Super-miniature multi-hot-film probe for sub-Kolmogorov resolution in high-Re turbulence

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Abstract. The work reported here is motivated by the discovery of far more important role played by the sub-Kolmogorov scales than commonly believed. The first part is devoted to an overview of main results and issues that prompted the present developments. The emphasis is made on a number of manifestations of nonlocal nature of turbulence involving direct and bidirectional coupling of conventionally-defined inertial and dissipative ranges showing (a) that both concepts are ill-posed and (b) that further progress requires sub-Kolmogorov resolution. The second part contains a presentation on design, manufacturing and tests in laboratory of a micro-hot-film sensor using modern micro-fabrication technologies, as a basis for a probe of much smaller scale than available today with access to quantities like vorticity and strain at sub-Kolmogorov scales in high-Reynolds-number flows.

1. Introductory notes

There is a common view that the smallest physically-relevant scale in turbulent flows is the Kolmogorov length scale \( \eta = (\nu^3/\langle \epsilon \rangle)^{1/4} \). If so, then in order to spatially resolve the smallest relevant eddies, sensors of the order of size as the Kolmogorov length scale are needed. However, experimental observations in high-Reynolds-number flows show that there exist long tails in the PDF of the local dissipation, \( \epsilon = 2\nu s_{ij}s_{ij} \), corresponding to even smaller scales, the sub-Kolmogorov scales, in the PDF of the local Kolmogorov length scale, figure 1 (Tsinober, 2009, and references therein).

It appears that these sub-Kolmogorov scales, conventionally defined as dissipative, are directly and bidirectionally coupled with the conventionally-defined inertial range in turbulence at high Reynolds numbers (Tsinober, 2009; Kholmyansky & Tsinober, 2009). This coupling is manifested in several non-trivial consequences including those of paradigmatic nature (see below), and is expected to have an impact on modeling of turbulent flows in which nowadays the dissipative range is modeled or parameterized via empirical closures in terms of inertial range and/or just large-scale flow properties. Thus there is a need for access to sub-Kolmogorov scales exactly like to the unresolved scales in model testing. It is noteworthy that access to scales smaller than \( \eta \) has never been achieved neither experimentally nor via DNS of Navier–Stokes equations (NSE) at high Reynolds numbers. Recently a single-wire nano-probe was used in grid-generated turbulence at \( \text{Re}_\lambda \sim 10^2 \) with dimensions \( 0.1 \times 2 \times 60 \mu m \). It had operating
Figure 1. PDF of the local dissipation divided by the mean one (left). The corresponding PDF of the local Kolmogorov scale divided by the mean one (right). Field experiment in Sils Maria, Switzerland, 2004. Re = 7 \cdot 10^3 (see Tsinober, 2009).

characteristics very similar to those of conventional hot-wire probes, but with considerably better spatial resolution and frequency response (Bailey et al., 2010). This probe, however, cannot be used as a building block for a multi-hot-sensor one, which is the main goal of our development. Results at similar Re were obtained in DNS of NSE in a periodic box (Schumacher, 2007).

The required resolution cannot be achieved in DNS in the foreseeable future at high Reynolds numbers, but judging by our present experience and due to our expertise this is feasible experimentally and constitutes the main issue reported in the sequel.

2. The main results and issues that prompted the present developments

Here we present the main results which form the scientific basis for the present developments. Along with published, these include a selection of important unpublished results.

2.1. How “inertial” is the conventionally-defined inertial range (CDIR)?

The above includes questions as follows: are the CDIR properties really independent of dissipation (and/or large-scale forcing)? That is, whether the inertial range a well-defined concept and how clean and meaningful is the ‘decomposition’ on energy-containing, inertial and dissipative ranges? In particular, it appears that there exists a substantial number of dissipative (!) events, contributing essentially to the PDF of velocity increments in the conventionally-defined inertial range at high Reynolds numbers (Re \sim 10^4), see figure 2. The key feature is that this contribution is largest to the tails of the PDF of velocity increments showing that the CDIR is an ill-defined concept.

