Validation of a Piezo Based Integrated Process and SHM System on Hollow Composite Aircraft Part Made by Vacuum Infusion Using a 3D Printed Smart Mold

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ABSTRACT

During the last years the authors developed a novel hybrid multi-functional piezo / temperature sensor concept for flow front, cure and structural health monitoring of composite parts thus allowing monitoring of the production and the usage with the same sensor type. Within this paper, the authors present the latest validation results of the developed sensor and monitoring concept on a hollow composite aircraft part. The production of the part was done by vacuum infusion using a smart separable Al mold, made by selective laser melting to enable surface near complex cooling channels and lightweight design. Process parameters such as flow front propagation and degree of cure were successfully monitored during the production of the part. Finally, the ability of the co-cured sensor for passive acoustic emission monitoring for the occurrence of and localization of impacts and the application of guided ultrasonic waves was demonstrated.

INTRODUCTION

In order to bring the advantages of fiber reinforced polymers – high specific strength and stiffness – into applications where mass production is essential e.g. specific aircraft parts such as stringers or frames, automated manufacturing techniques have to replace the wide spread manual production. Depending on the part to be manufactured, infusion methods like Resin Transfer Molding (RTM) or Vacuum Infusion (VI) are such automated production techniques. Currently process monitoring in RTM processes are done by different type of sensors such as temperature sensors, pressure sensors or dielectric sensors for the determination of the degree of cure [1, 2, 3]. In order to monitor the structural integrity during use (SHM), further type of sensors such as piezo sensors, mainly glued to surface of the structure are under investigation [4, 5, 6]. Within the last years the authors developed a novel hybrid multi-functional piezo / temperature

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sensor concept for flow front, cure and structural health monitoring of composite parts thus allowing monitoring of the production and the usage with the same sensor type. The sensor performance and the overall monitoring concept was validated on different composite parts like flat plates and a PAX door edge-member [7, 8, 9], Within this paper, the authors present the latest validation results of the developed sensor and monitoring concept on a hollow composite aircraft part.

OVERALL MONITORING CONCEPT

Figure 1 shows the overall process and structural health-monitoring concept. In a first step the piezo-temperature sensors are placed at pre-defined positions in the mold. Then the dry preform will be placed in the mold. After closing of the mold, all sensors the piezo sensors are actuated by a frequency swept chirp signal and the current response for the determination of the impedance is measured via the Pt100 temperature sensor. During the production process (infusion and curing) the impedance spectra are measured over time and the change of the spectra –resonance frequency – was used to determine flow front arrival and the hardening of the resin and subsequent the degree of cure. When the curing cycle has been finished and the mold was cooled back to room temperature, the part together with the co-cured sensors will be deformed. The co-cured piezo transducers are than ready to be used as sensors and / or actuators of a passive (Acoustic Emission) and / or active (Guided Ultrasonic) SHM system, where the temperature sensors are used to account for temperature effects.

Sensor Concept

The sensor concept was inspired by the work of e.g. [10], where the impedance of a piezo sensor was determined out of the measured response of a shunt resistor in series to the piezo sensor actuated by a frequency modulated chirp signal. The developed multi-functional sensor shown in figure 2 consists of piezo disc of 15 mm in diameter and 2 mm in thickness with wrapped around electrodes. The upper electrode is connected to a Pt100 temperature sensor used a shunt resistor, which is soldered to a

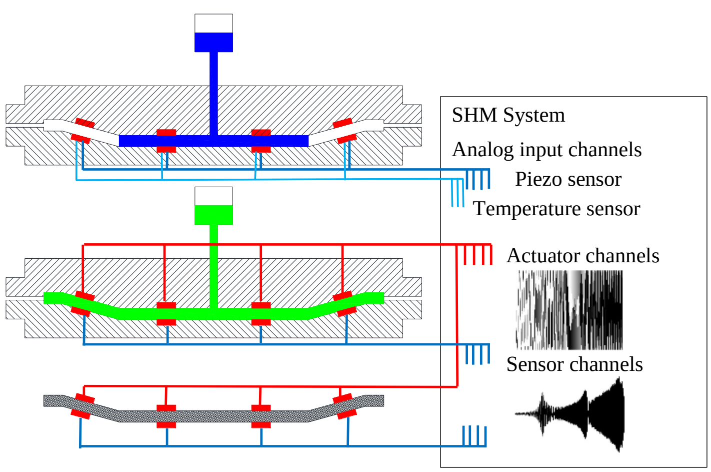

Figure 1. Illustration of the working principle of the integrated process and structural health monitoring system.

