



HAL
open science

Micro thermal anemometer (μ TA) for turbulence measurement : development, fabrication and characterization

Baptiste Baradel, Olivier Leon, Alain Giani, Philippe Combette, Fabien Mery

► To cite this version:

Baptiste Baradel, Olivier Leon, Alain Giani, Philippe Combette, Fabien Mery. Micro thermal anemometer (μ TA) for turbulence measurement : development, fabrication and characterization. 2021 Symposium on Design, Test, Integration & Packaging of MEMS and MOEMS (DTIP), Aug 2021, Paris, France. pp.01-06, 10.1109/DTIP54218.2021.9568498 . hal-03417015

HAL Id: hal-03417015

<https://hal.science/hal-03417015>

Submitted on 5 Nov 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Micro thermal anemometer (μ TA) for turbulence measurement : development, fabrication and characterization

Baptiste Baradel^{*†}, Olivier Léon^{*}, Alain Giani[†], Philippe Combette[†] and Fabien Méry^{*}

^{*} ONERA/DMPE, Université de Toulouse, 2 avenue Edouard Belin, Toulouse, France

[†] IES, Université de Montpellier, CNRS, Montpellier, France

Abstract—The present work provides details on the fabrication and the characterization of a micro thermal anemometer for measuring velocity fluctuations in turbulent flows. This device is based on a freestanding thin platinum wire of $60 \mu\text{m} \times 0.2 \mu\text{m} \times 1.5 \mu\text{m}$ acting as sensing element, placed in the middle of a $900 \mu\text{m}$ length bridge and supported by a silicon structure. A discussion is provided on the designing steps and the manufacturing process relying on micro fabrication techniques. A series of flow velocity measurements was conducted in a turbulent boundary layer to evaluate the response of this sensor. The results are discussed and compared with conventional hot wire anemometry measurements and semi-empirical models to highlight the relevance of this new sensor for turbulence studies.

Keywords— High Reynolds number turbulent flows, Thermal anemometry, Micro-sensor, Boundary layer.

I. INTRODUCTION

High Reynolds number (Re) turbulent flows are encountered in many scientific and engineering applications such as aircraft aerodynamics, turbomachinery or atmospheric boundary layers for instance. Such flows feature a large variety of eddy scales, thus providing broadband energy spectra when analyzing the associated velocity dynamics. Consequently, an accurate characterization of turbulent flows requires to precisely measure a broad range of temporal and spatial scales.

A common measurement technique used for characterization of turbulent flows is hot wire anemometry (HWA) [2][14]. Compared to other velocity measurement techniques such as PIV and LDV for example, HWA is arguably easier to setup and provides continuous time signals with a broad frequency content, typically up to a frequency cut-off of 80 kHz with a classical apparatus. HWA can however be considered as slightly intrusive and only provides single-point measurements for one velocity component in its simplest form. Furthermore, it has been emphasized over the past decades that the size of its sensing element can play an important role in the measurement process since small-scale fluctuations could be filtered-out when energy-containing eddies have a length scale smaller than the hot wire length l_w [1]. In the case of turbulent boundary layers (TBL), this is particularly evident in the near-wall region, where energy-containing streaks have a reduced spatial extent. With an experimental approach, Ligrani and Bradshaw [9]

proposed to manufacture probes with reduced dimensions. They highlight that failure to ensure a sufficiently small value of $l_w^+ \equiv l_w u_\tau / \nu$, with u_τ the friction velocity and ν the kinematic viscosity, yields underestimated values of velocity fluctuation. Consequently they suggested to rely on hot wire probes with a length such that $l_w^+ \leq 20$ to avoid filtering effects when studying TBLs. One difficulty arising however when reducing the length of the wire is to ensure that the classical criterion $l_w/d_w > 200$, with d_w the wire mean diameter, is approximately satisfied to reduce end-conduction effects [2]. The sensor not only needs to be smaller but also thinner to provide accurate measurements of small-scale fluctuations.

