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Uncertainty of flow velocity measurements due to refractive index fluctuations

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ABSTRACT

The measurement uncertainty of optical flow velocity measurements suffers from distortions by refractive index fluctuations in the imaging path. These fluctuations can occur, e.g. due to a contamination of the optical access or temperature and pressure gradients within the flow.

In this paper, the increase of the measurement uncertainty of particle image velocimetry (PIV) and Doppler global velocimetry (DGV) due to refractive index fluctuations in the imaging path is analyzed. Therefore flow measurements under the influence of refractive index fluctuations are performed. The results are validated and expanded by ray tracing simulations. Both experimental and numerical results confirm the different emergence of the measurement uncertainties of PIV and DGV.

1. Introduction

1.1. Motivation and problem description

Flow velocity measurements are essential for understanding and designing the flow characteristics in many technical applications such as turbo-machines or combustion chambers [1]. Thereby it is often preferable to use an optical technique, because it does not influence the measured flow [2]. One demand of all optical flow velocity measurement systems is their need of one or more optical accesses for illumination and observation of the measurement volume. Since measurements inside machines are considered, it is not possible to use a free beam setup. Hence, optical windows or endoscopic techniques have to be used.

However, the quality of the optical access can be decreased by random refractive index fluctuations. They have to be distinguished by their spatial and temporal scales. Both properties must be considered in relation to the observed diameter of the used tracer particles within the plane of the fluctuations shown in Fig. 1 and the measurement duration.

Refractive index fluctuations can result from a contamination of the optical windows by the tracer particles usually required for the measurement. Common tracer particle substances such as di-ethyl-hexa-sebacat (DEHS) [3] or olive oil [4] accumulate as droplets or thin films on the surface of the optical windows. Also temperature or pressure gradients inside the flow at applications like combustion chambers can cause refractive index fluctuations [5].

These fluctuations lead to aberrations, which distort the illumination and decrease the quality of the optical imaging. As a consequence the measurement uncertainty is increased. Although first considerations of these effects were presented in [6] it is not known, if they dominate the measurement uncertainty of common measurement principles.

1.2. State of the art

Known principles for optical velocity measurements are based on Doppler and time-of-flight evaluations [7]. Two common measurement techniques of each principle will be regarded here: the Doppler global velocimetry (DGV) [8] and the particle imaging velocimetry (PIV) [9]. It was shown that PIV as well as DGV are useful techniques for acquiring velocity data, e.g. in turbomachines [10–12]. Measurements in combustion chambers and flames were also performed with both techniques [13–15]. However, only little information regarding the influence of optical aberrations on the measurement uncertainty of the mentioned systems can be found in the open literature. In [16] distortions from a curved optical window were analyzed regarding the application of PIV. Yet, this is a deterministic aberration, which can be corrected by a calibration. In contrast, random, time-dependent fluctuations discussed in this paper cannot be corrected. In [17] it was reported that a contamination of the optical windows by seeding particles leads to slow refractive index disturbances, but no information about the quantity of the resulting measurement uncertainty was given.

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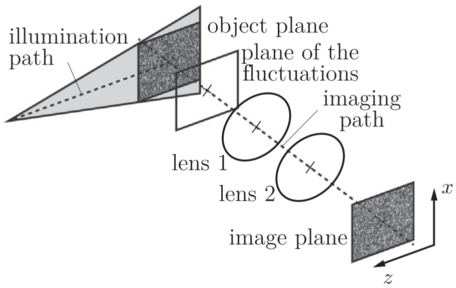

Fig. 1. Principal scheme of a distorted measurement.

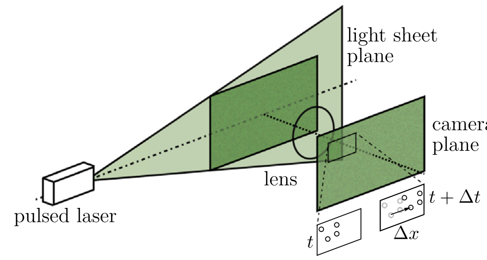

Fig. 2. Scheme of the measurement principle of PIV.

