FOS3D-AAC-D-1.1_4

FOS3D

Final Report

Contract no: 271853

FOS3D
D-1.1_4 – Management Report 4

Prepared by: **AAC**

Document control data			
Deliverable No. :	D 1.1_4	Document Code:	FOS3D-AAC-WP1-D 1.1_4
Version:	Issue 1		
Date of issue:	28-02-2014		
Author's name:	M. Scheerer	Signature:	
Task Leader's name:		Signature:	approved
WP Leader's name:	M. Scheerer	Signature:	approved
Coordinator:	M.Scheerer	Signature:	approved
Release status:	Confidential		

SUMMARY

1 References

[1] Description of Work of the Grant Agreement 271853

2 Introduction

This report untitled “FOS3D – D-1.1_3- Final Report 4” is the official deliverable D 1.1_4 of the FOS3D project. AAC is in charge of this deliverable.

This report deals with WP 1 “Management”.

Diagram locating of the deliverable “Final Report” in the FOS3D project:

	FOS3D Project (Fibre Optic system for Deflection & Damage Detection)

WP 1	Management

This report deals with the summary of all results achieved during the developing and testing of the FOS3D system for simultaneous deflection and damage detection with several multiplexed fiber optic sensors.

Partners involved in WP 1 “Management:

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3 Executive Summary

The aim of the project FOS3D was the development of a novel NDT for on-line monitoring of deflection and structural integrity of composite wings with an increased confidence degree in failure size and location detection. The main goal is to provide the information about the deflection value to the piezo-electric/shape memory alloy actuators in order to close the loop of a control system. Simultaneously, the proposed technique has to provide the information to the control system about the damage events, location and size by means of the technique of acoustic emission.
In a first a step the requirements include the geometry of the coupons and subcomponents to be tested, maximum and minimum deflection to be measured, type size and location accuracy for the damages to be detected and type of tests to be performed on the coupons and subcomponents have been defined. A typical wing shape for the trailing edge of morphing wing has been modeling to assess the response of the morphing wing due to actuation by piezo-electric foils. Out of the analysis the strain range and resolution for a morphing wing has been derived. In addition three different geometries – thin CFRP plate, a flat honeycomb panel (coupon), and a honeycomb panel with triangular cross section (subcomponent) – have been analyzed to evaluate the deflection behavior of the components simulating the behavior of morphing wings. The strain distribution on the upper and lower face sheet have been calculated along the fiber optic sensor and fed in an optical model to derive the optical phase change. Different shapes of fiber optic sensors – cylindrical shapes and elliptical shapes of different diameter and aspect ratios – have been analyzed regarding their measurement range and resolution. The results out of the FE analyses and measurement of the wave propagation properties of ultrasonic wave generated by a simulated Acoustic Emission event are used to assess the effect of sensor shape, orientation and placement on the range and resolution of the whole system leading to best suited sensor shapes and positions on the subcomponent. A CFRP panel of 2 mm in thickness analyzed before has been equipped with a fiber optic sensor of best suited geometry and the behavior of this sensor under combined deflection loads and simulated acoustic emission events has been measured. Different configurations of the light source – standard SLD and combined SLD with a laser diode – have been investigated. These first tests have proven the predictions from the analyses regarding the range for deformation measurement. In addition it could be demonstrated that the proposed fiber optic coil sensors are able to measure signals from deflection and from simulated acoustic emission events at the same time with the required resolution. For final verification testing a flat honeycomb panel of 200 x 400 mm² (coupon) and a honeycomb panel with triangular cross section of 400 x 400 mm² (subcomponent) has been purchased and the required fixation for the verification tests of both components was manufactured. In addition the required optoelectronic unit that converts the optical output from up to 4 individual fiber optic sensors in electric signals as input for the used conventional Acoustic Emission system was designed and manufactured. The damage detection part of the FOS3D system was tested on the coupon and the subcomponent, were impacts with different impact energies leading to non-damaging and damaging impacts were applied. Although the probability of detection of the non-damaging impacts is much better for the conventional AE system, all damaging impacts can be detected and located with an average localization error of around 25 mm on the coupons and with an average localization error of around 15 mm using the developed algorithms for damage detection, localization and quantification on subcomponents demonstrating the proper function of the damaging part of the FOS3D system regarding the detection of damaging impacts. The deflection monitoring part of the FOS3D system was tested on the coupon and the subcomponent were deflections of different amount were applied to the coupon and subcomponent and the response of the FO sensors was measured. When applying the best suited algorithm for processing of raw interference signals - Arcus tangent algorithm – all 4 FO sensors show very good linearity in the entire deflection range, from

zero to 20mm that corresponds with experimentally reached maximum local deflection angle of about 3°. Out of these data and initial requirements it was proved that FOS3D system can fulfill these requirements since minimum detectable phase angle signal reached in this investigation is of about 120mrad.
Finally, the main goal of the project was successfully proved by experimentally verification of capability of the FOS3D system for simultaneous deflection measurement and damage detection.

4 Project context and the main objectives

Within the 1st reporting period task 2.1: Definition of Requirements & Concept Setup of WP 2: Development of Monitoring Concept was planned to be done.

Within the EC Clean Sky - Smart Fixed Wing Aircraft initiative concepts for actuating morphing wing structures are under development. In order for developing a complete integrated system including the actuation, the structure to be actuated and the closed loop control unit a hybrid deflection and damage monitoring system is required.
The aim of the proposed project "FOS3D" is to develop and validate a fiber optic sensing system based on low-coherence interferometry for simultaneous deflection and damage monitoring. The proposed system uses several distributed and multiplexed fiber optic Michelson interferometers to monitor the strain distribution over the actuated part. In addition the same sensor principle will be used to acquire and locate the acoustic emission signals originated from the onset and growth of defects like impact damages, cracks and delaminations.

At the beginning of the project the requirements including the definition of the structure and used materials, values for the deflection and type, location and severity of damages for the FOS3D system will be defined. The aim of **WP2** is the analyses, design and experimental prove of concept of the FOS3D system. In order to limit the risk an Intermediate Monitoring Concept Review will be held in the middle of WP2.

The objectives of WP 2 are:

- Definition of the requirements regarding the deflection measurement and damage detection together with Delft University of Technology (DUT – previous topic leader) and Fraunhofer ENAS (new topic leader)
- Layout of the deflection and damage detection concept
- Modeling of the sensor response due to the actuation
- Placement of the sensors to achieve an optimized accuracy for the determination of the deflection and at the same time allow damage localization by triangulation
- Testing of the sensor performance on flat plates subjected to mechanical loads and damages defined in task 2.1

Task 2.1 Definition of Requirements & Concept Setup
Task 2.1 will be performed in close cooperation with DUT / Fraunhofer ENAS. In this task the necessary requirements for the design of the FOS3D system like maximum and minimum deflection, deflection resolution, type, and severity and localization accuracy of the most critical damages will be defined. In addition the structure to be monitored will be defined: that includes material (fibers and matrices), lay up design and geometry of the coupons and subcomponents.
In particular **IMA** will consider different fiber-optic sensing configurations in order to meet technical requirements that both partners and DUT will define. Additionally IMA will take part in definition of sensing system as a whole bearing in mind its twofold role: deflection and damage detection. Since these two tasks are located in different frequency range, the first one belongs to low-frequency while second to high-frequency, IMA will paid

attention how to design optoelectronic circuit in the receiving unit to be able to effectively collect the data.
In particular **AAC** will give its inputs regarding the damage detection, localization and quantification abilities of standard Acoustic Emission systems using standard AE sensors and PZT tapes.

Within the 2nd reporting period WP 2 was planned to be done.

Within the EC Clean Sky - Smart Fixed Wing Aircraft initiative concepts for actuating morphing wing structures are under development. In order for developing a complete integrated system including the actuation, the structure to be actuated and the closed loop control unit a hybrid deflection and damage monitoring system is required.
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At the beginning of the project the requirements including the definition of the structure and used materials, values for the deflection and type, location and severity of damages for the FOS3D system will be defined. The aim of **WP2** is the analyses, design and experimental prove of concept of the FOS3D system. In order to limit the risk an Intermediate Monitoring Concept Review will be held in the middle of WP2.

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- Placement of the sensors to achieve an optimized accuracy for the determination of the deflection and at the same time allow damage localization by triangulation
- Testing of the sensor performance on flat plates subjected to mechanical loads and damages defined in task 2.1

Task 2.1 Definition of Requirements & Concept Setup
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In particular **AAC** will give its inputs regarding the damage detection, localization and quantification abilities of standard Acoustic Emission systems using standard AE sensors and PZT tapes.

Task 2.2 Modeling of Sensor response

In this task IMA and AAC will develop a model for simulation of interaction between the sensor and structure. For modeling the response of the structure due to actuation a two-step approach is used. In a first step a 3D FE model of the coupons and the subcomponents using the materials and lay up defined in talks 2.1 will be built by AAC. These models will be subjected to different deformations to establish a correlation between local strains to be measured by the FOS3D system and the deflection of the coupons and the substructure. These correlations serve as input for task 5.2. 3D models will be built in ANSYS Multiphysics in order to be able to include the actual piezoelectric actuator in the analyses. Pre & Post processing of the composite structures will be performed by ANSYS Composite PrePost (ACP). In a second step the strain distribution in the area of the fiber optic sensors will be used as input for the optical model to be developed by IMA. The model will ensure calculation of optical path difference generated in sensing coil in dependence on intensity and nature of an external perturbation. For example, relatively low speed action (quasi-DC change) of PZT or SMA actuator will cause a sensor response that will differ a lot from the high speed AC excitation originated from a damage possibly occurred in this operation.

Task 2.3 Sensor placement and resolution

Results from the previous task will be used for determination of most critical points over the wing. According to this IMA and AAC will define the arrangement, shape and number of necessary sensors. In this way will be defined the spatial resolution of the whole sensing system.

Task 2.4 Sensor Performance testing

In this task IMA will manufacture and integrate an experimental set up using fiber-optic configuration previously described as a starting platform. This configuration will be entirely investigated on the optical table in regard of: type of low-coherence light source (pigtailed SLD, LED, bulb), coherence length, optical power budget, low-noise driver for light source (temperature and current stabilization), fiber-optic passive splitter, 3x3 fiber-optic coupler, sensor shape, size and number of turns (round, spiral, meander), type of photodiode, design of receiving block, bandwidth, type of adhesive, etc.,

Within the 3rd reporting period Task 3.1: “Testing of coupons with defined damages” and Task 3.2: “Testing of coupons under different mechanical loads” of WP 3: Testing of coupons, Task 4.1: “Testing of subcomponents with defined damages” and Task 4.2: “Testing of subcomponents under different mechanical loads” of WP 4: Testing of Subcomponents and Task 5.1: “Algorithm for damage detection & location” and Task 5.2: “Correlation between sensor output and deflection” of WP 5: Algorithm Development was planned to be done.

