Designing an optical set-up of differential laser triangulation for oil film thickness measurement on water

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Based on the differential laser triangulation principle, an optical system configuration for measuring the oil film thickness on water is designed and developed. A semiconductor laser of 650 nm wavelength with the maximum power of 5 mW is used as a light source, the magnification of the imaging system is 1.4; the range of the measurement is 0.1 mm–10 mm; the resolution is 2.3 μm and the measurement accuracy is 10 μm theoretically. Experiments are conducted with block gauges and feeler gauges, and the experimental results, with absolute error less than $\pm 25 \mu\text{m}$ and the maximal measurable thickness 12 mm, indicate that this system presented in this paper can fulfill high accuracy.

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I. INSTRUCTION

As petroleum is increasingly exploited at sea and transported by sea, oil spill is becoming a serious problem in the world due to its severe impact on environment, economy, and so on, so the detection and quantification of oil-on-water thickness is a very practical issue. With knowledge of the oil slick thickness, more effective schemes can be chosen to deal with oil spill. Several methods based on different principles have been proposed so far.^{1–12} For example, Abdul-Wahab¹ adopted on a method of measuring the thickness of the oil layer in seawater based on the difference of electrical conductivity between oil and seawater. Patsayeva *et al.*² proposed a method of measuring the oil film thickness by using the water Raman signal suppression of different oil films. In the case of Reddyhoff *et al.*,³ an ultrasonic pulse was projected onto an oil film, and then by exploring the phase shift of the reflected wave, the oil film thickness was obtained. In Brown's research,⁴ a Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor was developed to acquire the oil film thickness by calculating the time-of-flight of ultrasonic waves in oil. And Byfield and Boxall⁵ carried out the measurement of oil spill by using the peak of near-infrared radiance ratio. More recently, our research team^{10,11} proposed an optical method based on differential laser triangulation for measuring the thickness of oil film in the sea surface. The paper is intended to design the optical geometrical configurations of an airborne disposable cast. Relevant theory is analyzed in details; the experimental system setup is developed; the experiment is then performed with block gauges and feeler gauges and the research results are given.

II. PRINCIPLE

A diagram of an optical system for measuring oil film thickness on water with differential laser trigonometry, as shown in Fig. 1, consists of two optical subsystems: the upper optical system, as shown in Fig. 1(b), and the lower optical system, as shown in Fig. 1(c). In Fig. 1(b), a laser beam, converged by lens and focused, casts to point *S* of the upper

surface of oil film with an angle of incidence α , then the reflected/scattered light from point *S* is imaged by an imaging lens and an image spot forms on the CCD. In Fig. 1(c), laser light is focused by lens and incident to point *A* on the air-water interface at an incident angle θ , the refraction light *AB* is obliquely incident to point *B* on the water-oil interface, and the imaging lens collects part of light scattered or reflective light from point *B*, through or reflected to point *B'* of the lower surface of the oil film to image spot on CCD image plane. The imaging plane and the optical axis of the laser beam are vertical to the optical axis of the imaging lens. The marked line *MM* in Fig. 1 is the benchmark plane that is a virtual one and can be chosen arbitrarily theoretically. From the geometry of Fig. 1, oil film thickness *d* on water is given by^{10,11}

$$d = d_1 - d_2, \quad (1)$$

$$d_1 = \frac{(u - f)h_1}{f} \cos \alpha, \quad (2)$$

$$d_2 = \frac{(z - f)\sqrt{n_1^2 - n_0^2 \sin^2 \theta}}{n_0 f} h_2, \quad (3)$$

where, d_1 and d_2 are the displacements from point *S* and point *B* to the reference planes *MM*, and the directions are indicated by an arrow, h_1 and h_2 represent the corresponding displacements of the image spot on the image plane, respectively, u and z are the object distances of the upper optical system and the lower optical system, f is the focal lengths of the imaging lens, n_1 and n_0 are the refractive indices of water and air, respectively.

