PAPER • **OPEN ACCESS**

The TecALSens project: new solutions for load sensors in aeronautics

To cite this article: Valerio Carli 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1226** 012105

IOP Conf. Series: Materials Science and Engineering 1226 (2022) 012105 doi:10.1088/1757-899X/1226/1/012105

The TecALSens project: new solutions for load sensors in aeronautics

Authors: Valerio Carli[1]

[1]tecsis GmbH, Offenbach am Main, Germany. valerio.carli@tecsis.de

Abstract. In this paper the TecALSens project, developed within the Systems ITD of the Clean Sky 2 programme, is presented. The objective of the project is to design and validate a novel load sensor for aeronautic application based on thin-film sensing technology. So far, thin-film as sensing element has not been used in commercial aeronautic products: The outcome of this project tries to close this gap by providing a new class of load sensors complying with demanding aeronautic requirements. More and all electric aircraft configuration can benefit from the implementation of force measurement. This is an example of revolutionary approach to A/C design and a key enabler for achieving the environmental goals set by the European agenda up to 2050. Current project activities show very promising results: TecALSens provides a new approach to the design and manufacturing of load sensors for aeronautic applications. Especially, this new class of load sensors overcomes some of the drawbacks of strain gauge-based solutions. The final outcome of the project complies with the expected technology readiness level (TRL) 5. TecALSens outcome widens the possibilities offered by force sensing in aeronautics and strongly supports the evolution of aircraft design toward a more environmental friendly approach.

1. The TecALSens project in Clean Sky 2

Current environmental challenges require new approaches in almost all today's technological sectors. Also in aeronautics, environmental issues are taken in serious consideration and many efforts are devoted to define and implement new ideas and emerging technologies. More-electric and all-electric aircraft configuration is one of the revolutionary approaches to aircraft design and a key enabler for achieving the environmental goals set by the European agenda [1][1]. Major contribution to this new aircraft architecture is given by partial or full replacement of current hydraulic and pneumatic systems with electric drives: primary and secondary flight controls, landing gear, braking system and engine are the targeted systems that can mostly benefit from this new approach. In the Systems ITD[2] [2] , one of the pillars of the European Joint Technology Initiative Clean Sky 2, efforts are focused for pursuing the maturation of technologies and solutions for more- and all-electric aircraft configuration. The TecALsens project has been set-up upon successfully applying to the call for proposal CfP07-SYS-02-36 presented in the Systems ITD. Main objective of the project is the development of a load sensor for force measurement in aeronautics and based on enhanced sensing technology.

2. Objective of the project

Implementation of load measurement in aeronautics opens new technological scenarios and load sensors play a key-role for the implementation of more and all electric-aircraft configurations [3]. Load measurement enables a robust control of the new electrical devices, assessing their correct functionality and ensuring safe performances: Reliability of the new devices is a key issue for their successful integration [4]; force measurement provides a valuable support to error detection and monitoring of

[1] Europe has defined a clear and aggressive road map for facing current climate challenges. ACARE (Advisory Council for Aeronautical Research in Europe) has defined up to 2050 (ACARE Flightpath 2050) clear targets for reducing the amount of pollutant from air traffic: reduction of CO_2 emissions by 75% per passenger kilometre, reduction of NOx emissions by 90%, reduction of perceived noise by 65%.
[2] ITD - Integrated Technology Demonstrator

IOP Conf. Series: Materials Science and Engineering 1226 (2022) 012105 doi:10.1088/1757-899X/1226/1/012105

system performances. As an example, jamming of electro-mechanical actuator can be detected by measuring at the right position the force exerted by the device.

Main objective of the project is the design and experimental validation of a load sensor for aeronautics based on enhanced sensing technology. The objective is twofold: development of a load sensor for integration in aircraft systems considering all constrains and requirements. Use of improved strain gauge technology as sensing element for the device.

Primary and secondary flight control, electro-mechanical-actuator (EMA), landing gear of a helicopter have been taken into consideration as application scenario. A preliminary analysis and feasibility study for the integration of the load sensor in these systems have been performed. Five different applications have been evaluated and ranked. This with the objective of identifying the most suitable application: The wheel axle of a helicopter has been selected as target application for the final development and validation of the load sensor.

