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PVDF SENSOR ARRAYS FOR APPLICATIONS IN AEROSPACE

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Abstract. The development of the next generation of engines, specifically the Geared Turbofan Engine (GTF Engine), presents a significant challenge. One of the key objectives is to provide a stable flow over the entire range, including at the edges, in order to achieve an 11% reduction in fuel burn. This objective is aligned with the EU's climate-neutral aviation Clean Sky 2 program [1], which aims to reduce CO_2 and noise emissions by approximately 30% by the year 2030. To achieve this, it is necessary to optimize the aircraft structure to reduce internal and external noise generated by TBL pressure fluctuations. This requires high fidelity characterization of the wall pressure spectrum in spatial wavenumber space and in temporal frequency. Existing sensor solutions, such as bulky and expensive semiconductor-based pressure sensors, do not meet all the requirements. To address this limitation, a new high-performance wall-mounted sensor array for surface unsteady pressure and wall shear stress measurements has been developed. This new sensor array overcomes the limitations of existing solutions by providing more information about the interactions, as well as improved resolution and frequency domain capabilities. This will enable the development of more efficient and environmentally friendly aircraft engines.

The authors conducted tests in a supersonic wind tunnel using the developed sensor arrays and a reference sensor system from Kulite. Results demonstrate that the new sensor system is able to match the reference sensor signal precisely. The sensor system is flexible and can be integrated into all surfaces in aerospace. This technology can improve the accuracy and efficiency of SBLI applications, leading to more effective and fuel-efficient aircraft designs.

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Key words: PVDF Sensors, Sensor array for unsteady wall-pressure measurements, 3D sensor integration.

1 INTRODUCTION

The development of the next generation of engines, specifically the Geared Turbofan Engine (GTF Engine), presents a significant challenge. One of the key objectives is to provide a stable flow over the entire range, including at the edges, in order to achieve an 11% reduction in fuel burn. This objective is aligned with the EU's climate-neutral aviation Clean Sky 2 program [1], which aims to reduce CO_2 and noise emissions by approximately 30% by the year 2030. To achieve this, it is necessary to optimize the aircraft structure to reduce internal and external noise generated by TBL pressure fluctuations. This requires high fidelity characterization of the wall pressure spectrum in spatial wavenumber space and in temporal frequency. The current state-of-the-art for pressure sensors in aerospace applications involves bulky and expensive semiconductor-based pressure sensors, such as silicon-based piezoresistive sensor solutions from company Kulite [2]. However, these sensors have limitations in resolution and frequency domain and do not provide sufficient information about the interactions that occur during flight. To address these limitations, a new high-performance wall-mounted sensor array for surface unsteady pressure and wall shear stress measurements has been developed. This new sensor array utilizes PVDF-foils, a flexible and thin material that can be structured to form small electrodes for piezoelectric sensors. The sensor array is designed to be compact and does not require any bumps or bond wires for contacting, making it small in size and highly integrated. Overall, this new sensor technology represents a significant improvement over the current state-of-the-art for pressure sensors in aerospace applications. The high-performance wall-mounted sensor array provides more information about the interactions that occur during flight and has improved resolution and frequency domain capabilities, allowing for more efficient and accurate measurement of pressure and shear stress.

Our paper presents a 3D piezoelectric sensor array setup designed for use in SBLI (Separated Boundary Layer Ingestion) applications. We will focus on the sensor manufacturing technology, electronics, packaging, and some ideas for shielding in detail. The sensor system is designed to be compact and does not require any bumps or bond wires for contacting, making it very small in size. The electrical path could be realized vertical, resulting in a very short distance.

