INFUSION 4.0 – FLOW FRONT DETECTION IN COMPOSITE PARTS WITH FIBER OPTIC SENSORS

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Abstract
The BMWi research project Infusion 4.0 of Fraunhofer LBF and MT Aerospace ranked 3rd in the 2017 Innospace Masters Award for the DLR Challenge.

The goal of the project is the development of a digital flow front detection of a large scale composite part like a booster casing for space applications by fiber optic sensors. The parts are manufactured by vacuum infusion. A dry preform in a vacuum bag is infiltrated by resin. Each sensor fiber contains several of the more than 60 fiber optic sensors. The flow front is the line where the resin gets in contact first with the dry fibers.

The process monitoring needs the signals to be transmitted from the rotating part in the oven to a computer outside. Here a digital representation of the sensor location on the part shows when the flow front reaches the sensor.
Up to now, no such transparent information is available in the manufacturing process of such thick-walled parts and enhances the overall risk of vacuum infusion processes compared to other options. The new technology may enable a more automatic control of the manufacturing process in the future in the sense of Industry 4.0 and integrates sensors available for Structural Health Monitoring (SHM) in the earliest phase of the life cycle for an additional economic benefit.

Keywords: Vacuum Infusion, composite, fiber optic sensor, flow front detection, Process Monitoring, Industry 4.0, digital twin

1. CONCEPT

The main goal of the project is the development of a flow front detection technology for large scale monolithic composite parts by fiber optic sensors. The part investigated here is a composite booster casing but the Infusion 4.0 technology can be applied to other applications as well. The booster casings are manufactured by vacuum infusion that means a dry preform made of dry wound carbon fibers is infiltrated by resin in a vacuum infusion layup. During the infusion and the curing of the resin the part is slowly rotating in an oven to avoid resin accumulation. The area where the resin gets in contact with the dry fibers is the flow front. The visualisation of this currently invisible process step by a digital model is the goal of the Infusion 4.0 project. The manufacturing process itself was optimized in previous projects by MT Aerospace. Deviations of the flow front from the expected ideal state can be detected by the new technology and in the future a semi- or fully automatic industrial process can be developed in a more digital manufacturing environment which is a big step towards the intended 4.0 industrialization of future space components.
The digitalization of the mostly manual composite manufacturing processes may be relevant for other industries as well like aviation, the wind energy business or shipbuilding.

The more transparent manufacturing process enables new ways of quality control and faster ramp-ups of composite part production as well as more flexible reactions towards emerging market pulls. The more digital manufacturing process enables a more automatic quality-control- and test-process.

Fiber optical sensors which are used from the earliest phases of the life-cycle can also be used for health and inservice monitoring during assembly, transport, life and end of life of the part. The accumulated data over the lifetime can be used to design a better or lighter next generation of this part.

2. STATE OF THE ART

Vacuum infusion, flow front detection and fiber optic sensors are state of the art and are used separately in many other applications. These technologies are explained in detail in this chapter while the combination of these elements into the Infusion 4.0 technology is explained in chapter 3.

2.1. Vacuum Infusion Process

The manufacturing process of the booster demonstrator or pressure vessels in general, via infusion, consists of different production phases. First the dry preform has to be manufactured. In the case of this pressure vessel, modified carbon fibres are dry wound over a mandrel using a common winding machine.

After the preforming the vacuum bagging has to be realized. Different ancillary materials and the infusion periphery need to be applied to ensure the proper resin distribution and impregnation of the whole part (figure 1).

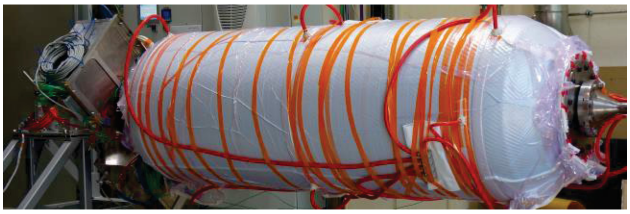

Figure 1: Composite booster casing in vacuum bagging material

The last manufacturing step is the infusion of the preform itself. The infusion and curing process takes place at 50° C rising to 125° C in an oven while the mandrel rotates slowly (see figure 2). Due to the vacuum pressure difference of one bar the resin is “pulled” into the preform through a special rotary feed through installed at one side of the mandrel. The infusion starts from middle of the part and the resin then flows to both bosses in the same time. When the resin reaches the dome regions the second vents at the equators are opened to increase the flow velocity.

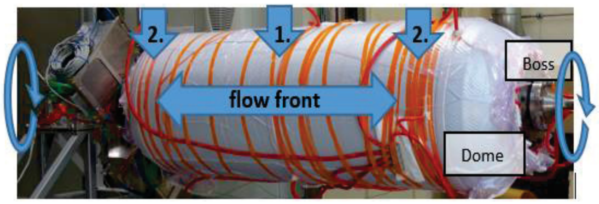

Figure 2: Illustration of the Vacuum Infusion Process

The infusion process sequence is as follows: 5-10 h preheating at 50 °C; 4 h infusion at 50 °C and 6 h curing 50 – 125 °C. In total about 90 kg of dry fibres and 35 kg of resin are needed.

Due to the huge part dimensions especially the high wall thicknesses of about $t \approx 12$ mm, the process durations and the big amount of material necessary a suitable monitoring technology is needed to detect the flow front and to decide when to open the second infusion vents and when everything is fully infiltrated. [1].

2.2. Flow front Detection

There are several project publications [2],[3],[4] or commercial technologies for flow front detection in composite or plastic manufacturing processes. Mostly the sensors are integrated on the toolside and not in the part. In Resin Transfer Moulding (RTM) processes with a high number of parts and considerable tooling cost flow front detection technologies are well known. Here a dry fiber preform is infiltrated by injecting resin under high pressure. Due to the high pressure the tool size is smaller than in typical infusion processes and many different sensor principles are used to monitor the highly automated serial RTM-production parameters. Sensors for pressure, temperature and special dielectric sensors for flow front monitoring are combined.

