

Towards a Lining Integrated Active Structural Acoustic Control System

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ABSTRACT

For future aircraft counter-rotating open rotor (CROR) engines are a promising technology to reduce their CO₂ footprint. Since the contribution of CROR engines to the cabin noise is higher than for jet engines, new strategies for the reduction of noise transmissions for frequency bands below 500 Hz are necessary. Active structural acoustic control (ASAC) systems are capable to reduce sound transmission of lining structures in this bandwidth. Sensors measure the vibrations of the lining to estimate its sound emission into the cabin. Based on these signals a controller calculates force signals for actuators on the lining. The actuator forces change the vibration behaviour of the lining in order to reduce its sound emission. For the realization of such a system in a real aircraft, manufacturing and maintenance issues have to be addressed.

Within work package 3 of the EU project ACASIAS an aircraft lining with an integrated ASAC system is developed. The size of the lining is app. 1300 x 1690 mm² (W x H) and it is simply curved. The radius of 2980 mm makes it relevant for a twin-aisle aircraft like the Airbus A350. The focus of research activities lies on the integration of components and the industrial manufacturing process of the lining. The components to be integrated are sensors, actuators and the corresponding wiring. A concept is proposed where each actuator and sensor is encapsulated in a kind of insert. The inserts smoothly integrate into the manufacturing process of the lining while they protect the actuators and sensors from humidity, dust, etc. The maintenance aspect is covered by the option to change each actuator or sensor upon insert level. The integrated wiring of the lining is left unaffected during an actuator or sensor replacement since connectors in each insert allow a nearly tool-free assembly/disassembly.

In this paper the progress of work package 3 is presented at a detailed design review (DDR) stage. Finally, the lining will be manufactured and equipped with a full ASAC system. Experiments will be conducted in the acoustic transmission loss facility at the DLR.

Introduction

CROR propulsion systems are a promising concept to reach a resource efficient transport demanded by the European Commission in the Horizon 2020 framework program. Due to their fuel efficiency they are discussed as an alternative to common jet engines. Within in the EU-project ACASIAS the active acoustic lining panel is seen as an enabler for the CROR technology. For sound pressure levels (SPL) of up to 130 dB in the nearfield of the engine [1] and fundamental blade passing frequencies around 100 Hz common insulation strategies fail in reducing the SPL in the cabin to an admissible level for the passengers. Many active methods like ASAC have been developed to reduce the noise transmission through single or double walled structures [2, 3]. In most of the contributions to this

subject laboratory equipment and rapid prototyping controls are used for the realization of the active system. Bringing active systems into real world applications requires small, cost extensive devices and a straight-forward manufacturing concept.

The objective of the ACASIAS project is to go the next step towards the integration of ASAC systems in aircraft linings. This will be achieved by selecting off-the-shelf components for the control system and by creating a production-friendly integration approach. In this paper the setup for an active acoustic lining as technology demonstrator is discussed. First, the dimensions of the lining are defined followed by a component selection process which incorporates different actuator and sensor types. Requirements for the wiring are set which lead to a routing map. Finally, the integration concept for the actuators and sensors in form of an insert is presented, taking maintenance issues into account.

Lining



Fig. 1: Lining panel (orange) in front of fuselage

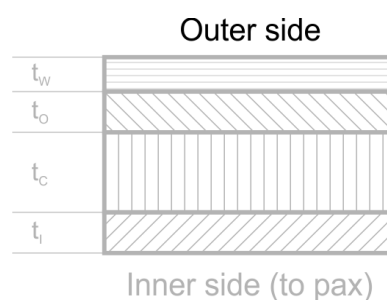


Fig. 2: Lining layup

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DLR is able to provide an A350-like fuselage panel with carbon fibre reinforced plastics (CFRP) skin and aluminium stringers and frames, see Fig. 1. It covers two frame widths and has the dimensions $1300 \times 1700 \text{ mm}^2$ (W x H). A wooden framework is available to mount the fuselage panel in the opening of the acoustic transmission loss test stand at DLR. According to the dimensions of the fuselage panel, the dimensions of the lining of app. $1300 \times 1690 \text{ mm}^2$ (W x H) are chosen. The lining is simply curved with a radius of app. 2980 mm. In the lower part of the lining the curvature slightly changes due to air outlets which are present in original linings of an A350. Windows are neglected since the effort and the costs for an adequate mould would be too high.

