Structure Design of A Laser Confocal Probe For Measuring the Micro-Sphere

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Abstract. To achieve the aim of precise position measurement of a target micro-sphere, approximately 0.2mm in diameter, a laser confocal probe, on an active focus adjusting principle, was introduced in this paper. For finding the effect way to improve the output signal, a mathematical modal of the photoelectric signal was proposed. Based on the mathematical modal, the diameter of the pinhole was decided and the optical path was adjusted, which forward the performance of the probe. The tuning fork stimulating, inductive coils and the pinhole adjuster device were designed according to the theoretical analysis, which were more convenient to the measure task. The stability of the intact oscillating unit was tested; and the optical and mechanical performance of the probe was validated by experiments using gage blocks combining with a calibrated micro-driven table. Besides, a more accurate signal processing method was suggested in this paper.

1. Introduction
Inertial confinement fusion, often referred to as ICF, inertial fusion or laser fusion, is means of producing energy by imploding small hollow micro-spheres containing thermonuclear fusion fuel [1]. The goal of ICF research is to simulate the controlled laboratory implosion of fusible material to a condition of ignition and burn. The micro-sphere capsule is the key element in the ICF system. In order to improve the motivation energy and transition efficiency of the ICF, a large number of laser beams are required to aim at the capsule simultaneously. The capsule is very small in diameter, about 200 micron [2]. The surface finish is in order of 10 nanometers [1]. Position measurement of the target micro-sphere must rely on a non-contact probe with a high performance-price ratio.

Optical non-contact probes have the advantages of no measuring force, high speed, etc [3]. Most of the optical non-contact probes have lower accuracy than contact ones. Because surface conditions including color, surface roughness, and inclination affect greatly on the accuracy of the probe [4]. Although out-of-focus probes have very high sensitivity near the focus, they have tiny measuring ranges [5-7]. Comparing with the traditional out-of-focus probe, the dynamic active confocal measuring instrument has high accuracy, wide measurement range and good dynamic performance. More important, it is suitable for measuring high reflective surfaces, such as high-accurate metallic and optical pieces [8]. The laser confocal probe is used here to catch the position of the spherical capsule.
2. Working principle

2.1. Principle of the confocal probe

Figure 1. Working principle of the confocal probe based on time difference measurement.

Figure 2. Relationship between the oscillation of the tuning fork and the variation of the position of the focusing point.

Figure 1 shows that a laser beam emitted from light source 1 is focused on surface 8 by lens attached to a tuning fork. The beam returned from measured surface 8 is reflected by beam splitter 2 and focus on pinhole 3. This means the surface 8 and the pinhole 3 are on the positions of conjugate foci of the whole optical system. Movement of the surface 8 can simulate different position to the object measured. Detector 4 transforms the light signal to an electric one. Oscillating tuning fork 5 is used to modulate the focal position of the optical system. A peak signal is formed on receiving element 4 while focal plane coincides with surface 8. In figure 2, while the tuning fork is oscillating, the focusing point moves accordingly. So the variation of the position of the focusing point \( \Delta' \) will be determined by the displacement of lens \( \Delta_o \). Here we can use the equation (1) to describe it [8].

\[
\Delta' = \frac{f_2 \Delta_o}{2\Delta_x^2 - (f_2 + f_1 - b)\Delta_o + f_2^2} + \Delta_o
\]  

(1)

where \( f_1, f_2 \) —— Foci of \( L_1, L_2 \), respectively, \( b \) —— Distance between the two lens when they are static. Because of \( \Delta_o \ll f_1, \Delta_o \ll f_2 \), the equation (1) could be written as:

\[
\Delta' = 2\Delta_0.
\]  

(2)

By virtue of poisons 3 and 8 (see figure 1) are at two conjugate foci of the whole optical system, the variation of position 3 could also be described like equation (1). Assuming the oscillating equation of the lens is,

\[
\Delta_o = A \sin \omega_0 (t + t_o)
\]  