III. DESIGNING THE OPTICAL SYSTEM

An optical system intended to be compact is designed to measure oil film with the thickness of the 0.1 mm–10 mm and the measurement absolute error is aimed at 0.01 mm. To meet the above requirements, a semiconductor laser with the power of 0–5 mW and the wavelength of $\lambda = 650 \text{ nm}$

FIG. 1. Schematic of oil film thickness measurement by differential laser trigonometry: (a) the integrated optical system, (b) the upper optical system, and (c) the lower optical system.

is used as a light source. At the distance of 45 mm–75 mm from the aperture of laser, the laser spot diameter ranges from 0.5 mm to 0.3 mm. In order to cast a smallest laser spot diameter (0.5 mm–0.3 mm) on the oil film surface, let the distance between semiconductor laser and the incident spot on the oil surface be 45 mm–75 mm. The imaging lens is Nikon lens with the focal length $f = 50$ mm and the aperture $D = f/2.8$. The CCD is a linear CCD (TCD1707D) with 7450 pixels and the pixel size of $\Delta x = 4.7 \mu\text{m}$.

A. Calculation of magnification

In Fig. 1, the lens images the laser spot reflected on the oil surface on the CCD, the magnification β of the imaging system in air is $\beta = v/u$, where v is the image distance between imaging lens and CCD, u is the object distance between imaging lens and laser spot on the oil surface. β can be changed by adjusting either or both of the object and image distances of the imaging lens.

1. CCD resolution limitation

According to error distribution principles,¹³ to acquire the measuring accuracy of $10 \mu\text{m}$, the resolution ε of each optical system is at least $\varepsilon = 10/\sqrt{2} = 7.07 \mu\text{m}$. From Eq. (2), we obtain $\Delta d_1 = \Delta h_1 \cos \alpha / \beta$, namely, $\varepsilon = \Delta x \cos \alpha / \beta$, where $\beta = fl/(u - f)$ is the magnification and $\alpha = 45^\circ$; then, these equations can be combined to give out the $\beta = 0.47$. To achieve high accuracy, based on empirical formula of the instrument design, the resolution to be taken is usually $\varepsilon/3$,¹⁴ so we get a typical magnification $\beta = 1.410$.

2. The field range limitation

To measure the thickness of the oil film ranging from 0.1 mm to 10 mm, it is obvious that the upper optical system and the lower optical system in Fig. 1 should be capable of measuring the maximum measurable thickness of at least 5 mm. For the CCD chosen, with the angle of incidence $\alpha = \theta = 45^\circ$, using Eq. (2), where $h_1 = 7450 \times 4.7 \mu\text{m}$, we can obtain the maximum $\beta = 4.95$.

3. The lens resolution limitation

According to Rayleigh principle,¹⁵ the resolution of the imaging system $\varepsilon = 1.22f\lambda/D$ should match the pixel size Δx of CCD,¹⁶ whose relation can be expressed as $\varepsilon = \Delta x / \beta$; the magnification can be calculated to be $\beta = 2.12$ for our optical system.

In terms of the limitation above, the range of magnification should be 0.47–4.95. Figure 2(a) shows a relation between the resolution and the magnification; when $\beta = 1$, the resolution ε is $3.323 \mu\text{m}$; when $\beta = 1.4$, the resolution $\varepsilon = 2.374 \mu\text{m}$; when $\beta = 2$, $\varepsilon = 1.664 \mu\text{m}$. As can be seen from Fig. 2(a) that the larger a magnification is, the higher a resolution can be obtained. However, the size of the focused light spot is affected by the magnification β ; Fig. 3 shows the images of the light spots for

FIG. 2. The relation between resolution ε (a) and the conjugate distance L' (b) and magnification β .

