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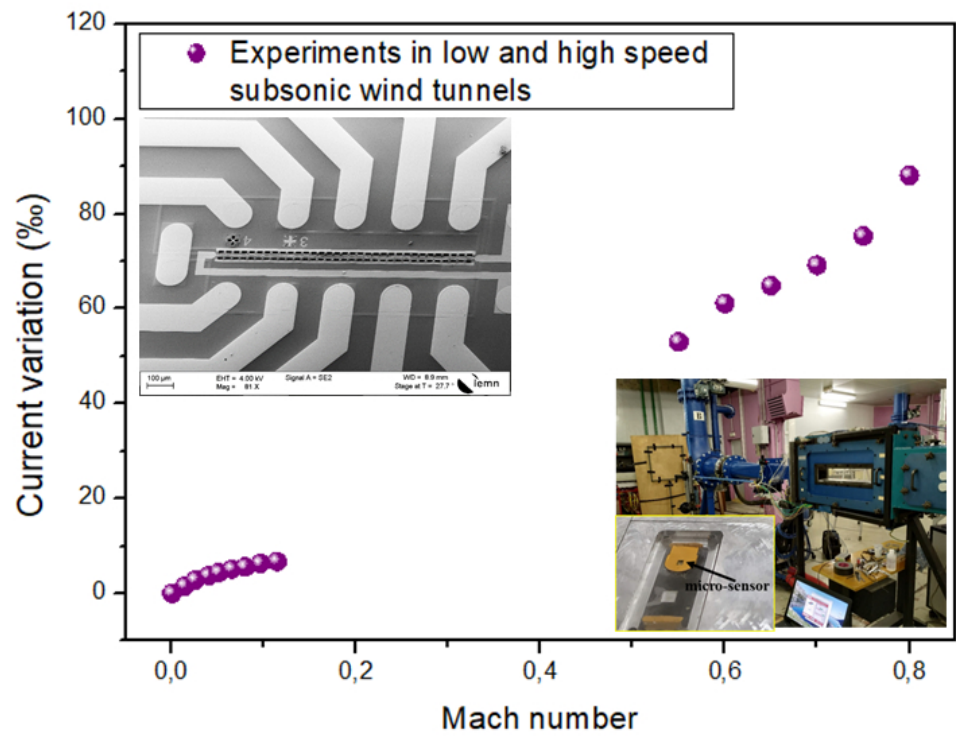
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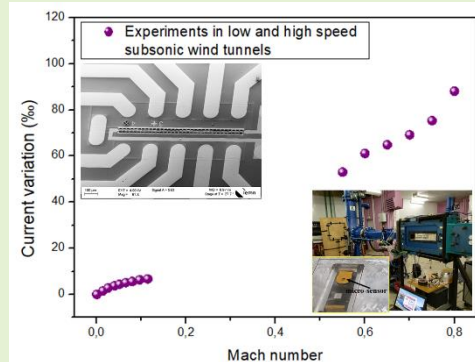


MEMS high temperature gradient sensor for skin-friction measurements in highly turbulent flows

C. Ghouila-Houri, A. Talbi, R. Viard, Q. Gallas, E. Garnier, P. Molton, J. Delva, A. Merlen, P. Pernod

Abstract—This paper presents and discusses the results obtained with a MEMS (Micro-Electro-Mechanical System) high temperature gradient sensor for time-averaged and fluctuating skin-friction measurements in highly turbulent flows. Designed as a robust wall-mounted suspended hot-wire structure, the micro-sensor was made using conventional microfabrication techniques, compatible with microelectronics for designing integrated smart systems. Successfully implemented into two air wind tunnels, the sensor was tested in a large range of turbulent flows, with mainstream velocities going up to 270 m/s (Mach number of 0.79), which corresponds to the mean velocity of airliner cruise flights. The experiments demonstrated the wide dynamic range of the micro-sensor without reaching its limits. The micro-sensor thereby demonstrated its value for measuring turbulence in aerodynamic applications, being particularly suitable for aeronautics.

Index Terms—Key-words alphabetic order



I. Introduction

CHARACTERIZED by a disorderly behavior with vortices whose size, location and orientation constantly vary, turbulence has been and still is a complex field of research in fluid mechanics, and this since its introduction by O. Reynolds in 1933. Aerodynamicists aim at understanding, predicting and controlling turbulence for the impacts of such research are of great interest in our society: predicting the behavior of turbulent flows in order to control and manipulate them would, in many fields of application, save energy, improve systems performances and protect the environment [1].

