EXPERIMENTS WITH MICRO-MACHINED MULTI-ARRAY HOT-FILM PROBE TOWARDS FIELD EXPERIMENTS WITH SUB-KOLMOGOROV RESOLUTION

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Abstract This is a report on implementation of the next stage of a project, motivated by the discovery of far more important role, played by the sub-Kolmogorov scales in high Reynolds number turbulence than commonly believed. The main results and issues that prompted the present work are in [1] – [3] and references therein. At this stage we report on the first successful experiments with a unique micro-machined hot-film multi-array probe. This includes design, assembly, implementation and testing of such probe in laboratory conditions [4]. The probe is enabling to access, along with all three components of turbulent velocity fluctuations, also all nine components of the spatial velocity gradients tensor, including the option of obtaining the stream-wise velocity derivatives without employing the Taylor hypothesis, as well as velocity temporal derivatives. The key feature of the micro-machined multi-array probe (typically five arrays), with each array consisting of four micro-machined hot-film sensors, is that it is six times smaller than the conventional multi-array probe, based on arrays with four hot wires [5] – [6], used in the atmospheric surface layer at Taylor micro-scale Reynolds number up to $Re_\lambda \approx 10^4$. This part of work relates to Reynolds numbers $Re_\lambda < 500$ and employs several laboratory flows.

INTRODUCTION, TECHNICAL ASPECTS AND RELATED

There are fundamental reasons [3] for the necessity of accessing the full velocity gradient tensor. Among these is the essentially dissipative and rotational nature of turbulence, and not just in small scales. Moreover, there is a special aspect of paradigmatic nature that velocity derivatives have to be accessed at sub-Kolmogorov scales, in which reside the strong dissipative events exerting non-trivial impact on the conventional 'inertial' range. Therefore, a multi-array hot-film probe, based on a single micro-machined sensor as a building block, is a much needed measuring tool.

So far successful attempts were made to manufacture and employ a single micro-machined hot-film sensor in flows past a grid and in turbulent pipe flow by Princeton group [7] – [8] and also by our group in a confined circular jet [1] and [9], the latter with the main purpose to check the performance of the sensor as a building block of a five-array (i.e., 20 hot sensors) probe. Except of miniaturization there are special requirements to the single sensing element in view of the goal to manufacture a multi-hot-sensor probe, enabling access to all the components of the velocity gradient tensor. In particular, not only the single sensing element, but also its support has to be miniature in order to minimize the interference of its own supporting structure and from the neighboring sensing elements. The sensor design, fabrication and probe assembly procedure are described in detail in [9] – [10]. The version used for probe assembly was the 45°, 60 μm, nickel on silicon nitride (SiN) sensing element. The thickness of the sensing element film was 170 nm (70 nm SiN and 100 nm nickel) and its width was 3 μm. The assembled probe is shown on Fig 1.

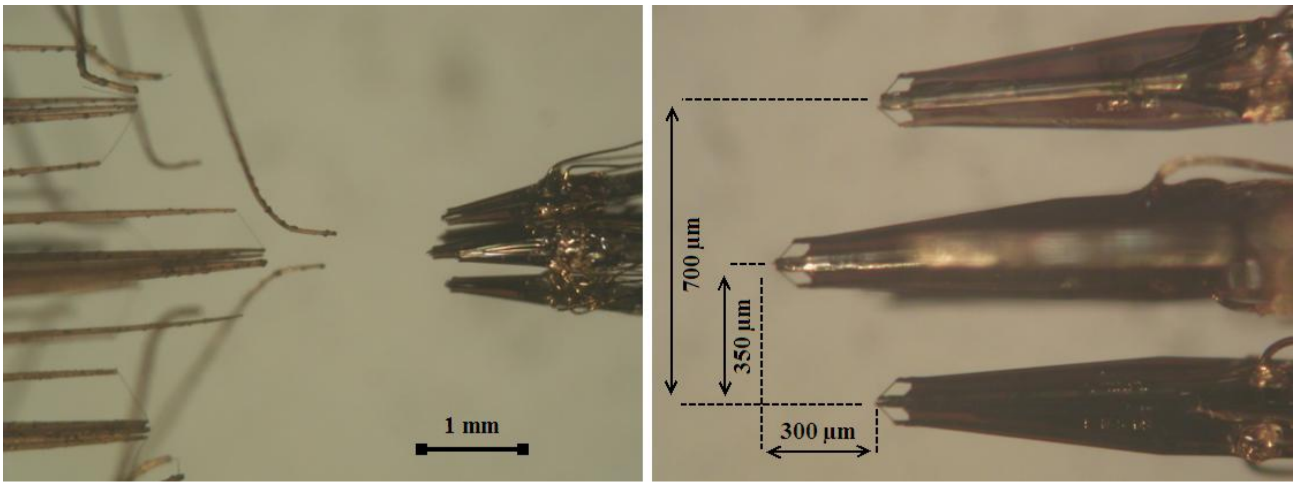

Figure 1. Micro-photo of a micro-machined probe next to a conventional one (left). Array separation dimensions of the micro-machined probe (right).

PHYSICAL TESTS

We performed what we call physical testing, by which we mean experiments, directed to test the probe performance in several flow conditions. These include flow in channel of rectangular cross section [11], in its bulk and in the proximity of its smooth and rough walls; we also had a look in the confined jet, produced by our calibration unit [5].

We remark that, as expected, the conventional results, concerning the velocity field, appeared in good agreement with the common knowledge. In this report we put the emphasis on the field of velocity derivatives, such as vorticity, strain and related – in conformity with the main concern of this work. Moreover, special attention is given to the properties, which are expected to possess qualitative universality [3].

