

Axicons in Action

Unique wavefront sensing for adaptive optics

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Axicon lenses convert incident plane waves into approximations of Bessel beams. Because of the circular profile of an axicon beam the lenses are suited for use in corneal surgeries and optical trapping. The unique features of axicon lenses also enable an interesting type of wavefront sensor. Such a sensor can measure low order aberrations without a separate reference wavefront optical train. Axicons focus light along the optical axis, and the position shifts if aberrations are introduced to the beam. That creates variation in the intensity distribution measured by an image sensor. In addition, the center of an axicon lens, the apex, scatters some of the incident light. The focused light and the scattered light can interfere, creating a self-referenced interferogram.

In 1954, John McLeod reported on his work of developing a new type of optical element, the axicon (Fig. 1). An axicon is a figure of revolution with the property that a point source object on the axis of revolution is imaged in a line along the optical axis. McLeod's original paper described several realizations, including reflective hollow cylinders, cylindrically symmetric toroidal surfaces, and even a thin circular window in an otherwise opaque disk. McLeod described the one specific shape that currently defines the axicon: a cone.

One of the properties of the cone-shaped axicon – hereafter just referred to as the axicon – is that it will take a plane wave or Gaussian beam and produce a ring-shaped output beam. The thickness of the ring is related to the initial beam diameter, and the diameter is a function of the apex angle of the



Fig. 1 Axicons – conical prisms – offer special characteristics due to their special shape.

cone and distance from the axicon. That ring-shaped profile closely approximates a non-diffractive Bessel beam. So the axicon is suitable for a variety of diverse applications. One is the use of the axicon for an adaptive optics wavefront sensor (WFS).

Adaptive optics (AO) refer to the technology that allows a mirror to change its shape and compensate for aberrations in a beam. This can improve imaging and beam delivery in applications like ophthalmological instruments or laser welding. The most effective way to compensate for aberrations is to measure them rapidly and accurately. That is the task of wavefront sensors. Several different types of them are used, with each having characteristics that make them suitable for a specific application. There is no perfect wavefront sensor, though, so there's always room for a new approach.

One of those new approaches is built around the 70-year-old axicon design. The axicon beam intensity pattern changes with beam aberrations, but that's only appropriate for low-order large aberration sensing. A newer approach is to use scattering from the axicon apex as a point-source, and recombine the scattered beam with the main propagated beam. This approach combines the speed of single image acquisition with the accuracy of interferometry.

Introduction to axicons

In the same way that Wilhelm Roentgen's first investigations of X-rays included just about everything that was known about them for the next hundred years, John McLeod's description of his axicon is just as comprehensive now

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as seventy years ago. His paper describes a variety of rotationally symmetric designs that focus light not on a perpendicular focal plane, but in a line right on the optical axis. Although McLeod outlines simulations and measurements for several designs, he waxes about the cone: “The simple cone... may be the most useful form of axicon. It is somewhat simpler than other forms to make and its range and illuminance are practical [1].”

His optimism was well-founded. The cone design is conceptually and practically straightforward. The shape is essentially that of a trapezoid with two adjacent right angles, that is, a rectangle that has had one corner pulled out a bit. A piece of glass with that profile will deviate a beam incident on the flat side towards the thicker part. If that shape is rotated about the thick end, the result is a cone. The cone, being conceptually just like many prisms at different rotational angles, will bend incident light towards the optical axis. Light incident at a given distance from the center will focus at a specific location on the optical axis.

This is a consequence of the fact that an axicon deviates light incident normal to its plane surface at an angle related to its index of refraction and apex angle. The light incident along a specific radius from the center of the axicon is all refracted at one identical angle, so that a slice of the incident light propagates as a parallel beam that crosses the optical axis. The distance from the center of the axicon to the edge of the beam defines the thickness of the beam. Axicons are defined by taking that cross section and rotating it about the center edge, so the same magnitude angular deviation is introduced along each radius of the axicon. The result is a hollow circle that does not change in thickness as it propagates. For example, if a 6 mm diameter collimated beam is incident at the center of the axicon, the resulting ring will have a width of half the beam diameter, so 3 mm in this case. That thickness will be maintained even as the overall ring

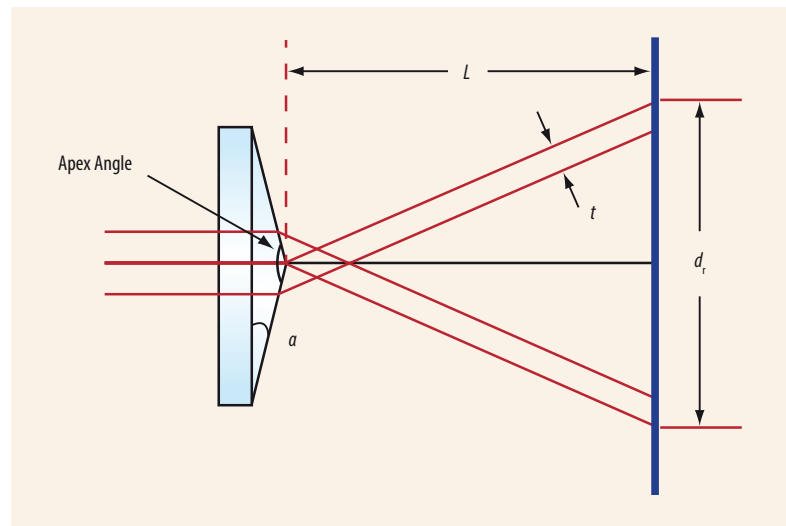


Fig. 2 An axicon's unique property is its capability of closely reproducing Bessel beams aligned with the laser so that the laser beam travels along the axicon's optical axis.

diameter increases with propagation distance.

