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Advanced landing gear fibre optic sensing and monitoring system

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Abstract

In this paper an advanced optical-based landing gear load sensing and monitoring system is presented. The system measures load and torque at the landing gear wheels and provides this data for use by the aircraft systems for integration with aircraft health monitoring, hard landing detection, flight management, flight controls and ground controls. The system relies on optical sensing with fibre Bragg gratings which have various advantages.
A complete sensing system was developed in the European Union Clean Sky 2 Joint Technology Initiative ALGeSMo. This involved: the integration of dedicated optical fibres into a composite structure, the development of an optical harness (cable and connectors) meeting aircraft installation requirements, the readout of the optical fibre sensors with state-of-the-art miniature optoelectronics and the processing and communication of the data.
Apart from specific tests on the various components, a bespoke test rig was developed to rigorously test the whole sensing and monitoring system on an A320 main landing gear slider tube to validate the performance of the system. The system-level tests performed on the test rig showed a very good correlation with applied loads and additional conventional (strain and temperature) sensors. It demonstrates that loads along all three axis of the landing gear and the torque about the wheel axle can be accurately measured. Tests performed at cold and elevated temperatures however revealed that the generally applied one-dimensional temperature compensation equation is not accurate enough for this application, due to the non-uniform non-stationary temperature field.
The ALGeSMo project yielded several noticeable successes. The research activities have advanced the state of the art in several key areas for the deployment of optical sensing systems for safety-critical applications, such as integration of optical fibres into composite material, robust optical connections, avionic-compliant optical interrogator and landing gear load measurement up to technology readiness level TRL5.

Keywords: structural health monitoring, load monitoring, fibre Bragg gratings, embedding, landing gear

Introduction

Within the European Union Clean Sky 2 Joint Technology Initiative ALGeSMo (Advanced Landing Gear Sensing and Monitoring, https://algesmo.eu/) an advanced optically-based landing gear load sensing and monitoring system was developed. The ALGeSMo Consortium included three entities of the Airframe Systems division of Meggitt (two in the UK and one in Switzerland) and two partners located in the Netherlands, PhotonFirst (formerly Technobis Fibre Technologies) and the Netherlands Aerospace Centre (NLR). This project took place between September 2016 and October 2020.

Landing gear are light, compact and heavily loaded aircraft components that do not have any structural redundancy and are therefore designed according to the safe-life philosophy [1] of not allowing any cracks to develop. For many decades attempts have been made to monitor the whole or part of the landing gear. Examples of the latter are tire pressure indicators, brake temperature monitoring and shock strut pressure or position monitoring which provide an indication of the health of these landing gear components and can reduce maintenance costs, see reference [2] for a more detailed overview. Also, several structural overload detection systems have been developed, after which the landing gear needs to be thoroughly inspected for any damage. Accelerometers have been applied for this task [3] providing indirect measurement (by presuming a fixed relation between the loads at the wheels and the acceleration at the measurement locations). These are not always accurate measurement of the real loads acting on the landing gear, for instance, in the case of asymmetric landings.

Since the beginning of the jet era, many companies have tried to design load monitoring systems for aircraft landing gears. Some were specifically focused on detecting hard landing and some were aimed at providing weight and balance data during aircraft loading, see [4] from 1956, itself a continuation of a patent filed in 1945. Despite several decades of research, new systems are still proposed nowadays, for instance [5].

Various technologies have been proposed, some very simple (e.g. a marker that hits a lead target and leaves a mark on it in case of excessive landing gear deflection) and some more complex (using modern electronics to trigger alerts on the aircraft on-board maintenance system). Mechanical, electromagnetic, piezo, strain gauge-based, pressure-based and more recently optical systems have been proposed in the past. None of them have been used in service for long periods of time due to a lack of reliability and convenience [6], considering that the brake torque limiting system used on the Boeing 747-400 is a limiter rather than a measurement system, i.e. it does not provide an absolute load value. Moreover, most of these systems only measured vertical loads. They are mostly installed in the pins (rotating articulation of the foldable landing gear structure) or in the landing gear leg (vertical or quasi-vertical structural part).

More recently optical sensors have been applied to landing gear health monitoring. In [7] optical fibre Bragg gratings (FBG) were bonded to the most stressed locations of the landing gear and have been applied in combination with accelerometers in a health monitoring system and were demonstrated on a nose landing gear (NLG). Embedding of FBGs in composites is another option and for instance has been applied in a composite drag strut of a landing gear to measure the strains for health monitoring purpose [8].

The ALGeSMo optical system does not only measure the vertical loads on the landing gears like the previously fielded system. It measures the loads along all three axis as well as the torque about the wheel axles, see **Figure 1**. It therefore allows more benefits than just weight and balance measurement (centre-of-gravity determination) seen in previous systems. Additional capabilities of the ALGeSMo system include: 1) overload detection, typically hard landings, but also ground loads; 2) health monitoring and on-condition maintenance; 3) landing gear weight optimization, due to accurate load monitoring; 4) real-time brake control, based on the brake torque; 5) improved aircraft handling, for instance the effects of towing and short turns on the life consumption can be determined. Beside these benefits, more novel ideas such as runway pot hole detection are envisaged.

Due to all these benefits landing gear structural health monitoring (SHM) is the most promising business case for aircraft. However, despite all the benefits on-board landing gear load sensing and monitoring systems do not exist yet on the market.