The following figure 3 shows flow fronts measured by electric sensors and verified by glass plates in a RTM process.

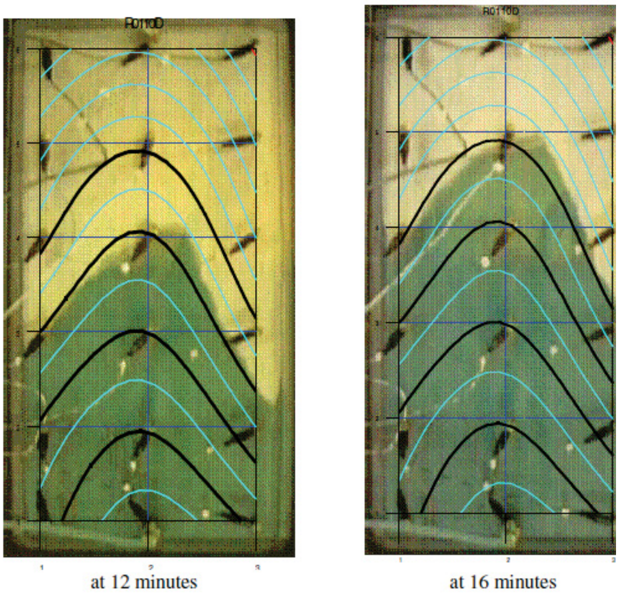

Figure 3: flow front detection with electrical sensors in an RTM process [2]

Such large sensors cannot be used on a highly loaded composite part as the composite fibers would be undulated and disturbed by the notch effect of such sensors.

2.3. Fiber Optic Sensing

The integration of sensors in composite parts has been the topic of many projects mainly in the field of Structural Health Monitoring SHM. [1],[5]-[17]

The goal of this project is to use the fiber optic sensors starting from the earliest phases of the life cycle to compensate the high investment necessary for this technology.
Fiber optic sensors can measure relevant loads in service and have a similar strength, fracture strain and lower stiffness compared to carbon fiber. The diameter is such that the sensor does not damage the base structure by notches. For the same reason it can also be used for process monitoring.
One physical principal of fiber optic is the light propagation by total reflection in fiber optic cables. These consist of a core which is the optical wave guide, a cladding layer which reflects the light and a jacket which protects the fiber. The core and the cladding layer consist of glass. The core has a higher refractive index as the cladding layer which leads to the reflection of the light. Single Mode fibers have a small core diameter of 9µm compared to an overall diameter of around 125µm [18].

Inside every optical fibers several sensor locations can be embedded which is called multiplexing.
Fiber optical sensor technology can be divided in several family trees by the methods used for multiplexing (figure 4).
Either local discrete sensor locations can be used where an active sensor zone is embedded in the fiber or distributed sensing where natural imperfections in glass fibers are used for optical fingerprints. In the latter case virtual sensor locations can be defined in the software.

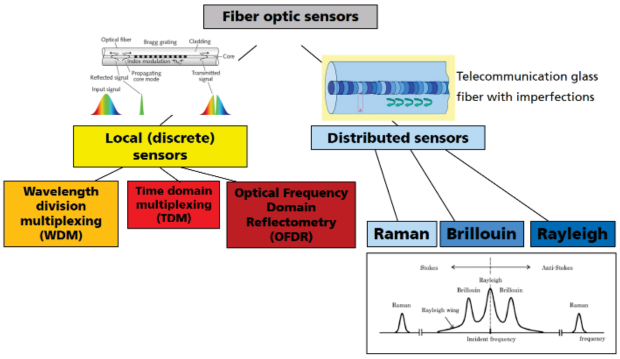

Figure 4: fiber optic sensors compared by methods of multiplexing picture sources [19],[20],[21]

2.3.1. Discrete local sensing

A very common discrete sensor is the Fiber Bragg Grating (FBG) in the following figure.

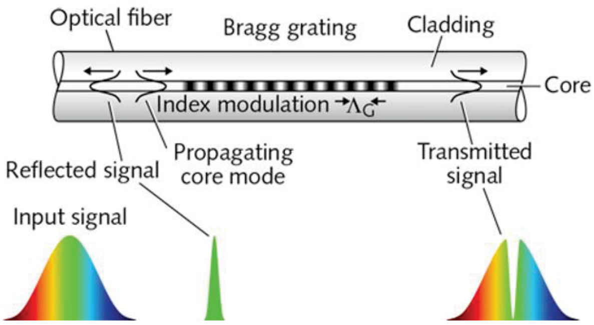

Figure 5: Fiber Bragg Grating (FBG) [19]

This sensor type is a periodic change in the refractive index within the core of an optical fiber. It is created by a laser etching process. The FBG is inscribed in the exposed core of the fiber either during production in the draw tower or afterwards by removing and reapplying the cladding. By using a laser pulse the FBG is embedded like a bar code or grating pattern printed inside the fiber forming a periodic change in the refractive index of the fiber's core. This grating pattern is subjected to factors like temperature or mechanical strain by the same amount as the fiber is stretched or compressed. This response can be measured as a shift in wavelength of the reflected light for this sensor.

The deconfliction of the multiple sensor signals in a single fiber can be done in several ways.

Wavelength Domain Multiplexing (WDM) uses different FBG with different wavelength to discriminate between sensor locations. WDM is done by producing an optical fiber with a sequence of spatially separated gratings. The output of the multiplexed sensors is processed through wavelength selective instrumentation, and the reflected spectrum contains a series of peaks, each associated with a different Bragg wavelength. Each sensor wavelength has to be separated from the next so that no overlap is possible during the measurement.

