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Overview of IEMN micro-sensor technologies: from turbulence measurement to aerodynamic flow control

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Abstract

This paper presents the three main technologies of micro-sensors developed by the IEMN (Institute of Electronics Microelectronics and Nanotechnology) for aerodynamic applications. The first sensor is a hot-wire probe shape micro-sensor based on a nano-crystalline diamond structure and a stress compensative metallic layer. With microscale dimensions, this device was fabricated using micromachining techniques. It was calibrated up to 30 m/s. The second micro-sensor is a bidirectional wall shear stress transducer. The micro-sensor is designed as a wall suspended micro-hot-wire, with two lateral temperature detectors for flow direction detection. It also presents microscale dimension and was fabricated using micromachining techniques. Integrated in flat plate in two different wind tunnels, the micro-sensor was tested for incompressible and compressible flows, up to M=0.8. An array of such micro-sensors also equipped a flap model for flow separation control. Finally, the third technology is a thermal based pressure micro-sensor. Using the Pirani effect, the micro-sensor is highly sensitive around atmospheric pressure and successfully measured wall pressure in wind tunnel.

1. Introduction

Turbulence has been a complex field of study in fluid mechanics, characterized by disorderly behaviour with vortices whose size, location and orientation vary constantly. In fact, understanding, predicting and controlling turbulence are the three major goals of research in this area. The consequences are crucial: predicting the behaviour of turbulent flows in order to control and manipulate them would, in many fields of application, save energy, improve system performance and protect the environment. The most obvious example is the one of transport industry, which is confronted to the problem of aerodynamic drag on vehicles. However, turbulence is an unresolved problem in classical physics that does not present a simple solution and numerical simulation used to predict the behaviour of turbulence highly rely on empirical data [1]. Turbulent high Reynolds numbers flows generate very short spatial and temporal scales: spatial scales whose order of 100 µm or less and time scales require a bandwidth of at least 10 kHz [2]. Experiments thus require small, fast, implementable sensors in various configurations and models, and allowing non-intrusive measurements of the flow.

In this paper, we present the different technological solutions developed by the IEMN (Institute of Electronics Microelectronics and Nanotechnology) to address this challenge. Based on microtechnology, the devices present submillimetre characteristic lengths. We will present three main sensor technologies: an original nano-crystalline diamond based micro-hot-wire probe designed for freestream flow velocity measurements[3], a skin friction and direction sensitive micro-sensors designed for flow separation control strategies ([4]–[6]) and a pressure micro-sensor based on the Pirani effect ([7], [8]).

2. Nano Crystalline Diamond (NCD) based hot-wire micro-anemometer

2.1 Design

The first device presented in this paper is a micro scale thermal anemometer based on Nano Crystalline Diamond (NCD) thin film. A scanning electron microscopy (SEM) image of the device is shown on Figure 1 (a). For proof of concept, the sensitive element consists of a self-compensated stress multilayer (Ni/W) patterned to form a wire with length, width, and thickness respectively close to 200 µm, 5 µm and 2 µm. The wire is deposited and supported by prongs made of NCD thin film. Due to its high young modulus, NCD allows a very high mechanical toughness without the need of a thicker support for the hot wire. Also, depending on grain size, the NCD is able to present thermal conductivity smaller than 10W/mK, providing good thermal insulation from the substrate and less conductive end losses to the prongs, as shown on Figure 1 (b) which is a thermal imaging of the device.

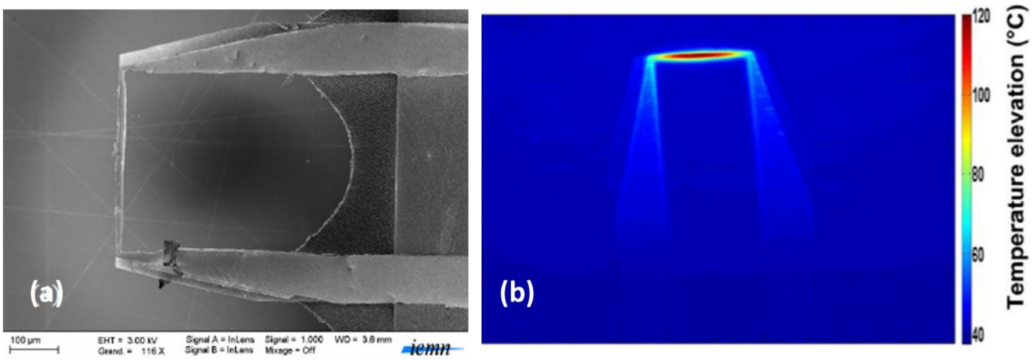

Figure 1: (a) SEM image of the IEMN hot-wire micro-sensor [9] (b) Thermal imaging of the micro-sensor [3]

2.2 Testing

The micro-sensor was calibrated for flow velocities going up to 30 m/s. The calibration setup is composed of a pressurized gas supply feeding a Dantec dynamics calibrator equipment, which produces a free jet. For constant current measurements, the probe was connected to a Keithley 2400 source-meter and ohmmeter to extract the resistance versus velocity response. The relative resistance variation versus fluid velocity is presented in Figure 2 for two different current supplies of 3 mA and 4 mA. The hot wire sensitivity decreases with increasing fluid velocity due to heat losses through forced convection.