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Transport industry is directly concerned by this field of research as it is confronted to the problem of aerodynamic drag on vehicles. For this application field, controlling turbulence means manipulating the laminar-turbulent transition of the flow around the vehicle, avoiding or suppressing the separation of the boundary layer at the rear, controlling flow instabilities impacting the vehicle structure or reducing the noise pollution... all of them in order to reduce the environmental impact of vehicles by decreasing power and fuel consumptions and limiting CO₂ and NO_x emissions.

The complexity of turbulence lies in the fact that it is an unresolved problem in classical physics and it does not present a simple solution. In case of simplified geometries and low Reynolds number flows, analytical solution or solutions found using numerical simulations can be found. However, targeting industrial applications means working with high Reynolds numbers flows and with complex geometries. Numerical simulations are in this case not enough to provide solutions and it is then impossible to predict the behavior of turbulence in these configurations without relying on empirical data [2]. In other words, numerical calculations need experimentations that are representative of the simulated situation (high Reynolds number flows, complex geometries).

Experimentally working in high Reynolds numbers turbulent flows generates however very short spatial and temporal scales, as reviewed in [3]: considering aeronautic applications, scales of interest present spatial scales of 100 μm or less and time scales require a bandwidth of at least 10 kHz. The need for space-and-time resolved metrology systems is thereby at stake in experimental aerodynamics. More precisely, the aerodynamicists require sensors allowing the measurement of

1 skin-friction on models also called wall shear stress, which
2 corresponds to the tangential viscous force of the fluid at the
3 wall. This parameter is indeed crucial in turbulence equations
4 along with wall pressure fluctuations.

5 Micro Electro Mechanical Systems (MEMS) are devices
6 whose characteristic lengths are submillimeter meaning that
7 they can sense the required spatial scales in fluids mechanics. In
8 addition, downscaling leads to an increase of the sensitivity to
9 small and fast fluctuations and is consequently suitable for
10 addressing the time-scale challenge in fluid mechanics. MEMS
11 sensors dedicated to fluid mechanics and aerodynamics have
12 therefore been developed, particularly for the measurement of
13 turbulence in reactive flow control. In 1999, Löfdahl and Gad-
14 El-Hak published a synthesis on MEMS sensors for the study of
15 turbulent parietal flows [4]. They presented the principles of
16 transduction used to measure wall shear stress and pressure
17 respectively, and compared the devices made until the end of
18 the 1990's. Since then, the developments have concerned
19 geometries, structures and micro-fabrication processes and
20 conditioning for experimental setups, but the principles of
21 operation are still based on the same transduction mechanisms.

22 For the measurement of wall shear stress, these mechanisms
23 are divided into two families: direct techniques and indirect
24 techniques.

25 The first category directly measures the friction force applied
26 to the surface through a floating element. The floating element
27 is a mass suspended above the substrate and held by moveable
28 tethers such as springs. The friction moves the floating element
29 and the measurement of the displacement induces the one of
30 wall shear stress. A recent example of such device is the
31 capacitive sensor developed in 2011 by Chandrasekaran and co-
32 authors, using a structure of interdigitated electrodes deposited
33 on a membrane [5]. The capacity is evaluated by electrodes
34 overlapping. The friction will move the membrane, which will
35 spread the electrodes, and thus vary the capacities on both sides
36 of the floating element. The dimensions of the device range
37 from 3.5 μm , minimum distance between the electrodes, to 2000
38 μm , size of the floating element. The micro-sensor has been
39 calibrated up to 2.9 Pa. The sensor has a dynamic response up to
40 its resonant frequency at 6.2 kHz. However, the dimensions of
41 the floating element are millimetric whereas the scales of
42 friction are less than one millimeter for high Reynolds flows.
43 The sensor is also sensitive to pressure and vibration.

44 The second method carries out an indirect measurement of
45 wall shear stress. It requires an empirical or theoretical
46 correlation to relate the measured magnitude to the shear stress.
47 This category includes thermal sensors exploiting the heat
48 transfer between a wire heated by an electric current and the
49 flow: the average velocity gradient and thermal transfers near
50 the wall are both proportional to wall shear stress. Depending
51 on the design, the wire can be deposited on a membrane or free
52 in the flow.

