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Research on laser Doppler velocimeter for vehicle self-contained inertial navigation system

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ABSTRACT

An idea of using laser Doppler velocimeter (LDV) to measure the velocity for the vehicle inertial navigation system was put forward. The principle of measuring its own velocity with laser Doppler technique was elaborated and reference-beam LDV was designed. Then Doppler signal was processed by tracking filter, frequency spectrum refinement and frequency spectrum correction algorithm. The result of theory and experiment showed that the reference-beam LDV solved the problem that dual-beam LDV cannot be used for measuring when the system was out of focus. Doppler signal was tracked so that signal-to-noise ratio was improved, and the accuracy of the system was enhanced by the technology of frequency spectrum refinement and correction. The measurement mean error was less than 1.5% in velocity range of 0–30 m/s.

1. Introduction

The inertial self-contained navigation system is an important component in aviation, astronautics, ship and landing military equipments. Its main function is getting angular and line motion of the vehicle by the inertial instrument, calculating the position, velocity and attitude of the vehicle, and providing these parameters for guidance and attitude control system to control the vehicle. Now the angular motion information of the vehicle is received by different kinds of gyro, and the line motion information is offered by accelerometer. But most of available accelerometers are based on measuring the force, that is to say, the acceleration is offered through measuring the inertial force based on Newton's second law. So, this kind of accelerometer has two shortcomings [1]: firstly, the measured result is an apparent acceleration, not the absolute acceleration. In order to calculate the absolute acceleration, it needs complicated calculation to measure the acceleration produced by gravitational-field; secondly, the result contains error term which is produced by overloading the vehicle.

Since Yeh and Cummins confirmed that we can get the velocity of fluid using the technology of laser Doppler frequency shift on 1964 [2], laser Doppler velocimeter (LDV) has developed quickly in aviation, astronautics, mechanics and medicine [3–7]. An LDV has great advantage of high accuracy, good linearity, fast dynamic response and noncontact measurement. A conventional LDV is widely used to measure the velocity of other objects, but there is no LDV measuring the self-velocity. This paper describes a laser Doppler velocimeter for measuring the self-velocity of the inertial navigation system.

2. Theory

When the vehicle system is moving on the ground with a velocity $\boldsymbol{v}$, the whole optical system on the vehicle is also moving with a velocity $\boldsymbol{v}$ (Fig. 1). The moving light source sends up a beam of laser W_1 whose frequency is f_0 on an immobile particle P on the ground. Based on the Doppler effect, the frequency of the light that particle P receives is given by

$$f_1 = f_0(1 + \boldsymbol{v} \cdot \boldsymbol{e}_1 / c) \tag{1}$$

where $\boldsymbol{e_1}$ is the unit vector of the incident light, and c is the speed of light in vacuum.

Almost at the same time, the moving photodetector receives the scattered light W_2, which transmits exactly along the negative direction from particle P.

The frequency of the light that photodetector receives is given by

$$f_2 = f_1(1 - \boldsymbol{v} \cdot \boldsymbol{e_s} / c) \tag{2}$$

where $\boldsymbol{e_s}$ is the unit vector of scattered light W_2. Using Eq. (1), Eq. (2) reduces to

$$f_2 \approx f_0[1 + \boldsymbol{v} \cdot (\boldsymbol{e}_1 - \boldsymbol{e_s})/c] \tag{3}$$

Because W_2 transmits along the negative direction, $\boldsymbol{e_s} = -\boldsymbol{e}_1$, Eq. (3) reduces to

$$f_2 = f_0(1 + 2\boldsymbol{v} \cdot \boldsymbol{e}_1 / c) \tag{4}$$

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Therefore, Doppler frequency is given by

$$f_D = |f_2 - f_0| = 2\mathbf{v} \cdot \mathbf{e}_1/\lambda \quad (5)$$

where λ is the wavelength of the laser.

From Eq. (5), we know, the Doppler frequency depends only on the velocity. So, we can acquire the velocity of the vehicle inertial navigation system by detecting the Doppler frequency.

