Wind parameter determination at various distances using a sensor based on Particle Tracking Velocimetry

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***Abstract*—A novel optical wind sensor, which is able to measure the wind in a distance with the help of optical techniques, is presented here. The problem of conventional wind measuring systems is that they measure the wind locally where the wind sensor is located. In some monitoring systems, for example in weather based dynamic line rating for overhead lines, it is necessary to measure the wind in a certain distance. The paper introduces a new optical wind sensor based on Particle Tracking Velocimetry and shows results how such a sensor can perform and how it is possible to increase the measuring range of the wind sensor.**

***Keywords*—Particle Tracking Velocimetry, Particle Image Velocimetry, Optical Wind Sensor, Image Processing, Particle Detection**

I. Introduction

The aim of the novel optical wind sensor is to enable measurement of wind parameters at a distance. In the case of indirect methods in weather based dynamic line rating, a measurement of the undistorted wind at the location of the overhead lines without turbulences caused by the building structures of the sensor's mounting location can be achieved. Since the wind parameters are one of the most important weather parameters in dynamic line rating [1], it seems meaningful to measure the wind more efficiently.

Particle Image Velocimetry (PIV) is widely used to measure flows in liquids [2]. In a typical setup a laser system illuminates tracer particles, and the camera takes pictures from these particles. The captured images from the camera are used to characterize the movement of the particles. Several researches of using PIV for air and wind flow measurements have been done and shown feasible results [3] [4] [5]. Particle Tracking Velocimetry (PTV) uses the same setup [6]. The two have also in common that they determine velocity from particle movements in a fluid during a certain time interval. Unlike PIV, which focuses on the displacement of small groups of particles, PTV tracks individual particles. In PTV setups the particle density needs to be lower [7]. Air and wind flow measurement studies using PTV also showed viable results [8] [9].

One of the key differences of the novel wind sensor to PIV and PTV is that no tracer particles are added to the system. This is also necessary because the whole sensor system is placed at some distance from the measurement location. The avoidance of tracer particles also incorporates an easy installation and maintenance of the system. Furthermore, the wind sensor uses a conventional Sony system camera with a CMOS sensor as a detection system.

II. Measurement Setup and Measurement Software

The wind sensor setup consists of a laser and an optic system that provides an expanded beam for detecting existing air particles in the measurement area. One control unit can control both the laser and a wind generator, another control unit the camera used for detection. During a measurement, the desired parameter settings can be passed on to the respective devices. The images of the air particles captured by the camera to determine the wind parameters are transferred during a measurement to the main computer, which handles the image processing and calculation of the wind parameters. A 532 nm green laser with 50 mW power is used as the light source, since the color green is privileged by the Bayer filter when creating an RGB image [10]. Initial tests with lasers of different wavelengths also showed that the green laser achieved the best results. A rough representation of the setup is shown in Fig. 1.

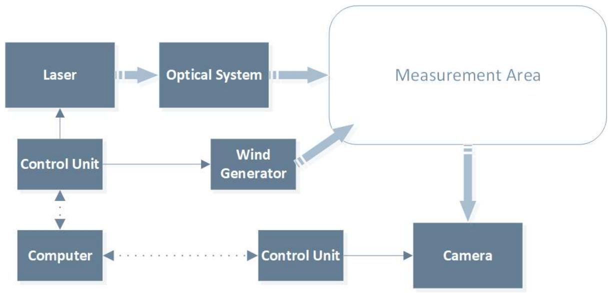

Fig. 1. Setup of the measuring system and the communication system

For this setup single long exposure images were used for wind parameter determination. Thus, particle trails can be observed in the images. To additionally determine the wind direction, the laser can be pulsed with a specific pattern. In order to obtain analyzable information, a number of image processing steps are performed. The sequence of image processing steps is shown in Fig. 2. Each image captured by the camera is read into the developed image processing software. To remove noise and other unneeded information from the images, the image passes through various filters. To obtain high-contrast images that contain only the essential information, the image is segmented into a binary image. An algorithm then ensures the selection of usable information from the image. To increase the usable information, the image can be enhanced beforehand by artificially adding pixels. An example of a segmented image is shown in Fig. 3.

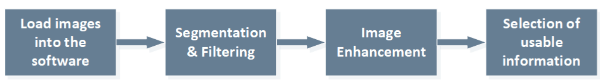

Fig. 2. Sequence of image processing steps

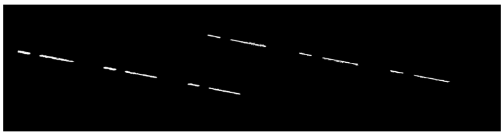

Fig. 3. Example of particle trails in a section of a segmented image using a certain pulse pattern

For the wind speed calculation, the program then evaluates a weighted average of the last captured images. The number of images that are included in the total calculation can be set in the parameter settings. It should be mentioned that each image can contain different numbers of particles and therefore the information content of each captured image for the total calculation is different. For the wind direction, the median over the detected particles is used for the calculation.

