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Non-mechanical scanning laser Doppler velocimetry with sensitivity to direction of transverse velocity component using optical serrodyne frequency shifting

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ABSTRACT

This paper proposes a non-mechanical axial scanning laser Doppler velocimeter (LDV) with sensitivity to the direction of the transverse velocity component using optical serrodyne frequency shifting. Serrodyne modulation via the electro-optic effect of a $LiNbO_3$ (LN) phase shifter is employed to discriminate the direction of the transverse velocity component. The measurement position is scanned without any moving mechanism in the probe by changing the wavelength of the light input to the probe. The experimental results using a sensor probe setup indicate that both the scan of the measurement position and the introduction of directional sensitivity are successfully demonstrated.

1. Introduction

Velocity distribution measurement has been an essential technology in many researches and industries. A differential laser Doppler velocimeter (LDV) is a standard apparatus for measuring fluid flows or moving objects because of its noninvasive nature, small measurement volume giving fine spatial resolution, and a linear response. To measure velocity distribution, various techniques for mechanically scanning the measurement position for a differential LDV have been reported [1–6]. In these techniques, a moving mechanism is used in transmitting optics, e.g. a movable lens [1], moving mirrors [2–4], a galvanometer-type scanner [5], or a rotating transparent plate [6]. For axial scanning, a scanning range of 60–200 cm from the output lens was reported by using a movable lens [1], and 10 mm by using rotating mirrors [3]. For a practical use, an LDV with a compact sensor probe, which can be easily handled and is generally separated from the main body, is desirable. Several non-scanning LDVs with sensor probes have been reported [7–10]. To realize a scanning LDV with a compact and reliable sensor probe, we have proposed scanning LDVs without any moving mechanism in their probes [11–15]. In these non-mechanical scanning LDVs, the measurement position is scanned by changing the wavelength input to the probe, and diffraction gratings are used inside the probe instead of a moving mechanism. These LDVs have advantages because they are durable against mechanical impact on the probe and free from abrasion compared with conventional scanning techniques using a moving mechanism in the probe.

To apply the proposed scanning technique to most velocity measurement applications, introducing directional sensitivity, i.e. measurement of the sign of the velocity component, is indispensable. For introducing directional sensitivity into an LDV, optical frequency shifting [8,13,16–22] is commonly used. The fiber-optic LDV with a compact probe capable of providing directional information has been proposed [8], although this LDV was a non-scanning type. We have proposed a non-mechanical scanning LDV with directional sensitivity [13]. In these LDVs, Bragg cells using the acousto-optic effect were employed for optical frequency shifting. However, typical Bragg cells are bulky and require high-power RF sources.

Optical serrodyne modulation is another promising method to obtain direct optical frequency shifting. Serrodyne modulation via the electro-optic effect of a $LiNbO_3$ (LN) phase shifter does not require high-power signals. In addition, waveguide-based LN phase-shifter chips are commercially available, and a beam can be easily input and output using optical fibers via butt coupling between the chip and fiber. This advantage contributes to simplifying the structure for optical frequency shifting and realizing LDVs based on fiber optics compared with the use of Bragg cells. Several LDVs with directional sensitivity by optical serrodyne modulation have been reported [18,19,21,22], although these LDVs were for single-point velocity measurement.

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In this paper, we propose a non-mechanical scanning LDV in which optical serrodyne frequency shifting using an LN phase shifter is employed to discriminate the direction of the transverse velocity component. The introduction of directional sensitivity and the scanning function are experimentally demonstrated using a sensor probe setup.

2. Concept

The concept of the proposed non-mechanical scanning LDV is illustrated in Fig. 1. This LDV consists of a main body including a tunable laser and LN phase shifter, and a probe including transmitting and receiving optics. In the same manner as the axial scanning LDVs reported in Refs. [11,13], the measurement position is axially scanned by the wavelength change of the light input to the probe by using diffraction gratings in the transmitting optics. The beam from the tunable laser is split into two beams with a polarization beam splitter (PBS). One of the beams is directly input to the probe, and the other is input to the LN phase shifter to shift its optical frequency by serrodyne modulation. The two beams are input to the probe via two polarization maintaining fibers (PMFs). In the probe, each beam is passing through each of two sets of the transmitting optics arranged symmetrically in which the beam is collimated and diffracted on the grating. The two beams cross each other at the measurement position. The scattered beams from the moving object are monitored with a photodiode (PD) via the receiving optics. The measurement position can be axially scanned when the wavelength changes because the directions of the two beams diffracted on the gratings change with the wavelength. Because the tunable laser and phase shifter can be separated from the probe, the probe can be kept simple and reliable.