This subject of hot wire probe miniaturization has been of interest for the last four decades, see for example [16] [10], but it is with the development of MEMS fabrication technique that the most reliable micro hot wire anemometers were obtained. Recently, a research team at Princeton University managed to build miniaturized probes [1] [15], referred to as Nano-Scale Thermal Anemometer probes (NSTAPs). These micro-sensors have a ribbon-like sensing element with a length of about $60 \mu\text{m}$, a width of $1 \mu\text{m}$ and a thickness of about $0.1 \mu\text{m}$. Such sensors showed a response time reduced by an order of magnitude compared to a classical hot wire and were reported to be reasonably robust. Lastly, this year, Le-The *et al.* [8] detailed the design of a similar micro hot wire anemometer with a platinum nano-wire featuring a reduced width of 300 nm, for a length of $70 \mu\text{m}$ and a thickness of 100 nm. This device was obtained using an extremely delicate fabrication process for the manufacturing of the platinum sensing element and was shown to provide satisfactory velocity measurements.

Building on these past works, the present study intends to show that reliable micro-thermal anemometry probes with reduced dimensions can be obtained using a different design than the ones explored in the literature while relying on relatively simple fabrication techniques. This article is organized as follows. First, a discussion on the design and the fabrication process is provided. Then, a characterization of the probe in a constant temperature anemometry (CTA) mode is performed and discussed. The measurements obtained with this probe in a zero-pressure TBL are finally presented.

II. DESIGN AND FABRICATION PROCESS

A. Probe design and materials

A schematic of the prototype of our micro thermal anemometer (μ TA) is shown in figure 1. This probe is made of a freestanding thin platinum strip of $60 \mu\text{m} \times 0.2 \mu\text{m} \times 1.5 \mu\text{m}$ acting as sensing element, placed in the middle of a $900 \mu\text{m}$ long bridge and supported by a silicon structure. For these dimensions, by calculating the equivalent diameter of the sensitive element the criterion $l_w/d_w > 200$ is not satisfied since a ratio around 100 is obtained. However, as the detector is not a wire but a ribbon, the application of this dimensioning criterion has not been proven. In the future, a thorough study on the end-conduction effects needs to be conducted.

Here, contrary to the most recent micro-anemometers manufactured at Princeton University[15] or at the University of Twente [8], it was decided at first not to give the sensor a profiled shape. Indeed, for this prototype, only simple micro fabrication techniques that do not allow to easily realize a 3D shaping of the sensor were considered. One function of the bridge is thus to keep the sensing element away from the silicon support prongs and thus reduce their possible influence on the measurements. Moreover, such a bridge structure with a width of $10 \mu\text{m}$ was previously shown to be very robust even with greater lengths [4]. This design should thus provide a satisfactory structural resistance to flow dynamic pressure that is essential for high Re flow applications.

Robustness is also ensured by a suitable choice of the material placed between the silicon (*Si*), that is the main material of the probe mechanical structure, and the platinum (*Pt*), that is the material of the sensing element, since its function is to bound the platinum to the bridge. Silicon Nitride (SiN_x) was selected for this purpose. First of all, this material is a dielectric material which acts as an electrical insulator and since *Si* and *Pt* are both conductive (or semi-conductive) it is necessary to isolate them from each other. Secondly, the SiN_x has a high Young modulus ($E > 180 \text{ GPa}$), thus providing significant robustness to the bridge. Lastly, the nitride used is deposited by LPCVD (Low Pressure Chemical Vapor Deposition), which is a material deposition technique at low pressure and high temperature. According to Temple-Boyer [13], this way of depositing the nitride on the silicon surface allows to obtain a material with low residual stresses in tension. This ensures the flatness of the platinum, especially of the sensing element, all along the bridge and consequently the structural resistance of the device. For the fabrication of the μ TA, $200 \mu\text{m}$ thick double-side polished Silicon 4 inches wafers double-side coated with 200 nm of SiN_x deposited by LPCVD are used. These wafers are cleaned of organic matter with an RCA-1 cleaning solution to remove any possible contamination. Then a 200 nm thick platinum layer with an adhesive layer is deposited by EBPVD (Electron Beam Physical Vapor Deposition) *in situ*. Finally, before starting the fabrication process