$\beta = 1$, $\beta = 1.4$, and $\beta = 2$, respectively. Because of various optical distortion parameters and external stray beams, the laser spot imaged on the CCD becomes none ideal Gaussian beam. When the magnification of imaging system becomes larger, the noise and the non-uniformity of the laser spot are magnified accordingly. When the magnification becomes smaller, less pixels of the CCD are taken. Thus, the beam focuses on the center of the light spot, and the noise becomes less significant as seen in Fig. 3. It is observed in Fig. 3 that the light spot is not an ideal Gaussian intensity profile with increasing magnification β . The smaller the size of the light spot is, the higher the precision of the center or centroid of light spot is extracted; so a low magnification is better.

In addition, the size of the optical system setup is related to the magnification. For a single optical system in air, the light path satisfies the following relations:

$$\begin{cases} \frac{1}{u} + \frac{1}{v} = \frac{1}{f} \\ u + v = L' \\ \frac{v}{u} = \beta \end{cases} \quad (4)$$

where, the conjugate distance $L' = f \cdot (\beta + 1)^2 / \beta$. Figure 2(b) shows the conjugate distance L' as a function of the magnification β . For the magnification β from 0.5 to 2, the conjugate distance L' is less than $4.5f$; when $\beta = 1$, $L' = 200$ mm; when

$\beta = 1.4$, $L' = 205.7$ mm; when $\beta = 2$, $L' = 225$ mm. So $\beta = 1$ is better for a compact structure of the equipment.

To meet the resolution, the conjugate distance and the measuring accuracy demands, we carry out the experiments of different magnification β using block gauges and feeler gauges of different thicknesses, instead of the oil film. According to function (4) $\beta = v/u$, by changing the object distance and image distance the magnification is changed. The experiment results are shown in Fig. 4 for the objects being measured of 0.1 mm, 5.3 mm, and 9.3 mm in thickness. In Fig. 4, the standard deviation is less than 0.028 mm in the $2 \times$ light path, 0.022 mm in the $1 \times$ light path, 0.015 mm in the $1.4 \times$ light path; the average absolute error is less than ± 0.019 mm for $\beta = 2$; ± 0.057 mm for $\beta = 1$; ± 0.006 mm for $\beta = 1.4$. As a result, we choose a magnification $\beta = 1.4$. Using Eqs. (2) and (3), the resolution of the upper optical system is $2.4 \mu\text{m}$, and $3.9 \mu\text{m}$ for the lower optical system.

B. Geometrical system

After choosing the magnification $\beta = 1.4$, with Eq. (4), we get the object distance $u = 85.7$ mm and the image distance $v = 120$ mm. Then, an optical system is designed, which is a symmetrical structure for the upper system and the lower optical system in the air. As the structural size required by the buoy in the horizontal direction should not be greater than 200 mm, the total reflection prism of $25 \times 25 \times 20 \text{ mm}^3$

FIG. 3. The focused image in the different β : (a) $\beta = 1$; (b) $\beta = 1.4$; and (c) $\beta = 2$.

FIG. 4. The experimental results in the different β , the object thickness (a) 0.1 mm; (b) 5.3 mm; and (c) 9.3 mm.

and K9 glass are introduced (shown in Fig. 8), and the optical geometrical size is then decreased. Considering the refraction of water, the measuring range of the lower light path is changed. In Fig. 5, which represents the optical system under the water, given that the center of lens is denoted as point O , the optical axis of the imaging lens and the optical axis of the laser beam intersect at a point O' , and the horizontal spacing between O and O' is denoted by L . The laser beam is incident into the surface of air-glass with the angle of $\theta = 45^\circ$; the lens collects the reflected light, then $\varphi = 45^\circ$. Supposing $x'_2 = 12$ mm is the equivalent light path of the measurement range x_2 in the air, from the geometric relations we get $\gamma = 11^\circ$, $\varphi_1 = 51^\circ$, $\varphi_2 = 49^\circ$. And let be $L = 60.6$ mm, $x_3 = 13.3$ mm, using Eq. (3), the measurement range corresponding to the water is $x_2 = 17.9$ mm.