2 SENSOR ARRAY CONCEPT

One of the fundamental problems in fluid mechanics is the flow separation from a solid surface, which occurs for example in airfoil wings application. This separation is undesired due to the initiation of complex eddies and vortices, mostly resulting in increased drag and noise[1]. Precise monitoring of the separation and the boundary layer condition is essential to the

[1] Blake M.K. Mechanics of Flow-Induced Sound and Vibration. AP New York (1986)

development of systems for active flow control and of great importance for the understanding of flow phenomena such as transition, separation, and the reattachment. Active control of transition would contribute to the reduction of noise and skin friction drag, and thus improve air travel safety and airplane efficiency and noise pollution inside of the cabin and in proximity to airports. This breakthrough will open a completely new possibility in this research area.

For surface unsteady pressure and wall shear stress measurements different measurement methods implementing single pressure sensors like pinhole [3], piezoresistive [4][5][6], capacitive [7] and piezoelectric [8][9] can be used. Their choice is depending on different requirements like range, spatial and frequency resolution. Semiconductor based microsensors can be manufactured using standard CMOS technology quite easily and show very good performance. But they are not suitable for large-area measurement as they are small and bulky. Another disadvantage is the complexity of electronic circuits needed to compensate their humidity, temperature, dust and residual stress dependencies. Some research groups are using wall microphone array as their use is much cheaper than semiconductor single sensors [10][11]. Capacitive MEMS microphones are widely adopted in many applications, such as smartphones, tablets and PCs. These microphones have excellent acoustic performances but dust or liquids of any kind can permanently damage them. Most researcher to date use piezoresistive pressure sensors from company Kulite (often XCQ series Kulites®) for their work. Our sensor array is constructed using PVDF-material (Polyvynylidene fluoride – a flexible piezoelectric material). This material shows high piezoelectric effect and has some technological advantages. It can be extruded into very thin foils, or additively printed in small flexible electrodes. Features with some µm thickness can be realized. Such extremely flexible features allow construction of sensing devices which can be adapted to the morphology of the experimental setup used in aerospace application. Material properties of the PVDF material can be seen in the table below [9].

Table 1: Relevant PVDF properties in compare with other piezoelectric materials

Property	Units	PVDF	PZT	$BaTiO_3$
Density	$10^3 kg/m^3$	1.78	7.5	5.7
Relative permittivity		12	1,200	1,700
d_{31}	(10^{-12}) C/N	23	110	78
g_{31}	(10^{-3}) Vm/N	216	10	5
k^{31}	% at 1kHz	12	30	21
Acoustic impedance	$(10^6) kg/m^2 sec.$	2.7	30	30

Metal layers (Ag, Al, Au) are used on both sides of the foil for electrical contacts. They have been patterned using different methods (laser etching, wet etching, milling and additive using screen printing) to form small electrodes for the piezoelectric sensors. The figure below shows the sensor array foil schematically [12][13][14].

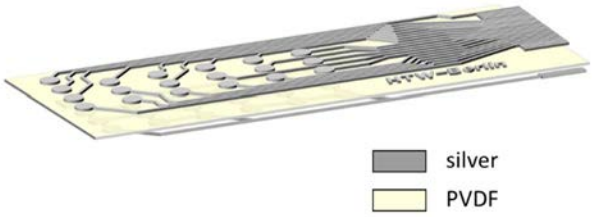
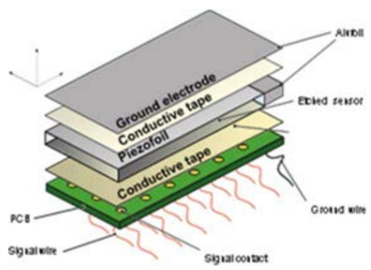
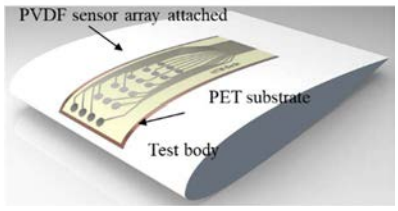


Figure 1: The schematic of the PVDF piezoelectric sensor foil used in this project. The silver structures can be realized additively or substractively at both PVDF-surfaces.

