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Flight-testing of a MEMS wall shear stress thermal sensor on a microlight aircraft

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Abstract— This paper reports the realization of thermal MEMS (Micro Electro-Mechanical Systems) sensors designed for wall shear stress measurement during real flight on a microlight aircraft. Based on constant temperature anemometry and calorimetric principle, the micro-sensors measure the viscous shear stress occurring at the wall of a structure interacting with a fluid flow and detect the flow direction. A proper packaging was realized for ensuring a flush but robust integration of the devices on a pod fixed on a microlight aircraft. Real flight-testing demonstrated the ability of the micro-sensors to realize aerodynamic measurements up to 250 km/h on the microlight aircraft.

Keywords—MEMS thermal sensor, Wall shear stress sensor, Flight-testing

I. INTRODUCTION

Aircraft instrumentation is mainly composed of average measurement sensors indicating the mean velocity, the mean altitude the mean exterior temperature and so on, of the aircraft. However, the localized values of velocity and wall shear stress on the plane is of great interest, particularly for flow control applications. Flow control aims at locally manipulating the turbulent flow field to induce favorable changes in the main performances such as decreasing the drag or the noise radiation. Controlling turbulence then requires the measurement of its localized properties and the today instrumentation of aircraft is not sufficient. A network of small sensors, placed strategically on the plane, could give important information on the interaction of the main flow field with the structure.

The measurement of aerodynamic flow led to the development of micromachined sensors based on thermal transduction. The basic principle consists in electrically heating a metallic or semiconductor wire and measuring the heat losses due to forced convection with the fluid flow. Two main kinds of sensors were developed: hot-wires and hot-films. In hot-wires, the wire is free in the flow field and only fixed on both extremities ([1], [2]). Suitable for aerodynamic measurement in wind tunnel environment even in highly turbulent flows [3], these sensors are too fragile to be implemented on an aircraft. In hot-films, the wire is deposited on a film or a membrane. More robust, these

sensors can be flush mounted on the surface ([4], [5]) but the measured heat loss is a combination of conduction in the wall and forced convection with the flow. Since they are both robust and non-invasive (flush-mounted), hot-film probes are widely used for measuring the wall shear stress on models ([6]–[8]).

The integration and use of thermal micro-sensors on real vehicles is another step of technology maturity. The literature gives few examples of thermal sensor embedded on real vehicles. Demonstrations were provided on a unmanned aerial vehicle [9] and on an airplane [10] both using coated hot-film probes.

Developed as a compromise between hot-films and hot-wires and with the objective of real flight application, the high temperature gradient micro-sensors designed at IEMN is composed of wall suspended wires, mechanically supported by periodic perpendicular micro-bridges ([11], [12]). The sensors were successfully tested in various configurations: in low [13] and high-speed wind tunnels [14] and on models [15]. In this paper, we present the utilization of such micro-sensors for real flight experiments realized on a microlight aircraft. The first part of the paper will describe the design of the sensor and the packaging developed for ensuring the flush and robust integration of the chip on a pod fixed on the microlight aircraft. The second part will present the setup on the microlight aircraft and discuss the results obtained during the flight campaign.

II. DESIGN AND PACKAGING OF THE SENSOR

A. Design of the thermal micro-sensor

The thermal micro-sensor developed for wall shear stress measurement is designed as a compromise between fragile but highly sensitive hot-wire probes and robust but slower hot-film probes. Indeed, the micro-sensors is composed of 3 free-standing wires mechanically supported by perpendicular SiO₂ based micro-bridges. The wires are separated from the substrate by a 20 μm deep cavity ensuring a high thermal insulation for a hot-wire like behavior. The micro-bridges provide a mechanical robustness of the structure without enhancing thermal loss by conduction

