DETERMINATION OF THE PROFILE OF DISTANT OBJECTS WITH THE HELP OF A COHERENT AUTODYNE LIDAR

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The results of experiments on determining the profile of reflecting objects with the help of a coherent autodyne lidar are presented. The limits of the Doppler frequency shift are determined.

Laser autodyne Doppler lidars can be successfully used for remote measurements of the characteristics of moving surfaces,[1–3] such as the parameters of oscillations of a surface, velocity, albedo, and range.

In this paper we study the possibilities of remote determination of the profile of objects with the help of a coherent autodyne lidar. We shall study the simplest coherent autodyne Doppler system (Fig. 1), in which the frequency of the sounding radiation is shifted on reflection from the surface 2 moving in a direction perpendicular to the beam. The photodetector 3 detects a signal at the frequency of the shift Δf, measuring which gives information about the velocity of the reflecting object: $\Delta f = |kv|$. This detection scheme does not permit determining the direction of motion, since

$$|(f_0 + kv) - f_0| = |(f_0 - kv) - f_0| = kv.$$

In some cases, however, additional information about the parameters of the reflecting surface can be obtained. Thus, for example, if it is known that the surface undergoes periodic oscillations (the surface of a vibrating machine-tool bench, that shaft of a turbine, etc.), then the Doppler frequency shift cam be related with the frequency of the oscillations of the surface f_{osc} and the amplitude of the oscillations x_0: $\Delta f = 2k_{osc}x_0k$. Figure 2 shows the experimental measurements of the amplitude of the oscillations of the surface of a rotation machine performed with the help of a lamer Doppler autodyne and a piezoelectric transducer. In the case when the relative motion occurs in a direction perpendicular to the optical beam the spectrum of the signal contains information about the character of the profile of the reflecting surface. Slow variations of the profile correspond to low velocities of the relative motion and small Doppler frequency shifts, and vice versa. Figure 3 shows the spectra of the signals of am airborne laser autodyne Doppler lidar which were obtained by sounding the surface of a lake (a) and field (b). The flight altitude was equal to 800 and 710 m and the velocity of the aircraft was equal to about 190 km/h. The measurements were performed in the summer of 1987 from an 11–14 airborne laboratory. The optical arrangement of the lidar is analogous to the scheme shown in Fig. 1. The radiation was collimated with a Cassegrainian mirror telescope with a 160 mm aperture. The power of the cw CO_2 laser was equal to 2.7 W. In the measurements some of the radiation reflected from the Brewster window of the gas-discharge tube was recorded. A FSG-22a photodetector, cooled to a temperature of 77 K, was used to detect the optical radiation.

FIG. 1. Block diagram, of the simplest autodyne: 1) laser, 2) surface, 3) photodetector.

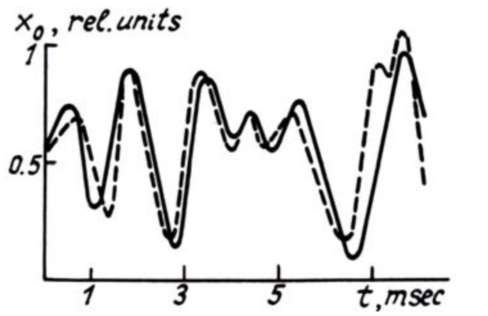

FIG. 2. Measurements of the amplitude of the oscillations. The solid line shows the measurements performed with a Doppler autodyne and the dashed line shows the measurements performed with a piezoelectric transducer.