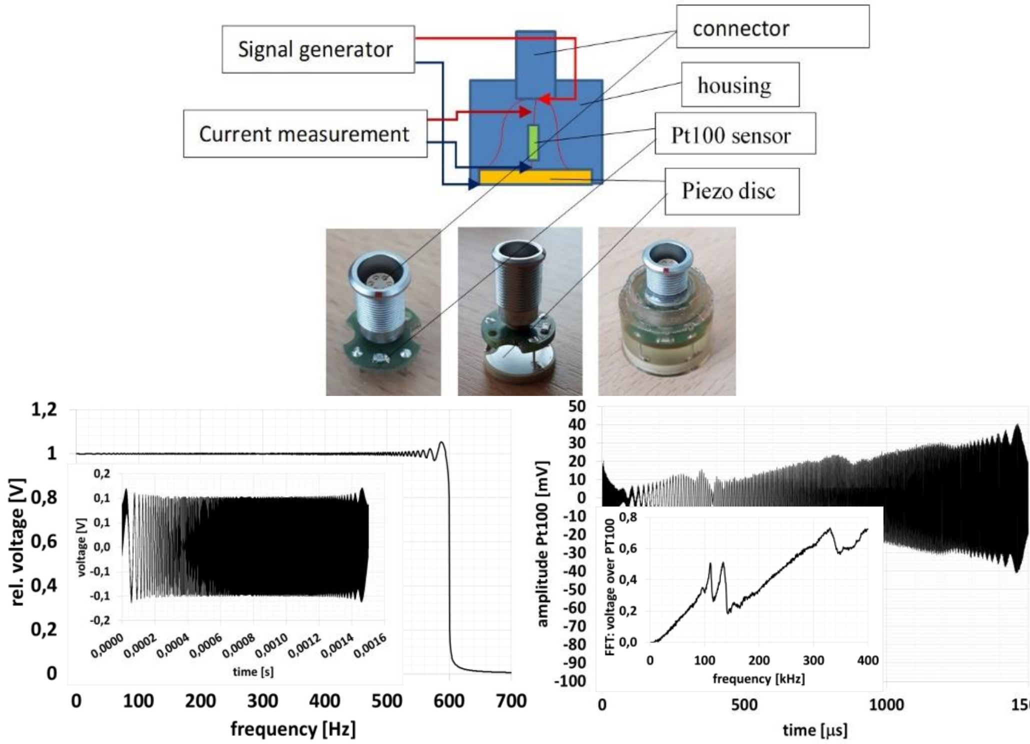

Figure 2. Concept and picture of the multifunctional piezo / temperature – sensors for integrated process and structural health monitoring (top) and Actuation signal with FFT of the actuation signal (left side) and typical measured voltage signal and FFT of the voltage signal over the Pt100 sensor.

circuit board that also host the connector. The piezo – Pt100 assembly is embedded in an epoxy housing (diameter of 20 mm and height of 10 mm). In order to measure the impedance of the Piezo a signal generator is connected to the ground electrode of the piezo and the PT100 temperature sensor. The current through the piezo is measured via the Pt100. For actuation, a frequency swept chirp signal with a starting frequency of 0 kHz and end frequency of 600 kHz with flat frequency response [10] is used. The response voltage over the PT100 was measured and out of the FFT of the voltage response, the admittance of the piezo sensor is determined (see bottom of figure 2).

VALIDATION OF SENSOR AND MONITORING CONCEPT

Test Component And Smart Mold Concept

The selected component for the validation of the sensor and monitoring concept, shown in figure 3 (left side), is a hollow composite part with varying shape and thickness along its major axis made by vacuum infusion of a dry preform. The special shape of the part requires a separable inner mold to allow a successful demolding after curing. Four parts of the mold were manufactured by selective laser melting to allow a thin wall, mechanical stable design with complex shaped surface near heating channels (middle of figure 3). During the design of the mold four places for the sensors were defined – two at the upper and two in the lower part of the mold indicated by the two larger holes in figure 3. Only these two parts of the mold were