Other multiplexing methods not used in this project are Time Domain Multiplexing (TDM) which uses a time of flight measurement to discriminate FBG sensors on a fiber. The advantage is the use of the same FBG wavelength for each sensor which enables interchangeability and reduces cost but the sensors cannot be spaced closely.
Another method is Optical Frequency Domain Reflectometry (OFDR). While the number of sensors with the other methods is limited to a typically single digit number of sensors per fiber with OFDR much more sensors with overlapping wavelength can be used. Here the interrogator is much more complex.

2.3.2. Fiber optic fingerprints

Every glass fiber used for telecommunication has imperfections that can act as a fiber optic fingerprint. The reflections at these imperfections are called Rayleigh backscatter and can be measured with very complex interrogators in the form of fiber optic backscatter reflectometry (FOBR).

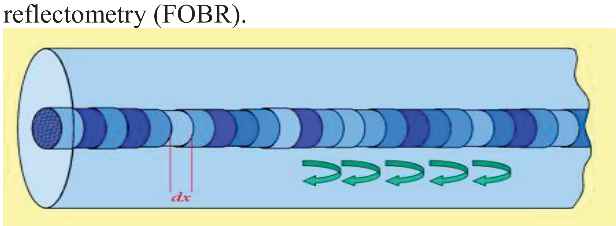

Figure 6: Imperfections in standard telecommunication glass fibers can be used for fiber optic fingerprints [20]

The sensor locations are of a high number and not physical but virtual. These are defined in the software based on the fingerprinting of imperfections.
While the flow front moving through the composite part can be tracked with discrete sensors only stepwise at the sensor location with this type of sensor it can be tracked in principle continuously if it is moving alongside the fiber.
There are other similar methods for longer distances and lower resolution based on Brillouin and Raman effects.

2.3.3. Advantages and Disadvantages

The strain acting on the fiber either by mechanical forces or temperature expansion changes the signal and this directly interacts with the reflected light spectrum.
For strain measurements fiber optic sensors directly convert strain in a corresponding signal while metallic strain gauges use indirect methods like electrical resistance.
The strain signal is not affected by electrical or magnetic fields and several sensor locations can be interrogated in one fiber (multiplexing).
The disadvantages are the high cost of each component of fiber optic technology and the high temperature response of the sensor. While a temperature compensation of the signal is easy with metallic strain gauges more effort has to be used with fiber optic sensors. Here at some sensor locations the mechanical strain must be decoupled by tubes from the fiber so that only the temperature affects that sensor. This is then used to compensate the temperature effect in the software.

2.3.4. Medium Detection with fiber optics

Fiber optic sensors have been used to measure the level of liquids in tanks due to the high chemical resistance.
The measuring principle for fiber Bragg sensors when detecting a liquid medium can be multifold though not all effects and interactions are completely understood up to now:

-The medium flow acts on the fiber and the hydrodynamic resistance bends the fiber. This difference in strain at the sensor location creates signals.

-The temperature of the medium compared to the tooling and dry fiber is different and either heats or cools the sensor. Even small changes like 0.1°C can be measured in the sensor signal.

-If the fiber does not have an opaque jacket at the sensor location a direct interaction of the medium with the refractive index of the cladding layer is possible.

The basic working principle of using fiber Bragg grating sensors has been shown in other projects [22]-[26]. In one project thermosetting resin was replaced with vegetable oil in order to reuse the sensor multiple times.

In this project fiber Bragg grating sensors of several suppliers are tested in several steps in a test pyramid of ascending complexity coming closer to reality with each step.

3. DEVELOPMENT OF THE INFUSION 4.0 TECHNOLOGY

The Infusion 4.0 technology consists of an interface to connect the composite part with fiber optic cables, a solution for transmitting the data from the rotating part and a software for the analysis and display of results.

3.1. Software for Flow Front Detection

The fiber optic signal is continuously monitored during the heat up of the tool. This baseline signal is analysed and monitored. Any deviation of this signal by a certain threshold and step change (based on preliminary tests) triggers the flow front detection as in the following figure.

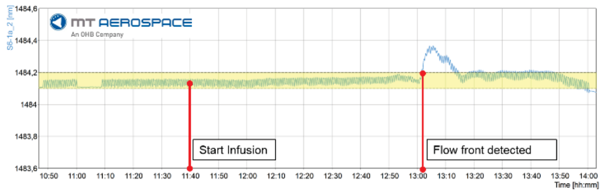

Figure 7: wavelength change due to the arrival of a resin flow front in a composite part

Discrete sensors like FBG deliver a binary state from “sensor is dry” to “sensor is wet”. Distributed Sensors are principially able to show the continuous progress of the flow front through the part.

The signal however is also changed by either temperature, strain or reflectivity. The critical elements in this project are the signal analysis of multiple such sensor locations with filters and the visualization of the flow front in a digital twin of the part on a monitor. As in all Industry 4.0 projects the Human Machine interface is very important so that the digital twin can be interpreted easily.

Once the sensor state has changed to “wet” this is frozen so that it can not change back again by later signal changes. On the monitor the signal of the mapped sensors on a digital representation of the component changes from red to green. This analysis is done nearly parallel for all sensors.
The creation of a software for the analysis and visualization (figure 8), the data acquisition and the transfer from the rotating part in the oven as well as the verification in a realistic laboratory test are important aspects of the project.