2.2. Is ‘anomalous scaling’ an attribute of the inertial range?

The consequence of the above-mentioned largest contribution of the dissipative events to the tails of the PDF of velocity increments is that it is the presence of these dissipative events which is responsible for what is called anomalous scaling. This is clearly seen from figure 3. Thus the anomalous scaling is not an attribute of the conventionally-defined inertial range (CDIR), and the latter (just like the dissipative range, CDDR) is not a well-defined concept.

2.3. Is 4/5 law a pure inertial relation at large Re?

The viscous term \( v.t. = 6\nu d \langle (\Delta u(r))^2 \rangle / dr \) in the Kolmogorov 4/5 law \( \langle (\Delta u(r))^3 \rangle = -(4/5)r + v.t. \) is negligible at large Re (Kholmyansky & Tsinober, 2008). However, a crucial point here is that the neglected viscous term in the Kolmogorov 4/5 law does not contain ALL the viscous contributions. Those present in the structure function \( \langle (\Delta u(r))^3 \rangle \) itself remain (figure 2) and
Figure 2. Histograms of the increments of the longitudinal velocity component for the data in which the strong dissipative events (when at least at one point $x$ or $x + r$ the instantaneous dissipation $\epsilon > q\langle \epsilon \rangle$) are present; with removed strong dissipative events for the threshold $q = 3$ and for the dissipative events themselves with the same threshold; $r/\eta = 100$ (Kholmyansky & Tsinober, 2009).

Figure 3. Scaling exponents of structure functions at $Re \sim 10^4$ for the longitudinal velocity component corresponding to the full data and the same data in which the strong dissipative events (see caption of figure 2) with various thresholds $q$ were removed (Kholmyansky & Tsinober, 2009). With $q = 3$ the higher-order structure functions ($p \geq 4$) exhibit Kolmogorov scaling $p/3$.

Figure 4. Contributions of the strong dissipative events (see caption of figure 2) to the third-order structure function as a function of the threshold $q$ for various separations $r$ (blue circles $r = 4$, green squares $r = 40$, brown triangles $r = 400$, red crosses $r = 4000$); in the insert: scaling exponents of the third-order structure function as a function of the threshold $q$ (Kholmyansky & Tsinober, 2009).

keep the 4/5 law precise: without the dissipative events just mentioned the 4/5 law does not hold! In this sense the 4/5 law is not a pure inertial law even at $Re \sim 10^4$. Indeed, strong dissipative events do contribute to the 4/5 law (figure 4), and removing them leads to an increase of the scaling exponent above unity (see insert in figure 4).

It is noteworthy that the contribution of the dissipative events in the 4/5 law in the form $\langle (\Delta u(r))^3 \rangle = -(4/5)r$ is not small in spite of considerable cancellation between the negative
and positive events. An interesting feature is that most of the contribution of the dissipative events to the skewness \( S = \frac{\langle (\Delta u(r))^3 \rangle}{\langle (\Delta u(r))^2 \rangle^{3/2}} \) in the CDIR comes roughly from two ranges \( r/\eta \): in proximity of 50 and 5000 (figure 5). Another noteworthy feature characterizing the contribution of the dissipative events is that the skewness \( S \) for the sets with removed dissipative events and for the sets of the dissipative events only are pretty similar (figure 5).

**Figure 5.** The skewness \( S = \frac{\langle (\Delta u(r))^3 \rangle}{\langle (\Delta u(r))^2 \rangle^{3/2}} \) for the same data with removed strong dissipative events (see caption of figure 2) for the threshold \( q = 3 \) and the dissipative events themselves for the same threshold.

### 2.4. Enstrophy and strain production

Here we tested a similar issue concerning the enstrophy production \( \omega_i \omega_j s_{ij} \) and strain production \( s_{ij} s_{jk} s_{ki} \). The common view is that the origin of both quantities and corresponding processes is purely inertial. It appears that both quantities contain a substantial contribution from the dissipative events (DE). This is clearly seen from figure 6 and figure 7 showing the contribution of DE and examples of the PDFs of \( \omega_i \omega_j s_{ij} \) and \( s_{ij} s_{jk} s_{ki} \) for the whole data, the sets with removed dissipative events and for the sets of the dissipative events only.

