

A hybrid Piezo / Temperature Sensor for Production and Structural Health Monitoring of Composite Structures - development and lessons learned

Michael Scheerer, Zoltan Simon, Michael Marischler, Bernhard Rittenschober

Abstract. Within this paper, the authors present an overview of the different development steps of a hybrid piezo / temperature sensor and lessons learned out of validation of the sensor performance during production of the composite parts by resin transfer moulding and the detection of defects during usage. For production monitoring the change of the electro-mechanical impedance of the piezo during resin infusion and curing was taken as measure for the flow front arrival and indication of the degree of cure. The ability of the co-cured sensors for damage detection and localization either by Acoustic Emission or ultrasonic guided waves was assessed on different relevant composite parts.

Key words: Structural Health Monitoring, Piezo, EM impedance, Acoustic Emission, Guided Waves, Composites, Process monitoring.

1 INTRODUCTION

To bring the advantages of fibre 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 must replace the widespread manual production. Depending on the part to be manufactured, infusion methods like Resin Transfer Moulding (RTM) are such automated production techniques. The most important steps in the production of complex composite parts by resin infusion are to reach a full impregnation of the dry pre-form and to guarantee a full curing of the resin in the form. Therefore, the control of process parameters like flow front propagation and determination of the degree of cure are important to produce high-quality parts. Currently process monitoring in RTM processes are done by temperature sensors, pressure sensors, dielectric sensors or conventional ultrasonic sensors for the monitoring of the flow front and the determination of the degree of cure which

Michael Scheerer & Zoltan Simon & Michael Marischler
Mechanical Testing, Simulation and NDT Group, Aerospace & Advanced Composites GmbH Wiener Neustadt, Austria,
e-mail: michael.scheerer@aac-research.at

Bernhard Rittenschober
Research & Development, ALPEX Technologies GmbH, Mils, Austria
e-mail: bernhard.rittenschober@alpex-tec.com

are mostly integrated directly in the mould [1, 2, 3]. To be able to monitor the structural integrity during use (Structural Health Monitoring - SHM), further types of sensors such as piezo sensors, which are mainly glued to surface of the structure are under investigation [4, 5, 6]. Fibre optic sensors such as fibre Bragg grating sensors were used for process monitoring. These sensors will remain in the part and can be used for structural health monitoring [7]. A critical aspect is the ingress / egress point from the part and the connection of the fibre optic sensors.

Within the last years the authors developed a novel hybrid multi-functional piezo / temperature sensor concept for flow front, cure and SHM 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 were validated on different composite parts like flat plates, a passenger aircraft (PAX) door edge-member and a hollow composite aircraft part. [8, 9, 10, 11]. In the following chapters an overview of the different development steps of the sensor and lessons learned out of validation of the sensor performance.

2 OVERALL MONITORING CONCEPT

Figure 1 shows the overall process and structural health-monitoring concept. In the first step the piezo sensors are placed at pre-defined positions in the mould. Then the dry preform will be placed in the mould. During the production process (infusion and curing) the impedance spectra are measured over time and the change of the spectra – e.g. the 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 mould is cooled back to room temperature, the part together with the co-cured sensors will be de-moulded. The co-cured piezo transducers are then ready to be used as sensors and / or actuators of passive (Acoustic Emission - AE) and / or active (Guided Ultrasonic Waves) SHM system, where the temperature sensors are used to account for temperature effects.

