Optical Metrology with a Hartmann Mask

1. Aim of the Experiment

To *understand the principle of the Hartmann test for wavefront sensing* and to use it to measure the wavefront aberrations, to determine the radius of curvature of a double-convex lens, and also to determe the prism angle of a Fresnel biprism.

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2. Learning Outcomes

After completing this experiment, you will be able to:

- **i.** Explain how local wavefront slopes are measured using a Hartmann mask.
- **ii.** Acquire and process spot images using a camera.
- **iii.** Relate spot displacements to wavefront shape and optical path difference.
- **iv.** Measure the radius of curvature of a bi-convex lens by measuring the distortions
- **v.** Measure the prism angle of a Fresnel Biprism.

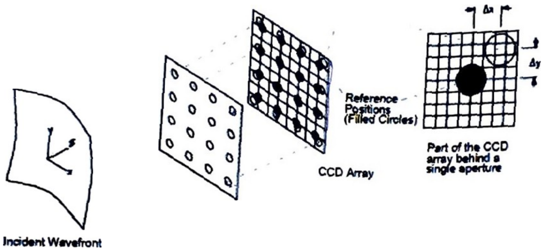

Figure 1. Hartmann wavefront sensor operation fundamentals

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3. Background Theory

3.1 Hartmann Test

The Hartmann test is a classical wavefront sensing technique used in optical metrology. A Hartmann mask consists of an array of small apertures arranged in a regular grid. When a plane wavefront passes through the mask, each aperture produces a spot on a screen or detector located downstream. For an ideal plane wavefront, the spots form a regular grid matching the aperture layout. However, if the incoming wavefront is aberrated, the local tilt (slope) of the wavefront at each aperture causes the corresponding spot to shift. By measuring these spot displacements in the x and y directions, the local gradients of the wavefront can be reconstructed, allowing estimation of the overall wavefront shape.

3.2. Background

The Hartmann test was introduced by Johannes Hartmann in the early 20th century as a method to test astronomical lenses and telescope optics. Since interferometry was experimentally challenging then, the Hartmann test provided a robust, geometric method to diagnose lens aberrations.

Its fundamental principle is to **sample a wavefront locally** and then reconstruct its shape from the measured deviations. This idea underpins most modern wavefront sensing techniques.

3.2 Relation to Modern Wavefront Sensors

The Hartmann test is the conceptual precursor to the Shack–Hartmann wavefront sensor, widely used in adaptive optics, ophthalmology, and laser beam characterization.

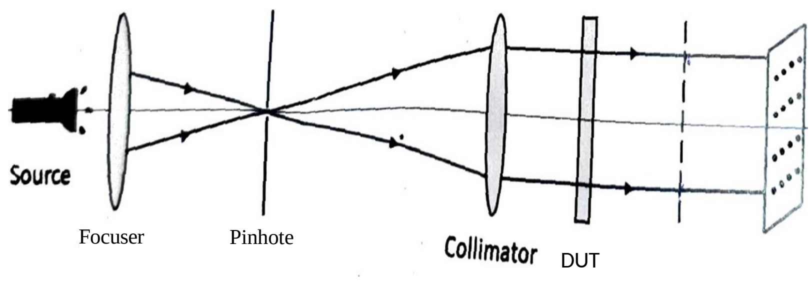

Figure 2. Schematic of the Hartmann Test

4. Experimental Setup

4.1 Components

1) White light source

2) Focusing lens

3) Pinhole (spatial filter)

4) Collimating lens

5) Hartmann mask (4 × 4 aperture array)

6) Translucent screen

7) Webcam / CCD camera

8) Computer with MATLAB

9) Devices Under Test (DUTs):

- **a)** Double-convex lens
- **b)** Fresnel biprism

4.2 Optical Arrangement

A collimated beam is produced using a source, pinhole, and a collimator. The collimated beam passes through the DUT (either bi-convex lens or a Fresnel prism in our case) and then through the Hartmann mask. The resulting spot pattern is recorded on a translucent screen using a webcam.

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5. Software Tools

The experiment uses MATLAB programs provided in the laboratory:

- `webcam_recordingvideo.m` – live image display
- `thresh_calibrate_fastpeakfind.m` – reference calibration and centroid detection
- `sh_movie.m` – real-time wavefront reconstruction and peak-to-valley calculation

Note that you are only required to run the MATLAB codes in the given system and interpret the outputs.

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6. Experimental Procedure

6.1 Image Verification

1. Run `webcam_recordingvideo.m`.
2. Adjust the webcam position and focus until all 16 spots are clearly visible.
3. Ensure uniform brightness and minimal background noise.

6.2 Reference Calibration (No DUT)

1. Remove any optical element between the collimator and Hartmann mask.
2. Run `thresh_calibrate_fastpeakfind.m`.
3. Crop the image so that only the 4×4 spot pattern is included.
4. Check that the program correctly identifies all spot centroids.
5. If necessary, adjust the Gaussian threshold until the message indicates successful peak detection.

This reference pattern represents an approximately plane wavefront.

6.3 Aberration Measurement (With DUT)

1. Insert the DUT between the collimator and the Hartmann mask.

2. Run `sh_movie.m`.

3. Observe the reconstructed wavefront in real time.

4. Record the peak-to-valley wavefront value, Δ (in metres).

Note: Do not look directly into the bright light source.

