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MEMS calorimetric transducers for flow separation detection and control

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Abstract

Robust micro machined high temperature gradient calorimetric (HTGC) transducers were developed for flow separation control. Based on thermal principle, the transducers measure the mean and fluctuating bidirectional shear stress that is particularly useful for flow separation detection. More than a hundred micro-sensors were simultaneously micro-machined using MEMS technology. A flexible array of calorimetric micro-sensors was implemented with miniaturized electronics on a flap model also equipped with pulsed jet actuators. Flow control experiments were successfully conducted as the natural separation occurring on the model was detected the HTGC micro sensors and controlled by pulsed jet actuation.

1. Introduction

Boundary layer separation is an unwanted and sometimes dangerous phenomenon in aeronautics. Indeed, separation occurring over flaps is responsible for large performance losses especially during take-off as it simultaneously drastically increases drag and reduces lift. Therefore, it is a promising candidate for flow control with objectives of delaying or suppressing its apparition. In active flow control strategies, actuators disturb the flow to induce a positive change in its behaviour. Adding a set of sensors allows indicating the state of the flow and adapting the command to the actuators in closed-loop control strategies.

The wall shear stress plays a key role in flow separation phenomenon: the point of separation is characterized by a shear stress null at the wall and the recirculation area is characterized by a negative shear stress. Therefore, accurate time-resolved wall shear stress measurement is crucial for implementing a closed-loop control. Flows at moderate Reynolds numbers exhibits typical length scales of 100 µm at the wall or less and time-scales require several kilohertz of bandwidth [1]. Micro-electro-mechanical systems (MEMS) are thereby a technical solution to resolve turbulent flows. Mechanisms for measuring wall shear stress are divided into two families: direct techniques and indirect techniques.

The first category directly measures the friction force applied to the surface via a floating element type balance. The floating element is a mass suspended above the substrate and held by moveable tethers such as springs. The friction moves the floating element and the measurement of the displacement induces the one of wall shear stress.

The second method carries out an indirect measurement of wall shear stress. It requires an empirical or theoretical correlation to relate the measured magnitude to the shear stress. This category includes thermal sensors exploiting the heat transfer between a wire heated by an electric current and the flow. Indeed, Stanton et al [2] established in 1920 that the average velocity gradient and thermal transfers near the wall or at the wall are both proportional to the wall shear stress. Löfdahl and Gad-El-Hak [3] presented in 1999 a review on MEMS based shear stress sensor and discuss the advantages and drawbacks of each techniques.

This paper reports high temperature gradient calorimetric (HTGC) micro-transducers designed and developed for flow control applications. Based on calorimetric heat transfer, these sensors measure both the amplitude and sign of wall shear stress. Finite Element Method simulations performed on COMSOL Multiphysics evaluated the HTGC sensors response to bidirectional wall shear stress. MEMS technology allowed the design, development and manufacturing of

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the sensors in clear room facilities at the Institute of Electronics, Microelectronics and Nanotechnology (IEMN). The calibration was realized in wind tunnel facilities at ONERA the French Aerospace Lab, by implementing the HTCG micro-sensors at the wall. Finally, a flexible array of HTGC sensors was developed with miniaturized electronics designed by Thurmelec. The array was implemented on a flap model for performing flow control experiments. The flap model was equipped with pulsed jets actuators in addition to the HTGC micro sensors array.

2. Design, fabrication and characterization of the HTGC micro-sensors

2.1 Numerical simulation on COMSOL Multiphysics

Calorimetric sensors are composed of a central heater and temperature detectors on both side. The working principle exploits the asymmetry of the thermal boundary layer. With a non-heated fluid flow, upstream detectors will sensor a cooler temperature than downstream detectors. The difference of temperature indirectly gives the amplitude and the sign of the wall velocity. In the present HTGC micro-sensor structure, the sensitive part of the sensor, presented in Figure 1, consists in three parallel micro-wires, suspended over the substrate and mechanically supported by silicon oxide micro-bridges [4,5]. The central wire combines heating and wall shear stress measurement as a classical hot-wire. The two other wires, arranged on both sides of the central wire, use the calorimetric principle to detect the flow direction.