**Figure 6.** Contributions of strong dissipative events (when at point \( x \) the dissipation \( \epsilon > q \langle \epsilon \rangle \)) to the enstrophy and strain production as a function of the threshold \( q \).

### 2.5. Filtering approach

The results described here are by necessity of qualitative nature as we used one-dimensional filter which was a standard Gaussian filter of width \( r \). The filtered quantities are denoted as \([\ldots]\).
We looked at the sub-grid scale (SGS) stresses $\tau_{ik} = [u_i u_k] - [u_i][u_k]$ and the SGS energy flux $\Pi(x; r) = -\tau_{ik}[s_{ik}]$. Again this was done for the whole data, for the sets with removed dissipative events and for the sets of the dissipative events only. Representative examples are shown in figure 8 and figure 9. The main point is again the essential contribution of the dissipative events to the SGS stresses $\tau_{ik} = [u_i u_k] - [u_i][u_k]$ and the SGS energy flux $\Pi(x; r) = -\tau_{ik}[s_{ik}]$ in the conventionally-defined inertial range with a considerable dependence on the threshold $q$ — both reduced with the decrease of $q$. It is noteworthy that the magnitude of the SGS energy flux, $-\tau_{ik}[s_{ik}]$, is changed with $q$ also due to its influence on the alignment between the tensors $\tau_{ik}$ and $[s_{ik}]$.

Thus — as in the case of the 4/5 law — both the SGS stresses and the SGS energy flux are not purely inertial quantities though the width $r$ is in the CDIR. This is precisely because the contribution of viscous effects is not limited by the viscous terms corresponding, e.g., to the Laplacian in the filtered equations. Therefore, though both the SGS stresses and the SGS energy flux “are identical to those that would be obtained by coarse-graining not the NSE but instead the incompressible Euler equations” (Eyink, 2008), this does not help as they are identical in form only. The SGS quantities in the two are essentially different due to nonlocal effects.

The bottom line of the above overview is that nonlinear and purely-inertial are not synonymous, i.e., in the CDIR the nonlinear interactions are not synonymous to purely-inertial ones even at $Re$ as large as $10^4$. Namely, the nonlinear interactions even at such high Reynolds numbers consist of purely inertial ones with an essential contribution from the viscous (and cross-) interactions.

It is noteworthy that the data used here (Gulitski et al., 2007; Kholmyansky et al., 2001, and references therein) was somewhat spatially underresolved, $(1 - 3)\eta$. This means that...
Figure 8. Invariants of the SGS stress tensor, \( \tau_{ik} = [u_i u_k] - [u_j] [u_k] \), at \( \text{Re} \sim 10^4 \) corresponding to the full data and the same data in which the strong dissipative events (see caption of figure 2) with various thresholds \( q \) were removed.

Figure 9. SGS energy flux, \( \Pi(x; r) = -\tau_{ik} [s_{ik}] \) at \( \text{Re} \sim 10^4 \) for the longitudinal velocity component corresponding to the full data and the same data in which the strong dissipative events (see caption of figure 2) with various thresholds \( q \) were removed.

The conclusions are to some extent qualitative. However, with properly resolved data the strong dissipative events, lost in the underresolved case, would only enhance the tendencies just described above. This is in agreement with the fact that essentially the same results are obtained using the same data smoothed over up to eight sequential samples. However, this is sufficient only qualitatively since the strong dissipative events are lost in the underresolved case. Thus for quantitative purposes one needs sub-Kolmogorov resolution in order to resolve these dissipative “events”. The key issue here is a probe enabling access to sub-Kolmogorov scales.

