Flow disturbance due to presence of the vane anemometer

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Abstract. This paper presents the results of the preliminary experimental investigations of the disturbance of velocity field resulting from placing a vane anemometer in the analyzed air flow. Experiments were conducted in a wind tunnel with a closed loop. For the measurement process, Particle Image Velocimetry (PIV) method was used to visualize the flow structure and evaluate the instantaneous, two-dimensional velocity vector fields. Regions of inflow on the vane anemometer as well as flow behind it were examined. Ensemble averaged velocity distribution and root-mean-square (RMS) velocity fluctuations were determined. The results below are presented in the form of contour-velocity maps and profile plots. In order to investigate velocity fluctuations in the wake of vane anemometer with high temporal resolution hot-wire anemometry (HWA) technique was used. Frequency analysis by means of Fast Fourier Transform was carried out. The obtained results give evidence to a significant spatially and temporally complex flow disturbance in the vicinity of analyzed instrument.

1. Introduction

Vane anemometers are commonly used to measure air velocity and determine volume flow rate in many industrial applications such as mining ventilation systems. The sensing element is a vane rotor, the rotational speed of which is proportional to the velocity of the flowing air stream. This measurement method belongs to a category of invasive measurement techniques. Placing vane anemometer in the analyzed flow leads to a significant disturbance of the flow structure. This effect may adversely affect other probes used to measure velocity and other physical quantities of the flow nearby the vane anemometer. Similar issue is addressed in [1], where flowfield in the wake of a low-velocity heated sphere anemometer was analyzed with use of Particle Image Velocimetry (PIV). Influence of the disturbed inflow on various types of vane anemometers was investigated [2, 3, 4]. However, there is lack of knowledge concerning the flow structure in the sole vicinity of this type of instrument. Such knowledge is fundamental for understanding and identifying perturbation introduced by components of the instrument in the measurement area.

Flow disturbance in front of and behind vane anemometer head was experimentally investigated by means of pointwise measurement method - hot-wire anemometry (HWA) [5]. In the present study, non-invasive optical measurements methods, such as PIV was applied. The aim of this paper is to analyze the disturbance of velocity field resulting from placing the Vane Anemometer μAS4 in the analyzed flow. This instrument (figure 1) is a hand-held device with a head diameter of 100 mm and thickness of 60 mm for measuring flow velocity of air or other gases in the range of 0.2 to 20 m/s. It was designed and produced by The Strata Mechanics Research of the Polish Academy of Sciences (SMRI PAS). Its rotor consists of eight acid-resistant blades. Shield bearing system consists of two hemispherical brackets with a diameter of 5 mm.
2. Experimental setup and procedures
The experimental setup is presented in figure 2. The experiments were conducted in a wind-tunnel with a closed loop and a freestream turbulence intensity of 0.5% (located in SMRI PAS). The temperature was stabilized at 20°C and relative humidity at 35%. The test section was made of transparent polycarbonate walls with the dimensions of 500 x 500 x 1,500 mm. The air was used as an experimental fluid. The measurements and calculations were performed for the three flow velocities $U_\infty = 1$ m/s, $U_\infty = 5$ m/s and $U_\infty = 10$ m/s.

PIV method was used for the velocity vector fields calculations. Oil particles (DEHS), about 1 micron in diameter were used as a seeding. The measuring field was illuminated with light sheet generated by a double-pulse Nd:YAG laser of energy about 220 mJ per pulse. Laser sheet thickness was approximately 1 mm. The digital images were acquired using one sCMOS camera with resolution of 2,560 x 2,100 pixels. For each measurement, a set of 250 double frame images were recorded with the frequency of 5 Hz, which resulted in an overall time of one measurement of around 50 seconds. The time between two subsequent frames was synchronized with the two laser pulses and varied from about 100 µs to 1000 µs, depending on the flow velocity. During the calculations, the particle displacements were determined with use of 32 x 32 pixels sampling windows overlapping by 50%, which represent an interrogation area of about 1.4 x 1.4 mm. One of the cross-correlation methods, namely iterative multi-grid interrogation technique [6], was used as vectors’ calculation algorithm. Background reflections in PIV images from components of the vane anemometer were suppressed by generating a reference background intensity map that was then subtracted from each individual digital image [7].

