Development of a multi-hole probe for atmospheric boundary layer measurements

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ABSTRACT: The characteristics of five-hole probes are investigated in this paper with the intention of applying them for wind tunnel measurements of empty boundary layers and far-field wakes of buildings or building groups. Angular and dynamic calibration of the probes and pressure sensors were accomplished. With the spectral reconstruction of the original pressure signals a temporal resolution up to a few hundred Hertz could be achieved using low-cost pressure sensors. Miniaturization of the probe is limited by the available manufacturing technologies and the damping effect of small diameter pressure holes at higher frequencies, so a balance between spatial and temporal resolution can be found. The possibility to measure the instantaneous wind vector using a simple, low-cost technique is however promising.

1 INTRODUCTION

1.1 Motivation

Flow instruments, which can supply data from one or more components of the wind vector in a given point (HWA, LDV) are widely used in wind-tunnel investigations. In the last few decades, the LDV and HWA probes were preferred on the field of turbulence research. However, these methods have their own disadvantages. The LDV technique requires optical accessibility and seeding, and the HWA sensors are highly sensitive to dust and temperature of the fluid, and need calibration before each measurement session. Moreover, the costs of the before mentioned measurement techniques are increasing by the number of measurable velocity components. Our purpose is to develop a robust, low-cost, compact miniature five-hole probe \cite{1}, which can be used to measure all three components of the instantaneous velocity vector and thus, to calculate the turbulent properties of atmospheric boundary layers (ABL), reproduced in wind tunnel. Although the velocity vector is limited to a 50-degree incident angle (in case of seven-hole probes to 70 degree), and thus, reversed flows cannot be measured, empty boundary layers and far-field wakes of buildings or building groups seem to be an ideal subject to be measured by multi-hole probes. In both cases, temporal resolution has a high importance, as any change in a boundary layer appears first as a change of turbulent quantities and not in that of mean velocities.

1.2 Basic considerations

The lowest layer of the ABL is, especially above urban built-up areas highly turbulent, so we can expect high flow angles which might exceed the range of a multi-hole probe. To check this, a 2-component LDV measurement of an urban boundary layer was performed in a large,
open test section wind tunnel. Thickness of the BL was about 0.3 m, with $\alpha = 0.3$, and turbulence intensities in main flow direction of up to 35%.

From the coincident $u$ and $v$ burst velocities flow angle distributions were determined at all heights. As Figure 1 shows, the extreme values can reach more than +/- 80 degrees at the height of the roughness elements, however, for most points, 99% of all captured values lie within the +/- 40 degree interval. This means that except the lowest level of the BL, a multi-hole probe with a calibration for this range can measure velocities with a negligible error.

Figure 1: a. Turbulence intensity in an urban boundary layer, measured in wind tunnel. b. Min./max. wind vector angles in horizontal plane. c. Angle distributions at two different heights. d. Percentage of samples within the +/- 40 degree range.

2 PROBE DESCRIPTION

2.1 Probe configuration

In a first attempt, we apply a probe with 4 mm diameter, 45° cone half-angle, soldered and turned from copper tubes. Angle definitions and pressure connections can be taken from Figure 2.

Figure 2: 5-hole probe angle definitions, sensor connections.

To increase spatial resolution, the shrinking of probe head will be necessary at a later stage. For manufacturing such a probe one has two options: in case of ultra precision machining, the probe head can be created by turning and the holes of a diameter of 0.2-0.4 mm can be drilled using Electric Discharge Machining. Wall thickness down to 50 $\mu$m is possible. The other way is the use of additive manufacturing. The Objet 30 Pro printer tested by us produced a
rather rough surface, and the practical size limit for bores was above 0.3 mm. (Fig. 3 and 4.) At smaller diameters, the perfect removal of the support material from the pressure bores can be difficult. However new fluid-based 3D printing technologies offer much higher resolution and better surface quality, thus a further reduction of tip diameter is possible.

Figure 3: Cross-section of the 5-hole probe for additive manufacturing.

Figure 4: View of probe tip.

2.2 Pressure sensors and communication

The pressures at the probe ports are measured by miniature, temperature-compensated pressure sensors (Sensortechnics HCLA, for specifications see Table 1.). Sensors were assembled in a plastic box (Fig. 5).

To reduce noise, the pressure transducers communicate with the measurement PC through 400 kHz I²C bus using a I²C-USB interface. While the first interface tested (Code Mercenaries IOWarrior56) gave 2ms sensor readout time for a single sensor, another, more expensive type (National Instruments NI 8452) allowed about 0.4 ms readout time, and for all 6 sensors 1.25ms on average, which corresponds to approximately 800 Hz sampling rate. (Fig. 6.) As the signal is not perfectly uniform, it has to be time-stamped during data acquisition, and resampled later at a uniform sampling rate.