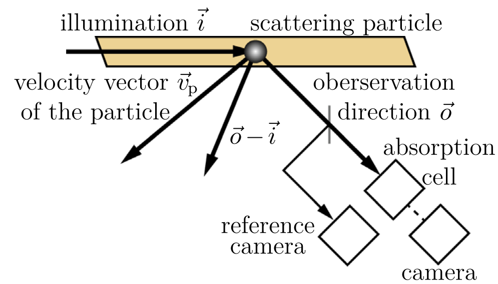

Fig. 3. Measurement principle of DGV.

In [6] aero-optical distortions due to an optically inhomogeneous flow were studied and an explanation of the resulting distortions was given for PIV. However, neither a contamination of the optical elements nor a time dependency of the refractive index fluctuations was considered.

1.3. Aim and structure

In this paper, the measurement uncertainty due to refractive index fluctuations for both PIV and DGV is investigated. Refractive index fluctuations can occur in the imaging path, as well as in the illumination path and also during the scattering process in the observed flow media. Here, we will focus on refractive index fluctuations in the imaging path, because such fluctuations are assumed to have a significant influence on measurements in turbomachines and combustion chambers.

At first, a brief summary of the measurement principles of PIV and DGV is given in Section 2 and the expected effects are explained qualitatively. In Section 3, two refractive index fluctuations occurring in the imaging path are characterized. They result from a propane gas flame and a glass plate contaminated with tracer particles. Subsequently, measurements with both DGV and PIV under the influence of these fluctuations are presented. Because the refractive index fluctuations cannot be repeated exactly in the experiment, the practical results are validated by theoretical findings acquired with ray tracing simulations in Section 4. As a result, the influence of refractive index fluctuations in the imaging path is summarized and the consequence for the application of DGV and PIV is pointed out in Section 5.

2. Fundamentals

For the Doppler effect based measurements a DGV is used. The time-of-flight measurements are performed with a standard PIV system. Both techniques are potentially capable of acquiring two-dimensional flow field velocity data without traversing and are therefore well suited for flow velocity measurements inside turbomachines or combustion chambers [10–12]. In the following a short summary of the measurement principles of DGV and PIV as examples of a Doppler and a time-of-flight approach is provided. Subsequently, the expected influences of refractive index fluctuations on each measurement system are described qualitatively and compared with each other.

2.1. PIV

The concept of PIV was first described in [18,19]. A good overview and summary can be found in [20]. The measurement volume is seeded with tracer particles and illuminated by a pulsed laser light sheet, as depicted in Fig. 2. A camera acquires two frames with the time separation Δt within the light sheet plane synchronously to the pulsed illumination. To determine the flow velocity field, the images are separated in multiple interrogation areas and a cross-correlation between the two images is performed for each area. This yields the displacement Δx of the tracer particles in each interrogation area. Using

$$v = \frac{\Delta x}{\Delta t} \tag{1}$$

the flow velocity v can be calculated.

2.2. DGV

The measurement principle of DGV is described in [21–23] and depicted in Fig. 3a. The measurement volume is illuminated from the direction $\vec{i}$ by a laser source with the wavelength λ and the light scattered by the tracer particles is observed by a camera through an absorption cell in the direction $\vec{o}$. Due to the Doppler effect, the scattered light is shifted by the Doppler frequency f_D. Because of the frequency dependent transmission of the absorption cell, the frequency shift f_D is converted into a change of the received light intensity. The intensity is then normalized to the mean stray light power acquired by the reference camera, yielding the transmittance of the absorption cell. By means of a calibration, a relation between the transmittance and the Doppler frequency can be obtained. Using the measured Doppler frequency f_D, the component of the scattering particle velocity $\vec{v}_p$ parallel to the direction $\vec{o} - \vec{i}$ can be measured according to the equation:

$$v = \frac{(\vec{o} - \vec{i})}{|\vec{o} - \vec{i}|} \cdot \vec{v}_p = f_D \cdot \frac{\lambda}{|\vec{o} - \vec{i}|}. \tag{2}$$

2.3. Comparison regarding optical distortions in the imaging path

In general, a contamination of the optical access leads to two major effects, which can affect the measurement results: absorption and refraction.

The absorption of light occurs, e.g. due to the deposition of tracer particles at the optical windows and causes a decrease of the received light power. Particularly with respect to nontransparent tracer materials such as titanium dioxide the light power is reduced drastically. Regarding DGV, the random error is indirectly proportional to the scattered light power (thermal noise dominates) or to