3. Optical system

In the condition of fluctuation of the ground surface, a dual-beam LDV is not suitable, because we cannot focus the crossing point of the two beams on the ground all the time. In this paper a reference-beam LDV has been designed. The optical schematic of this velocimeter is shown in Fig. 2. The light source is a 9 mW polarized He–Ne laser operating in a small number of longitudinal modes and the TEM_{00} transverse mode. The output of the laser passes through the collimation and compression lens, which compresses the diameter of the laser beam and controls the divergence of the laser. The next element in the optical train is the beam splitter that divides the input beam into a transmitted and 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, Polaroid, optical filter and pinhole diaphragm onto the avalanche photodiode. We call the reflected beam "reference beam". The transmitted beam passes through the stop on the ground so that scattered light was distributed in all direction. The light which transmits exactly along the negative direction passes through the stop. Then it is partly reflected by the beam splitter. After that, it also passes through the Polaroid, optical filter and pinhole diaphragm onto the avalanche photodiode. We call the transmitted beam "signal beam". As s result, inference fringes form on the light sensitive surface of the avalanche photodiode. Based on the square-law effect of photodetector, the output signal of the avalanche photodiode contains the beat frequency term—Doppler signal. It is acquired by the data acquisition board, and is passed into the navigation computer which extracts the Doppler frequency and calculates the self-velocity of the inertial navigation system. Here Eq. (5) reduces to

$$f_D = 2v\cos\theta/\lambda \quad (6)$$

where θ is the angle between incident light and the velocity vector of the system.

From Eq. (6), we know

$$v = \lambda f_D/(2\cos\theta) \quad (7)$$

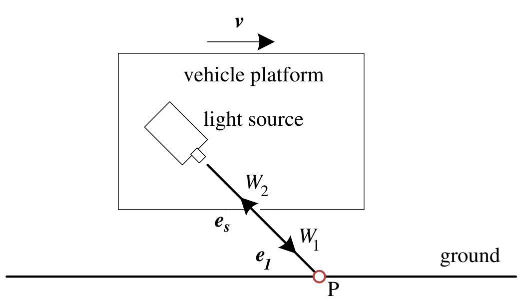

Fig. 1. Reference-beam Doppler.

4. Signal processing

4.1. The universal thought of signal processing

A variety of signal processing techniques were examined for use in LDV. These included counting, wideband phase locked loops, correlation, and fast Fourier transform (FFT) processing. Each method has advantages for specific applications, but it was decided that the FFT approach was best suited to measure widely varying surface type. But firstly, the velocity of the system changed ceaselessly such that the Doppler frequency also changed quickly. So, the common bandpass filter could not meet the requirement of LDV; secondly, if we put the frequency of spectral peak as Doppler frequency, the accuracy would not be high [8].

In this paper, tracking filter, frequency spectrum refinement and correction algorithm was put forward to solve the above two problems. That is to say, in the navigation computer, the output of avalanche photodiode passed through a high-pass filter to remove the direct current term, and then passed through the tracking filter to improve the signal-to-noise ratio. After that, FFT was used

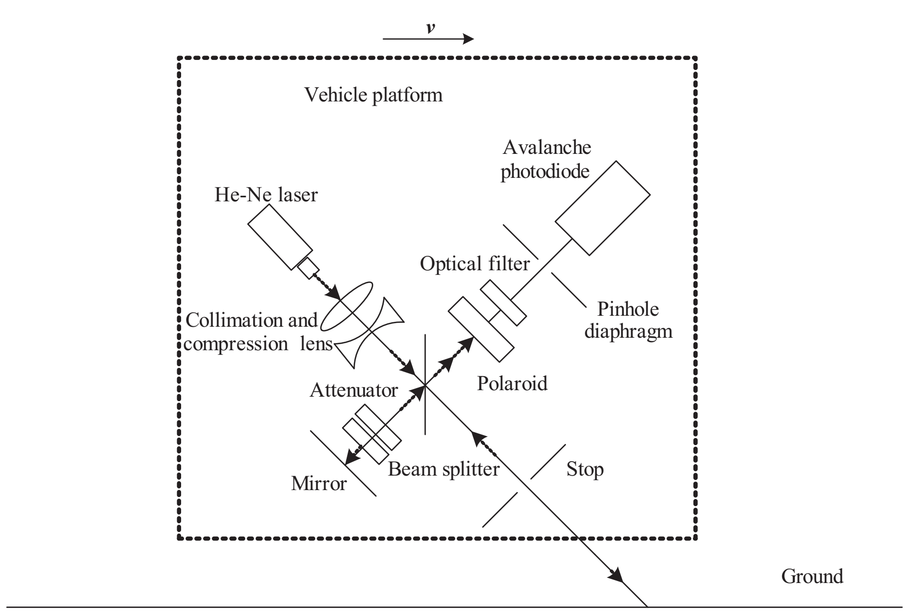

Fig. 2. The optical figure of measuring velocity system on vehicle.