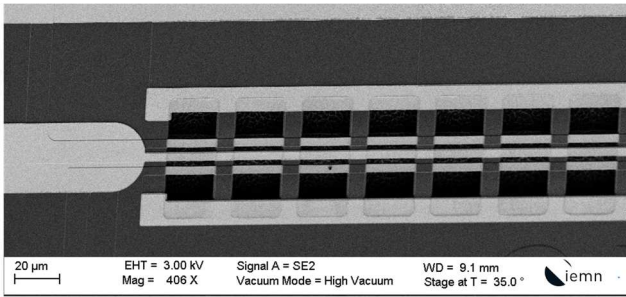


Fig. 1. Scanning electron microscopy image of the sensitive part of calorimetric micro-sensor

unlike hot-film probes. Fig. 1 shows a Scanning Electron Microscopy (SEM) image of the sensor sensitive part. The central wire is the heater. Made of Ti/Au it is heated by an Joules effect. The two lateral wires are Ni/Pt based cold-wires measuring the temperature on both sides of the heater. The micro-sensor is designed to work simultaneously as a hot-wire probe using the middle wire and as a calorimetric sensor using the difference of temperature between the two lateral wires. Calorimetric sensors present the advantage of a differential measurement that allows measuring both the amplitude and the sign of the wall shear stress.

B. Packaging for flight experiments

For the previous experiments done on low and high speed wind tunnels and on models, a flexible PCB packaging was realized to have a mounting robust and as flush as possible, as shown on Fig. 2 (a). However, the sensor chip has front side electrical contacts meaning that the sensor chip was not perfectly flush mounted, but 100 μm below the surface of the PCB. Nevertheless, this integration was the best suited for the model experiments on which the area of integration was limited and a flexible solution was require.

Since the flight experiments allowed more surface for the sensor integration, we improved the packaging by using a rigid PCB, as shown on Fig. 2 (b). Front side contacts were realized using conductive epoxy.

Wind tunnel facilities in ONERA Lille allowed testing the operation of the micro-sensors before real flight experiments. The micro-sensors in both packaging were integrated in a turbulent boundary layer wind tunnel with a fluid velocity going up to 40 m/s. The novel packaging demonstrated a high sensitivity to wall shear stress, for mainstream velocities going up to 40 m/s, as shown in Fig.3. Compared to what was obtained with the flexible PCB flip chip integration, the sensitivity is about 10 times improved.

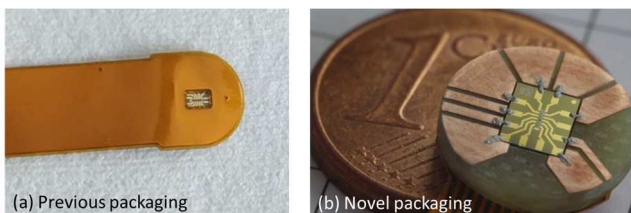


Fig. 2. (a) Flexible flip-chip packaging used for integrating the calorimetric micro-sensors in wind tunnel facilities and on models (b) Rigid PCB based packaging developed for the microlight aircraft flight experiments

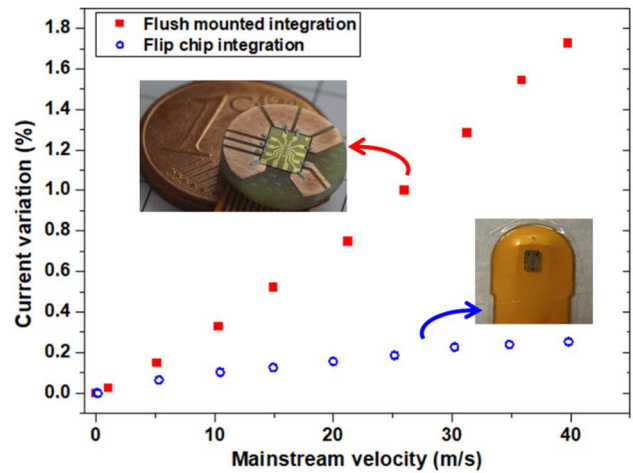


Fig. 3. Current variation of the heater as a function of the mainstream velocity in the turbulent boundary layer wind tunnel in ONERA Lille: comparison between the two packaging solutions.

III. FLIGHT EXPERIMENTS

A. Set-up on the microlight aircraft

Real flights tests were performed using a Flight Design CTSW microlight aircraft. It is equipped with a 3 blades propeller and a Rotax 912s engine, characterized by a gear box ratio of 1/2.43. PODs are set up on the airplane landing gear. One is instrumented with a calorimetric micro sensor, as illustrated in Fig. 4. The POD to ground communication is realized using a radio module embedded inside the POD along with the conditioning electronics of the calorimetric micro-sensor.