C. Relative position of the upper and lower optical systems

Physically, the method can measure any oil film thickness on water; however, the range of oil film thickness on water is limited due to the system parameter. The relative position of the upper and lower optical systems determines the range of the thickness to be measured. In Fig. 6, AA and $A'A'$ is the boundary of measurable area of the upper oil surface, and BB and $B'B'$ is the boundary of measurable area of the lower oil surface. The distance x_1 between AA and $A'A'$ planes repre-

sents the measurement range of the upper optical system, and when the air-oil surface (spot S shown in Fig. 1) in this area, the reflected/scattered laser spot of the surface can be imaged on CCD. In the similar way, the distance x_2 between BB and $B'B'$ planes is the measurement range of the lower optical system, when oil-water surface (spot B shown in Fig. 1) in this region, the laser spot on this surface can be detected by CCD. The measurement ranges of the upper and lower systems are partially overlapping. Assuming that the distance between AA plane and $B'B'$ plane is x . When the parameter x is fixed, the relative position of the upper and lower optical systems can be determined. The CC' plane is the waterline.

In this system, the oil films with the thickness of 0.1 mm–10 mm should be measured. When the measuring range of the upper surface x_1 and lower surface x_2 do not overlap each other, which means that the plane BB and $A'A'$ coincide, the position of the 0.1 mm oil film that can be measured should be fixed. In order to keep the upper surface of 0.1 mm oil film in the range of x_1 , and lower surface in the range of x_2 , the

FIG. 5. The lower optical system under the water.

FIG. 6. Schematic of measurement range of the optical system.

FIG. 7. The measurement range of oil film in different thickness, (a) thick oil film and (b) thin oil film.

oil should keep stable at the coincidence border of the ranges. Because of the impact of the wave on the water surface, it is hard for the oil to stay at one position, but we only can keep the oil in a certain ranges. So, in order to make the oil film measurable in a larger scope, the upper and lower optical path is designed to overlap each other partially, as can be seen in Fig. 6.

For the thick oil films of 5 mm–10 mm and the thin oil films of 0.1 mm–5 mm, as shown in Figs. 7(a) and 7(b), respectively. Supposing that m_1 and m_2 are the thicknesses of the thick oil film and the thin one, from the geometric relationship shown in Fig. 7, the measurable range is $\min(x - m_1, x_1, x_2)$ and $\min(x_1 + x_2 - x + m_2, x_1, x_2)$ for the thick oil and the thin one, respectively. In our system, let be $x_1 = 12$ mm, $x_2 = 17.9$ mm, the maximum measurable range is the range measurable for the oil film of 0.1 mm (see Fig. 7(b)), then $x = 18$ mm. The measurable range is 12 mm for the thin oil film of 0.1 mm–5 mm, and $17.9 - m_1 = 12$ –7.9 mm for the thick oil film of 5 mm–10 mm, respectively.

D. The optical system configuration

The optical system structure we designed is as shown in Fig. 8 of which the horizontal size is 174.9 mm. Obviously, it is a compact system and feasible. The maximal measurable thickness of the upper optical system is $x_1 = 12$ mm and the corresponding one for the lower optical system is $x_2 = 17.9$ mm. The glass thickness of the optical window is 3 mm; the CC' plane, namely, waterline in plane, is 25.3 mm from the upper plane of the lower optical window. For the 10 mm-thick oil film, the measurable range is 3.6 mm above waterline and 4.3 mm under waterline; for the 0.1 mm-thick oil film, the measurable range is 8.5 mm on waterline and 3.5 mm under waterline.

IV. EXPERIMENTAL RESULT

The experimental system setup for measuring oil film thickness on water as shown in Fig. 8 is developed, and experiments have been carried out in the laboratory. A block gauge or a feeler gauge is used as an object to be measured, instead of the oil film, whose upper surface is above the water and lower surface below the water. Laser beam is cast to the gauge surface, and the reflected light spots of surfaces are imaged on two CCDs. The centers of the two image spots are extracted by centroid method. In the centroid method, grayscale of each pixel is used to as weight, and by taking the weighted

average of all the pixel grayscale of image spot the center of the laser is extracted. The thickness can be calculated using Eqs. (1)–(3), the experiment results are shown in Tables I and II. The maximum deviation between the nominal value and the measured value is $\pm 25 \mu\text{m}$ and the standard deviation of the system is less than $31 \mu\text{m}$. The main reason why the accuracy is lower than the theoretical one is not the optical system designed but light spot image processing. The light spot here is not a good Gaussian intensity profile, and the error of the center of light spot extracted by centroid method is too large. The higher accuracy can be obtained by improved image spot extracted algorithm, which has been proven by present study.