Optical schemes with a shift of the frequency are usually employed to determine uniquely the direction of motion of the reflecting surface. This solution can also be used in autodyne systems. In this case, however, certain specific features arise. We shall examine a variant of a laser autodyne Doppler lidar whose block diagram is shown in Fig. 4. The laser 1 generates radiation at the frequency f_0, part

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of which is diverted by a beam-splitting plate 2 into the frequency shifter (for example, a rotating disk) while the rest of the beam passes to the reflecting or scattering object and returns to the laser. In this manner three waves with the frequencies f_0, f_1(the frequency of the radiation from the frequency shifter), and f_s (the frequency of the radiation reflected from the moving surface) are mixed in the cavity. The photodetector 5 records three Doppler signals at the frequencies $f_1 = |f_0 - f_s|$, $f_2 = |f_1 - f_s|$, $f_3 = |f_0 - f_1|$. The signal at the frequency f_3 does not carry useful information and is eliminated with a rejection filter. The condition under which the direction and velocity of the motion of the reflecting surface is determined uniquely is quite simple:

$$v_1 \geq 2v_{max} \tag{1}$$

where v_1 is the linear velocity of the reflecting surface of the disk in the frequency shifter and v_{max} is the maximum value of all possible velocities of the lidar relative to the surface of the earth. We shall prove the condition (1). The condition (1) can be rewritten in the form

$$f_s < (f_1 + f_0)/2$$

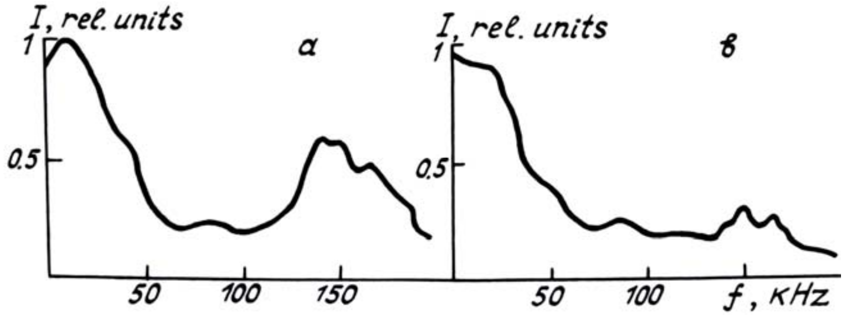

FIG. 3. The spectra of the signal obtained by sounding the surface of a lake (a) and the surface of a field (b).

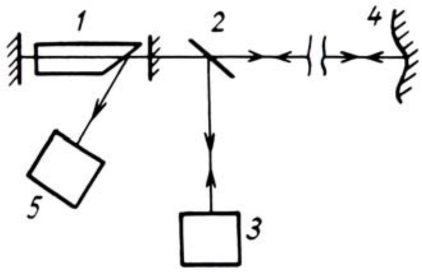

FIG. 4. Block diagram of autodyne with a frequency shift: 1) CO_2 *laser; 2) beam-splitter; 3) frequency shifter; 4) surface; 5) photodetector.*

Assume that

$$f_s > \frac{f_1 + f_0}{2}, \quad \text{or} \quad f_s = \frac{f_1 + f_0}{2} + \Delta f \tag{2}$$

Then the expressions for the two pairs of Doppler signals corresponding to different velocities of the reflecting surface cam be written as follows:

$$f_1 = \left| f_0 - \left[\frac{f_1 + f_0}{2} + \Delta f \right] \right| ;$$

$$f_1' = \left| f_0 - \left[\frac{f_1 + f_0}{2} - \Delta f \right] \right| ;$$

$$f_2 = \left| f_1 - \left[\frac{f_1 + f_0}{2} + \Delta f \right] \right| ;$$

$$f_2' = \left| f_1 - \left[\frac{f_1 + f_0}{2} - \Delta f \right] \right| ; \tag{3}$$

From here it is obvious that for two different velocities

$$v = \left[\frac{f_1 + f_0}{2} + \Delta f \right] / k$$

$$v' = \left[\frac{f_1 + f_0}{2} - \Delta f \right] / k \tag{4}$$

we have two identical pairs of Doppler frequencies

$$f_1 = f_2', \quad f_2 = f_1'$$

Thus an ambiguity arises under the condition (2). If $f_s = \frac{f_1 + f_0}{2}$, then $f_1 = f_2$. In the case when the condition (1) is satisfied the velocity is determined uniquely, i.e., to each pair of Doppler frequencies there corresponds a unique value of the velocity.

