Optical Methods in Experimental Mechanics

Part 26: Subjective Speckle

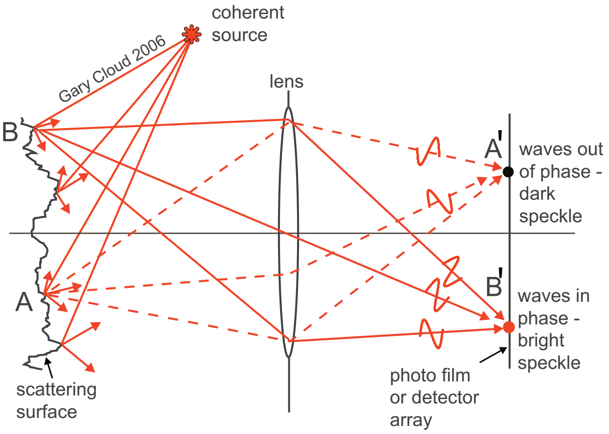
REVIEW AND PURPOSE

The previous article dealt with the formation of objective speckle that is created when coherent light is scattered by an object and made to fall directly on a sensing medium such as a photographic film.

This brief article describes the formation of so-called subjective speckle, the second and most useful of the two fundamental types of speckle. It appears whenever a lens is used to create an image of an object that is illuminated by coherent light. Much of what was learned about objective speckle applies to this new type.

FORMATION OF SUBJECTIVE SPECKLE

The sketch below illustrates how subjective speckle is formed.



As usual, an expanded laser beam is directed onto an object that has a matte surface so as to scatter the incoming waves. Some of the scattered waves are collected by a lens and redirected onto a screen, a photographic film, an analog television sensor, or a digital detector array. Assume that the scattered waves that do not enter the lens are blocked from reaching the image screen. Also assume for temporary convenience that the distances between object, lens, and screen are proportioned so that a focused image of the object appears on the screen.

Portion of Mayan figure photographed under helium–neon laser illumination at *f*-22 aperture. The intrusive effects of subjective laser speckle are apparent. Digital photograph by Gabriel Isaicu of Michigan State University, Mechanical Engineering Department, January 2007.

Subjective coherent light speckle:
- *is so-named because a lens is used,*
- *affects all pictures taken with coherent illumination,*
- *is of great practical value in measurement.*

To create objective laser speckle patterns:
- *illuminate an object having a matte scattering surface with an expanded laser beam,*
- *use a lens to create an image of the illuminated object on a screen, a photo film, or a sensor array.*

The series, Optical Methods—Back to Basics, *is written by Prof. Gary Cloud of Michigan State University in East Lansing, Michigan. It began by introducing the nature and description of light and will evolve, with each issue, into topics ranging from diffraction through phase-shifting interferometries. The intent is to keep the series educationally focused by coupling text with illustrative photos and diagrams that can be used by practitioners in the classroom, as well as in industry. Unless otherwise noted, the graphics in this series were created by the author.*

The series author, Prof. Gary Cloud (SEM fellow), is internationally known for his work in optical measurement methods and for his book, Optical Methods of Engineering Analysis.

If you have comments or questions about this series, please contact Jen Proulx, journals@sem1.com.

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The important fact in this case is that the waves scattered from any single point of the object are focused to a corresponding point of the image, as suggested by the sketch. A cone of waves originating at point A of the object and entering the lens (here shown as dashed lines) are all redirected to converge at image point A'. These converging waves have traveled various path lengths, and they arrive at the image point with a variety of phases. They interfere with one another to produce a particular brightness at the convergence point. Perhaps those arriving at point A' experience predominately destructive interference and so image point A' will be dark. At screen point B', which is the image of object point B, the waves (solid lines) might interfere constructively to produce a bright speckle. Other points of the image will experience other mixtures of phases, and the brightnesses will lie between totally black and maximum intensity. The brightness distribution will be random, and the brightnesses of adjacent points are not related to one another.