3. A probe enabling access to sub-Kolmogorov scales

3.1. The previously used probe.

The main essential attribute is that this probe (figure 10) enables access to all three components of turbulent velocity fluctuations, \( u_i \), all nine components of the spatial velocity gradients tensor, \( \partial u_i / \partial x_j \) (and thus, e.g., to vorticity and strain), and velocity temporal derivatives, \( \partial u_i / \partial t \), with synchronous data on fluctuations of temperature, \( \theta \), its spatial gradient, \( \partial \theta / \partial x_j \), and temporal
3.2. The new probe
Since each hot-wire sensor in the probe mentioned above was manufactured using conventional techniques – its size was prescribed by the wire diameter, $D$, which led to a limited from below sensor length ($L \approx 200D$). The modern micro-fabrication technology enables us to fabricate a micro-hot-film sensor as a basis for a multi-hot-sensor probe of much smaller scale.

Figure 11. An example of the basic sensor shape. There are 3 sizes of such sensor permitting to investigate first the physical and mechanical limitations on the larger ones and then to go down to smaller design tests. The width $W_1$ of the sensing tip varies between 20 and 200 $\mu$m; the rest of the geometry changes proportionally to that width. The thickness of the sensor is constant, due to fabrication and aerodynamic issues, and it is equal to 3 $\mu$m. The thickness of the sensing element film is 30 nm.

The design. During the first phase of the design, the basic shape of the sensor has been proposed, such that it would fit the concept of the array structure, which was implemented in the latest modification of the multi-array hot-cold-wire probe. This structure, shown in figure 10 above, includes five arrays, each array consisting of four sensors. Each sensing element of each sensor in the array is inclined at different angle toward the flow, so the set of the signals permits determination of the velocity vector at the point of the array, and the whole probe provides the spatial and temporal velocity derivatives without invoking the Taylor hypothesis. The basic shape and the dimensions of the micro-machined sensor are shown in figure 11.

The second phase of the design task is the design of the sensing element tip. The proposed multi-array probe is to be fabricated in such a way that each sensor in the array would feel the flow from different plane. Then using the approximation of the multi-dimensional signals, obtained by calibration, we can calculate the velocity vector. The main design concepts for this are presented in figure 12. One of the questions to be answered during future experiments is which of the concepts would perform better in high Reynolds number turbulent flows in laboratory and/or in the field experiment.
**Figure 12.** The basic structure of a four-sensor array. The sensing element with straight inclined tip is shown as well as with 45° cut and inclined tip. An issue of the heat transfer needs to be considered, therefore additional design has been planned — a hanging tip. Its difference from the basic designs is that the silicon substrate in the sensor tip area will be removed leaving just enough material to support the connection leads.

**Figure 13.** Sensing element tip fabrication steps.

*The fabrication.* The fabrication of a prototypical hot-film sensor for turbulent flow experiments is done using micro-fabrication technologies. In order to be compatible with design dimensions the process sequence is chosen. The process flow includes use of 4 masks, with ⟨100⟩ SOI (silicon on insulator) wafer with a 3 µm device layer, 0.5 µm BOX (buried oxide) layer and a 400 µm handle as the starting material. The main stages of the micro-machining process include wet and dry etches, evaporation and sputtering of metal layers, lift-off process and oxide PECVD (plasma enhanced chemical vapor deposition).

First, a SOI wafer is etched using wet etch to form a 3 µm cavity (figure 13). The 54.7° inclined walls of the cavity will be the substrate for the sensing element. The sensor would work properly only if the substrate is non-conducting both electrically and thermally. For this reason the next step is a PECVD of 0.5 µm oxide layer. Then a 30 nm metal layer is evaporated over the whole wafer, and we get the desired structure of the sensing element after a lift-off process, figure 13. In our case, due to the structure topography, in order to perform the lift-off process, additional MicroChem’s LOR 5A lift-off resists was coated prior the Shipley S1818 photoresist. The LOR (lift-off resist) enhances the photoresist adhesion and mostly performs as an undercut layer in bi-layer lift-off processing for better control of the width of the deposited line. The metal layer was deposited using EDWARDS-306 e-beam evaporator. Similarly we form the 400 nm thick gold leads and contact pads. Then a 3 µm device layer is etched by DRIE (deep reactive ion etching) using the fourth mask.