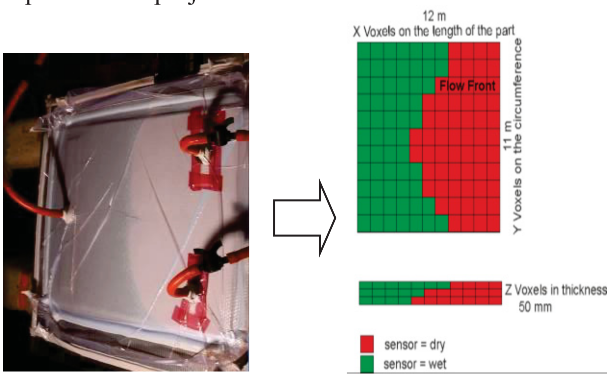

Figure 8: physical flow front on the left and digital twin on the right (initial image for the Innospace Masters award 2017)

3.1.1. Online processing of the fiber optic signal

The objective of the online signal-processing algorithm is to detect and visualize the flowfront in composite parts during the infusion process. Therefore, the algorithm analyses the signals of the fiber optic sensors housed in the composite part. In steady state operation conditions, the output of the sensors is equal to a corresponding wavelength for each sensor. Additional strain on the fiber optic sensors leads to a shift of the steady state output wavelength. Accordingly, the algorithm analyses the dynamic proportion of every sensor signal. Raw data from the fiber optic sensors contain a steady-state output wavelength, measurement noise and a harmonic component due to the revolutions induced by the electrical drive. Figure 9: shows a sample signal of a fiber optic sensor.

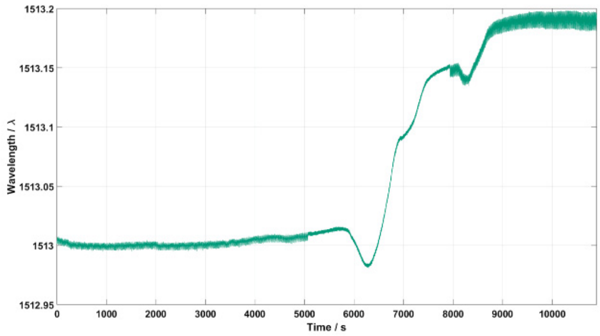

Figure 9: Sample signal of a fiber optic sensor in the composite part
To analyze the dynamic proportion of the sensor signals, first the algorithm removes the steady-state output wavelength. Furthermore, the algorithm performs a smoothing by means of a moving average filter (noise in the sensor data is removed). Based on the preprocessed data the algorithm determines the gradient of each sensor signal and detects changes in the output wavelength. Figure 10 illustrates the multi-channel signal-processing chain for the detection of the flow front.

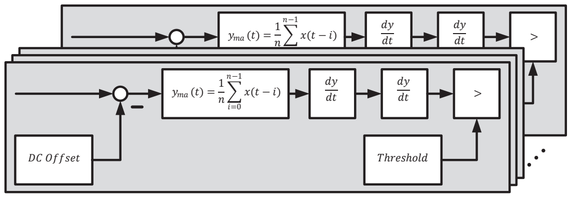

Figure 10 Multi-channel signal-processing chain for the detection of the flow front of composite parts

It is the purpose of the software to give insight regarding the progress of the infusion process to operating staff. To achieve this, a graphical user interface (GUI) presents the results of the analysis clearly. The user interface features indicators for every single sensor blended over an unwound view of the skin as shown in Figure 11. An Excel sheet (Setup Source) contains the positions of the sensors and size and shape of the tank. The GUI shows the indicators for each sensor at the position within the tank. Once the process starts, the GUI processes the data from a comma separated data source file (Data Source) and the indicators stay red as long as no resin has been detected and turn green when the sensor has detected resin. To verify the detection the operator can check the actual sensor data by clicking on the indicator. A chart shows the filtered sensor data and the operator can deactivate and reactivate the corresponding sensor by toggling a checkbox. The spatially distributed sensor indicators allow the operator to follow up on the flow front spreading throughout the work piece and control the infusion process accordingly.

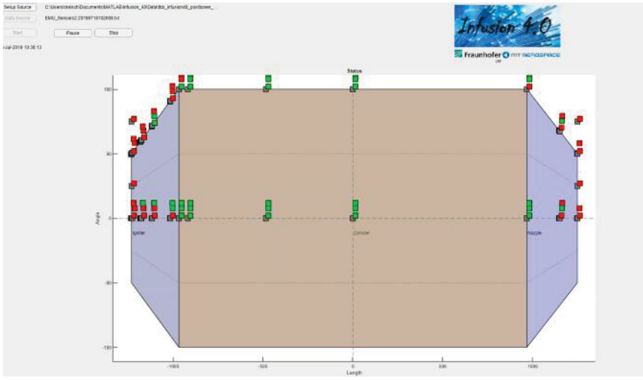

Figure 11: Digital twin representation of the composite booster casing with sensor locations

3.2. Fiber optic interfaces for composite parts

A critical area when embedding sensors in composite is the fiber ingress or egress where the fragile glass fibers leaves the laminate. While the glass fiber is protected within the composite, the fiber is flexible and has no bending support at this location. Many projects have lost fiber optic data signals at this point just outside the composites. At this location a repair is mostly impossible due to the insufficient remaining fiber. In the clean sky project an elastomer connector hub was developed by Fraunhofer LBF for this reason offering a solid counterpart for fiber optic connectors directly on composite parts [27]. By this way the part can safely be separated from the measuring chain. In this project MT Aerospace developed a metallic connecting solution for this critical area. Both methods can be used in either automatic tape laying or like here in winding processes.

3.3. Data transfer from the rotating part

The transmission of fiber optic signals from a rotating part like the composite booster casing rotating in the oven is possible in two forms.

The light can be transmitted by an optical slip ring so that it is transferred into electrical signals outside the rotating environment. Optical slip rings are commercially used for welding robots with fiber lasers, underwater or other robotic systems, military applications or in the wind energy industry for the pitch control of rotor blades. The data transfer is possible through oil or glass prisms. This limits the number of channels possible, the mechanical robustness and the size of the slip ring. Optical slip rings are also limited in their temperature range by plastic parts in connectors or sealants. The big advantage of optical slip rings is the high data transfer possible. The other advantage is the safe operation of the expensive interrogator outside the oven.