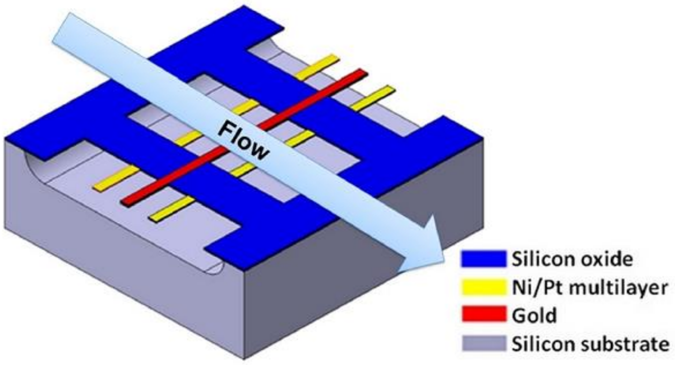

Figure 1: Schematic of the HTGC micro-sensor design [4]

Each wire is 3-µm-wide for 1-mm-long, for a less than 1 µm thick. A 20 µm deep cavity isolates them from the substrate to avoid heat losses by conduction and to increase the convective heat transfer. The wires are then within the flow, enabling hot-wire like behaviour while ensuring a non-intrusive measurement. The high aspect ratio of the wires enables a high temperature gradient in the flow direction and a homogeneous temperature profile along the wire. The periodic silicon oxide bridges allow the structure to be mechanically robust despite the wires length.

A 3D finite-element simulation was performed using COMSOL Multiphysics with the *Heat transfer in fluids and solids* module, to study the sensor working behaviour. The simulated cell corresponds to an 80-µm-long part of the sensitive structure, with three micro-bridges (Figure 2 (a)), but with boundary conditions fixed such that the cell can be considered infinitely duplicated. The temperature of the substrate walls is fixed at the initial one, and the heater is heated with a constant power. Additionally, the mesh is unstructured in COMSOL computation, and is composed of about 3 million elements.

As shown in Figure 2 (a) and (b), when the gold resistor is heated by an electric current, the heat is transferred to the measurement wires and the surrounding fluid, in a symmetric thermal boundary layer, without flow. The heat distribution is calculated for in the sensor structure (wires and bridges) and the fluid for a 7 mW heating power.