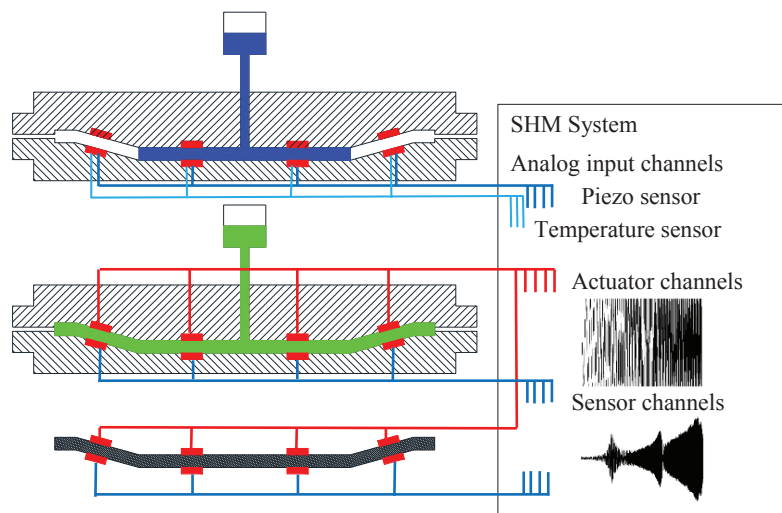


Figure 1: Illustration of the working principle of the integrated process and structural health monitoring system.

2.1 Sensor designs and hardware

The design of the sensor is mainly driven by the production process. The following aspects were considered: the sensor including connector and wiring must operate at temperatures up to 180°C (curing temperature of the resin), the mould with the mounted sensors must be vacuum tight (evacuation of the closed mould cavity prior to resin infusion) and the sensor must be robust to survive the demoulding process. Figure 2 shows the 1st and 2nd generation of sensors.

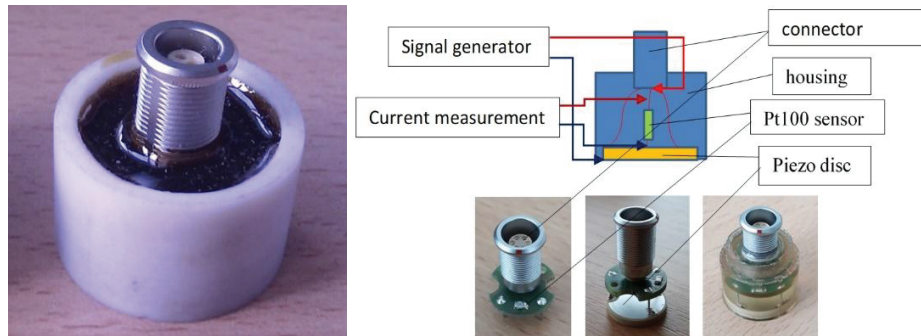


Figure 2: 1st generation - pure piezo (left) and 2nd generation piezo / temperature sensor (right)

The 1st generation sensor consists of a piezo disc of 15 mm diameter and 2 mm thickness with wrapped around electrodes connected to co-axial connector embedded in epoxy resin cylinder. The whole assembly is embedded in PTFE cylindrical ring, used to tighten the sensor in the RTM mould. The 1st generation sensor system requires two different data acquisition units for process monitoring (impedance analyser) and SHM (AE system with signal actuator card), where the measurement of the impedance spectra for cure monitoring using a conventional impedance analyser took rather long time leading to a low time resolution of the monitoring of the production process.

The concept of the 2nd generation sensor was inspired by the work of [12], where the impedance of a piezo sensor was determined out of the measured response of a resistor in series to the piezo sensor actuated by a frequency modulated chirp signal. The developed multi-functional sensor shown in figure 2 (right) consists of the same piezo disc as the 1st generation sensor. The upper electrode is connected to a Pt100 temperature sensor, used as shunt resistor, soldered to a 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). To measure the impedance of the piezo a signal generator is connected to the ground electrode of the piezo and the Pt100 temperature sensor. For actuation, a frequency swept chirp signal with a starting frequency of 0 kHz and end frequency of 600 kHz with flat frequency response [12] 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 figure 3).

For data collection a LCR meter type 7600 from Quadtech for the measurement of the electrical impedance of the sensors during curing (only in case of 1st generation sensors) and a combined active/passive SHM system consisting of two 4 channel acoustic emission cards (type

PCI-DISP-4 from PAC), one switchable arbitrary waveform generator card (type: ARB-1410 from PAC) for the actuation of burst signals in up to 4 actuators was used.