53 The first kind is commonly called a hot film sensor. This type
54 of sensor is specifically designed for near-wall measurements
55 because it is easy to mount on the surface of a wall or a model
56 ([6]–[8]). For example, Sheplak et al., in 2002, developed,
57 manufactured and characterized a hot film micro-sensor with
58 dimensions of: 4 μm x 200 μm for the hot wire and 200 μm
59 diameter for the membrane [6]. In this traditional design,

although reaching very small dimensions, they added a cavity of
10 microns under the membrane, whose pressure is close to the
vacuum, in order to thermally insulate the membrane of the
wall. They performed a static sensor calibration in a laminar
flow, up to 1.7 Pa, and for different temperature values. The
micro-sensor could also be dynamically characterized up to
20 kHz. It therefore meets the requirements of aerodynamicists
in terms of spatio-temporal scale, but no test in high-speed
flows has been reported in the literature. Moreover, despite the
presence of the vacuum cavity to reduce heat loss, the
conduction in the membrane remains significant, and the
cooling of the heating wire is not only due to the forced
convection with the fluid but also to the conduction in the
membrane, which constitutes a measurement bias.

The second case, in which the wire is free in the flow, is
regularly used in aerodynamic metrology for measuring the
velocity of the flow at any point of the fluid. The sensing metal
wire of the sensor is attached on extremities by two prongs, then
the probe is introduced into the flow to measure the velocity.
Since 2010, the University of Princeton developed a hot wire
nanoprobe for turbulent flow measurements ([9], [10]). The hot
wire is 130 nm thick by 2 microns wide and 60 microns long.
The bandwidth of this sensor is greater than 10 kHz. The spatial
and temporal resolutions reached by this sensor are fine and
agree with the Kolmogorov scales. . Recently, they adapted
their structure to reach supersonic flows applications [11]. At
almost the same time, the IEMN also developed and patented a
micro- hot wire sensor of similar design ([12]–[14]). The added
value came firstly from the use of nanocrystalline diamond for
the realization of prongs, as it allows a better thermal insulation,
and secondly from the use of W / Pt multilayer structures to
obtain a natural compensation of the stresses of the
measurement wire, thus increasing the robustness of the wire,
and in fact allowing operation for higher speed flows. Several
micro-sensors of different sizes have been characterized. In the
work of these two teams, the design is that of a conventional hot
wire sensor, thus implying measurements in the flow, away
from the walls.

In this paper, we present a thermal based MEMS sensor
designed for high sensitive skin-friction measurements and
tested in highly turbulent subsonic flows. The design of the
micro-sensor is a hybrid structure reaching a compromise
between conventional hot-films and hot-wires as presented
above. As presented in section II, the microstructure combines
free standing hot-wire, avoiding conduction in the substrate, and
mechanical robustness, using suspended periodic perpendicular
spports. This design enables a high temperature gradient
localized in 3 μm x 1 mm area. The section III of the paper is
dedicated to experimental studies performed in turbulent flows.
The experiments took place in two different wind tunnels: the
first one being “low-speed” up to 40 m/s, and the second done
providing high-speed turbulent subsonic flows, with velocity
going up to 270 m/s, corresponding to Mach number of
 $M = 0.79$, the Mach number being the ratio of the airflow
velocity to the velocity of sound in air. The velocities
considered in this second wind tunnel reach the one
considered in aeronautics.

II. HIGH TEMPERATURE GRADIENT MICRO-SENSOR

The thermal micro-sensor at stake in this paper is of hybrid design that allow to take advantages from both hot-wire and hot-film sensor structures. It indeed consists in a wall mounted robust micro-hot-wire as schematically presented in Figure 1 (a). Isolated from substrate conduction by a few micrometers deep cavity, the micro-hot-wire benefits from forced convection with the flow field boundary layer. Perpendicular micro-bridges, periodically placed along the wire, ensure the structure robustness despite a high aspect ratio, as the wire is 1 mm long for 3 μm wide and 830 nm thick. The micro-bridges are 10 μm wide for 30 μm long.

Figure 1 (b) present a Scanning Electron Microscopy image of the sensitive part of the sensor corresponding to the schematic.