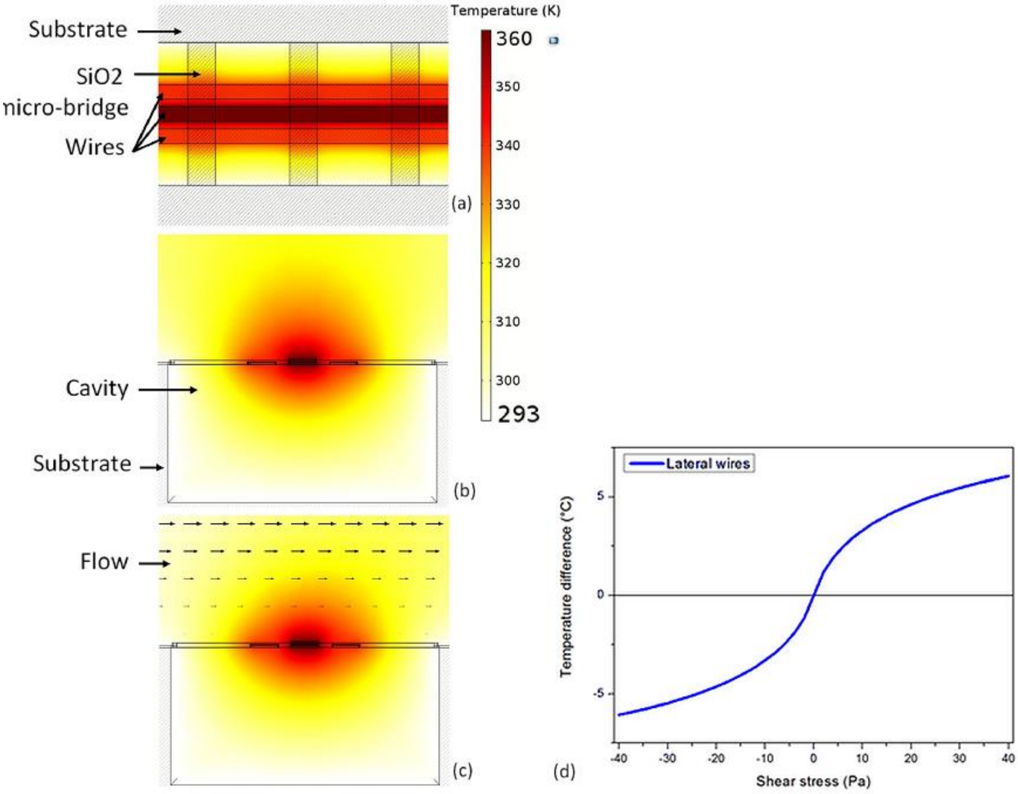

Figure 2: COMSOL Finite element simulations – Constant power at 7 mW : (a) heat distribution in the wires plane with flow at rest, (b) heat distribution in the plane perpendicular to wires with flow at rest, (c) heat distribution in the plane perpendicular to wires for a wall shear stress of 2 Pa (d) HTGC sensor response for shear stress going from -40 Pa to + 40 Pa [5]

In Figure 2 (c), the flow cools the structure by forced convection leading to a temperature decrease, and the thermal boundary layer is deformed. The forced convection through air is included into the heat transfer equation via the velocity profile with zero velocity at the wall, modelled using the following equation, valid because the velocity field considered is in the linear sublayer region of a boundary layer.

$$u = y \cdot (\tau/\mu)$$

where u is the flow velocity, μ the dynamic viscosity and τ the shear stress.

The result in Figure 2 (d) shows the HTGC sensor response to bidirectional wall shear stress with negative gradient of temperature for negative shear stress and positive response for positive shear stress.

2.2 Fabrication and characterization

The HTGC micro sensors were manufactured using MEMS techniques in cleanroom facilities at IEMN. The process includes 15 steps detailed in previous work [4]. On a 3 inches wafer, more than a hundred sensors are simultaneously fabricated.

The Figure 3 presents Scanning Electron Microscope images of the realized devices with the global sensing structure in (a) and a zoom on the thermal microstructure in (b). The thermal microstructure was characterized using a 4-probes station and infrared camera for determining its thermal behaviour. Among other parameters, the temperature coefficient of resistance was evaluated at 2400 ppm/°C. Details of electro-thermal characterizations can be found in [5].

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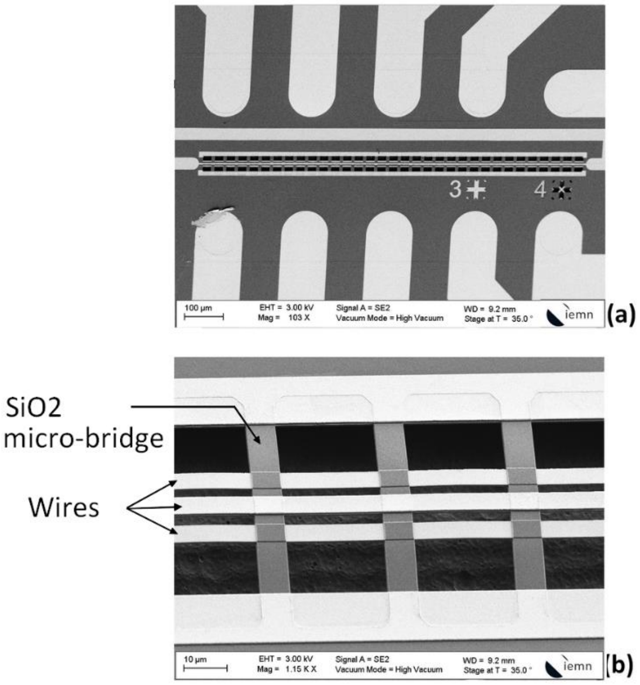

Figure 3. SEM pictures of a manufactured sensor: (a) global structure (b) zoom on the sensitive part

The HTGC micro-sensors were calibrated in wind tunnel facilities at ONERA Lille for bidirectional wall shear stress. They reached 2.5% voltage variation for 2.4 Pa. Their particularity to detect the shear stress sign in addition to its amplitude make them particularly useful for aerodynamic applications like the detection of flow separation.