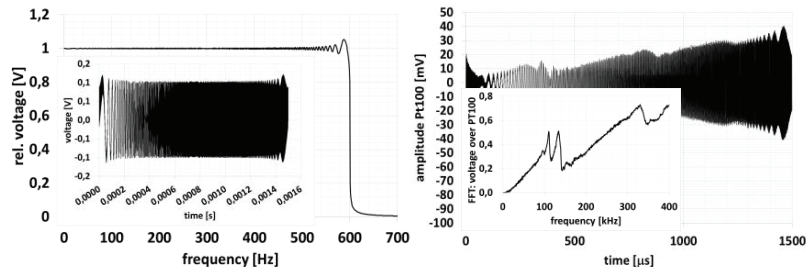


Figure 3: Actuation signal with FFT of the actuation signal (left side) and typical measured voltage signal and FFT of the voltage signal over the Pt100 sensor.

The comparison of both measurement methods – classical via impedance analyser and by chirp actuation – for a typical soldered piezo-pt100 assembly and a sensor shown in figure 2 are in very good agreement.

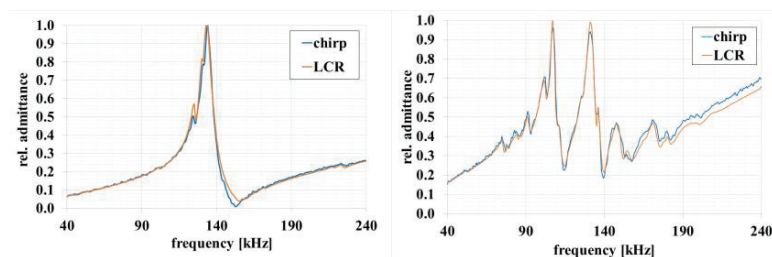


Figure 4: Comparison between both measurement methods for a typical soldered piezo-pt100 assembly (left) and a sensor (right)

3 INVESTIGATED COMPOSITE PARTS

For the validation of the sensor performance for process and structural health monitoring three different composite parts shown in figure 5 were selected: a pax door edge-member with integrated 1st generation pure piezo sensors, a flat composite plate and a hollow composite aircraft part with integrated 2nd generation piezo / temperature sensors.

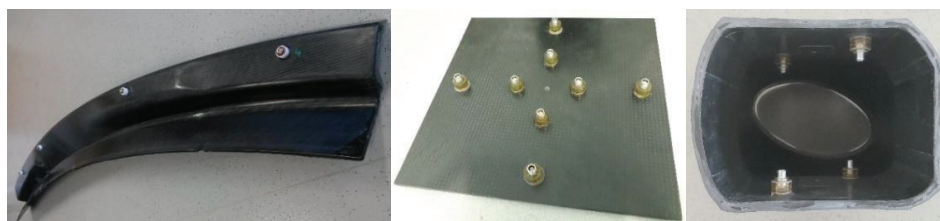


Figure 5: Composite parts for sensor validation: pax door edge-member with integrated 1st generation piezo sensors, flat plate and hollow aircraft part with integrated 2nd generation piezo / temperature sensors.

4 VALIDATION OF 1ST GEN. SENSOR ON A PAX DOOR EDGEMEMBER

4.1 Production process

Resin infusion of the preform was done in a temperature-controlled mould placed inside a press with an injection facility from Tartler at a maximum injection pressure of 5 bar and a constant temperature of 55°C. The following production steps were performed: placement of 4 piezo sensors in mould, placement of the preform in mould, closing of mould and heat up to 55°C, connection of the injection facility and heat up of the resin to 55°C, evacuation of mould, resin injection, closure of vents and inlet point and curing at 85°C for 8 hours with online cure monitoring, cooling of the mould and demoulding of the part.