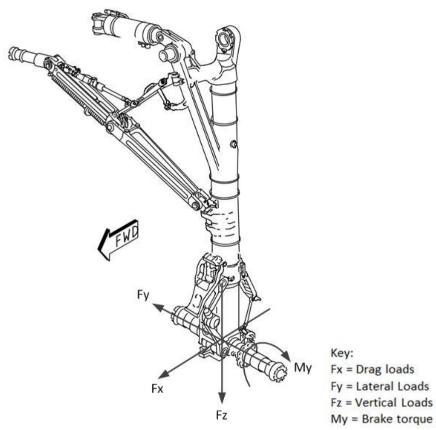

Figure 1. Landing gear load convention.

The ALGeSMo optical system measures load and torque at the landing gear wheels and provides these data for use on the aircraft systems for integration with aircraft health monitoring, flight management, flight controls and ground controls. The system allows a step change in the way landing gear is utilised and managed in operational and flight situations, leading to a new paradigm in aircraft availability and operability. The development and integration of such a system is responding to the market and environmental needs for increased aircraft availability, reduced maintenance costs, reduced fuel consumption and increased safety.

Unlike the previous systems, ALGeSMo relies on optical sensing [9] with fibre Bragg gratings (FBG) rather than strain gauges. The optical sensing principle of ALGeSMo does not present the usual drawbacks of the typical strain gauges used so far, mainly issues of drift over time and corrosion sensitivity. An FBG is a small segment (typically 5 to 10 mm in length) in an optical fibre in which a periodic variation of the refractive index is inscribed by an ultraviolet laser. The segment reflects particular wavelengths of the light and transmits all others, as depicted in **Figure 2**. Stretching or compressing the fibre causes a shift of the reflected wavelength which has a linear relation with a strain and/or temperature value. The typical optical fibre has a diameter of only 250 μm, including the cladding layer on the outside of the glass fibre core to keep light confined to the core, and an outer protective coating layer, and can have multiple sensing locations in one fibre.

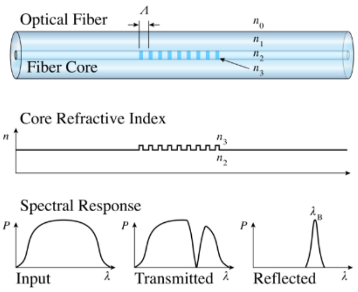

Figure 2. Principle of a Fibre Bragg Grating sensor, from Wikipedia.

Optical sensing based on FBGs has a number of appealing advantages for application within aircraft structures, such as light weight, tolerant for harsh environments (inert to a wide range of chemicals and radiation depending on the applied coating, magnetic fields), long term stability and durable, completely passive and no interference with other signals [10]. The optical fibres can be embedded in the (composite) structure or surface mounted. The former has the advantage that the fibre is well protected and the latter has the advantage that a sensor can be installed at any time during manufacturing and operational life and that a broken fibre can be replaced.

The measurement instrument for the FBG sensors, known as the interrogator, has made important advancements to make it fit for the application and installation [11]. Traditionally, interrogator instruments are built from combining telecom-derived components, which come with limitations in adaptation and scaling for a solution in a demanding application. To make the transition for the required high sampling rate, large number of sensors and fibres, yet small footprint allowed (ARINC600 compatible) and also making the solution fit for aerospace compliance, integrated photonics is used as technology enabler [12]. Integration of the optical functionalities onto a chip, and dedicated photonic package and module development, allows the total system solution and supply and manufacturing needed towards compliance [13].

The ALGeSMo project covered the development of a complete optical system, discussed in more detail in section 2. This included: integration of dedicated optical fibres into a composite structure, the development of optical harness (cable and connectors) meeting aircraft installation requirements, the readout of the optical fibre sensors with state-of-the-art miniature optoelectronics and the processing and communication of the data. Apart from specific tests on the various components, a special test rig was developed to rigorously test the whole system on a main landing gear slider tube, discussed in detail in section 3.

System description

Introduction

The ALGeSMo Consortium has created a novel optically-based landing gear load and torque monitoring system by combining and developing the latest research and most promising current technologies with the objective to deliver:

- A fibre Bragg grating (FBG) optical sensing system using wavelength division multiplexing (WDM) techniques to accurately detect and translate landing gear strain and torque to the aircraft control systems. The WDM technique uses FBGs having different nominal wavelengths to discern between the reflected signals contrary to time multiplexed systems where all FBGs have the same nominal wavelength and separation of the signals is done on the time of flight.
- A state-of-the-art, highly accurate, robust and reliable integrated photonics fibre-optic interrogator that results in the smallest system currently available anywhere in the world. This has made integration and certification of the system highly achievable compared to existing optical interrogator systems.
- Detailed design of system architecture and integration in the aircraft to ensure that the appropriate design assurance level (DAL) requirement can be achieved. Aircraft integration comprises of the integration of the optical signal processing unit in a robust and reliable avionic units and integration of the sensors into new and existing large passenger A/C landing gear axles.
- Definition and build of loading and calibration rigs in order to characterise sub-system and system components using a full landing gear slider tube assembly.
- Completion of system testing and partial qualification testing to de-risk the technology and demonstrate technology readiness level (TRL) 5. Which shows that the

technology has been successfully validated in an industrially relevant environment.