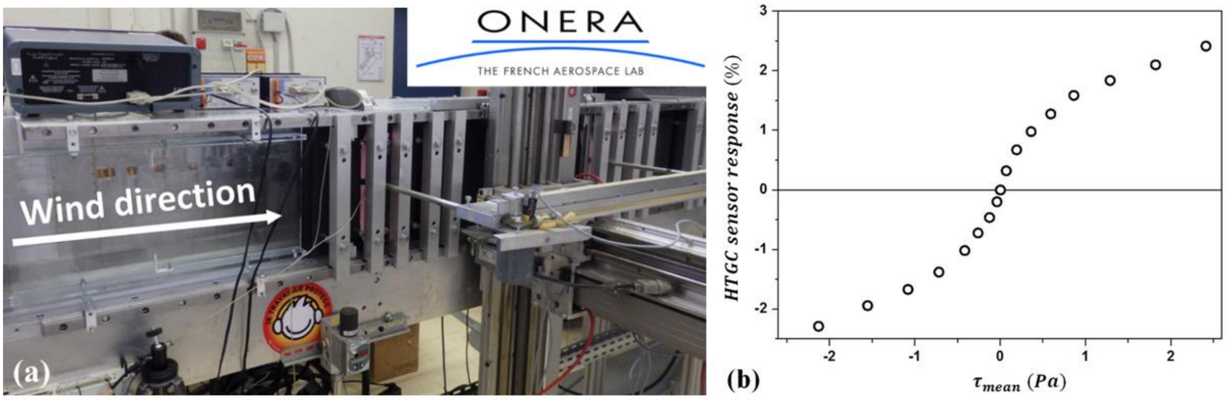

Figure 4. Wind tunnel facility I ONERA Lille (a) HTGC micro sensors response to bidirectional wall shear stress ranging -2.4 Pa to + 2.4 Pa [1]

3. Flow control experiments on a flap model

This part is dedicated to flow control experiments on a flap model. Flaps are used on airplanes (Figure 5 (a)) to delay separation during take-off and landing. Figure 5 (b) presents the schematic of the experiment with the flap model preceded by a long flat plate for stabilizing the boundary layer, and the HTGC micro-sensors disposed along the flap chord.

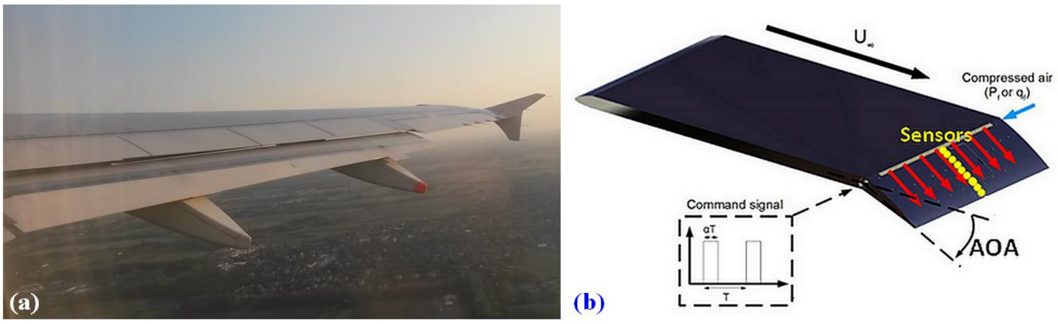

Figure 5: (a) Flap on A340 – photograph taken by one of the co-authors (b) Schematic of the experiment with the flap model instrumented with the micro-sensors disposed along the cord.

The experiments were performed in the large L1 wind tunnel in ONERA Lille (Figure 6 (a)) with a test section of 2.40 m diameter and the 10 meters length. The flap is unslotted, has $c = 20\ mm$ long chord and is based on NACA 4412 airfoil shape.

As seen on Figure 6 (b), twelve micro-sensors have been implemented in the flap model with embedded miniaturized electronics designed and manufactured by Fluiditech. The two sensors on top, close to the leading edge have individual electronics. A flexible 3 mm thick strip of ten sensors with shared electronics takes place in the thinner part of the model and reaches up to 30 mm far from the trailing edge. The twelve sensors are flush-mounted in the model and the flexible strip enables to follow the airfoil shape camber.

