Structural integrated sensor and actuator systems for active flow control

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ABSTRACT

An adaptive flow separation control system is designed and implemented as an essential part of a novel high-lift device for future aircraft. The system consists of MEMS pressure sensors to determine the flow conditions and adaptive lips to regulate the mass flow and the velocity of a wall near stream over the internally blown Coanda flap. By the oscillating lip the mass flow in the blowing slot changes dynamically, consequently the momentum exchange of the boundary layer over a high lift flap required mass flow can be reduced. These new compact and highly integrated systems provide a real-time monitoring and manipulation of the flow conditions. In this context the integration of pressure sensors into flow sensing airfoils of composite material is investigated. Mechanical and electrical properties of the integrated sensors are investigated under mechanical loads during tensile tests. The sensors contain a reference pressure chamber isolated to the ambient by a deformable membrane with integrated piezoresistors connected as a Wheatstone bridge, which outputs voltage signals depending on the ambient pressure. The composite material in which the sensors are embedded consists of 22 individual layers of unidirectional glass fiber reinforced plastic (GFRP) prepreg. The results of the experiments are used for adapting the design of the sensors and the layout of the laminate to ensure an optimized flux of force in highly loaded structures primarily for future aeronautical applications. It can be shown that the pressure sensor withstands the embedding process into fiber composites with full functional capability and predictable behavior under stress.

Keywords: adaptive structures, smart materials, piezoelectric actuators, flow control

1. INTRODUCTION

As part of the Collaborative Research Center (CRC) 880 “Fundamentals of High Lift for Future Commercial Aircraft” the Technische Universität Braunschweig and the German Aerospace Center (DLR) develop an adaptive airfoil for novel high-lift devices. The increase in future air traffic will lead to additional flights from smaller airports near urban areas. Therefore measures must be taken to reduce the noise level during takeoff and landing phases. The efficiency of short takeoff and landing (STOL) aircraft depends particular on the achievable uplift coefficient induced by supplementary high-lift devices. One first step to optimize the performance of commercial aircraft could be the structurally conformal integration of sensors and actuators into the airfoil to save weight and reduce air drag. At the end of the desired functional integration stands the development of adaptive airfoils, which include all systems for active flow control to implement novel high-lift devices which adapt to each flight phase. One part of this system is a very compact oscillating piezo actuated lip of a blowing slot ahead of a Coanda flap. To avoid flow separation on the Coanda flap, a closed loop controlled system is evolved in order to dynamically adjust the Coanda jet to the current state of flight. The flow condition is measured using micro fabricated pressure and hot film sensors which are integrated into the airfoil. Using an additional pressurized mass flow $\dot{m}$ the velocity of the Conada jet is controlled by an adaptive lip that varies the height h of the blowing slot (Figure 1).

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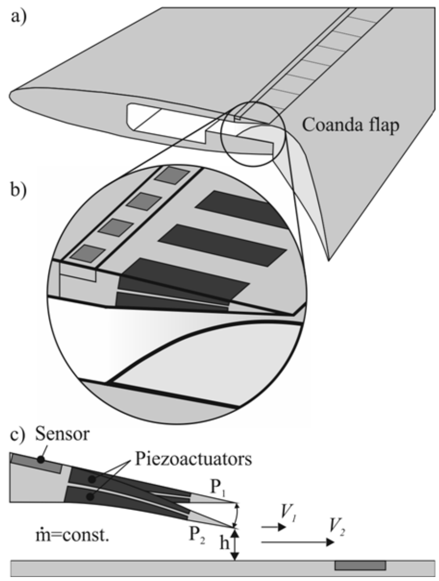

Figure 1. Coanda-Flap including an actuated lip a) gives an overview, while b) shows a detailed view on the actuated lip [1].

1.1 Airfoil

The Coanda effect on airfoils with highly deflected flaps has been investigated at the Institute of Fluid Mechanics for years using the well-known reference airfoil DLR F15 [2]. The sensitivities and optimal geometries for Coanda radius and slot height were determined numerically [3, 4] and verified in wind-tunnel experiments [5, 6]. Recent studies show further increases in efficiency by adding a shape adaptable leading edge (droop nose) [7]. The advantages of the droop nose configuration are improved stall behavior, reduction of the necessary mass flow for blowing by almost 30 %, and reduction of pitching moment by 15 %.