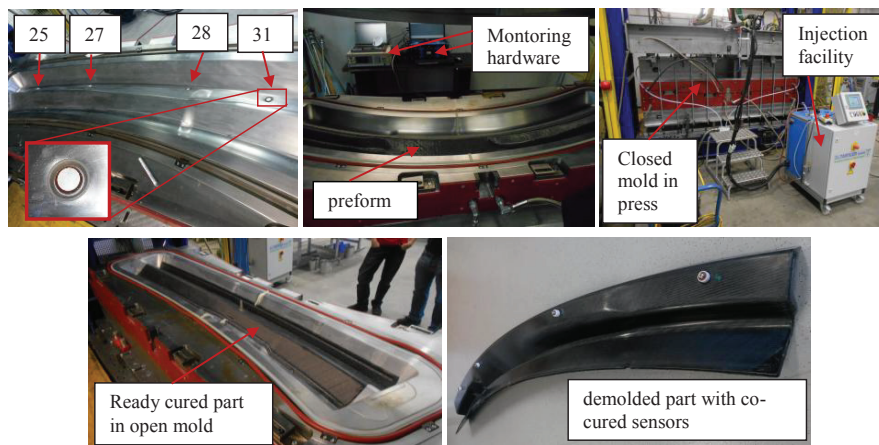


Figure 6: Production steps: sensors (25, 27, 28, 31) mounted in mould, preform in mould (measurement equipment connected), closed mould with infusion facility, open mould with part, part with co-cured sensors

4.2 Cure Monitoring

Once the infusion has been finalized the mould was heated to 85°C and the impedance spectra of sensor 31 were measured in a frequency range between 140 kHz and 200 kHz every 90s. Figure 7 shows the change of the impedance spectra and change of the impedance at 1st anti-resonance frequency and change of the anti-resonance frequency during curing.

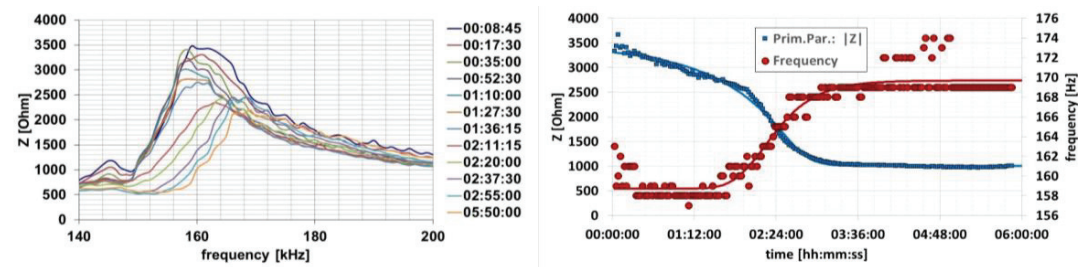


Figure 7: Change of the impedance spectra and the change of the impedance at anti-resonance frequency and the change of the anti-resonance frequency during the time of curing measured by sensor 31

Figure 7 clearly illustrates the change in the impedance spectra around the first radial anti-resonance frequency. Totally the impedance at first radial anti-resonance frequency change from 3.5 k Ω to around 1 k Ω during curing and the anti-resonance frequency change from 158 kHz to around 170 kHz. In addition, once curing has been finished both parameters are stable over time indicating the finalization of the curing process.

4.3 Wave propagation

For validation of the co-cured transducers for SHM each transducer was used as actuator and sensor. For actuation 3-sin burst signals at centre frequencies between 20 kHz and 300 kHz were used. Prior to the measurement of the wave propagation the group velocities of the different guided wave modes were calculated using the software DISPERSE. Figure 8 shows the calculated group velocities and the measured response of sensors 25, 27 and 28 due to the actuation of transducer 31 at 40 and 80 kHz.

