Challenges of an Industrialized Acousto-Ultrasonic Sensor System Installation on Primary Aircraft Structure

Nicolas Dobmann, Martin Bach, Benjamin Eckstein

CHALLENGES OF AN INDUSTRIALIZED ACOUSTO-ULTRASONICS SENSOR SYSTEM INSTALLATION ON PRIMARY AIRCRAFT STRUCTURE

N. Dobmann, M. Bach, B. Eckstein

Airbus Group Innovations, Airbus Allee 1, 28199 Bremen
Nicolas.Dobmann@airbus.com

ABSTRACT

At laboratory level, secondary bonding of Acousto-Ultrasonics sensor systems is well established and has proven its reliability in applications from coupon level up to flight test installations. However, the applied sensor secondary bonding is a manual process with high amount of required auxiliaries and tools and is hence associated with high costs. In transition from sensor installation under laboratory conditions to the installation of large-scale sensor networks within an aircraft serial production process, costs associated with sensor installation become a decisive factor.
By developing the sensor co-bonding approach, an installation method for fiber reinforced plastics host structures is created which requires significantly less work, auxiliaries and tools. Yet, while a considerable reduction of installation cost seems achievable, the application of sensor co-bonding as an industrialized process for aircraft primary structure is clearly more challenging.
The present paper outlines specific advantages of sensor co-bonding and discusses challenges ahead on the way towards an industrialized sensor installation on aircraft primary structures.

KEYWORDS : *Acousto-Ultrasonics, sensor integration, secondary bonding, co-bonding*

INTRODUCTION

Unknown associated costs and final system parameters impede a reliable profitability assessment of Acousto-Ultrasonics (AU) systems. However, savings potential in comparison to established NDT processes is essential for the application of any SHM Technology on aircraft. Hence, there is considerable need to identify substantial influences on the cost-benefit equation of the system as early in the development process as possible.

In this regard, the physical integration of the sensor system constitutes an important aspect. In the domain of Acousto-Ultrasonics, the established integration process for the sensor network is based on secondary bonding. While this process has proven its reliability from laboratory to flight test applications, high manufacturing costs are associated with the sensor system installation in application of the secondary bonding process. High manufacturing costs of this sensor integration approach primarily stem from vacuum bagging and continuous heat field applied to achieve consistent and qualitatively high bond results throughout the entire sensor system. In order to reduce manufacturing costs associated with the sensor system installation on prepreg-based composites, a co-bonding approach for AU sensor systems was introduced.

1 SENSOR CO-BONDING

The sensor co-bonding approach utilizes the host structure curing cycle as bonding process which creates a significant reduction of the manufacturing effort involved with AU sensor system integration. No host structure treatment in the bonding area of the sensor system is required as the prepared sensor system is placed directly on the uncured host structure surface. The remaining steps to establish a reliable bond between sensor system and host structure coincide with the production process of the host structure. Following general advantages can be realized by sensor integration using the co-bonding approach:

<u>Reduction of manual work</u>
Tasks such as host structure surface preparation and vacuum bagging do not apply for the sensor co-bonding process. While in contrast to the secondary bonding process, the connector interface of the sensor system has to be installed in a separated manufacturing step [1], manual work required for sensor co-bonding can be considered as significantly reduced.

<u>Reduction of auxiliaries and production infrastructure requirements</u>
Since no separate vacuum bagging set-up is required, respective costs of auxiliaries necessary for the set-up can be saved. Simultaneously, the production infrastructure does not have to provide a vacuum source and equipment to generate a steady thermal field, such as required by the secondary bonding process.

<u>Increased automation potential</u>
Especially host structure surface treatment and vacuum bagging are distinct obstacles for an automated sensor system installation by secondary bonding. Since host structure surface preparation and separate vacuum bagging is not part of the sensor co-bonding process and manual work involved in the basic process essentially consists of the sensor system placement on the host structure, automation potential of this sensor integration approach is considerably higher. Similar automated processes in the production of composite aircraft fuselage panels such as automated fiber and stringer placement could provide the technological foundation and infrastructure to automate sensor system placement.