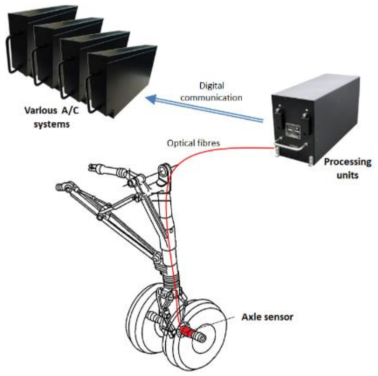

Figure 3. High-level overview of the optically-based landing gear load sensing and monitoring system.

Reaching the technical goals of this research project will pave the way to a production system to be fitted on future Airbus aircraft. **Figure 3** provides a high-level vision of the system more detailed in the next paragraphs.

Fibre optics processing unit

The fibre optics processing unit (FOPU) is a small, fully integrated avionic unit containing an optical interrogator, i.e. a device that reads an analogue optical signal in order to extract a specific property, depicted in **Figure 4**.

Optical interrogators are typically bulky, fragile devices with high power consumption. This is not compatible with use on an aircraft. The FOPU was made possible by the technology developed by the ALGeSMo consortium. The application-specific photonic integrated chip (ASPIC) technology developed by PhotonFirst allowed the system to have a small and robust interrogator.

The optical interrogator (**Figure 5**) is integrated into a unit together with processing and communication electronics (**Figure 6**). The combination of the optical interrogator and the processing and communication electronics makes the FOPU a novel product. It generates light in a specific bandwidth, sends it to each of the axle composite sensors, reads the light signal coming back from the axle sensors and processes it to convert a wavelength into a load value. The FOPU has 6 channels, one optical fibre per wheel location for 2 main landing gears (MLG) and 1 nose landing gear (NLG), each having two wheels. The system can sample at 512 Hz per channel. It also performs some self-diagnosis functions. It is an avionic unit installed in the aircraft avionic bay and is as per the standardized ARINC 600 2MCU format (dimensions and interfaces). The analogue single mode signal connection between the FOPU and its rack was especially complex because of the slight angle between the rack and the unit imposed by the ARINC 600 standard. A fruitful collaboration with a connector supplier led to the development of a new reliable and robust connection for this type of environment. This is another clear example of how the ALGeSMo project went beyond the previous state of the art.

Figure 4. FOPU prototype- External view – ARINC 600 2MCU rackable avionic unit.

Figure 5. Optical part FOPU prototype with 6-channel FBG interrogator fitted with heat sinks from PhotonFirst (known as Technobis Fibre Technologies before 2021).

Figure 6. FOPU prototype - Digital processing part.

Optical interrogators are traditionally systems not designed for operation in harsh environment applications. One of the objectives of ALGeSMo was to bring this technology to aerospace standards. The first set of tests performed on the FOPU demonstrated that it can withstand the kind of environment found on aircraft in an avionic bay. The FOPU has been subjected to, among others, high temperature, low temperature, vibration, shock and humidity. The FOPU showed satisfactory results in all of these tests, and in many others. It is considered safe for flight and the route towards further qualification clear.

Axle sensor

The objective of the optical system is to measure the loads at all wheel locations of a landing gear axle by means of FBGs. For this a special axle sensor was developed, depicted in **Figure 7**.

Figure 7. Axle sensor prototype, including clamping mechanism.

The axle sensor is the sensing element of the system and consists of optical fibres with FBGs embedded into a thin cylinder-shaped composite carrier. There are two sensors per axle, one sensor each for the port and starboard wheels. The axle sensor is located inside the axle bore and is held in place by a bespoke clamping mechanism which is currently designed to allow fitment of the sensor into an unmodified Airbus A320 axle. The clamping mechanism secures the carrier in such a way that any loading in the axle is transmitted though the composite and detected by the optical fibres.

Since the axle sensor is located in an area of varying temperature, especially for the MLG with a braking systems and subjected to large temperature variations, the local temperature is also measured by the optical fibres within the sensor allowing for temperature compensation of the measured strain response. The axle sensor is connected to the FOPU by means of a bespoke optical harness, designed to deal with the harsh environmental conditions of the landing gear area.

It is a common practice to embed optical fibres in stiff composite panels designed for a narrow temperature range, e.g. structural part, typical using carbon fibres. However, embedding optical fibres in a thin, flexible composite panel designed to withstand high temperature is a novelty. This brings some constraints not seen on typical low-temperature structural panels, like:

- Carbon fibres composite are too stiff for the ALGeSMo axle sensor, so glass fibres are used. Glass fibres have different mechanical properties to carbon which make integration of the optical fibre more difficult.
- Resins able to withstand the high temperatures (above 150 °C) seen by the ALGeSMo axle sensors create problems not seen with low-temperatures resins. They are cured at higher temperature and can generate non-uniform mechanical strain on the optical fibre after curing.
- Embedding optical fibres can cause significant light loss due to micro bending or result in an inhomogeneity in the FBG sensor strain pattern, such as a birefringence, that can hinder an accurate readout [14 , 15].

The ALGeSMo team successfully tackled these challenges, and in that respect went beyond the previous state of the art.

Fibres and connectors

The few optical avionic equipment currently in-service are communication equipment (data transfer). They transfer digital signals into multi-mode optical fibres. The ALGeSMo optical system is a sensing system as opposed to a data-transfer system and uses FBG as sensing elements. Therefore, it transfers analogue signals into single-mode optical fibres. Analogue signals are much more sensitive to perturbations and power loss, and single-mode fibres have significantly smaller cores than multi-mode ones. This makes the connections a lot more challenging than on existing systems, especially under varying temperatures and vibrations.