Within the EC Clean Sky - Smart Fixed Wing Aircraft initiative concepts for actuating morphing wing structures are under development. In order for developing a complete integrated system including the actuation, the structure to be actuated and the closed loop control unit a hybrid deflection and damage monitoring system is required.
The aim of the proposed project "FOS3D" is to develop and validate a fiber optic sensing system based on low-coherence interferometry for simultaneous deflection and damage monitoring. The proposed system uses several distributed and multiplexed fiber optic Michelson interferometers to monitor the strain distribution over the actuated part. In addition the same sensor principle will be used to acquire and locate the acoustic emission signals originated from the onset and growth of defects like impact damages, cracks and delaminations.

At the beginning of the project the requirements including the definition of the structure and used materials, values for the deflection and type, location and severity of damages for the FOS3D system will be defined. In **WP2** the analyses, design and experimental prove of concept of the FOS3D system has been successfully completed and both planned milestones: MS1: "Intermediate Monitoring Concept Review" and MS2: "Monitoring concept developed" has been successfully reached.

The objectives of WP 3 are:

- Validation of the developed sensor concept on coupons subjected to different deflections and deformations.

Task 3.1: Testing of coupons with defined damages
In this task IMA and AAC will test the already established sensing set up but now applied on a real composite plate. In particular IMA will prepare the top surface of the palate and then glue the fiber-optic coils by a structural adhesive in arrangement, shape, size and numbers in accordance of results in the previous work package.
After curing of adhesive the whole system will be tested by AAC. For online damage detection impacts of different incident impact energy leading to different delamination sizes will be introduced on different locations by an automated impact testing machine. The size of the damages will be determined by ultrasonic C-scan evaluation. In addition bending tests of already impacted specimen will be performed in order to apply the ARC Acoustic Emission on Demand Algorithm developed by AAC for damage localization and quantification.
The main focus in this investigation will be on detection of high-frequency acoustic signals that travels through the plate.
The FOS3D will be verified against a calibrated multichannel AE system from Physical Acoustics regarding passive damage detection.

Task 3.2: Testing of coupons under different mechanical loads
In this task IMA will test sensor response versus different mechanical loads similar with those that will occur in the wing flap structure after PZT or SMA actuation. Actually, in serial of experiments we have to find correlation between measured signals, i.e. calculated optical phase difference and magnitude of deflection of flap. Hence, the main focus in this test will be on measurement of low-frequency signals
The FOS3D will be verified against a calibrated deflection and strain measurement system from HBM regarding the low frequency strain measurements.

The objectives of WP 4 are:

- The objective of the WP 4 is the validation of the developed sensor concept on subcomponents subjected to different deflections and deformations.

Task 4.1: Testing of subcomponents with defined damages
In this task IMA and AAC will test the already validated sensing set up applied on a real composite subcomponent.
In this task IMA will participate in thoroughly investigation of every particular component of sensing system in order recognize capability of the system as whole and eventually to optimize some points. The most critical criteria will be if our system could "hear" the structure under stress and what would be the "threshold" in terms of damage size and location. Because of that we will systematically investigate sensor response in dependence on different location of the damage of the same size. In another testing campaign the location will be fixed bit the damage size will be increased. Again, the main challenge will be to catch the fast transient acoustical signals and to evaluate the shape

and amplitude of them and to calculate the time-of-flight (TOF) between the every sensor and damage.
The FOS3D will be verified against a calibrated multichannel AE system Physical Acoustics regarding passive damage detection.

Task 4.2: Testing of subcomponents under different mechanical loads
In this task IMA will overtake the main activities in characterization of every particular system component when the subjected plate is under load. The main goal will be to identify the main features of the system as a whole when a pseudo DC load produces deflection and what is resolution of the system in terms of the least resolvable deflection. In order to reach this goal we will systematically produce load of different intensity, rate, place, etc. From this investigation we will obtain data about overall dynamic range of the system as well as repeatability and reliability of the system.
The FOS3D will be verified against a calibrated deflection and strain measurement system from HBM regarding the low frequency strain measurements.

The objectives of WP 5 are:

- The objectives of WP 5 is the development of an algorithm that allow the detection, localization and quantification of damages based on the method of Acoustic Emission and a second algorithm that correlates the senor output signal with actual deflection of the morphing substructure.

Task 5.1: Algorithm for damage detection & location
In this task AAC will develop an algorithm for damage detection, localization and quantification using the concept of Acoustic Emission. Both online direct impact detection and Acoustic Emission on Demand by using the friction of the damage fronts will be used to quantify and locate the damage. As composite materials are used special care will be laid on the orthotropic and dispersive propagation nature of the acoustic wave in the triangulation algorithms for damage localization.

Task 5.2: Correlation between sensor output and deflection
In this task IMA will make a thoroughly analyses of different algorithms for signal processing of low-coherence interferometric data. After evaluation procedure based on SNR and processing speed one or two of them will be developed, e.g. “cross-multiplication-differentiation” and “arc tan” algorithms. The algorithms will be tested by simulation and then on the real signals. The main goal of the complete procedure is stabilization of raw interferometric signals and calculation of optical phase difference. The last data presents the useful signal that is in direct correlation local strain field at the location of the FO sensor. In task 2.2 a correlation between the deflection and the local strain fields at the locations of the different FO sensors have already been assessed. The inversion of this correlation will than result in a new correlation between the measured strain field around the different FO sensors and the produced deflection. Finally when including the relation between the optical phase difference and the strain field a direct correlation between the optical phase differences at the location of the different sensors and the produced deflection will be established and used as algorithm to calculate the deflection as function of the phase differences of the different FO sensors.

5 S & T results/foregrounds

Within Task 2.1: Definition of Requirements & Concept Setup of WP2: Development of Monitoring Concept, the necessary requirements for the definition of the FOS3D System has been defined in cooperation with the new topic leader Fraunhofer ENAS. The requirements include the geometry of the coupons and subcomponents, maximum and minimum deflection to be measured, type size and location accuracy for the damages to be detected and type of tests to be performed on the coupons and subcomponents.
A summary of the requirements is given in table 1.

Item	Parameter 1	Parameter 2	Requirement
Subcomponent	Overall size		400 x 400 mm²
	Cross section	Shape	triangle with reinforcements honeycomb and wedges at the end (available material)
		dimension	According to the dimensions of the sent wing shape: around 400 x 100 mm²
	Maximum deformation	Tangential angle at end point	5°
	Resolution of deformation measurement	Tangential angle at end point (tbd.)	0.1°
Coupons	Overall size		100 x 300 mm²
	Cross section	Damage detection	thin flat plate
		Deflection measurement	Sandwich panel with proper thickness
Material for coupons & Subcomponents	Material		CFRP (available material: face sheet of the A340 spoiler)
	Layup		-45/45/0/90/45/-45 (available face sheet material: A340 spoiler)
	Sandwich core		Nomex core (A340 spoiler)
Damages for coupons & Subcomponents	Type [1]		Delaminations caused by impacts
	Size to be detected [average value out of 1]		300 mm² (d ~ 20 mm)
	Error of localization [average value out of 1]		5% relative to the average sensor spacing (maximum 25 mm)

Table 1: Requirements for the system definition

These requirements have been used for the definition of the FOS3D system. Therefore a typical wing shape for the trailing edge of morphing wing has been delivered to the coordinator AAC by Fraunhofer ENAS for further analyses. Originally all this information are planned to be delivered by the original topic leader Delft University of Technology. As up to the end of the 1st reporting period no information about the morphing wing structure has been supplied to the consortium, it was agreed between the consortium and the new topic leader, that all required information for the definition of the system will be done based on modeling the response of the morphing wing due to actuation by piezo-electric foils up to the maximum deflection defined in table 1.

Within **Task 2.1**: Definition of Requirements & Concept Setup of WP2: Development of Monitoring Concept, the response of a morphing wing structure – supplied by Fraunhofer ENAS – due to the actuation by piezo-electric layers placed on the below the top and bottom face sheet has been modeled via a Finite element model. Figure 1 shows the deformed morphing wing for an applied voltage of 30 V leading to maximum deflection angle of 5° and deformation angle as function of the maximum strain difference between the upper and lower face sheet.

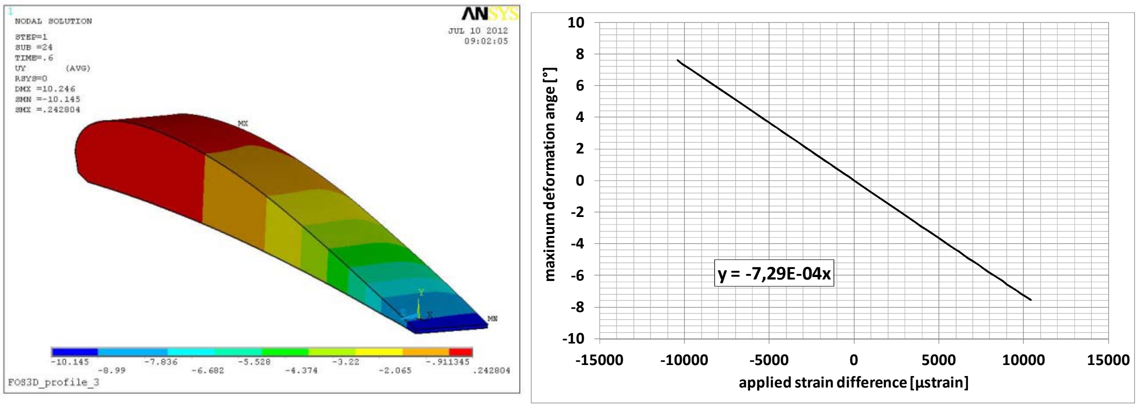

Figure 1: Deformed morphing wing for an applied voltage of 30 V leading to maximum deflection angle of 5° (left side), deformation angle as function of the maximum strain difference between the upper and lower face sheet (right side)

Out of the model the strain difference between the upper and lower face sheet of around 6800 µstrain leading to the required deformation angel of 5° was calculated and later on used as requirement for the definition of possible fiber optic sensor shapes in the modeling of the behavior of the coupons and subcomponents. Beside the analyses of the morphing wing, the concept of the acoustic emission on demand algorithm and direct impact detection was described. For the Concept set-up all required part of the fiber optic measurement unit including the Low coherence source, the photodiodes, the optical fibers used for the sensors and the 3x3 fiber-optic couplers have been described. Out of the analyses a concept for the whole FOS3D system has been derived as shown schematically in figure 2.