The lining panel is a sandwich part. Together with the industrial advisory board member Diehl Aviation the layup of the panel has been defined, see Fig. 2. On top of an inner prepreg layer with thickness t_l a honeycomb core of thickness t_c is placed. The core is covered with a single layer of open prepreg of thickness t_o . The wiring of the sensors and actuators is on top of this prepreg. The first idea of placing the wiring between the inner prepreg and the core is rejected since it exists the

Description	Material	Thickness
Wiring		$t_w < 0.04 \text{ mm}$
Outer layer	Gurit PF811-G231-32	$t_o = 0.2 \text{ mm}$
Core	Nomex honeycomb	$t_c = 6.5 \text{ mm}$
Inner layer	Gurit PH600-G227-40	$t_l = 0.19 \text{ mm}$

Tab. 1: Lining materials

probability that the wiring pushes through the prepreg and becomes visible on the passenger's side. Table 1 summarizes the layout data. The desired thickness of the final lining is 7.0 mm. The lining is mounted at six points of the fuselage structure. Three clips at the upper and three clips at the lower part of the lining are hooked into shock mounts located at the frames.

Sensors

The objective of the active acoustic lining approach is to provide an autonomous part which is independent from external inputs apart from electrical power. Therefore, microphones sensing the sound pressure level at the passenger's ears are excluded by default. The so-called remote microphone technique [4] enables the estimation of emitted sound of a structure based on acceleration measurements on the specific structure. In case of the active acoustic lining the sensing is realized as follows: The accelerations are input into a pre-calculated observer that estimates the sound pressure levels at selected positions in front of the lining. The accelerations have to be measured in normal direction of the lining's surface.

For the selection of suitable accelerometers, common laboratory equipment is not taken into account. The prices for sensors and cables are too high for any practical application. Instead, micro-electro-mechanical systems (MEMS) accelerometers are a cheaper alternative. Usually, they are provided as integrated circuits (IC) which have to be applied to a printed circuit board (PCB) together with additional electric components and connectors.

The requirements for this application that have to be fulfilled by an accelerometer are limited to the mass, the footprint size and the measurement range. Table 2 summarizes the requirements for the sensor. The measurement range derives from previous projects where experiments at linings were conducted.

Description	Value
Mass	max. 20 g
Footprint size	max. 20 x 20 mm ²
Measurement bandwidth	min. 500 Hz
Measurement range	min. 2 g = 19,62 m/s ²

Tab. 2: Sensor requirements

A market survey based on an internet research is created, where only large suppliers were taken into account. Several types of sensors can be identified which fulfil the given requirements. However, these sensors differ in their connectivity. Three main interfaces are identified: Analogue connection, serial peripheral interface (SPI) and Inter-Integrated Circuit (I²C).