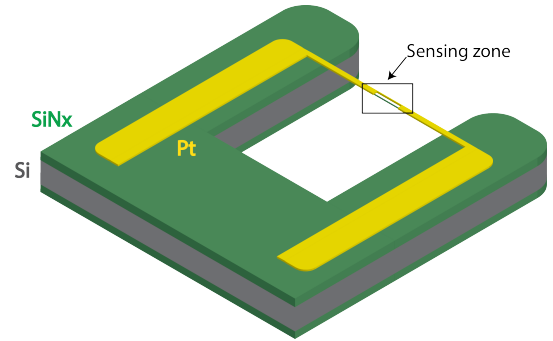


Figure 1. 3D model of the micro thermal anemometer

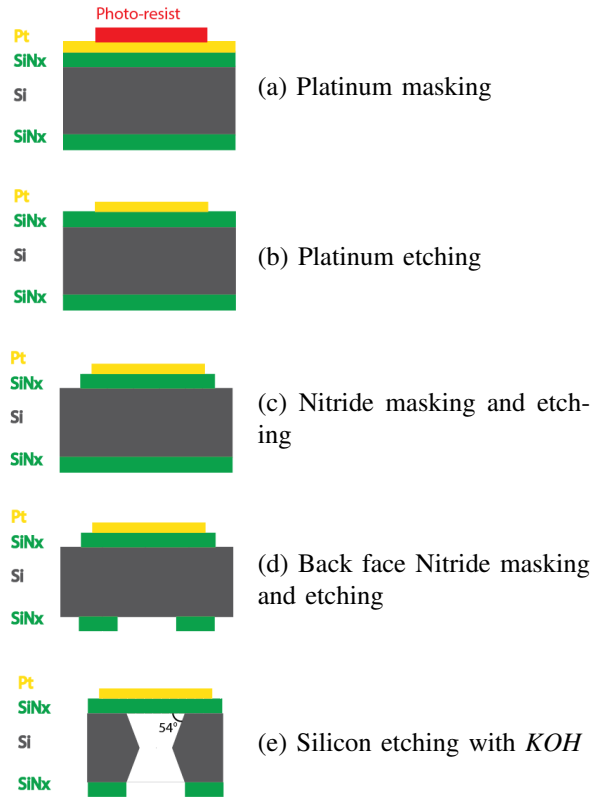


Figure 2. Summary of the manufacturing steps of the μ TA (cross-section of the suspended wire)

of the μ TA, the stack of materials used has the following structure: $\text{SiN}_x(0.2 \mu\text{m})/\text{Si}(200 \mu\text{m})/\text{SiN}_x(0.2 \mu\text{m})/\text{Pt}(0.2 \mu\text{m})$.

B. Fabrication steps

The manufacturing steps of the μ TA are based on standard semi-conductor fabrication techniques summarized in figure 2. Firstly, each layer, starting by the top one, is patterned using photo-lithography and dry etching. Regarding the photo-lithography steps, the different photo-lithographic masks used for the front side layer are presented with their dimensions figure 3. To obtain the desired dimensions, a S1805 positive photo-resist is used and deposit by spin coating to obtain a 600 nm thickness layer. Moreover, the optical aligner and UV insulator selected for this process is

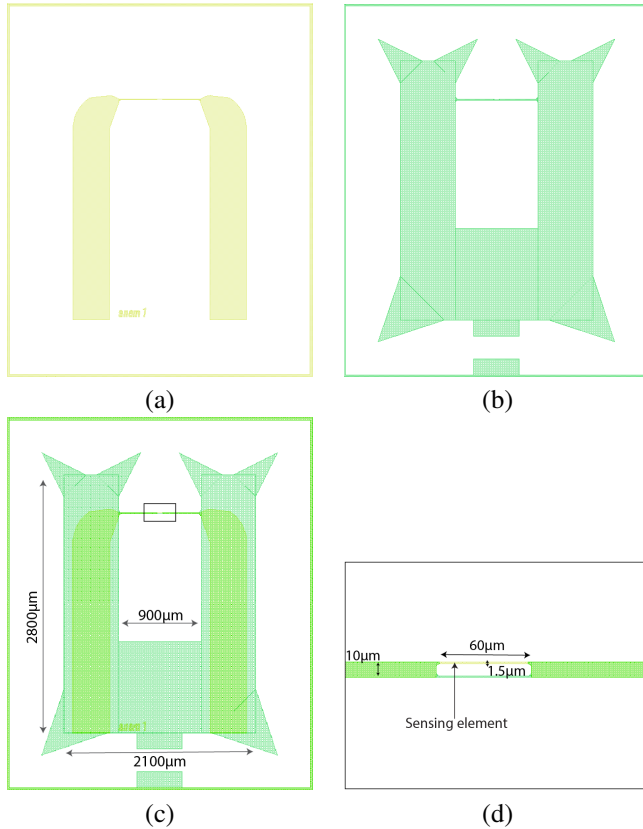


Figure 3. (a) Platinum photo-lithography mask. (b) Nitride front face mask. (c) Superposition of the platinum and nitride masks. (d) Zoom on the sensing element