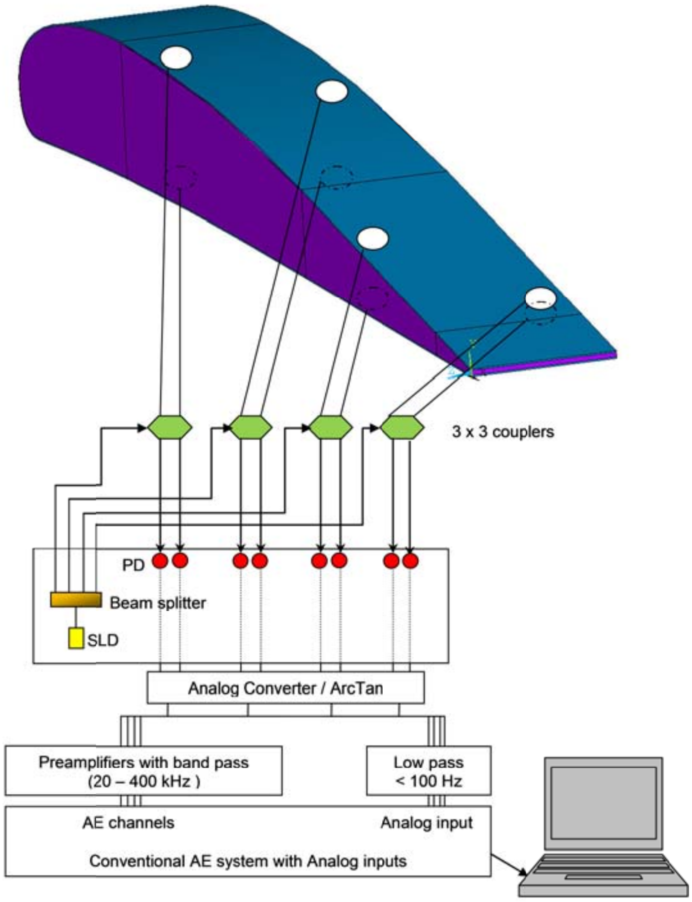

Figure 2: System architecture of FOS3D

Within **Task 2.2**: Modeling of Sensor response of WP2: Development of Monitoring Concept, three different geometries – thin CFRP plate, a flat honeycomb panel (coupon), and a honeycomb panel with triangular cross section (subcomponent) – have been analyzed to evaluate the deflection behavior of the components simulating the behavior of morphing wings. All components have been deformed up to the maximum deflection angle of 5° or to the maximum strain difference between the upper and lower face sheet acting on a morphing wing of 6800 µstrain (out of deliverable D-2.2-Concept set-up of). The strain distribution on the upper and lower face sheet have been calculated along the fiber optic sensor and fed in an optical model to derive the optical phase change as shown in figure 3.

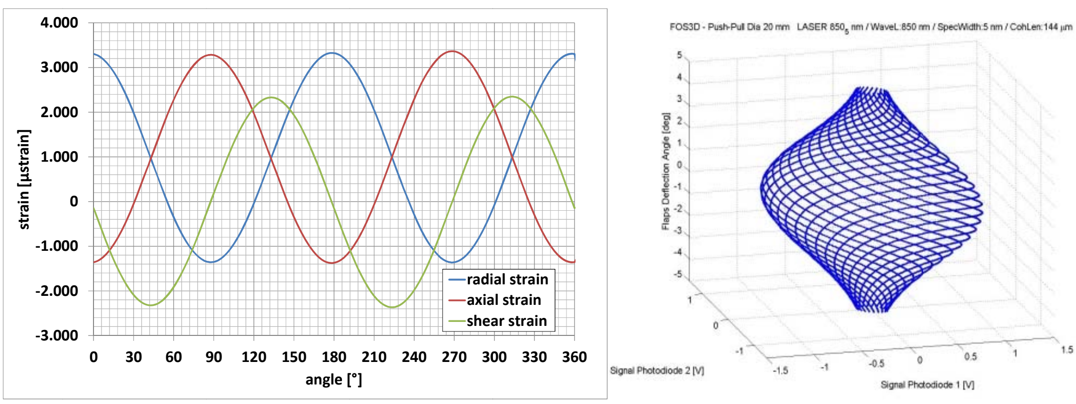

Figure 3: Strain components as function of the angle along a fibre optic coil of 20 mm in diameter for a maximum deflection of 15 mm at the position of highest strain (left side) and Interferometric patterns obtained for push-pull two sensing coils for light source at 850nm and coherence length 144µm (right side)

The results of the FEM analyses of the different components can be summarized as following:

- The total elongation of cylindrical coils of 10 and 20 mm in diameter exceed the measurement range of the existing SLD source with a coherence length of 30 µm.
- One possible solution is to used elliptical shaped fibre optic sensor taking advantage of the poison effect of the face sheets leading to a reduction of the total elongation to stay within the measurement range of the SLD
- Another solution would be to change the measurement range of SLD´s by using other types or measurement configuration as described in the summary of the results of the optical model below.

Results of calculation of phase change, optical path difference (OPD) and simulation of interferometric signals for two different sensing configurations and two different diameters of measuring fibre optic coil show:

- Critical parameter in low-coherence interferometric sensing configuration for detection of deflection of morphing wing is coherence length of used light source.
- The main requirement in sensing configuration is that the coherence length of light source has to be larger than effective elongation of optical fibre, i.e. OPD in sensing arm.
- Effective elongation of optical fibre depends on physical length of fibre-optic coil, i.e. on diameter of the coil, exposed to the load.
- Effective elongation of optical fibre depends on sensing configuration as well. Hence, the push-pull two sensing coils configuration has larger elongation than single sensing coil.
- The most promising candidates among the low-coherence sources are superluminescent diodes (SLD) at 1310nm and 1550nm of high-power and long coherence length.
- Superluminescent diode SLD-76-HP at 1550nm and coherence length of 60µm could be successfully used for single sensing coil configuration of 10mm in diameter
- An important drawback of single sensing coil configuration of 10mm in diameter is large loss of optical power.
- From practical point of view fibre optic coil of 20 mm in diameter is much more tolerable against the optical power losses
- Other geometries of fibre optic sensing arm are possible, e.g. ellipse makes a trade-off between the coherence length of light source and effective elongation of optical fibre.
- Light sources of relatively small coherence length of about 100 to 300µm match very well the OPD of the interferometer
- It is possible to achieve the required coherence length by filtration of part of the optical spectrum or by operation of laser diode under threshold
- The most promising solution is to combine low- and high coherence sources (LCS and HCS) to provide absolute measuring of initial wing position and large dynamic range of deflection

The results out of Task 2.1 and Task 2.2 lead to a fulfilment of **MS1: Intermediate Monitoring concept review** as the analyses of the presented monitoring concept show the potential to fulfil the requirements defined within Task 2.1

Within **Task 2.3** Sensor placement and resolution of WP2: Development of Monitoring Concept the results out of task 2.2 and analyses of the wave propagation properties of ultrasonic waves generated by simulated acoustic emission events have been used to assess the response of different types of sensors distributed over the whole subcomponent to define the best suited sensor shape and position of the fiber optic sensors.

Based on three aspects:

- Optical power losses depending on the shape of the sensor
- The results from the simulation work for the deflection monitoring part of the system
- Simulation and experimental results regarding the wave propagation and damping of ultrasonic signals originated

The best suited shape and position of the fiber optic sensors to achieve the required range and resolution of the combined deflection and damage monitoring system has been defined.

The best suited shape for the deflection monitoring and damage detection by acoustic emission are cylindrical coils with 1 winding together with the proper SLD of suited coherence length to cover the required measurement range of either 6800 µstrain or 5° deflection angle. The cylindrical shape has to following advantages over other sensor shapes like ellipses:

- Complete symmetric shape showing no directivity for the detection of AE events
- Much less sensitivity to deviations from the perfect shape like aspect ratio and tilt angle as for elliptical sensors
- Much less optical power losses compared to other sensor shapes
- Much less sensitivity of the sensor position on the total elongation of the sensor compared to elliptical sensors.

Based on the analyses of the wave propagation properties of simulated AE events – wave velocity and damping – the maximum sensor spacing of around 400 mm has defined. In order to be able to cover regions with varying strains and thicknesses during morphing the preferred positions of the fiber optic sensors are along the x – direction on the upper and lower face sheet as the variation in y –direction is remarkable smaller. As the strain distribution is symmetric about the x-z plane the sensors can be placed on similar distances from both edges. Based on both considerations the following placement of the sensors shown in figure 33 was finally chosen.