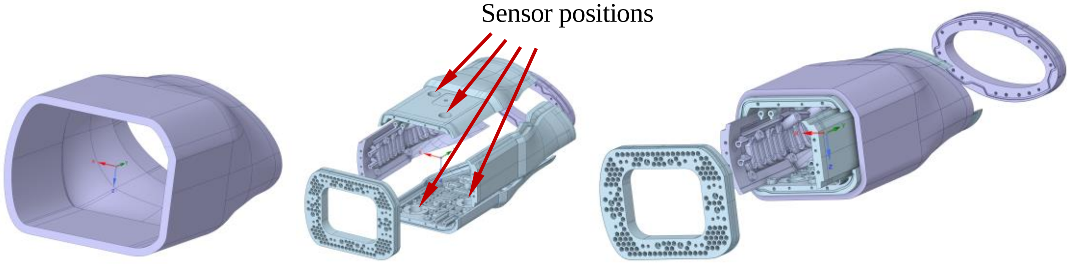

Figure 3. Hollow composite part (left), mold concept (middle) and de-molding concept after curing.

possible to allow a successful demolding of the parts with the co-cured sensors. The movement of the six different parts of the mold during the demolding after curing are shown on the right side of figure 3.

Measurement Hardware

The system used for process and structural health monitoring consisted of two 4 channel acoustic emission cards (type PCI-DISP-4 from PAC) and an arbitrary waveform generator card (type: ARB-1410 from PAC) connected to a 4-channel multiplexer card. All acquired signals were amplified with preamplifiers of type PAC WD with an amplification of 40 dB. Details about the hardware can be found in [6].

Production Process With Online Monitoring

The production of the component was done by vacuum infusion from the two edges. Therefore, the sensors were placed in the upper and lower part of the mold. Then the dry preform was placed around the instrumented mold and fixed. In 3rd step the vacuum bagging with the two injection lines was set up and evacuated. After heating the mold to the required injection temperature of 70°C the resin was injected from the thin oval side till the flow front reaches the thick portion of the part. The second injection from the thick edge was started to allow both flow fronts to coincide at vacuum suctions. Once the whole preform is infiltrated, the whole setup was heated to the curing temperature of 95°C. This temperature was kept for several hours till the curing was finalized. The different steps of the production process till successful demolding of the part with the co-cured sensors is shown in figure 4. Two process parameters were assessed during the production of the plate: the propagation of the flow front and the curing state (degree of cure) after successful impregnation of the dry preform. Therefore, all four sensors were actuated by the chirp signal (left side of figure 2) and the admittance was measured during the whole production process with a sample rate of 5 Hz. Figure 5 shows development of the admittance around the 1st radial resonance of sensor 3 and the development of the temperatures and the 1st dominant resonance frequencies of all four sensors (sensors 1 and 2: front, sensors 3 and 4: back) for the whole production process. It can be seen that the shape of the admittance curve change during the different production steps. The rise in temperature lead to a global change of the slope of the admittance vs. frequency curve, which is mainly due to change of the resistance of the Pt 100 sensors and was used to measure the temperature during production outside the resonance region at 250 kHz (ellipse in figure 5). In addition, the change in temperature from 25°C (blue)

