The emphasis here is on qualitative aspects.

The experiments were performed at summer 2006 by the team of three: G. Gulitskii, M. Kholmyansky and S. Yorish.
The emphasis here is on qualitative aspects.

This is a first set of experiments with the main motivation (but not the only) to evaluate the feasibility of using the multi-hot-wire system in studies of fractal generated turbulence with the emphasis on what can be done. The outcome is essentially positive, but it has to be stressed that all results are crude and require checking, especially as concerns the quantitative aspects, e.g. numbers. Therefore the presented results can be seen as preliminary and mostly qualitative only.

All the results below refer to the centerline only.
Manganin is used as a material for the sensor prongs instead of tungsten because the temperature coefficient of the electrical resistance of manganin is 400 times smaller than that of tungsten.
The noise of the system is below 0.15% in RMS.

Probe in calibration position.

The calibration unit.
Misha and Probe in calibration position
TABLE VII. \( T = 0.91 \text{ m} \) tunnel square grid geometry. The errors on \( \sigma \) are estimated by assuming the thickness of each iteration to be accurate within plus/minus the diameter of the manufacturing cutting laser (0.15 mm).

<table>
<thead>
<tr>
<th>( N )</th>
<th>( D_f )</th>
<th>( \beta_t )</th>
<th>( \beta_L )</th>
<th>( \sigma ) (%)</th>
<th>( M_{\text{eff}} ) (mm)</th>
<th>( t_r )</th>
<th>( R_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.00</td>
<td>0.00</td>
<td>0.00</td>
<td>25±2.0</td>
<td>26.6</td>
<td>17.0</td>
<td>0.49</td>
</tr>
<tr>
<td>5</td>
<td>2.00</td>
<td>−0.18</td>
<td>−0.21</td>
<td>25±1.7</td>
<td>28.6</td>
<td>28.0</td>
<td>0.43</td>
</tr>
</tbody>
</table>
3' x 3' LOW SPEED WIND TUNNEL

40 b.h.p. MOTOR

WIDE ANGLE DIFFUSER

SCREEN K = 2.5

9" x 9" SETTLING CHAMBER

18" REMOVABLE WORKING
(Section - 3 x 3" Cross Section)

CONTRACTION
Designed by
Holopainen method

3 SCREENS
K = 1.6

HONEYCOMB

TOP SPEED = 150 ft sec.
TURBULENCE LEVEL = 0.05 %

18' LONG WORKING SECTION WITH REMOVABLE SECTION, AND
SHEAR FLOW GRIDS.

FAN CAPABLE OF OPERATION OVER POWER FACTOR RANGE 0.5 - 2
MEAN VELOCITY AND FLUCTUATION RMS

Grid 1- Tr 28

Grid 2- Tr 17
Grid 1 - Tr 28

MEAN vel. components at the tunnel axis

\[ y = -0.0606x^2 - 0.1165x + 15.07 \]
\[ y = -0.0397x^2 + 0.1594x + 0.0616 \]
\[ y = -0.0272x^2 + 0.109x - 0.2062 \]

RMS vel. components at the tunnel axis

\[ \text{rms } u1 \]
\[ \text{rms } u2 \]
\[ \text{rms } u3 \]

Grid 2 - Tr 17

MEAN vel. components at the tunnel axis

\[ y = -0.0565x^2 - 0.3048x + 15.251 \]
\[ y = 0.0418x^2 - 0.2983x + 0.5139 \]
\[ y = 0.0125x^2 - 0.0751x - 0.0435 \]

RMS vel. components at the tunnel axis

\[ \text{rms } u1 \]
\[ \text{rms } u2 \]
\[ \text{rms } u3 \]
TURBULENT ENERGY PRODUCTION

Grid 1- Tr 28

Grid 2- Tr 17

Turbulent energy production
ISOTROPY INDICATORS

velocity

Grid 1 - Tr 28

Grid 2 - Tr 17
# ISOTROPY INDICATORS

**velocity derivatives - grid Tr28**

\[
\frac{\partial u_i}{\partial x_k}
\]