Regarding the sensing element, sensing technology selected for the new load sensor should be able to overcome the main disadvantages of bonded strain gauges, which can be considered today's standard load sensing technology in aeronautics. Considering this project, main disadvantages of bonded strain gauges are: manual production processes, large installation space (especially for redundancy), limited long-term stability due to bonding. Limited strain transmission can affect accuracy of load measurement.

In TecALSens, an analysis and selection of current sensing technologies for load measurement in aeronautics has been performed. This for identifying the most suitable sensing technology considering also the application selected for load sensor integration, the technology readiness level (TRL) of the product expected at the end of the project and the environmental conditions. The analysis has been conducted considering current systems for which load measurement represents a meaningful feature, for instance the applications evaluated in the initial phase of the project, and load sensors applications available in literature[3] [5], [6]. Technical characteristics and performances of different sensing technologies for load measurement have been considered and evaluated for the analysis [7], [8] .

The outcome of the analysis has shown that load sensing based on resistive measurement principle can be considered reference technology in aeronautics. Conventional bonded strain gauge makes use of the resistive measurement principle for load measurement, upon which strain of the material determines a change in resistance and can be related to the applied load. The analysis has been focused on sensing technologies based on the resistive measurement principle. Four type of sensing technology have been considered: strain gauge, thin-film sensor, piezoelectric, semi-conductor (or piezo-resistive). Further consideration regarding expected TRL at the end of the project, technical limitation due to the environment and the applicability have restricted the choice to bonded strain gauges and thin-film sensors [9]. Considering the request of the call, thin-film sensing technology will be considered for the development of the load sensor. It is worth mentioning that LVDT (linear variable differential transformer) sensor, based on the inductive principle, are also well known and established in aeronautics but not suitable for the application selected. Load measurement based on thin-film enables to overcome some of the drawbacks of bonded strain gauges. Especially, following advantages can be presented: production and application are fully automatic, stability of quality is ensured; very small installation space also for redundancy (2 full bridges in few square millimetres possible, with temperature compensation); application of thin film element by welding ensures long-term stability; adhesion of thin film on the supporting material ensures full strain transmission.

[3] This survey has been conducted considering three main criteria: 1) only civil A/C applications and not military or aerospace (which indeed provide interesting examples). 2) For comparison, only sensor technologies which are normally used in-flight. Other technologies mostly used for testing purposes either on-ground or in-flight have not been evaluated. This considering TRL level and technology maturation. 3) Load sensor solutions currently applied on flying aircrafts.

For what concerns TRL of the load sensor expected at the end of the project, requirements have been assigned considering real environment in terms of loads, electro-magnetic disturbances and other external factors able to affect load sensor performances. Load sensor must comply with DO254 and DO160G standards. The former defines quality standards for electronic design. The latter describes the environmental conditions under which the sensor must ensure proper performances. Electronics is expected to be "simple"; this means that it must be pure analogue, avoiding any digital component like complex hardware and micro-controller. Further, it is expected that the sensor is able to measure the loads independently in two perpendicular directions: Z-direction (parallel to the helicopter yaw axis) and X-direction (parallel to helicopter roll axis). For both directions, operative and limit[4] loads in positive and negative directions have been assigned. Mechanical and electrical integration of the sensor is one of the driving requirements for a real implementation. Electrical and mechanical interface represent therefore a key issue for the success of this device.

3. Design of the sensor

Mechanical and electronic design are complementary considering the final layout of the device, the fulfilment of all requirements and the requested performances. The design of the load sensor has been planned in two batches: in the first batch, all components have been designed, developed and manufactured and several samples have been assembled for testing. Main focus in this phase was on the electro-magnetic properties and on sensor's force measurement performances. The outcome of first batch experimental verification has been analysed and design improvements have been defined. In the second batch, design improvements have been implemented for complying with all requirements. Fifteen prototypes have been manufactured and tested considering load measurement performances and those requirements that have not been verified or fulfilled in the first batch.

