Study on a reference optical system applied to the outline loss measurement of complicated three-dimension object

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In this paper, laser Doppler reference optical technique is studied, and an optical system with high resolving power which is applied to longitudinal displacement measurement of complicated 3-D object is brought forward. Structure of the measuring optical head is designed reasonably. The experiments prove that the new-type reference optical system can achieve the outline loss measurement of object with the relative error of 0.3%.

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With the rapid development of technology, there is increasingly interest in the outline loss measurement of complicated 3-D object and the longitudinal displacement or vibration measurement of object in small space. Now laser Doppler technology has achieved to the longitudinal displacement measurement[1] for precision gauge successfully. But utilizing this method, a light spot with diameter about 2 mm illuminated in the measured mobile surface (such as shining metal surface), which has low space resolving power, cannot resolve the measurement problem for nonmetal revolving object loss and its subtle structure. Therefore based on study of laser Doppler reference optical technique, practical reference optical system and corresponding measurement system are designed. The experiment proved that the results are satisfied when the system is applied to the loss measurement of special shape object.

The measurement optical system of surface loss of special shape object is shown as Fig. 1. The laser beam of frequency f_0 enters the acoustooptic modulating 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 $(f_0 - f_c)$. The 0 order diffracted light is focused by L_1, L_2 and turned into the circular polarized light passing 1/4 wave plate G_2. The circular polarized light is converged on the surface of revolving object M (or on the hole) with very small diameter and scattered. After passing G_2, L_2, L_1, and M_2, it is turned into the linearly polarized light, of which polarizing direction is changed 90° to the 0 order diffracted light. The linearly polarized light (being parallel polarized light to prism R, expressed as P) enters and passes along the same propagation direction of the polarized prism R, together with the -1 order diffraction light (being vertical polarized light to prism R, expressed as S) which is reflected by M_1 and M_5. In the end, they pass M_3, M_4, G_3 and R, two polarized vectors (S'_P, P'_P; P'_S, S'_S (S', P' to R); $|P'_P = P'_S|$, $|S'_S = S'_P|$) are obtained respectively in the transmission and reflecting direction of prism R, among which the change of light vibration directions are shown as Fig. 2 after passing 1/2 wave plate G_3 (at the moment, the angle between the fast axis of G_3 and the -1 order diffraction light vector S is 22.5°), and then each of them is converged on the photosensitive surface of photoelectric receiver E_1, E_2 by L_3 and L_4, respectively. After the differential amplifier, the signal of frequency $(f_c + \Delta f)$ is input into lock-in amplifier with the reference signal of frequency f_c to pick up the Doppler frequency shift signal Δf. Adjusting the 1/2 wave plate G_1 can make the intensities of the two polarized components to be nearly equal ($|P'_P| = |S'_P|$, $|S'_S| = |P'_S|$). In order to make installation and adjustment easier, He-Ne laser with coherence length larger than 2 m is used for light source.

According to the laser Doppler effect[2], for the reference optical system shown as Fig. 1, when the object revolves the position where each point of its surface hole is illuminated by light, the longitudinal displacement will appear along the optical axis of the system and then lead to the Doppler shift of light. If $\theta_1, \theta_2 \leq 1.5°$,

$$\Delta f = \frac{v}{\lambda}(\cos\theta_1 + \cos\theta_2) \approx \frac{2v}{\lambda}, \tag{1}$$

where v is the variational speed of the longitudinal dimension of the hole or the displacement speed in its

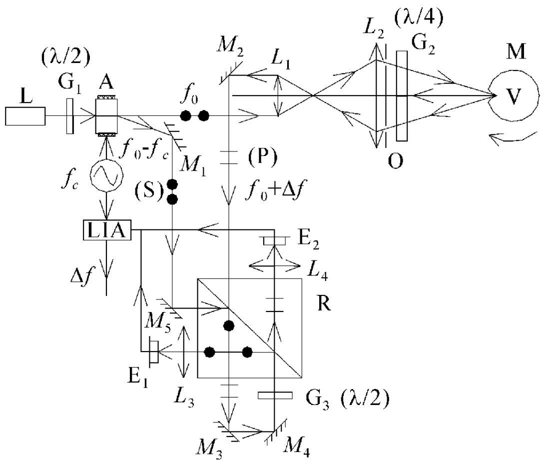

Fig. 1. Optical measuring head.