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>$X=3.1m$</strong></th>
<th>1.00</th>
<th>1.15</th>
<th>1.05</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.69</td>
<td>1.03</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>1.57</td>
<td>1.05</td>
<td>0.74</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>$X=4.1m$</strong></th>
<th>1.00</th>
<th>0.73</th>
<th>0.79</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.60</td>
<td>0.63</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>1.62</td>
<td>0.66</td>
<td>0.52</td>
</tr>
</tbody>
</table>
INTEGRAL AND TAYLOR MICRO-SCALES
Grid 1- Tr 28

Integral scale at the tunnel axis

Integral scale, cm

Longitudinal distance, m

0.698 1.688 3.113 4.103

0.698 1.688 3.113 4.103

Taylor microscales (Case MEAN)

λ, cm

x, m

0 1 2 3 4

0 1 2 3 4

Grid 2- Tr 17

Integral scale

Integral scale, cm

Longitudinal distance, m

0.698 1.688 3.113 4.103

0.698 1.688 3.113 4.103

Taylor microscales (Case MEAN)

λ, cm

x, m

0 1 2 3 4

0 1 2 3 4
Taylor Micro-Scale RE

Grid 1- Tr 28

Grid 2- Tr 17

Reynolds numbers (Case MEAN)

Reynolds numbers (Case MEAN)
ENERGY DISSIPATION
Dissipation rate at the tunnel axis

Normalized dissipation rates at the tunnel axis

Grid 1- Tr 28

Grid 2- Tr 17
Normalized dissipation rates at the tunnel axis, v2

- $\lambda_1$
- $\lambda_2$ Gr.1 Tr28
- $\lambda_3$

$x, m$

$C_D$
THIRD ORDER MOMENTS

Grid 1 - Tr 28

Grid 2 - Tr 17

Skewness
\[ \frac{\partial u_1}{\partial x_1} \frac{\partial u_2}{\partial x_2} \frac{\partial u_3}{\partial x_3} \frac{\partial u_i}{\partial x_k}, i \neq k \]

0.73 0.65 0.65 0.05 ÷ 0.1

0.18

0.38

Re_{\text{t}} \sim 10^4 \text{ Field experiment}

\( \langle \omega_{ij} \rangle_{\text{t}} \), \( \langle \omega^2 \rangle_{\text{t}}^{3/2} \), \( \langle s_{ij} \rangle_{\text{t}} \), \( \langle s_{ij} s_{jk} s_{ki} \rangle_{\text{t}}^{3/2} \)

\( \frac{0.21}{S_{\frac{\partial u_1}{\partial x_1}}} = 0.7 \)  \( \frac{0.42}{S_{\frac{\partial u_1}{\partial x_1}}} = 0.7 \)

Skewness of derivative components
at the tunnel axis

\( x, m \)

0.698 1.688 3.113 4.103

\( S \)

-1.5 -1 -0.5 0 0.5 1 1.5 2

\( S \)

0.698 1.688 3.113 4.103

x, m
THIRD ORDER MOMENTS

Grid 1- Tr 28

Grid 2- Tr 17

Skewness characteristics at the tunnel axis

\[
\begin{align*}
\frac{\partial u_i}{\partial x_1} & \quad \frac{\partial u_2}{\partial x_2} & \quad \frac{\partial u_3}{\partial x_3} & \quad \frac{\partial u_i}{\partial x_k}, & \quad i \neq k & \quad \frac{\langle \omega_i \omega_k \delta_{ik} \rangle}{\langle \omega^2 \rangle^{3/2}} & \quad 0.1 \\
0.73 & \quad 0.65 & \quad 0.65 & \quad 0.05 \div 0.1 & \quad 0.18 & \\
\end{align*}
\]

Re_\lambda \sim 10^4 Field experiment

\[
(0.21) S \frac{\partial u_1}{\partial x_1} = 0.7
\]