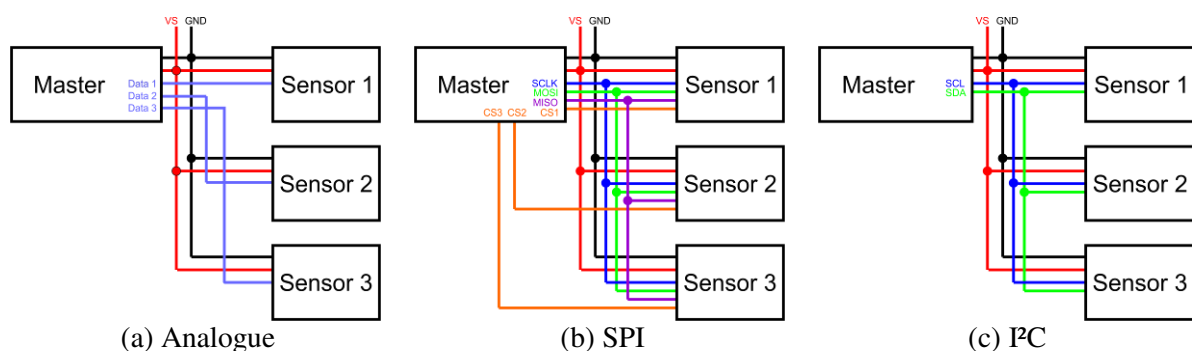
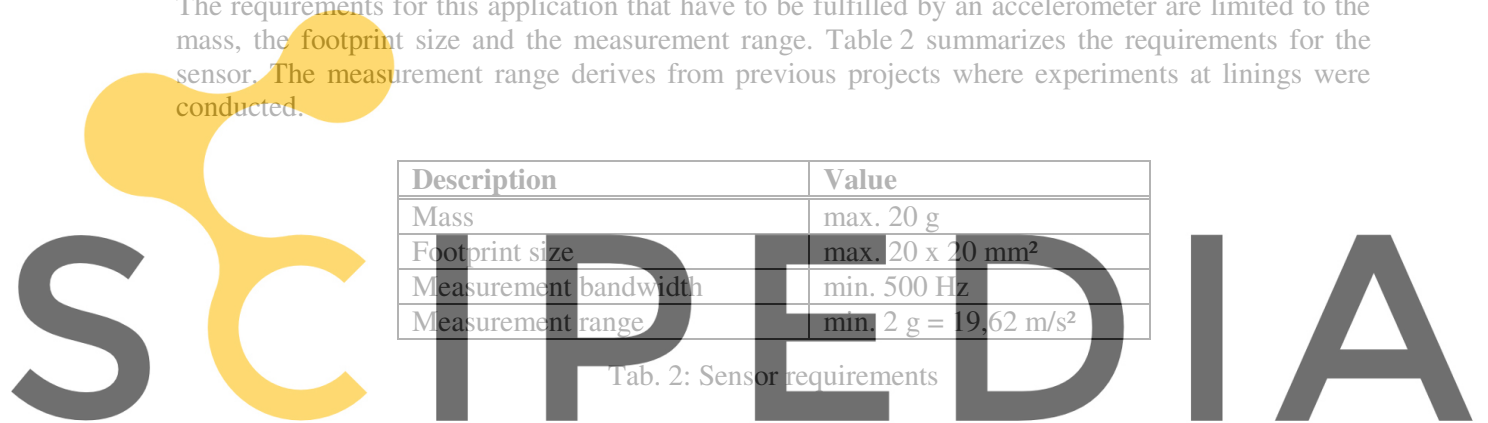


Fig. 3: Sensor interface types

Figure 3 compares the wiring effort of the three interface types. While the analogue connection uses only a single data line, the two digital busses SPI and I²C need at least two bus lines. Another benefit of sensors with analogue interface is the easy to implement synchronized sampling of signals. With analogue interfaces the master has to provide synchronized sampling, the data is always available. The sensors with digital busses have to be synchronized by the master and have to be addressed for data transfer. Timing issues are possible and the address space is limited for a larger amount of sensors. Therefore, the analogue interface is preferred for this application.



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The further selection process leads to an accelerometer by ANALOG DEVICES[®]. The ADXL 354 has a measurement range of 2 g and a bandwidth of 1.5 kHz. Its footprint size of 6x6 mm² is ideal suited leaving enough space for additional circuitry. Figure 4 shows the accelerometer on an evaluation board and its pin configuration.

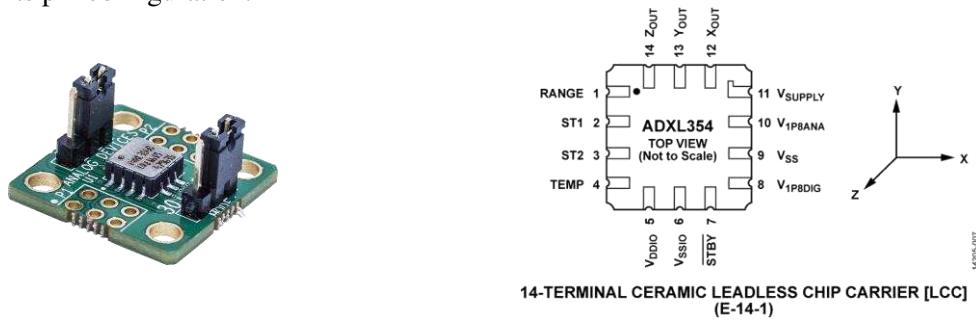


Fig. 4: Accelerometer ADXL 354¹

Actuators

The fundamental CROR frequencies in the given load case are located close to 120 Hz. The bandwidth of the actuators therefore has to cover the interval from 100 to 500 Hz. Electrodynamic exciters are best suited for this bandwidth. First, piezo actuators were taken into account, but finally fell off due to poor performance in this frequency bandwidth. At best they could complement the exciters as a kind of tweeters for passenger announcements.

