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Communication

Simple and Efficient Non-Contact Method for Measuring the Surface of a Large Aspheric Mirror

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Abstract: A non-contact measurement method for measuring large aspheric surfaces with a laser tracker is proposed. Using an air-bearing probe eliminates the need to contact the optical surface and improves measurement efficiency and accuracy. Using this method, we measured the surface of an aspheric mirror 3 m in diameter and 13.6 m in the radius of curvature. The preliminary experimental result indicates that the error of surface measurement is 0.8 µm (RMS).

Keywords: optical metrology; laser tracker; large-scale measurement; non-contact measurement

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1. Introduction

Accurate measurement of the surface of a large optical mirror is often critical to the performance of the optical system. A variety of methods exists to measure the surface of a large mirror. The co-ordinate measurement directly measures the co-ordinates of surface points, which is significant for controlling the profile and geometric parameters of the mirror and is commonly used before deflectometry and interferometric testing [1–3].

Co-ordinate measuring machines (CMMs) are commonly used to measure an object's physical geometrical characteristics. A probe is driven with linear X-Y-Z stages and mechanically measures the Cartesian co-ordinates of an object. This method is not an in-situ measurement and is usually implemented on small mirrors [4].

A swing-arm optical co-ordinate measuring machine (SOC) is also a very useful metrology tool for testing aspheric mirror surfaces. The instrument is based on ingenious geometric principles. The probe trajectory lies on a spherical surface defined by the mirror's center of curvature. For measuring aspheric surfaces, the probe, aligned parallel to the normal to the optical surface at its vertex, reads only the surface departure from spherical. This type of profilometer's ability to measure in situ is a tremendous advantage; however, it needs careful calibration to improve its accuracy [5].

The laser tracker is widely used in optical shops for testing and alignment, mainly due to its flexibility, mobility, and convenience [6–9]. A laser tracker is essentially a portable co-ordinate measuring machine. It utilizes a laser interferometer (IFM) and two encoders to track and measure the sphere-mounted retro-reflector (SMR) position as it moves through space [10,11]. The tracker measures spherical co-ordinates instead of Cartesian co-ordinates, so it can provide a spherical reference within 1 µm, which is ideal for measuring concave primary mirrors since most of the interests are the departures from spheres.

Laser tracker surface measurement has been proved an accurate and effective way to guide asphering, loose-abrasive grinding, and initial polishing of large mirrors [12]. By using the scanning measurement method, the co-ordinates sampling time can be shortened to a few minutes, even for mirrors with a diameter of up to meters [13]. However, the method has three disadvantages: noise, friction, and centering error of SMR.

1. The SMR ball must constantly contact the mirror during scanning sampling. However, residual abrasive particles will break the contact between the SMR ball and the mirror surface, thus introducing measurement noise into the scanning profile.

2. Traditional contact scanning also exhibits some level of static and dynamic friction. The level of friction changes with surface roughness and cleanliness, and it can vary dramatically from grinding to polishing. Friction-wear of the SMR ball will result in obvious surface measurement error. Furthermore, the friction may lead to scratching of the mirror, which is unacceptable, so the scanning method is not an ideal choice for fine polishing or the finished mirror.
3. When the orientation of SMR varies during scanning, the centering error of the SMR will also be the main component of measurement uncertainty. Thus, the measurement process relies on the operator's operational experience.

To solve the problems, researchers have developed a Laser Tracker Plus system [14]. An air puck carries the SMR with three miniature flexible rubber air bearings that can glide across a polished surface without scratching. The SMR rests directly on the glass while tracker data are recorded. Air pressure is applied to lift the puck and SMR ~1 mm above the surface while the air-bearings remain nearly in contact with the glass. The puck slides to the next position with minimal force and slowly lowers the SMR to the surface as the air bleeds out. This system was established to guide loose abrasive grinding and initial polishing of the off-axis primary mirror segments of the Giant Magellan Telescope (GMT). However, it is too elaborate and less efficient for our purpose.