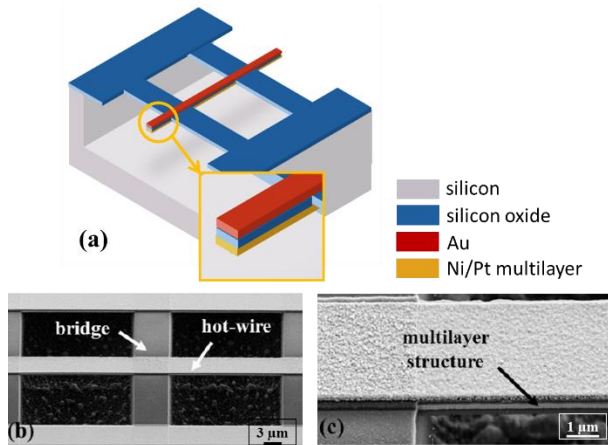


Fig. 1. (a) Schematic of the wall-mounted hot-wire micro-sensor (b) SEM picture of the device (c) Zoom on the multilayered structure of the hot-wire.

As shown on both Figure 1 (a) and Figure 1 (c), another characteristic of the presented micro-sensor compared to conventional designs is the fact that heating and measurement are uncoupled. Indeed, the micro-hot-wire is a multilayer structure with on top the heater (Au layer) on which the heating current is applied, then an insulator layer (silicon dioxide) and underneath the measurement wire (Ni/Pt). This allows to uncouple heating and measurement circuits in the electronic conditioning of the micro-sensors. The regulation of the hot-wire temperature is realized by adapting the heating current depending on the temperature measurement realized on the measurement wire.

The fabrication process of the wall mounted hot wire sensor is displayed on Figure 2 and is similar to the one presented in [15] for a calorimetric micro-sensor. Given their micrometer range dimensions, the micro-sensors chips were manufactured in the IEMN cleanroom, using conventional microelectronic techniques. The devices are therefore compatible with on chip integration.

The process starts by passivating the wafer surface with silicon dioxide. A lift-off process is next used to realize the measurement wires (Figure 2 (a)). The deposition of the Ni/Pt

multilayer is done using metallization by evaporation. Plasma Enhanced Chemical Vapor Deposition is then used to deposit another passivation layer. It corresponds to the electrical insulation layer between the heater and the measurement wire. The gold heater is deposited and patterned using lift-off process again (Figure 2 (b)). Reactive Ion Etching is then exploited to etch the silicon dioxide, shaping the micro-bridges (Figure 2 (c)). The final fabrication step consists in opening the cavity using chemical vapor xenon difluoride etching process (Figure 2 (d)).

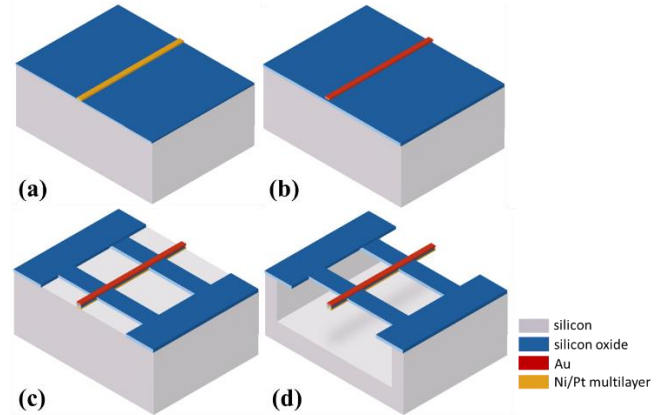


Fig. 2. Fabrication process of the micro-sensors: (a) Fabrication of the measurement wire (b) Fabrication of the heater (c) Etching of the micro-bridges (d) Opening of the cavity

Figure 3 (a) presents the finished wafer with the different micro-sensors chips separated from each other. The fabrication process and the masks used for it allow the simultaneous fabrication of more than a hundred micro-sensors on a 3 in. wafer.

Each chip is then front-side molded on a flexible packaging as presented in Figure 3 (b). This packaging allows robust integration of the micro-sensors inside wind tunnels or model, as presented in [16]. However, it presents a disadvantage: the micro-sensor is under the wall of about 100 μm which lowers the sensitivity to wall shear stress. Indeed, like conventional thermal flow sensors, the micro-sensors measure the heat transfer between the heater and the boundary layer. Its below position lowers the interaction between the thermal boundary layer of the micro-hot-wire and the fluidic boundary layer of the flow.