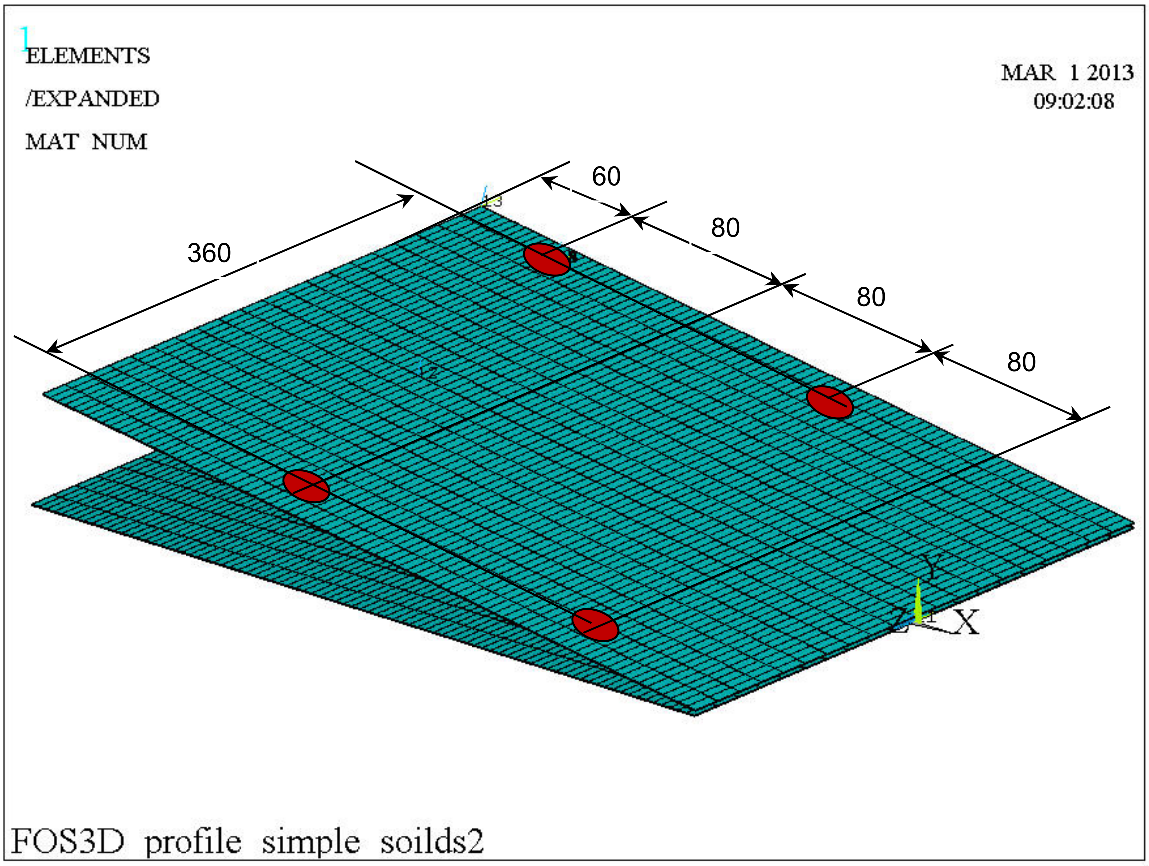

Figure 4: Proposed Sensor placement on the subcomponent

Within **Task 2.4** “Sensor Performance testing” a CFRP panel of 2 mm in thickness analyzed within task 2.2 has been equipped with a fiber optic sensor of best suited geometry and the behavior of this sensor under combined deflection loads and simulated acoustic emission events has been measured. Different configurations of the light source – standard SLD and combined SLD with a laser diode – have been investigated. Figure 4 show the raw data from both fiber optic coils – measurement coil and reference coil – as function of the deflection coil (left side), filtered signal from PD-1 (low pass for deflection detection: red and band pass for acoustic emission detection green)

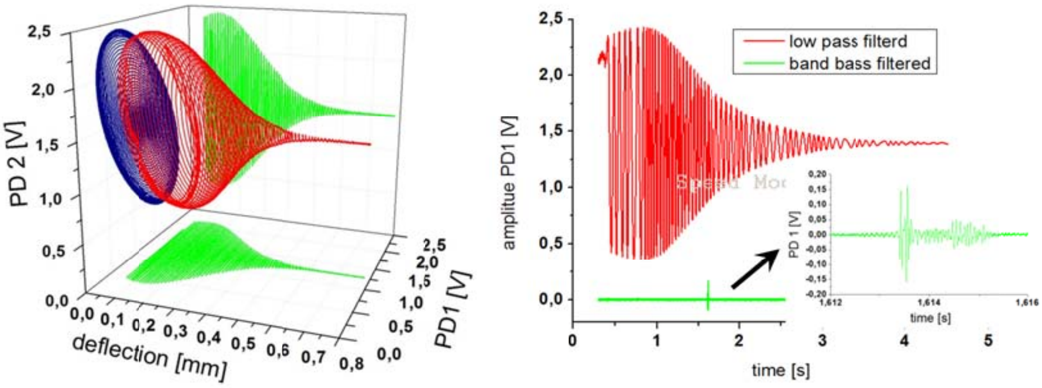

Figure 5: Raw data from both fibre optic coils – measurement coil and reference coil – as function of the deflection coil (left side), filtered signal from PD-1 (low pass for deflection detection: red and band pass for acoustic emission detection green)

These first tests have proven the predictions from the analyses regarding the range for deformation measurement. In addition it could be demonstrated that the proposed fiber optic coil sensors are able to measure signals from deflection and from simulated acoustic emission events at the same time with the required resolution.

The results out of Task 2.3 and Task 2.4 lead to a fulfilment of **MS2: Monitoring Concept Developed**. It could be demonstrated by analyses that a proper selection of the sensor shape and placement over the structure lead to the required range and resolution regarding the deflection monitoring part and to the required detection capabilities of the damage detection part. In addition first prove of concept tests on CFRP plates demonstrate the predictions from the simulations regarding the deflection monitoring part and the capability of the senor concept to simultaneously monitor deflection and detect simulated Acoustic Emission events.

For the preparation of **WP3** a flat honeycomb panel of 200 x 400 mm² (coupon) and for **WP 4** a honeycomb panel with triangular cross section of 400 x 400 mm² (subcomponent) has been purchased and the required fixation for the verification tests of both components was manufactured. Figure 1 show photos of the coupon, subcomponent and the fixation with the mounted coupon.

Figure 6: Photos of the coupon, subcomponent and the fixation with the mounted coupon

Besides the manufacturing of the coupon, subcomponent and fixation for verification testing in **WP3** and **WP4**, the required optoelectronic unit that converts the optical output from the individual fiber optic sensors in electric signals as input for the used conventional Acoustic Emission system was designed and manufactured. The concept of the system is schematically presented in Figure 2.

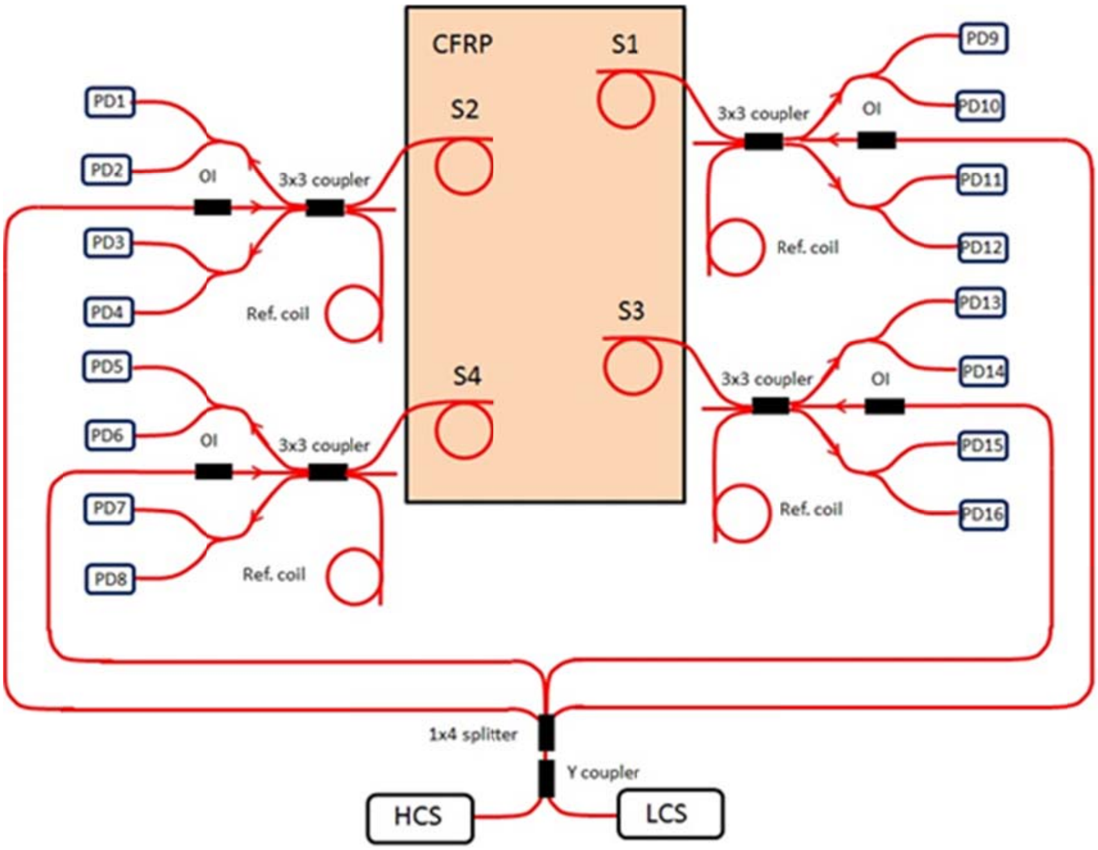

Figure 7: Schematic presentation of multiplexed LCS_HCS sensing configuration composed of four fibre-optic sensors: S1-S4. Testing coupon: CFRP honeycomb plate in size of 400x200x50 mm. HCS high-coherence source, LCS low-coherence source, photodiodes PD1, PD3, PD5, PD7,PD9, PD11, PD13, PD15 (HCS), PD2, PD4, PD6, PD8, PD10, PD12, PD14, PD16 (LCS), OI optical isolator, WDMC wavelength division multiplexing coupler

It is composed of four multiplexed fiber-optic sensors denoted by S1-S4. The sensors are in the coil form of 20mm in diameter with just one turn, which are adhesively bonded onto CFRP coupon. They are made by turning of single-mode optical fiber Corning e28+ of 9/125/250µm of core, cladding and coating diameters, respectively. Reference coils are in a close proximity to the sensing ones. Both coils are parts of the output arms of a 3x3 coupler which is used to build up two Michelson interferometers. Their static phases are mutually shifted for about 120° that assures obtaining of quasi-quadrature interference signals. The interferometers are supplied by high- and low-coherence radiation generated by high- and low-coherence sources emitting at 1550nm and 1310nm of light wavelength. Both radiations are combined by a “Y shape” wavelength division multiplexing coupler (WDMC) and further distributed, via 1x4 splitter, towards every single sensor into the middle input arm of the 3x3 coupler. Interference signals were obtained by recombination of back reflected signals from the fiber tips of the sensing and reference output arms. The third output arm is inactive and its fiber tip is polished to 8° in order to avoid possible spurious signal. Two interference signals of one sensor are bifurcated by WDM “Y splitter” to four photodiodes. The WDM splitter separates raw interference signals in a way to have a couple of two high- and a couple of two low-coherence signals. Therefore we have 16 photodiodes, which signals simultaneously get in the FOS3D sensing system depicted in Figure 3. Figure 3 shows a photo of the developed opto-electronic unit assembled in a 19´´ rack.