3.1. Design of electronic

The electronics has been designed for complying with all requirements regarding electro-magnetic compatibility, expected accuracy and performances stability. The complete electronic assembly is made of 14 different modules placed on two printed circuit boards. Selection of the electronic components has been done considering 30 year service life of the sensor, stability of its performances and the assigned temperature range. The shape of the printed board circuits has been defined considering the assembly with the other components and the mechanical stability of the complete electronic unit with respect to shock and vibration requirements.

3.2. Design of mechanical parts

Mechanical design of the load sensor must satisfy several functions: support the correct positioning of the sensing element for load measurement in two directions; ensure load transfer from the wheel axle to the sensing elements; provide suitable protection to all components with respect to environmental effects; ensure suitable mechanical and electrical interfaces for integration in the system selected as application.

The wheel axle can be considered as a hollow slender body subjected to bending loads in two perpendicular directions, constrained on one side and free on the other side, roughly like a cantilever with variable cross section along its axis.

Different solutions have been drafted and the final design of the load sensor is represented by a slender body able satisfy the conditions for load measurement and to fulfil project requirements.

The outer shape of the load sensor is complementary to the inner geometry of the wheel axle. As represented in figure 1, the load sensor in its final configuration is inserted in the inner hollow space of

[4] At ultimate load case, it is accepted that the landing gear may suffer some damages and load measurement is meaningless.

IOP Conf. Series: Materials Science and Engineering 1226 (2022) 012105 doi:10.1088/1757-899X/1226/1/012105

the wheel axle: mechanical connection between both bodied ensures the transfer of wheel axle deformation due to landing, on-ground and braking loads to the load sensor and to the sensing elements.

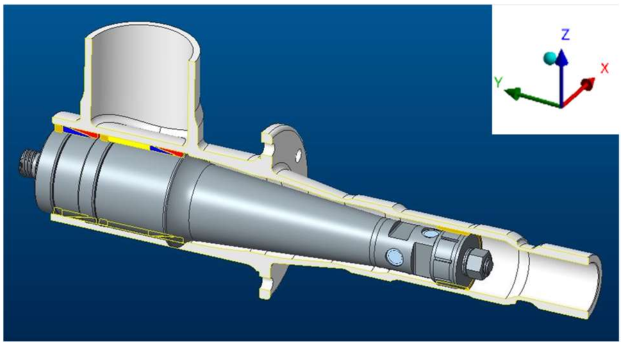

Figure 1. CAD representation of the load sensor mounted in the wheel axle with the reference system.

In figure 2, the load sensor in its final configuration is represented. The one-piece-body visible in the picture is the measuring spring: this is the main structural element of the load sensor, which provides several functional properties.

Figure 2. The complete load sensor manufactured for testing.

The measuring spring has been designed for hosting both thin-film sensors. As elastic element, the measuring spring is responsible of transferring the deformation due to the loads to the sensing elements. It has been modelled using a finite-element software: by means of the numerical simulation the overall geometry, the shape of the cross-sections along the Y-axis and the deformation of the sensing elements have been determined. Thin-film sensors are positioned at the thinner part of the measuring spring, as depicted in figure 3. Their position has been defined considering several conditions: point of application of the loads acting on the wheel axle; capability of capturing the loads with the necessary reliability in both directions; influence of the load acting in one direction on the measurement in the other direction (cross-measurement); durability of sensing element; system's mechanical reliability by transferring loads to the sensing element.

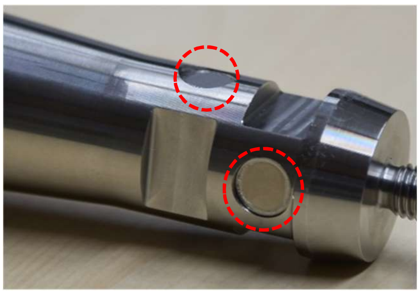

Figure 3. Final section of the measuring spring hosting both thin-film sensors. The picture shows thin-film sensor covers.