2. PRESSURE SENSORS FOR FLOW SENSING

2.1 Sensor design

The schematic cross section of a microfabricated pressure sensor to be used for flow sensing is shown in Figure 2. The sensor is made of n-doped silicon substrate. It comprises a wet etched reference chamber isolated from its surrounding by a deformable membrane that holds a thicker boss structure in the center. Positive doped piezoresistors are applied to the membrane's surface using a diffusion doping process. The electrical connection is realized by aluminum tracks. A glass substrate encapsulates the reference chamber.

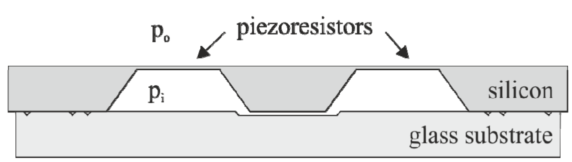

Figure 2. Schematic cross section of a pressure sensor.

For mechanical protection and electrical passivation the sensor surface is covered with a thin layer of silicon nitride; opened at the contact pads for electrical connection. With a difference between the chamber pressure p_i and the ambient pressure p_0 the membrane deflects and the mechanical surface stress in the membrane leads to a resistance change of the piezoresistors. The resistors are connected as a Wheatstone bridge in order to reach high sensitivity when decreasing and increasing resistances placed at opposing locations are used. Further information on the sensor can be found in [8]. For tensile stress tests two sensor designs with similar pressure sensitivity but different alignments of the piezoresistors (see Figure 3) were used.

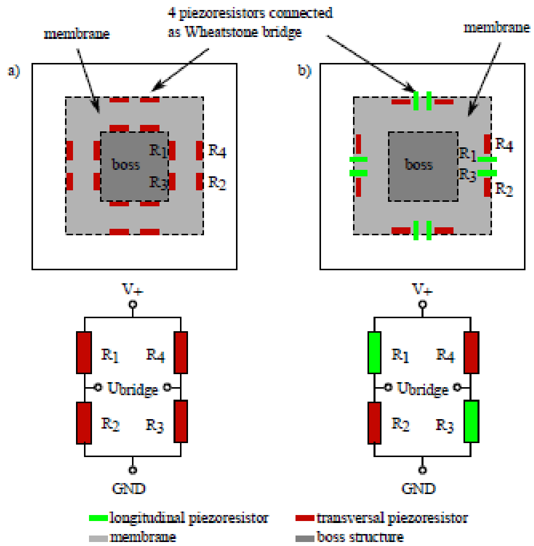

Figure 3. Pressure sensor designs with a) only transversal oriented piezoresistive paths and b) transversal oriented paths mixed with longitudinal oriented paths.

In version (a), all piezoresistors *R1* to *R4* are aligned transversally to the local directions of deformation in the membrane. Increasing and decreasing resistances in the Wheatstone bridge are realized by selecting areas with compression stress (close to the boss; increasing resistance) as well as tensile stress (close to the solid frame; decreasing resistance). In version (b) longitudinal (*R1*, *R3*) together with transversal (*R2*, *R4*) resistor orientations were used in order to obtain both longitudinal and transversal piezoresistive effects. All resistors are placed on the tensile stress area, so the resistance of longitudinally aligned resistors increases and the resistance of transversally aligned resistors decreases with increasing ambient pressure.

3. ADAPTIVE SLOT-LIP FOR FLOW CONTROL

The preliminary design of the slot-lip is based on FEM calculations. A modular design of the slot-lip in span wise direction providing separately controllable digits is aimed for better controllability and adjustability. Figure 4 shows the current state of design for one slot-lip segment.

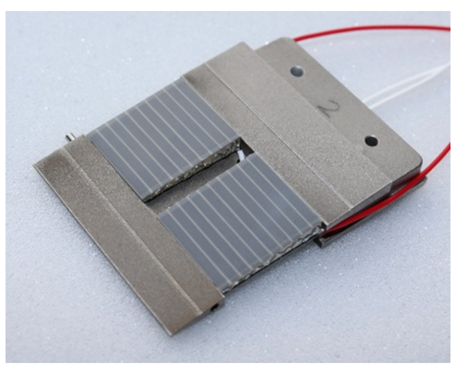

Figure 4. Current design of a slot-lip segment.