2 CO-BONDING CHALLENGES

In order to enable a survey of the effective costs associated with sensor integration, the industrial sensor integration process has to be considered long before it is implemented because requirements of the serial production process and the structural application can develop significant influence on integration costs of the system and thereby system profitability. In order to transition the laboratory based sensor system installation to a process suitable for an aircraft primary structure application as part of the industrial production chain, several manufacturing issues have to be addressed. For the sensor system installation on aircraft fuselage panels taken into consideration in this paper, several issues have been identified which potentially narrow the benefit of the co-bonding approach.

<u>Manufacturing errors</u>
While manufacturing errors occurring in application of the sensor secondary bonding process, e.g. loss of vacuum pressure during adhesive curing, only affect the sensor system itself, manufacturing errors occurring within or due to the sensor co-bonding process, can also affect the host structure. This makes error-proneness of the sensor system installation process an even more important issue if co-bonding is applied. For instance, sensor system sections can drift out of position during autoclave preparation and wrinkling or tilting of sensor system sections may cause not allowable fiber misalignments in the host structure. As a result, costly repair or even scrapping of extremely expensive fuselage panels may be required. Hence possible manufacturing errors have to be

evaluated under serial production conditions and minimized. The residual risk of an not allowable impact on the host structure due to manufacturing errors has to be considered in the cost-benefit analysis for the co-bonding process.

Fiber misalignments

In addition to random manufacturing errors, co-bonding of the sensor system can lead to a systematic detrimental effect on host structure properties. As depicted in figure 1, the co-bonded sensor system can cause fiber misalignments in the host structure. In the illustrated case, fiber misalignment in the area of a Lead Zirconium Titanate (PZT) disc can be assumed to be caused by pressure discontinuities created by the protruding position of this component of the sensor system. Since already low degrees of fiber misalignment can have considerable effect on mechanical properties such as stiffness [2] and compressive strength [3], this constitutes a significant aspect of co-bonding AU sensors.

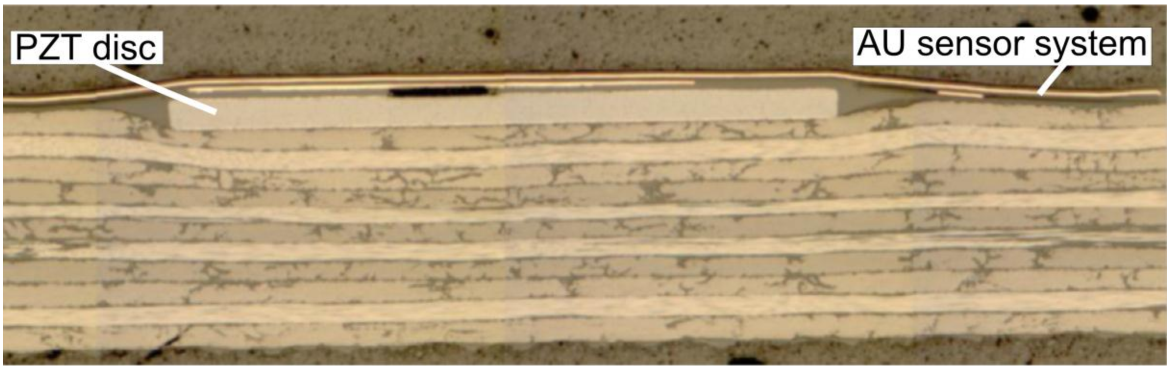

Figure 1: Micrograph of fiber misalignments underneath a PZT of an AU sensor system (Acellent Smart Layer®)

Consequently, an important development task will be the establishment of allowable degrees of fiber misalignment on the one hand and correspondent optimization of sensor system and process on the other. While glass fiber reinforced plastic (GFRP) prepeg applied underneath and on top of the sensor system strips for insulation and protection reasons have shown to reduce fiber misalignments, reliable minimization of fiber misalignments can only be achieved by an adaption of the sensor system contour of the surface bonded to the structure. Solely an entirely flat contour generating an even pressure distribution at the interface to the host structure can be considered to provide consistently low or nonexistent fiber misalignments. To achieve applicability of the sensor co-bonding process, proof will have to be furnished that the risk of causing fiber misalignments exceeding allowable degree is acceptably low and provide means to detect not allowable degrees of fiber misalignment.