(3)

where \( A \) —— Amplitude, \( \omega_0 \) —— Frequency, \( t_o \) —— Original phase, \( t \) —— Change of the phase. The original position of the probe is the balance position of the oscillating period, which could also be called reference position, so \( t_o = 0 \). Insert equation (3) to equation (2), we could obtain the oscillation function of the focusing point:

\[
\Delta' = 2A \sin \omega_0 t
\]  

(4)

During one period of the oscillating, the focusing point passes through the pinhole twice, which will cause the light-receiving element 4 to output two peak-signals. To calculate variation of the time-interval of these two peaks, we could obtain the relative position of the measurement surface to the reference surface. The following section will show the forming process of these two peak signals.
2.2. Mathematical model of the pinhole and light receiving units
As shown in figure 3, the light was appropriately focused on the pinhole with energy $I_0$. Assuming that the diameter of the light on the pinhole was $d_p$, diameter of the pinhole was $d$ and diameter of the focusing point was $d_k$. When the diameter of the focusing point on the pinhole was larger than $d$, the receiving energy of the detector at this time was expressed as:

$$I_1 = I_0 \frac{d^3}{(d_p)^3}$$

(5)

When the tuning fork oscillates to one position, the focusing point will also move to one position, the dashed ellipse in figure 3. The displacement of the two positions was $S$. So, the variation of the radius of the optical point on the pinhole was $\Delta d_p$,

$$\Delta d_p = s \times \text{ctg} \alpha$$

(6)

where $\alpha$ ——— Complementary angle of the incident angle. So, energy that the detector received was:

$$I_1 = I_0 \frac{d^3}{(d_p + 2s \times \text{ctg} \alpha)^3}$$

(7)

Assuming $s$ was the displacement of the focusing point after $\Delta t$, from equation (4), we can get the following function:

$$I_1 = \frac{d^3}{(4A \times \text{ctg} \alpha \times \sin \omega \Delta t + d)^3} I_0$$

(8)

Here, we used software to simulate equation (8). Apparently, parameters $\alpha$ and $d$ were crucial to the qualities of the output waves. The parameters were set as follows, $d=0.02\text{mm}$, $A=0.01\text{mm}$, diameter of the lens 10mm, focus 30mm. The average frequency of the oscillating unit was 343.5Hz. $\omega = 2\pi f = 2\pi 343.5$, where $f$ ——— Oscillating frequency of tuning fork. $I_0 = 1$. Matlab simulation result is shown in figure 4.

3. The design of mechanical and optical structure
The sketch map of the probe is shown in figure 5, including pinhole and photo-electrical detector adjuster, tuning fork (made of 5J53 constant elasticity alloy and experienced heat treatment); and lens GCL-010613 achromatic- doublets, which had little spherical aberration for its characteristics. The laser source of the probe was a semiconductor laser, with central wavelength 650nm, output power 7mw; and the receiving element Si PIN photodiode GT101. A pinhole, 0.02mm in diameter, was singled out basing on the above mathematical model analysis.
It must be emphasized that, considering the difficulty of adjusting the focusing, we adopt the method of integrative structure with the pinhole and detector combined in a three-dimensional adjustable device, with a two-dimension adjustable scope ±1.5 mm and adjustable accuracy 0.005mm. In fact, the light energy is so tiny for the reason of light splitting and tiny size of the pinhole that the signal noisy must especially be noticed. The detector may be assembled directly behind the pinhole; almost all the light signals can be received by the detector. As long as the beam is appropriately in the center of the work area of the detector, the measurement can be perfect. And the filter should be mentioned for its utility to eliminate the beams beyond or less than 650nm wavelength. Besides, the oscillating unit here was driven by solenoid coils (see figure 5), with the stimulant coil diameter 0.07mm, 1600 loops and the inductive coil diameter 0.04mm, 3500 loops. It could be found that the bigger the diameter of the coil was, the stronger the electromagnetic suction was, and the more the loops were, the stronger the inductance was [9].