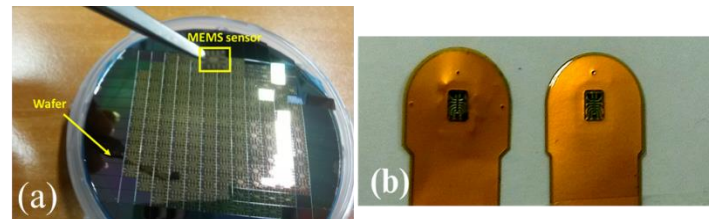


Fig. 3. (a) Wafer with finished micro-sensors chips (b) Micro-sensors integrated in flexible robust packaging

Characterizations performed on the micro-sensor chips demonstrated its electro-thermal performances with a temperature gradient as high as 90 $^{\circ}\text{C}$ for 10 mW of power consumption [17]. We used a thermal infrared camera for evaluating the thermal profile as shown in Figure 3. The

microstructure is heated at 40°C for realizing the thermal image. We measured a high temperature gradient with a variation of temperature of 70°C for 7.7 mW of heating power. This imaging system also showed that the heating is confined in the 3- μ m-wide wire: the thermal insulation from the substrate is successfully achieved.

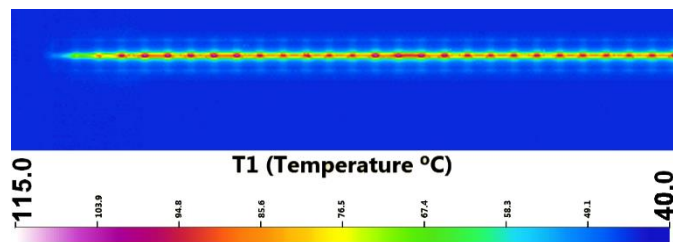


Fig. 3. Thermal imaging of the micro-sensor heated with 7.7 mW and achieving 70°C of temperature variation [17]

III. TESTING IN TURBULENT BOUNDARY LAYER WIND TUNNELS

This paper is dedicated to the experiment performed in a highly turbulent wind tunnel, with flow velocities going from low speed to high speed, up to Mach number $M = 0.79$, which corresponds to about 270 m/s in mainstream velocity. To achieve such velocity range, we performed experiments in two different wind tunnels. The wind tunnel presented in Figure 5 (a) is installed in ONERA Lille and the flow velocity can be managed between 5 and 40 m/s. In terms of Mach number, it corresponds to a maximum of $M = 0.12$. In the following pictures and discussion, it will be referred as “low-speed” wind tunnel when compared to the other equipment. The second wind tunnel, shown in Figure 5 (b), is referred as S8Ch in ONERA Meudon and will be referred as “high-speed” wind tunnel in the paper. This equipment is designed to work with flow velocities going from 180 m/s to 270 m/s, i.e. from $M = 0.55$ to $M = 0.79$. Figure 5 (b) also displays the integration of micro-sensor in a flat plate in the wind tunnel.

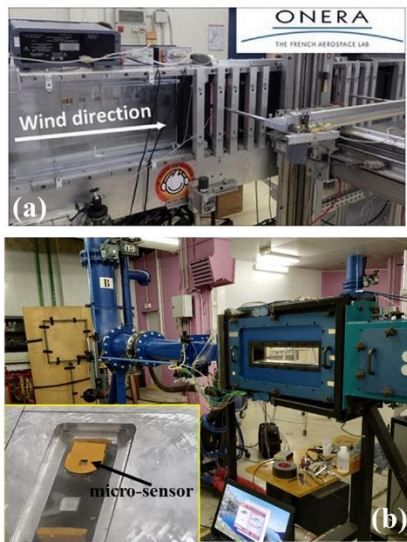


Fig. 5. (a) Turbulent boundary layer “low-speed” wind tunnel in ONERA Lille (b) S8Ch “high-speed” wind tunnel in ONERA Meudon

In the low-speed wind tunnel of ONERA Lille, previous works reported the evaluation of wall shear stress in the turbulent boundary layer, using Coles-Fernholtz method ([18], [19], [16]). This method exploited the characterization of the boundary layer using a conventional motorized hot-wire probe. We calibrated the wall-mounted hot-wire micro-sensor in the wind tunnel, for time-averaged wall shear stress up to 3.2 Pa, as shown in Figure 6. The maximum current variation obtained reached more than 6 ‰.