The range of the optical wind sensor is increased by increasing the distance of the camera to the measurement area. The greater the measuring distance, the more difficult it is to obtain evaluable images, because, on the one hand, the deflected laser light entering the camera decreases and, on the other hand, the particles in the air are also more difficult to detect due to their small size (µm range). The following experiments therefore investigated how the use of lenses with higher focal lengths can improve the results of the optical wind sensor.

III. Results

To verify the measurement results of the optical wind sensor, reference values of different anemometers were recorded and compared. Three anemometers with different technologies were used for this purpose to determine a reference value for the wind speed. The measuring instruments are an ultrasonic anemometer, a hot wire anemometer and an impeller anemometer. To verify the wind direction the ultrasonic anemometer was used. The experiments were done in the laboratory with a modified 120 mm fan as a wind generator, which allows a focused wind flow.

Measurements in dark background conditions from different distances with different camera lenses are considered here. Furthermore, it was investigated how the results improve when selecting different focal lengths for the camera at increased measuring distance using telephoto lenses. For each individual measurement, consisting of an averaging of 20 individual camera captures, fan loads of 40 %, 60 %, 80 % and 100 % were examined, each representing a wind speed, where 100 % fan load represents a wind speed of 2 m/s. The fan was positioned at an angle of -10°.

For the evaluation of the optical wind sensor, the wind parameters calculated by the wind sensor are compared with the wind parameters obtained from the reference measurement with the conventional anemometers. From this, the error is determined. In addition, the number of particles detected by the software was determined and a detection rate

$$D = \frac{n_p}{n_{total}} \cdot 100\ \% \tag{1}$$

was defined, where n_p is the number of images with detected particles and n_{total} is the total number of images captured.

A. Measuring Distance of 375 mm

These measurements serve as a starting point and were taken at a short distance of 375 mm with a focal length of 70 mm. The wind speeds and wind directions calculated by the optical wind sensor (blue) are listed here with the reference values (orange) in Fig. 4. The relative error of the wind speed is below 10 % for all fan loads. On average, a relative error of 3.77 % could be achieved over the fan loads.

With higher wind speed, the standard deviation also increases. On average, the standard deviation is 0.387 m/s. For the wind direction, a mean absolute error of 2° could be obtained with a mean standard deviation of 18.94°. Although the wind generator in the setup has a focused wind flow, there are still vortices, resulting in higher standard deviations for the wind direction. In the measurements, an average of 52.5 particles could be achieved with an average detection rate of 80 %.

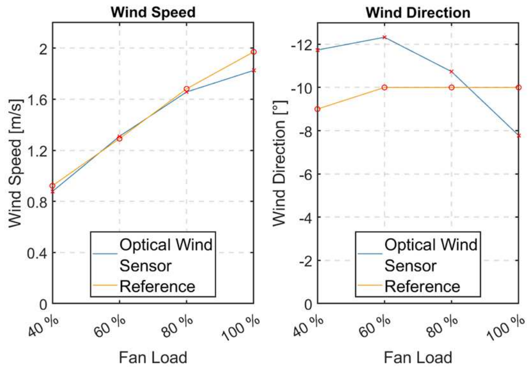

Fig. 4. Measured wind speed and wind direction using a focal length of 70 mm at a measuring distance of 375 mm

B. Measuring Distance of 1875 mm

For the next step, the distance of the camera to the measurement area is increased to 1875 mm. Camera lenses with focal lengths of 70 mm, 180 mm and 300 mm are used here. In the following, the averaged values over the used fan loads (40 %, 60 %, 80 % and 100 %) are listed for each focal length. The results for a measuring distance of 1875 mm are presented in Fig. 5.