Different configurations of bending transducers are considered and investigated in order to realize the upwards and downwards movement of the slot-lip tip. Two monomorphic designs and one trimorphic design were investigated. The monomorphic concepts are unable to actuate in two directions except a preload is applied. A preload in this case can be a pre-applied electrical voltage or a pre-applied mechanical deformation. In contrast to this the bending transducer concept featuring a trimorphic configuration enables actuation upwards and downwards without being limited to preload the slot-lip. These considerations and a detailed FEM analysis result in the selection and further development of the trimorphic bending actuator for the slot-lip. This is underlined by Figure 5 as it depicts the higher potential of a possible active tip deflection (Δu) for the trimorphic configuration over the whole differential pressure (Δp) range. At an assumed differential pressure of 6 bar, the overall displacement of the slot-lip is 0.255 mm and meets the required value of 0.2 mm with a buffer of just over 25 %. Only a shift of the initial position of the slot-lip is detected, which can be easily adjusted at the assembling.

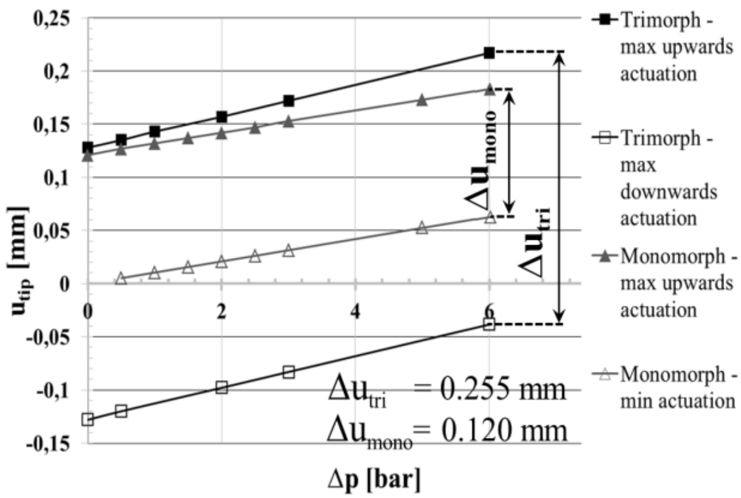

Figure 5. FEM calculation of active lip tip deflection of tri- and monomorphic concepts at different differential pressures.

The slot-lip comprises several segments in span wise direction, adding up to an overall length of approx. 1000 mm. This design allows a separate control of each segment and therefore a much higher controllability of flow. Every segment, with its backbone structure (substrate) made of stainless steel holds several trapezoidal actuators on the upper and lower side, bonded with an adhesive to it. The current design comprises 2 segments on each side.

The actuation of the slot lip is realized by trapezoidal multilayer piezo actuators, using the d_{33}-effect. These precisely cut actuators have their origin in the SCMAP-NCE51 Stacked Ceramic Multilayer Actuator manufactured by Noliac A/S. They are considered to feature a superior lifetime, a large operating temperature range from -40 °C to 150 °C. The demanded low operating voltage is fulfilled by the use of this actuator type as it operates from -20 V to 200 V. This is a significant advantage over Macro-Fiber Composite (MFC) and Active Fiber Composite (AFC) actuators. As shown in a previous study a maximum free strain of approx. 1400 µm/m at a 10 times lower operating voltage can be achieved for multilayer actuators [9]. Named after their composition of multiple material layers these actuator types are built up of 100 µm thin piezo ceramic layers and alternating interdigital electrode layers connected with an elastic connector electrode on each side of the actuator (in the direction of main expansion). The multilayer actuators used are further more diced from a compact stack that features a ceramic insulation layer as outer surface, and is embedded in a polymer afterwards. This provides a mechanical stabilization on the one hand and an electrical insulation with a diffusion-resistant coating on the other hand.

4. INTEGRATION OF PRESSURE SENSORS INTO COMPOSITES

4.1 Embedding process

The pressure sensors are embedded in a laminate of unidirectional glass fiber reinforced plastic (GFRP) prepreg (HexPly® 913 from Hexcel Corporation). For the development of the integration technology several specimens for tensile tests are produced whose dimensions are matched to the geometry of the integrated sensors. The laminate is made up of 22 individual layers with a 0°/90° layout, where 7 individual layers correspond to the thickness of one sensor (Figure 6). In the integration areas the layers are cut out in order to avoid adverse thickenings. The samples are processed under vacuum in an autoclave and cured at 120 °C for 2 h at a pressure of 3 bar. The function of the embedded sensors is checked after the lamination process by static pressure tests.