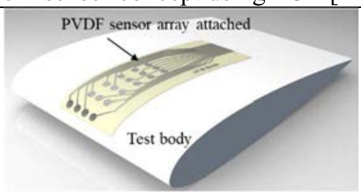
For sensor integration we use four system concepts in this project. The 3D system concepts are shown in the figure 2. In the first one, the sensor foil (figure 1) will be integrated directly on the PCB surface using a conductive tape for mechanical stabilization and electrical contact. Also, a shielding system can be realized by adding a ground electrode on top of the piezo foil to reduce the noise in the system. Vertical vias have been implemented in the PCB for electrical contacting. This concept allows a compact and easy to be used sensor system**.** In the second concept, the sensor foil is laminated on the surface of the test body in WTT (Wind Tunnel Test).



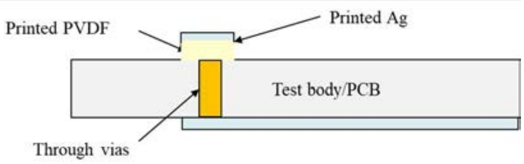
a) 3D sensor concept using PCB [12]



b) 3D concept using PET as carrier



c) Concept using gluing method to integrate sensor foil on test body



d) Concept using additive method to print PVDF and metal features / electrodes

Figure 2: Four integration concepts implemented in our project. Top left – concept using FR4 PCB with shielding layers (completed), top right – sensor foil using milled Ag-electrodes laminated on a PET carrier (work on going), bottom left – sensor foil with printed metal electrodes directly integrated onto the test body (work completed), and bottom right – sensor PVDF and metal features are printed on one foil carrier (work on going)

3 TECHNOLOGY

3.1 Sensor design

Different sensor layouts with 18 and 48 single sensor elements have been successfully realized. The single sensor elements do have different diameters (1,5mm to 4mm). As the generated charges and sensor dynamics are a function of the sensor size, it's a crucial parameter. Figure below shows the diameters and the layouts of the arrays with 18 sensors and 48 sensors.

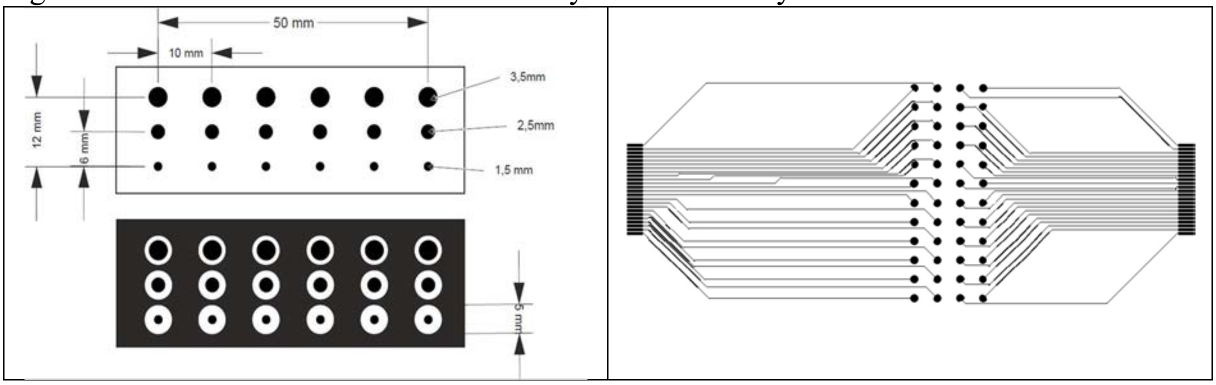


Figure 3: Sensor array with 18 single sensor elements for concept 1 (left) and right 48 sensor array for concepts 2, 3 and 4. Black are the metal structures. The sensor electrodes are in the range of 1,5mm-4mm. Sensor pitch is 5mm.