At the same time, the fact that the admission of a certain degree of fiber misalignment may require reinforcement of the structure to compensate for the detrimental effect of fiber misalignments has to be considered. Yet, testing conducted within the SARISTU project [4] indicates that applied GFRP layers and the sensor system itself already provide sufficient fortification to compensate for fiber misalignments caused in application of the current process and non-optimized sensor system contour.

Qualification considerations

In regard of manufacturing-related qualification expenditures, a distinction has to be drawn between system integration into an aircraft in development and equipment of an existing aircraft with AU technology as retrofit solution. Qualification effort for secondary and co-bonded sensor systems can be assumed similar if accounted for in the initial qualification process of the aircraft. However, in case AU technology is integrated as retrofit, higher qualification effort has to be assumed on the co-bonding side since certified manufacturing processes of primary structure are altered and primary structure is modified.

Manufacturing NDT

Consideration of the panel quality assurance process leads to another challenge to the sensor co-bonding process. At Airbus, the quality assurance processes requires a rigorous porosity inspection of CFRP fuselage panels, which involves ultrasonic scanning of 100% of respective CFRP components. In currently applied processes, porosity content is determined by analyzing back wall echo amplitudes obtained through the ultrasonic scan [5]. This process is impeded by the presence of the co-bonded sensor system as back wall echoes are altered significantly. As visible in the c-scan representation of a co-bonded sensor system section in figure 2, back wall echoes are distinctly diminished in the lateral border area and locations of the PZT transducer discs. Caused by altered scattering and acoustic impedance conditions, blue coloring indicates back wall echo amplitude decrease of up to 80% in respective areas. Since areas of not allowable back wall echo amplitudes due porosity content cannot be distinguished from areas of not allowable back wall echoes due to altering effects of the co-bonded sensor system, reliable porosity detection is impossible with current manufacturing NDT processes. A basic solution in this case is the exclusion of the bonding area of the sensor system from porosity detection which has to be considered in the structural design, i.e. the maximum of not detectable porosity content in the bonding area may have to be compensated by structural reinforcement. Since this would increase, among other cost factors, the weight which has to be attributed to the sensor system, adaption of manufacturing NDT processes omitting structural reinforcement due to co-bonded sensor systems remains an important topic.

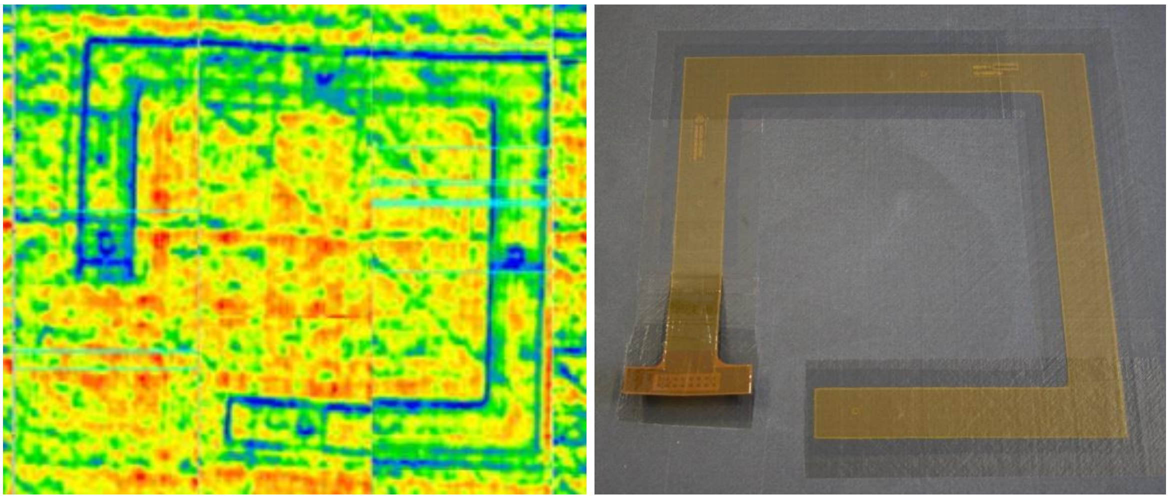

Figure 2: Ultrasonic C-Scan sample of a co-bonded sensor system section (Acellent Smart Layer®):

Stringer integration

Current network design for secondary bonded sensor system sections provides that sections of multiple stringer bays are concentrated to one common connector interface. This connector illustrated in figure 3 provides the sensor system interface to the interrogation unit.

