Application of target tracking method using an Arago spot and divergent beam for in-chamber measurement

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Abstract. A position measurement method using the Arago spot and a divergent beam is discussed for the in-chamber measurements of an inertial fusion energy (IFE) target. By employing a divergent beam, the actual displacement of the target is measured by the magnified displacement of the Arago spot, and the shadow of the target is also magnified, whereas the diameter of the Arago spot is not enlarged significantly. This fact enables us to measure the small displacement of the target with high measurement accuracy over a large measurement range. The Arago spot can be identified by the maximum intensity in the diffraction pattern due to the magnified target shadow. A measurement accuracy of 0.2 µm is achieved with a measurement range of 2 to 10 m for a 5-mm-diameter target.

1. Introduction
In a direct drive inertial fusion energy (IFE) power plant, required accuracy of the engagement between a spherical fuel target and driver beams is ±20 µm at the center of a reaction chamber [1]. To achieve successful implosion, the position measurement of the target must be carried out with greater accuracy.

Recently, the Arago spot was used for an IFE target tracking system [2]. The Arago spot is a bright spot which appears at the central portion of the diffraction pattern formed in the geometrical shadow of a spherical obstacle. Thus, the center of the Arago spot agrees with the center of the projection of a spherical obstacle. This fact enables us to measure the position of the target by means of the Arago spot. We studied the accuracy of the position measurement method using the Arago spot in the case of collimated beam illumination [3]. A measurement accuracy of 0.2 µm was achieved when the distance \( z' \) between a 5-mm-diameter target and a CCD camera Arago spot recording system was 5 cm. However, the measurement performance decreased with increasing distance \( z' \) because the diameter of the Arago spot increased as well. We proposed the use of divergent beam illumination to remove the limitation of the distance \( z' \) in order to apply the Arago spot to in-chamber measurement [4].

In this paper we will discuss the position measurement method using the Arago spot and a divergent beam in detail, comparing the measurement results for divergent and collimated beam illumination.

2. Measurement principle
Figure 1 shows the geometry for the position measurement. A spherical target is placed in the object plane with its center set at the origin \( O \) and is illuminated by a divergent beam emitted from a point
source $S$ located on the $z$ axis at a distance $L$ from the object plane. The Arago spot is observed in the observation plane, which is parallel to and at a distance $z'$ from the object plane. Suppose that the center of the target moves from $O$ to a point $P$ in the object plane. For a divergent beam the target displacement $\Delta d = OP$ in the object plane is magnified as the distance $z'$ increases. The corresponding displacement of the Arago spot $\Delta d' = O'P'$ in the observation plane is therefore magnified and written as $\Delta d' = M \Delta d$, where $M$ is a magnification factor, given by

$$M = 1 + z'/L.$$  \hspace{1cm} (1)

When the Arago spot is much smaller than the shadow of the target, or the Arago spot resides well within the target shadow, the diameter of the Arago spot $D_{\lambda}$ is proportional to the distance $z'$ and the wavelength of the incident light $\lambda$ and is inversely proportional to the radius of the target $a$ for both divergent beam illumination and collimated beam illumination, that is,

$$D_{\lambda} = 2Kz'\lambda/a,$$  \hspace{1cm} (2)

where $K = 0.38$ [5]. The measurement error in the observation plane is mainly subject to the accuracy to determine the center of the Arago spot. Consequently, the measurement error is proportional to the diameter of the Arago spot, $\gamma D_{\lambda}$, where $\gamma$ is a proportional constant. To measure the target displacement $\Delta d$ in the object plane correctly, $\Delta d' > \gamma D_{\lambda}$ is required in the observation plane, in turn, $\Delta d > \gamma D_{\lambda}/M$ in the object plane. Using equations (1) and (2), and assuming $z' >> L$, we have

$$\Delta d > \frac{2\gamma K\lambda}{a} \frac{Lz'}{L + z'} \approx \frac{2\gamma K\lambda}{a} L.$$  \hspace{1cm} (3)

Since the right term in inequality (3) is independent of the distance $z'$, we can measure the displacement $\Delta d$ of the target free from the limitation of the distance $z'$ as long as the distance $L$ satisfies the following inequality:

$$L < \frac{a\Delta d}{2\gamma K\lambda}.$$  \hspace{1cm} (4)

For example, to measure the displacement $\Delta d = 1$ $\mu$m at the distance $z' = 10$ m for the target radius $a = 2.5$ mm and the wavelength $\lambda = 632.8$ nm, the distance $L$ should be set at less than 26 cm. In the calculation, $\gamma = 2\%$ is employed based on our previous work [3].