It has to be mentioned here, that the conducting lines have to be optimized further as they are contributing noises. It could be also implemented as shielding layer to reduce the signal noise.

3.2 Sensor Fabrication and integration

We use three material systems to fabricate the sensor arrays. First PVDF foil material from company TE Connectivity has been used [13]. The PVDF thickness are 28µm, 52µm and 110µm. The foils from TE are coated with Silver ink and NiCu metallization (11µm). The metal electrodes and conducting lines have been patterned using wet etching, laser etching and milling. The last one shows the best results regarding structure performances. Laser and wet etching are less compatible and can harm the PVDF layer. The second is the combination PVDF foil (110µm) and printed Ag ink using screen printing technique in our lab. It allows a quick manufacturing of large scale sensor arrays. And, the third is all printed version using PVDF and Ag inks. This combination has the potential to fabricate sensor arrays directly at the place of interest. The figure below shows the setup for milling and a sensor array prototype with 18 sensors. It can be shown, that large scale PVDF sensor foils can be fabricated and applied in such harsh environments.

The interconnection is another critical issue, since an appropriate interface between metal and signal conditioning system is needed in order to prevent unwanted noises and signal degradation. Various ways exist to create connections like penetrative techniques and non-penetrative one. Penetrative techniques would alter the shape of the film. In our work non-penetrative techniques using anisotrope conducting glue (3M™ 9703). A small real 3D sensor system using rigid PCB with through vias and conducting glue has been realized. An Aluminum can be applied on top as floating electrode to shield the sensor array.

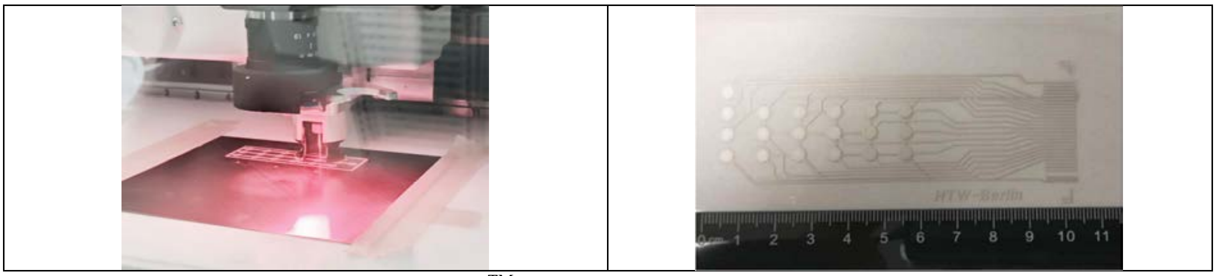


Figure 4: Set up for milling using LPKF™ Protomat S63 (left, and right a sensor array with electrodes and conducting lines on top.

Proper signal conditioning and amplification system is needed to obtain a signal readable with a good SNR (signal to noise ratio). The PVDF shows not only piezoelectric behavior but also pyroelectric and temperature dependency. The table and figure below show the amplifier design and the electrical circuit.

Table 2: Charge amplifier design parameters.

Op-Amp	C_f	R_f	R_i	C_p	f_r
TLC-272	100 pF	100 MΩ	56 Ω	10 pF	15.9 Hz

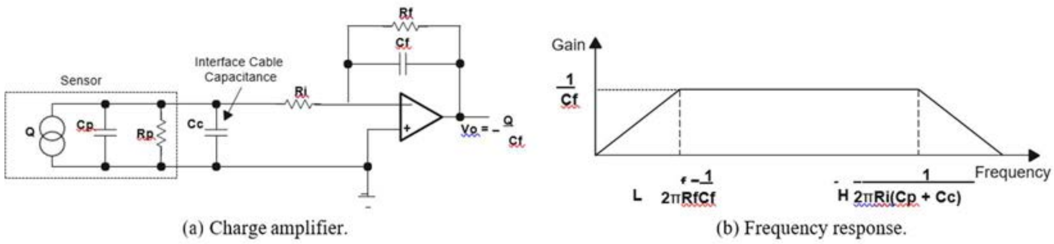


Figure 5: Electrical circuit of a charge amplifier and its frequency response [12]

