Diffraction patterns in the shadows of disks and obstacles

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We compare the Fresnel diffraction pattern of a thin circular disk with that of a square obstacle, specifically evaluating the on-axis field strength. Photographs of the diffraction patterns reveal some curious features for the square obstacle. Second, the precise electric and magnetic fields behind a conducting circular disk are evaluated without invoking the Fresnel approximation and contrasted with the rigorous electromagnetic result for a metal sphere. The calculations show that the two cases differ only slightly in the Fresnel region. In the near-field new computational results for the sphere are analyzed.

I. Introduction

Experimental observation and analytical calculation of diffraction patterns in the shadow predate the time of Fresnel and the presentation of his theory of diffraction. Mainly the research on shadow region diffraction patterns has dealt with the particular case of a circular disk. In the Fresnel approximation the diffraction pattern behind a circular disk can be computed using Lommel functions. The pattern is characterized by a concentric ring structure and a bright central spot, Poisson’s spot. Early observations were reported by Hufford.1

Other obstacle shapes are interesting as well and produce unanticipated results. The pattern behind a square obstacle can be evaluated straightforwardly in terms of Fresnel integrals or Cornu’s spiral. This type of calculation was performed by White2 to understand resist images created by near-contact printing. He observed an intensity node in the center of the shadow for sufficiently large print gaps. Computer calculations based on a FFT algorithm exhibit other more striking features.3 Kathuria and Herziger4 performed calculations behind square annular apertures but did not describe these unusual features. Our efforts have not uncovered detailed calculations or observations of these diffraction pattern features in the open literature, although a photograph of the pattern in the shadow of an opaque square appears in the ATLAS OF OPTICAL PHENOMENA.5 (Diffraction pattern photographs from other shapes were presented by Harris.6) The complementary problem of Fresnel diffraction by a square aperture is described and photographically displayed in elementary optics texts.) The surprising features in the square obstacle diffraction pattern are discussed in Sec. III, and photographs clearly display them.

Rigorous electromagnetic treatments of diffraction problems are limited to a relatively small number of cases. Hence, one often resorts to some level of approximation in evaluating the diffraction pattern. In Sec. II we review applicable diffraction integrals and present careful, precise expressions suitable for computing the axial electric and magnetic fields behind large apertures and obstacles even at close distances. Essentially, these expressions employ only the approximation that the aperture field may be replaced by the incident field. In Sec. IV these fields are evaluated for a large, thin, perfectly conducting circular disk without invoking the Fresnel approximation because it is not necessary.

Rigorous solutions for thin, conducting disks are known. However, the solutions are either applicable only to small disks or calculable for disks of a couple of wavelengths in diameter.7-9 Experimental observations for the axial fields are available,10 but again these involve small disks. As a result the precise calculations derived in Sec. IV are useful in analyzing the large, conducting disk diffraction problem.

Diffraction by a spherical particle is a basic problem of great interest and can be treated rigorously.11-13 The fundamental nature and applicability of this problem have prompted a large amount of research, much of which involves only far-zone calculations. It is only recently that near-field calculations have been performed.14-16 In Sec. IV new computational results are presented for the axial fields behind a large, per-
fectly conducting sphere. The Poynting vector and electric and magnetic fields are analyzed in the far zone, Fresnel region, and near field. Especially in the near field, the behavior of the fields is quite interesting.

The bright spot observed at the center of the shadow of the sphere is similar to Poisson's spot behind a circular disk; in fact, a metal sphere is often used to demonstrate the appearance of the bright spot behind a circular object. However, one cannot expect the details of the diffraction patterns produced by these two obstacles to be similar. They are two physically different problems. Different axial intensities have been observed. The near-field calculations in Sec. IV show that the details are not at all identical. Nevertheless, a comparison of the careful, precise calculations for the disk with the rigorous results for the sphere shows that there is a convergence in behavior starting in the Fresnel region.

II. Diffraction Integrals

In an earlier paper we discussed diffraction integrals applicable to these types of calculation. Some of the formulas are repeated here for convenience, and other needed expressions are also presented. The reader is also referred to an earlier paper by Mahajan. The diffraction geometry is illustrated in Fig. 1. An infinitely thin, perfectly conducting plane screen containing an aperture A is placed in the x,y plane at z = 0. Assuming an exp(-iωt) time dependence, we write the following expression for the electric field \( E(r) \) in the right half-space, i.e., \( z \geq 0 \):

\[
E(r) = \frac{1}{2\pi} \nabla \times \int_A \mathbf{n} \times E(r') \frac{\exp(ikR)}{R} \, dx' \, dy',
\]

where

\[
R = |r - r'| = \sqrt{(x - x')^2 + (y - y')^2 + z^2},
\]

\( \exp(ikR)/R \) is the free-space Green's function, \( k = \omega/c \) is the wavenumber, \( \mathbf{n} \) is a unit normal pointing in the +z direction, and \( E(r') \) is the exact electric field in the aperture. The integration extends only over the aperture \( A \) because the screen is a perfect conductor. The magnetic field is determined by

\[
\mathbf{H}(r) = \sqrt{\varepsilon/\mu} \times \mathbf{E}(r),
\]

where \( \varepsilon(\mu) \) is the permittivity (permeability) of the medium. It is important to note that we have made no assumptions regarding the value of the electric field in the aperture.