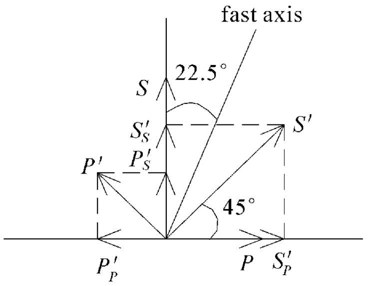

Fig. 2. Polarization resolution.

longitudinal; θ_1 and θ_2 are the angles included between the incident ray or the scatter ray with speed direction of the longitudinal displacement, respectively; λ is the wavelength of the laser (0.6328 μm). By means of counting the number N of pulses of the picked Doppler signals, the maximum distortion dimension or longitudinal displacement (x) of the hole is described as

$$N=\int_0^t \Delta f \mathrm{d}t=\int_0^t \frac{2v}{\lambda}\mathrm{d}t=\frac{2}{\lambda}\int_0^5 v\mathrm{d}t=\frac{2x}{\lambda}, \tag{2}$$

therefore,

$$x=\frac{N\lambda}{2}. \tag{3}$$

The displacement measurement values only have relation to the count of pulses recorded and have nothing to do with the longitudinal displacement speed and its changes. Therefore, applying this method to outline loss measurement of object is very convenient.

In fact, to achieve pulses counting the signal should be process firstly, i.e. a digital filter is used to filter the digital signal after sampling and AD conversing to the picked Doppler signals, finally through shaping, subdividing and counting pulses, the longitudinal displacement (or depth) of the object (in hole) is obtained.

The essential point of calculating the structure parameter of the reference optical system lies in the measuring head composed of L_1, L_2. Because its parameters have relation to the installation, adjustment of the measured object and signal noise ratio or measurement accuracy, measurement range. These parameters are mutually restricted (the conclusion can be proved through following calculation and analysis), therefore it is important to design reasonable parameters. The measuring head (L_1-L_2) of the optical system is shown in Fig. 3.

According to above consideration, the technique requirements of measuring head are brought forward: diameter of focal spot $2w'_{20}$ is 0.05 mm; work distance l'_2 is 250 – 270 mm; defocal value $\Delta l'_2$ (or Z'_2) is about 0 – 3 mm.

Supposing diameter of the light spot of the incidence Gauss beam lighted on the lens L$_2$ is about 2 mm, the focal length F_1 of the lens L$_1$ 10 mm, and eliminate the spherical error, in that case the waist radius[3] of the focused light is described as

$$w'_{10}=\frac{F_1\lambda}{\pi w_1(l_1)}\approx\frac{10\times 0.6}{3\times 1}=2(\mu\mathrm{m}).$$

The corresponding common focal parameter is

$$f'_1=\frac{\pi(w'_{10})^2}{\lambda}=5\times 2^2=20(\mu\mathrm{m}).$$

It is obvious that if the radius of focal spot is very small, it must require less focal length lens, then the work distance and displacement value are reduced too, vice versa.

Taking the size of focal spot, work distance and the displacement value into consideration, and ensuring Brewster's incidence of prism R ($f_2=f'_1\ll|x_2|$), supposing the focal length F_2 of the lens L_2 equals 20 mm (eliminate the spherical error) and the crosswise amplifying rate β_2, according to geometrical optics (because f_2 or w_{20} is very small)[3]

$$\begin{aligned}x_2&=F_2/\beta_2=20/12\approx 1.6(\mathrm{mm}),\\ x'_2&=\beta_2\cdot F'_2=12\times 20=240(\mathrm{mm}),\\ l'_2&=F'_2+x'_2=20+240=260(\mathrm{mm}),\end{aligned}$$

where x'_2 is the distance between the waist and the focus of L_2 in image space, l'_2 the image distance of waist, and the waist radius in the image space of lens L_2 is described as

$$w'_{20}=\beta_2\cdot w_{20}=\beta_2\cdot w'_{10}=12\times 2=24(\mu\mathrm{m}),$$

focal spot depth

$$\begin{aligned}&2Z'_2=2f'_2=2\pi(w'_{20})^2/\lambda=5760(\mu\mathrm{m})\approx 5.8(\mathrm{mm}),\\ &w'_2(Z'_2)=\sqrt{2}w'_{20}\approx 34(\mu\mathrm{m}).\end{aligned}$$