The second option is to convert the light signal into electrical systems with an optical interrogator within the rotating system and transfer signals only through an electrical slip ring. Here the robustness and temperature range of the slip ring is much higher. With the size of the slip ring, there are increasing electrical impedances that affect the frequency range as well as the cable length that can be used via the slip ring. This complicated interaction limits the signal to noise ratio that means that the signal robustness is reduced with size while additionally the data rate is limited. Electrical slip rings can be a data bottleneck for digital data transfer and it can be necessary to transform the signal through additional devices before and after the slip ring to achieve the necessary signal quality.

When an electrical slip ring is used for high speed data transmission there are several effects that are only briefly described here. Any slip ring inevitably leads to some level of reactance and non linearity in high frequency applications which reduces the signal to noise ratio. More information can be found in [28]-[30]

The most important influences to be considered are:

-Resistive/ ohmic noise by the contacts of the slip ring running over imperfections of the slip ring. Mechanical imperfections lead to resistive variations and lead to voltage variations in the signal.

-Insertion Loss: Any interconnection in a cable leads to a reduction in signal power.

-Return Loss: Reflections from discontinuities within the signal line reduce the signal power further.

-Frequency dependant noise: This crosstalk means the interaction between signals in nearby cables.

-Deterministic noise: This so called Jitter is a phase delay in the time domain of a signal. A slip ring that is used in a rotary transmission can lead to an impedance mismatch. Any impedance mismatch at high operating frequencies leads to this effect. A simple connector in a high frequency cable or any other component like a slip ring leads to this phase delays in the frequency domain or jitter in the time domain.

To avoid resistive noise a slip ring should be run-in before use to reduce the imperfections before operation. Electrical shielding and grounding of every component of the electrical system as well as high quality contact pins and twisted pair cables are the established methods to enable high speed data transfer. A similar design and quality like for controlled impedance twisted pair cables as CAT5 to CAT7 has to be reached for every component in a slip ring transmission. Even when following all design guidelines even small details can create a bottleneck in high frequency slip ring transmissions.

In the following figure 12 the selected measuring chain is shown. It consists of the fiber optic sensors integrated in the dry composite preform. The fiber is connected through a vacuum connector to the interrogator. Here the signal is transformed into electrical signals. These are transmitted as Ethernet signals and converted to a Profinet signal in an industrial DSL modem. With a maximum data rate of 30 Mbit/sec. with four cables or 15 Mbit/sec. with two cables this signal is transmitted through the slip ring. This converted signal running through the slip ring offers a higher interference resistance. The power supply for all electrical components is also transmitted into the rotating environment via the slip ring. The electrical components and the slip ring are cooled by compressed air and the data is transmitted outside the oven via a high temperature cable. Outside the data is reconverted back to Ethernet signals and connected to a laptop for analysis and visualization.

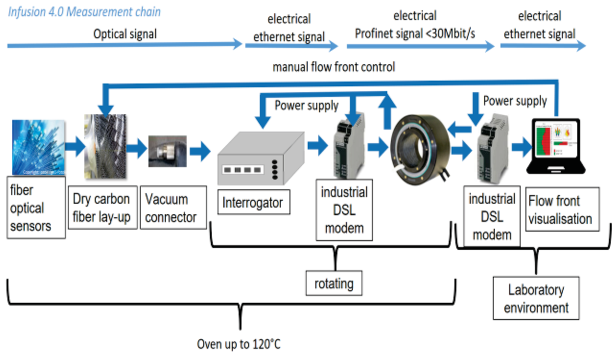

Figure 12: Measuring Chain for the Infusion 4.0 technology

4. VERIFICATION OF INFUSION 4.0

The verification of the Infusion-4.0-technology is done in a test pyramid consisting of consecutive levels of rising complexity. The first step is to submerge the fiber optic sensor in resin and monitor the signal during this event. In the form of a technology down selection the most successful sensors based on the signal response are selected for three plate level test. Here a vacuum infusion of a long flow-path of about 1 meter but narrow width is done. The thickness of the plate is representative to real life structures.
In this test level the effects of vacuum and temperature are added resulting in additional but more realistic disturbances to the signal. Here only some sensors are successful and the most promising are selected as candidates for the final test.

4.1. Sensor tests

In this project fiber optic sensor of five suppliers with fiber Bragg gratings and distributed sensor technologies are investigated.
A number of sensors and fibers are used for the first test step. Some reference fibers and target sensors are put in test environments like a sloped metal plate. Then droplets of resin are used to stimulate a signal representative for a flow front (figure 13).

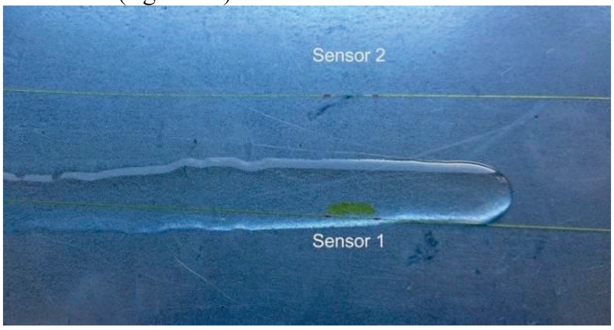

Figure 13: droplet test with resin and a reference sensor

As the infusion process starts in an oven at 50°C this environment is imitated roughly in tests.
In another test (figure 14) a fiber with sensor is placed in a U-like tube and this is slowly filled with resin from one side.

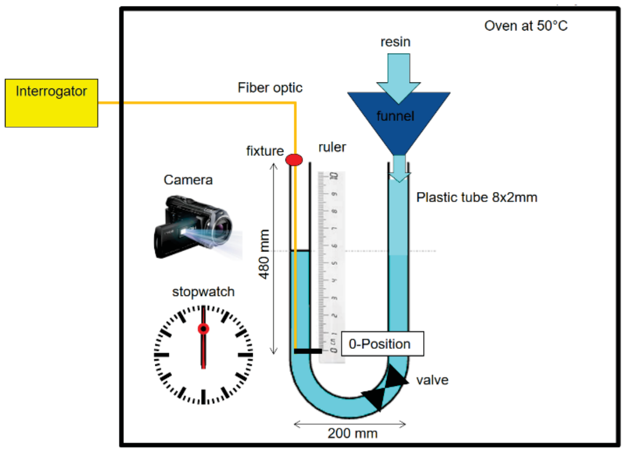

Figure 14: test of a sensor in slowly rising resin

Most of the tests are successful and the scoring based on criteria defined before the test is very close to one another. The sensors showing the best signal responses in these tests are selected for the next level. The following figure 15 shows one example signal.