The connectors, see **Figure 8**, have been carefully selected for their performance, whilst still complying with the weight and dimension constraints. Special care was given to the connectors susceptible to be disconnected and reconnected during line maintenance. They have to be easily cleanable without specific equipment. Expended beam connectors were selected for their greater tolerance to contamination. Other connectors within the fuselage are as per the MIL-38999 standard and use butt-type contacts. The connectors located on the landing gear legs are further protected by being placed in an enclosure.

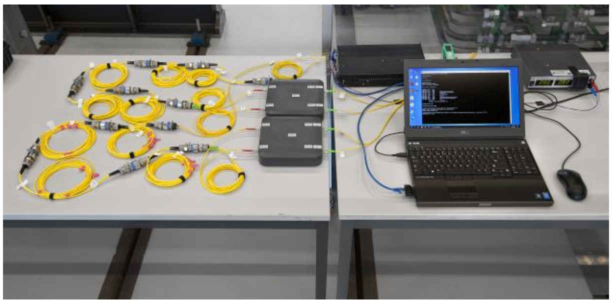

Figure 8. FOPU and part of the optical cables (without final harnessing) and connectors.

Results and Discussion

Test setup

A pair of axle sensors was fitted on an actual A320 MLG (**Figure 9**) and installed (upside down) into a bespoke test rig designed and built at NLR, see **Figure 10**, suitable to test both MLG and NLG up to limit loads over a wide temperature range.

Figure 9. Main landing gear slider tube with installed heater bands.

Figure 10. ALGeSMo bespoke test rig.

The loads at the landing gear wheels were applied by 12 actuators as depicted in **Figure 10** and **Figure 11**. The drag loads (Fx, see also **Figure 1**) were applied at each wheel location by actuators A1 and A2. The lateral/axial loads (Fy) were applied at each wheel location by A3 and A4, including the moment Mx caused by the wheel diameter. The high vertical loads (Fz) were applied by two actuators at each wheel location, A5/6 and A7/8. The brake torque (Mz) was also applied by two actuators at each brake flange location, A9/10 and A11/12.

Elevated temperature loading was applied by heater bands (**Figure 9**) at the wheel locations simulating heat conduction from the brake flanges to the axle. Cold temperature tests were performed with a climate chamber installed around the centre part of the MLG, **Figure 12**, able to reach temperatures in the axle under -50°C.

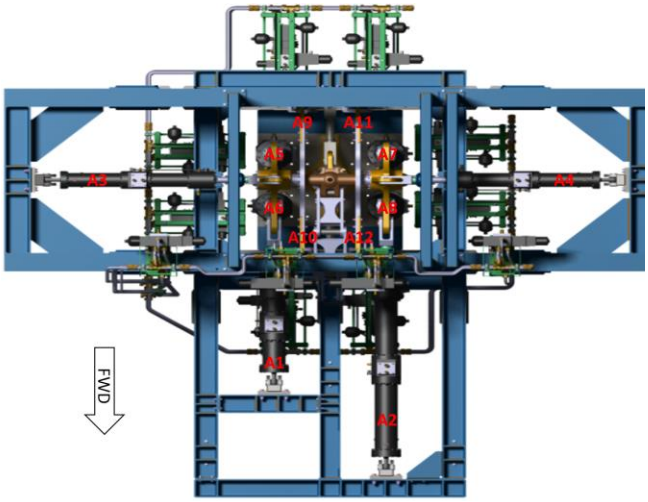

Figure 11. Top view test rig with indicated actuator locations.

Figure 12. Climate chamber at the centre part of the MLG.

With the test rig a test campaign was performed on the whole fibre optic sensing system, including the FOPU, all optical cabling and connectors as specified by Airbus and the MLG with two installed axle sensors. The following test sequence where applied:

1. Functional and commissioning tests
   To check correct operation of the test rig and all equipment.
2. Calibration tests
   To generate the calibration matrix that transforms FBG strains into wheel axle loads.
3. Elevated and cold temperature tests
   To test the axle sensor performance at operational temperature loads.
4. Dynamic and flight tests

To test the axle sensor at realistic operational loads.
5. Performance tests
To test the system at extreme limit loads that can occur during the lifetime of an aircraft.

Besides these tests, shock and vibration tests were also successfully performed to verify correct operation of the system during normal aircraft operations like taxiing, landing or when the aircraft encounters sudden gusts in flight.
For the calibration and performance tests a set of limit load (LL) cases was supplied by Airbus, consisting of 343 different ground handling and landing load combinations in the various load directions as indicated in **Figure 1**, representative of once in a lifetime extreme loads that can occur once in a lifetime during operation of the aircraft, for instance with one or more deflated tires. For the calibration tests, the LL set was scaled by a factor 0.2 (denoted 20% LL), representative of the load levels during normal operation, but also calibration tests were performed at 40% and 60% LL to examine the linearity of the system. For the performance tests, loads were increased up to 90% LL (not 100% to prevent any damage to the axle) at the end of the test campaign. Calibration tests were also performed at elevated and cold temperatures.
The dynamic tests comprised of a small set of faster changing load cases following a certain load profile, as prescribed by Airbus. The flight profile tests comprised of a set of operational load cases and corresponding loading times representative of normal aircraft operation during a single flight.