Proper deformation of the thin-film sensors generates the signal proportional to the loads applied and responsible of the measurement. The position of the thin-film sensors has been analysed for complying with the conditions presented above. Especially, amplitude of the signal from the sensing elements has been considered in relation to their position. Figure 4 shows the variation of the signal in mV/V of the thin-film sensor depending on the position along the Y-axis. Sensing elements are welded at the selected positions within drill holes in the measuring spring and are rotated 90 degrees with respect to each other, according to the directions of the loads to be measured. Orientation of the sensing element with respect to the applied loads is crucial for correct load measurement. For this, a small pivot is responsible for mounting the load sensor with the right orientation: The pivot is screwed through the wheel axle in the threaded hole on the upper side of the measuring spring (clearly visible in figure 2) and keeps the load sensor in the correct position by preventing its rotation.

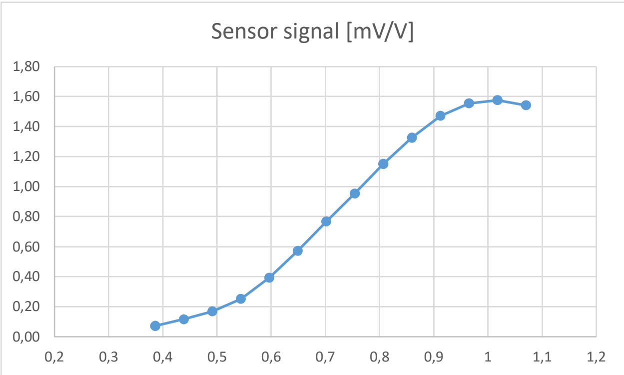

Figure 4. Sensor signal depending on the position of the thin-film along Y-axis of the measuring spring (normalized).

The measuring spring also hosts both electronic units necessary for processing the raw signal from the sensing elements and transferring the load measurement to the on-board electronics. As shown in figure 5, a dedicated chamber within the measuring spring accommodates both electronic units and provides space for the mechanical fixture. This is necessary for protecting the electronics from shock, vibration and in-service loads. Each electronic unit is connected to the corresponding sensing element by wires. The electronic chamber is closed by the electronic cover on which the connector for power supply and data transmission is welded. All openings must ensure no penetration of external matters (water, humidity, aggressive fluids, sand, dust, etc.): electronic and thin-film covers are welded on the measuring spring and the connector is welded on the electronics cover. For avoiding corrosion and degradation of the outer surface of the sensor, stainless-steel has been used for manufacturing all components exposed to external matters.

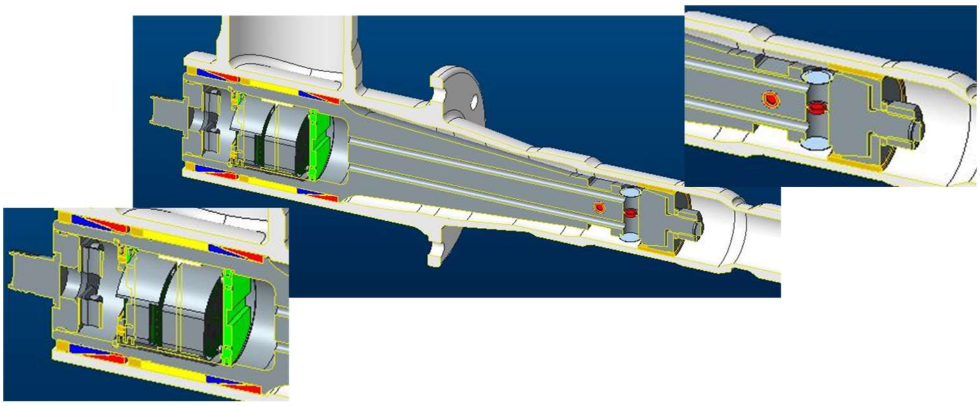

Figure 5. CAD picture of the cross-section of the load sensor. Right side: position of thin-film elements (red spots). Left side: electronic units within the dedicated chamber.

4. Mechanical interface

Deformation of the thin-film elements is necessary for measuring the loads. Transfer of loads from the wheel axle to the sensing elements through the measuring spring requires suitable constrain of the load sensor within the wheel axle. The solution adopted avoids any modification of wheel axle geometry, which is a constrain of the project. Mechanical connection of the load sensor with the wheel axle occurs at the section of the measuring spring with wider diameter and at its final conical section. Figure 6 shows the load sensor inserted in the wheel axle and a close-up of sensor's parts responsible for mechanical connection.

