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Investigation of measurement sensitivities in cross-correlation Doppler global velocimetry

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A B S T R A C T

Cross-correlation Doppler global velocimetry (CC-DGV) is a flow measurement technique based on the estimation of Doppler frequency shift of scattered light by means of cross-correlating two filtered intensity signals. The signal characteristics of CC-DGV result in fundamental limits for estimation variance as well as the possibility for estimator bias. The current study assesses these aspects theoretically and via Monte Carlo signal simulations. A signal model is developed using canonical numerical functions for the iodine absorption cell and incorporating Poisson and Gaussian signal noise models. Along with consideration of the analytical form of the Cramér–Rao lower bound, best practices for system settings are discussed. The CC-DGV signal processing routine is then assessed by a series of Monte Carlo simulations studying the effect of temperature mismatch between flow signal and reference detector cells, velocity magnitude, and discretization error in the frequency modulation. A measurement bias was observed; the magnitude of the bias is a weak function of the cell temperature mismatch, but it is independent of the flow velocity magnitude. The measurement variance was found to approach the Cramér–Rao lower bound for optimized conditions. A cyclical bias error resulting from the discrete nature of the laser frequency sweep is also observed with maximum errors of ±1.0% of the laser frequency scan step size, corresponding to peak errors of ±0.61 m s^{-1} for typical settings. Overall, the signal estimator is found to perform best for matched cell temperatures, small frequency step size, and high velocity regimes, where the relative bias errors are collectively minimized.

1. Introduction

Doppler global velocimetry (DGV) is a measurement technique capable of providing non-intrusive, spatially resolved flow field measurements [1]. While advances in other measurement systems such as particle image velocimetry (PIV) have appropriately found widespread acclaim and opened new avenues of flow research, several aspects of DGV warrant continued interest. Specifically, the available dynamic range and comparatively reduced restrictions on particle resolvability enable its use in optically challenging facilities [2].

Since the introduction of DGV, several modifications and variants have been developed. A significant development came with the transition to high power continuous wave lasers, which offer narrower bandwidth and better frequency stability than pulsed laser systems [3]. With pulsed systems, velocity uncertainty of 2 m s^{-1} was once considered the state of the art [4]. In 2004, a system designated the “two-frequency (2ν) planar Doppler velocimetry” method was introduced, marking another phase in the evolution of the technique [5]. In this approach, the output frequency of a single laser is tuned to two frequencies in situ during data acquisition; a single detector acquires both the Doppler shifted signal image and the reference image in a full-transmission region of the vapor absorption spectrum. This single detector scheme was also employed in “frequency-modulated (FM) DGV” and the related technique “frequency-shift-key DGV,” the former of which can achieve minimum velocity standard deviations of 0.02 m s^{-1} [6,7].

Cross-correlation DGV (CC-DGV) was recently introduced by the present authors as a complementary approach to related multiple frequency methods, particularly valuable in the high-speed flow regime [8]. As with two-frequency (2ν), frequency-modulated (FM), and frequency-shift-key DGV, a single camera is required per component of velocity measured, thus eliminating errors due to camera registration and uneven beam-splitting effects.

All DGV techniques are based on the well-known Doppler shift equation

$$\Delta\nu=\frac{\left(\hat{o}-\hat{i}\right)\cdot V}{\lambda} \quad (1)$$

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where $\Delta\nu$ is the Doppler shift frequency of scattered light, $\hat{o} - \hat{i}$ is the directional sensitivity vector made up of the difference of the scattered light direction $\hat{o}$ and the incident laser light direction $\hat{i}$ unit vectors, $\bar{V}$ is the flow velocity vector for the scattering medium, and λ is the incident laser wavelength. In its present form, the equation is valid with the assumptions that the local measured velocity is much less than the speed of light, and that the magnitude of any modulation of the laser frequency is much less than the laser frequency itself [9]. The former assumption is accurate on the order of parts per million in supersonic flows. The latter condition, which applies to several forms of DGV including two-frequency (2ν) DGV, frequency-modulated (FM) DGV, and cross-correlation (CC) DGV, is similarly valid to parts per million or lower.

Absorption-based DGV techniques directly measure of Doppler frequency shift using a vapor absorption cell as a transfer function between light intensity and Doppler shift frequency [$\Delta\nu$ in Eq. (1)]. Systems employing 532 nm lasers and molecular iodine vapor cells have become common in DGV systems due to the tunability of the laser frequency and the presence of multiple, readily described features in the iodine absorption spectrum [10]. The process by which the Doppler shift frequencies are determined from raw intensity signals differs amongst the above-mentioned DGV techniques.

The focus of the present study is on sensitivities specific to cross-correlation DGV and the signal processing routines involved therein, such that CC-DGV is the only technique considered. As has been previously done for FM-DGV, the article investigates the effects of Doppler shift determination only, without consideration of the sensitivity vector [9]. For an analysis of the influence of the sensitivity vector, the reader is referred to Charrett et al. [11].