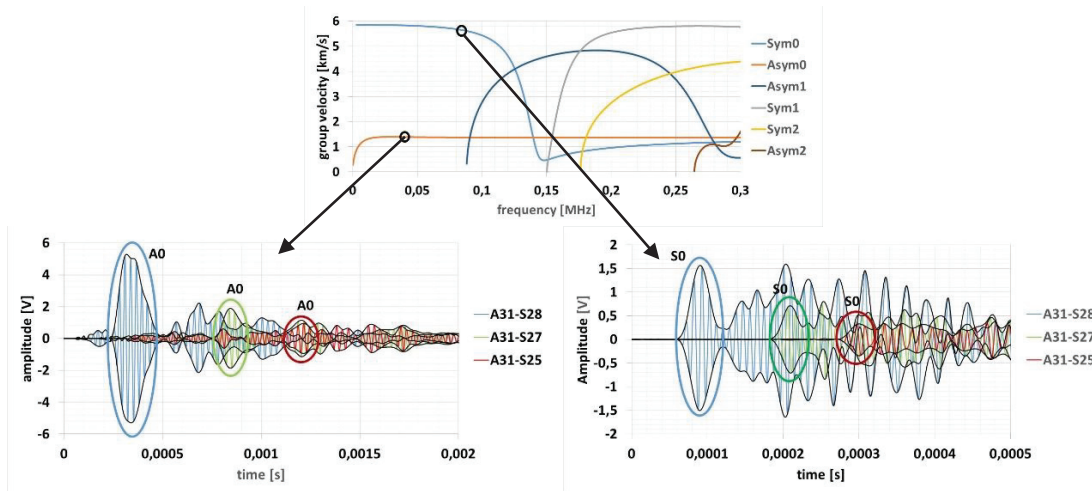


Figure 8: Calculated group velocities (top) and the measured response of sensors 25, 27 and 28 due to the actuation of transducer 31 at 40 kHz (bottom left) and 80 kHz (bottom right).

Only the S0 and the A0 mode is present below the cut of frequency of 85 kHz. At 40 kHz the A0 mode and at 80 kHz the S0 mode is dominant. The measured arrival times for the S0 mode at all sensors correspond well with the predictions made with DISPERSE (5670 m/s for the S0 mode at 80 kHz), where the measured group velocity for the A0 mode of 1250 m/s is somewhat lower compared to the calculations (1400 m/s).

5 VALIDATION OF 2ND GEN. SENSOR BEHAVIOUR ON A FLAT PLATE

For validation of the 2nd generation sensor a composite plate of 350 x 350 mm² with 9 layers of non-crimp fabric (NCF) with a quasi-isotropic fibre architecture [0/90/45/-45]_s and a total thickness of 7.8 mm was produced. Eight piezo-temperature sensors were placed in the lower part of the mould as shown in figure 9 (left side). Sensors labelled T1 to T4 show the position

of the sensors used for temperature monitoring and sensors labelled Ch1 to Ch4 show the position of the sensors used for flow front and cure monitoring by the measurement of the admittance during production. Prior to the production of the plate an infiltration simulation was performed with the Finite Element (FE) software PAM-RTM to determine the infiltration time (middle of figure 9) and the expected arrival time at the sensor locations Ch1 to Ch4 of the flow front during infiltration.

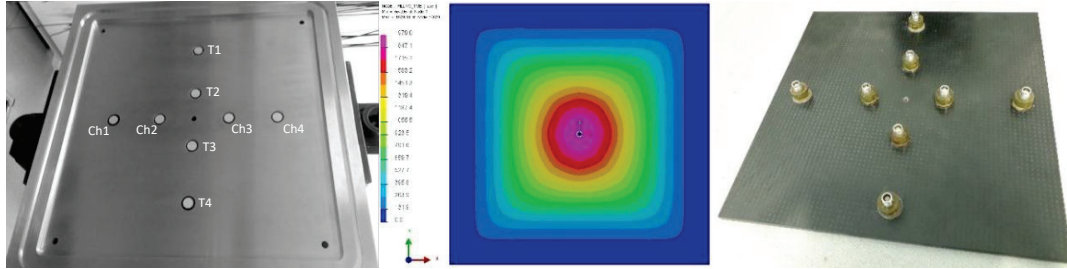


Figure 9: Left side: lower part of the production mould with the mounted sensors for temperature (T1 – T4) middle: flow front and cure monitoring (Ch1 – Ch4) during production and right side infiltration time out of the PAM RTM Simulation.

5.1 Process Monitoring

During the production of the plate the propagation of the flow front and the degree of cure after successful impregnation of the dry preform were determined. The temperatures on 4 positions (T1-T4) and the admittance of the sensors on 4 further positions (Ch1 – Ch4) were measured with a sample rate of 1 Hz. To illustrate the transient behaviour during the whole production step, the peak frequency of the 1st resonance was extracted out of the admittance data. The evolution of the temperatures (T1 – T4) and the peak frequencies of the 4 other sensors (Ch1 – Ch2) are shown in figure 10.

