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Influence of speckle effect on doppler velocity measurement

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A B S T R A C T

In a coherent Lidar system, velocity measurement of a target is achieved by measuring Doppler frequency shift between the echo and local oscillator (LO) signals. The measurement accuracy is proportional to the spectrum width of Doppler signal. Actually, the speckle effect caused by the scattering of laser from a target will broaden the Doppler signal's spectrum and bring uncertainty to the velocity measurement. In this paper, a theoretical model is proposed to predict the broadening of Doppler spectrum with respect to different target's surface and motion parameters. The velocity measurement uncertainty caused by the broadening of spectrum is analyzed. Based on the analysis, we design a coherent Lidar system to measure the velocity of the targets with different surface roughness and transverse velocities. The experimental results are in good agreement with theoretical analysis. It is found that the target's surface roughness and transverse velocity can significantly affect the spectrum width of Doppler signal. With the increase of surface roughness and transverse velocity, the measurement accuracy becomes worse. However, the influence of surface roughness becomes weaker when the spot size of laser beam on the target is smaller.

1. Introduction

Coherent Doppler Lidar is a powerful tool in velocity measurement of moving targets [1–5]. For laser coherent detection, the wavelength of laser is so small that most of the targets can be regarded as rough surface targets. Moreover, in most practical applications, the targets do not directly move towards the direction of laser emission and there is a transverse velocity of the target with respect to the Lidar platform. Both effects can lead speckle field distribution in receiving plane [6–9]. Ideally, a Doppler signal, without the effect of speckle noise, is represented by a single spectral line in the frequency domain [10]. However, the speckle effect caused by surface roughness and transverse velocity will lead to variations in amplitude and phase of the echo signal and result in broadening of Doppler spectrum in frequency domain which contributes to the reduction of velocity measurement accuracy [1].

The broadening of spectrum caused by speckle effect has been widely studied [11,12]. Several groups experimentally reported the dynamic speckle in self-mixing sensors [13–15] and Rothberg et al. have deeply investigated the laser speckle in laser vibrometry [15–18]. However, the discussion of speckle effect pertained to velocity measurement in coherent Lidar system was limited. The most recent literature [19] analyzed the speckle effect on the spectral broadening of self-mixing signal. But only small beam spot sizes were chosen during the experiments and target's surface roughness was not taken into consideration. Based on the statistical optics foundations and dynamic speckle theory, this paper for the first time investigates the speckle model in a coherent Lidar system to predict its influence on velocity measurement accuracy in a qualitative manner. And the surface roughness and transverse velocity of the target are taken into account for the contribution on the measurement accuracy.

The structure of this paper is as follows: Section 2 gives the full derivation of speckle effect's influence on velocity measurement accuracy. The parameters of the target involved in the speckle effect are also listed and the simulation results are given. Section 3 describes the coherent Lidar system in the experiments. In Section 4, the experimental results with different beam spot sizes, roughness of target's surface and transverse velocity are presented. The influences of target's surface roughness and transverse velocity on the velocity measurement are discussed. The last section is the conclusion.

2. Analysis of the influence of speckle effect on velocity measurement

The spatial coordinates of an objective and observation plane are shown in Fig. 1. We consider the case where a light field is focused on a rough surface through a lens. Suppose the target

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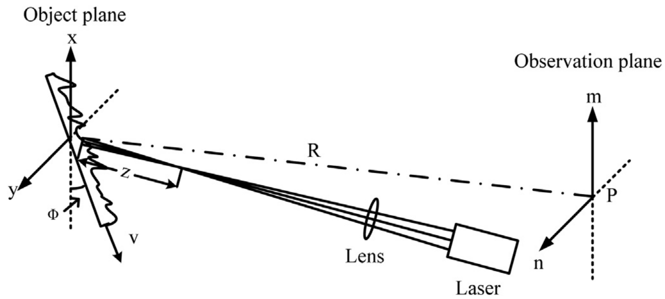

Fig. 1. Schematic diagram of the optical system.

moves along a direction with an angle $\varnothing$ from the x axis. The incident light is reflected and scattered by the rough surface and produces speckle field distribution in the observation plane with (m, n) coordinate system at a distance R.