a Karl Suss MJB4 which allows motif resolution down to $1\ \mu\text{m}$ with a vacuum contact between mask and sample. This aligner can only be used for front side alignments, therefore for back side lithography the EVG 620 aligner is used. Once the pattern is transferred to the photo-resist by UV insulation, the material layer is etched. The etching is accomplished using Reactive Ion Etching (RIE) with a Corial 210IL ICP-RIE etch system. Once each material layers are etched and patterned the last step is to machine the silicon substrate. Keeping the process simple, since the choice was made not to profile the sensor, the samples are dived in an alkaline solution of 40% potassium hydroxide (KOH) at 80°C to etch the silicon and free the platinum sensing element of the device. The KOH solution has the particularity not to react with platinum and nitride. It is also etching silicon according to its crystalline angles. In the present case, this angle is about 54° from the vertical axis (see figure 2(e)). Consequently a particular attention have been carried to the photo-lithography masks design to take into account this issue. In the present case, triangular shapes have been added at each corner of the probe to compensate on eventual lateral underetching. This specific shape and the dimension of these compensations were chosen following the specification of Pal and Tao [12]. The device obtained following this process is shown figure 4 and compared to classic hot wire anemometry probe.

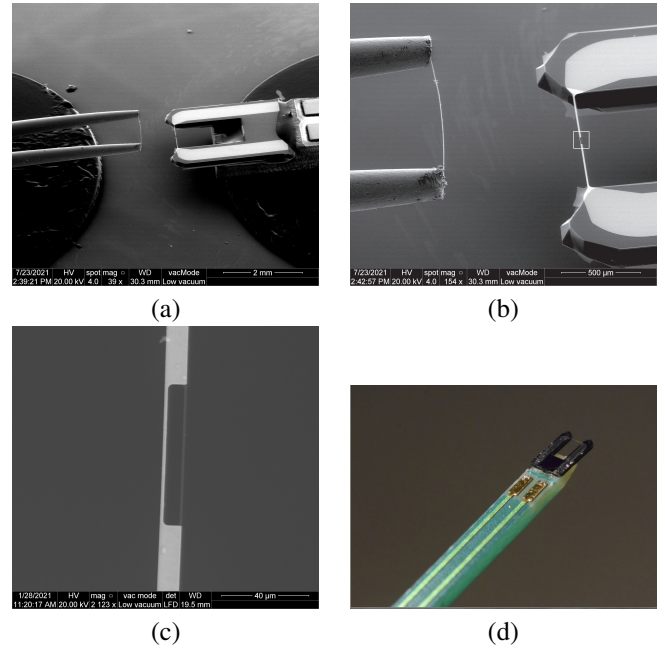


Figure 4. (a) Scanning Electron Microscopy (SEM) image of a 55P15 probe from Dantec Dynamics (on the left) next to a micro thermal anemometer (on the right). (b) Zoom on both sensing elements. (c) Zoom on the μTA sensing element. (d) μTA mounted on a PCB support.

III. PROBE CHARACTERIZATION

The fabricated μTA has a sensing element of $60\ \mu\text{m} \times 0.2\ \mu\text{m} \times 1.5\ \mu\text{m}$. This leads to a characteristic cold resistance R_0 of about $100\ \Omega$. The temperature coefficient α was estimated to be around $0.0036\ \text{K}^{-1}$, a value that is close to the bulk platinum one ($0.0038\ \text{K}^{-1}$) and thus to the one of commercial hot wire anemometry probes. This result is of particular interest compared to other micro-anemometers that have reached values of $\alpha = 0.0021\ \text{K}^{-1}$ at most [8]. To make sure there is no change in the thermoresistive parameters of the manufactured devices over time and that they will behave properly during measurement, the μTAs were operated at a temperature of 200°C for one hour. Following this protocol, a maximum variation of about 5% on R_0 and α was noticed. More importantly, no variations were observed during all velocity measurements performed, that is after several hours of operation, providing a good measurement repeatability.

To perform measurements, the μTAs were mounted on a homemade PCB connector, shown in figure 4(d), that was designed to fit the electrical connection of a commercial hot wire probe support. This connector also avoids adding contact resistances between the sensor and the electric circuit, which is the case when conductive glue is used to hold miniature probes on commercial prongs as in the work of Vallikivi *et al.* [15] and Le-The *et al* [8].