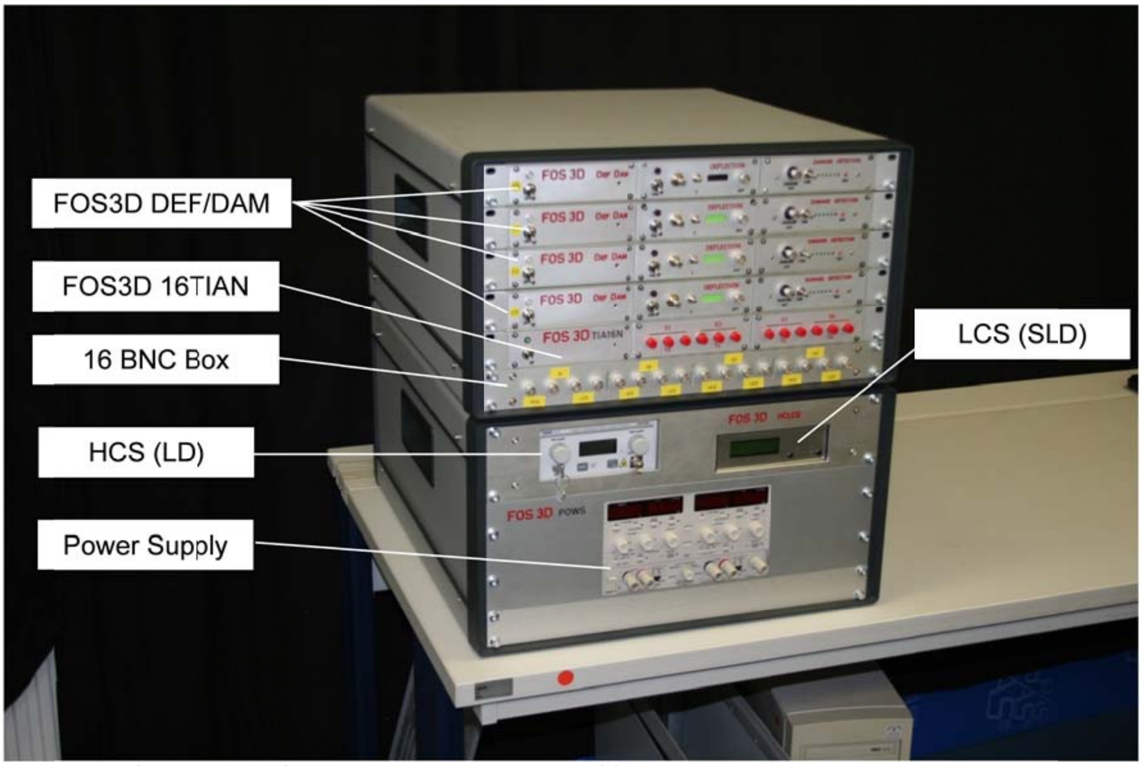

Figure 8: Overall view of sensing system composed of five main blocks: power supply; high-coherence source (laser diode), HCS (LD); low-coherence source (superluminescent diode), LCS (SLD); four units for damage detection and deflection measurement by on-line signal processing, FOS3D DEF/DAM; optoelectronic and fibre-optic unit with integrated transimpendance amplifiers and photodiodes (FOS3D 16TIAN)

FOS3D–SPSx4 is designed for processing signals of four independent sensors based on 3x3 fiber optic couplers and sensing and reference fiber optic coils.
The system is arranged into a 19” rack compartment. It is composed of following devices:

1. FOS3D-PowerS, Triple DC power supply, providing ±12V/500mA and +7V/3A, 19”, 3U height
2. FOS3D-HCLCS, Laser diode-high coherence light source and driver, 19”, 2U height
3. FOS3D-HCLCS Superluminiscence diode-low coherence light source and driver, 19”, 2U height
4. FOS3D-TIA16, 16-channels transimpedance amplifier, including the fiber-optic link for low and high coherence light management, 19”, 1U height
5. FOS3D-DefDam, Processor unit aimed for processing of four electrical signals belonging to one sensor, 19”, 1U height, 4 devices

Within **Task 3.1**: Testing of coupons with defined damages of WP3: Testing of coupons, the damage detection part of the FOS3D system was tested on a flat composite honeycomb plate, were impacts with different impact energies leading to non-damaging and damaging impacts, were applied. The achieved results of the developed system were compared against results of a conventional Acoustic emission system. In summary it can be concluded that the noise level of the damaging part of the FOS3D system is an order of magnitude higher compared to the conventional AE system. This noise is mainly caused by the interaction of the transimpedance amplifier with the conventional AE pre-amplifier.

Assessment of the probability of detection (POD) for pencil breaks, non-damaging and damaging impacts have been performed with both systems. A summary of the assessment is shown in the following figure.

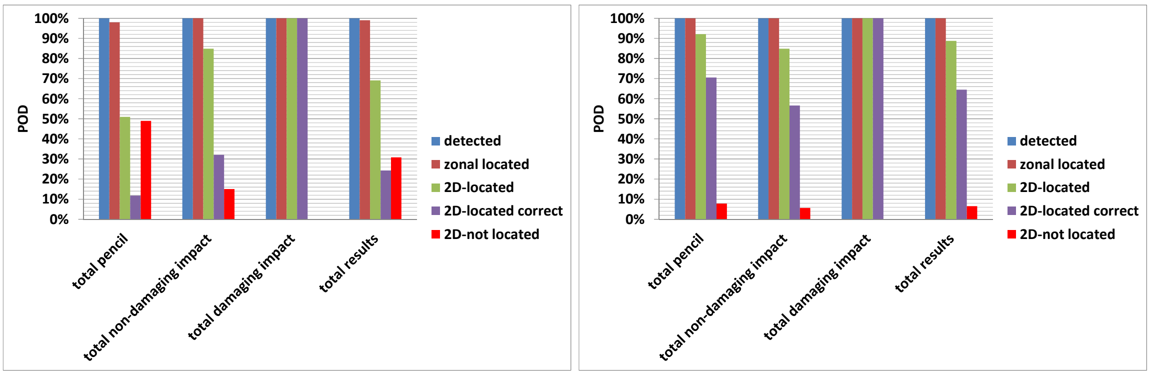

Figure 9: POD for both system (left FOS3D, right conventional AE system)

It can be seen that all simulated impact events – pencil breaks, non-damaging and damaging impacts can be detected and located by the algorithm of zonal detection (region around first hit sensor) with a POD of more than 98% with both systems.

For the pencil breaks and non-damaging impacts a clear better POD of around 62% regarding correct localization has been achieved with the conventional AE system. The reason for that can be found in the higher threshold that has to be used by the FOS3D system caused by the higher noise.

Nevertheless all three damaging impacts can be detected and located with an average localization error of around 25 mm with both systems demonstrating the proper function of the damaging part of the FOS3D system regarding the detection of damaging impacts as shown under the description of task 5.1.

Within **Task 3.2**: Testing of coupons under different mechanical loads of WP3: Testing of coupons, the deflection monitoring part of the FOS3D system was tested on a flat composite honeycomb plate, were deflections of different amount were applied to the coupon and the response of the FO sensors was measured. The achieved results of the developed system were compared against results of a calibrated deflection measurement system. We experimentally determined sensitivity and noise floor of the system of about 10mV per every fiber optic sensor. Potentially, the main noise source could be high-coherence laser diode. This noise value determines the minimum measurable deflection magnitude of about 16μm that is in a range of required value.

Diagrams in Fig. 5 present linear relationships between the Phase Angle change of fiber-optic sensors and coupon deflection. The same linearity was proved by simultaneous measurement of coupon deflection by an independent reference sensing technique. Out of the diagrams we determined sensitivity of every single fiber-optic sensor expressed as slope of linear fitted line given in rad/mm. Their sensitivity depends on the location on the coupon surface. Sensor S4 shows the smallest sensitivity because the smallest induced strain in the optical fiber.