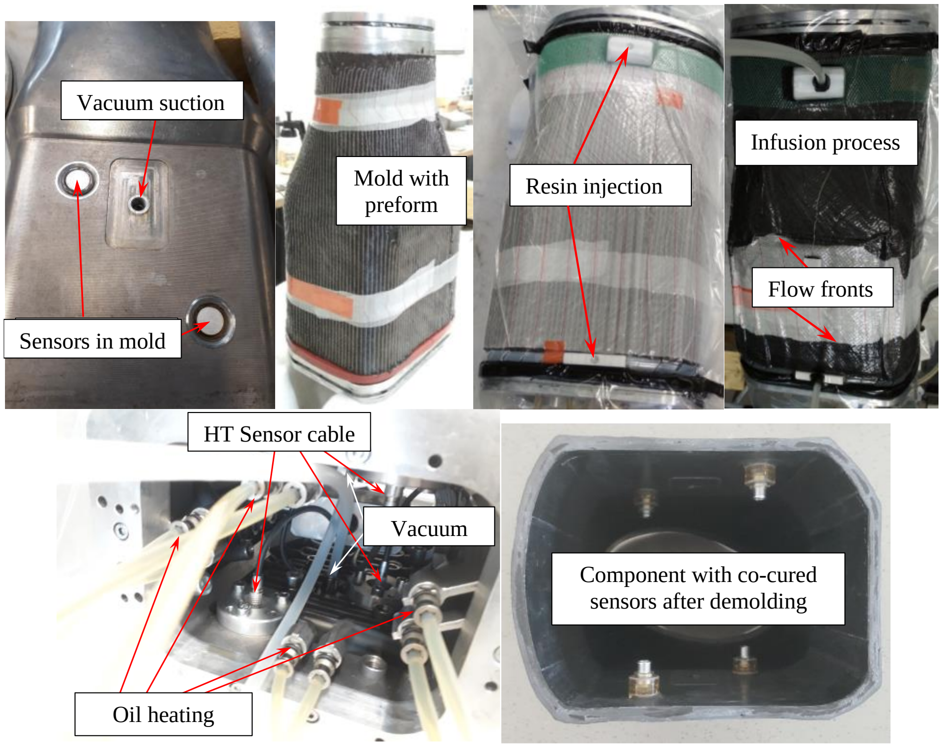

Figure 4. Steps in the production of the component – Sensor placement, preform placement, vacuum bagging, infusion, curing and demolding

to 70°C (orange) leads to a decrease of the 1st major radial resonance frequency from 132 kHz to 127 kHz. More details about the effect of temperature on the sensor were given in [9]. Due to the interaction of the flowing resin with sensor 3 the resonance frequency at 127 kHz was shifted about 15 kHz towards 142 kHz (orange doted). A further increase of the temperature for curing to 95°C reduces the resonance frequency to 138 kHz. Similar to the interaction with flowing resin the curing of the resin led to a rise of the 1st resonance frequency from around 138 kHz to around 152 kHz. In order to illustrate the transient behavior during the whole production step, the peak frequency of the 1st resonance was extracted out of the admittance data. One can clearly observe the drop of the 1st resonance frequency during heating to 70°C

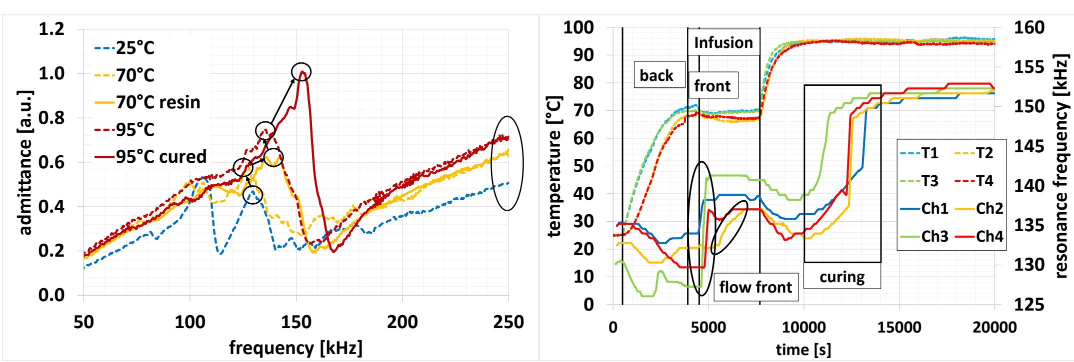

Figure 5. Development of the admittance around the 1st radial resonance of sensor 3 and the development of the temperatures and the 1st dominant resonance frequencies of all four sensors for the whole production process (sensors 1 and 2: front, sensors 3 and 4: back).

(till 4000 s). At this time the infusion was started from the thin oval part (back) and continued till the flow front reaches the thick portion of the part. Then the 2nd infusion from the thick edge (front) was started (time of 5000 s). Sensors 1,3 and 4 show a rapid increase in the 1st resonance frequency indicating the appearance of the flow front at the sensors. Sensor 2 shows a delayed and less steep increase in the 1st resonance frequency indicating a slower propagating flow front. In the curing period (time 10.000 to 14.000 s) all 4 sensors show a rise in the resonance frequency till approximately 152 kHz which indicates the fully cured state after around 1 hour and 6 min. It can be seen, that the curing was not homogenous shown by 1st rise in resonance frequency of sensor 3 at around 11.000 s followed by sensors 2 and 4 at 12.300s and sensor 4 at 13.000 s. The measured curing time is in line with the recommendations from the resin supplier to use a curing cycle of 2 hours. In summary it can be concluded that the measurement of the change of the 1st major radial resonance frequency of the developed sensor over time is very well suited to trace the position of the flow front during infiltration and the degree of cure during curing of the part.

Structural Health Monitoring

After the production and demolding of the part all four sensors were successfully co-cured on the surface (see figure 4). In the following chapters the usability of the co-cured sensors for actuation and reception of guided ultrasonic waves as well as detection and localization of simulated defects by acoustic emission were discussed. For comparison and damage simulation four additional single smart layer sensors from Accelent were glued on the opposite side of the part at the position of the co-cured piezo-temperature sensors.