B. Results and discussion

The experiments were conducted at 1500 ft of altitude. Four speed steps were investigated: 100 km/h, 150 km/h, 150km/h and 250km/h. For the last step of speed, the pilot encountered difficulties maintaining the 250 km/h and consequently this step has a velocity comprised between 230 km/h and 250 km/h. The series of velocity steps was realized twice. Fig. 5 presents the results obtained during the flight experiments: it displays the output voltage corresponding to the difference of voltage from the two lateral wires, as a function of time.



Fig. 4. Set up of the microlight aircraft flight experiments: photograph of the Flight Design CTSW microlight aircraft with a zoom on the PODs and on the calorimetric micro-sensor chip

Several phases are distinguishable on the measurements. First, up to about 600s, the microlight aircraft is at rest with no velocity. From 600s to about 800s corresponds the taxiing phase with several turns done by the airplane. Then the sudden increase corresponds to take off. After that, the velocity steps study began. As shown on Fig.5, the calorimetric micro-sensor detected the steps of velocity with a good repeatability since the experiments were conducted twice. In each case, the four steps are easily identifiable.

The time resolution of the calorimetric micro-sensor enabled also the detection of the propeller signature. Indeed, Fig. 6 displays the power spectral density of the signal at rest and on each airspeed step. The measured fundamental frequencies are 76 Hz, 87.5 Hz, 92 Hz and 106 Hz respectively for 100 km/h, 150 km/h, 200 km/h and 250 km/h. These frequencies are in agreement with the engine constructor documentation. Harmonics of these frequencies can also be observed in the spectra.

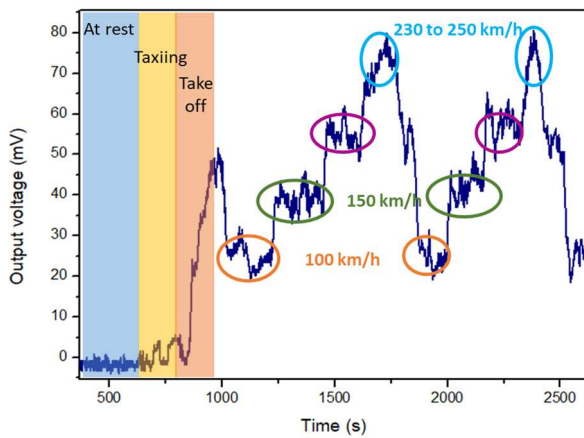


Fig. 5. Voltage difference of the two lateral wire as a function of time during the real flight experiments with identification of the different moments of the flight.

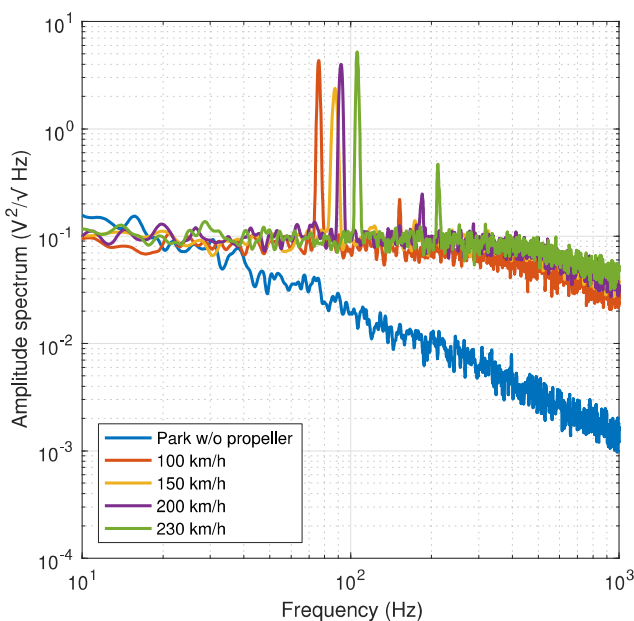


Fig. 6. Amplitude spectrum measured at rest and for each airspeed step

IV. CONCLUSION

This paper presented the latest achievements on the calorimetric micro-sensors developed at the IEMN. A novel packaging integration was designed in order to allow real flight experiments. Flight experiments were successfully conducted on a Flight Design CTSW microlight aircraft with several results. The calorimetric micro-sensor detected the airspeed steps realized by the microlight aircraft along with the preliminary steps of taxiing and take off. Time-resolved measurements allowed to detect the propeller signature at the different velocities. These flight experiments demonstrated the maturity of the calorimetric micro-sensor technology for real aerodynamic application in outdoor conditions.

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