An easily reproducible method is demonstrated to solve the above problems without elaborate devices. The proposed method is accurate enough to be useful to anyone fabricating large optics and needing a safe way to assess the values of the geometric parameters and surface errors during grinding and initial polishing, be it for entrance quality control or troubleshooting a malfunctioning optical system.

2. Methodology

A non-contact probe was developed to co-operate with the laser tracker to scan and measure the large optical surface. As shown in Figure 1, the probe comprises a corner cube retroreflector, an air-bearing pad, the preload, and the air tube.

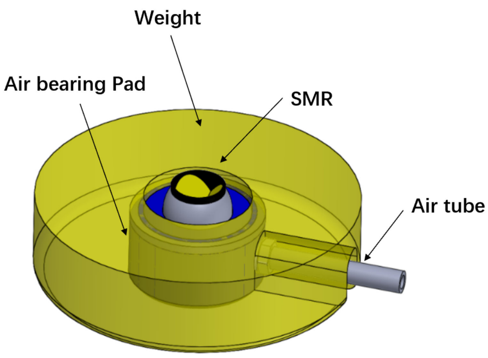

Figure 1. Schematic diagram of the non-contact probe.

A retroreflector is used as a co-operative target for co-ordinate measurement of the laser tracker, and it can be a corner cube retroreflector or an SMR.

An air-bearing pad is used to isolate the retroreflector from the testing surface. The air-bearing uses a thin film of compressed air (an air gap of several microns) to support a load. Therefore, there is no physical contact between moving parts and the optical surface. The air-bearing provides superior scanning performance compared to traditional mechanical scanning: it has no friction and will not be worn by friction. The fluid film acts to average out small-scale errors (such as residual micrometer-size abrasive particles), so the measurement is less sensitive to surface contaminants. In addition, the distance between the retroreflector's vertex and the pad's air floating surface is a constant value. Therefore, it does not suffer from the centering and sphericity issues of a traditional SMR.

Some factors must be considered and weighed during non-contact probe design, including pad form and size, preload, and air pressure.

2.1. Pad Form and Size

The spherical air-bearing with a matching radius (the radius of the air-bearing surface is equal to or close to the vertex curvature radius of the aspheric surface) is an ideal choice for making a non-contact probe. However, it may not be commercially available. Instead of customizing spherical air-bearing, a flat round air bearing can be used in most circumstances. In this case, the size of the air-bearing pad must be considered. For a large mirror with a radius of curvature R, the surface sag is given by the following formula:

$$Sag_{PV} \approx R - sqrt\left(R^2 - r^2\right) \tag{1}$$

where r is the radius of the air-bearing pad. Therefore, the mean sag can be expressed as:

$$Sag_{average} \approx \frac{\int_0^{2\pi} \int_0^r \left(R - sqrt\left(R^2 - \rho^2\right)\right)\rho d\rho d\theta}{\pi r^2} \tag{2}$$

Figure 2 shows the relationship between the radius of curvature of the measured surface and the average sag for a Ø25 mm and a Ø50 mm pad (calculated by Formula (2)). In order to make the probe float on the surface, the flying height of the air-bearing should exceed the average sag, which means that the size of the pad is proportional to the surface's radius. For most large aspherical mirrors, the asphericity is on the order of several hundred microns to several millimeters; thus, the sag difference between the center and outer edge of the mirror can be neglected for the pad with the appropriate size.