GUIDED WAVES

Figure 6 top left shows the position of the sensors in unwind view of the thick part of the component spanning around 1.5 times the circumference to illustrate all shortest distance of each sensor pair. Each co-cured sensor was actuated with a 3-sin burst signal of 35V between 30 kHz and 200 kHz and the response of all other sensors, including the additional smart layer sensors were captured. The response of the co-cured sensor is similar to the smart layer sensor, where to amplitude of the co-cured sensor is higher. Such behavior is expected as the piezo of the co-cured sensor is larger. One can clearly see the faster propagating symmetric mode followed by the asymmetric mode (see top left of figure 6). For each actuator - sensor combination the propagation velocity of the quickest symmetric mode was measured (bottom left of figure 8 for actuator 1) and evaluated against the propagation angle relative to the circumference of the part. Due to the anisotropic stiffness of the part, the propagation velocity strongly varies with the propagation direction. As approximation the wave front was assumed to be an ellipse with the fastest and lowest velocity of 8000 m/s and 3500 m/s respectively, best fitting the measured results (bottom right of figure 6).

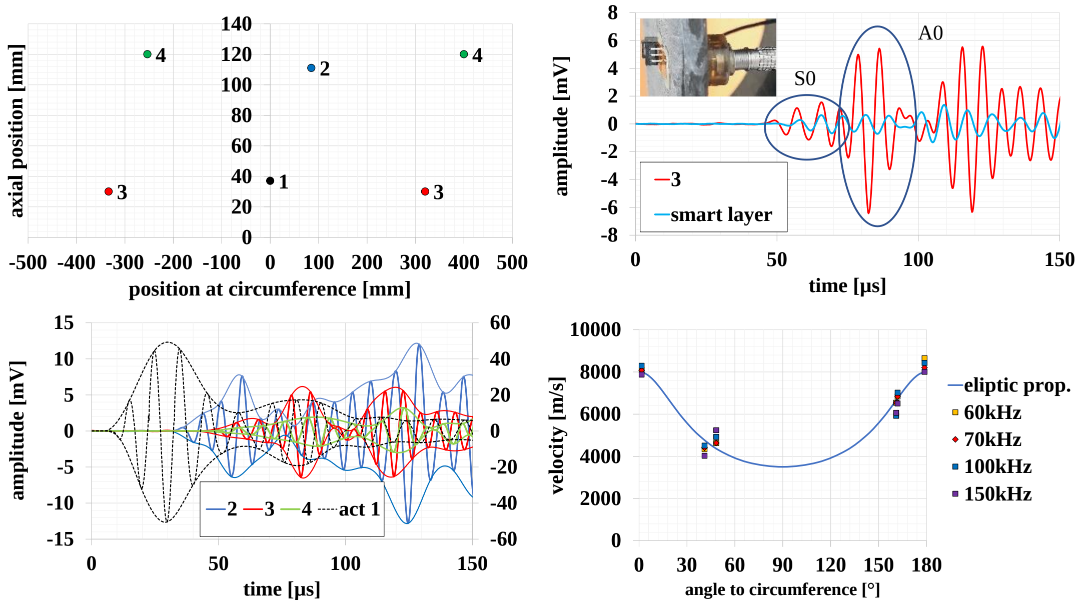

Figure 6. Position of the sensors (top, left), the response of sensor 3 and the smart layer sensor due to actuation of sensor 1 (top right), the response of sensor 2, 3 and 4 due to actuation of sensor 1 (bottom left) and the propagation velocity of the fastest mode as function of the propagation direction (bottom right).

ACOUSTIC EMISSION

To prove the ability of the co-cured sensors for detection and localization of AE events two different types of AE events were introduced: 3-sin bursts between 30 and 200 kHz introduced by the smart layer sensors (position of the co-cured sensors) and pencil breaks between the co-cured sensors. Event localization was done by a standard cylindric localization algorithm, where the arrival time was determined by 1st threshold crossing. In order to be able to account for the elliptic wave front the dimension in y-axis were increased by a factor of 8000/3500 (ratio of the maximum to minimum propagation velocity). All 3-sin burst signals with frequencies higher than 90 kHz can be localized (left side of figure 7: green dots smart layer above sensor 1, red dots: sensor 2 and yellow dots: sensor 3). At lower frequencies the amplitude of the quicker symmetric mode was below the threshold for at least one of the sensors leading to wrong localization values. All pencil lead breaks can be located (right side of figure 7: green dots: between sensor 1-2, red dots between sensor 2-3, yellow dots between sensor 3-4 and blue dots between 1-4).