As a base line for the selection of an appropriate actuator type the VISATON[®] EX45S is chosen. Previous experiences from the SYLVIA project [5] show that this type is able to gain sufficient performance and control authority. A market survey among leading exciter manufacturers like DAYTON[®], VISATON[®], TECTONIC[®] and ELAC[®] is compiled to find adequate candidates. The purpose is to identify exciters with higher or equal forces factors (Bl) than the base line. Additional requirements are only imposed on the mass and the footprint size, see Tab. 3. The mass is oriented at the mass of the base line exciter.

Description	Value
Mass	max. 100 g
Footprint size	max. 50 x 50 mm ²

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 Tab. 3: Actuator requirements

Different exciters were tested and a few have been selected for further experiments on an iron sprung foundations in the lab. A load cell is attached to the foundation. On top of the load cell four exciter types are mounted successively. Estimation of the exciter current is realized with voltage measurement over a 0.1 Ω resistor. The exciters under test are a DAYTON[®] DAEX25-VT4, an ELAC[®] 83005, an ELAC[®] 84005 and the base line VISATON[®] EX45S. The frequency response function (FRF) from input current to output force is determined. According to [6] the force factor Bl can be estimated from this FRF for frequencies $\omega \gg \omega_e$, where ω_e is the exciter eigenfrequency. The result is shown in Fig. 5. The eigenfrequencies ω_e of the exciters under test are located around 100 Hz. The force factor Bl can be estimated in the bandwidth 500 – 600 Hz since the FRF is constant and $\omega \gg \omega_e$ is valid. Both ELAC[®] exciters beat the base line exciter from VISATON[®] while the one from DAYTON[®] falls short of it. Due to the shown performance, the ELAC[®] 84005 is chosen for this application.