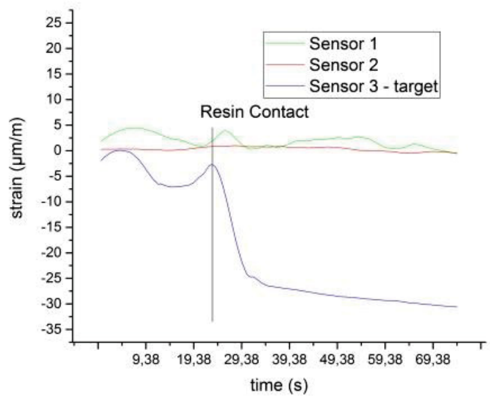

Figure 15: Example fiber optic signal during resin contact

4.2. Tests on plate level

In the next test three CFRP-plates of 1000 mm x 250 mm with several optical fibers each are manufactured. The vacuum infusion process used for the plate is very similar to the manufacturing of a booster casing. The fiber lay-up is such that the flow front runs through the length of the part. The sensor locations are at a length of 500 mm to stabilize the flow front in the first half meter. At 900 mm length another sensor location is used to take another measurement (see figure16). Temperature compensation is achieved by putting a sensor inside a tube thereby eliminating mechanical strain. In this test the vacuum also affects the signal and the temperature profile is the same as for real booster casings.

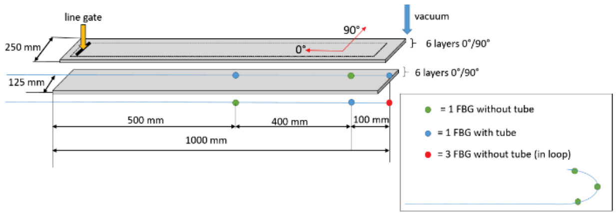

Figure 16: plate test using vacuum infusion and fiber optic sensors

For the selected sensor types there are different results in signal response.
Though the distributed sensing offers a great potential for continuously monitoring a flow front or other events it is decided to use more established FBG technology for the Full scale test.

4.3. Full Scale test

The final test is a full scale representative booster casing made of CFRP of about 2,5 m length and 0,8 m diameter. The carbon fiber is dry wound on a metal mandrel. During the winding process the optical fibres are integrated in the preform. By using a laser measurement system mounted at the winding machine, the fibers are placed in between different layers and at certain locations (figure 17).

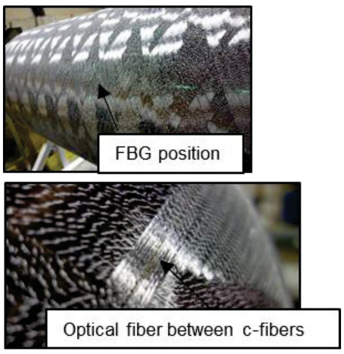

Figure 17: Integration of optical fibers in the winding process

They are then bonded on the preform using an epoxy binder. The FBG regions are kept free to guarantee the exact load transmission from the resin into the optical fibres. [1]

In this project 63 strategically placed fiber optic sensors are used using symmetry lines of the rotating structure for a dense network of sensors. Also some sensors are positioned atop each other to detect the flow front in laminate layers. The following figure shows the dry preform after winding

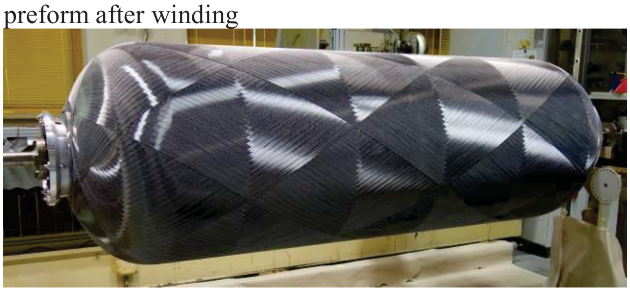

Figure 18: Dry carbon fiber preform of the booster casing containing the fiber optic sensors

The vacuum bagging and flow lines are applied. The first flow line is circumferential in the middle of the cylinder. The other two flow lines are also circumferential at the transition from the cylindric part to the domes and are opened about 1 hour after the start of the vacuum infusion.

The optical signal is transferred through vacuum tight fiber optic connectors. These enable a safe, robust and removeable connection between the mechanical sensorized part and the interrogator. There are two metallic boxes rotating with the part containing electronic components. One contains the interrogator and the rotating DSL modem. The other contains equipment for thermocouple measurements. Both boxes are mounted on metallic arms and rotate with the composite part. The electrical slip ring enables the power supply and transmits the sensor signals.
A data rate of around 15Mbit/ sec. is achieved which is sufficient for the monitoring of this slow process. An additional mechanical slip ring supplies vacuum for the vacuum infusion, compressed air for cooling and resin transfer into the composite part.