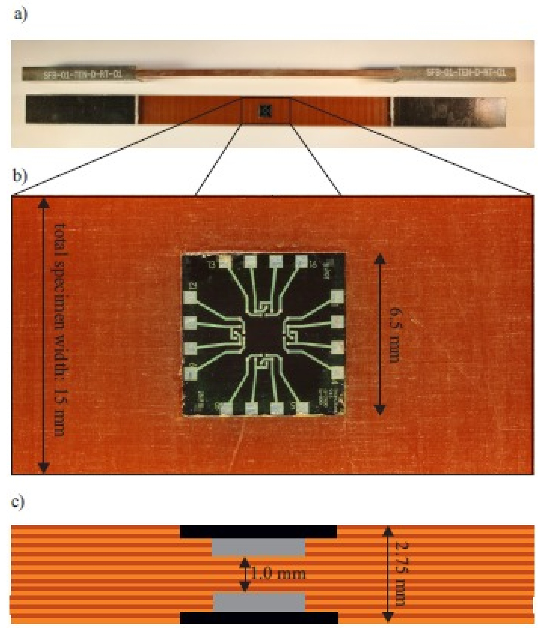

Figure 6. a) tensile test sample, b) detailed view of the embedded sensor, c) schematic cross section of tensile test sample.

4.2 Tensile stress test

The test setup is designed to obtain the sensor signals as well as the mechanical deformation of the sensor and the composite material itself. The samples are clamped in a tensile testing machine and loaded to fracture. Simultaneously to force and elongation the electrical signals of the sensors are recorded. The sensor voltage (*V+* to *GND*) is set to 1 V. Using an optical 3D measuring system (ARAMIS) the areal deformation of the specimen is captured, which is not possible with traditional measuring systems such as strain gages. With a suitable choice of the resolution the true 3D stress-strain behavior of the samples can be determined and the plain strain tensor for each measurement point can be received. Measurements on all devices are started with a comparable time base. The tests are performed for both sensor designs up to visible fracture of the sensor.

4.3 Results

In Figure 7 (b) you can see the local stress-strain behavior of a loaded sample with a tensile force of 1 kN. Around the area of the embedded sensor increased strain values are detected. The strain tensor shows that the force flow is diverted around the embedded sensor which results in strain peaks in this area and this finally leads to fracture of the composite at a tensile force of about 15 kN. First failures of the pressure sensors are initiated much earlier at a tensile force of about 4 kN. It can be seen that high differences occur between the low strains within the sensor area (square in the middle) and the stresses in the surrounding composite. The material interfaces perpendicular to the external tensile stress direction are exposed to local strain concentrations at the transition zone between the sensor and the composite. Finally the sensor begins to lose its mechanical connection to the laminate.

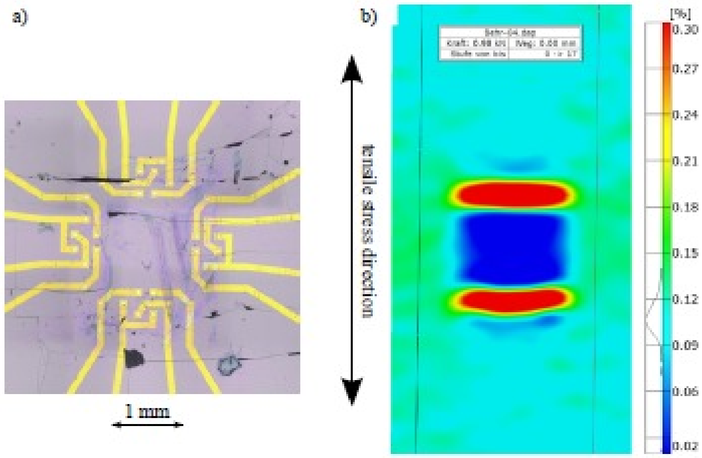

Figure 7. a) sensor damage after tensile stress test, b) mechanical deformation of the sample at 1 kN.