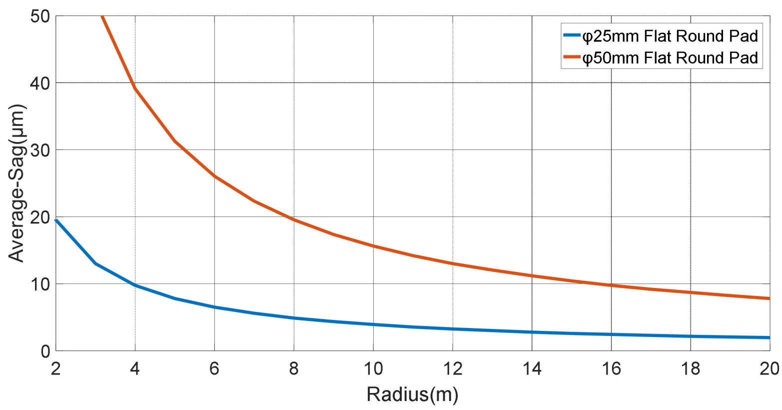

Figure 2. The relationship between the radius of curvature of the measured surface and the average sag for a Ø25 mm and a Ø50 mm pad.

2.2. Preload and Pressure

To increase the stiffness of the air-bearing and maintain a constant air gap during the scanning, the non-contact probe should be preloaded. Using a weight much heavier than the expected variation in the loading of the bearing preloads the air-bearing, so it rides at a smaller air gap and makes it less prone to surface slope variations (usually 10 degrees for large mirrors) and traction force.

Figure 3 shows the relationship between load and lift of a Ø25 mm pad under a working pressure of 4.1 Bar (data are from the pad's specification). It can be concluded that the air gap change is more sensitive to the light load. However, the heavy load will increase the moving mass. For large mirrors with active support, the heavy load would lead to rigid-body motion of the mirror and introduce measurement error.

The air supply should be clean and regulated to constant pressure. Typical operating pressures range from 1 to 6 bar depending on the stiffness, load capacity, and air gap. Figure 4 shows the experiment result of the relationship between pressure and lift for a Ø25 mm pad with a 0.4 kg load, and the maximum repeatability of lift is 0.5 μm.

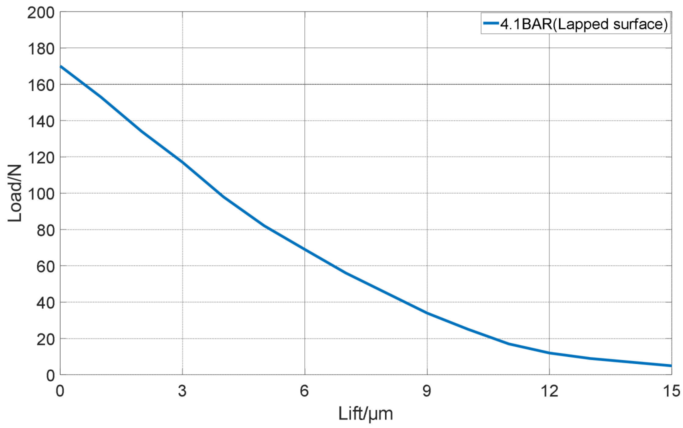

Figure 3. Relations between load and lift for a Ø25 mm pad.

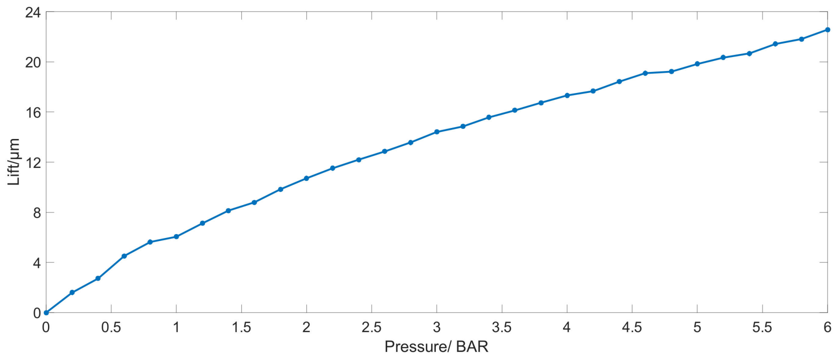

Figure 4. Relationship between pressure and lift for a Ø 25 mm pad (0.4 kg load).