4 MEASUREMENT AND CHARACTERIZATION

The experimental investigations was carried out in the supersonic wind tunnel at the Chair of Aerodynamics of Technische Universität Berlin. A schematic representation is shown in figure 6 [12]. The tunnel has continuous indraft operation: the air is sucked in by a centrifugal compressor, driven up to 16 000 rpm by a 400 kW electric DC motor, it goes through a heated drying chamber in the basement of the laboratory , and after passing past the settling chamber and screens, to reduce the turbulence level, it gets inside the test section, which is composed of a Mach 2 supersonic nozzle and a shock generator responsible for generating an incident SBLI with the (turbulent) floor boundary layer.

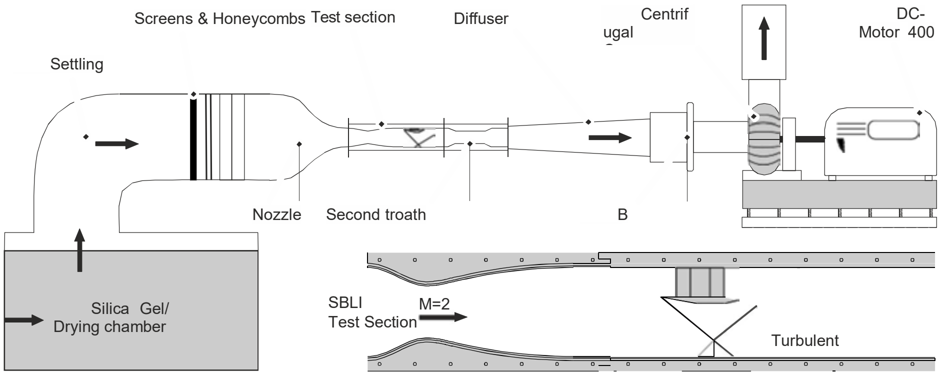


Figure 6: Schematic representation of the supersonic wind tunnel present at TU Berlin with a focus on the turbulent SBLI test section [12].

The flow field of interest is a turbulent shockwave boundary layer interaction generated by means of a shock generator with various flow deflection angles (6˚-10˚) used to create incident shocks of different strength. The topology of this kind of flow is shown in figure 7: the oblique shockwave, impinging on the turbulent boundary layer, generates a strong adverse pressure gradient. This separates the boundary layer and creates a separation bubble with reversed flow between the separation point S and the reattachment point R and with a characteristic length L_{sep}. The curvature of the bubble induces converging compression waves in the incoming flow that merges into a separation shock, interacting with the incident shock, and forming the characteristic Λ-foot of the separated SBLI. Another important parameter to consider for the following investigations is the interaction length L_{int} defined as the distance between the extrapolated impingement point x_{imp} (from inviscid shock theory) and the interaction onset x_0 where the wall pressure starts to rise.