The complex amplitude of light field at point P in the observation plane can be expressed as [9]:

$$A(m, n) = \iint_{-\infty}^{\infty} U(x, y)\exp[-j2kx\tan\varnothing]\exp[j\varphi(x, y)] K(x, y; m, n)\,dxdy \tag{1}$$

where $U(x, y)$ is the complex amplitude of incident light field; $-2kx\tan\varnothing$ stands for the additional phase shift caused by target's incline at the angle $\varnothing$from the perpendicular orientation; k is the wave number of the incident light; $\varphi(x, y)$ is the variable phase due to the rough surface; $K(x, y;m, n)$ is the weight function when the light transmits in free space.

In a coherent Lidar system, the incident light field is a Gaussian beam. Therefore, $U(x, y)$ will be represented as follow:

$$U(x, y) = (\omega_0/\omega)\exp(j2\pi/\lambda)\exp[-(x^2+y^2)/\omega^2]\exp[-j\pi(x^2+y^2)/\lambda\rho] \tag{2}$$

With ω_0 being the radius of the beam waist; ω and ρ are width and radius of the wavefront-curvature of the beam at the objective plane which has a distance z from the location of beam waist, respectively. These two parameters are functions of z:

$$\omega = \omega(z) = \omega_0(1+z^2/a^2)^{1/2} \tag{3}$$

$$\rho = \rho(z) = z(1 + a^2/z^2) \tag{4}$$

where $a = (\pi\omega_0^2)/\lambda$.

According to Fresnel approximation, weight function $K(x, y;m, n)$ is:

$$K(x, y;m, n) = (j/\lambda R)\exp(-jkR)\exp\left\{-jk\left[(m-x)^2+(n-y)^2\right]/2R\right\} \tag{5}$$

Referring to the geometry in Fig. 1, the autocorrelation function of complex amplitude A can be expressed as:

$$\begin{aligned} R_A(t_1, t_2) &= E\left[A(t_1)\cdot A^*(t_2)\right] \\ &= E\Big\{\iint_{-\infty}^{\infty} U(x_1, y_1)\exp(-jkx_1\tan\varphi)\exp\left[j\varphi(x_1, y_1)\right] \\ &\quad K(x_1, y_1; m, n)dx_1dy_1 \\ &\quad \cdot \mathrm{conj}\Big(\iint_{-\infty}^{\infty} U(x_2, y_2)\exp(-jkx_2\tan\varphi)\exp\left[j\varphi(x_2, y_2)\right] \\ &\quad K(x_2, y_2; m, n)\Big)dx_2dy_2)\Big\} \\ &= \iiiint_{-\infty}^{\infty} E\left\{\exp\left[j\varphi(x_1, y_1) - j\varphi(x_2, y_2)\right]\right\} \\ &\quad \exp\left[j2k(x_2 - x_1)\tan\varphi\right]\cdot U(x_1, y_1)U^*(x_2, y_2)K(x_1, y_1; m, n) \\ &\quad K^*(x_2, y_2; m, n)dx_1dy_1dx_2dy_2 \end{aligned} \tag{6}$$

where $E[\bullet]$ is the expected value operator.

$\varphi(x, y)$ represents the variable phase caused by rough surface and $\varphi(x, y) = -2k\gamma(x, y)$, where $\gamma(x, y)$is the surface roughness. Assume that $\gamma(x, y)$ has Gaussian distribution whose mean value is zero and variance is σ, the variable phase also has a Gaussian distribution [20,21]. Then we can get

$$\begin{aligned} &E\left\{\exp\left[j\varphi(x_1, y_1) - j\varphi(x_2, y_2)\right]\right\} \\ &= \exp\left\{-4k^2\sigma^2\left[(x_1-x_2)^2+(y_1-y_2)^2/\tau_0^2\right]\right\} \end{aligned} \tag{7}$$

where τ_0 is the correlation length of the surface.