FIG. 8. Diagram of the optical system configuration (red-dashed line is the optical axis of the imaging lens, two blue lines denote the upper optical system and corresponding AA plane and $A'A'$ plane, and two green lines are the lower optical system and corresponding BB plane and $B'B'$ plane).

TABLE I. Thickness measurement results of 1.4 mm–9.4 mm block gauges (Unit: mm).

No.	Nominal value								
	1.4	2.4	3.4	4.4	5.4	6.4	7.4	8.4	9.4
1	1.431	2.438	3.422	4.407	5.407	6.432	7.411	8.416	9.399
2	1.428	2.429	3.428	4.408	5.402	6.410	7.420	8.406	9.405
3	1.431	2.425	3.424	4.402	5.400	6.429	7.412	8.405	9.397
4	1.402	2.424	3.425	4.400	5.432	6.435	7.408	8.414	9.409
5	1.432	2.418	3.419	4.403	5.429	6.405	7.411	8.415	9.418
6	1.425	2.415	3.418	4.402	5.402	6.437	7.412	8.424	9.411
7	1.425	2.392	3.419	4.397	5.409	6.407	7.415	8.406	9.414
8	1.432	2.382	3.419	4.393	5.408	6.437	7.407	8.403	9.420
9	1.429	2.387	3.423	4.398	5.423	6.429	7.406	8.404	9.410
10	1.379	2.374	3.411	4.419	5.398	6.427	7.409	8.409	9.407
Average thickness	1.421	2.408	3.421	4.403	5.411	6.425	7.411	8.410	9.409
Standard deviation	0.017	0.023	0.005	0.007	0.012	0.013	0.004	0.007	0.007
Absolute error	0.021	0.008	0.021	0.003	0.011	0.025	0.011	0.010	0.009

Therefore, we can confidently say that the optical system we designed in this paper can achieve high measuring accuracy and the method presented is also feasible.

V. CONCLUSION

We focus on the design of optical geometrical configurations of the differential laser triangulation for measuring the oil film thickness on water surface in this paper, and the experiment system setup is developed. With this optical system setup the block gauges and feeler gauges are measured and the measurement accuracy is basically achieved; the measurement range is 0 mm–12 mm, and the measurable range can be extended according to the actual requirement. The higher precision is obtainable by the improved algorithm of the image spot extracted, and further experiments such as on the mea-

suring accuracy, measurement range, and oil film thickness measurement are under investigation at present. This method and the optical setup promise a brilliant prospect.

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TABLE II. Thickness measurement results of 0.1 mm–0.5 mm feeler gauges (Unit: mm).

No.	Nominal value				
	0.1	0.2	0.3	0.4	0.5
1	0.099	0.227	0.294	0.407	0.423
2	0.106	0.180	0.301	0.427	0.483
3	0.127	0.197	0.307	0.381	0.462
4	0.145	0.192	0.322	0.357	0.494
5	0.088	0.171	0.284	0.427	0.517
6	0.108	0.224	0.288	0.412	0.498
7	0.120	0.176	0.297	0.434	0.473
8	0.100	0.202	0.306	0.415	0.525
9	0.111	0.200	0.324	0.413	0.525
10	0.077	0.177	0.286	0.430	0.500
Average thickness	0.108	0.195	0.301	0.410	0.490
Standard deviation	0.019	0.020	0.014	0.024	0.031
Absolute error	0.008	−0.005	0.001	0.010	−0.010

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