¹ Image source: analog.com

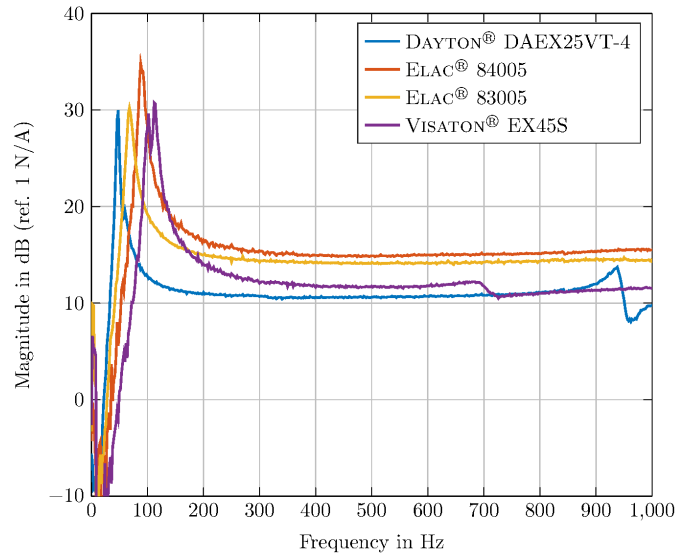


Fig. 5: FRF from exciter current to exciter force

Actuator & Sensor Definition

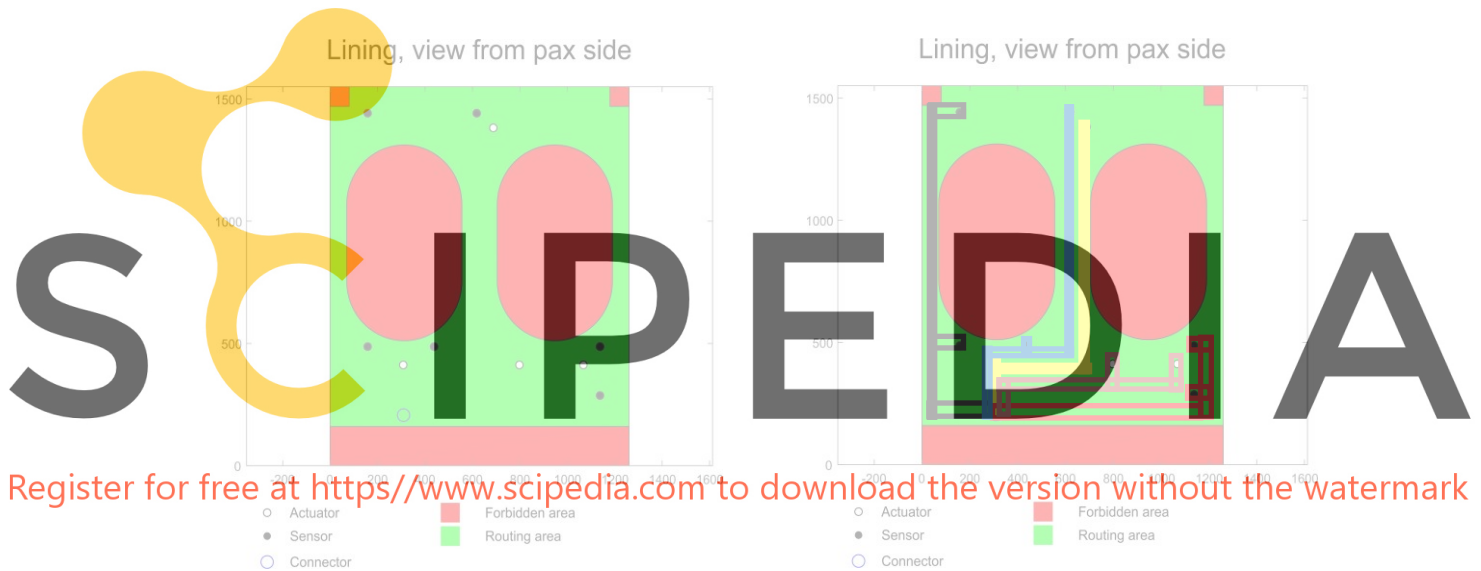


Fig. 6: Placement of actuators and sensors

Fig. 7: Routing of wiring

The actuators and sensors are defined in a two-step procedure. Firstly, the required number and secondly, the placement of the transducers is determined. This process is not independent from the dominant noise sources (load case) present in the aircraft. Here, two different load cases are considered for the definition of the remote sensors and the actuators. These are, first, a multi-tonal excitation of a CROR engine and, second, a broadband excitation typical for a turbulent boundary layer excitation (TBL). For the sensor definition, the defining load case is the broadband excitation whereas the actuators are defined for the CROR load case. In both cases the number of transducers is more important than the placement. A detailed description of the process of actuator and sensor definition is provided in [4]. The following description briefly summarizes the main considerations and results of this process.

Theoretically, for the deterministic CROR load case, a single remote sensor is sufficient to estimate the pressure at the virtual locations. However, the use of a single remote sensor is considered unreasonable with regard to robustness because its failure would tie the whole system. Furthermore, in the broadband case, an accurate pressure estimate requires a sufficient number of remote sensors. A quantification of sufficiency is provided by the multiple coherence function. Therefore, it is applied as a metric to, firstly, define the required number and, secondly, the best combination of remote sensors. The best sensor configuration with six remote sensors (see Fig. 6) achieves a mean

coherence value (averaged in the considered frequency range and over all microphones) of app. 80% which explains roughly 90% of the SPL in front of the lining (for the broadband load case).