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7. Measurements and Analysis

7.1 Double-Convex Lens

Let:

- Δ = peak-to-valley wavefront value at the screen
- h = half-height of the Hartmann screen (given: h = 16 mm)
- L = distance between the lens and the screen
- R = distance from the screen to the centre of curvature of the lens

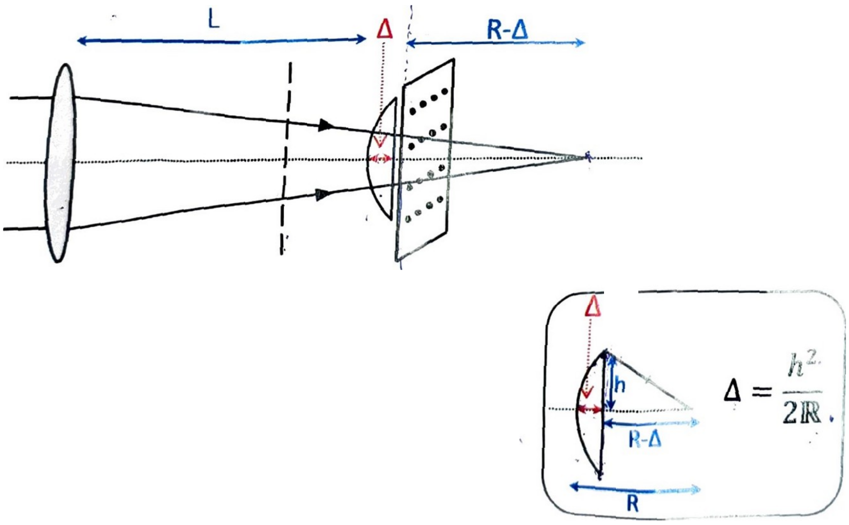

Figure 3: Hartmann test setup for measuring the radius of curvature of a double convex lens.

From geometrical considerations, we can derive

$$\Delta = h^2 / (2R) \quad (1)$$

The total radius of curvature of the lens is then:

$$R\_total = (R - \Delta) + L \quad (2)$$

Your task is to calculate R_total and compare it with the radius of curvature of the same lens from its focal length.

7.2 Fresnel Biprism

A Fresnel biprism introduces a small angular deviation between two parts of the wavefront. In this activity, we have to use our experimental setup replacing the bi-Convex lens as the DUT with a Fresnel Prism.

Let:

- Δ = measured peak-to-valley wavefront value
- h = half-height of the Hartmann screen
- θ = prism angle

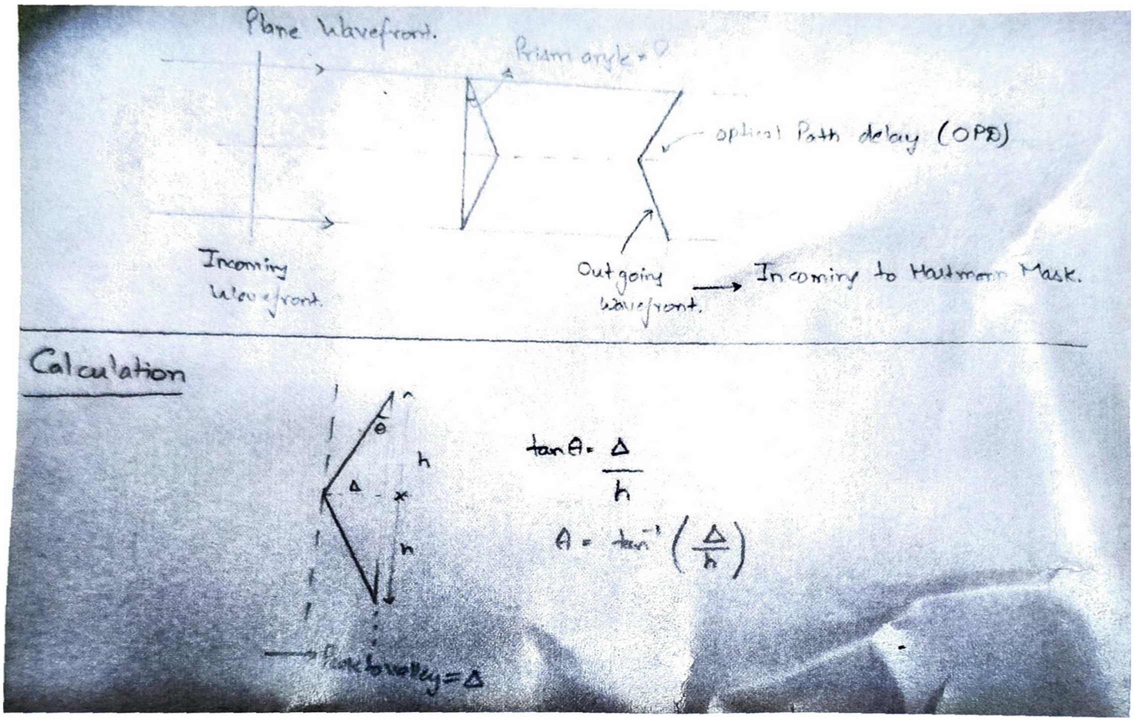

Figure 4: Hartmann test setup for measuring the angle of a Fresnel prism.

Using simple geometry, we have

$$\tan \theta = \Delta / h \tag{3}$$

For small angles, we can approximate $\theta \approx \Delta / h$ (in radians)

Your task is to calculate the prism angle.

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8. Sources of Error (Important)

- Misalignment of optical components
- Poor centroid detection due to low contrast or noise
- Non-ideal collimation of the input beam

- Assumption of small-angle and paraxial approximations

You should comment on how these factors affect the final results and uncertainty.

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9. Some Questions

1. Why does spot displacement correspond to wavefront slope?
2. How does the Hartmann test differ from a Shack–Hartmann sensor?
3. Why is reference calibration necessary?
4. What limits the spatial resolution of the wavefront measurement?
5. Why is the small-angle approximation valid for a Fresnel biprism?
