Liquid mirror direction reference in the measurement of laser direction

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Abstract. During the measurement of the direction of a laser beam, the direction reference is the key functional unit. A liquid mirror direction reference is proposed in this article for the direction measurement of laser beam. The material of this liquid mirror is oil silicon, and the stability and direction accuracy is studied by experiments. A laser-direction measurement system based on the silicon oil mirror is designed and the theory of the measurement is illustrated.

1. Introduction
In the measurement fields, the vertical laser beam has been widely used. In the construction field, a vertical laser beam is always adopted to measure the verticality of buildings. Moreover, the vertical laser can also be utilized in the precision measurement field to measure the precise displacement in the vertical direction. During the measurements, the vertical laser beam serves as a vertical direction reference. However, if the “vertical laser beam” is not perfectly aligned with the true vertical direction, there will be cosine error introduced into the measurement results, resulting in a significant uncertainty for precise measurements. To evaluate the cosine error caused by the direction imperfection of the vertical laser beam, there should be a precise direction reference applied in the measurement.

In this paper, a liquid mirror direction reference is proposed in this article for the direction measurement of laser beam. And a laser-direction measurement system based on the liquid mirror is designed.

2. Liquid mirror
2.1 Stability of the liquid mirror
The structure of the liquid mirror is simple. It simply consists of the liquid(silicon oil) and its bearing container (as shown in Fig. 1). Because of its good fluidity, the liquid mirror is susceptible to external influencing factors such as air turbulence and foundation vibration, resulting in the liquid losing stability and jitter. Based on the theory of hydrodynamics, the ability of liquid to resist external disturbance is inversely proportional to its fluidity. The weaker the fluidity is, the greater the viscosity coefficient of the liquid is, and the stronger the liquid resistance to the external disturbance will be.

The alcohol was generally chosen as the material of liquid mirror in the direction measurement experiments. Considering the bigger the liquid viscosity coefficient is, the stronger the liquid resistance characteristics of the external disturbance ability will be, a relatively larger liquid-viscosity liquid than ethanol, namely silicone oil, is chosen as the liquid mirror material in our experiment. The viscosity coefficient of silicon oil at 20°C is about 0.35Pa·s, while alcohol is only 0.002Pa·s at 20°C, which is 100 times smaller.
In order to understand the stability of liquid mirror with silicone oil as material, the short-term stability of silicone oil level mirror was investigated by experimental way, which is compared with alcohol level mirror. Under the same experimental conditions, a laser beam shoots to the liquid surface of silicon oil and alcohol, and the two reflected laser beams image in a charge coupled device (CCD). Hence the image of CCD can reveal the stability comparison of two liquid material shown in Fig. 2. It shows that the short-term variation amplitude of laser beam reflected by silicone oil is about 1.5 μm, which is much smaller than that of alcohol (about 5 μm) under the same external condition. Therefore, the stability of silicon oil much better and it is chosen as the material of the liquid mirror.

In addition, silicone oil at room temperature also has the characteristics of extremely slow-evaporation rate which is even negligible. This feature of silicon oil can guarantee the depth of the oil will not change after a long time. And the cleanliness of CCD will also not be influenced by the oil.

### 2.2 Direction accuracy of the liquid mirror

As the reference of the direction measurement of the laser beam, the direction precision of the liquid mirror (silicon oil) is the key parameter which is more important than the stability mentioned above. Due to the influence of liquid surface tension, adhesion between liquid and container and liquid weight, liquid surface cannot be a perfect plane in real situations. The surface tension of the liquid has the tendency to minimize the surface area of the liquid, and the adhesion, between the contacting surfaces of the liquid and the container, has a tendency to prevent the reduction of the area. For liquid water, the surface tension is less than adhesion, so the surface tend to "shrink" the liquid surface area (spherical under the same volume has the minimal surface area). Since the tension surface cannot overcome the adhesion and the gravity, the surface not arches to form spherical surfaces, but downwardly to form a concave surface as shown in Fig. 3 (a). On the contrary, if it is mercury, its surface tension is relatively large, it can overcome the weight and adhesion. Therefore, when mercury...
is placed in the container, the liquid surface will appear as the form of convex liquid surface, as shown in Fig. 3 (b).

![Fig. 3 Comparison of the different liquid surface shapes](image)

As a liquid, the silicone oil is also influenced by the surface tension (21nN·M⁻¹), adhesion and the liquid weight, so the surface of the silicon oil cannot be a perfect plane. In practice, it is a sphere. Only the geometric centre position of the silicon oil surface is equivalent to the horizontal surface. Out of the geometric centre position, the surface direction would be non-horizontal due to the curvature of the liquid surface.

The curvature of the sphere oil surface will cause the angle of the reflected light to be different when the incident beams arrive on the different positions of the liquid surface (shown in Fig. 4). If the angle difference is greater than the accuracy requirement of the direction measurement system, the direction uncertainty of silicone oil mirror would not meet the requirements of the measurement system, and cannot be used as a reference. Therefore, the surface directional characteristics of silicone oil mirror must be accurately observed.

![Fig. 4 Angles of the reflection laser will be different when the reflection position on the sphere surface of the liquid is different.](image)

### 3. Laser-direction measurement system

#### 3.1 Principle of the system

The measurement objective of the laser-direction measurement system is the deviation angle of the measured beam from the vertical. The principle and structure of the system are shown in Fig. 5. The system uses the silicon oil mirror as the horizontal reference. Through the optical path in the system, the vertical deviation angle of the measured light is converted to the dual-spot distance on the focal plane of a convex lens, where the charged couple device (CCD) will measure the spot distance. The measurement system can be divided into four functional units (A, B, C, D). The A unit is a laser beam preprocessing unit, which is composed of an adjustable aperture, a filter and a laser splitter. The function of A unit firstly is to adjust the incident-laser-spot diameter to 2mm so as to adapt it to the surface size of CCD; secondly the laser intensity will be weakened to 20-30μW in A unit which is in the best light intensity range of CCD; and finally the splitter splits the incident laser into two beams by 1:1, respectively traveling into the B unit and C unit. The B unit is a liquid level reference unit, which consists of the silicon oil mirror and corner cube reflector. The C unit is a reference measuring unit consisting of the corner cube reflector and a linear motion platform. This unit is to make the incident laser beam 1 mirror on the oil surface according to the normal line of the oil surface by being reflected on the surface of the liquid mirror. The C unit is a reference measuring unit consisting of the corner cube reflector 2 and a linear motion platform. This unit is to make the incident laser beam 2 be reflected by the cube corner prism 2 and return along the original direction, then comparing with the direction of the laser beam 1. The linear motion platform can carry the corner
cube reflector 2 along the vertical direction to compensate the angle error of the corner cube 2. The D unit is a laser-spot-location information acquisition unit, which is composed of a convex lens, a surface array charge coupled device (CCD) and a computer. The CCD is placed on the lens one-focal-length position and it transmits the laser-spot-location information to the computer.

Fig. 5 Setup of the system for measuring the direction of a laser beam to the vertical

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