The first important check is the so-called continuity test intended to inspect the kinematic relation div $\mathbf{u} = 0$. It is well illustrated by the joint PDFs of $A=\partial u_1/\partial x_1$ and $B=-(\partial u_2/\partial x_2+\partial u_3/\partial x_3)$, see Fig 2. If div $\mathbf{u} = 0$ is strictly fulfilled, $A=B$. For real measured data this never happens, and the correlation coefficient between A and B is a good indicator of the quality of the data. The correlation coefficients for all reported experiments are shown in Table 1.

We follow to a large extent the pattern of the work, done by the group of Prof. A. Tsinober employing a conventional multi-hot-wire five-array probe, and some of their results are used for comparison. For the latter along with the results, obtained in this work for moderate Reynolds numbers, we use the results from field experiments at large Reynolds number, obtained using multi-sensor probes based on conventional hot wires [5].

A chosen number of basic issues as concerns the phenomena, manifested in the field of velocity derivatives, will be presented, for full report see [4]. These include vorticity, strain and related, e.g., enstrophy and strain production; geometrical statistics; depression of nonlinearity; acceleration and Taylor hypothesis.

Table 1. Correlation coefficients between A and B in various experiments with micro-machined probes.

Wind tunnel experiments in the proximity of the rough wall				Wind tunnel experiments in the proximity of the smooth wall					Confined jet experiments		
Distance from the wall, mm									*x*/*D*		
20	50	150	250	5.0	7.5	10	15	25	20 *a*	20 *b*	25
0.77	0.70	0.77	0.79	0.76	0.76	0.70	0.76	0.75	0.64	0.64	0.55

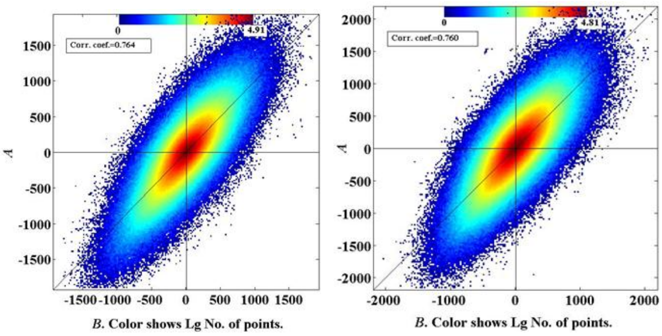

Figure 2. Examples of joint PDFs of $A=\partial u_1/\partial x_1$ and $B=-(\partial u_2/\partial x_2+\partial u_3/\partial x_3)$. Wind tunnel experiments. Left – at 20 mm from rough wall, right – at 7.5 mm from smooth wall.

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References

[1] Y. Borisenkov, M. Kholmyansky, S. Krylov, A. Liberzon and A. Tsinober, A. Super-miniature multi-hot-film probe for sub-Kolmogorov resolution in high-Re turbulence. *J. Physics: Conference Series,* **318**: 072004/1–10, 2011.

[2] A. Tsinober, *An Informal Conceptual Introduction to Turbulence,* Springer, 2009.

[3] A. Tsinober, *The Essence of Turbulence as a Physical Phenomenon,* Springer Verlag, 2014.

[4] Y. Borisenkov, G. Gulitski, M. Kholmyansky, S. Krylov, A. Liberzon, A. Tsinober, Micro-machined super-miniature hot-film multi-array probe for field experiments with sub-Kolmogorov resolution, *Journal of Turbulence.* **16/6** : 525-539, 2015.

[5] G. Gulitski, M. Kholmyansky, W. Kinzelbach, B. Lüthi, A. Tsinober and S.Yorish, Velocity and temperature derivatives in high-Reynolds-number turbulent flows in the atmospheric surface layer. Parts 1–3. *J. Fluid Mech.* **589**: 57–123, 2007.

[6] M. Kholmyansky, A. Tsinober and S. Yorish, Velocity derivatives in the atmospheric surface layer at $Re_\lambda=10^4$, *Phys. Fluids,* **13**:311–314, 2001.

[7] S.C.C. Bailey, G.J. Kunkel, M. Hultmark, M. Vallikivi, J.P. Hill, K.A. Meyer, C. Tsay, C.B. Arnold and A.J. Smits. Turbulence measurements using a nanoscale thermal anemometry probe. *J Fluid Mech.* **663**:160–179, 2010.

[8] M. Hultmark, M. Vallikivi, S.C.C. Bailey and A.J. Smits, Turbulent pipe flow at extreme Reynolds numbers, *Phys. Rev. Lett.,* **108**:1–5, 2012.

[9] Y. Borisenkov, M. Kholmyansky, S. Krylov, A. Liberzon and A. Tsinober, A. Multiarray Micromachined Probe for Turbulence Measurements Assembled of Suspended. Hot-Film Sensors *Journal of Microelectromechanical Systems,* doi: 10.1109/JMEMS.2015.2417213, 2015.

[10] Y. Borisenkov, Micro-Machined Super Miniature Hot Film Multi-Array Probe for Measurements in Turbulent Flows with sub-Kolmogorov Resolution, Tel-Aviv University, 2014.

[11] O. Friedland, V. Troshin and A. Seifert, Wind loads and Control of Flexible Structures Embedded in a Turbulent Boundary Layer, in *54th Israel Annual Conference on Aerospace Sciences,* Tel-Aviv & Haifa, Israel, 2014.