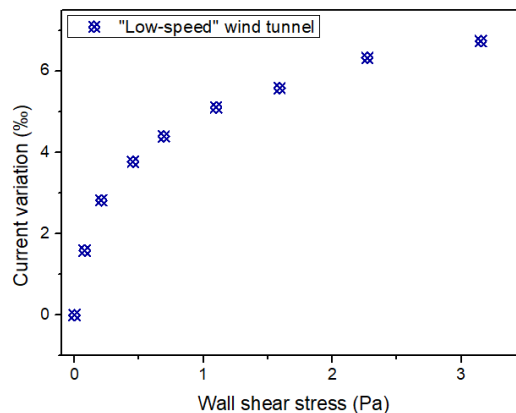


Fig. 6. Time-averaged calibration of the wall-mounted hot-wire micro-sensor in the low-speed wind tunnel in ONERA Lille

The high-speed wind tunnel however presents velocities too high to be able to measure the local wall shear stress and the equations used in Coles Fernholtz method are not valid for high Mach number flows. Indeed, with the increased velocity, the characteristics of the fluid are changed, namely the density and the dynamic and cinematic viscosities. Also, temperature at the wall could be modified too. Therefore, this experiment focused on the physics of the wall mounted hot-wire micro sensor response with two objectives:

- first, observing the increased skin friction at the wall when increasing the flow velocity and
- second, at constant mainstream velocity, measuring different skin friction intensity depending on the position of the micro-sensor on the plate. Indeed, the wall shear stress decreases along a flat plate in turbulent boundary layer regime: it is then higher in upstream position than in downstream position

Therefore two sets of experiments were performed, one in “downstream position” as shown in Figure 7 (a) and one in “upstream position”.

Figure 7 (b) presents the results obtained during the experiments. The red results present the time-averaged measurements obtained in downstream position for a Mach number varying between 0.55 and 0.79. The micro-sensor current variation increases with high sensitivity from about 52‰ at $M = 0.55$ to near 90‰ at $M = 0.79$ and is thereby coherent with expected behavior. The same experiment was performed placing the micro-sensor upstream, at the beginning of the flat plate. The measured skin friction is much higher with current variation reaching about 110‰. For each value of Mach number, the upstream position measures a higher skin friction, which is in accordance with the second objective.

These results demonstrated the robustness and the

usefulness of the micro-sensor for flow measurements in high-speed flows, compatible with velocities on airliners (Mach number around 0.7 - 0.8).

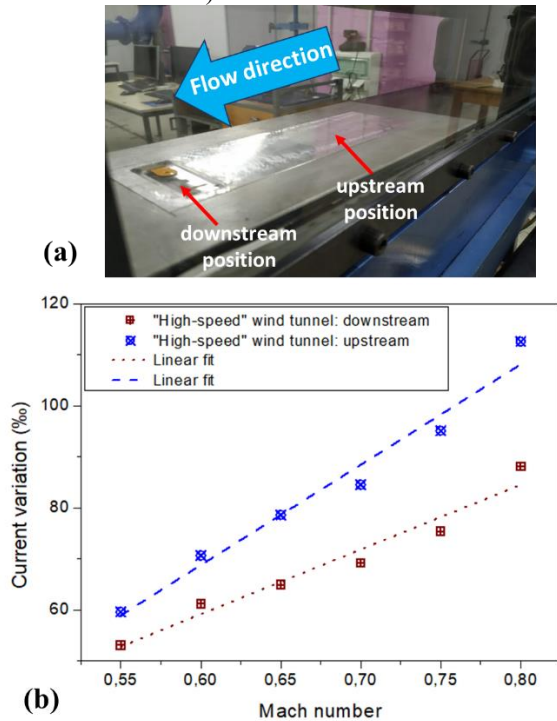


Fig. 7. (a) Experimental setup of the micro-sensor inside the high-speed wind tunnel in S8Ch at ONERA Meudon (b) Results: measured time-averaged current variation with Mach number, for two different positions of the micro-sensor on the flat plate, upstream and downstream.