Re_\lambda \sim 10^2 grid

Skewness characteristics at the tunnel axis

- Grid 1: \(\langle wiwjsij \rangle \) norm
- Grid 2: \(\langle sijsjksi \rangle \) norm
FOURTH ORDER MOMENTS

Grid 1- Tr 28

<table>
<thead>
<tr>
<th>Flatness</th>
<th>$\frac{\partial u_i}{\partial x_k}$</th>
<th>$\frac{15}{7} \left( \frac{s^4}{s^2} \right)$</th>
<th>$\frac{9}{5} \left( \frac{\omega^4}{\omega^2} \right)$</th>
<th>$\frac{\langle \omega^2 s^2 \rangle}{\langle \omega^2 \rangle \langle s^2 \rangle}$</th>
<th>$\frac{3 \langle (\omega^2 s_{ik})^2 \rangle}{\langle \omega^2 \rangle \langle s^2 \rangle}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>20 $\div$ 25</td>
<td>17.5</td>
<td>27.6</td>
<td>6.7</td>
<td>3.6</td>
</tr>
<tr>
<td>Gaussian</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Re $\sim 10^4$ Field experiment

Flattness characteristics at the tunnel axis, Gr.1 Tr28

Flattness characteristics at the tunnel axis, Gr.2 Tr17
Re, $\sim 10^2$ Grid experiment 1992

<table>
<thead>
<tr>
<th>$x/M$</th>
<th>8</th>
<th>17</th>
<th>30</th>
<th>38</th>
<th>64</th>
<th>90</th>
<th>B. layer $y/\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>0.41</td>
<td>0.46</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.56</td>
</tr>
<tr>
<td>$S_2$</td>
<td>0.32</td>
<td>0.41</td>
<td>0.44</td>
<td>0.55</td>
<td>0.40</td>
<td>0.37</td>
<td>0.32</td>
</tr>
<tr>
<td>$S_3$</td>
<td>0.31</td>
<td>0.34</td>
<td>0.38</td>
<td>0.33</td>
<td>0.20</td>
<td>0.14</td>
<td>0.68</td>
</tr>
<tr>
<td>$S$</td>
<td>0.12</td>
<td>0.13</td>
<td>0.16</td>
<td>0.16</td>
<td>0.14</td>
<td>0.15</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 7. Values of $S_a = -\langle (\partial u_a/\partial x_a)^2 \rangle/\langle (\partial u_a/\partial x_a) \rangle^2$ and $S = \langle \omega_i \omega_j s_{ij} \rangle/\langle \omega^2 \rangle/\langle (s_{ij}) \rangle^2$

<table>
<thead>
<tr>
<th>$x/M$</th>
<th>8</th>
<th>17</th>
<th>30</th>
<th>38</th>
<th>64</th>
<th>90</th>
<th>B. layer $y/\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$</td>
<td>3.97</td>
<td>3.99</td>
<td>4.07</td>
<td>4.27</td>
<td>3.95</td>
<td>3.97</td>
<td>9.09</td>
</tr>
<tr>
<td>$F_2$</td>
<td>4.29</td>
<td>4.42</td>
<td>4.48</td>
<td>4.72</td>
<td>4.62</td>
<td>4.46</td>
<td>11.5</td>
</tr>
<tr>
<td>$F_3$</td>
<td>1.04</td>
<td>0.93</td>
<td>0.88</td>
<td>0.88</td>
<td>0.76</td>
<td>0.82</td>
<td>2.09</td>
</tr>
<tr>
<td>$F_4$</td>
<td>4.77</td>
<td>4.90</td>
<td>5.10</td>
<td>5.30</td>
<td>5.21</td>
<td>4.95</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Table 8. Fourth-order moments of velocity derivatives

