, since it resulted compatible with ULTEM and guaranteed an optimal viscosity for the application, as well as a high performance for stress analyses. A compatible blue dye was added to the adhesive to make the procedure visible through the material. The mixture was inserted into the channels through the sinks with a 0.6 mm rounded-head nozzle, halting the injection as soon as it was observed to come out from the end of the channel on the interface side with the elevator. The component was then left for curing under heat lamps for 5 hours at 55°C.

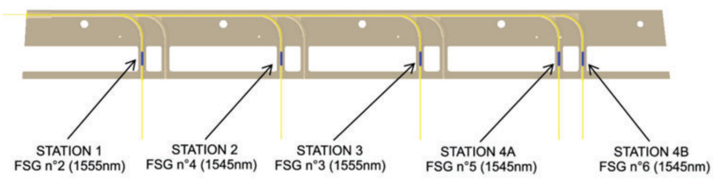

Figure 3: Designated position for each embedded sensor

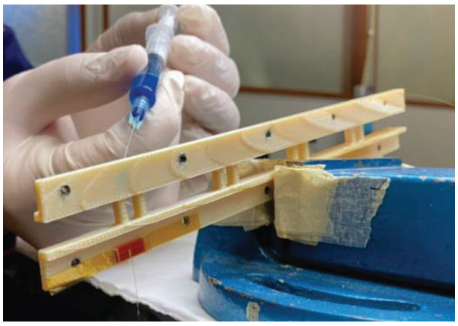

Figure 4: Injection of the glue

Calibration

The calibration of the system of sensors was performed by using the specialized equipment of the company. The deformable structure was secured to the other components with five screws per side, tightened with a torque wrench to guarantee the repeatability of the constraint after each installation. Five holes were drilled on a dummy elevator at 10 mm behind the hinge axis. Each hole was loaded singularly and then in combination with others to accurately reproduce a set of calibration hinge moments on the elevator, chosen in accordance with the expected loads during testing. A first-order calibration vector, which links the signals to the loads, was calculated by performing a regression between the vector of all applied hinge moments and the matrix containing the measured wavelength variations from all the sensors. The sensor embedded in station 4B (Fig.3) was excluded from this calculation as it was damaged during the installation and the output signals resulted altered with respect to the expected one.

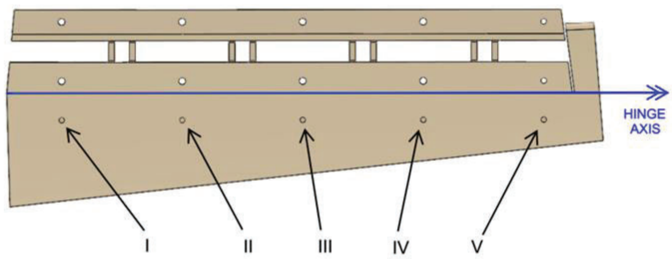

Figure 5: Calibration points on the elevator

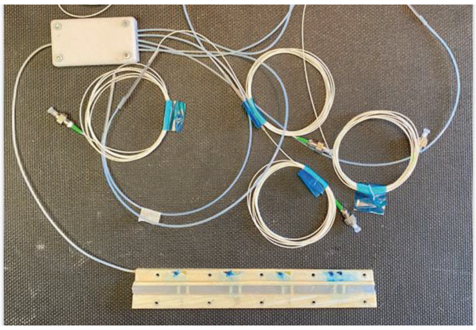

Figure 6: Detail of the final product

Results

Since FBGs are sensible to both mechanical and thermal deformation, the model was accurately designed in a way that the temperature-related wavelength shifts during testing resulted to be significantly smaller than the mechanical ones. Despite that, the effect of temperature oscillations during testing was not considered negligible, and it was decided to perform a thermal calibration of the sensors directly in the wind tunnel environment, by investigating their response during a heating cycle in relation to the data provided by a thermocouple installed inside the fuselage of the model. Temperature variations were also reduced by limiting the duration of each test, conducting them in a continuous sweep mode in pitch, with an α-sweep rate of 0.5°/s. The campaign involved installing the full horizontal tail assembly on the corresponding aircraft model (Fig. 7) and testing three different elevator deflections δ of 0°, +12.5° and -12.5° at wind speeds of 40 and 50 m/s. The tests were repeated several times to assess the level of repeatability of the measurements.
The averaged results for the examined conditions, normalized with respect to the maximum tested α and the maximum measured hinge moment, are presented in Fig. 8, 9 and 10.