Table 1: HCLA pressure sensor specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>16 x 12.7 x 6.7 mm</td>
</tr>
<tr>
<td>Range</td>
<td>0-250 Pa (central bore) +/-250 Pa (side bores)</td>
</tr>
<tr>
<td>Response time</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Linearity and hysteresis error</td>
<td>0.05 %FS (typical) 0.25 %FS (max)</td>
</tr>
<tr>
<td>Temperature effect</td>
<td>&lt;0.02 %FS/°C</td>
</tr>
<tr>
<td>Internal A/D resolution</td>
<td>12 bit</td>
</tr>
</tbody>
</table>

Figure 5: Sensor box.

Figure 6: Sensor readout times for 6 sensors.
3 CALIBRATION

3.1 Dynamic calibration

While there are commercial multi-hole probes with high temporal resolution available, in which sensors are built closely to the probe tip, the currently applied sensors need a mounting distance of a few 100 mm away from the probe due to size of the sensor box. Thus connecting tubes will have an influence on the temporal resolution of the system. To test the dynamic responses, the calibration rig on Figure 7 was built, consisting of a loudspeaker, an audio amplifier, a signal generator, an A/D input/output device (NI USB 6009) and a reference pressure transducer (Endevco 8507/C-2).

![Figure 7: Dynamic calibration rig.](image)

Different tube pipe combinations were exposed to sinusoidal pressure waves of 50 Pa amplitude. Frequency was increased by 1Hz steps from 1 to 500 Hz. The amplitude and phase of pressure signals compared to the reference signal was determined at each frequency (Fig. 8.). Copper and steel tubes of 0.2 and 0.5mm inner diameter and 20-130mm length as well as connecting PTFE tubes of 0.8mm inner diameter and 0.15-0.35m length were tested.

![Figure 8: Amplitude and phase response of the pressure sensors at different bore and tubing dimensions.](image)

3.2 Signal reconstruction

Knowing the amplitude and phase shift of the tubing and sensor system allows the reconstruction of the original pressure signal. After calculating the Fourier transform of the signal, the amplitudes of each frequency component are multiplied by the reciprocal of the amplitude ratio and their phase is shifted in opposite direction. Finally the original signal is
recomposed in time domain. Examples measured at the dynamic calibration facility are shown in Figure 9.

Figure 9: Reference, original and reconstructed signals at 45Hz (left) and 180Hz (right)

A major disadvantage of signal reconstruction is that signal noise is amplified, too. This is proven by noise measurement shown in Figure 10. Note that the reference sensor has the lowest noise, but has a 50Hz peak due to the analogue output signal. The reconstructed signal’s noise is the same at low frequencies, but a multiple of the original at higher frequency. The resulting increase of noise is shown in Table 2. To suppress the higher noise in the reconstructed signal, it is advisable to measure at higher dynamic pressure, that means at higher wind tunnel speed.

Table 2: Standard and highest deviation of signal noise.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Standard deviation [Pa]</th>
<th>Max. deviation [Pa]</th>
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</thead>
<tbody>
<tr>
<td>reference</td>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>measured</td>
<td>0.3</td>
<td>1.9</td>
</tr>
<tr>
<td>reconstructed</td>
<td>1.2</td>
<td>6.0</td>
</tr>
</tbody>
</table>

3.3 Angular calibration

Angular calibration can be performed using a small 0.35 x 035 m test section blower type wind tunnel. (Fig.11.) Positioning accuracy is 0.02° for θ and 0.25° for φ.

Figure 10: Amplitude spectra of signal noise.  
Figure 11: Angular calibration rig.
During calibrations of the 4mm diameter probe in a narrow range of +/-20 degree angle, 600 individual points were measured at constant 24 m/s wind speed. Error distribution of $\alpha$, $\beta$, and $q$ (dynamic pressure) captured by 600 random measurements are shown in Figure 12.

![Figure 12: Measurement errors during a calibration check at 24 m/s.](image)

6 OUTLOOK

Calibration maps of the 5-hole probe for a wider range and lower velocity, and a direct comparison of boundary layer profiles measured by the 5-hole probe and by LDV is planned to be presented at the conference. Based on the results of dynamic calibration, a probe with maximized pressure bore diameter should be designed to reduce the influence of noise at the signal reconstruction.

7 ACKNOWLEDGEMENTS

Special thanks to Balázs Istók (Dept. of Fluid Mechanics) for manufacturing the 4mm probe, to Darrin Dickinson (EnvisionTEC GmbH) and Péter Rimóczi (Varinex Zrt.) for the 3D printing of probe samples. The support of the project K 108936 “Flow and dispersion phenomena in urban environment” of the Hungarian Scientific Research Fund is gratefully acknowledged. This work is connected to the scientific program of the "Development of quality-oriented and harmonized R+D+I strategy and functional model at BME" project. This project is supported by the New Széchenyi Plan (Project ID: TÁMOP-4.2.1/B-09/1/KMR-2010-0002).

8 REFERENCES