To measure the flow front during the manufacturing process the entire measurement equipment including the optical interrogator need to be enclosed in special cases and insulated against the outside temperatures of the oven but also to prevent overheating by its generated lost heat. Therefore special insulated cases are designed using normal pressure to keep the temperature of the measurement equipment under 60° C [1].
To ensure an online monitoring of the process great effort has to be done to transmit the gained data from all the different equipment’s out of the rotating part to monitor and control the process (figure 19)

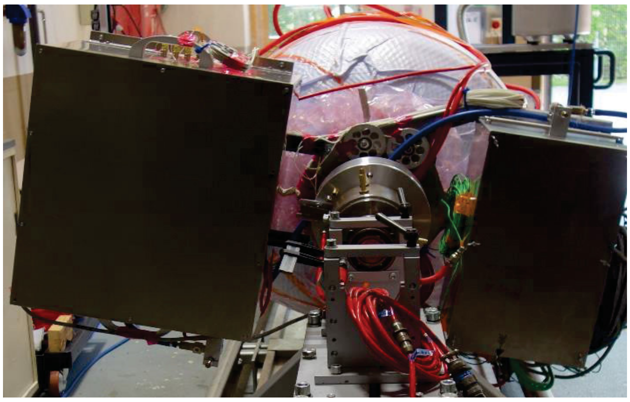

Figure 19: Boxes containing the electronics

The next figure shows the part in the oven

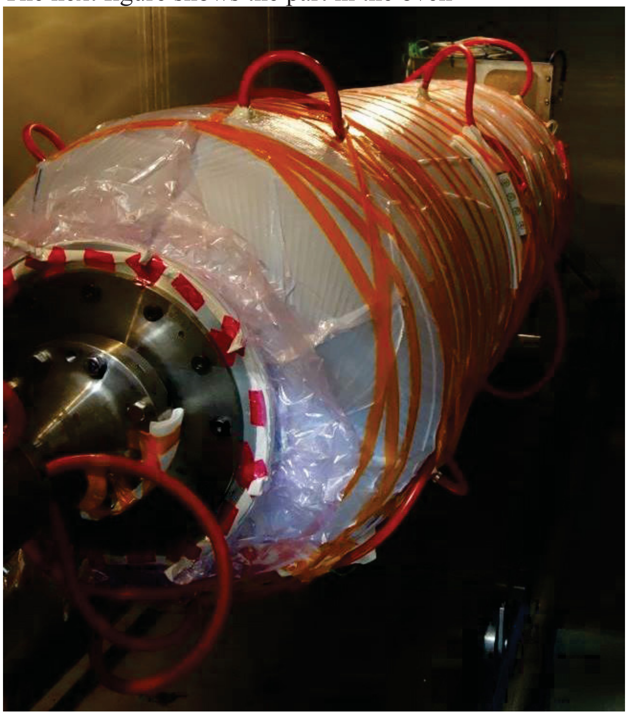

Figure 20: composite booster casing during the Infusion 4.0 verification

The following figure 21 shows the monitors outside the oven. These enable the supervision of the fiber optic data. On the left is the raw data of individual fibers and on the right the monitor shows the mapping of the binary sensor state (dry in red and wet in green). In the future a fully automated process might be enabled based on the fiber optic sensor signals and integrating additional critical process parameters.
The full scale test for the verification of the Infusion 4.0 technology was done on July 18th 2019. The comparison between the expected flow front based on the measured resin in the part and the sensor data shows a good correlation.
On the one hand the test indicates that the infusion strategy developed by MT Aerospace is quite sophisticated already but on the other hand also reveals potential improvemets especially regarding the overall infusion time.

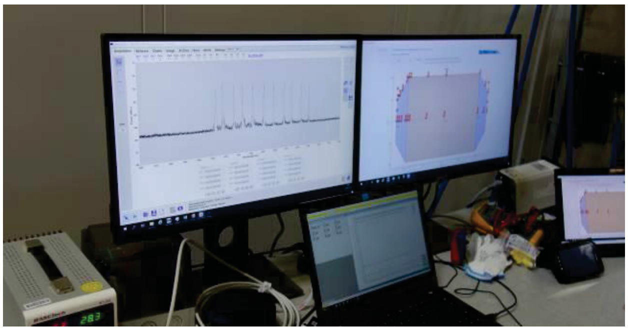

Figure 21: control station outside the oven

5. DISCUSSION OF RESULTS AND FUTURE APPLICATIONS

Infusion 4.0 shows very promising results which can raise the infusion technology to a new level. With this technique, the infusion process can be optimized, so that an optimal amount of resin is in the manufactured part and the production time is reduced. On top of this, the fiber sensors remain in the structure and can be used for structure health monitoring applications. A variety of products like pressure vessels or tanks can be equipped with the sensors and can help to bring the infusion technology in different fields of application and industries. Besides the monitoring of the infusion process fibre optical sensors can also monitor other composite manufacturing processes, like the wet filament winding process, the thermoset automated fiber placement process (TS-AFP) and the thermoplastic automated fibre placement process (TP-AFP). During the project Infusion 4.0 a first step for the capability of an automated alignment and embedding of the optical fibres was acquired which can also be used for the above mentioned processes. Although it is not necessary to detect the flow front during the wet filament winding and TS/TP-AFP other parameters need to be monitored like e.g. the temperatures, the compaction during layup and curing and the degree of curing. With the embedded optical fibres it is then possible to realize an in-service and structural health monitoring. For example filling levels and temperatures during the operation can be monitored as well as critical strain and stress states and even the detection of damages inside the laminates are possible with guided waves.

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[1] D. Stelzl, A. Pfleiderer, P. Ortmann, T. Wiedemann, M. Duhovic, M. Resch, "Embedded Fiber Bragg Gratings for the Process and Structural Health Monitoring of Composite Boosters for Space Applications" 12th International Workshop on Structural Health Monitoring, Stanford 2019

[2] Lee W, M. Rice et.al. , „RESIN TRANSFER MOLDING PROCESS,“ [Online]. Available: http://www.aschome.com/administrator/images/support/pdf/1347830613.pdf.

[3] M. LeGault, „In-mold sensors: In-situ process monitoring for RTM,“ 8 3 2013. [Online]. Available: http://www.compositesworld.com/articles/in-mold-sensors-in-situ-process-monitoring-for-rtm. [Zugriff am 20 06 2017].