The number of actuators is determined by the requirement of sufficient control authority to counteract the SPL in front of the lining induced by the CROR engine. The SPL produced in the laboratory by a loud speaker array in front of the fuselage is roughly 113 dB and the SPL estimated for a real CROR engine is 130 dB [1]. Therefore, the selected actuator configuration must provide a stroke excess of at least 17 dB (app. a factor of 7). The evaluation of actuator FRF (voltage to sound pressure) for different positions on the lining provides an estimate of the required actuator number and, furthermore, permits the selection of the most suitable positions. It turns out that four actuators of the type VISATON® EX45S are able to cancel the SPL in front of the lining for external SPL up to 130 dB (with a safety factor of two imposed on the actuator control voltage). See Fig. 6 for the final actuator placement. The results can be transferred to any other actuator type with a known FRF (current to force, see Fig. 5) characteristic. It can be deduced from Fig. 5 that the chosen actuator type ELAC® 84005 is more powerful than the VISATON® EX45S. Hence, the required control authority for external SPL up to 130 dB is guaranteed by this choice.

Wiring



Fig. 8: FPC examples

All sensors and actuators of a single lining have to be connected to the corresponding controller. This is realized by routing all connection lines to a single main connector at the bottom of the lining, see Fig. 6. The wiring and the main connector are placed at the outer side of the lining pointing towards the fuselage, compare Fig. 1. The wiring consists of flexible printed circuits (FPC), see Fig. 8, connecting two actuators/sensors at a time with the lining connector. The objective of the routing is to minimize the width of each FPC since it is limited by the manufacturing process. Figure 7 shows the final routing of the wiring. Two actuator FPC (brown & yellow) and three sensor FPC (black, blue & red) are needed to connect all items.

The requirements on the wiring with respect to voltage and current are estimated roughly using values from the datasheets of the selected actuator and sensor types. For the actuator an absolute peak voltage $U_{\text{peak}} = 15 \text{ V}$ is given [7]. The minimum resistance is the one of the voice coil at DC $R_e = 6.15 \Omega$. The absolute peak current of the exciter is therefore estimated with

$$I_{\text{peak}} = \frac{U_{\text{peak}}}{R_e} = 2.44 \text{ A} \quad (1)$$

The maximum supply voltage $U_{\text{supply}} = 3.6 \text{ V}$ is given in the datasheet of the ADXL354 [8]. In measurement mode the chip sinks $150 \mu\text{A}$. With a safety factor of two the maximum supply current is estimated with $I_{\text{s,max}} = 300 \mu\text{A}$.

The conductor cross-sections are determined by the maximum currents of actuators and sensors. Figure 9a shows the symbolic cross section of the sensor FPC. The substrate in yellow is the base for the sensor lines. The copper lines are illustrated in orange. The numbers give their width and their distance in mm. According to Fig. 3a four wires are needed to connect two analogue sensors. The common ground and power lines are located in the centre while the data lines are outside.

The actuator FPC has a comparable design. Figure 9b shows four lines on the substrate. Each actuator needs to separate wires. Due to higher currents the width of the lines are significantly higher than for the sensor lines. The height of both FPC is set to 0.035 mm.

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2	0,2	0,5	0,2	0,25	0,2	0,5	0,2	2	mm	6,05
data1		gnd		pwr		data2				

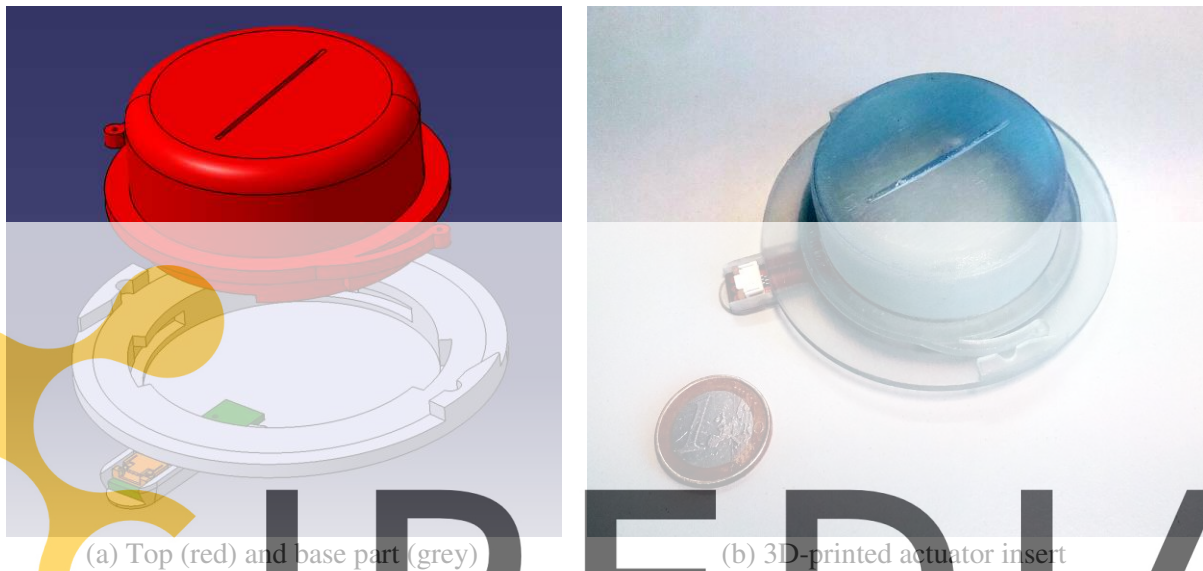
(a)