From above we can see that when the hole dimension of the revolving object is changed 2 mm along the longitudinal, the size of the focal spot and the incidence light direction of polarized prism R do not change a lot.

Following, the structure parameters of the double-circular aperture diaphragm (O) are analyzed and calculated. For receiving more accurate Doppler signals, the diaphragm is set in the measuring head, which is shown as Fig. 3.

From Fig. 3, $\tan\Delta\theta_2=\frac{\phi}{l'_2}$ ($l'_2=260$ mm), supposing diameter of the diaphragm

$$\phi=2F_2w_1(l_1)/F_1=4\mathrm{mm},$$

then

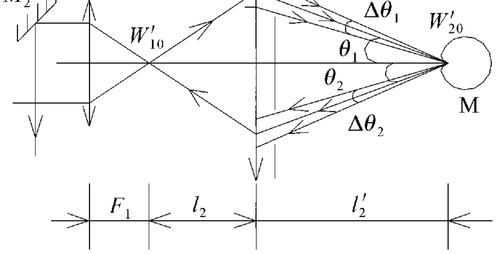

Fig. 3. Structure of optical head.

$$\Delta\theta_1 \approx 1^\circ \approx \Delta\theta_2,$$
$$\cos\Delta\theta_1 = \cos\Delta\theta_2 = \cos 1^\circ = 0.9998 \approx 1.$$

Therefore from Eq. (1) the Doppler frequency shift $\Delta f \approx 2v/\lambda$.

It is obvious that the error arose from the designed double-aperture diaphragm or different directions of incident ray and scatter ray for the Doppler frequency shift (Δf) can be neglected and the above parameters supposed are reasonable. But the arrangement of the double-circular aperture diaphragm decreases intensity of the received scattering light. Therefore, in order to make full use of the scattering light that passes the diaphragm, the wave plate G_1-G_3, polarized prism R, lenses $L_3 - L_4$ and photoelectric receiver E_1, E_2 with low noise and high sensitivity are used in the system, especially lock-in amplifier is adopted to ensure the pick of Doppler signals in the circuit.

Utilizing reference optical system with high resolving power (displacement 2 mm, diameter of light spot is about 50 μm) designed as above, when the intensity ratio of the 0 order and the -1 order diffracted light is 10 : 1 through adjusting 1/2 wave plate G_1, photoelectric signal of high signal noise ratio can be obtained. The photoelectric signals are transformed to Doppler voltage signals after passing lock-in amplifier, the voltage signals are sampled and are input computer to be processed (including A/D conversion, digital filter, waveform subdividing, pulses count and displacement display and so on). The 3D object that placed in the distance of 260 mm and has loss in the surface is measured. Its surface is Gauss type revolving curved surface and there is a hole (depth 2 mm, area 3 mm^2) near the middle waist. The measured depths of the hole are listed in Table 1.

Table 1. The Measured Depth Values of the Hole ($\overline{X} \approx 2001$ μm, unit: μm)

X_i	ΔX_i	ΔX_i^2	X_i	ΔX_i	ΔX_i^2
2010	9	81	1997	−4	16
2007	6	36	2002	1	1
2008	7	49	1998	−3	9
1994	−7	49	2003	2	4
1990	−11	121	2005	4	16

$$\sigma(X) = \sqrt{\frac{\sum_1^n \Delta X_i^2}{N-1}} = \sqrt{\frac{382}{9}} \approx 6(\mu\text{m}),$$
$$\frac{\sigma(X)}{\overline{X}} \times 100\% \approx \frac{6}{2001} \times 100\% \approx 0.3\%.$$

The experimental results prove that the relative error of longitudinal displacement are satisfied.

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