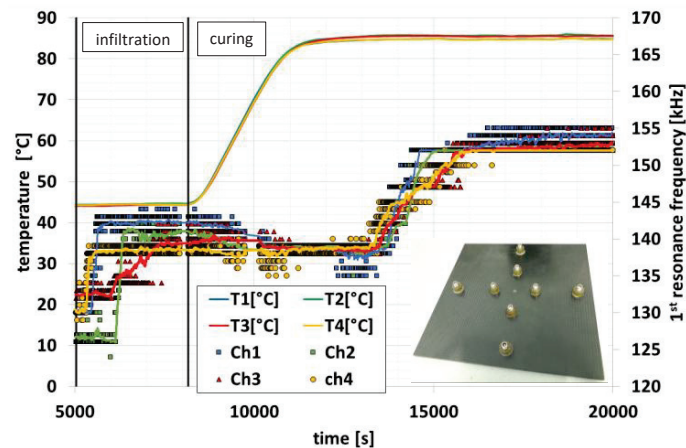


Figure 10: Evolution of the temperatures (T1 – T4) and the peak frequencies of the 4 other sensors (Ch1 – Ch2).

The left part in figure 10 (between 5000 s and 8000 s) shows the period of infiltration and the remaining part (above 8000 s) show the period of curing. The temperature signals indicate a very homogeneous temperature distribution during the whole process. During infusion the steep increases of the frequency for different times of the sensors indicating the different arrival times of the flow front – first for the outermost sensors Ch1 and Ch4 followed by the inner sensors Ch3 and Ch2. During curing all 4 sensors show an increase of the resonance frequency indicating the starting of cure at around 13200 s (1 hour and 23 min after the start of the curing cycle). A stable resonance frequency was reached after around 2 hours and 15 min indicating the completion of the curing step. As the transient behaviour for all 4 distributed sensors are similar, a homogenous curing of the part can be assumed. The measurement of the change of the 1st 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.

5.2 Guided Waves

For guided wave actuation 3-sine burst signals with centre frequencies of 40 kHz and 80 kHz were used to assess the suitability of the developed sensor for the detection of simulated defects under variable temperature conditions. Artificial damages in shape of added mass (weight of 170g / diameter of 25 mm) were placed on several positions on the plate. The baseline of the plate was measured at different temperatures ranging from 22°C to 60°C. For the measurement of the ultrasonic response each co-cured transducer was used as actuator and sensor leading to 8 x 7 matrix of actuator - sensor combinations. Figure 11 shows the measured response of sensor Ch4 due to the actuation of sensor T1 at different temperatures and after the application of the simulated damage. In addition, the residuals between the different baselines and the damage and the best suited baseline is shown in the lower part of figure 11.

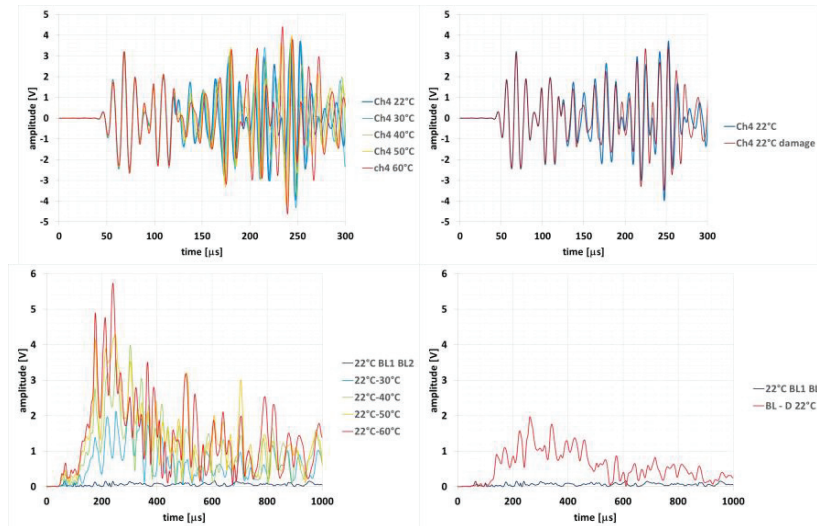


Figure 11: Measured response of sensor Ch4 due to actuation of sensor T1 at different temperatures and after the application of the simulated damage (top) and residuals between the different baselines and the damage and the best suited baseline (bottom).