A divergent beam offers another merit which cannot be obtained in the case of a collimated beam. Figure 2 shows the calculated intensity profiles of the diffraction pattern for a target placed at $(\xi, \eta) =$

![](image1.png)

**Figure 1.** Geometry for position measurement.

![](image2.png)

**Figure 2.** Intensity profiles for target placed at $(\xi, \eta) = (0, 0)$ $\mu$m illuminated by divergent and collimated beam. The calculation parameters are $a = 2.5$ mm, $\lambda = 632.8$ nm, $z' = 10$ m, and $L = 10$ cm.
(0, 0) μm illuminated by a divergent and collimated beam. The radius of the target \( a = 2.5 \) mm, the wavelength \( \lambda = 632.8 \) nm, and the distance \( z' = 10 \) m are employed in the calculation. The distance \( L = 10 \) cm is assumed in the case of a divergent beam. The central lobe of unit intensity corresponds to the Arago spot. In the case of a collimated beam, the intensity of the side lobes, which correspond to concentric fringes around the Arago spot, increases with distance from the center of the Arago spot, and the maximum intensity exists outside of the target radius. On the other hand, in the case of a divergent beam, the maximum intensity is obtained at the center of the Arago spot, and the intensity of the side lobes and the region outside of the target radius is considerably low. This is because the shadow of the target is magnified by a magnification factor \( M \), while the Arago spot is not enlarged by \( M \) even for divergent beam illumination. The Arago spot is chiefly formed by the diffracted beams at the edge of the target, whereas the shadow of the target is just a projection of the target. From a practical point of view, the maximum intensity does not exist except for the center of the Arago spot. Therefore, we can easily locate the center of the Arago spot, i.e., the center of the target by the maximum intensity in the diffraction pattern.

3. Experiment and results

The experimental setup is based on figure 1. Steel balls with diameters \( D_S \) of 3.0, 5.0, and 8.0 mm are employed as the spherical targets. The light source is a He-Ne laser which emits unpolarized light of 5 mW with a wavelength of 632.8 nm. The diffraction pattern is magnified by an objective (10×; NA, 0.25) and is then recorded by a CCD camera (Canon IXY DIGITAL 500) with 2592 × 1944 pixels of 3.8 μm × 3.8 μm pixel sizes and 8-bit gray level. In the diffraction pattern recorded by the CCD camera, the spatial coordinates are represented in terms of CCD pixel coordinates, \( X \) and \( Y \). To compare the measurement performance, the center of the Arago spot, \( X_c \) and \( Y_c \), is calculated separately by means of the weighted mean method and arithmetic mean method [3]. The former processes the recorded intensity as 8-bit value; the latter, as binary value.

Figure 3 shows the recorded diffraction patterns at a distance of \( z' = 10 \) m for the steel balls illuminated by a divergent beam and collimated beam. The captured area of each diffraction pattern is about 4.2 mm × 4.2 mm with respect to the Arago spot. In the case of divergent beam illumination, the intensity of the concentric fringes around the Arago spot is low, and the outside region of the target radius is almost dark because the shadow of the target expands beyond the target radius with a magnification factor \( M \). However, the Arago spot is not enlarged by \( M \), holding its diameter almost the same as or a little larger than that in the case of collimated beam illumination. The displacement of the target, on the other hand, is observed as the magnified displacement of the Arago spot by a magnification factor \( M \). Since the ratio of the displacement of the Arago spot to its diameter becomes much larger than that for a collimated beam, the determining accuracy of the center of the Arago spot is improved by a divergent beam. It is also important to mention that the Arago spot can be identified by the maximum intensity in the diffraction pattern when a divergent beam is used because the region outside of the target radius is covered by the magnified target shadow. Therefore, we can determine the center of the Arago spot with relatively simple algorithms without the influence of the intensity of the concentric fringes and the region outside of the target radius that deteriorates the measurement.