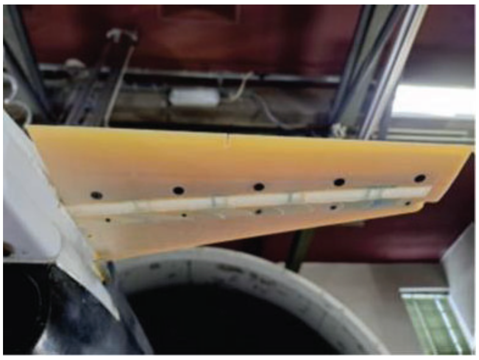

Figure 7: Full assembly mounted on the model

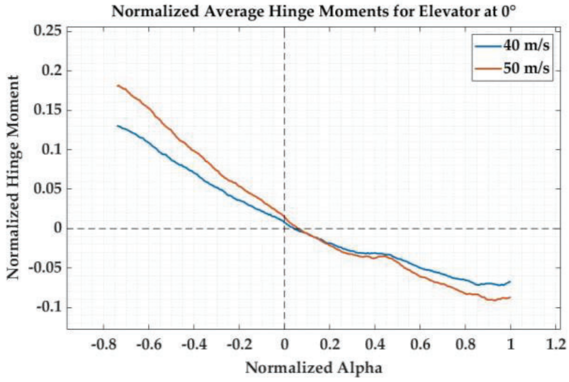

Figure 8: Results for non-deflected elevator

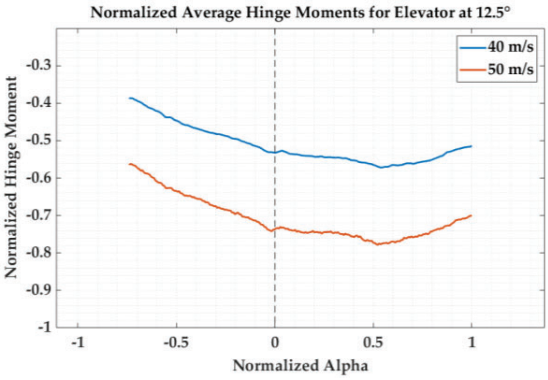

Figure 9: Results for +12.5° elevator deflection

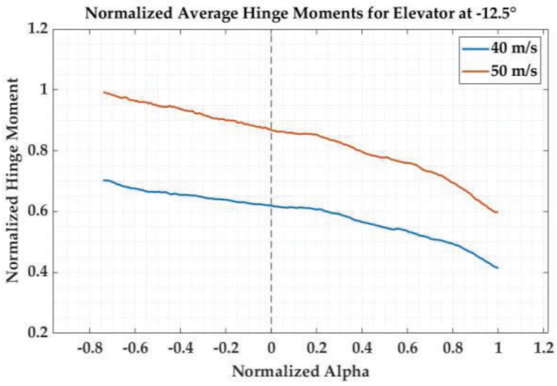

Figure 10: Results for -12.5° elevator deflection

Conclusion and future improvements

This work proves how the production of a wind tunnel model's component with embedded optical fiber sensors is possible with a low-invasive and re-usable solution and can produce successful results which otherwise could not be achieved with conventional measurement systems. In fact, the collected measurements resulted compatible with the expected ones, indicating that the experimental setup and procedures were appropriately designed and executed. However, to extend the application range of the component and allow for testing at higher wind speeds, it should be stiffened, for example by increasing the size of the deformable stations. Future developments should also explore other additive manufacturing techniques, including metallic 3D-printing, to improve the durability of the component and to overcome the structural limitations related to the use of polymeric materials. Finally, the back-up configuration proposed in this work could be exploited to include, for each station, an unconstrained sensor for compensation of temperature effects. All these upgrades clearly have the potential to improve the performance of the system.

References

[1] C. Tropea, A. Yarin, J. Foss, ''Springer Handbook of Experimental Fluid Mechanics'' (2007). DOI: https://doi.org/10.1007/978-3-540-30299-5

[2] A. Kersey, M.A Davis, H.J. Patrick, M. Leblanc, K. Koo, C.G. Askins, M. Putnam, E. Friebele, ''Fiber Grating Sensors'', Journal of Lightwave Technology (1997) vol. 15, issue 8, pp. 1442 – 1463. DOI: https://doi.org/10.1109/50.618377

[3] S. Pinto, ''Development and testing of optical fiber based monitoring systems for a wind tunnel application'', Politecnico Di Milano, URL: http://hdl.handle.net/10589/148372