Diffraction and Photography

Whenever light goes around an object or passes through an opening it spreads and produces an interference pattern consisting of alternating light and dark regions. It's what causes the fuzziness at the edges of shadows. This phenomenon, known as **diffraction**, is of concern to photographers because of the apertures in their lenses. Although smaller apertures increase depth of field and reduce distortions caused by certain lens imperfections, they also increase the amount of image degradation caused by diffraction. The effects of diffraction have been quantified long ago by complicated mathematical and numerical analyses for many kinds of apertures. Of particular relevance to photography are the results for a circular aperture. They are discussed below.

Consider the configuration shown below, with a point source at infinity, an aperture of diameter D, a lens of focal length F, and a viewing "screen".

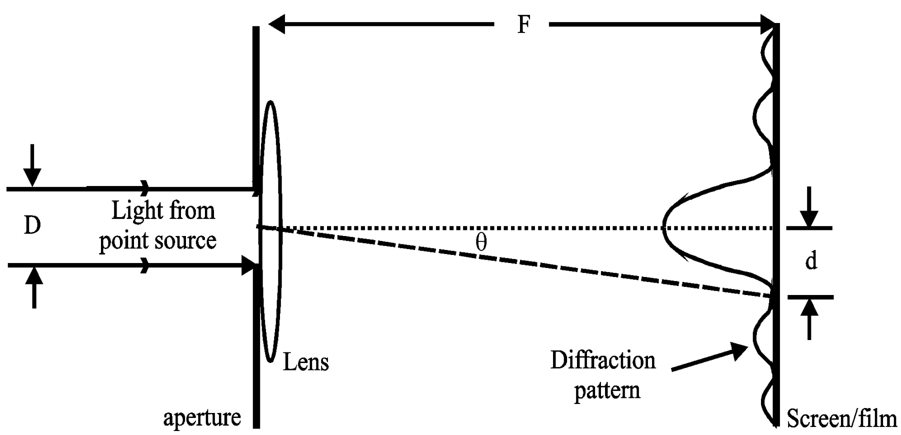

Figure 1

When the light passes through the aperture it **diffracts**, forming a pattern at the screen consisting of a bright central disk (Airy's disk) surrounded by a series of alternating dark and bright rings. The intensities of the bright rings diminish rapidly with distance from the central disk, with the maximum intensity in the first bright ring being less than 2% of that in the central disk, and each succeeding ring being roughly half as bright as the preceding one. The ring radii depend on the diameter of the aperture and the wave length of the light. In particular, **Fraunhofer diffraction** theory predicts that the first dark ring occurs at the (small) angle θ given by

$$\theta = 1.22\frac{\lambda}{D} \qquad (1)$$

(The size of the diffraction pattern shown in the figure has been greatly exaggerated for clarity.) Whenever light passes through an opening you can be sure that diffraction is occurring. But according to equation (1), increasing the diameter of the aperture will shrink the central disk and cause the rings to merge with it. Eventually you will not "see" a diffraction pattern. Conversely, decreasing the diameter will enlarge the central disk and make the rings more prominent.

Suppose that you have two point sources of light and that their diffraction patterns are evident. If the point sources are close enough to each other there will be some overlapping of the patterns. If they are too close, the central disk of one pattern will encroach on that of the other, and the images of the point sources will no longer be "resolved". **Rayleigh's criterion** for the resolution of diffraction patterns requires that the centers of the two central disks be separated by at least the radius of the first dark ring. In other words, their angular separation should be no smaller than given by equation (1), which implies that their linear separation should be at least

$$\begin{aligned} d &= F\theta \\ &= 1.22\frac{F}{D}\lambda \\ &= 1.22\, f\lambda \end{aligned} \qquad (2)$$

where f=F/D is the lens' f-stop. Using the approximate value of λ=0.00056 mm for white light we get

$$\frac{1}{d} = \frac{1460}{f} \qquad (mm^{-1}) \qquad (3)$$

Since d is the minimum allowed separation of "resolved" central disks, 1/d is a measure of the maximum achievable resolution in terms of the number of "resolved" disks per millimeter. It is inversely proportional to the lens' f-stop. For example, at f/4 you can achieve about 365 disks/mm but at f/11 diffraction effects limit you to no better than 133 disks/mm. These linear resolutions should be compared with the resolving capabilities of good films (300 lines/mm) and good lenses (200 lines/mm). Clearly, diffraction can become problematic for large f-stops. But large f-stops is where you want to go for the greatest depth-of-field. It's a trade-off.

So what f-stop should you use? If you're using good film and a good lens and you want good depth of field, then obviously go for the largest f-stop that still produces tolerable diffraction effects. What is tolerable? It depends on what you will be doing with the image. If you intend to look at it from a closer perspective than when you took the photo, then it becomes a subjective decision. Diffraction-caused loss of resolution may force you to smaller f-stops but only you can judge what is small enough. On the other hand, if you will be viewing the image from the same perspective as you viewed the original scene with the naked eye, then your eyes' resolving power becomes the limiting factor. If the smallest angle that your eye can resolve is θ_{eye} then you won't perceive diffraction-caused loss of resolution as long as

$$\theta < \theta_{eye} \tag{4}$$

or, using Equation (1),

$$\begin{aligned} & 1.22\frac{\lambda}{D} < \theta_{eye} \\ \Rightarrow\quad & f < \frac{F}{1.22\lambda}\theta_{eye} \end{aligned} \tag{5}$$

where the units of F and θ_{eye} are millimeters and seconds of arc respectively. For the average human eye, θ_{eye}=60 seconds, so degraded resolution due to diffraction will not be apparent if f<(0.426)F. Table 1 shows the maximum f-stop for some typical lenses.

Table 1

Focal length (mm)	Maximum f-stop
15	6
35	15
50	21
80	34
100	43
200	85
300	128

A photographic subject can be regarded as a large set of point sources, each of which is mapped onto film as a bright central disk surrounded by fainter bright rings. The subject's image is defined by the distribution of the central disks while the distribution of overlapping bright rings contributes "background noise". For large apertures the noise is very localized and insignificant, but for small apertures the rings spread out and affect a larger area of the image. Fortunately, the intensity of this noise is quite low --- the first bright ring is about 6 stops fainter than the central disk! Yes, diffraction noise produces loss of contrast, but you're not likely to see it.

References:

F. A. Jenkins and Harvey E. White, “Fundamentals of Optics”, McGraw-Hill, New York, 1957.