Fourth moments of velocity derivatives defined as

$$F_1 = \frac{15}{7} \langle s^4 \rangle, \quad F_2 = 3 \frac{\langle \omega^2 s^2 \rangle}{\langle \omega^2 \rangle \langle s^2 \rangle}, \quad F_3 = 3 \frac{\langle \omega_i s_{ij} s_{ik} \rangle}{\langle \omega^2 \rangle \langle s^2 \rangle}, \quad F_4 = \frac{9}{5} \frac{\langle \omega^4 \rangle}{\langle \omega^2 \rangle^2}. $$
PDFS OF EIGENVALUES OF THE RATE OF STRAIN TENSOR
ALIGNMENTS OF VORTICITY AND THE VORTEX STRETCHING VECTOR, $W_i = \omega_k s_{ik}$
Grid 1 - Tr 28

\[ \cos(\omega, W) \text{ at the tunnel axis. Gr.1 Tr28} \]

- \( x = 0.698 \text{ m} \)
- \( x = 1.688 \text{ m} \)
- \( x = 3.113 \text{ m} \)
- \( x = 4.103 \text{ m} \)

Grid 2 - Tr 17

\[ \cos(\omega, W) \text{ at the tunnel axis. Gr.2 Tr17} \]

- \( x = 0.698 \text{ m} \)
- \( x = 1.688 \text{ m} \)
- \( x = 3.113 \text{ m} \)
- \( x = 4.103 \text{ m} \)
ALIGNMENTS OF VORTICITY AND EIGEN-FRAME OF THE RATE OF STRAIN TENSOR
Gr.1 Tr28 at the tunnel axis. $x=3.113$ m

Gr.2 Tr17 at the tunnel axis. $x=3.113$ m

Gr.1 Tr28 at the tunnel axis. $x=4.103$ m

Gr.2 Tr17 at the tunnel axis. $x=4.103$ m
PDFS OF ENSTROPHY AND STRAIN PRODUCTION

Grid 1- Tr 28

Grid 2- Tr 17
Gr.1 Tr28 at the tunnel axis. $x=0.698$ m

Gr.2 Tr17 at the tunnel axis. $x=0.698$ m

Gr.1 Tr28 at the tunnel axis. $x=1.688$ m

Gr.2 Tr17 at the tunnel axis. $x=1.688$ m
PDFs of Velocity Derivatives

\[ \frac{\partial u_i}{\partial x_k} \]
Gr. 1 Tr28 at the tunnel axis. x=3.113 m

- \( \frac{\partial u_1}{\partial x_1}, \text{1/s} \)
- \( \frac{\partial u_2}{\partial x_1}, \text{1/s} \)
- \( \frac{\partial u_3}{\partial x_1}, \text{1/s} \)

- \( \frac{\partial u_1}{\partial x_2}, \text{1/s} \)
- \( \frac{\partial u_2}{\partial x_2}, \text{1/s} \)
- \( \frac{\partial u_3}{\partial x_2}, \text{1/s} \)

Relative frequency

- \( 10^{-2} \)
- \( 10^{-4} \)
- \( 10^{-6} \)

- \(-400-200 \) to \( 400 \)
Gr.1 Tr28 at the tunnel axis. \( x = 4.103 \) m
JOINT PDFS OF ENSTROPHY AND RATE OF STRAIN PRODUCTION
More qualitative than others, e.g. the tails of the R-Q plots do not sit at the line where the discriminant $D=0$, which is not the case in ‘normal’ turbulence. It has to be seen whether this is a genuine flow property or is it mainly ‘instrumental’ or both.

\[
Q = \frac{1}{4} \left( \omega^2 - 2s_{ik} s_{ik} \right)
\]

\[
R = -\frac{1}{3} \left( s_{ik} s_{km} s_{mi} + \frac{3}{4} \omega_i \omega_k s_{ik} \right)
\]
Gr.1 Tr28. At the tunnel axis, $x=0.698$ m

![Graph 1](image1)

Space

$(27/4)R^2 + Q^3 = 0$

Gr.2 Tr17. At the tunnel axis, $x=0.698$ m

![Graph 2](image2)

Space

$(27/4)R^2 + Q^3 = 0$

Gr.1 Tr28. At the tunnel axis, $x=1.688$ m

![Graph 3](image3)

Space

$(27/4)R^2 + Q^3 = 0$

Gr.2 Tr17. At the tunnel axis, $x=1.688$ m

![Graph 4](image4)

Space

$(27/4)R^2 + Q^3 = 0$
IN LIEU OF CONCLUSIONS
As mentioned at the very beginning the presented results are mostly of qualitative nature. Here we bring some preliminary conclusions which can be considered as “safe” along with some “less safe” considerations.