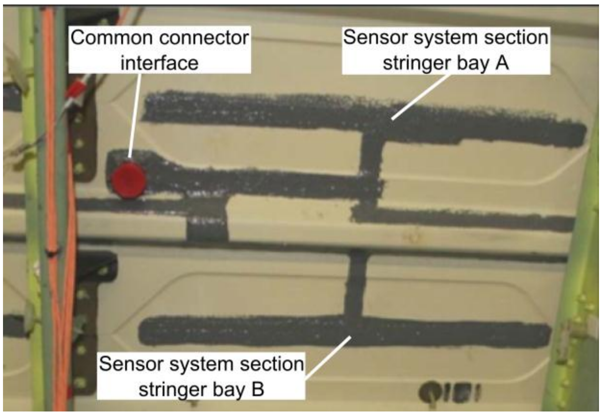

Figure 3: Secondary bonded sensor system sections (sealed): Central connector for sensor system sections of multiple stringer bays

In modern CFRP fuselage panel production processes stringers are already in place during the curing cycle of the skin, which at a first glance seems to allow identical routing of the sensor system. However, sensor system routing is constricted by the integration process of the stringers. Since adhesive protruding at the stringer edges during the autoclave process must not be obstructed and the protruded adhesive constitutes an important indicator for the bond quality, the sensor system cannot be readily placed across stringer edges. Mitigation approaches can be the equipment of every stringer bay section with a separate interface or the installation of interconnecting sections after the curing cycle. Yet, this involves an increased manufacturing effort, possibly increased sensor system weight and additional interfaces which can constitute additional source of error. Consequently, the co-bonding of sensor system sections which can extend over multiple stringer bays remains a development goal.

3 GENERAL CHALLENGES OF AU SENSOR SYSTEM INTEGRATION

In addition to the installation process, sensor system integration also requires quality assurance and repair processes which have to be established and integrated into the production chain:

Process integration

Various details which have to be considered render the integration of the processes associated with the sensor system installation into the production chain a comprehensive task. While the production chain segment for sensor installation by co-bonding is inevitably defined, the most suitable segment for the sensor system integration still has to be determined in case secondary bonding is applied. Multiple criteria such as available production infrastructure, accessibility of the installation area, impact on and at the same time the impact of other manufacturing processes have to be considered. Similarly, sensor system quality assurance and repair processes have to be integrated into the production chain.

Sensor system quality assurance and repair process

The establishment of sensor system quality assurance and repair processes requires considerable development work. Parameters to determine the condition of the sensor system, for instance sensor health, sensor bonding condition and sensor position have to be established and means to assess respective parameters under industrial conditions have to be developed. This has to be accompanied by the establishment of tolerances for the assessed parameters.

For cases in which sensor quality assurance yields not allowable deficits, a repair process for the sensor system has to be developed. For the sensor system considered in this paper, there are three basic repair approaches:

- Removal of the deficient sensor system section and subsequent replacement installation
- Installation of the replacing sensor system section on top of the deficient section (without removal)
- Removal of deficient sensors and installation of the replacing sensor system section on top of the deficient section

Figures 4-7 exemplify the repair approach listed last. This repair approach initiated within the SARISTU project provides that deficient sensors are removed by a milling cutter, as depicted in figures 4 and 5. Subsequently, the replacement section is installed in the same location using 2K epoxy adhesive and cured in application of a heat source and a vacuum bagging setup depicted in figure 6. In the illustrated trial, the electrical interconnection to the main sensor system was successfully established by conductive adhesive, simultaneously cured in the vacuum bagging setup. The result of the Smart Layer® section repair is displayed in figure 7.