Due to the change of temperature the signals were stretched in time – the higher the temperature the higher the stretching – indicating a change of group velocity. In addition, the amplitudes change due to a change of the damping in the material. In case of the simulated damage the signal position remains nearly unchanged, and the major change was observed in the amplitude caused by the absorption of the wave by the simulated damage. When the best baseline (baseline with the closest temperature to the damage measurement) was used, the damage could be clearly detected (much higher residuals compared to the residuals from two baselines at similar temperature – bottom left of figure 11). In case of a temperature difference of about 8°C the residuals between the two baselines already reach the same level as the residuals between the intact and damaged plate making it very difficult to discriminate between temperature effects or potential damages.

All raw data have been fed in near field sparse array beam forming algorithm described in more detail in [5]. Figure 12 show the colour coded images of the localized damages using this beam forming algorithm and the data of the 40 kHz (top) and 80 kHz (bottom) measurement assuming a group velocity of 1250 m/s of dominant A0 mode for beam forming using the best baseline (left). The middle and right part of figure 12 show results when a baseline is taken at 30°C with and without temperature compensation by frequency shift algorithms [12].

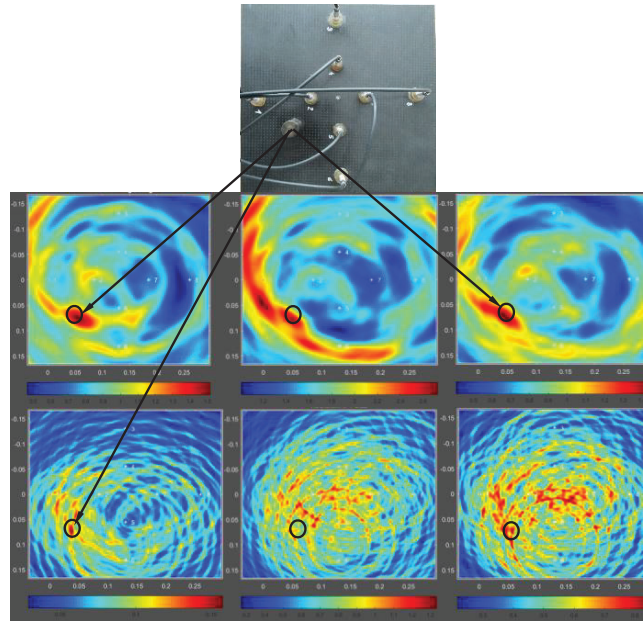


Figure 12: Colour coded images of the localized damages using a sparse array beam forming algorithm, top: 40kHz, best baseline (left), baseline @ 30°C (middle), temperature compensated baseline @ 30°C bottom: 80kHz, best baseline (left), baseline @ 30°C (middle), temperature compensated baseline @ 30°C.

The simulated damage could be detected and located (red coloured region) for both actuation frequencies at 40 kHz and 80 kHz when using the best baseline (left part of figure 12). In case the baseline was assessed at 30° it is still possible to locate the damage in case of 40 kHz, but

additional false positives appear. In case of 80 kHz actuation a clear damage detection and location is not possible (middle part of figure 12). When a temperature compensation algorithm based on a frequency shift [12] was applied it was possible to achieve nearly similar results for the case of 40 kHz using the best baseline. In case of 80 kHz actuation the results could be improved but the appearance of several false positives makes a clear damage detection and localization extremely difficult. Such observations are in line with previous works [12] where the effect of temperature on damage detection increase with the temperature difference and the actuation frequency indicating the importance of knowledge of the temperature during damage assessment.

6 2ND GENERATION SENSOR BEHAVIOUR ON A HOLLOW AIRCRAFT PART

Finally, the ability of the developed sensor for detection and localization of acoustic emission signals was assessed on the hollow aircraft part shown in figure 5.