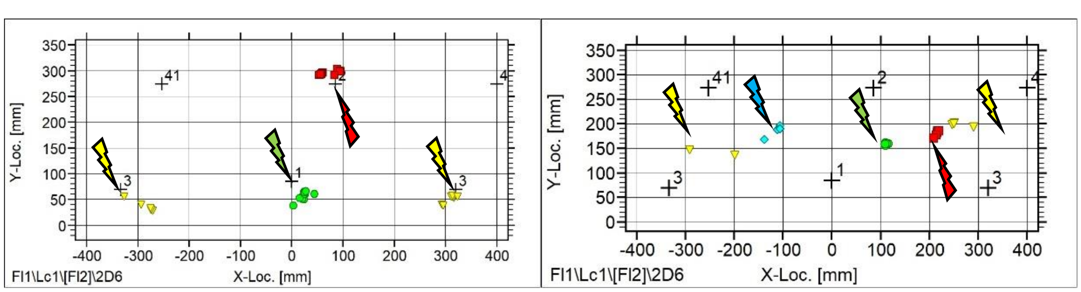

Figure 7. Location of simulated AE events: 3-sin bursts (left side), pencil breaks (right side)

CONCLUSION

A novel multifunctional piezo-temperature sensor to be used in an integrated process and structural health-monitoring concept for composite parts has been successfully validated on hollow composite part in a laboratory environment. The developed transducers were very well suited to monitor the different production steps during resin infusion and curing – flow front propagation and resin curing by tracking the change of the 1st resonance frequency of the piezo sensor. The integrated Pt 100 sensor was very well suited as temperature dependent shunt resistor for impedance-based process and cure monitoring.

After the production all transducers were co-cured to the part demonstrating the ability of the developed transducers to be used in infusion production processes. The co-cured transducers were very well suited to be used as actuators and/or sensors of an active guided wave or passive acoustic emission based SHM system. Simulated impact defects can be detected and located by acoustic emission using the information of the guided wave propagation properties.

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REFERENCES

1. A. Aktas, S.W. Boyd, R.A. Shenoi, “MONITORING AND SIMULATION OF THE VACUUM INFUSION PROCESS”, Proc. of the 19th ICCM (2013), pp. 4913
2. I. Partridge and G. Maistros, ‘Dielectric Cure Monitoring for Process Control’, Chapter 17, Vol. 5, Encyclopaedia of Composite Materials (2001), Elsevier Science, London, page 413
3. N. Liebers, D. Stefaniak, M. Kleineberg, M. Wiedemann, „Sensor guided cure processes – a study of productivity and quality optimization potential”, Proc. of the 19th ICCM (2013), pp. 2321
4. V. Giurgiutiu “Structural Health Monitoring with Piezoelectric waver active sensors”. Academic Press, 2008
5. C. Boller, F-K. Chang, Y. Fujino “Encyclopedia of Structural Health Monitoring”. John Wiley & Sons Ltd., 2009
6. M. Scheerer, A. Peldszus, M. Stadtschnitzer, R. Wagner “Modern Acoustic NDT Methods for the off- and online Detection of Damages in Composite Aeronautic Structures”. Proc. 3rd IALCCE, Vienna, Austria, pp. 1430–1437, 2012
7. M. Scheerer, Z. Simon, M. Marischler, T. Roser, B. Rittenschober, „Validation testing of an integrated process and structural health monitoring system based on piezoelectric sensors on a PAX door edgemember made by RTM”, Proc. of the 8th. EWSHM, 05.-08.07.2016, Bilboa, Spain
8. M. Scheerer, Z. Simon, M. Marischler, B. Rittenschober, „Validation of a multifunctional hybrid piezo / temperature sensor for process and structural health monitoring of CFRP structures”, Proc. of the 9th EWSHM, 10.-13.07.2018, Manchester, UK.
9. M. Scheerer, Z. Simon, M. Marischler, B. Rittenschober, „Influence of Production and Environmental Parameters on the behavior of hybrid Piezo / Temperature Sensors for Production and Structural Health Monitoring of Composite Structures”, Proc. of the 12th IWSHM, 10.-12.09.2019, Stanford, USA.
10. B. Xu, V. Giurgiutiu, “A Low-Cost and Field Portable Electromechanical (E/M) Impedance Analyzer for Active Structural Health Monitoring”, Proc. of the 5th. IWSHM, Sept. 15.-17.09.2005, Stanford, USA