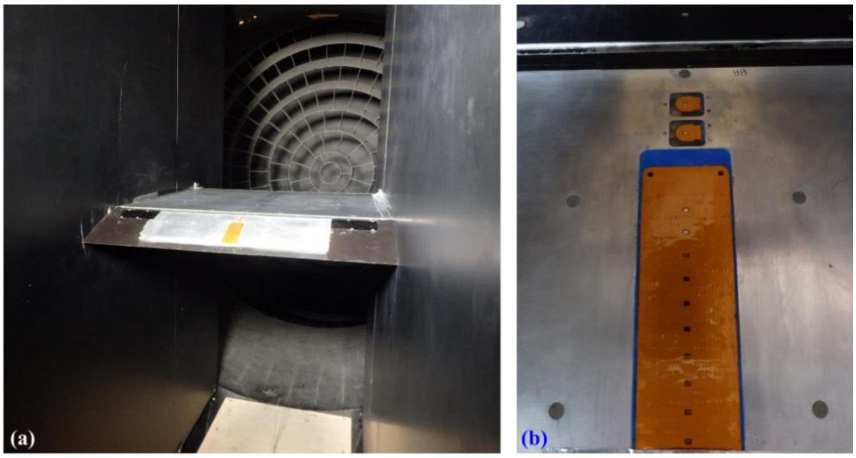

Figure 6: (a) Flap model with implemented micro-sensors (b) Zoom on the twelve micro-sensors: two individual sensors at the leading edge and a strip of ten sensors with shared electronics

The flow control experiments consisted in detecting the natural separation on the flap at first and then determining the effect of control provided by the pulsed jets. The Figure 7 presents the result obtained. In Figure7 (a), the natural separation occurring on the flap while changing its angle is detected by the array of sensors. More precisely, the sensors measuring both the variation of amplitude and the sign of the wall shear stress, they detected the moving separation point from the trailing edge to the leading edge. In Figure 7 (b), the efficiency of pulsed jets control is demonstrated for the $x/c = 0.3$ measurement point.

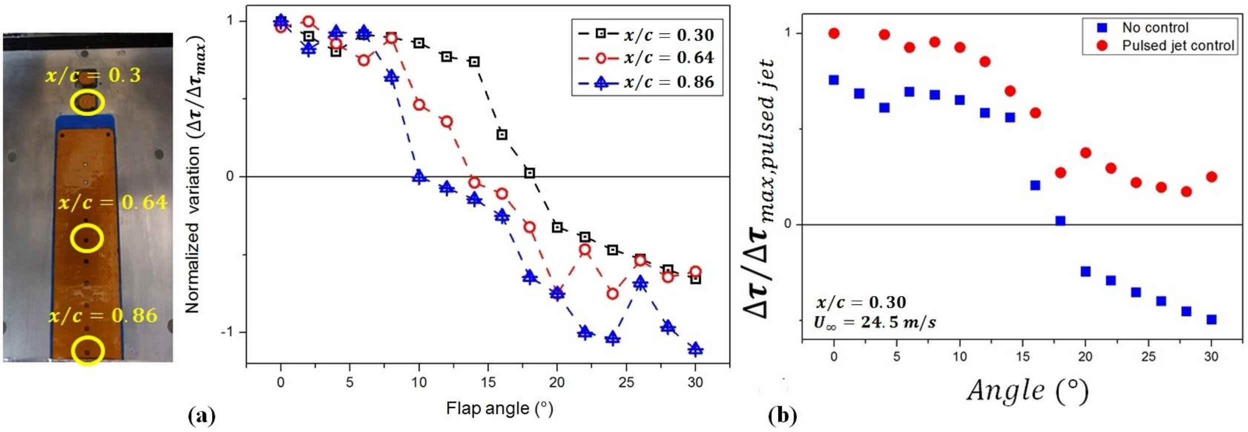

Figure 7: (a) Detection of separation: normalized response of the micro-sensors located at $x/c = 0.2$, $x/c = 0.64$, $x/c = 0.86$ for $U_\infty = 24.5\ m/s$ (b) Control of separation: normalized response of the micro-sensor at $\boldsymbol{x/c = 0.3}$ without control and with pulsed jet control. [6]

4. Conclusion

This paper presented MEMS based HTGC wall shear stress transducers designed for flow control applications. Simulations performed on COMSOL Multiphyscis stated the working principle of the transducers and particularly the calorimetric principle enabling the measurement of the flow direction in addition to the one of the amplitude of the wall shear stress. Several devices were manufactured in cleanroom facilities and calibrated in wind tunnel. The calibration was performed for shear stress ranging from -2.4 Pa to + 2.4 Pa and further work aims at widening the dynamic range.

The final part of the paper presented an example of flow control experiments realized with the HTGC micro-sensors: 12 micro-sensors were implemented in a flap model equipped with pulsed jets actuators. The flow separation occurring on the flap while changing the angle of attack was detected by the HTHGC micro-sensors as well as the effect of active control on avoiding separation. Ongoing work aims at setting closed loop flow separation control on the same model using the HTGC micro-sensors signals as feedback loop.

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