When increasing the flow velocity from $M = 0.11$ (maximum reached in the low speed wind tunnel) to $M = 0.79$ (maximum reached in the high speed wind tunnel), the fluctuating value of the wall shear stress is also increased importantly. In turbulence physics, the turbulent structures of the flow are smaller in spatial and temporal scale as the Mach number increases. Measuring the frequency weighted Power Spectral Density (PSD) allows interpretations regarding turbulent fluctuations of wall shear stress. The Welch's method was used to obtain the PSD, with a Hamming type window.

The turbulent spectrum is characterized by a rounded shape corresponding to the turbulent energy of eddies in the flow. The energy increases up to a maximum before decreasing when the structures are small enough to suffer from viscous forces. The interval of frequency centered in the hump is characteristic of the turbulent eddies that transport energy in the flow. When the velocity regime of the flow changes, the turbulent spectrum is shifted towards higher frequencies: in other words, the turbulent structures of the flow are smaller and more energetic in high-speed flow than in low speed flows.

The wall mounted hot-wire micro-sensor demonstrated this fact as presented in Figure 8. The black curve corresponds to the turbulent spectrum measured in the low-speed wind tunnel, for 36 m/s mainstream velocity, corresponding to $M = 0.10$. In red is plotted the turbulent spectrum for $M = 0.79$ (about 270 m/s of mainstream velocity), measured in the high-speed wind tunnel. The amount of turbulent energy is clearly higher on the whole range of frequencies. For a mainstream velocity of

36 m/s, the maximum of the hump is reached for 700 Hz. For $M = 0.79$ (270 m/s), the hump is reached for 5.3 kHz. The factor between the two Mach number is also obtained between the two hump frequencies.

At more than 10 kHz however, the current electronic conditioner of the constant temperature regulation showed limitations, with a resonance peak disturbing the measurements, shown at the right of the graph of Figure 8. This limitation avoided the complete dynamic characterization of the wall mounted hot-wire micro sensor in highly turbulent flows. Nonetheless, Figure 8 is a positive first result demonstrating the micro-sensor capacity to measure fluctuations of skin friction at high velocity. Ongoing work on the electronic will expand the bandwidth of the micro-devices and future work will demonstrate the full turbulent spectrum of high-speed subsonic flows. Then, measurements in transonic and supersonic flows will be foreseen.

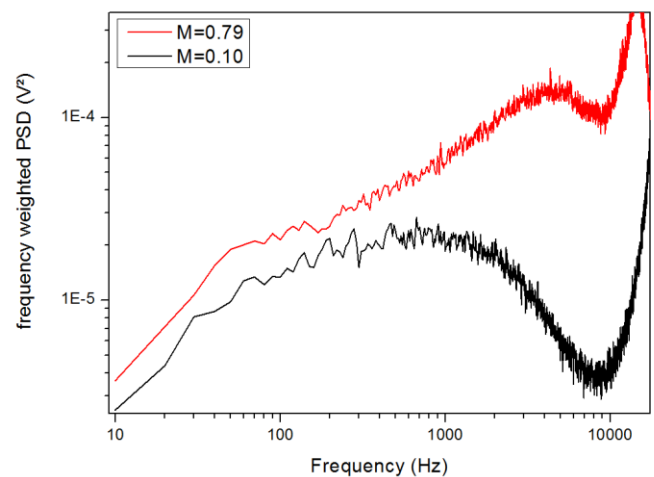


Fig. 8. Frequency-weighted power spectral density measured for two flow velocity regimes: one in low-speed regime, with Mach number of 0.1 and one in high-speed regime with Mach number of 0.79

IV. CONCLUSION

To conclude, this paper presented the latest achievements performed on a wall-mounted hot-wire micro-sensor designed for time-averaged and fluctuating wall shear stress measurements in highly turbulent flows. The section II presented the fabrication process of the micro-device using microelectronic compatible techniques and realized in the IEMN cleanroom. The section III described and discussed the different wind tunnel experiments performed with the micro-device.

The sensor successfully measured the mean and fluctuating wall shear stress in turbulent flows at different Mach numbers. Further work will focus on increasing the sensor sensitivity to small spatial and temporal turbulent scales for testing its response in transonic and supersonic flows.

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