The basic physics of subjective speckle formation are that:
- *each point of the screen image receives light waves from only one corresponding point of the illuminated object,*
- *each wave travels its own particular path length to a screen image point,*
- *the multitude of waves arrive at the image point with a multitude of different phases,*
- *the waves all interfere with one another as they arrive at the point,*
- *at some points the waves are predominately in phase, so they constructively interfere to create a bright speck,*
- *at other points, the waves are predominately out of phase so they form a dark speck,*
- *many points have a mixture of phase differences, so the result is a gray spot.*

The lens aperture is assumed to be "small" relative to the lens-to-image distance (paraxial approximation). The interferences will be close to the collinear case and oblique interferences need not be incorporated into this simple model. Also, as is true for objective speckle, oblique interference considerations provide one approach to estimating speckle size limits. If the object-lens-image distances are not set up so that a sharply focused image is formed, then waves from adjacent object points will arrive at any given image point. The interferences will produce different brightness results, but the geometry of the system is not changed so as to affect the model described above. The reason for this surprising claim is that, as will be seen presently, only lens focal length and aperture are important.

The simple model described is sufficient if the lens aperture is small relative to lens–image distance, in which case the interference systems are close to the collinear case. Otherwise, oblique interference must be considered.

EFFECT OF DIFFRACTION LIMIT

A "perfect" lens, should such a thing exist, cannot exactly map object points to image points because of fundamental limitations on spatial resolution. Diffraction theory, as presented in Parts 11–15 of this series, implies that a lens cannot transmit spatial frequencies beyond a certain level that depends on the size of the lens aperture. That is, there is a fundamental "smallness" limitation on the size of object information that can be imaged by any given lens, no matter how perfectly it is made. Information that is of smaller scale than a patch or cell of this size is lost or averaged over the cell. This resolution cell size defines the diffraction limit of a lens. At the image there is a corresponding resolution cell whose size is related to the object cell size by the magnification factor of the optical system.

As a result of this diffraction limit, the waves creating an image do not travel directly from object point to image point. Instead, they go from object cell to image cell, and the waves arriving within a cell are mixed together so as to interfere. The irradiance within a cell depends on the way in which the waves falling into that cell interfere with one another. The implication is that the size of the smallest speckle created by a lens is the same as the diffraction-limited cell size.

The resolution of even a perfect lens is limited by diffraction, so:
- *there is a fundamental limit on the smallness of information that can be resolved in an image,*
- *smaller scale detail will be averaged over the diffraction-limited patch or cell,*
- *the waves coming into an image cell will mix and interfere,*
- *the speckle size would seem to be the same as the cell size.*

A more exact approach to describing the effect of a lens on the speckle pattern is to say that the brightness of any point of the image is the result of superimposing the lens point spread functions for adjacent object points. Intuition suggests that the diffraction-limit and the point-spread approaches yield about the same result, but the latter is a complexity that is beyond the scope of these articles and, indeed, is difficult to pursue.

EFFECTS OF LENS ABERRATIONS AND IMPERFECTIONS

The resolution capability of any "real" lens is further compromised by the classic optical aberrations (e.g., astigmatism, coma) and by manufacturing defects. These cause the resolution cell size to be larger than the lower bound imposed by the fundamental diffraction limit. In turn, the speckles are larger, and speckle size is estimated with difficulty because it depends on the nature of the particular lens exemplar in hand.

Lens aberrations and exemplar defects enlarge the resolution cell size considerably beyond the diffraction limit.

HOW IS SUBJECTIVE SPECKLE OBSERVED?

Subjective speckle is very easy to observe or record; in fact, it is ubiquitous when images are created with coherent illumination. All the demonstrations outlined in Part 24 of these articles involved subjective speckle because images were formed with the lens of the eye. Any image recorded using a camera lens or, likely, a pinhole aperture will contain this type of speckle. Photographic film resolution, television raster scan frequencies, and digital photography pixel size will affect the perceived speckle in ways similar to those described for objective speckle.

Subjective speckle is ubiquitous in images made with coherent light and, so, is easily observed.

WHAT NEXT?

The next articles will deal with estimations of speckle size and brightness distributions. ■