Design of differential optical system of in-plane remote displacement measurement

Shunzhong He (贺顺忠), Xin Yao (姚 欣), Chengzhi Jiang (蒋诚志),
Jinfeng Liu (刘金凤), Yanyu Liu (刘彦宇), and Lincai Chen (陈林才)

The National Key Lab of Precision Measuring and Testing Technique and Instrument, Tianjin University , Tianjin 300072

Received August 22, 2002

In this paper, an optical system for in-plane remote displacement measurement is brought forward. The remarkable characteristic of this optical system is to use a big aperture lens to focus the waists of two Gauss beams on a scatter which have been expanded and collimated, so good laser Doppler signals and high measurement accuracy are achieved. The experiments prove that the measurement system consisting of this optical system, a lock-in amplifier and a digital filter can be used to measure the in-plane displacement of scatters in distance of 50 m with the relative accuracy of 1%.

OCIS codes: 220.4830, 030.1670, 140.3430.

In the applications of laser Doppler technique, the SNR of Doppler signals lies on the magnitude of overlapping light spot, and the measurement accuracy has close relation to the divergence of the two beams in the overlapping region. If the two beams overlap in a small region and are plane wave overlapping, high SNR and measurement accuracy would be achieved. But, the existing optical systems[1] for in-plane displacement measurement cannot meet these demands and the Doppler signals of the systems are too faint to be utilized. In this paper, a new optical system is designed, in which waists of two Gauss beams are focused on scatter by a big aperture lens after being expanded and collimated, and the smallest overlapping light spot and plane wave overlap are achieved, so the SNR and the measurement accuracy will be improved greatly. The experiments prove that the measurement system consisting of this optical system, a photoelectric receiver, a lock-in amplifier and a homomorphic filter can be used to measure the in-plane displacements of common paper in distance of 50 m.

The optical system of in-plane remote displacement measurement is shown in Fig. 1.

The laser beam of frequency f_0 is reflected by M_1 and passes 1/2 wave plate G, then enters the acoustoopic modulator A (the modulating frequency f_c is 40 MHz) by Bragg diffraction angle to form the 0 order diffracted light of frequency f_0 and the +1 order diffracted light of frequency ($f_0 + 40$ MHz). The two beams are collimated by L_1-L_2 and L_3-L_4, respectively, and then pass the big aperture lens L_5 (of focal length F_5) and converge on the moving object (such as common paper) M by angle θ to generate the Doppler differential signals of frequency ($f_c + \Delta f$). The diffused light passes L_5 and is reflected by M_3, and the reflected light is converged on the photoelectric receiver E by L_6 and the photoelectric signals ($f_c + \Delta f$) are obtained.

According to laser Doppler effect[2], when the measured object is moving by velocity v, the Doppler beat signals of diffused light are described as

$$\Delta f = 2\frac{v}{\lambda}\sin(\theta/2). \tag{1}$$

We can see that a big aperture lens can be adopted to achieve good signals.

By means of counting the number N of pulses of beat signals, the displacement x of object M can be obtained.

$$N = \int_0^t \Delta f \mathrm{d}\tau = \int_0^t \frac{2v}{\lambda}\sin(\theta/2)\mathrm{d}\tau = \frac{2\sin(\theta/2)}{\lambda}x, \tag{2}$$

so the displacement is

$$x = \frac{\lambda}{2\sin(\theta/2)}N, \tag{3}$$

and by applying differential to x, the error can be obtained

$$\sigma(x) = \sqrt{(\frac{\partial x}{\partial \lambda}\Delta\lambda)^2 + (\frac{\partial x}{\partial N}\Delta N)^2 + (\frac{\partial x}{\partial \theta}\Delta\theta)^2},$$

or

$$\frac{\sigma(x)}{x} = \{(\frac{\Delta\lambda}{\lambda})^2 + (\frac{\Delta N}{N})^2 + [\frac{\Delta\theta}{2\tan(\theta/2)}]^2\}^{1/2}. \tag{4}$$

It is obvious that the displacement measurement accuracy lies on the stability of mode and the power of laser, the counting errors and the changes of the converging angles of the differential beams. But, the laser beams that come from He-Ne laser ($\lambda \approx 630$ nm) belong to basic mode Gauss beams, and their wave fronts are spheric waves of different sphere centers (only the waists are planes, namely, $z = 0$, $R(z) \rightarrow \infty$)[3]. So, if

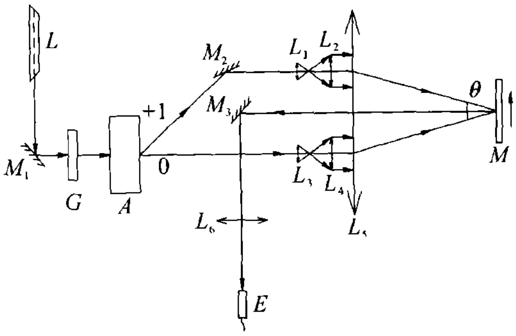

Fig. 1. Optical measuring system.

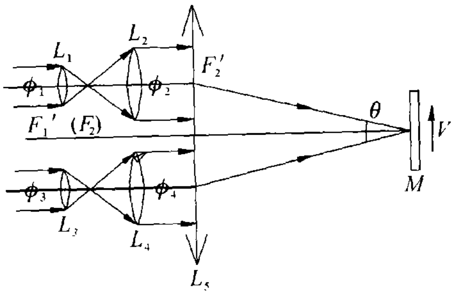

Fig. 2. Optical measuring head.