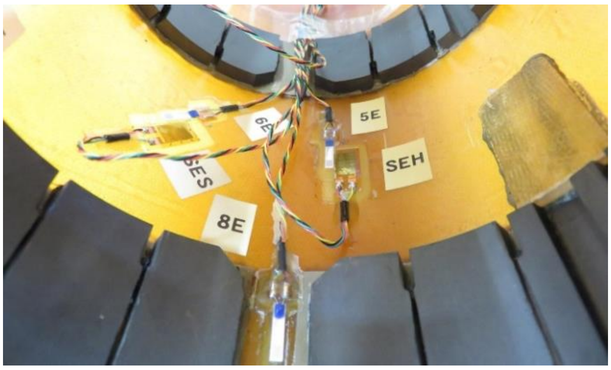

Figure 13. Instrumented axle sensor.

A set of prototype axle sensors (**Figure 7**) were manufactured by Meggitt UK containing two optical fibres with 6 FBGs per fibre that measured the strains from which the wheel loads are computed using the calibration matrix and two FBGs to measure the temperature within the axle sensor.
To validate the strain and temperature measurements of the FBGs, additional strain gauges (SG) and temperature sensors (PT100) were installed on the inside of the axle sensor at the different FBG locations, see **Figure 13**. These sensor responses, together with the actuator loads were measured with a separate data acquisition system. **Figure 14** shows a comparison of the response between an embedded FBG and surface mounted strain gauge installed at the same location for the first 37 cycles of the 20% LL calibration spectrum. The strain responses of both sensor types match very well (the axle sensor has a small thickness) demonstrating the correct strain measurement of an embedded FBG.

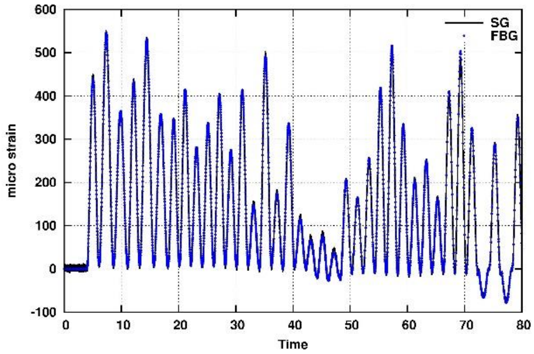

Figure 14. Strain gauge and FBG response comparison for 20% LL.

Calibration tests

A calibration matrix was generated by means of linear regression [16] on the measured FBG strain responses and actuator loads during a 20% LL test at room temperature, comprising of the 343 different load combinations. The two axle sensors are independent of each other therefore a separate calibration matrix ($\boldsymbol{C}$) was generated for each. A zero load zero strain condition was enforced, yielding zero constants in the calibration matrix. **Figure 15** depicts a comparison of the computed loads ($F_{comp}=\boldsymbol{C}*\varepsilon$) from the measured FBG strains, calibration matrix and applied loads for the 20% LL test. This shows a linear behaviour over the normal operation load range. Also, calibration tests were performed at 40% and 60% LL to confirm linearity of the system at high loads (e.g. during hard landings).

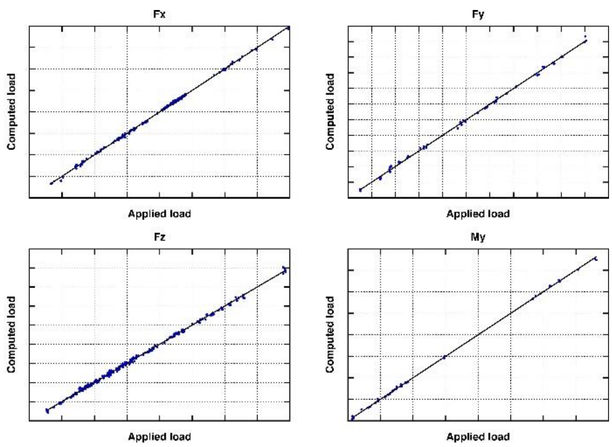

Figure 15. Comparison computed against applied loads at 20% LL RT.

Dynamic tests

To examine the load prediction capabilities of the axle sensor system for a more realistic load profile, a dynamic load as prescribed by Airbus was applied, which describes a short faster (1 Hz) load profile (repeated 5 times) with differing load combinations in the various actuator directions (apart from Fy) with a maximum of around 30% LL. From the FBG strains, the wheel loads were computed using the calibration matrix determined from the 20% LL calibration test at room temperature, and compared with the applied loads, see **Figure 16**. A very good correlation was obtained. The relative errors with respect to the maximum load, (Fcomp-Fexp)/maxload*100%, are depicted in **Figure 17** and are well within the specified bounds by Airbus, indicated by the red dashed lines.

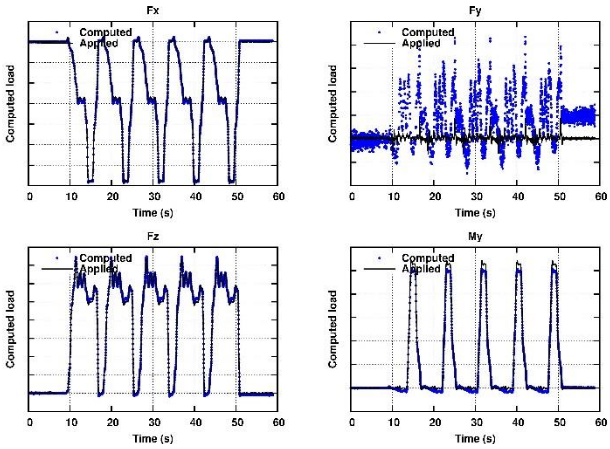

Figure 16. Comparison computed versus applied loads for the dynamic test at room temperature.