Among the motivations for the described experiments was the existence of a significant finite region of kinetic energy buildup reported first by Hurst & Vassilicos 2007 (HV) as exhibited among other things by existence of $x_{peak}$ as is seen from slides 14 and 15. The latter exhibits significant TKE production at all flow accessible locations which is mainly due to streamwise gradients. Hurst, Hurst, Vassilicos 2007 and Seoud & Vassilicos 2007 (SV) do not quite observe this.
# The Taylor microscale as estimated using also full energy dissipation and enstrophy exhibits a tendency to become constant with distance as observed by HV and SV.

# The energy dissipation rate appears to be smaller that in regular grids as exhibited in lower values of $C_\varepsilon \sim 0.1 - 0.25$ again in agreement with observations by SV. However, our results may be underestimated due to the underresolution of small scales (the probe is too large).

# The streamwise velocity derivative skewness is pretty close to the conventional value 0.5, whereas it flatness is between 4 and 5 which is a somewhat smaller then observed in flows past regular grids at the same Re_ω. There seems to be an issue regarding the choice of Re_ω as a parameter for comparison: as pointed by SV the relation between Re_ω and Re is qualitatively different for fractal grids.
The statistics of the eigenvalues of the rate of strain tensor is very similar to that observed in ordinary turbulent flows. The alignments between vorticity and the vortex stretching vector is similar to the "usual" at two farther locations, but close to Gaussian at the two closest locations. This should be contrasted to the alignments between vorticity and the eigenframe of the rate of strain tensor which are essentially the same at all locations as in "usual" turbulent flows, i.e. the flow field is everywhere non-Gaussian. It has to be mentioned that at these locations the flow is far from being similar to "regular" turbulent flow and has distinct low frequency peaks.
The PDFs of enstrophy and strain production are qualitatively similar to that observed in ordinary turbulent flows at the three farthest locations, but are less skewed. At the closest location both are practically symmetric, and the PDFs of the strain production have much larger tails. These observations indicate that close to the grid the flow has reduced nonlinearity and is dominated by irrotational disturbances.

The PDFs of the components of velocity gradient tensor are qualitatively similar to that observed in ordinary turbulent flows, but the diagonal components are less skewed (the off diagonal are symmetric).

More qualitative than others are the R-Q plots, e.g. the tails of the R-Q plots do not sit at the line where the discriminant $D=0$, which is not the case in 'normal' turbulence. It has to be seen whether this is a genuine flow property or is it mainly 'instrumental' or both.
Summarizing both a number of important differences along with several similarities with ‘ordinary’ grid flow were observed. Again we remind that the presented results and conclusions are preliminary and mainly qualitative - the quantitative aspects, e.g. numbers, require additional processing and checking. One of the key issues is the Reynolds number dependence. More conclusions to come after more work done on checks, additional processing (which includes the off center line data and a number of additional quantities) and related.
MEANWHILE SOME QUESTIONS OF CONCEPTUAL NATURE
(There are much more)
MEMORY

# What is the mechanism that turbulence does remember what happened (say, ‘locked in one scale’) at the inflow position and after undergoing some ‘adventures’ in the production region at $x < x_p$?

# Why the flow does not remember, e.g. the strong inhomogeneity at the inflow position and in the production region?

STABILITY

Same as above — how/why this state (i.e. the one beyond $x_{peak}$ claimed to be homogeneous and isotropic and ‘locked in one scale’) remains stable, i.e. why the flows does not want to turn into ‘normal’ turbulence?