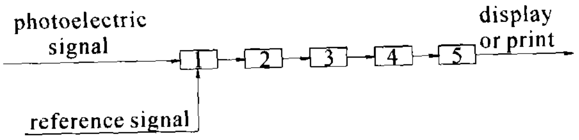

Fig. 3. Signal processing. 1: Lock-in amplifier; 2: sampling; A/D conversion; 3: digital filter; 4: homomorphic filter; 5: subdivision counting.

two laser beams like this overlap directly (such as the distance is 20 m), not only the spot (25 mm) is big, but also the converging angles of the beams in the overlapping region change. If using a collimating system to compress the divergence, the diameter of spot will be large; if using a lens to focus the two beams in the distance, because waists are not in the spot, the spot will be large too. In a word, invariable converging angles and the smallest spot cannot be obtained at the same time by utilizing these methods, so the measurable distance is limited.

According to the imaging principle of the waist of Gauss beam[3], for L_5 lens, if the radius of waist in object space is $\omega_{50} = 20$ mm, the object distance $l_5 = 0$ and F_5=50 m, then

$$f_5 = \frac{\pi\omega_{50}^2}{\lambda} = \frac{3.14}{0.63} \times (20)^2 \approx 2000\,\mathrm{m},$$

$$\omega_{50}' = \frac{\omega_{50}}{\sqrt{1+(f_5/F_5)^2}} = \frac{20}{\sqrt{1+(\frac{2000}{50})^2}} \approx 0.5\,\mathrm{mm},$$

$$l_5' = \frac{F_5}{1+(F_5/f_5)^2} = \frac{50}{1+(\frac{50}{2000})^2} \approx 49.970\,\mathrm{m},$$

where ω_{50}' is the radius of waist in image space and l_5' is the image distance. This waist diameter (2×20 mm) of the beam (of L_5) can be achieved by a beam expanding and collimating system. If the diameter of the waist of the beam is 2 mm, the focal length ratio of the two lenses in the system is

$$\frac{F_2}{F_1} = \frac{\phi_2}{\phi_1} = \frac{2\times 20}{2\times 1} = 20.$$

Based on these analyses and calculating, an optical measuring head shown in Fig. 2 is designed. We can see that the waists of the two differential beams can overlap on the moving object by the use of this system, so high SNR and measurement accuracy can be obtained.

Table 1. The Measured in-plane Displacements (40 mm) of Common Paper in Distance of 50 m (V_i=X_i − $\overline{X}$, $\overline{X}$=40.485≈40.48 mm, Unit: mm)

X_i	V_i	V_i^2	X_i	V_i	V_i^2
40.030	−0.46	0.21	40.846	0.36	0.13
40.043	−0.44	0.19	40.784	0.30	0.09
40.740	0.26	0.07	40.735	0.25	0.07
40.778	0.29	0.08	40.046	−0.44	0.21
40.810	0.33	0.11	40.038	−0.45	0.20

To achieve satisfactory result, some optical and electrical methods should be used. For optical methods, the acoustooptic modulator is used, with the modulating frequency of 40 MHz to enhance the abilities of anti-jamming and restraining noise; the 1/2 wave plate can make the intensities of the two diffraction beams of the acoustooptic modulator equal; all the lenses are coated to increase transmission and all the reflectors are coated ($R > 99.9\%$); the big aperture lens is used to receive light signals; the B-GJ3 PIN photo-electric receiver of high sensitivity and low noises is used to do photoelectric conversion. For electrical methods, a lock-in amplifier is adopted to pick signals (Δf); a digital filter is applied to the digital signals obtained from sampling and A/D conversion; especially a homomorphic filter is used to reconstruct the lost signals resulted from the influences of surface texture structures; finally the pulses are subdivided and counted. The whole course of signals processing is shown in Fig. 3.

In fact, we apply above system to measure the in-plane displacements of common paper (the displacements are controlled by the leading screw driving system of a measuring microscope; the power of laser is 15 mW), and the experimental results are listed in Table 1.

The displacement error

$$\sigma(X) = \sqrt{\frac{1}{n-1}}\left(\sum_1^n V_i^2\right)^{\frac{1}{2}} \approx 0.39,$$

$$\frac{\sigma(X)}{\overline{X}} \times 100\% \approx \frac{0.39}{40.48} \approx 0.96\% \approx 1\%.$$

The experimental result indicates that the Doppler differential optical system is vital to obtain simultaneously high SNR and measurement accuracy, and it is the best optical system for in-plane remote displacement measurement at present. When it is used for the in-plane displacement measurements of common paper in distance of 50 m, the results are satisfactory.

S. He's e-mail address is jllyy76@sina.com.

References

1. X. Hong, S. Z. He, C. Z. Jiang, and L. C. Chen, Acta Optica Sinica (in Chinese) **20**, 11 (2001).
2. L. E. Drain, *The Laser Doppler Technique* (in Chinese) (Tsinghua University Press, Beijing, 1980) p. 105, p. 137.
3. B. K. Zhou, Y. Z. Gao, and J. H. Chen, *Principles of Laser* (in Chinese) (National Defence Industry Press, Beijing, 1980) p. 349, p. 357.