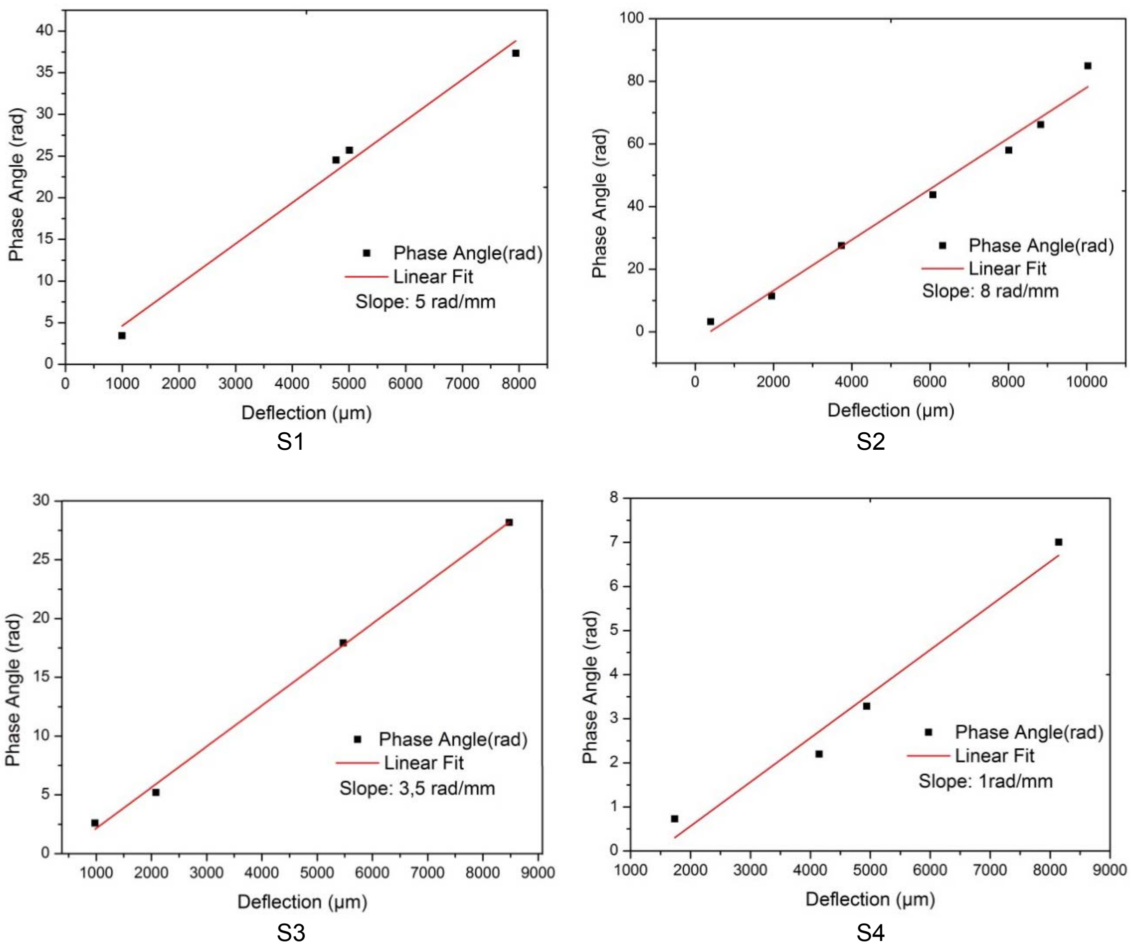

Figure 10: Sensitivity of fibre-optic sensors of the FOS3D system

Within **Task 4.1**: Testing of subcomponents with defined damages of WP3: Testing of subcomponents, the damage detection part of the FOS3D system was tested on a composite honeycomb plate with a triangular cross section, were impacts with different impact energies leading to non-damaging and damaging impacts, were applied. The achieved results of the developed system were compared against results of a conventional Acoustic emission system. In summary it can be concluded that the noise level of the damaging part of the FOS3D system is an order of magnitude higher compared to the conventional AE system as already shown on the test campaign performed on the coupons. This noise is mainly caused by the interaction of the transimpedance amplifier with the conventional AE pre-amplifier.

Assessment of the probability of detection (POD) for pencil breaks, non-damaging and damaging impacts have been performed with both systems. A summary of the assessment is shown in the following figure.

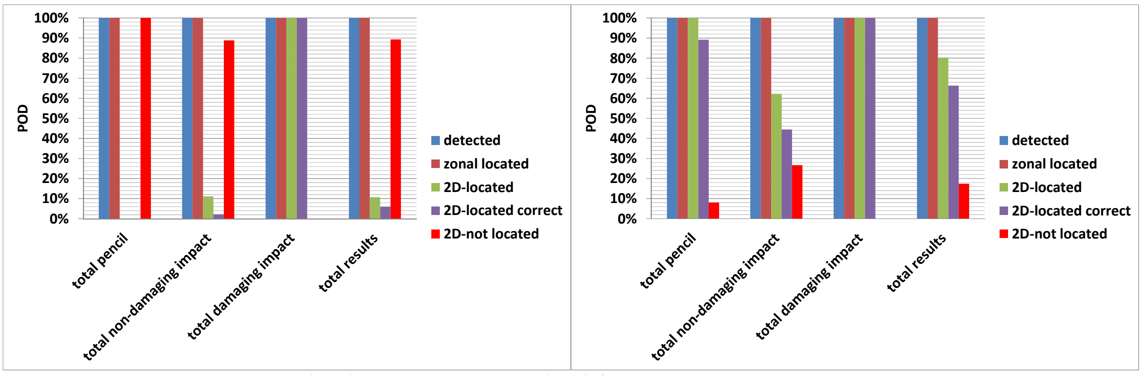

Figure 11: POD for both system (left FOS3D, right conventional AE system)

It can be seen that all simulated impact events – pencil breaks, non-damaging and damaging impacts can be detected and located by the algorithm of zonal detection (region around first hit sensor) with a POD of 100% with both systems.

For the pencil breaks and non-damaging impacts a clear better POD of around 62% regarding correct localization has been achieved with the conventional AE system. The reason for that can be found in the higher threshold that has to be used by the FOS3D system caused by the higher noise.

Nevertheless all four damaging impacts can be detected and located with an average localization error of less than 15 mm with the FOS3D systems demonstrating the proper function of the damaging part of the FOS3D system regarding the detection of damaging impacts as shown under the description of task 5.1.

Within **Task 4.2**: Testing of subcomponents under different mechanical loads of WP4: Testing of subcomponents, the deflection monitoring part of the FOS3D system was tested on a composite honeycomb plate with triangular cross section, were deflections of different amount were applied to the coupon and the response of the FO sensors was measured. The achieved results of the developed system were compared against results of a calibrated deflection and strain measurement system. In this task we presented FOS3D Def/Dam sensing system as a whole as well as through its main blocks. Some parts are optimized such as method of manufacturing and application of fiber-optic sensors, FOS3D TIA16N transimpendance unit, and deflection module in the FOS3D-DefDam system as well as arcus tangent software. We experimentally proved capability of the system for simultaneous deflection and damage detection of honeycomb subcomponent by laboratory test in IMA and final test in AAC.
We experimentally determined sensitivity and noise floor of the system of about 10mV per every fiber-optic sensor. Overall sensitivity was increased by involving of the aforementioned optimizations, especially push-pull sensor arrangement and extremely short sensing arms. Minimal detectable deflection of about 6µm is reached that is of about 30 times better than required.
Diagrams in Figure 7 present linear relationship between the phase angle change of fiber-optic sensors and subcomponent deflection. The linearity was proved by reference sensing technique for deflection measurement using inductive displacement gauge.

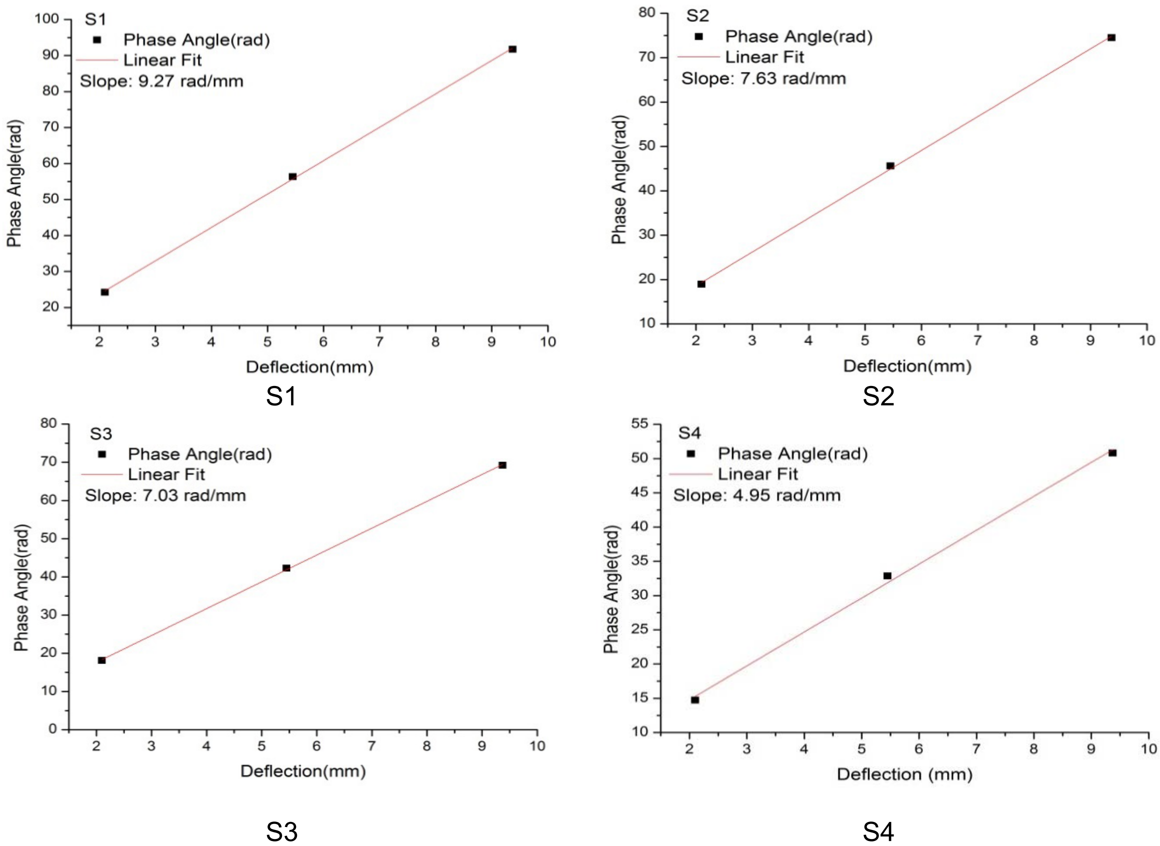

Figure 12: Sensitivity of fibre-optic sensors of the FOS3D system

The same linearity between phase angel change and induced strain was proved by final test through the simultaneous measurement of subcomponent deflection and strain distribution by strain gauges applied over the structure.

Figure 8 shows summarized results of calibration of FOS3D system in respect with strain gauge signals as an independent reference technique for subcomponent deflection of 20mm. Out of slope of liner fitting line of phase angle signals vs. strain for this case we can see that sensors have very similar sensitivity; S1=0,099rad/με and S3=0,081rad/με while sensor S2 and S4 of 0,087rad/με. As we said above, a small variation in the slope originates from imperfection in manufacturing of fiber-optic sensors, including coil forming and gluing of sensors.

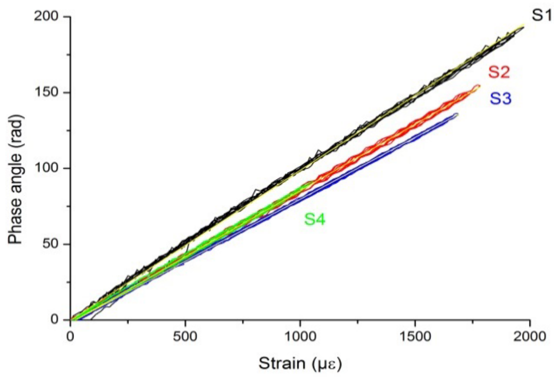

Figure 13: Calibration diagram of phase angle (rad) vs. strain for all four fibre-optic sensors for subcomponent deflection of 20mm, deflection; yellow colour- linear fit line

Out of the diagrams we determined sensitivity of every single fiber-optic sensor expressed as a slope of linear fitted line given in rad/mm. Generally, all sensors have

similar sensitivity but how large a phase signal will come out it depends on the location over the subcomponent surface.
Finally, we determined the calibration diagrams for fiber-optic sensors expressed as phase angle signal (rad) vs. strain (με) and determined overall sensitivity about 0,1rad/με of every sensor.