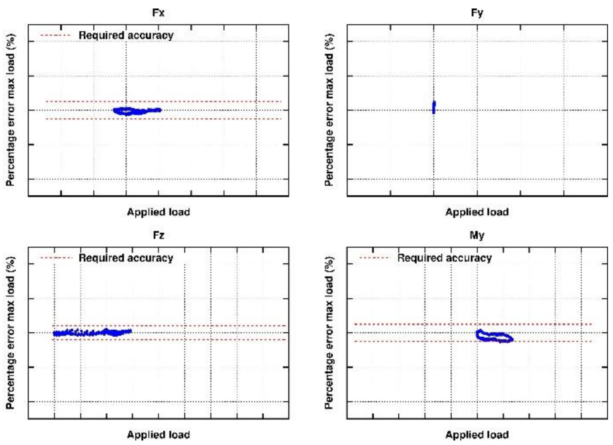

Figure 17. Relative percentage load error (Fcomp-Fexp)/maxload* 100% for the dynamic test at room temperature, red dashed lines is the required Airbus accuracy.

No accuracy was specified for Fy (axial direction) due to the expected lower accuracy caused by the high stiffness of the axle in this direction, but the variation here is also similar to those observed for the other loads. The load in axial direction (Fy) was zero during this test and the computed loads (blue line) show some noise (amplified in the figure for clarity) consisting of load components in the other directions.

Flight tests

For this test a load profile as prescribed by Airbus was applied, representative of a real flight, consisting of a towing, taxiing and take off phase, a landing phase (starting around 1500 s) and a taxiing and parking phase. Both taxiing phases contained turns and brakes. At the start and end of the test the applied test rig axle loads were reduced to zero, causing the loads in the plots to go to zero.

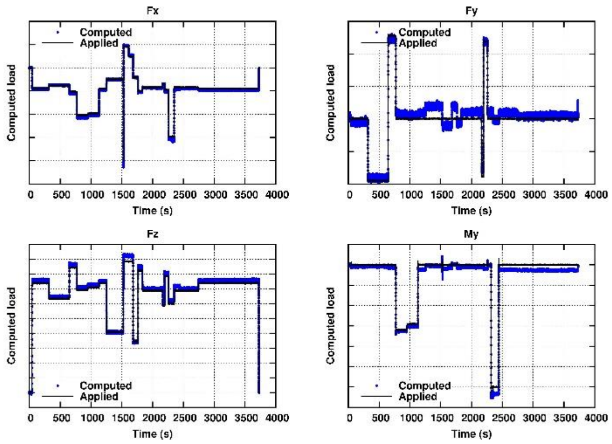

Figure 18. Comparison computed versus applied loads for the flight test at room temperature.

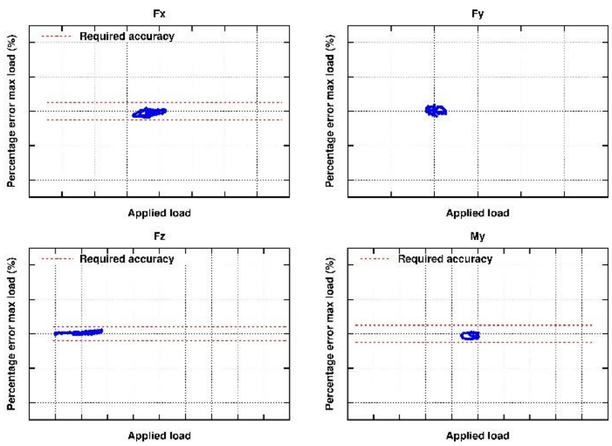

Figure 19. Relative percentage load error (Fcomp-Fexp)/maxload* 100% for the flight profile at room temperature, red dashed lines is the required Airbus accuracy.

The computed loads for both axle sensors are close to the applied loads, see **Figure 18**. The load in axial direction (Fy) are most difficult to measure accurately due to the stiffness in this direction. Nevertheless, the error in the computed load profile is still low and only shows some deviations when the applied load in axial direction is zero while a load is applied in the other directions (visible in the response). The relative error for the different loads is depicted in **Figure 19** and show some variation within the tolerance limits. To generate these error plots, the FOPU data had to be manually synchronised with the data acquisition system that measured the applied actuator loads. Any synchronisation error causes a larger percentage load error, due to the corresponding time shift in both the actual and computed load profiles, which is only of significance in the tests.

Performance tests

A last series of performance tests were performed on the MLG axle up to 90% LL, gradually increasing the load level in steps of 5% starting at 75%. These tests were carried out at room temperature to examine the behaviour of the sensing system and especially the axle sensor at extreme loads. At these load levels, the axle sensor should not fail and the clamping mechanism of the axle sensors should not come loose. Ideally, the system should even be able to measure these loads accurately. No higher load levels than 90% were applied to ensure the MLG axle remained undamaged for use in possible future testing. At each of the four load levels again the full limit load spectrum of 343 load cycle combinations was applied. The axle sensors were able to withstand these high load levels without any failure and the whole optical system was able to measure the load levels, although much less accurate as indicated in **Figure 20** depicting the computed loads using a 20% LL calibration matrix. This may well be due to non-linear effects at these high load levels. The displacement of the sensors in the axle were monitored and no sliding of the axle sensors could be observed. Hence, the whole system performed very well but with a lower accuracy. Normally the landing gear is replaced and scrapped after such high load levels.