The co-ordinate measurement also needs probe 'radius' compensation. The probe 'radius' consists of three parts, as shown in Figure 5:

1. L1, the distance between the cube corner retroreflector and the bearing's floating surface. This length is a constant value and can be calibrated by measuring a plane with an SMR and non-contact probe (without air supply) respectively and calculating the distance between the fitting planes.
2. L2, floating height, usually a few microns, depends on the pad stiffness, which varies with air pressure and surface condition; it can be measured with the laser tracker or indicator by turning the air supply on or off.
3. L3, the sag related to the surface geometry, which can be directly calculated.

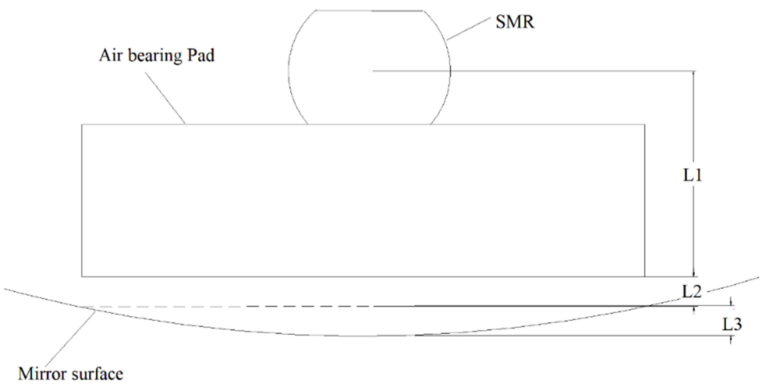

Figure 5. Schematic representation of the composition of probe 'radius'.

3. Experiment and Results

The preliminary experiment was carried out on a Ø3 m concave off-axis polished mirror, with a radius of curvature of 13 m. An API laser tracker model Radian was set up at the center of curvature of the mirror on the test tower.

The non-contact probe is made with a Ø25 mm flat round air bearing and preloaded at 0.4 kg. A 0.5-inch hollow SMR is placed on the center of the pad, and the 'radius' of the probe is 12.55 mm. The non-contact probe works under a pressure of 2.5 bar, and 16 uniformly spaced radial lines were sampled. The scanning speed is approximately (0.3~0.5) m/s, and it takes about 3 min to measure the entire surface.

The preliminary data from this testing are quite encouraging; the optical measurement data (surface measured with interferometer and CGH) show that the mirror surface has 20 nm RMS figure error. The measurement result of the laser tracker is 4.4 μm in peak-to-valley (PV) and 0.8 μm in RMS, respectively, as shown in Figure 6, confirming that high precision of the non-contact scanning method in this geometry is achieved.

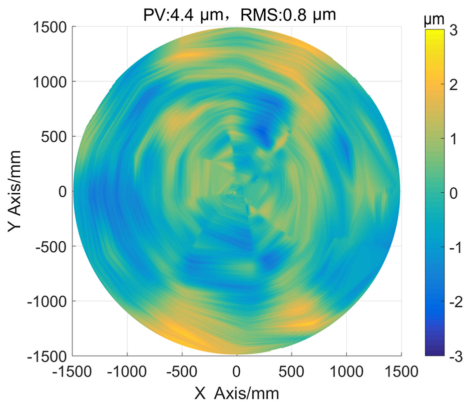

Figure 6. Surface map obtained by laser tracker using a non-contact probe.

4. Conclusions

The developed non-contact probe adopts the principle of an air-bearing, which is especially suitable for testing large optical elements in the fine polishing process. Compared to traditional SMR contact probes, the method is safer and less sensitive to surface contaminants. A validation experiment was carried out on a 3 m off-axis mirror, and the experimental results were satisfactory. Further development would add a probe-positioning system, allowing automatic measurement and increasing sampling density. Also, non-contact probes for testing mirror surfaces with a small radius of curvature and other geometry parameters will be investigated.

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