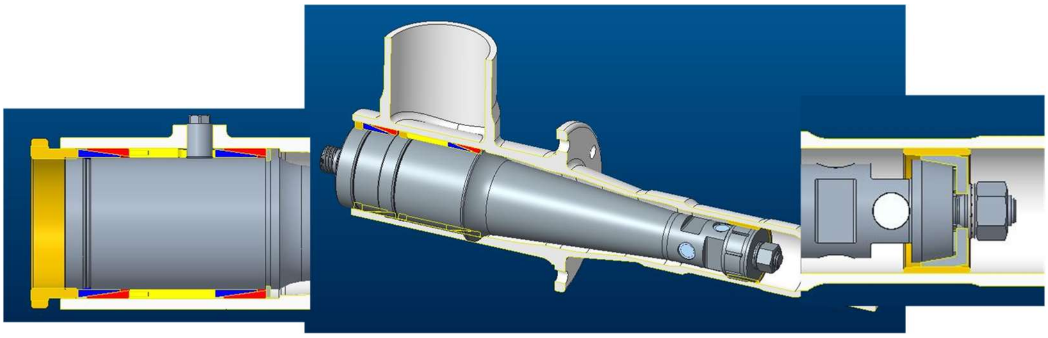

Figure 6. CAD representation of the load sensor within the wheel axle. Clamping elements on the left and right side are visible.

A set of wedge-like elastic elements provides the clamping force necessary for mechanical connection of the load sensor with the wheel axle. At the wider section of the measuring spring, two sets of elements have been mounted: blue elements are pressed beneath the red elements by the threaded ring on the left side. The axial force determines the wedging of both elements couples and their radial deformation: Blue and red elements are pressed against the outer surface of the measuring spring and the inner surface of the wheel axle, respectively. Normal forces due to the radial deformation along with friction generate the necessary clamping forces.

On the right side, clamping principle is the same. A wedge-like elastic element is pressed against the conical surface of the final part of the measuring spring by the screw nut. This generates the force necessary for the connection. Torque of the threaded ring and of the nut have been determined for maximizing transfer of loads to sensing elements. Considering the solution adopted, deformation of the load sensor mostly occurs at its tapered part. Indentations close to the thin-film sensors have been designed for adjusting strain level of the sensing elements according to the criteria described in the previous section.

5. Experimental results and accuracy

The load sensor developed in TecALSens must fulfil very harsh requirements for complying with TRL 5 and for possible short-time implementation in a real application. Environmental requirements and performance properties have been verified experimentally and some tests are still running.

Regarding EMC requirements, the sensor has been successfully validated: All DO160G EMC requirements assigned to the device have been fulfilled. Several tests have been successfully conducted with the support of an external laboratory.

Requirements regarding not EMC-related external effects like shock and vibration, temperature and external agents, have been fulfilled by experimental validation and by analysis of load sensor design. Stainless steel and welding of all openings ensure high resistance against aggressive agents and no penetration of any matter, since the openings are hermetically sealed.

Load sensor performances have been partially verified at tecsis and tests are still running. For this, a test rig has been designed and manufactured. Figure 7 shows the result of load measurement in X-direction.

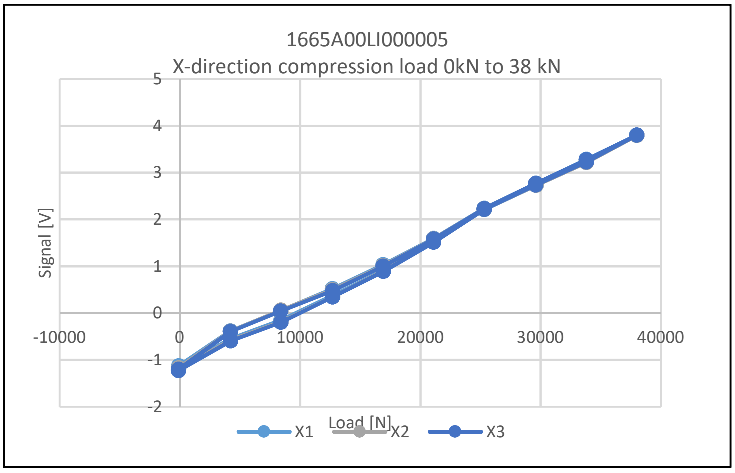

Figure 7. Results of test in X direction.