2	1,7	0,25	1,7	0,5	1,7	0,25	1,7	2	mm	11,8

(b)

Fig. 9: Cross sections of the sensor (a) and the actuator FPC (b)

Inserts



(a) Top (red) and base part (grey)

(b) 3D-printed actuator insert

Fig. 10: Concept of the two-part insert

The main aspect of work package 3 of ACASIAS is enabling an industrial manufacturing process for the active lining by integrating actuators, sensors and wiring. The requirements for the integration concepts can be summarized as follows:

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- Protection of items from moisture intrusion
- Smooth electrical connection between wiring and items
- Seamless integration into manufacturing process
- Robust mechanical connection for load application (actuator) and signal quality (sensor)
- Repair and maintenance on item level

For the integration of sensors and actuators a concept with inserts is proposed. Each item is enclosed in a two-part insert, see Fig. 10. The base part is integrated into the sandwich panel of the lining. The removable top part houses the sensor or actuator. The mechanical connection of the two parts is realized with a bayonet connector that is inserted and turned for fastening. Two snap connectors prevent the loosening of the parts. Since actuators and sensors have different footprint sizes and heights, two versions of inserts are manufactured. They only differ in dimensions but the design remains the same for both.

The base part is connected to the FPC by an external connector on a printed circuit board (PCB). The connector is mounted on a tab outside of the base part. The PCB, see Fig. 10a in green, reaches through the outer shell of the base part and has contact surfaces on top.

After the insertion process of the FPC the external connector is sealed with resin to prevent moisture intrusion. Depending on the item in the top part, the PCB has two surfaces for an actuator and three for a sensor. Spring contacts in the top part contact to the surfaces during fastening of the bayonet connector and establish the connection between items and wiring. The entire insert is sealed with an

O-ring between top and base part. The application of loads from actuator to lining is accomplished with circumferential shoulders at the top and at the base part.

The industrial integration process therefore roughly outlines as follows:

- Build layup of sandwich lining structure in a mould
- Crush the honeycomb core at actuator and sensor locations to create a sink for all base parts
- Add additional prepreg snippets to reinforce the sinks
- Cure the lining
- Apply the wiring and the main connector
- Integrate all base parts, connect them to the FPC and seal the connectors
- Plug in all top parts

A detailed description of the manufacturing process can be found in [9].

Conclusion & Outlook

Within this paper a concept for the integration of actuators, sensors and wiring in a lining panel is proposed. Inserts allow the realization of an industrial manufacturing process. The chosen actuator and sensor types enable a cost efficient setup of an ASAC system in a cabin environment comparable to an Airbus A350. Maintenance requirements are met since the top parts of the insert are changeable. The placement of all components of the ASAC system in a lining gives the opportunity to even create a retrofit solution for existing turboprop aircraft.

Next steps in WP 3 will be component test where a base part of an insert is set into a lining sample and connect to an FPC. Function test will approve the concept. In the remaining time of the project an entire lining panel will be manufactured as proposed in the last section. It will be equipped with actuators and sensors. A controller that implements ASAC will be designed and applied to the lining. Acoustic experiments at DLR will prove the performance of the entire system.

Acknowledgments

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