Because $x_1 = x_0 + vt_1\cos\varnothing$, $x_2 = x_0 + vt_2\cos\varnothing$ and $\tau = t_2 - t_1$, we can conclude that $x_2 = x_1 + v\tau\cos\varnothing$. Because there is no motion in y direction, we can consider that $y_2 = y_1$. Substitute Eqs. (2), (5) and (7) into Eq. (6) and select $(m, n) = (0, 0)$ as observing point, then the time autocorrelation function becomes

$$\begin{aligned} R_A(\tau) &= \frac{\omega_0^2}{\lambda^2R^2\omega^2}\cdot\exp\left(-4k^2\sigma^2v^2\tau^2\cos^2\varphi/\tau_0^2\right)\cdot\exp(j2kv\tau\sin\varphi) \\ &\iint_{-\infty}^{\infty}\exp\left[\frac{x_1^2+(x_1+v\tau\cos\varphi)^2+2y_1^2}{\omega^2}\right] \\ &\cdot\exp\left\{\frac{j\pi}{\rho}\left[(x_1+v\tau\cos\varphi)^2 - x_1^2\right]\right\} \\ &\cdot\exp\left\{\frac{jk\left[(x_1+v\tau\cos\varphi)^2 - x_1^2\right]}{2R}\right\}dx_1dy_1 \end{aligned} \tag{8}$$

Perform the integration, the final expression of $R_A(\tau)$ can be expressed as

$$R_A(\tau) \approx \frac{\omega_0^2}{2\lambda^2R^2}\bullet\exp\left\{-\frac{(v\cos\varnothing)^2\tau^2}{2}\left[\frac{32\pi^2\sigma^2}{\lambda^2\tau_0^2}+\frac{2\pi^2\omega^2}{\lambda^2R^2}+\frac{1}{\omega^2}\right] + j\frac{4\pi v\tau\sin\varnothing}{\lambda}\right\} \tag{9}$$

The power spectral density (PSD) of autocorrelation function is the Fourier transform of $R_A(\tau)$ [22]. Suppose $S_A(f)$ is the normalization of PSD, then

$$S_A(f) = \frac{F\{R_A(\tau)\}}{\max\left(F\{R_A(\tau)\}\right)} = \exp\left[\pi^2\left(f - \frac{2v\sin\varnothing}{\lambda}\right)^2/a^2\right] \tag{10}$$

where $a^2 = \frac{(v\cos\varnothing)^2}{2}\left[\frac{32\pi^2\sigma^2}{\lambda^2\tau_0^2}+\frac{2\pi^2\omega^2}{\lambda^2R^2}+\frac{1}{\omega^2}\right]$.

The uncertainty of velocity measurement is defined as [10]:

$$\delta v = \frac{\lambda}{2}\bullet\mathrm{FWHM} = \frac{v\cos\varnothing\sqrt{2\ln 2}}{2\pi}\left[\frac{32\pi^2\sigma^2}{\tau_0^2}+\frac{2\pi^2\omega^2}{R^2}+\frac{\lambda^2}{\omega^2}\right]^{1/2} \tag{11}$$

According to the above analysis, we find that the velocity measurement uncertainty is affected by the transverse velocity, correlation length, laser wavelength and spot size. Therefore, we calculate the velocity measurement uncertainty δv with respect to the above parameters.

From the simulation results Fig. 2(a) we can see that when the surface roughness is small, it is better to choose laser with short wavelength for velocity measurement. While when the roughness becomes bigger, the uncertainty is increasing but it is about the same for all laser wavelength. Fig. 2(b) shows that large correlation length of the target can enhance the coherence of laser echo and reduce the speckle effect, so it is helpful to measure the velocity more precisely when the correlation length of the target surface is bigger. Fig. 2(c) proves that small spot size on the target is a better choice than a larger one because a large illuminated area will experience more speckle effect. Fig. 2(d) illustrates that when the target's transverse