From the standpoint of the direction of motion of the eflector there exist three situations:

1) $f_1 + f_2 < f_3$, which corresponds to an approaching reflector.
2) $f_1 = f_2 = f_3$, which corresponds to a reflector at rest, and
3) $f_1 + f_2 > f_3$, which corresponds to a receding reflector.

Since, apart from the state of rest, $f_2 > f_1$ and in practice it is convenient to use simple criteria, Eqs. (1) and (3) can be replaced by the following conditions; $f_{max} < f_3$ and $f_{max} > f_3$. Since, aside from the state of rest $f_{min} = f_1$, the value and sign of the velocity are determined as follows:

$$v = \begin{cases} \lambda f_{min}/2\pi, & \text{if } f_{max} < f_3; \\ 0, & \text{if } f_{min} = f_{max} = f_3; \\ -\lambda f_{min}/2\pi, & \text{if } f_{max} > f_3. \end{cases} \tag{5}$$

The velocity of the relative motion (5) can be related with the profile of an extended surface, if the lidar or the surface move along a straight line perpendicular to the optical beam. We shall place the Cartesian coordinate system and the origin on the surface. Assume that the radiation propagates along the abscissa axis and the relative motion of the lidar and the surface as a whole occurs along the ordinate axis. Then

$$\frac{dy}{dx} = \frac{v_y}{v_x}, \tag{6}$$

where (x, y) are the coordinates of the point on the surface from which the radiation is reflected, v_x is the velocity of the relative motion perpendicular to the beam, and v_y is the relative velocity of motion along the beam (approaching and receding reflector). It follows from Eqs. (6) and (5) that for the relative motion given by Eq. (5) the profile of the surface can be found as follows to within a constant:

$$y(\Delta t) = \begin{cases} \frac{\lambda}{2\pi}\int\limits_t^{t+\Delta t} f_{min}(t)dt, & \text{if } f_{max} < f_3; \\ 0, & \text{if } f_{min} = f_{max} = f_3; \\ -\frac{\lambda}{2\pi}\int\limits_t^{t+\Delta t} f_{min}(t)dt, & \text{if } f_{max} > f_3. \end{cases}$$

In the case when Δx is small (for example, $\Delta x \ll \rho_y$, where ρ_y is the radius of the spatial autocorrelation function $y(\Delta x)$), $y(\Delta x)$ will be a quite smooth function without losses of the higher spatial frequencies.

In a laboratory experiment performed using the method described above the optical scheme shown in Fig. 5 was employed.

The radiation source consisted of an automatic tunable cw CO_2 laser, which contains a serially produced GL-501 gas-discharge tube 1, a cavity mirror 2 mounted on a piezoelectric corrector, a diffraction grating 3 (100 lines/mm), a diaphragm 4 for selecting the transverse modes, a rotating mirror 5, and a photodetector 6. The wavelength of the laser is tuned by rotating the mirror 2 around an axis perpendicular to the plane of the figure. Precise tuning on the center of the line is performed with the help of piezoelectric corrector on which the mirror 2 is mounted. A microcomputer controls the process of rough and precise tuning.

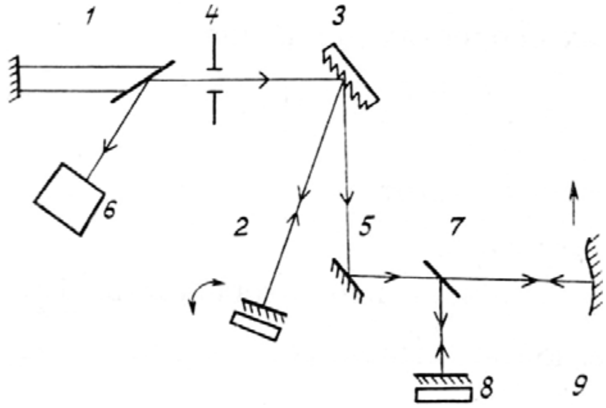

FIG. 5. Block diagram of autodyne with frequency-tunable laser: 1) gas-discharge tube of CO_2 *laser: 2) cavity mirror mounted on a* piezoelectric corrector; *3) diffraction grating; 4) diaphragm; 5) rotating mirror; 6) photodetector; 7) beam-splitter; 8) mirror on piezoelectric corrector; 9) reflecting surface.*