Our micro-anemometers were then connected to an electronic circuit to be used in real conditions and to characterize their performance against commercial anemometer probes. Here, a Constant Temperature Anemometer (CTA) module designed by Dantec Dynamics was used. The CTA Wheat-

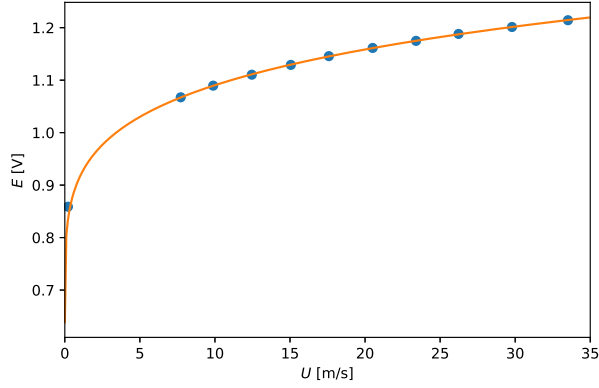


Figure 5. Calibration curve of one of the μ TA following King's law. Circle symbols: calibration points, line: King's law curve fitting. $R^2 = 0.9957$

stone bridge was set to 1:1 mode and an external resistor was used to control the overheat ratio. The commercial probe used for comparison was a 55P15 probe from Dantec Dynamics. The operating temperature of the μ TA was set to 200°C since such a temperature does not introduce parameters variations, providing an overheat ratio around 0.7. For the 55P15 probe, the overheat ratio was set to 0.8 that led to a working temperature of about 220°C . Since it was shown that the overheat ratio does not significantly influence the measurement quality [7], this parameter will be kept to these values during all measurements for each probe. The frequency cut-off f_c of each probe was evaluated using a Square Wave Test response. This determination was performed in a wind tunnel with a uniform air flow of mean velocity $U = 25\text{ m s}^{-1}$. The frequency cut-off of the μ TA was evaluated to be around 240 kHz, that is four times larger than the one obtained with the 55P15 probe. This result thus ensures that this probe is able to capture events with reduced time scales, on the order of a few microseconds. Furthermore, a test of probe robustness was also conducted by increasing the flow velocity during this calibration phase. No failure was observed up to the maximum velocity achievable with this wind tunnel, that is up to $U = 55\text{ m s}^{-1}$.

IV. RESULTS AND DISCUSSION

A. Experimental setup

The performance of this μ TA prototype for turbulence studies was investigated by studying an isothermal, zero-pressure turbulent boundary layer developing on a flat plate with an external velocity of 25 m s^{-1} . Velocity profiles in the TBL were obtained at an axial location on the flat plate where the Reynolds number $\delta^+ \equiv \delta u_\tau / \nu$ was close to 2000, with δ the estimated boundary layer thickness. For comparison purpose, measurements were performed using a 55P15 probe (Dantec Dynamics) and a μ TA under very similar aerodynamics conditions.

B. Calibration

Velocity calibration of the probes was performed following a conventional approach for either the μ TA or the 55P15

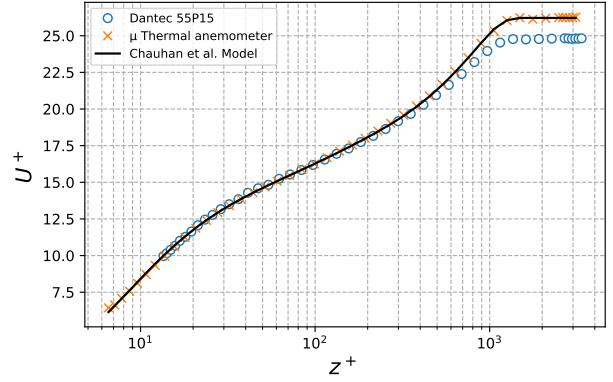


Figure 6. Profiles of mean streamwise velocity as function of the wall distance, expressed in inner scaling.