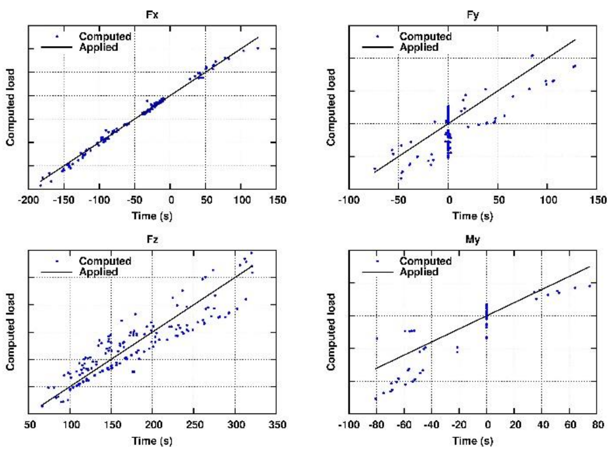

Figure 20. Comparison computed against applied loads at 90% LL at room temperature.

Temperature tests

Elevated temperature tests were performed using heater bands at the axle sensor locations to simulate the heating of the axle after substantial braking. Heat is transferred from the brake flanges on which the brake assembly is mounted to the axle by convection. Temperatures can locally rise above 130 °C. **Figure 21** shows the temperature response measured with an isolated temperature FBG and a PT100 sensor installed on top of it during one of the elevated temperature tests. Both temperature responses coincide, demonstrating that accurate temperatures can be measured with an FBG.

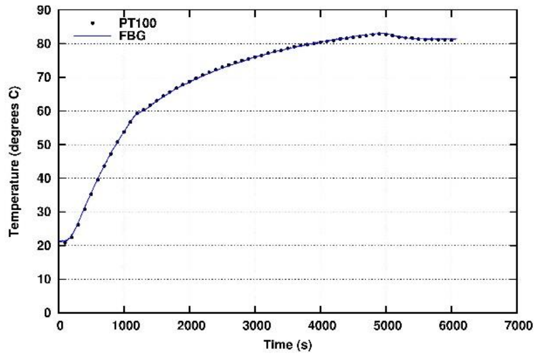

Figure 21. FBG8 and PT100 temperature response during warmup to 80 °C.

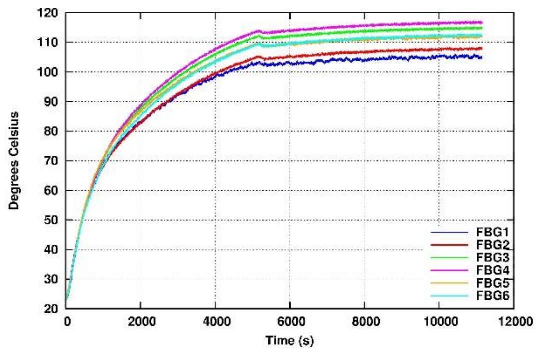

Figure 22. Temperature change at the FBG locations during heating of the axle.

During heating of the MLG axle, the change in temperatures were measured, showing a non-uniform temperature distribution over the axle sensor in axial direction but also a significant difference in circumferential direction. The latter is caused by the nearby vertical slider that acts as a heat sink. During the design of the axle sensor only an axial temperature distribution was foreseen. The temperature compensation using only two temperature FBGs positioned on both sides of the strain FBGs turned out to be insufficient to compensate for the temperature effect in circumferential direction. Hence, PT100 sensors were installed on the axle sensor at the six strain FBG locations to also measure the temperature distribution in circumferential direction. **Figure 22** depicts the temperature change during heating at these locations, showing a temperature difference between the FBGs of about 15 degrees Celsius. The heat input during the warmup phase was hereby manually adjusted once to reach an axle sensor temperature of approximately 110 degrees Celsius, visible as a kink in the plots.

The generally applied temperature compensation is based on a single degree-of-system temperature correction equation [17].

$$\frac{\lambda - \lambda_0}{\lambda_0} = (1 - p)\varepsilon + \alpha(T - T_0) \qquad (1)$$

In which λ_0 is the nominal wavelength measured after installation of the FBG at temperature T_0, p is the strain optic coefficient and approximately equal to 0.22 and α is an overall coefficient of thermal expansion (CTE). The wavelength λ and the temperature T are both measured. The CTE value (α) depends on the optical fibre and material in/on which the FBG is installed. The FBGs are embedded in a composite tube made of glass fibre having a CTE of around 22 με/°C and the optical fibre has a CTE of approximately 7.5 με/°C [17]. The overall CTE value of 22.5 με/°C was determined in an oven test on the axle sensor. The axle sensor however is subsequently clamped inside the landing gear axle made of high strength steel (300M) having a CTE of 11.34 με/°C. An optimal CTE of 13.7 με/°C was therefore determined on the MLG axle with a heating test.

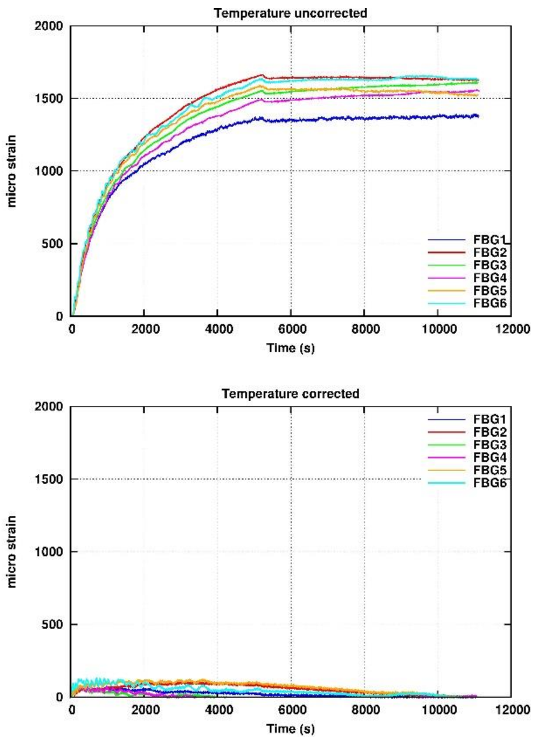

Figure 23. Temperature uncorrected (top) and corrected (bottom) FBG strain responses during warmup to 120 °C.