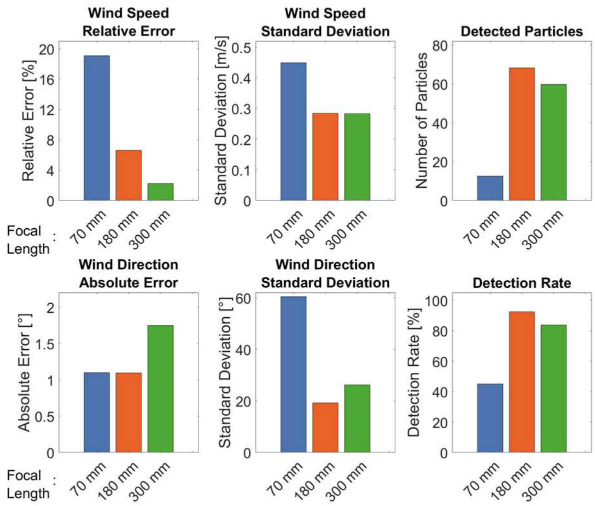

Fig. 5. Average errors and standard deviations as well as number of detected particles and detection rate using different focal lengths at a measuring distance of 1875 mm

For the wind speed, it can be observed that the error decreases with higher focal length. The standard deviation also decreases slightly here. For the wind direction, the results for the absolute errors were about the same, with a higher standard deviation for a focal length of 70 mm. It is noticeable that with a higher focal length, the number of detected particles in the images also increases. Furthermore, it can be observed that using the focal lengths of 180 mm and 300 mm, the number of particles and the detection rate are higher than with the focal length of 70 mm. The reason for this is, that with higher focal lengths smaller air particles could be captured in the images.

C. *Measuring Distance of 3750 mm*

Now the measuring distance is increased to 3750 mm. The measurement results are presented in Fig. 6. It can be observed that on average, with a nearly constant standard deviation at approximately 0.3 m/s, the average relative error of the wind speed is higher at a focal length of 70 mm (34.17 %) than at higher focal lengths (e.g. at a focal length of 600 mm an average relative error of 6.84 % could be achieved). Compared to the measuring distance, the focal length of 70 mm is low, so that the particles on the images are also significantly smaller, making segmentation during image processing more difficult.

In addition, there is the quantization error in the processing of the pixels from the images. This can be seen in particular in the wind direction calculation. Due to the fact that particles are only a few pixels in size, an angle calculation is difficult at low focal lengths and high measuring distances because of the low angular resolution in the images. At a focal length of 70 mm, an average absolute error of 6.47° could be obtained, whereas at a focal length of 600 mm, an average absolute error of 0.85° could be achieved. Furthermore, it can be observed that by increasing the focal length, the average number of particles and the detection rate tend to increase.

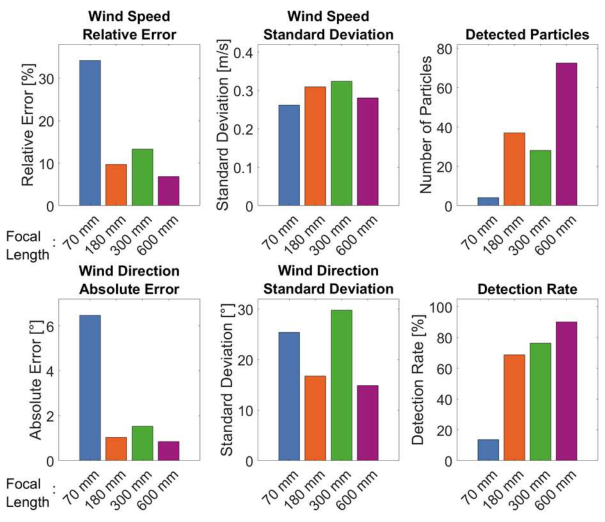

Fig. 6. Average errors and standard deviations as well as number of detected particles and detection rate using different focal lengths at a measuring distance of 3750 mm

D. *Discussion*

From the measurements it can be concluded that by increasing the measuring distance from the camera to the measurement area at a constant focal length, the imaging conditions tend to deteriorate, resulting in a decrease in the number of particles and detection rate. This can be observed at the measuring distance of 3750 mm with a focal length of 70 mm. The individual particles on the images are small (fewer pixels) at low focal length and thus are more difficult to segment. Therefore, the number of high-quality particles in the images for the wind parameter calculation decreases. Moreover, the quantization error is also larger in the parameter calculation than at higher focal length. However, a lower focal length increases the camera's field of view, which would allow more particles to be captured quantitatively. Accordingly, if the quality of the captured particles is good enough for image processing at a certain focal length, it can also provide better results than a higher focal length.

IV. Summary

A novel optical wind sensor based on Particle Tracking Velocimetry was introduced here, which is able to measure the wind in a distance without adding tracer particles. The experiments have shown that feasible results can be obtained using a modified PTV setup, which detects movements of existing air particles. The wind sensor is possible to determine accurate wind speed and wind direction values with the described setup in various measuring distances. Up to a measuring distance of 3750 mm, wind speeds could be determined with an average relative error below 7 % and wind directions with an average absolute error less than or equal to 2°. With a higher measuring distance, a corresponding lens with a higher focal length should be used to improve the measurement results. Here, it is important, that the lens also offers an adequate field of view.

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