Axicon-based systems are commonly used to create ring-like beams for laser processing of materials or laser hyperopic refractive surgery. They are also used in optical trapping applications where the ring profile confines particles in the central dark region. Axicons are commonly used for measurement and alignment, research, and medical applications requiring a ring-shaped laser output, and can even be used to extend the depth of focus in imaging systems.

Booming adaptive optics

Adaptive optics are benefitting from some rapidly improving technologies and decreasing costs. The primary active element in an AO system is the deformable mirror (DM). Such mirrors consist of a thin continuous reflective membrane or many segmented reflective surfaces. The reflective surfaces are positioned on some form of movable actuator. When the actuators are moved, the mirror changes its surface profile. In the past, DMs were large and required banks of high voltage equipment. Now, a number of miniaturized DMs are available, such as a MEMS DM manufactured by Iris AO that has 111 actuators controlling 37 mirror

segments in a 3.5 mm diameter mirror. Such mirrors are compact, capable, easier to use, and much less expensive than first generation deformable mirrors.

Miniaturized DMs have opened up a new range of applications for adaptive optics. In addition to the original astronomical and defense applications, these DMs are enabling new applications in laser welding, free-space communications, and ophthalmological instruments. The DMs do not operate alone. The actuators must be provided with the proper signal to reduce aberrations in the system. The most efficient methods for determining the appropriate control voltages are with wavefront sensors.

Wavefront sensors

Wavefront sensors are placed within the optical train to be corrected. They pick off a part of the beam and measure the aberrations. The most common wavefront sensor is the Shack-Hartmann sensor. This sensor measures the wavefront slope across a set of subapertures. The subapertures are defined by a lenslet array. When light propagates through the lenslet array it is broken up into a number of small beams which are detected at an image sensor. If the incoming light is an unaberrated plane wave, the

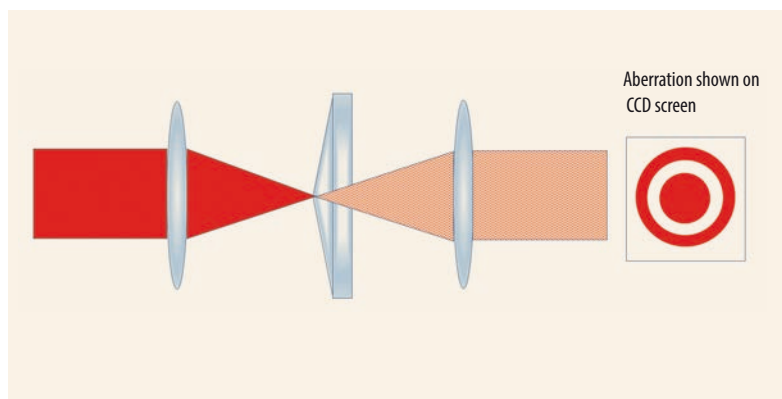


Fig. 3 Schematic representation of axicon wavefront sensor. The beam is focused on the apex of the axicon which created a diffraction pattern. The change of the rings in dimension, quantity, and shape gives an idea of the aberrations in the system.

lenslets focus light at their null positions. When aberrations are present, the positions of the focused beams from each subaperture are shifted a distance proportional to the average tilt in the subaperture. Those tilts are then processed to calculate a set of voltages to drive the actuators.

A shearing interferometer is a quite distinct type of WFS. A shear plate creates two copies of a beam, spatially offset from one another by a small deviation. An unaberrated beam creates a set of straight fringes. When the beam is aberrated, the fringes are distorted. To provide control signals for both axes, two orthogonal shearing interferometers are necessary, and the wavefront can then be mathematically reconstructed to high accuracy.

Another distinct form of wavefront sensor is the pyramid sensor. The shearing interferometer and Shack-Hartmann WFSs are placed in collimated space. The pyramid wavefront sensor consists of a four-sided prism, placed at the focal plane of a lens in the optical train. Each of the four facets of the pyramid sensor deviates a portion of the beam onto a detector. If the beam is unaberrated, each facet will produce an image at the same relative location and of the same shape. When aberrations are introduced, the symmetry of the distribution is disturbed, and an estimate of low-order aberrations can be calculated.

That's not a complete catalogue of wavefront sensors currently used in AO systems. Each WFS has specific advantages and disadvantages that suit it for a given application, but the number of applications is growing and the perfect WFS has yet to be developed. That's why work continues on developing new wavefront sensors, including an innovative wavefront sensor based on the axicon.