The measured temperature uncorrected FBG strains are depicted in the top picture of **Figure 23**. Using the overall CTE value and equation (1) turned out to be insufficient to compensate for the temperature effects over the whole temperature range, which should result in zero strain for all FBGs over the whole heating phase, due to the absence of any external load. The temperature corrected FBG strains are depicted in the bottom picture of **Figure 23**. A small but significant strain response is still present over part of the temperature range that will affect the overall accuracy of the load sensing system. The cause of this lies in the strain distribution in the axle sensor (clamped inside the axle and not free to expand) caused by the non-uniform temperature field. The strain gradients in the small axle sensor change with the changing temperature field and are for a single (FBG) location therefore dependent on the whole temperature field. Hence, the one-dimensional temperature compensation equation does not suffice for this application and should include other temperature sensors to compensate for the strain gradients caused by the temperature gradients in the axle sensor, i.e. a multi-degree of freedom temperature correction is required.

Figure 24 shows a comparison of the computed and applied loads for a 20% LL test at 110 °C. The computed loads are determined from the temperature corrected FBG strains using the calibration matrix determined at room temperature. The variability is somewhat higher and Fx and Fz show a mean shift of the data points, caused by the inaccurate temperature compensation. The relative errors with respect to the maximum load, (Fcomp-Fexp)/maxload*100%, are depicted in **Figure 25** and are still more or less within the bounds specified by Airbus. The accuracy thus can be improved by a multi-degree-of-freedom temperature compensation algorithm. Similar results were obtained from the cold temperature tests.

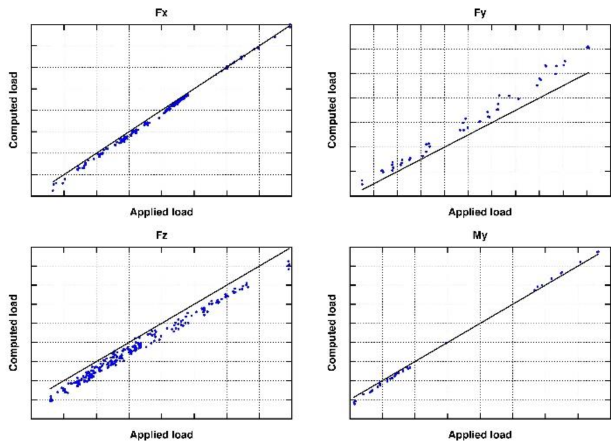

Figure 24. Comparison computed against applied loads at 20% LL at 110 °C.

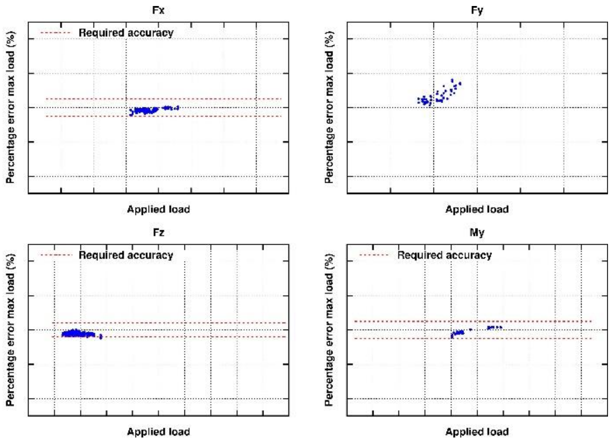

Figure 25. Relative percentage load error (Fcomp-Fexp)/maxload* 100% at 20% LL 110 °C, red dashed lines is the required Airbus accuracy.

Conclusions

The ALGeSMo project research activities have advanced the state-of-the-art in several key areas for the deployment of optical sensing systems for safety-critical applications, such as integration of optical fibres into composite material, robust optical connections, avionic-compliant optical interrogator and landing gear load measurement.

The system-level tests performed on the bespoke full-size test rig showed very promising results. Loads along all three axis of the landing gear and the torque about the wheel axles were measured and showed a very good correlation with additional conventional strain gauges and temperature sensors as well as with the applied loads. Demonstrating that strain and temperature can be reliably measured with embedded FBGs in a composite tube and that the sensing system is able to measure all four load components accurately. The tests performed at cold and elevated temperatures however revealed that the simple one-dimensional temperature compensation equation is not suitable for this application, due to the non-uniform non-stationary temperature field over the axle sensor, causing a higher error in the predicted load components when using a calibration matrix determined at room temperature. This can be further improved by taking into account the temperature measured at multiple locations and a multi-dimensional temperature compensation equation.

The technology building blocks developed during this project can also be used in other aerospace applications, not only for landing gear load measurement. There is a general consensus in the aerospace industry that optical sensing can bring significant benefits in the field of structural health monitoring.

Declaration of conflicting interests

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