[4] G. SCOTT D. SCHWAB, „Sensor System for Monitoring Impregnation and Cure During Resin Transfer Molding,“ POLYMER COMPOSITES, APRIL 1996, Vol. 17, No. 2, p. http://onlinelibrary.wiley.com/doi/10.1002/pc.10616/pdf, 1996.

[5] R. P. BEUKEMA, „Embedding Technologies of FBG Sensors in Composites: Technologies, Applications and Practical Use,“ in 6th European Workshop on Structural Health Monitoring, Dresden, 2012.

[6] R. J. Black, J. M. Costa, L. Zarnescu, D. A. Hackney, B. Moslehi und K. J. Peters, „Fiber-optic temperature profiling for thermal protection system heat shields,“ 27 10 2016. [Online]. Available: http://opticalengineering.spiedigitallibrary.org/article.aspx?articleid=2578405. [Zugriff am 20 06 2017].

[7] B. Bröcher, „Faseroptische Sensoren zur Prozeßüberwachung in der Mikrosystemtechnik,“ Diss. RWTH Aachen, Aachen, 2000.

[8] P. Foote, „Integration of structural health monitoring sensors with aerospace, composite materials and structures,“ Mat.-wiss. u. Werkstofftech. 2015, 46, No.2, pp. 197-203, 14 Nov 2014.

[9] H. Hanselka et.al., „Schadensüberwachung mit Wandlermatierialien,“ 02 2006. [Online]. Available: https://www.tu-darmstadt.de/media/illustrationen/referat_kommunikation/publikationen_km/themaforschung/2006_2/Seite_20_27.pdf. [Zugriff am 15 06 2017].

[10] M. Lehmann, „LOAD MONITORING OF COMPOSITE STRUCTURES,“ in JEC End user Forum Aeronautics Forum, Paris, 2009.

[11] A. B. H. H. K.-H. H. M. Lehmann, „STRUCTURAL HEALTH MONITORING OF FIBER COMPOSITES,“ in SoSDiD 2008, Darmstadt, 2008.

[12] „Monitoring System for Delamination Detection – Qualification of Structural Health Monitoring (SHM) Systems,“ in Conference on Damage in Composite Materials, Stuttgart, 2006.

[13] Conchin Contell Asins et.al., „DEVELOPMENT, MANUFACTURING AND TESTING OF A 1:1 SCALED SMART MORPHING LEADING EDGE DEMONSTRATOR,“ in GREENER AVIATION 2016, Brüssel, 2016.

[14] B. Soller, „Monitoring Carbon Composite Structures With Optical Fiber Sensors,“ Tech Briefs, 01 04 2010. [Online]. Available: http://www.techbriefs.com/component/content/article/ntb/features/feature-articles/7794.

[15] Sanborne E. et. al., „Distributed Fiber Optic Strain Measurement Using Rayleigh Scatter in Composite Structures,“ Springer, [Online]. Available: https://link.springer.com/content/pdf/10.1007%2F978-1-4614-0222-0_56.pdf.

[16] C Keulen et .al., „Embedded fiber optic sensors for monitoring processing,“ 9th International Conference on Damage Assessment of Structures (DAMAS 2011), Oxford, 2011.

[17] Dominik M. LAVEUVE et. al., „SHM - Reliability Demands On the Multidisciplinary Challenge of Structural Health Monitoring,“ in NDT in progress, Prague, 2009.

[18] https://www.thefoa.org/tech/ref/basic/fiber.html

[19] https://www.laserfocusworld.com/fiber-optics/article/16555204/fiberoptic-sensing-leveraging-three-decades-of-fiber-bragg-grating-sensing-technology

[20] https://lunainc.com/fiber-optic-solutions/luna-researchers-harness-the-power-of-fiber-fingerprints/

[21] Jing Wang, Distributed Pressure and Temperature Sensing Based on Stimulated Brillouin Scattering https://www.semanticscholar.org/paper/Distributed-Pressure-and-Temperature-Sensing-Based-Wang/50665ffe8ca3c08430a2bb6191e4da3dee3b3a45

[22] J. Oelhafen, R. Fernandez, D. Niefnecker, S. Zaremba, and K. Drechsler. 2015. "Flow Front and Cure Monitoring with Fibre Optic Sensors for Thick CFRP Laminates ," 20th International Conference on Composite Materials, Copenhagen,

[23] N. u. S. R. Gupta, „Fiber optic sensors for monitoring flow in vacuum enhanced resin infusion technology (VERITy) process,“ National Aerospace Laboratories, Elsevier, Bangalore, 2008 .

[24] J. Rodriguez-Lence F. et. al., „SMART SENSORS FOR RESIN FLOW AND COMPOSITE CURE MONITORING,“ [Online]. Available: http://iccm-central.org/Proceedings/ICCM12proceedings/site/papers/pap1100.pdf. [Zugriff am 20 06 2017].

[25] Luna Inc., „Enginnering Note EN-FY1318 Measuring Liquid Level Using Fiber Optic Sensing,“ 13 08 2013. [Online]. Available: http://lunainc.com/wp-content/uploads/2013/09/LT_TD_EN-FY1318_MsrGasolineHeight_Rev3.pdf. [Zugriff am 20 06 2017].

[26] X. Song, „Vacuum Assisted Resin Transfer Molding (VARTM):Model Development and Verification,“ Virginia Polytechnic Institute and State University , Blacksburg, Virginia, 2003.

[27] Mihail LILOV et.al. , „Development of a Structural Health and Load Monitoring System and its Implementation into an Aircraft Flying Demonstrator,“ in EWSHM 2016, Bilbao, 2016.

[28] https://www.moog.com/content/dam/moog/literature/MCG/AvoidingDataBottlenecks.pdf

[29] https://www.moog.com/content/dam/moog/literature/MCG/311_When_Ethernet_Rotates_White_Paper.pdf

[30] https://www.machinedesign.com/technologies/how-choose-slip-rings-gigabit-ethernet-connectivity