Motivation

• Payloads that use refractive optics (lenses) will have a different focal length in vacuum.
• During the development and testing of experimental payloads, we want to offset the collimation of a beam to simulate vacuum without using a vacuum chamber.
• We need a device to measure the collimation of the adjusted beam: a shearing interferometer.

Shearing Interferometers

• Shearing interferometers are used to determine if a coherent beam of light is collimated, and to what degree.
• How it works (refer to Fig. 1):
  1. A coherent beam is directed toward a wedged optical flat.
  2. Part of the beam is reflected off the front surface; another part of the beam refracts into the wedge and then reflects internally; a last part of the beam refracts into and out of the wedge.
  3. Two parts of the beam interfere, producing fringes.
  4. The deviation angle of the fringes from the reference determine the degree of collimation (when the interference is not well-collimated it will have a radius of curvature $R$).

The angle of deviation of the fringes from the horizontal is given by [1]

$$\sin \xi = \frac{d^2}{2R} \sin \theta,$$

where the fringe spacing is $d$ dependent on the wavelength of the light $\lambda$, index of refraction of the wedge plate $n$, the wedge angle $\alpha$, and the angle of incidence of the incoming beam onto the wedge plate $i$, [1]

$$d = \frac{\lambda}{2n^2 \sin \alpha \sin i},$$

and $x$ is the shear, a measure of the separation between the two reflected beams, calculated from the angle of incidence and the thickness $t$ and index of refraction of the wedge, [2]

$$x = \frac{t \sin (D)}{\sin \theta},$$

where $D = \frac{\lambda}{2n^2 \sin \alpha \sin i}$. [2]

As a result, the radius of curvature is related to the fringe deviation angle by

$$R = \frac{t \sin (2D)}{\sin \theta},$$

with propagated error

$$dR = \frac{d^2}{2R} + \frac{1}{2} \left( \frac{dR}{R} \right)^2,$$

where $dR$ as the error in the parameter $R$.

The accuracy of the measurement of the radius of curvature is dependent on:

• Our knowledge of the thickness of the wedge plate, i.e. $t$.
• Our knowledge of the index of refraction of the wedge plate, i.e. $n$.
• Our knowledge of the incidence angle between the incoming beam and the wedge plate, i.e. $i$.
• Our knowledge of the plate’s wedge angle, i.e. $\alpha$.
• Our knowledge of the intrinsic angle between the wedge plate and the camera pixels and the measurement of the fringe deviation angle with respect to this reference, i.e. $\xi$.

Measuring the Fringe Deviation Angle

From the error budget, the uncertainty in the fringe deviation angle contributes most to the error in the radius of curvature. An extensive study was undertaken to compare different methods of determining the fringe deviation angle. The most successful method in achieving this measurement was the “Linear Fit” method, shown in Fig. 4, and is done as follows:

1. Co-add data images together to obtain higher signal-to-noise ratio, Fig. 4(a).
2. Apply FFT to the image data, Fig. 4(b).
3. Cut-off high frequencies to apply FFT and obtain a filtered image, Fig. 4(c).
4. Extract fringe centers, Figs. 4(d) and (e), using a Gaussian best fit with a general form

$$f(y) = A_0 e^{-\frac{(y-y_0)^2}{2\sigma^2}} + A_1 e^{-\frac{(y-y_0)^2}{2\sigma_1^2}} + B,$$

5. Calculate the fringe deviation angle from the slope, $\xi = \tan^{-1}(\text{cm}^{-1})$.

This technology demonstration found that the Linear Fit method achieved a fringe deviation angle error as low as $d\xi = 0.08^\circ$ from experimental data. The error can be reduced further if a larger range of the fringe is sampled (requiring edge noise to be reduced) and if more fringes are present. On a perfectly manufactured “ideal” fringe diagram, a fringe deviation angle error of $d\xi = 0.004^\circ$ was achieved.

Calibration Considerations

The measurement error of the angle from the image data, $\xi$, with respect to the reference was determined. Now, our knowledge of the reference must be considered due to:

• alignment error between the angle of the wedge plate and the CCD pixels, $\xi_r$
• alignment error in the translation of the wedge plate in its roll-pitch-yaw stage relative to the CCD

The alignment error $\xi_r$ is unlikely to be perfectly known, but the shearing interferometer can be calibrated with a perfectly collimated beam to obtain the value of $\xi_r$.

References