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A novel laser Doppler velocimeter and its integrated navigation system with strapdown inertial navigation

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ABSTRACT

In order to suppress the error accumulation effect of inertial navigation system (INS), an idea of building an integrated navigation system using a laser Doppler velocimeter (LDV) together with strapdown inertial navigation (SIN) is proposed. The basic principle of LDV is expounded while a novel LDV with advanced optical structure is designed based on the split and reuse technique, and the process of dead reckoning using an integrated system which consists of LDV and SIN is discussed detailedly. The results of theory and experiment show that: the split and reuse type LDV has great advantages of high accuracy and signal-to-noise ratio, which has greatly enhanced the position accuracy of the navigation system. The position error has been decreased from 1166 m in 2 h with pure SIN to 20 m in 2 h with the integrated system.

1. Introduction

With the fast development of the inertial technology, navigation systems have played an important role in civilian and military applications. As one of the most advanced navigations, the inertial navigation system (INS) has been led to widespread ongoing applications in many scientific fields for the advantages of autonomy, concealment and anti-interference [1]. But the position error accumulates as time goes on so that the navigation accuracy of INS is poor for a long time.

In order to enhance the navigation accuracy, zero velocity update (ZUPT) technique has been widely used in the vehicle-mounted inertial navigation system [2]. But it needs the vehicle stop periodically, which has a strong impact on the vehicle's flexibility and motility. In addition, odometer, Doppler log, and photoelectric velocimeter also can be used to assist the SIN, but all of them have inherent disadvantages [3,4,5]. For odometer, the wheel's slip, jump and lock will bring in the measurement error. Because of the large divergence angle of sound wave, Doppler log also has bad measurement accuracy and photoelectric velocimeter is based on the technique of spatial filtering, but its depth of field is so small that the signal is lost frequently.

Since Yeh and Cummins confirmed that we could obtain the velocity of fluid using the technique of laser Doppler frequency shift on 1964 [6], LDV has developed quickly in aviation, astronautics, mechanics and medicine for the advantages of good linearity, fast dynamic response, noncontact measurement and high resolution [7,8,9]. But in practical application, it is the shortage of inefficiency in light use that hampers conventional LDV applying into INS. The paper describes a novel LDV with split and reuse type to establish an integrated navigation system with SIN to enhance the navigation accuracy highly.

2. Principle of a novel laser Doppler velocimeter

2.1. Conventional reference-beam LDV

For the vehicle-mounted navigation system, on the condition of fluctuation of the ground surface, a dual-beam LDV is not suitable, in which the crossing point of the two beams cannot be focused on the ground all the time, and a reference-beam LDV is usually chosen as a speed sensor for navigation system [10].

The optical schematic of conventional velocimeter is shown in Fig. 1. The light source is a 50 mW solid-state green laser operating in a single longitudinal mode and the TEM_{00} transverse mode. The beam splitter divides the input laser beam into a transmitted and a reflected beam. The reflected beam passes through the attenuator on the mirror, then transmits along the negative direction and passes through the attenuator, beam splitter, and diaphragm onto the detector, which is called "reference beam". The transmitted beam passes onto the ground so that scattered light is distributed in all direction. The scattered light that transmits along the

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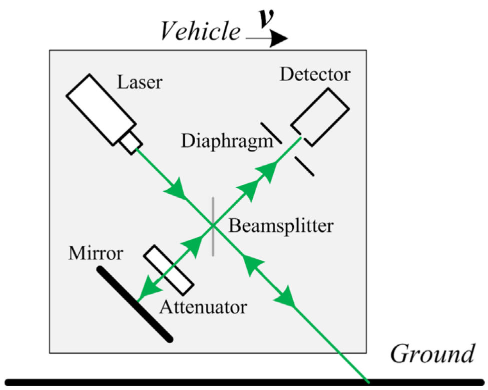

Fig. 1. Optical structure of conventional reference-beam LDV.

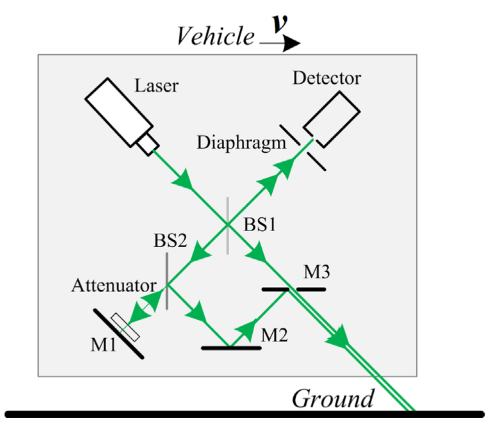

Fig. 2. Optical arrangement of split and reuse type LDV.