The axicon wavefront sensor

The pyramid sensor can be thought of as four independent prisms joined together at their high edges. When placed at the focal plane of a system, each of the four prisms creates one image on the subsequent detector. Differences in those spots indicate asymmetries in the focused spot, which, in turn, can be traced to aberrations in the incoming beam. The four images are sufficient to generate low order corrections in two axes. What if, however, the four-sided prism was replaced by a six- or ten-sided prism? One could reasonably expect that the additional images would provide more detailed information about asymmetries in the focused spot.

The axicon essentially consists of an infinite number of prisms (usually) joined together at their high edges. Where the pyramid sensor samples the focused beam at four projection angles, the axicon samples it at all possible projection an-

gles. As we have seen, the resulting image is a ring of constant thickness and – at a given distance from the axicon – constant diameter. In the same way as variations in the four images of the pyramid sensor indicate aberrations in the incoming beam, variations in intensity, diameter, or thickness of the ring created by the axicon give you an idea of the aberrations in the system.

Again, in the same way as the pyramid sensor, the intensity variations in the axicon can only be used to identify low-order aberrations. Of course, if there was a way to measure the phase across the axicon beam, then more detailed information could be pulled out of the image, but that would require an independent reference beam. Not only would that add cost and complexity to the system and reduce the often sparse photon budget even more, but it leads to a more fundamental problem: Where would the reference beam come from?

Such a reference beam would need to be coherent with the original beam to be measured, but the measurement beam already has aberrations. The trick would be to somehow create an unaberrated version of the incoming beam, but if that was easy then there would be no need for AO systems. An answer is to pick off part of the beam and create a point-diffraction interferometer (PDI).

A point diffraction interferometer uses diffraction from a point discontinuity to create a clean reference beam [2]. The idea is simple: no matter how many aberrations in a beam, some tiny portion of the focused spot will be unaberrated. If you put a pinhole at the center of the focused spot – a pinhole on the order of or smaller than the Airy disk – diffraction from the pinhole will create a “perfect” spherical wave. That perfect beam can then be recombined with the remainder of the original input beam to create an interference pattern, from which the phase of the original beam can be determined.

Researchers at University College Dublin combined the unique

imaging characteristics of the axicon with the conceptual simplicity of the PDI to create an axicon wavefront sensor [3]. To add even more to the simplicity, they used the blunt apex of the axicon as the point discontinuity for the PDI reference beam. The researchers found that small aberrations could be quantified by the PDI fringes while larger aberrations could be recovered from the intensity pattern that is created by refraction through the axicon.

For this application, a large apex-angle axicon is needed. The diffraction is the result of the microscopic flatness of the apex itself. That is, the axicon apex is not a perfect point, but a flat spot a few microns across. Diffraction from the slightly blunt apex forms the PDI reference beam which is combined with the remainder of the beam that propagates through the axicon.

Synergy

The development of the axicon wavefront sensor is an excellent example of technological developments and market forces converging to enable new applications. Advancing deformable mirror technology has increased the range of applications accessible to adaptive optics. An innovative combination of high-quality axicon components and the point diffraction interferometer has created a new capability. Improved computational power enables that capability becomes practical.

As adaptive optics find more applications, the need for additional wavefront sensors grows as well. Decreasing cost of components and improvements in correction algorithms are creating new market opportunities in biology and medicine, fabrication and manu-

facturing, and defense and civil applications in atmospheric propagation. The burgeoning market is also enabled by the introduction of new technologies in every aspect of the system, including wavefront sensors. Taking a cue from the many applications of the axicon lens, researchers added one more application: the axicon wavefront sensor. That sensor is now in the toolbox for engineers and scientists to enhance performance of their optical systems.

[1] *J. McLeod*, *JOSA* **44**, 8 (1954)

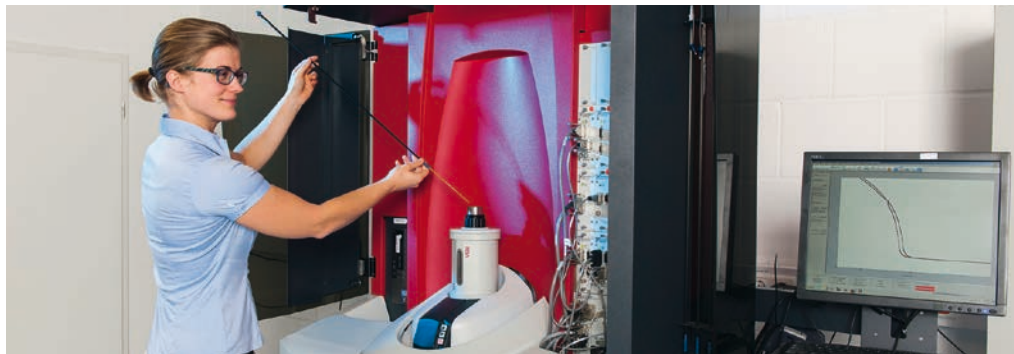
[2] *R. N. Smartt* and *W. H. Steel*, *Japan J. Appl. Physics* **14** (1975)

[3] *B. Vohnsen*, *S. Castillo* and *D. Rativa*, *Optics Letters* **36**, 6 (2011)



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