Within **Task 5.1**: Algorithm for damage detection & location of WP5: Algorithm Development, the required algorithms for damage detection, localization and quantification were developed and applied to the test results on the coupon and subcomponents measured by the damaging part of the FOS3D system. Different algorithms for the detection and localization of impact events taking into account the specific properties of the investigated coupon and subcomponent have been developed and compared against each other. The developed algorithms are:

- Occurrence & Classification of the impact by:
    - AE amplitude (if the amplitude is in saturation potential damaging impacts may have been occurred)
    - Average frequency content of the transient signals with amplitudes higher than 95 dB (gives a clear information if a damaging impact has been occurred)
    - AE energy will be used to quantify the impact damage size

- Algorithms for damage localization
    - Zonal Location Technique (Region around the first hit sensor)
    - Point Location (arrival time differences between individual sensor pairs are used for triangulation of the source). For point location the wave propagation properties were determined by simulation and by experiments and two different source location algorithms (circular and square shaped wave front) were evaluated. Finally the algorithm using a circular wave front gave the better results on the investigated coupons and subcomponents.

- Algorithms for damage quantification (different signal features such as AE energy and AE frequency were used).

As already described above four different types of impacts have been applied on the coupons and subcomponents:

- Pencil breaks (small – non damaging)
- Non damaging impacts with an impact hammer
- Damaging impacts with an impact hammer
- Damaging impact during morphing of the subcomponent

Figure 9 show the measured features during the damage testing campaign performed on the subcomponent.

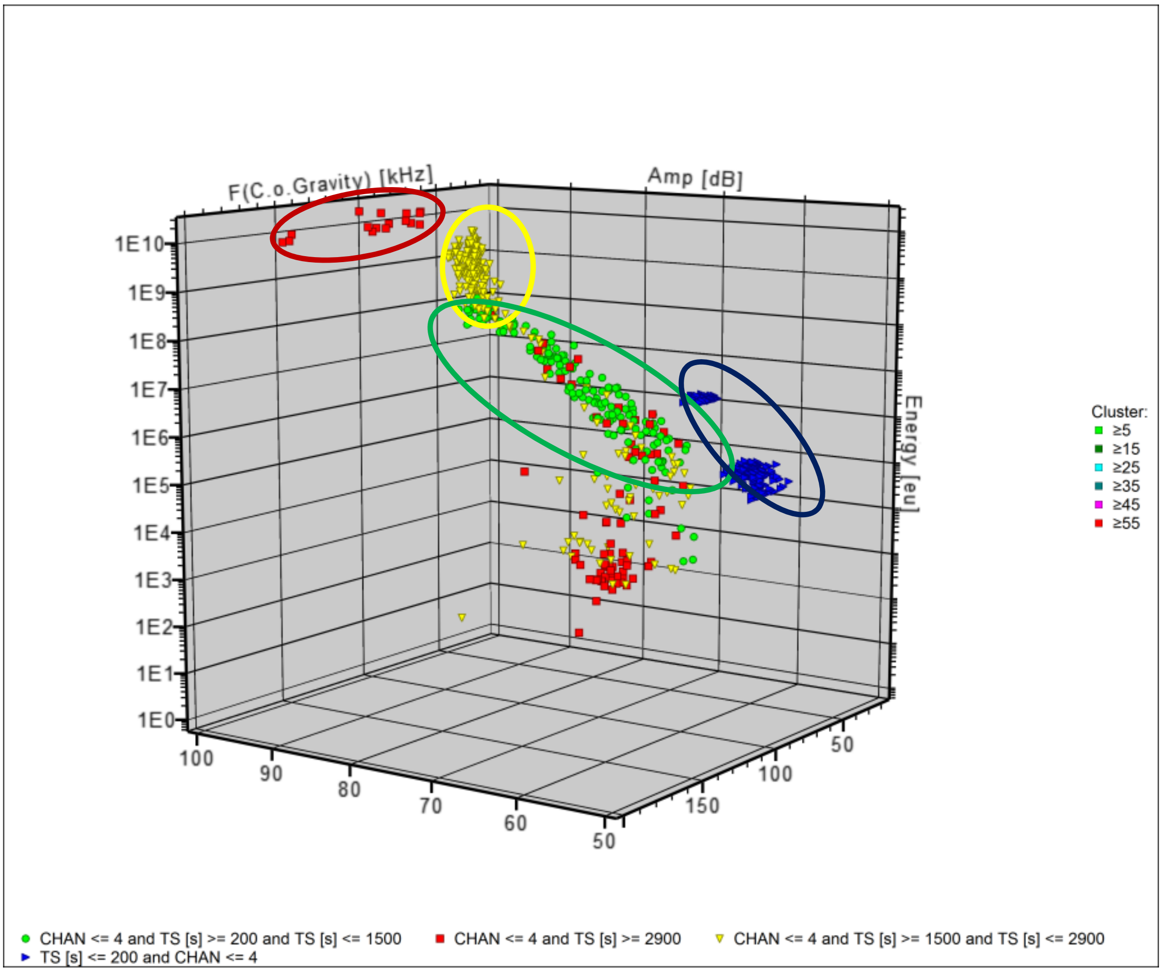

Figure 14: Energy as function of the amplitude and average frequency of the detected AE hits (blue dots: calibration / green dots: pencil breaks / yellow dots: non damaging impacts / red dots: damaging impacts)

It can be seen that the higher the impact energy the higher the amplitude, average frequency, energy and duration of the detected AE hits at the individual sensors. The maximum amplitude reaches values of 100 dB (saturation) already for the non-damaging impacts. Therefore the amplitude alone is not suited to discriminate between damaging and non-damaging impacts. The most sensitive parameter was the AE energy and the average frequency. All pencil breaks, non-damaging impacts and damaging impacts produce hits with a large scatter band of parameters such as amplitude, duration, energy and average frequency where the highest values of the 4 parameters increase with the applied incident impact energy beside the signal amplitude (already mentioned before). The measured hits with low amplitude, energy, duration or average frequency for the damaging and non-damaging impacts are mainly caused by the reflections from the boundaries. When looking at figure 9 three different clusters of hits can be separated:

- Red cluster: first hits due to damaging impacts
- Yellow cluster: first hits due to non-damaging but higher energetic impacts
- Green cluster: hits from pencil breaks and reflections from the boundaries of the non-damaging and damaging impacts

Although the sensitivity of the FOS3D system is lower compared to the conventional AE system, the FOS3D system was able to detect and locate the impact events with an average localization error of less than 15 mm in case of damaging impacts subcomponents as illustrated in the following figure.

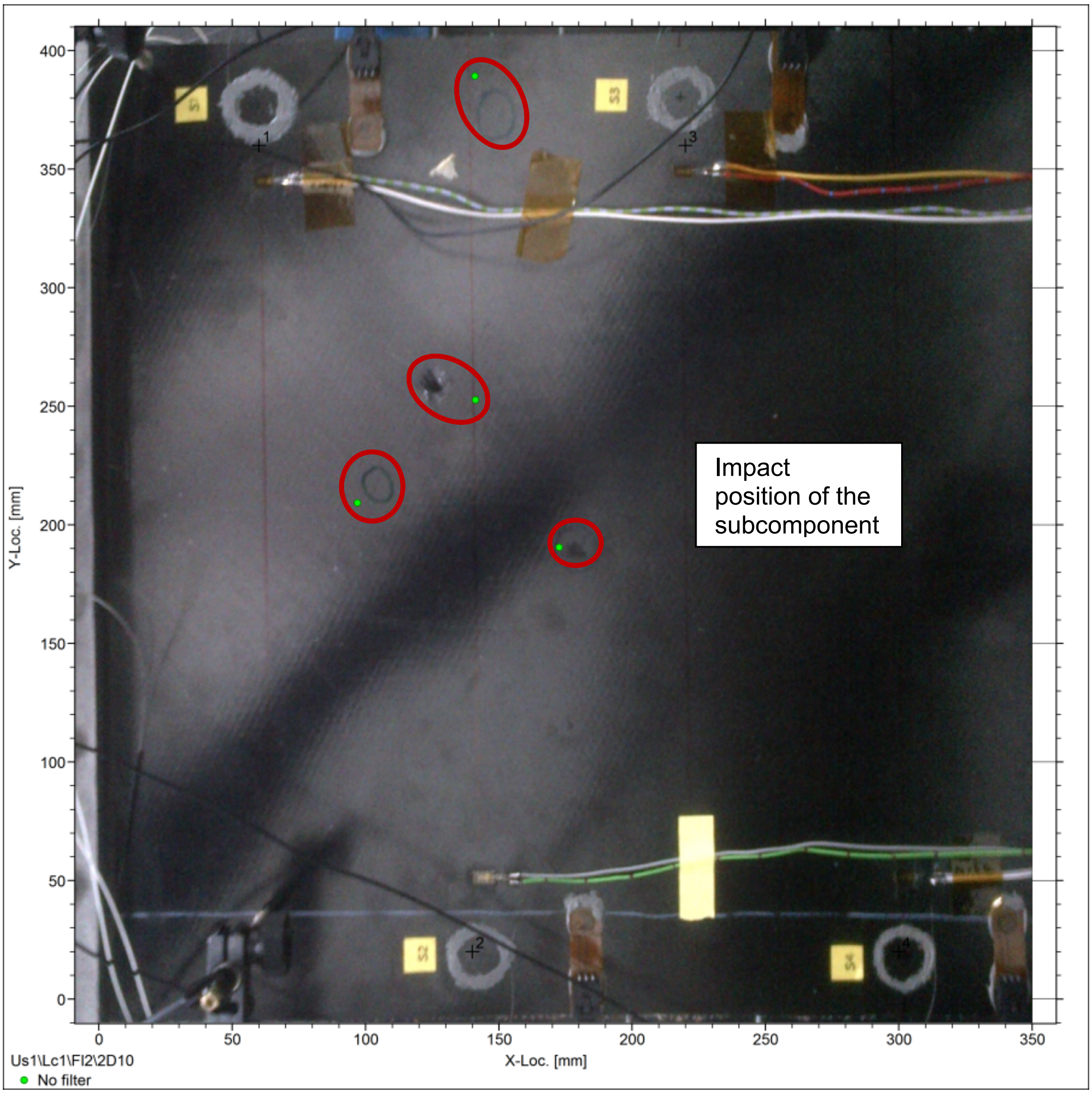

Figure 15: Position of the located impacts for all three impacts measured by the FOS3D system. The damaged honeycomb panel is shown in the background to illustrate the real impact positions compared to the located impact position by the FOS3D system

A clear quantification of severity of the impact damage by the evaluation of the AE energy was not successful and therefore other NDT methods have to be used after detection and localization of the damaging events by the FOS3D system.