4. Experiments and results

4.1. Stability of the oscillating unit

As the intrinsic frequency of the tuning fork has changed the value of \( d\omega_0 \), the time error induced is,

\[
\Delta t = -\frac{1}{\omega_0^2} \arcsin \left( \frac{\Delta w}{A} \right) d\omega_0
\]

When the change of the tuning fork swing aptitude is \( dA \), the time error is,

\[
\Delta t = -\frac{\Delta w}{\omega_0 A \sqrt{A^2 - \Delta w^2}} dA
\]

From the above equations (9) and (10), assuming that the oscillating frequency increases, the time error \( d\cdot t \) brought by the frequency and aptitude instability will be decreased; the time error induced by the oscillating fluctuation will increase sharply as the displacement of the oscillating lens is close to the aptitude. So the oscillating stability of the lens and the choice of the measurement scope are crucial [8]. We can calculate that the time error \( \Delta t_{\text{max}} \) was divided by one half of the tuning fork oscillating period, obtaining the value \( 4.1 \times 10^{-5} \), which can be ignored.

4.2. Analysis of the output wave

In order to simulate the task of micro-sphere capsule position measurement, we used the gage block combining with a calibrated micro-driven table, with the ratio of horizontal to vertical displacement is 50:1 and resolution 0.2μm. So, the vertical displacement of the gage block could feasibly simulate the micro-sphere, approximately 0.2mm in diameter. From the output waves, the actual photoelectric signal change in the measurement scope can be described clearly. The change of the balance place (the focusing spot appropriately covered the pinhole) and the fringe (hump signal) can be distinguished.
Certainly, the surface finish is important to the operation of the instrument. In the experiment, we set the reflectivity of the gage blocks close to that of the micro-sphere capsule. Favorably, the actual output waves coincide with the mathematical model. Using pinhole 0.02 mm in diameter, the photoelectrical output waves were steep, which was beneficial to measure task.

In figure 6, image a represented the balance place of the photoelectric signal, which the focusing spot appropriately covered the pinhole; images b, c denoted the output waves when the micro-driven table were set to the corresponding positions. And images d and e had the corresponding relationships with positions on the gage blocks. The images c and e described the two peak value signals respectively in two halves period of one period had combined, and they was useless to our measure task.

5. Discussion
After we obtain the signals of the oscillating tuning fork and photoelectric signals, the method of time difference was used to obtain the further result of the displacement. In figure 7, three comparators are adopted; comparator 1 will finish the measurement of the tuning fork oscillating period; in order to obtain four groups of time difference data, comparator 2 and 3 will form a window comparator to process signals. The average time difference value $\Delta t'$ can be obtained in equation (11):

$$\Delta t' = \frac{\Delta t_1 + \Delta t_2 + \Delta t_3 + \Delta t_4}{4} \quad (11)$$

$$\Delta t = \frac{\frac{T}{4} - \Delta t'}{2} \quad (12)$$

where $T$ —— Oscillating period of the tuning fork, while the others denote the difference phases (see figure 7). $\Delta t$, the time difference in equation (12), is what we required. We used the ultrafast 4 ns single supply comparators AD8612 as the comparator 2 and comparator 3 and AD8611 as the comparator 1. This method saves the cost of a displacement sensor [10] to detect the position the oscillating tuning fork and then obtain the signal of the objective position. The comparators output waves in figure 8 will be processed by the processing circuit based on FPGA (field programmable gate array) to obtain the time difference. In actual measure task, we should measure several points on the micro-sphere capsule and then set coordinates to obtain the position of it.
6. Conclusion

- Structure design of the laser confocal probe is proposed based on mathematical model;
- An approving mechanical and optical performance of the probe was tested by using gage blocks combining with a calibrated micro-driven table;
- A low-cost confocal probe based on time difference measurement is developed, with actual output waves coincides with the mathematical model ones.

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