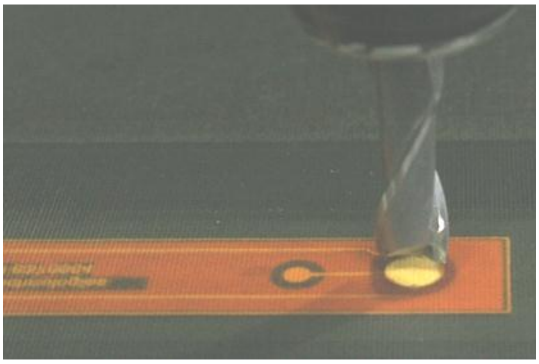

Figure 4: Mechanical PZT transducer disc removal

Figure 5: Co-Bonded Smart Layer® after PZT transducer disc removal

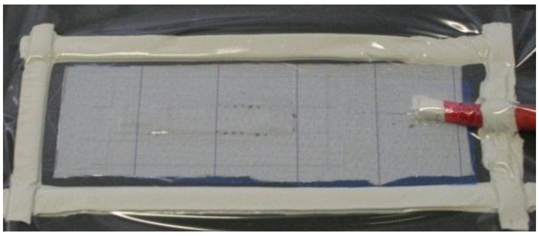

Figure 6: Installation of replacing Smart Layer® sensor strip: Vacuum bagging application

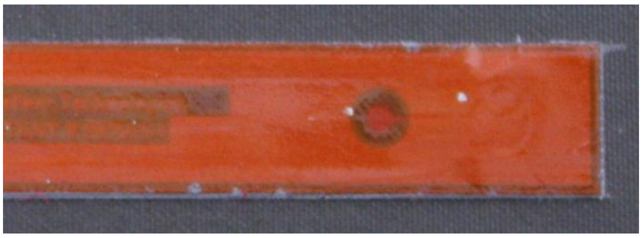

Figure 7: Smart Layer® after installation of the replacement section

The most suitable repair process will have to be determined in assessment of the criteria costs of the repair process, added weight, reliability of the process and repaired sensor system section as well as performance of the repaired sensor system section. Similarly, a repair process for in-service situations has to be developed. Since in-service conditions such as accessibility and applicable equipment differ from in-production conditions and in-service time constraints can lead to considerably elevated costs associated with the duration of the repair process, the application of different repair approaches for production and in-service conditions are conceivable.

The development of the repair process also involves the establishment of the repair strategy to be applied if a deficit in the sensor system is determined, i.e. if the replacement of single sensors or short sections should be possible or if larger sensor system sections have to be replaced in case single sensors or circuit paths are determined deficient. To permit an electrical interconnection to the replacement sensor system section, interfaces have to be incorporated in the sensor system. Conductive epoxy adhesive applied in the example process illustrated in figures 4-7 is a conceivable approach to establish a reliable electrical interconnection to the replacement sensor system, but further efforts will be made to create an interconnection solution which is easier to handle. An additional modification to the sensor system possibly required by the repair process may be a thickness increase of the GFRP layer underneath the sensor system to ensure the host structure is not affected by the repair. Hence, certain influence on the sensor system design and due to associated costs and resulting system weight on the general profitability of the system has to be considered. Adding to the fact, cost associated with the chosen in-service repair process delivers an important input to sensor system redundancy considerations. Cost of an in-service sensor system repair may entail that, where applicable, an initially denser network able to compensate a certain number of failed sensors may prove to be more economical.

CONCLUSION AND OUTLOOK

In comparison to the established secondary bonding approach, co-bonding provides several advantages such as reduced required manual effort, auxiliaries and production infrastructure as well as better suitability for an automated sensor system integration process. If applied to install sensors on primary aircraft structure as part of the industrial production chain, however, particular requirements apply. Since readily available solutions satisfying these requirements involve an increase of manufacturing effort and/or weight associated with the sensor system, the benefit of the co-bonding approach is potentially narrowed. Nevertheless, mitigation approaches and especially the aspect of an automated sensor installation provide a positive outlook for the sensor system integration by co-bonding. In case no further circumstances detrimental to the benefit of this sensor system integration approach are identified, distinct savings in integration cost can be considered achievable. Consequently, further work will continue to consist of the advancement of technical details. Yet, in light of application and industrialization aspects such as process integration as well as the development of repair and redundancy strategies, management of multiple interdependencies become an increasingly important challenge.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 284562.

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