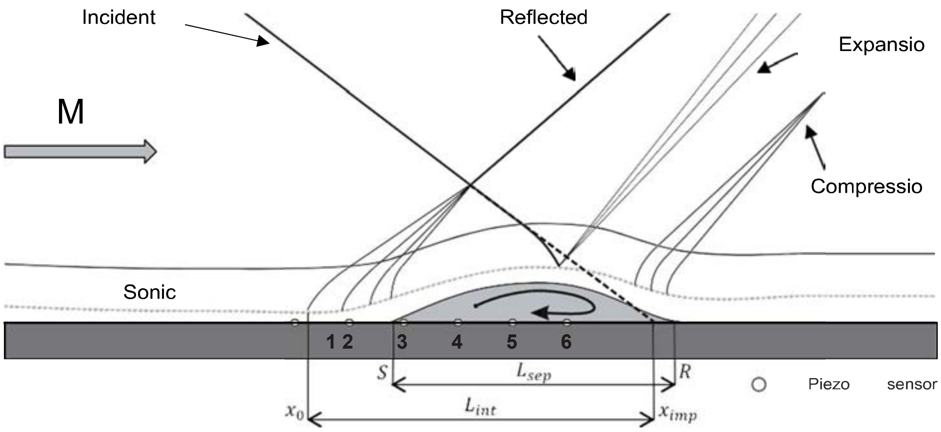


Figure 7: Representation of a separated shockwave-boundary interaction. The white circles are representing the positions of the PVDF sensors [12].

The figure 8 shows the sensor foil array integrated in the WTT in the turbulent flow layer.

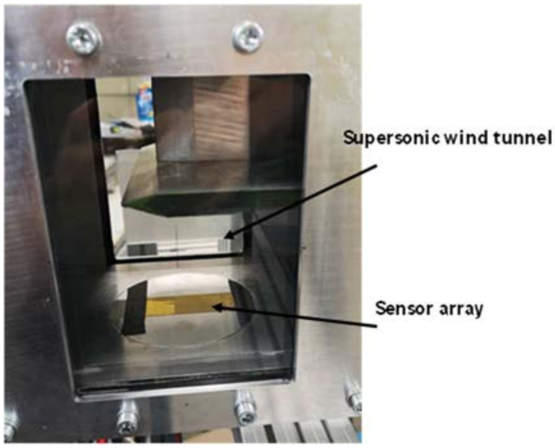


Figure 8: View of the window in the supersonic wind tunnel and the sensor array.

Signals with the new PVDF sensors and reference sensor from Kulite have been acquired. It can be demonstrate that the new sensor systems are able to match the reference sensor signal precisely. To investigate the unsteadiness in the boundary layer frequency domain has been analyzed. The figure 9 shows the two PSD spectra obtained with the new sensor and the reference sensor.

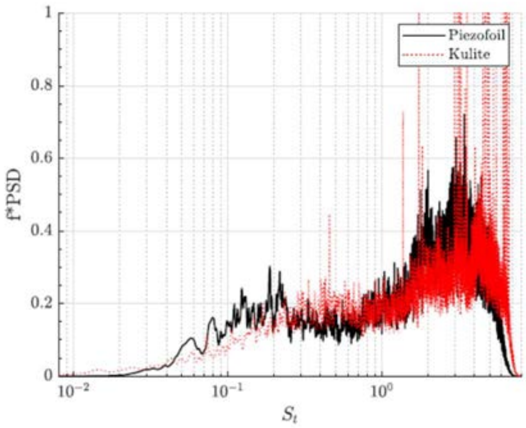


Figure 9: PSD (power spectral density) signals with new sensor and reference sensor from Kulite.

11 CONCLUSIONS

We present a novel 3D piezoelectric sensor array setup for use in Separated Boundary Layer Ingestion (SBLI) applications. The system's compact design eliminates the need for bumps or bond wires, resulting in a very small size. We provide information on the manufacturing technology, electronics, packaging, and shielding used in the setup to ensure its effectiveness and reliability. The PVDF thickness can be realized in µm range, which allows a very flexible sensor array conforming different morphologies in aerospace. The material shows very high sensitivity but needs complex conditioning electronics. The PVDF layer can be realized in foil or printed using ink. It has demonstrated that the sensors are able to match the reference sensor from Kulite. Works are still on-going to optimize the printing process of PVDF and metals, also to develop conditioning electronics and integration techniques. Piezoelectric sensors are commonly used for measuring mechanical stresses and vibrations, and our innovative design offers potential applications in various industries. Overall, our work presents an exciting development in the field of piezoelectric sensors. We are confident that our innovative approach will have an impact on SBLI applications and beyond.

12 ACKNOWLEDGEMENTS

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