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Research on heterodyne efficiency of laser Doppler velocimeter

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ABSTRACT

Heterodyne efficiency is a very important factor in a laser Doppler velocimeter (LDV). Gaussian-Airy mode is put forward to analyze the heterodyne efficiency. And the calculate formulas and results of simulation of heterodyne efficiency are given. The results of numerical analysis show that heterodyne efficiency of LDV depends on the parameters—x_0, A, θ and x_a. Heterodyne efficiency can reach 81.45%, when $x_0 = 3.59$, $A = 5.04$ and $\theta = x_a = 0$. At last, the antenna theorem of LDV is derived, and a defocused telescope system is used to adjust the waist's position and radius of the reference beam to match the signal beam.

1. Introduction

Since the first application of a laser Doppler velocimeter (LDV) to fluid velocity measurement [1], utilizing an LDV to determine velocities of gas liquid and solid surface has become a widely used technique in industrial and research applications [2–4].

Compared with direct detection, heterodyne detection has the advantage of high accuracy, high transformation gain, good filtering performance and so on. In LDV, reference beam and signal beam mix on the photosensitive surface of avalanche photodiode. The beat frequency of the two beams is the Doppler frequency, which is in proportion to the velocity of the measured object. In order to make full use of the echo signal, an LDV is designed to maximize the heterodyne efficiency.

So the paper analyzes the relationship between heterodyne efficiency and the optical parameters, and puts forward a method to maximize the heterodyne efficiency.

2. Laser Doppler velocimeter

In this paper a reference-beam LDV has been designed to offer the vehicle's velocity for a vehicle inertial navigation system. The optical schematic of this velocimeter is shown in Fig. 1. The light source is a 50 mW polarized solid-state laser operating in a single longitudinal mode 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 which 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 diaphragm and the antenna on the ground. The echo signal collected by the antenna 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 a result, reference beam and signal beam mix on the photosensitive surface of the avalanche photodiode. The Doppler frequency is given by

$$f_D = \frac{2v\cos\theta}{\lambda} \tag{1}$$

where v is the velocity of the vehicle, λ is the wavelength of the laser and θ is the angle between incident light and the velocity vector of the vehicle.

From Eq. (1), we know

$$v = \frac{\lambda f_D}{2\cos\theta} \tag{2}$$

3. Heterodyne efficiency of LDV

The receiver of a reference-beam LDV is shown in Fig. 2. The signal beam from ground is far-field weak scattered light, which can be treated as a plane wave for approximation. And the reference beam is a Gaussian beam with TEM_{00} transverse mode. To assist in understanding the description, a coordinate system is established (Fig. 2). The direction of the optical axis is z axis, and the vertical direction is r axis. Based on the theory of Fraunhofer diffraction, we know that the signal beam (plane wave) becomes a light with Airy

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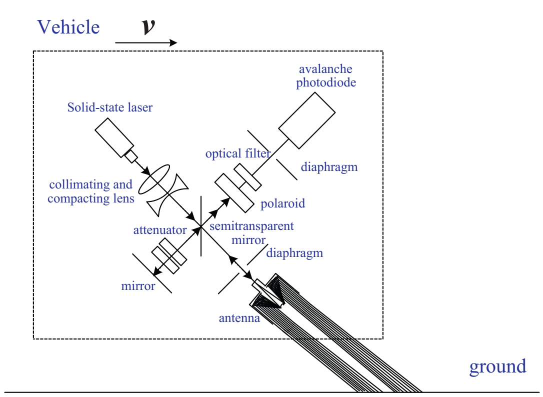

Fig. 1. Optical schematic diagram of LDV.

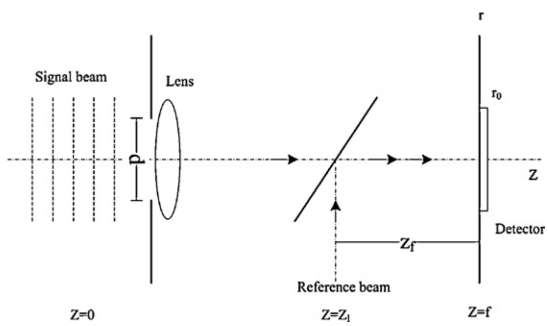

Fig. 2. Receiver of LDV.

distribution after passing the diaphragm. So the model of this kind of LDV is Gaussian-Airy model.

So the electric field of signal beam in complex notation is given by

$$U_s(r) = 2\frac{J_1(kdr/2f)}{kdr/2f}\exp\left(j\frac{kr^2}{2f} + jkf - \frac{\pi}{2}\right) \tag{3}$$

where k is wave number, d is the diameter of diaphragm, f is the focal distance of lens and J_1 is the first order Bessel function.