The relative resistance variation versus velocity exhibits the typical non-linear power characteristic in accordance with King’s law.

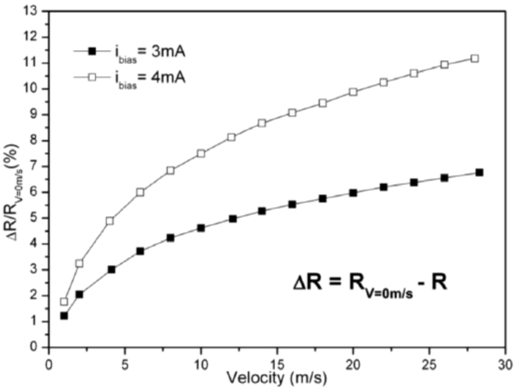

Figure 2: Calibration curves of the IEMN hot-wire micro-sensor for two heating currents [3]

3. Robust wall shear stress micro-sensor

3.1 Design

The second micro-sensor technology for aerodynamic flows measurement is a robust micro-machined high temperature gradient calorimetric transducer that were developed for flow separation control strategies. Also based on thermal principle, the sensors measure the mean and fluctuating skin friction and are sensitive to the flow direction, both making them particularly useful for flow separation detection. More than a hundred micro-sensors were simultaneously micro-machined using MEMS technology in the IEMN cleanroom facilities. The sensor structure is composed of a central wire, the heater, and two lateral wires acting as temperature detectors. The wires are wall suspended and mechanically supported by perpendicular microbridges. Figure 3 shows two SEM images of the sensor.

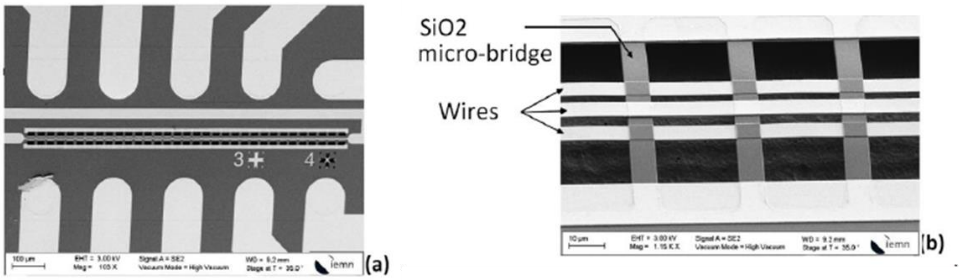

Figure 3: SEM images of the IEMN wall shear stress micro-sensor: (a) global view (b) zoom on the sensitive part [4], [5]

3.2 Experimental validations

Tested in a turbulent boundary layer wind tunnel in ONERA Lille, the micro-sensors were calibrated between -2.5 and 2.5 Pa of wall shear stress, as shown on Figure 4 (a). Dynamic measurement demonstrated a bandwidth of about 15 kHz for the measurement of the frequency weighted power spectral density that corresponds to the turbulence kinetic energy at the maximum wall shear stress (Figure 4 (b)). The spectrum given by the micro-sensor is comparable to the one obtained by a commercial hot-film probe but with a slightly higher bandwidth.

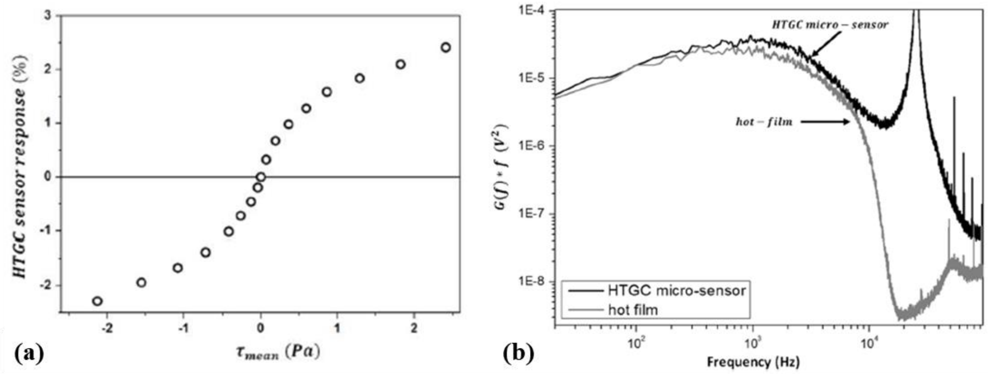

Figure 4: (a) Time-averaged calibration of the micro-sensor from -2.5 to 2.5 Pa (b) Frequency weighted power spectral density measured by the micro-sensor and a commercial hot-film probe for 2.5 Pa of shear stress [5]