negative direction is partly reflected by the beam splitter, and then, it also passes through the diaphragm onto the detector, which is called "signal beam". As a result, inference fringes form on the light sensitive surface of the detector. Based on the square-law effect of photodetector, the output signal contains the beat frequency term-Doppler signal, whose frequency is directly proportional to the velocity of the vehicle.

$$f_D = 2v \cos \alpha/\lambda \tag{1}$$

where f_D is Doppler frequency, v is the velocity of the vehicle, α is the inclination angle of the probe and λ is the wavelength of laser. So the velocity of the vehicle is given by

$$v = \lambda f_D/2 \cos \alpha \tag{2}$$

From the analysis for the optical structure of conventional LDV, it can be found that most of energy of the "reference beam" is attenuated to match that of the weak "signal beam". That is to say, nearly half energy of the laser is wasted, which is the major reason that the Doppler signal is lost frequently. In order to improve the utilization of laser energy, a novel LDV with split and reuse type is designed in the paper.

2.2. split and reuse type LDV

Fig. 2 shows the optical arrangement of a novel split and reuse type LDV which consists of a single-mode laser source, two beam splitters, an attenuator, a diaphragm, a detector and several mirrors. The light emitted from laser is divided by the beam splitter BS1 whose reflectivity is 50%. The transmitted beam illuminates on the ground through the center hole of the mirror M3. The reflected beam is divided by the beam splitter BS2 whose reflectivity is 98%. The reflected beam from BS2 illuminates on the ground in the same direction by the mirror M2 and M3. The transmitted beam from BS2 is retro-reflected by the mirror M1. The scattered light of the ground gets to detector through the path of the illumination beam, and the scattered light is homodyne with the reference beam from M1 on the photo sensitive surface of the detector. According to the theoretical formula of Doppler frequency, the velocity of the vehicle can be calculated easily. Here the alignment of the additional mirrors M2 and M3 is not an easy thing. The CCD should be used for adjusting the two beams parallel. In the optical structure, an eclectic degree should be chosen as the angle between the velocity and the beam. Because the scale factor and the intensity of scattered light are contradictory. If we enlarge the inclination angle, the intensity of scattered light will be enhanced but the scale factor will be reduced.

As can be seen from Fig. 2, for the light power that usually be filtered by an attenuator in the conventional reference mode configuration is split and reused to illuminate the road surface, the utilization rate of this configuration's light power is nearly twice than that of the conventional reference mode configuration. Hence the scattered light power is twice of the conventional reference mode configuration for the same road surface.

The signal-to-noise ratio (SNR) of the reference mode LDV is [11]

$$\mathrm{SNR} = \frac{\eta W_s}{h\nu \Delta f}, \tag{3}$$

where η is the quantum efficiency coefficient, h is the Plank coefficient, ν is the center frequency of the light, Δf is the bandwidth of the detector, and W_s is the scatted light power. For the high scatted light power of the split and reuse type shown in Fig. 2, the SNR of the instrument is improved compared with the conventional reference mode configuration, which is suitable to measure the vehicle velocity on the open road. In this novel configuration, most of the laser energy is used so that the intensity of the Doppler signal is increased.

3. Integrated navigation system based on LDV and SIN

Owing to the advantages of high accuracy and signal-to-noise ratio, the split and reuse type LDV can be used to setup an integrated navigation system together with SIN. The structured flowchart of the integrated navigation system is shown in Fig. 3. Firstly, SIN should finish the static quick alignment with the help of the position information from Global Positioning System (GPS); secondly, in order to eliminate the installation error, the vehicle should run in a straight line for several minutes to calibrate the scale factor of LDV; thirdly, dead reckoning is carried out by the integrated navigation system using the velocity information from LDV and the attitude information from SIN.

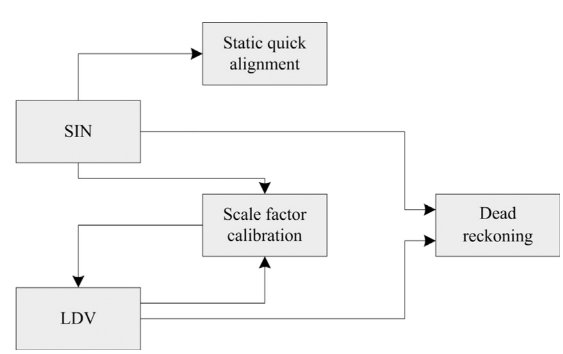

Fig. 3. Structure diagram of the integrated navigation system using LDV and SIN.