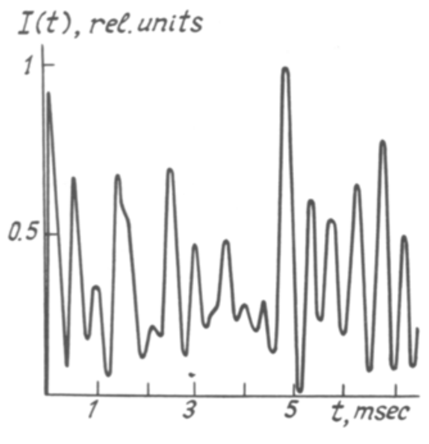

FIG. 6. Signal from the photodetector

The output radiation is split with a KBr plate 7 into two beams. The frequency shifter consists of a mirror 8 mounted on a piezoelectric corrector and is driven by a sawtooth voltage with a frequency of 100 Hz. The amplitude of the voltage applied to the piezoelectric corrector is set so that the condition (1), where v_1 is the velocity of the mirror, is satisfied. The surface 9 was moved in the direction perpendicular to the axis of the beam with a velocity of 1 cm/s. The signal from the photodetector 6 at the frequency

$\omega = f_{\min}$, separated with a bandpass filter, is shown in Fig. 6. Figures 7 and 8 show, respectively, the demodulated signal and the result of reconstruction of the profile of the reflecting surface.

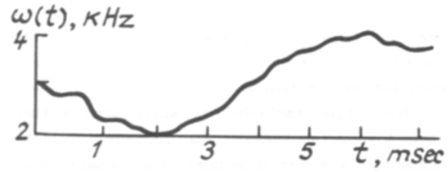

FIG. 7. Result of demodulation

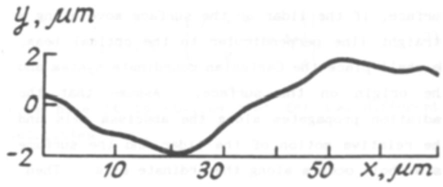

FIG. 8. The reconstructed profile of the reflecting surface

When surfaces with a complicated profile are sounded the conditions that are usually necessary for demodulation are not satisfied: $\Omega \ll \omega_0$, $\omega_m \ll \omega_0$, where Ω is the deviation, ω_0 is the central frequency, and ω_m is the frequency of the modulating function. In this case the signal frequency changes significantly in a time interval equal to one period. The following method of demodulation was used to process such signals. The frequency ω of the signal can be determined as follows, assuming that it is constant in the time interval $\Delta t \ll \frac{2\pi}{\omega_0}$;

$$\omega = \frac{1}{\Delta t}\sqrt{-\frac{\ddot{I}(\Delta t)}{I(\Delta t)}} = \frac{1}{t_1 - t_{1-1}} \times \sqrt{2 - \frac{I(t_{1-1}) + I(t_{1+1})}{I(t_1)}} \tag{7}$$

When the demodulator is implemented on a computer, as one can see from Eq. (7) there arises at the points of inflection of the function $I(\omega)$ an indefiniteness of the type 0/0. This is manifested in the fact that the function $\omega(t)$ has singularities. To avoid them the function $\omega(t)$ is not calculated at the point of inflection, but rather the missing point is reconstructed by interpolation. This method was used to demodulate the Doppler signal in reconstructing the profile (Fig. 8).

Thus we have shown that a coherent autodyne lidarn cam be used for remote determination of the profile of reflecting or scattering surfaces.

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