![Figure 3. Recorded diffraction patterns at \( z' = 10 \) m for \( D_S \): (a) 3.0, (b) 5.0, and (c) 8.0 mm. For divergent beam cases, the magnification factors \( M \) are calculated to be 92, 101, and 60 for each distance \( L \); for collimated beam cases, \( M = 1 \).](image-url)
accuracy in the case of a collimated beam.

Table 1 shows the position measurement results for a collimated beam when a 5-mm-diameter steel ball is moved over 50 µm at 1-µm intervals along the $\xi$ axis. The standard deviation $\sigma$ of measurement error and the maximum measurement error $E_{\text{max}}$ increase as the diameter of the Arago spot $D_A$ increases with increasing distance $z'$. We obtained a better performance using the weighted mean method to determine the center of the Arago spot. The ratio $E_{\text{max}} / D_A$, which corresponds to a proportional constant $\gamma$ in inequalities (3) and (4), shows a decreasing tendency when the distance $z'$ becomes large. This may be understood as follows. As the distance $z'$ increases, the Arago spot becomes large enough compared with the CCD pixel size. The number of pixels used to determine the center of the Arago spot also increases. As a result, the discrete effect of the CCD pixels in space is reduced, leading to a reduction of the ratio $E_{\text{max}} / D_A$.

The position measurement results for a divergent beam are shown in Table 2. The measurement is conducted over 30 µm at 1-µm intervals using a 5-mm-diameter steel ball. The diameter of the Arago spot $D_A$ is not magnified by a magnification factor $M$ but becomes slightly larger than that in the case of collimated beam illumination. In contrast, since the displacement of the Arago spot is magnified by a magnification factor $M$, the measurement performance is significantly improved by employing divergent beam illumination. A measurement accuracy of 0.2 µm is achieved.

### Table 1. Position measurement results for collimated beam illumination: $D_S = 5.0$ mm.

| $z'$ (m) | $D_A$ (µm) | $\sigma$ (µm) | $E_{\text{max}}$ (µm) | $E_{\text{max}} / D_A$ (%) | Weighted mean method |
|---|---|---|---|---|---|
| 2 | 388.8 | 1.25 | -2.97 | 0.764 | 1.57 |
| 4 | 766.4 | 1.29 | 4.11 | 0.536 | 1.96 |
| 6 | 1141.5 | 2.84 | 5.85 | 0.512 | 3.18 |
| 8 | 1518.1 | 2.63 | 6.60 | 0.435 | 2.57 |
| 10 | 1854.1 | 2.93 | -8.06 | 0.435 | 2.93 |

### Table 2. Position measurement results for divergent beam illumination: $D_S = 5.0$ mm.

| $z'$ (m) | $L$ (cm) | $M$ | $D_A$ (µm) | $\sigma$ (µm) | $E_{\text{max}}$ (µm) | $E_{\text{max}} / D_A$ (%) | Arithmetic mean method |
|---|---|---|---|---|---|---|---|
| 2 | 11 | 19.2 | 394.3 | 0.10 | -0.24 | 0.061 | 0.10 |
| | 70 | 3.86 | 395.2 | 0.18 | 0.54 | 0.137 | 0.18 |
| 10 | 10 | 101 | 1966.8 | 0.06 | -0.15 | 0.008 | 0.07 |
| | 40 | 26.0 | 1962.4 | 0.17 | -0.43 | 0.022 | 0.20 |

4. Summary

We have discussed a position measurement method using the Arago spot and a divergent beam, and have demonstrated the advantage of using a divergent beam. A measurement accuracy of 0.2 µm can be achieved when the distance between a 5-mm-diameter target and a CCD camera is within the range of 2 to 10 m. The presented method enables the position measurement of an IFE target in a reaction chamber with high measurement accuracy.

References

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