And the electric field of reference beam is given by

$$U_r(r) = \exp\left[-\frac{r^2}{\omega^2(z_f)}\right]\exp\left\{-j\left[k\left(\frac{r^2}{2R(z_f)} + z_f\right) - \Phi\right]\right\} \tag{4}$$

where

$$z_o = \frac{1}{2}k\omega_0^2 \tag{5}$$

$$\omega(z) = \omega_0\sqrt{1 + \left(\frac{z}{z_0}\right)^2} \tag{6}$$

$$R(z) = z_0\left(\frac{z}{z_0} + \frac{z_0}{z}\right) \tag{7}$$

$$\Phi = \arctan\left(\frac{z}{z_0}\right) \tag{8}$$

$$z_f = f - z_l \tag{9}$$

z_0 is the confocal parameter, ω_0 is radius of waist, $\omega(z)$ is radius of equiphase wave surface at z point and Φ is the initial phase.

David Fink has given the design formulas of heterodyne efficiency when the phase difference between signal beam and reference beam is a constant [5]

$$\eta_h = \frac{\left(\iint_D \left|U_s(r)\right| \cdot \left|U_r(r)\right| dS\right)^2}{\iint_D |U_r(r)|^2 dS \cdot \int_0^\infty \int_0^\infty \left|U_s(r)\right|^2 dS} \tag{10}$$

where η_h is heterodyne efficiency and S is the photosensitive surface of the avalanche photodiode.

If $kr^2/2f = kr^2/2R(z_f)$, that is to say

$$R(z_f) = f \tag{11}$$

the phase difference between signal beam and reference beam will be a constant.

In order to simplify the calculation, define two parameters as follows:

$$x = \frac{kdr}{2f} \tag{12}$$

$$A = \frac{k^2 d^2 \omega^2(z_f)}{4f^2} \tag{13}$$

Using Eqs. (5)–(9) and (11)–(13)

$$\omega_0 = \frac{\sqrt{A}f\lambda/\pi d}{\sqrt{1 + (Af\lambda/\pi d^2)^2}} \tag{14}$$

$$z_f = f\frac{(Af\lambda/\pi d^2)^2}{1 + (Af\lambda/\pi d^2)^2} \tag{15}$$

Generally, $0 \le A \le 40$ and $f\lambda/\pi d^2 \ll 1$, then Eq. (15) reduces to

$$z_f = 0 \tag{16}$$

From Eqs. (9) and (16), we know $f = z_l$, $R(z_f) = \infty$ and $\omega(z_f) = \omega_0$. It means that the maximal heterodyne efficiency can be achieved when the waist's position of the reference beam coincides with the photosensitive surface of the detector. Using Eqs. (3) and (4), Eq. (10) becomes

$$\eta_h = \frac{\left[\int_0^{r_0}\int_0^{2\pi} \frac{2J_1(kdr/2f)}{kdr/2f}\exp\left(-\frac{k^2d^2r^2}{4f^2\omega^2(z_f)}\right) rdrd\varphi\right]^2}{\int_0^\infty\int_0^{2\pi}\left[\frac{2J_1(kdr/2f)}{kdr/2f}\right]^2 rdrd\varphi \int_0^{r_0}\int_0^{2\pi}\exp\left(-\frac{k^2d^2r^2}{2f^2\omega^2(z_f)}\right) rdrd\varphi} \tag{17}$$

Combining Eqs. (12) and (13), Eq. (17) reduces to

$$\eta_h = \frac{8}{A}\frac{\left[\int_0^{x_0} J_1(x)\exp\left(-\frac{x^2}{A}\right)dx\right]^2}{1 - \exp\left(-\frac{2x_0^2}{A}\right)} \tag{18}$$

where $x_0 = kdr_0/(2f)$ and r_0 is the radius of the photosensitive surface of the avalanche photodiode.

But when the optical axis of signal beam and that of reference beam are not coincident strictly, the heterodyne efficiency becomes

$$\eta_h = \frac{8}{A}\frac{\left[\int_0^{x_0} J_1(x)J_0\left(2\frac{f}{d}\theta\right)\exp\left(-\frac{x^2}{A}\right)dx\right]^2}{1 - \exp\left(-\frac{2x_0^2}{A}\right)} \tag{19}$$

where θ is the mismatch angle of the two beams.

4. Numerical analysis

Based on the calculation formula of heterodyne efficiency, we know heterodyne efficiency depends on the optical parameter of detector x_0, the optical parameter of Gaussian beam A and the mismatch angle θ. Figs. 3–5 show the numerical curves of Gaussian-Airy heterodyne efficiency. Figs. 3 and 4 show the change curves of heterodyne efficiency η_h along with x_0 and A, respectively, when the mismatch angle θ is different at each time. And Fig. 5 shows the graph of relation between heterodyne efficiency η_h and the mismatch angle θ.

From the results of numerical analysis, we know that the mismatch angle has a great influence on the heterodyne efficiency,