To discriminate the direction of the transverse velocity component perpendicular to the axial direction at the measurement position, the frequency of one of the beams split with the PBS is preshifted by f_0 using the LN phase shifter driven by a sawtooth voltage signal with linear ramps and a nominal duty cycle of 100%. The phase of the light propagating the phase shifter linearly changes with the applied voltage. Serrodyne frequency shifting is achieved when the peak-to-peak voltage of the sawtooth signal applied to the phase shifter, V_{pp}, corresponds to $2n\pi$ phase shift, where n is an integer. Then, the preshift frequency f_0 is given by nf_s, where f_s is the frequency of the sawtooth signal. Then, the beat frequency monitored with the PD is biased by f_0, and the resulting beat frequency is the sum of f_0 and the Doppler shift at the measurement position, f_D, given by Ref. [23]

$$f_D = 2v \sin \theta(\lambda)/\lambda \tag{1}$$

where v is the transverse velocity component, λ is the wavelength, and $\theta(\lambda)$ is half the angle between the two beams at the measurement position. Because v and f_D have the same sign, the velocity component including its directional information can be derived from Eq. (1) using the measured f_D as the difference between the monitored beat frequency and f_0.

3. Experimental setup

An experiment was performed to demonstrate the scan and directional sensitivity in the proposed LDV. The experimental setup is illustrated in Fig. 2. A tunable laser (ANDO AQ4321A) was used as a lightsource. The wavelength λ was changed over 1525–1565 nm. The beam from the laser was input to a polarization controller and PBS, and split into two beams. The splitting ratio of the two beams was roughly controlled with the polarization controller. One of the beams was directly launched into the transmitting optics in the sensor probe setup with the vertically polarized state. The other beam was input to the phase shifter consisting of a straight waveguide on a z-cut LN substrate before it was input to the probe setup. Here, the rotational angle of the input PMF was adjusted so that the input beam was coupled to the TM mode of the waveguide. The sawtooth signal was applied to the electrodes on the waveguide of the phase shifter with a signal generator (NF Corporation WF1948). To avoid dc drift, the bias voltage of the sawtooth signal was set to zero. The frequency-preshifted beam from the phase shifter was input to the probe setup also with the vertically polarized state. Each beam input to the sensor probe setup was passing through lenses and incident on one of reflection-type ruled diffraction gratings with a grating period of 1.67 μm. The incident angle on the gratings was set to 50° where the angular dispersion of the first-order diffracted beam was 0.035°/nm at $\lambda = 1545$ nm [12]. Its first-order diffracted beam was incident on a target rotating in a vertical plane. The scattered beams on the surface of the target were detected with an InGaAs PD (Thorlabs PDA10CS). The beat signal was measured with a digital oscilloscope (Tektronix TDS2014C), and its spectrum was calculated with the fast Fourier transform (FFT). To determine the axial shift of the measurement position, the target was moved manually in the axial direction at the position where a peak of the beat signal appeared in its spectrum and its amplitude became a maximum. The vertical position of the target was set so that the distance between the measurement position and center of rotation was 18.3 mm. The rotational speed of the target was monitored with an encoder and frequency counter. We set $\theta(\lambda)$ to 15° and the distance between the grating and measurement position along the axial direction to 290 mm at $\lambda = 1545$ nm.

To investigate the condition of serrodyne modulation in this experiment, we measured the beat signal of the modulated and unmodulated lights using a setup of a Mach–Zehnder interferometer

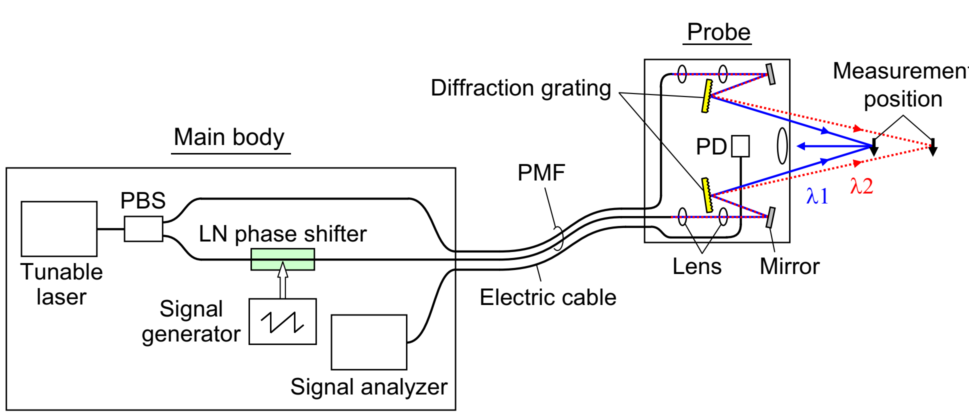

Fig. 1. Concept of proposed non-mechanical scanning LDV.