The micro-sensor was also tested in a highly turbulent wind tunnel in ONERA Meudon, for compressible flows going from Mach number 0.5 to 0.8. Two positions were studied on the flat plate (Figure 5 (a)): upstream and downstream. The shear stress should be higher upstream than downstream for a given flow velocity. As shown on Figure 5 (b), the response of the sensor indeed shows what physics states: the shear stress increases with the Mach number and for a given Mach number, the shear stress is higher in upstream position than in downstream.

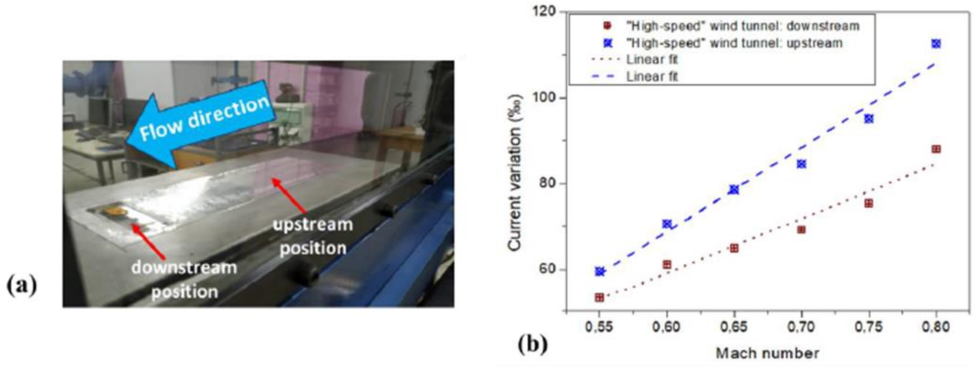

Figure 5: (a) Setup experiment in the high Mach number wind tunnel in ONERA Meudon (b) Response of the sensor for Mach number going from 0.5 to 0.8 [10]

Another experiment done on this technology is a flow separation control experiment on a flap model. A flexible array of calorimetric micro-sensors was implemented with miniaturized electronics on a flap model also equipped with pulsed jet actuators (Figure 6).

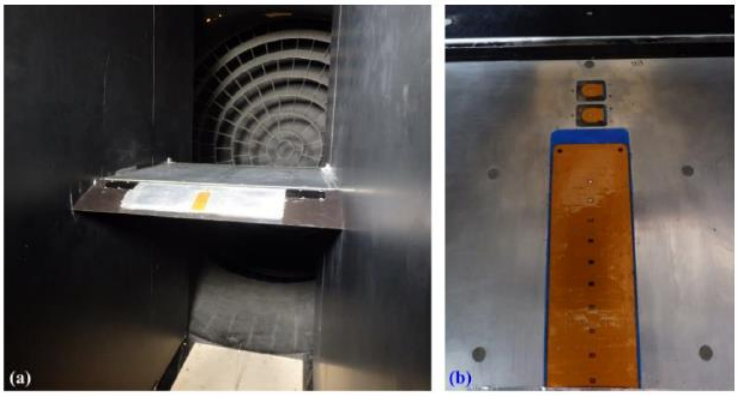

Figure 6: (a) Setup experiment with the flap model in L1 wind tunnel in ONERA Lille (b) Array of micro-sensors integrated in the flap model [6]

Flow control experiments were successfully conducted as the natural separation occurring on the model was detected by the micro sensors network (Figure 7 (a)) and controlled by pulsed jet actuation (Figure 7 (b)). Indeed, as shown on Figure 7 (a), the separation point is detected by the fact that the shear stress becomes negative for a separated flow. It is detected at 10°, 15° and 18° of flap angle for respectively $x/c = 0.86, 0.64$ and 0.3. On Figure 7 (b), we added pulsed jet actuation to control separation: indeed with pulsed jet control, the shear stress remains positive for all flap angles meaning that the flow is not separated. Ongoing work aims at increasing the bandwidth of the transducers and at implementing a closed-loop separation control on the flap model.