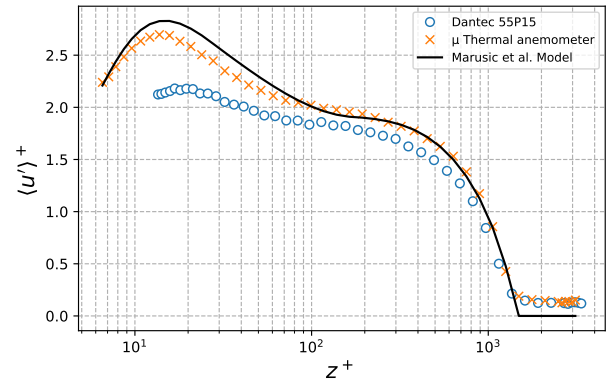


Figure 7. Profiles of rms streamwise velocity as function of the wall distance, expressed in inner scaling.

probe. For each series of boundary layer exploration, the selected sensor was moved outside of the boundary layer, in the freestream flow. The output CTA voltage was then recorded for different flow velocities in the windtunnel, monitored using a Pitot tube located next to the hot wire probe and using a calibrated differential pressure transducer. An analytical calibration law was then fitted to the results to provide a functional relationship between velocity U and the measured CTA output voltage E . In the present work, King's law that can be expressed as $E^2 = a + bU^n$ was considered [6], with a , b and n the fitting parameters. Despite the simplicity of such a law initially derived for cylindrical heated elements and the fact that the μ TA sensing element is shaped as a ribbon, excellent fits were obtained for this sensor with this calibration process as illustrated in figure 5. This observation is in agreement with the previous works testing micro-fabricated hot wire probes [15][8].

C. TBL measurements

Turbulent boundary layer profiles were acquired by traversing the probe from a near-wall location to the freestream region outside of the TBL by incremental steps following a logarithmic scale. The initial location of the

probe was adjusted to be as close as possible to the wall using a camera equipped with a macro lens. The probe was traversed using a precision linear stage with an accuracy of about $3\ \mu\text{m}$. Acquisitions were performed at a sampling frequency $f_s = 50\ \text{kHz}$ with a duration of 30 s per point and using a 24 bits acquisition module. From these temporal results, only two statistical quantities are now discussed: the mean streamwise velocity U and the root-mean-square (RMS) value of streamwise velocity u' .

First of all, the mean streamwise velocity profiles obtained with the μTA and the 55P15 probe can be compared and are shown in figure 6. In this plot all the quantities are expressed using inner scaling, thus such that $U^+ \equiv U/u_\tau$ and $z^+ \equiv zu_\tau/\nu$ where z is the distance to the wall. To get an indication on the consistency of the measurements and on the canonicity of the studied TBL, the measurement results of the two probes were fitted with the semi-empirical model proposed by Chauhan *et al.* [3]. In this figure 6, the mean profiles obtained with both types of probes and with the model overlap in the inner and logarithmic regions ($z^+ < 400$), showing the consistency of the mean velocity measurements. The deviations observed in the outer region reflect some differences in the test conditions leading to slight differences in the values of U_e^+ . This figure furthermore highlights that the μTA can reach locations much closer to the wall than with the 55P15 probe. The measurement point the closest to the wall was obtained for $z^+ = 6.5$, corresponding to a physical distance of about $60\ \mu\text{m}$, but closer measurements can likely be obtained.

Secondly, it is of particular interest to analyze the velocity fluctuation estimates since the μTA was designed to better measure fine-scale turbulent fluctuations. RMS values of streamwise velocity obtained with both types of probes are displayed in figure 7. In this plot, the semi-empirical model of Marusic *et al.* [11] is also represented to provide an approximate profile that should be expected with such a TBL at $\delta^+ \approx 2000$. In this figure, the measurements obtained with our micro-probes in the external region of the TBL ($z^+ > 200$) provide similar values compared to those obtained with a conventional probe, with slightly greater amplitudes. A satisfactory agreement is observed with the semi-empirical model. However, as expected from the literature [1], larger differences between the two types of probes appear in the inner region of the boundary layer. The μTA better captures the near-wall fluctuation peak, with an amplitude in rather satisfactory agreement with the one predicted by the model. In the present case, it can be emphasized that the dimensionless length of the 55P15 probe wire is $l_w^+ \approx 66$ while for the μTA sensing element one gets $l_w^+ \approx 4$, that is smaller than the criterion proposed by Ligrani and Bradshaw [9] ($l_w^+ < 20$) and verified by Hutchins *et al.* [5].