The described earlier vane anemometer was installed in the test section. The origin of the Cartesian coordinate system was set at the center of the bowl in the outflow region, as presented in figure 2b. The PIV measurement fields of interest were oriented in the $x - z$ and $x - y$ planes. The light sheet was set at
$y = 0$ and $z = 0$, respectively (figure 2). Regions of inflow on the vane anemometer as well as flow behind it were investigated.

The hot-wire anemometry technique was used to investigate velocity fluctuations at high temporal resolution in the wake of the vane anemometer. Especially two locations were of special interest - in the wake of rotor blades and in vortex shedding area forming behind cylindrical brackets. The measurement system (by SMRI PAS) was based on the ATU 2001 module and Constant Temperature Anemometer (CTA) probe with a single wolfram wire with the length of 2 mm and 5 µm in diameter [8]. Measurement points were aligned in the $x$ - $z$ and $x$ - $y$ planes and went through $x = 5$ mm (figure 2). In each point 16,384 samples were acquired with temporal resolution of 10 kHz.

3. Experimental results

Instantaneous flow field measurements by means of the PIV method can be used for statistical investigations. As a result ensemble averaged flow statistics can be obtained. For average procedure, a set of 250 instantaneous velocity vector fields were taken into account. An analysis of the number of images on average value of an arbitrarily chosen velocity vector components in measurement field are presented in figure 3.

![Figure 3](image)

Figure 3. Mean longitudinal (left) and transverse (right) velocity component in the measurement point (located in the wake of rotor blades) versus number of images for average procedure at $U_{\infty} = 5$ m/s.

In the figure 4 average, two-dimensional velocity vector fields and the corresponding contour plots for $U_{\infty} = 1$ m/s in two orthogonal planes $x$ - $y$ and $x$ - $z$ are presented. All geometrical dimensions are normalized by head diameter of the vane anemometer $D = 100$ mm. In order to characterize the flow disturbance, scalar fields of RMS (root-mean-square) of the velocity magnitude were determined (figure 5). Distribution of the turbulence level, assumed as in equation (1), was shown in the figure 6.

$$I = \frac{U_{RMS}}{U} \quad (1)$$

It can be found that in the wake of head of anemometer are regions of the velocity decrease corresponding to RMS increase. This is particularly visible in the neighborhood of the bowl and the edge of cover. Nearby the bowl, the turbulence level is approximately equal to 500%. For better illustration of this effect, sample profiles of the velocity magnitude for three values of $U_{\infty}$ and corresponding RMS values were extracted and presented on figure 7 and figure 8. In the $x$ - $z$ plane a strong influence of presence of the handle is visible. It results in growth of $z$ - component of velocity vector. Recirculation flow in the wake of the handle can be observed. The handle aerodynamic shadow pulls down the outflow of the head and makes the disturbance much more complex than resulting from the presence of the anemometer head only [5]. This remark is important since handle needs to be handled in order to place the instrument in the measurement area. Regardless on type of mounting it leads to further flow perturbation influencing also the velocity measurement done by the anemometer itself.

The bracket (located in the upper half of the head) gives influence to decrease of the velocity and increase of disturbance of the flow, as well. It is clearly visible on figure 8. Placing vane anemometer in
the flow disturbs also the inflow region. Its influence decreases rapidly with the distance, however it can be easily noticed in the distance of 100 mm from the edge of anemometer.

Figure 4. The results for $U_\infty = 1$ m/s. Ensemble averaged vector velocity field with contour plot of velocity magnitude in the $x - y$ (left) and $x - z$ plane (right).