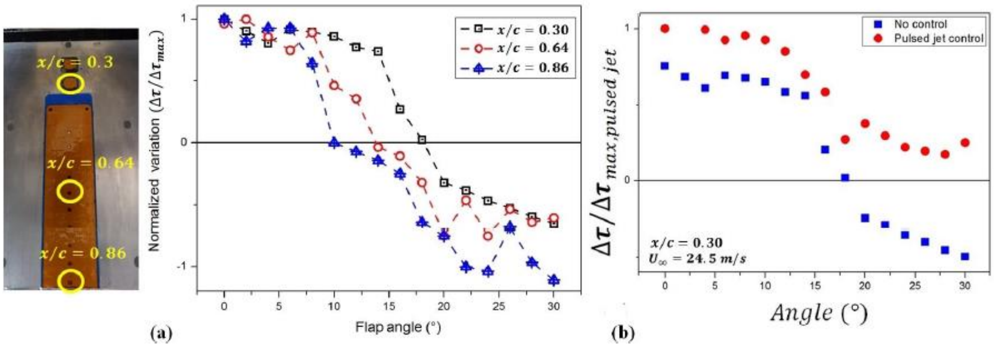

Figure 7: (a) Detection of the natural separation on the flap model (b) Detection of the effect of pulsed jet actuation avoiding separation to occur on the flap at $x/c = 0.3$ [6]

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4. Thermal pressure micro-sensor

The third technology of micro-sensor developed by the IEMN is a pressure micro-sensor using thermal transduction ([7], [8]). The Pirani effect exploits the pressure dependency of the thermal conductivity of gas. Pirani sensors are composed of a heater and a heatsink with a height controlled by between them. The heat is transferred from the heater to the substrate by the gas molecules that are in the gap. As pressure decreases, less and less molecules act as energy carrier and the thermal conductivity decreases until the hot-wire is thermally isolated. To work at atmospheric pressure, the microstructure needs a nanoscale gap. Figure 8 presents a schematic of the device along with two SEM images.

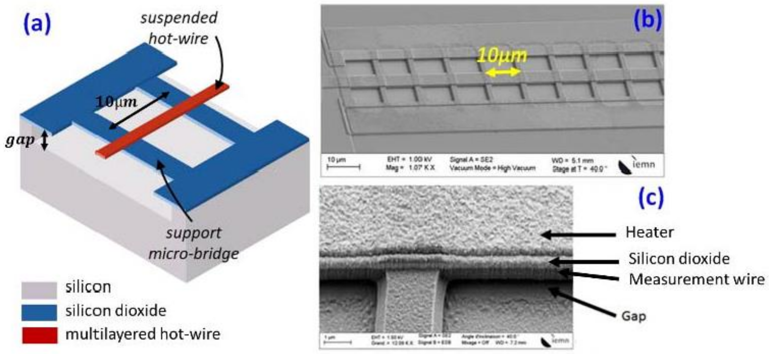

Figure 8: (a) Schematic of the Pirani micro-sensor; (b) and (c) SEM images of the micro-device [8]

The micro-sensor was then calibrated for various pressure going from 10 kPa to 800 kPa (Figure 9 (a)). The maximum of sensitivity is reached for the atmospheric pressure. The sensor was then tested in a wind tunnel in ONERA Lille, for velocities going up to 40 m/s. The measurement of pressure given by the micro-sensor is compared to the measurements obtained with a commercial membrane based sensor (Figure 9 (b)). We can see the decrease of pressure with increasing velocity as predicted.

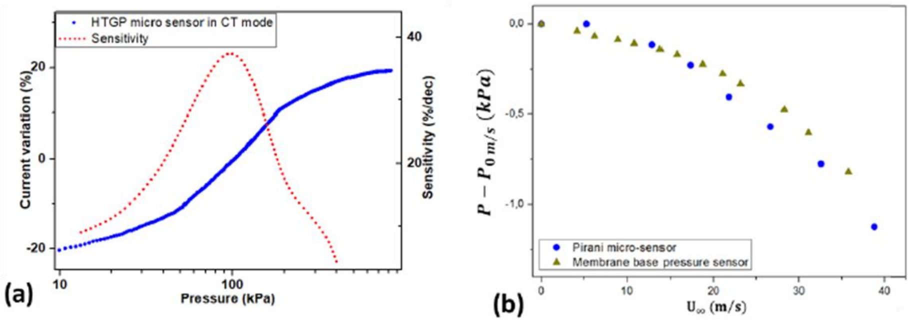

Figure 9: (a) Calibration curve of the micro-sensor with pressure (b) Measurement of wall pressure in ONERA Lille wind tunnel [8]

5. Conclusion

This paper presented the three main technologies of micro-sensors developed by the IEMN for aerodynamic applications, from turbulence measurement to flow control. The first device is a micromachined hot-wire probe for velocity measurements. Based on nanocrystalline diamond, it is robust and presents a good thermal insulation. The second device is a bidirectional wall shear stress micro-sensor. It was used for wall shear stress measurement in both incompressible and compressible flows. An array of such micro-sensor was also implemented in a flap model for flow separation control experiments. The final device is a pressure micro-thermal exploiting the Pirani effect, a thermal type of transduction. The first experiments in wind tunnel were performed and showed the capacity of the micro-sensor to measurement wall pressure.

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