At this point the wafer is cut, using diamond scriber, into 1 × 1 cm dies, and each devise on the die is wired using 4524 Kulicke & Soffa wire bonder with a 2 mil gold wire. Then, each of the dies is etched from the back side, using slightly modified wet etch process (Freyer, 1975), for 390 µm. As a rule, in the micro-machining industry, sensors wiring is the last stage before packaging, but in our case the final product should be a 3 µm thick device. It will not stand the pressure applied during the wire-bonding step. Any additional process on a die with already wired sensors is complicated because it is necessary to protect the front side with the connection wires. The wet etch process we used was modified for our needs. It worked well allowing us to visually control the etch depth while protecting the front side and the connection
wires from the etching solution. Next, another DRIE process is performed on the back side to etch additional 10 \( \mu m \) of the handle; this permits to get relatively (to the wet etch) low-stress 3 \( \mu m \) thick devices. Finally, HF vapour is used to get the released structures. The final product is a cantilever beam of 3 \( \mu m \) thick with the sensing element — inclined tip covered by thin metal layer — and connection leads from it to the pads at the tail with attached gold wires.

The advantage of using photolithography-based processes is the minimization of the device and large number of different devices that can be fabricated in one batch, therefore the study of the sensor parameters will be performed at no significant added cost.

The next stage of the fabrication is the assembling of the sensors to array and then to multi-array probe. This will be done using micro-manipulators while the conducting gold wires will help to hold the sensors. The array structure will obviously enhance the mechanical strength of the device built of 3 \( \mu m \) thick elements.

4. Preliminary work and results

Figure 14. Microphotograph of the preliminary version of the micro-hot-film sensor.

First, following the steps described above, several test fabrications were performed to check their feasibility. The first challenging part of the process flow was the lithography, evaporation and the lift-off process on an inclined surface. These steps were performed successfully. Further steps of the process flow were also performed. The tests helped to locate a few problems and to adjust the process correspondingly. Finally, a number of sensors were manufactured (preliminary version, see microphotograph in figure 14). Their performance was checked along several lines.

One of the questions was if there was a good electrical contact of the sensing element with the leads. Using an infrared camera (FLIR scientific grade camera, 640 \( \times \) 480 px, Multiphase Flow Laboratory, Technion, Haifa) we found the sensing element being uniformly heated by electrical current and the contact points staying cool. The sensor was connected to the anemometer and worked properly. Then simultaneous measurements were performed in laboratory turbulent flow, at the axis of a turbulent jet, using the micro-sensor and a traditional hot-wire probe, positioned side by side. An example of the power spectra of the velocity, obtained from these measurements, is presented in figure 15. It demonstrates good performance of the new sensor that works perfectly without interference of end- or substrate heat-conduction effects. The time resolution of the new probe is at least the same and presumably is better than of the old one in the frequency band to 25 kHz that the available electronics permitted. The spatial resolution is now being checked in experiments with pairs of probes positioned side by side at different small distances one from another.

5. Concluding remarks

Micro-machined multi-array hot-film probe is a promising platform for expanding our insight of the turbulent flows down to the smaller scales, the sub-Kolmogorov ones, once considered insignificant. Our present results on a single micro-miniature sensor are promising enough for building within a year a multi-hot-sensor probe enabling access to velocity derivative at these scales in high-Reynolds-number flows. The results of such experiments promise potentially
Figure 15. An example of the wide-range velocity power spectra in the center of the cross-section of a turbulent round jet at $x/d = 15$ and mean velocity $U = 4.5$ m/s, $Re_\lambda = 900$.

transformative results that will impact some of the major paradigms in our perception of turbulence including the concept of an inertial range, the role of dissipation at large Re, anomalous scaling and intermittency in the conventionally defined inertial range, and the so-called multi-fractal formalism.

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