The test rig enables application of loads in X and Z directions and a combination of both load cases. Preliminary results show good accordance to numerical simulation, good linearity of the signals and response of the whole system. More results will be generated by the final evaluation of sensor performances in batch 2.

Accuracy is maybe the most important performance indicator for a measuring system. The load sensor developed in TecALSens must comply with an accuracy of 15% as deviation of the load measured by the system with respect to the load acting on the wheel axle. Several quantities contribute to the total error, therefore to the deviation of the measured loads. The effect of temperature, voltage and time on the electronics has been taken into consideration and quantified during design phase. Selection of proper electronic components enables the minimisation of these disturbances on electronics' performances. The effect of temperature on zero signal, described by the quantity TK_0[5], has been experimentally quantified following the guidelines in [10]. Uncertainties of the measurement and errors will be evaluated through a statistical analysis of performance results. For this, guidelines in [10] describe the parameters for assessing load sensor performances. The total error will be quantified considering random and systematic error, following the guidelines in [11]. First results based on the available parameters show small single errors. Results of final performance measurement are still necessary for a complete evaluation of the total error.

6. Conclusion

Results of TecALSens project show that load measurement in aeronautics based on thin-film sensor is possible and successful. In this project, thin-film sensor offers several advantages and as sensing element is a valuable alternative to bonded strain gauges. Considering the results available, the load sensor developed fulfils almost all requirements, showing also that measurement in two direction at wheel axle is possible and reliable. TRL 5 at the end of the project appear a reasonable objective.

A new class of load sensor based on thin-film technology is therefore available, opening new possibilities for system development and maturation of more and all-electric aircraft configurations. The technologies developed in the project can be easily transferred to other applications. The analogue

[5] TK_0 describes the „Temperature effect on zero signal per 10K”, according to [11]

electronics and the thin-film sensor are fully qualified for the aeronautic environment and an extension to pressure and temperature measurements is possible.

The selection of the sensing technology, either thin-film sensor or bonded strain gauge or other sensing technologies, depends on several factors like the application selected, the material and the whole environment. A decision on which technology is the most suitable can be made only considering each single case.

7. Acknowledgments

The author acknowledge that “The project leading to this application has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821135”.

The author would like also to thank the colleagues of Liebherr-Aerospace Lindenberg GmbH for the support during the execution of this project.

References

[1] ACARE Flightpath 2050 – Europe’s Vision for Aviation
[2] Clean Sky 2 Joint Technology Programme V05
[3] Jianming L, Zhiyuan Y et al. 2016 *IEEE/CSSA Int. Conf. on Aircraft Utility Systems*
[4] Geilsdorf H: “Modellbasierter Entwurf der Synchronisationsregelung und Fehlerüberwachung elektrischer Einzelantriebe in Landklappensystemen” 2009 *PhD Thesis*, Shaker Verlag (in German)
[5] Maré JC: „Aerospace Actuators 2“, ISTE Ltd and John Wiley & Sons, Inc, 2017.
[6] Maré JC: „Aerospace Actuators 3“, ISTE Ltd and John Wiley & Sons, Inc, 2018.
[7] Stefanescu DM: “Handbook of force transducers – principles and components”, 2011 Springer
[8] Bethe K and Schön D 1980 *Philips tech. Rev.* **39**, No. 3-4, 94-101
[9] Lotichius J: “Modellbildung der Messunsicherheit resistiver Sensorsysteme“ 2017 *Ph.D. thesis*, Technische Universität Darmstadt
[10] VDI/VDE/DKD 2638 „Characteristics of force transducers. Terms and definitions”, 2008
[11] JCGM 100:2008: “Evaluation of measurement data — Guide to the expression of uncertainty in measurement”, 2008.