V. CONCLUSION

This work described the design choices and the fabrication process that were selected to manufacture a simple prototype of a micro-thermal hot wire anemometer having a sensing

element of $60\ \mu\text{m} \times 0.2\ \mu\text{m} \times 1.5\ \mu\text{m}$ placed in the middle of a longer bridge. This probe showed a satisfactory robustness to air flow velocity with a frequency response reaching 240 kHz. Similarly to other miniature probes presented in the literature, this μTA was observed to better capture small-scale velocity fluctuations compared to more conventional hot wire probes. It could furthermore be operated very close to the wall despite its simple geometry. The μTA thus appears to be an interesting device for turbulence studies that involve fine spatial and temporal scales.

The device presented here was however only a prototype and regarding the encouraging first results some upgrades can be made to the probe to still enhance its measurement performance. In the future works, the micro-sensor also needs to be tested in other flow conditions to better identify its limitations and capabilities.

REFERENCES

- [1] Sean C. C. Bailey, Gary J. Kunkel, Marcus Hultmark, Margit Vallikivi, Jeffrey P. Hill, Karl A. Meyer, Candice Tsay, Craig B. Arnold, and Alexander J. Smits. Turbulence measurements using a nanoscale thermal anemometry probe. *Journal of Fluid Mechanics*, 663:160–179, November 2010.
- [2] H.H. Bruun. Hot-Wire Anemometry: Principles and Signal Analysis. *Measurement Science and Technology*, 7, 2009.
- [3] Kapil A Chauhan, Peter A Monkewitz, and Hassan M Nagib. Criteria for assessing experiments in zero pressure gradient boundary layers. *Fluid Dynamics Research*, 41(2):021404, April 2009.
- [4] Sébastien Gauthier, Alain Giani, and Philippe Combette. Gas thermal conductivity measurement using a 3ω based sensor. page 5, 2012.
- [5] N. Hutchins, T. B. Nickels, I. Marusic, and M. S. Chong. Hot-wire spatial resolution issues in wall-bounded turbulence. *Journal of Fluid Mechanics*, 635:103–136, September 2009.
- [6] Finn Ekman Jørgsen. HOW TO MEASURE TURBULENCE WITH HOT-WIRE ANEMOMETERS. page 73.
- [7] L. V. Krishnamoorthy, D. H. Wood, R. A. Antonia, and A. J. Chambers. Effect of wire diameter and overheat ratio near a conducting wall. *Experiments in Fluids*, 3(3):121–127, 1985.
- [8] Hai Le-The, Christian Küchler, Albert van den Berg, Eberhard Bodenschatz, Detlef Lohse, and Dominik Krug. Fabrication of freestanding Pt nanowires for use as thermal anemometry probes in turbulence measurements. *Microsystems & Nanoengineering*, 7(1):28, December 2021.
- [9] P. M. Ligrani and P. Bradshaw. Spatial resolution and measurement of turbulence in the viscous sublayer using subminiature hot-wire probes. *Experiments in Fluids*, 5(6):407–417, November 1987.

- [10] P M Ligrani and P Bradshaw. Subminiature hot-wire sensors: development and use. *Journal of Physics E: Scientific Instruments*, 20(3):323–332, March 1987.
- [11] Ivan Marusic and Gary J. Kunkel. Streamwise turbulence intensity formulation for flat-plate boundary layers. *Physics of Fluids*, 15(8):2461–2464, August 2003.
- [12] Prem Pal and Kazuo Sato. A comprehensive review on convex and concave corners in silicon bulk micro-machining based on anisotropic wet chemical etching. *Micro and Nano Systems Letters*, 3(1):6, December 2015.
- [13] P Temple-Boyer, C Rossi, E Saint-Etienne, and E Scheid. Residual stress in low pressure chemical vapor deposition SiNx films deposited from silane and ammonia. *J. Vac. Sci. Technol. A*, 16(4):5, 1998.
- [14] Cameron Tropea, Alexander L. Yarin, and John F. Foss, editors. *Springer handbook of experimental fluid mechanics*. Springer, Berlin, 2007.
- [15] Margit Vallikivi and Alexander J. Smits. Fabrication and Characterization of a Novel Nanoscale Thermal Anemometry Probe. *Journal of Microelectromechanical Systems*, 23(4):899–907, August 2014.
- [16] William W. Willmarth and Lalit K. Sharma. Study of turbulent structure with hot wires smaller than the viscous length. *Journal of Fluid Mechanics*, 142:121–149, May 1984.