Figure 5. The results for $U_\infty = 1$ m/s. Contour plots of RMS of velocity vectors magnitudes in the $x - y$ (left) and $x - z$ plane (right).

Figure 6. The results for $U_\infty = 1$ m/s. Distributions of the turbulence level in the $x - y$ (left) and $x - z$ plane (right).
Figure 7. The results for $U_\infty = 1$ m/s, $U_\infty = 5$ m/s and $U_\infty = 10$ m/s. Normalized profiles of velocity magnitude (up) and RMS of velocity magnitude (down) in the $x$-$y$ plane.

Figure 8. The results for $U_\infty = 1$ m/s, $U_\infty = 5$ m/s and $U_\infty = 10$ m/s. Normalized profiles of velocity magnitude (up) and RMS of velocity magnitude (down) in the $x$-$z$ plane.
Temporal analysis of flow structures in the wake of vane anemometer was done with use of hot-wire anemometer. Acquired signals were analyzed by means of Fast Fourier Transform (FFT) and presented in frequency domain in figure 9. Results are presented for two measurement points: P1 \((x/D = 0.15, y/D = 0.25, z/D = 0)\) and P2 \((x/D = 0.15, y/D = 0, z/D = 0.25)\), as they are representative for others. P1 is located nearby rotor blade and point P2 corresponds to the region in the wake of bracket. It was found that the most intense periodical perturbation of the flow results from rotation of the rotor blades. Observed clear peaks were directly equivalent to rotational frequency of rotor (figure 9a). Other distinguishable frequencies visible on FFT amplitude spectra are either harmonic or subharmonic of these pulsations. One may also notice a weak velocity pulsation suggesting vortex shedding behind brackets. Other structural elements contribute to FFT amplitude spectra mostly frequency noise. Mentioned vortex shedding was resolved by estimating its frequency from equation (2), where \(Sr\) is the Strouhal number and \(d = 5\) mm is the diameter of the bracket. According to [9] Strouhal number was assumed to be equal to 0.2. Frequencies of peaks detected in the experimental data (figure 9b) - 40, 202, 396 Hz correspond to estimated values 40, 200, 400 Hz of \(f_k\), respectively.

\[
f_k = \frac{U_\infty Sr}{d}
\]  

(a)

(b)

Figure 9. The results for \(U_\infty = 1\) m/s, \(U_\infty = 5\) m/s and \(U_\infty = 10\) m/s. Fast Fourier Transform amplitude spectra of HWA signal measured at: (a) \(P_1 (x/D = 0.15, y/D = 0.25, z/D = 0)\) and (b) \(P_2 (x/D = 0.15, y/D = 0, z/D = 0.25)\).

4. Conclusion

Presence of the vane anemometer obviously disturbs the flow structure in front of it and much stronger behind it. Induced modification of flow in the sole vicinity of the instrument has a complex structure, possessing periodical and turbulent elements. Spatial flow field perturbations presented on figures 4-6 demonstrate that most of all the bowl and handle significantly decrease velocities in their wakes. Areas with the level of 50% of the velocity magnitude reduction are visible even in 200 mm behind the anemometer. Moreover, handle being relatively big comparing to the head makes a lot of aerodynamic shadow and creates a reverse flow.

Most of the flow perturbation results from non-movable parts of the anemometer. Flow behind rotor blades is much less disturbed than behind the bracket or bowl. Structure of the flow field modification is weekly dependent on the velocity of inflow.
Brief analysis in the temporal space proves the presence of velocity pulsations as well as turbulent structures. Distinguished characteristic frequencies in the amplitude spectra were identified as corresponding to the rotation speed of the rotor blades and vortex shedding behind brackets.

The results from the performed preliminary and fundamental research may be used to optimize mutual position of vane anemometers in the investigated flow. This application is of a special importance for instance in industrial ventilation systems such as mining excavations or shafts. In fact the location of accompanying sensors of any type (especially with a high temporal resolution) should be designed carefully as improper location may lead to large measurement errors.

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