CC-DGV measures spatially resolved velocities averaged over the frequency scan time of the incident laser. Light from a continuous wave laser with narrow bandwidth is discretely modulated in frequency over a range on the order of several gigahertz. The components of the CC-DGV system are depicted in Fig. 1. Two beam paths of unequal power are established by means of a polarizing beamsplitter; the primary path is sent through a flow seeded with small particles, and the second is used for reference signals. The reference beam path is further split with a 50–50 beamsplitter. One reference path is directed onto a photodiode sensor to monitor stability of the beam power. The second reference beam is sent through a reference iodine vapor absorption cell and onto a second photodiode sensor. This signal serves as a non-Doppler shifted reference for the absorption spectrum and is used in subsequent signal processing. At each frequency point, Mie-scattered light from the primary beam in the flow is collected and filtered through an iodine vapor absorption cell before being imaged by a detector camera [8].

The cross-correlation DGV processing routine is shown schematically in Fig. 2. Doppler frequency is determined via cross-correlation of the non-Doppler shifted reference signal with the time-history signal from each pixel of the detector sensing the Mie-scattered, Doppler shifted light from the flow region. At each instant in time, the normalized transmission through the iodine vapor absorption cells in the Mie-scattered and reference beam paths will be separated as a function of the Doppler frequency shift. Typical camera integration times are on the order of several hundred milliseconds, and total scan times are on the order of about two minutes; therefore, the signal received must be considered a time mean. Several particles passing through the measurement volume of each pixel at potentially different velocities may contribute to each intensity reading [2]. This effect from unsteadiness and turbulence means that the intensity signal may be biased either higher or lower depending on the laser frequency relative to the absorption spectrum at that point, and thus cannot be mitigated by systematic calibration. Note, however, that even in the worst cases at high speeds and turbulence levels, bias errors from turbulence on the order of 0.1% of the mean are typical [8].

As noted by Forkey et al., the transmission ratio through pure iodine vapor in an absorption cell is dependent on cell length (Beer's law), cell body temperature, and pressure within the cell [10]. For sealed cells of fixed size, the transmission becomes a function of temperature only, since vapor pressure itself is dependent on temperature. However, the line "center" location, where minimum transmission is achieved, is independent of temperature and remains constant. This characteristic enables CC-DGV to be performed without temperature stabilization of the vapor cells, as the Doppler shift can still be determined.

The aim of the present paper is to investigate and quantify

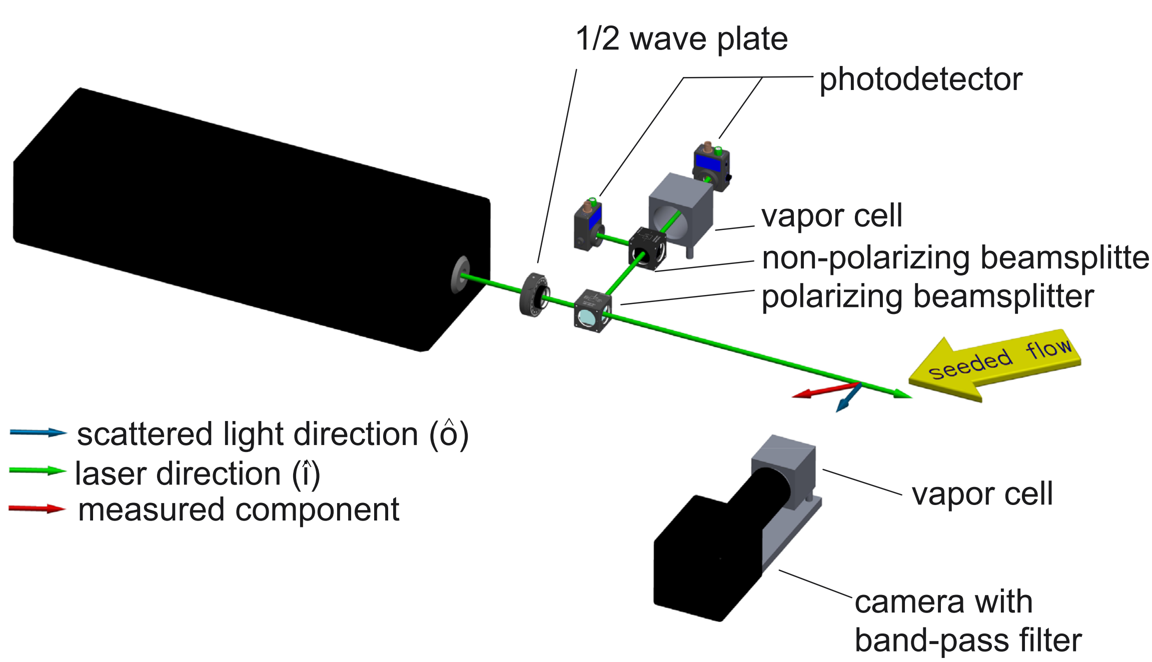

Fig. 1. Simplified CC-DGV configuration for one-component measurements. A secondary beam path provides a non-Doppler shifted reference, and monitors variations in laser power. The primary beam path illuminates a seeded flow and is imaged through a vapor cell. Figure and caption from Cadel and Lowe [8].