6.1 Wave propagation

Figure 13 top left shows the position of the sensors in an unwind view of the quasi-cylindrical part of the component. Each sensor was actuated with a 3-sin burst signal between 30 kHz and 200 kHz and the response of all other sensors, including the additional used piezo active waver sensors of type smart layer from Acellent glued at the same positions on the opposite side of the part were captured. The response of the co-cured sensor is like the smart layer sensor, where to amplitude of the co-cured sensor is higher. One can clearly see the faster symmetric mode followed by the asymmetric mode (top left of figure 13). For each actuator - sensor combination the propagation velocity of the quickest symmetric mode was measured (bottom left of figure 13 for e.g. 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.

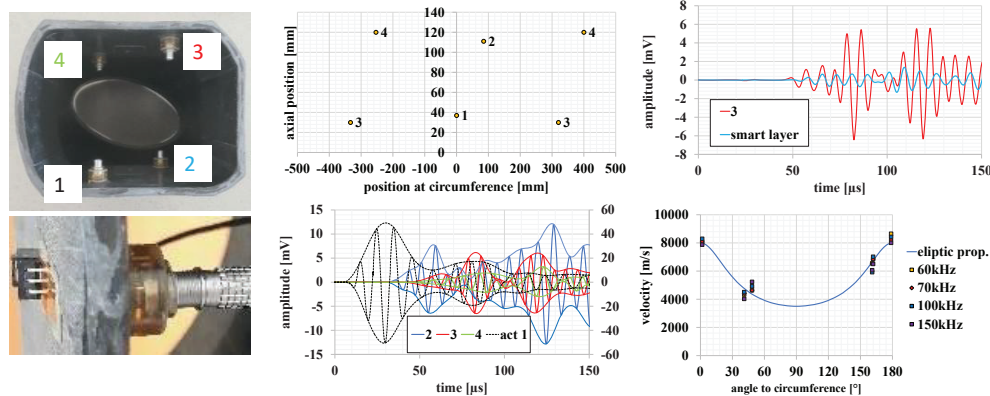


Figure 13: Position of the sensors (top, left), the response of sensor 3 and the smart layer sensor due to actuation of sensor 1 (top right), the response of sensor 2, 3 and 4 due to actuation of sensor 1 (bottom left) and the propagation velocity of the fastest mode as function of the propagation direction (bottom right)

6.3 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 algorithm, where the arrival time was determined by 1st threshold crossing. To be able to account for the elliptic wave front the dimensions in y-axis were increased by a factor of 8000/3500. All 3-sin burst signals with frequencies higher than 90 kHz can be localized (left side of figure 14: 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 (Hsu Nielson source) can be located (right side of figure 3: green dots: between sensor 1-2, red dots between sensor 2-3, yellow dots between sensor 3-4 and blue dots between 1-4).

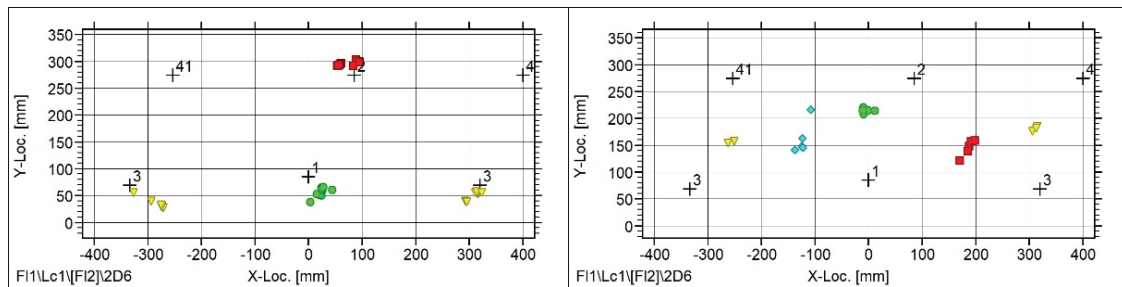


Figure 14: Location of simulated AE events: 3-sin bursts (left side), pencil breaks (right side)

7 CONCLUSIONS

A novel multifunctional piezo-temperature sensor to be used in an integrated process and structural health-monitoring concept for composite parts made by resin transfer moulding has been successfully validated on different composite parts 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 defects can be detected and located by passive acoustic emission and guided waves using the information of the guided wave propagation properties and the temperature information of the Pt100 sensor for temperature compensation.

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