Within **Task 5.2**: Correlation between sensor output and deflection of WP5: Algorithm Development, the required algorithms for the correlation between sensor output and deflection were developed and applied to the test results on the coupon and subcomponents measured by the deflection monitoring part of the FOS3D system.

A comprehensive analysis of different algorithms for processing of raw interference signals, taking into account complexity, accuracy, precision, speed of execution, etc., is presented. It was demonstrated that Arcus tangent algorithm is the best solution for accurate and reliable off- and on-line calculation of optical path difference and phase angle signals of fiber-optic sensors. An optimized version of this algorithm, which is able to update the analog output signal, representing the wing deflection, with rate of 100Hz is so called Abridge arcus tangent algorithm. The algorithm is embedded into the DSP hardware of FOS3D-DefDam for real-time calculation of phase angle signal in dependence on deflection of morphing wing.

Main characteristic of transportable FOS3D sensing system, calibration diagram of Phase angle signal (rad) vs. Deflection (mm), has been experimentally determined by numerous deflection campaigns of simple CFRP sample, honeycomb coupon and finally subcomponent. For this purpose the two independent reference techniques, inductive displacement gauge and strain gauges, have been used.

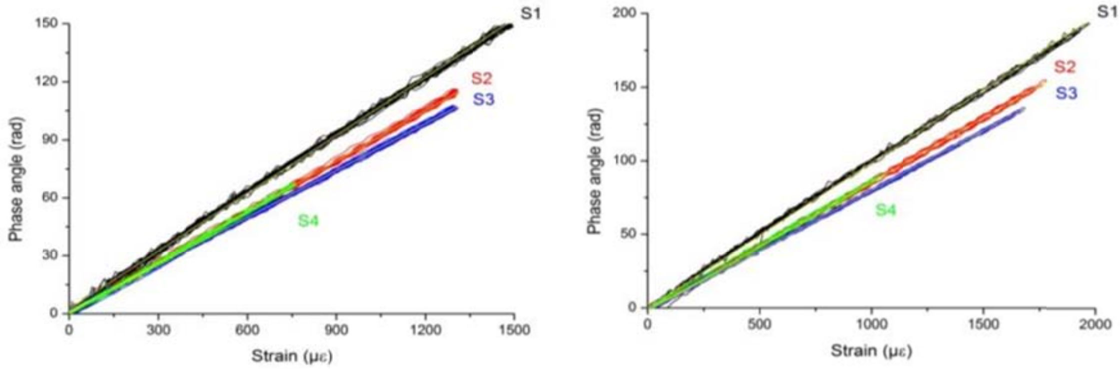

Figure 16: Results of deflection measurement of subcomponent for 15mm (left) and 20mm (right) of total deflection; Calibration diagram of phase angle (rad) vs. strain for all four fibre-optic sensors for 15mm of deflection (left side), Calibration diagram of phase angle (rad) vs. strain for all four fibre-optic sensors for 20mm of deflection (right side)

Overall sensitivity of all fiber-optic sensors of about 0,1rad/µε was determined out of calibration diagrams. It was also achieved very good linearity of all sensors in the entire deflection range, from zero to 20mm that corresponds with experimentally reached maximum local deflection angle of about 3° (1.8° average deflection angle) and induced strain of about 1000µε (see Figure 12).

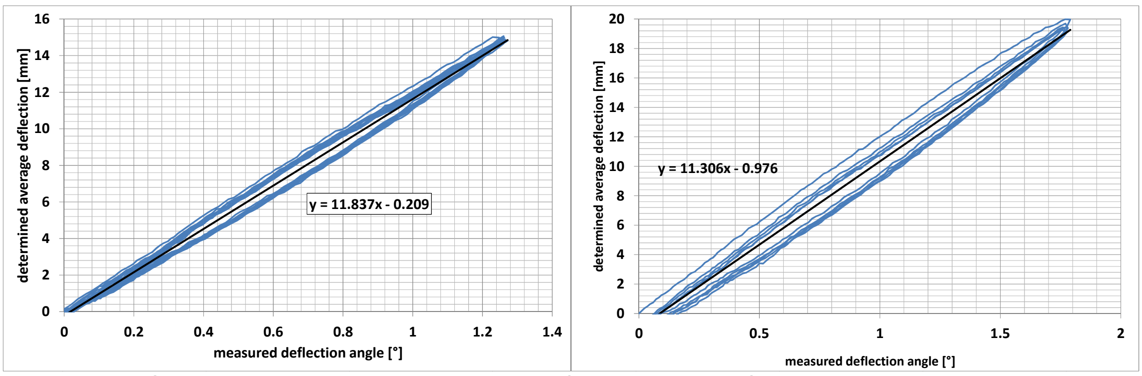

Figure 17: Correlation between the mean values of the calibrated FO sensor outputs with the measured corrected average deflection angle

Out of these data and initial requirements of resolution of 0.1° and deflection range of ±5°, required resolution of phase angle signal should be of about 3 rad that corresponds with about 30µε of measured strain. It was proved that FOS3D system can fulfil these requirements since minimum detectable phase angle signal reached in this investigation is of about 120mrad.

Finally, the main goal of the project was successfully proved by experimentally verification of capability of the FOS3D system for simultaneous deflection measurement and damage detection. Some improvements are still possible, especially in redesigning of the opto-mechanical housing and electronics.

6 Potential impact, dissemination activities and the exploitation of results

The expected final result of the project is a system – the FOS3D system - for the measurement of the deflection and at the same time assessment of the health status of morphing wing structures at TRL level 5 to 6 using light weight, low power consumption and embeddable fiber optic sensors. Such system is necessary for an automated control of the wing shape of morphing wings for optimum flight conditions that provides information about potential damages that occur under operation.

The system allows future aircraft structures made of self-sensing composite to be designed with weight reductions up to 25% or even more compared to current designs. As the airframe construction contributes about 20 % to 25 % to the total emission a reduction in weight clearly leads to reductions in CO2, NOx and other emissions as stated in the Strategic Research Agenda (SRA) and the Vision 2020 - Reduction of CO2 by 50% per passenger kilometer and reduction of NOx by 80% in landing and takeoff.
The self-sensing composite structures developed within FOS3D furthermore allow a paradigm change from currently costly Time Based Maintenance to maintenance on demand – Condition Based Maintenance. Such maintenance concepts using permanently attached sensors and/or actuators in difficult or even impossible to access areas lead to a strong reduction of dismantling time and afford to inspect such regions. As to date the current maintenance concepts contribute to about 20% of the Direct Operational Cost (DOC) of the aircraft, the new maintenance concepts enabled via the developments of the FOS3D project are required to meet the target to reduce aircraft operating costs by 50% through reduction in fuel consumption, maintenance and other direct operating costs.
As the production of composite structures is expensive due to the high material costs of carbon fibers and the costs of the currently only semi-automated production processes for high quality composite aircraft parts any reduction in the required amounts of composite material will directly reduce the environmental impact of the production.

6.1 Dissemination

Within **WP6 Dissemination** the coordinator was invited to the FOHEC conference held in Swindon UK, November 2012 to present the first results of the FOS3D project. Two conferences have been attended by the coordinator Michael Scheerer from AAC and from Zoran Djinovic from IMA and two papers listed below have been presented. A further presentation at the European Workshop on Structural Health Monitoring (EWSHM 2014) from Michael Scheerer and Zoran Djinovic is planned to be given.

Conferences

- M. Scheerer: FOHEC 2012 conference, Swindon, UK 21.11.2012
- M. Scheerer, Z. Djinovic: SPIE Smart Structures Conference, 10 – 14th March 2013, San Diego, USA,
- Z. Djinovic: International Workshop on Structural Health Monitoring (IWSHM 2013), Stanford University, Stanford, CA, September 10-12, 2013

Conferences Papers (published)

- M. Scheerer, Z. Djinovic, M. Schüller, Fiber optic system for deflection and damage detection in morphing wing structures, Proc. of the SPIE Smart Structures Conference, 10 – 14th March 2013, San Diego, USA
- Z. Djinovic, M. Scheerer, M. Tomic, M. Stojkovic, M. Schueller, Design and characterization of fiber-optic interferometric sensor for deflection and damage detection of morphing wing structures, Proc. Of the 9th International Workshop on Structural Health Monitoring, Stanford University, Stanford, CA, September 10-12, 2013

Planned Conferences

- Z. Djinovic, M. Scheerer: European Workshop on Structural Health Monitoring (EWSHM 2014), Nantes, France, from July 8 - 11, 2014

Papers (to be published)

- Z. Djinovic, M. Scheerer, M. Tomic, M. Stojkovic, M. Schueller, SIMULTANEOUS DAMAGE DETECTION AND DEFLECTION MEASUREMENT OF MORPHING WING STRUCTURES BY FIBER OPTIC SENSING SYSTEM, to be publ. in the Proc. of the EWSHM 2014, Nantes, France, from July 8 - 11, 2014

6.2 Exploitation Activities (planned)

The mentioned conferences on Structural Health Monitoring take place every year at the Stanford University (IWSHM) and at different places in Europe (EWSHM) and offer the possibility to show a hardware presentation of new developments on Structural Health Monitoring.

For further dissemination and exploitation of the project results it is planned to demonstrate the capabilities of the developed FOS3D system at one of the next conferences either in Stanford (2015) or Europe (2016).

Before a prototype system can be placed on the market, the mentioned improvements described in chapter 3.3.1 especially points 1, 2 and 3 have to be implemented.

For the extension of the system capabilities to multi-physical parameter monitoring (see point in chapter 3.3.1) a further proposal was sent to Clean Sky in the last call for proposals for green regional aircraft under the acronym “COMFOS”, but was not first ranked during evaluation.

Beside the application of the developed technology, potential customers from other application fields besides aeronautics, such as power plants, wind turbine plates or nuclear plants, where sensor should work in harsh environment will be informed about the capabilities of the FOS3D system.