The sensor signal output U_{bridge} with $p_0 = const.$ is shown in Figure 8. It can be seen that the signal of the sensor having only transversal piezoresistors remains nearly unchanged for all four Wheatstone bridges (compare with Figure 3) up to its damage indicated by sudden and steep output changes (blue line). In contrast, the signal of the sensor with the combination of longitudinal and transversal piezoresistors (red line) shows a continuous decrease or increase depending on strain direction versus bridge orientation with increasing external strain. Note that the different critical elongations for the two curves in Figure 8 do not indicate a trend because the point of damage varies already within the same design. The different signal behaviors are a consequence of the different alignments of the piezoresistors in combination with their interconnection within the Wheatstone bridge circuitry (Figure 3). Having the same alignment of all sensors within one bridge, all resistances are changed by the external stress with the same rate; the effect of external mechanical stresses is therefore compensated. In contrast, with the combination of longitudinal and transversal piezoresistors, external mechanical stresses in the directions parallel to the membrane surface have a similar result as pressure driven out-of-plane deflection of the membrane. The sensor is therefore not able to distinguish between variations of ambient pressure and external stresses parallel to the membrane. Figure 7 (a) shows a sensor after being loaded until fracture. It can be seen that most of the cracks are orthogonally aligned to the tensile stress direction. Furthermore cracks occur on the membrane as well as on the bulk material.

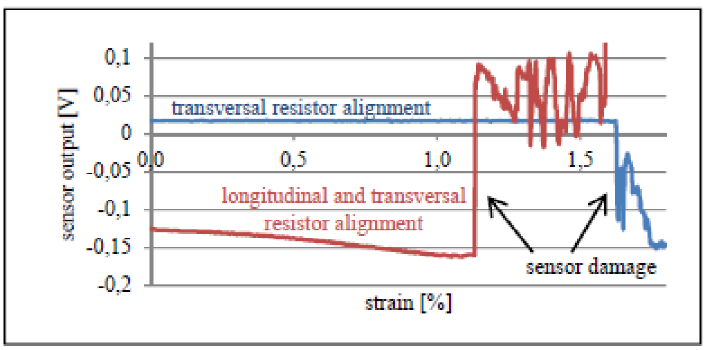

Figure 8. Output signals of different sensor designs during tensile test.

5. CONCLUSION AND OUTLOOK

Provided that suitable cut-outs are prepared in the prepreg MEMS pressure sensors can be integrated without damage and without perturbing surface steps during composite lamination processes. Tensile tests of composite samples with embedded sensors revealed that sensor signals unsusceptible to external tensile stress can be obtained with designs where four piezoresistors within a Wheatstone bridge configuration are all aligned in one direction. Furthermore, orthogonally orientated piezoresistors in one bridge allow quantifying the in-plane tensile stress due to external tensile forces.

At tensile load undesired stress concentrations occur in the vicinity of the interfaces between the composite and the embedded sensors which ultimately lead to device damage. The results of the experiments are used for adapting the design of the sensors and the layout of the laminate to ensure an optimized flux of force in highly loaded structures primarily for future aeronautic applications. To reduce local stress accumulation sensor outer geometries with sharp 90° corners should be avoided and the transition zone material should be optimized. This can be achieved by gradation of the material stiffness in the composite e.g. by embedded metal foils [Figure 9]. The goal is the prevention of stress peaks at the transition zone between composite and sensor. High tensile loads occur in stress concentrations at the interfaces between composite and embedded sensors which ultimately lead to component failure. By variable stiffness gradients the previously separation between rigid and flexible components may be canceled, which may lead to completely new design solutions.

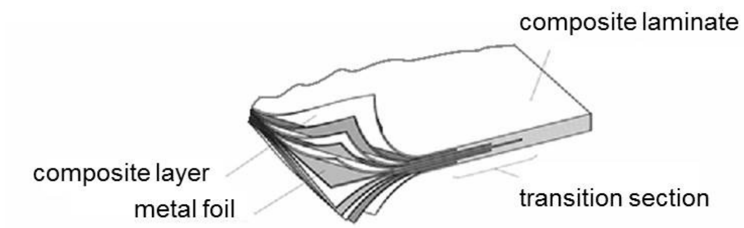

Figure 9. Laminate layout with metal interlayer for stiffness gradation.

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