At this point we restrict Eqs. (1) and (2) to on-axis points, i.e., \( (x,y) = (0,0) \), and apertures that are symmetric in \( x \) and \( y \). Without further loss of generality consider an incident electric field that is a normally incident, monochromatic plane wave polarized along the \( x \) axis with unit amplitude. This incident field and associated magnetic field can be described as

\[
E_{\text{inc}}(r) = \exp(ikx)\mathbf{x}; \quad H_{\text{inc}}(r) = \sqrt{\varepsilon/\mu} \exp(ikx),
\]

where \( \mathbf{x(y)} \) is a unit vector in the \( x(y) \) direction. Owing to the symmetry of the aperture and the idealization of an infinitely thin plane screen, we can make a statement about the symmetry of the exact electric field in the aperture; namely, \( E_x(x,y,0) \) is an even function in \( x,y \) and \( E_y(x,y,0) \) is an odd function in \( x,y \). When these symmetry considerations are applied to Eqs. (1) and (2), one obtains the following result: only the \( x \) component of \( \mathbf{E} \) and the \( y \) component of \( \mathbf{H} \) are nonzero. The expressions for \( E_x \) and \( H_y \) are

\[
E_x(0,0,z) = \frac{1}{2\pi} \int_A E_x(x',y',0) \frac{\exp(ikR_0)}{R_0} \times \left( ik - \frac{1}{R_0} \right) \frac{z}{R_0} \, dx' \, dy',
\]

\[
H_y(0,0,z) = \frac{\sqrt{\varepsilon/\mu}}{2\pi ik} \left[ -E_x(x',y',0) \frac{\exp(ikR_0)}{R_0} \times \left( z^2 + x'^2 + y'^2 \right) - \frac{2}{R_0} \left( ik - \frac{1}{R_0} \right) \right] \, dx' \, dy',
\]

where \( R_0 = |r - r'| = \sqrt{x'^2 + y'^2 + z^2} \).

To evaluate Eqs. (4) and (5) we will replace the true aperture electric field with the incident field. This approximation is reasonable for apertures that are much larger than a wavelength. The expressions become

\[
E_x(0,0,z) = \frac{1}{2\pi} \int_A E_{\text{inc}}(x',y',0) \frac{\exp(ikR_0)}{R_0} \times \left( ik - \frac{1}{R_0} \right) \frac{z}{R_0} \, dx' \, dy',
\]

\[
H_y(0,0,z) = \frac{\sqrt{\varepsilon/\mu}}{2\pi ik} \left[ -E_{\text{inc}}(x',y',0) \frac{\exp(ikR_0)}{R_0} \times \left( \frac{z^2}{R_0^3} \left( k^2 - \frac{3k}{R_0} + \frac{3}{R_0^2} \right) \right) \right] \, dx' \, dy',
\]
HY(Oz) = \frac{2\pi ik}{A} \left[ -E_{\text{inc}}(x',y',0) \exp(ikR_0) \right.
\times \left[ \frac{z^2 + x'^2}{R_0^2} \left( -\frac{ik^2}{R_0^2} + \frac{3}{R_0^2} \right) \right]
\left. + \frac{2}{R_0} \left( ik - \frac{1}{R_0} \right) \right] dx'dy'.

(7)

### III. Circular Disk vs Square Obstacle

First we consider a calculation that is valid in the Fresnel region. We define the lower boundary of this region for axial field points to be

\[ z^3 \geq \frac{x}{4\lambda} a^4, \]

where \( a \) is the characteristic dimension of the aperture or obstacle. At this position the error in computing the phase, \( ikR_0 \), using only the first two terms of the binomial expansion is <1 rad. Consider two particular obstacles: a circular disk of diameter \( 2a \) and a square obstacle of dimensions \( 2a \) by \( 2a \):

- For a circular disk:
  
  \[ A_{\text{circle}} = 1 - \text{circ}(\sqrt{x^2 + y^2}/a), \]  
  \[ V_{\text{circ}}(z) = \exp(ikz) \exp(\frac{izr^2}{\lambda z}), \]

- For a square obstacle:
  
  \[ A_{\text{square}} = 1 - \text{rect}(x/a) \text{rect}(y/a), \]  
  \[ V_{\text{square}}(z) = \exp(ikz) \left[ 1 + 2i[C(t_a) + iS(t_a)]^2 \right], \]

where

\[ t_a = a \sqrt{\frac{2}{\lambda z}}, \]

\( C(t_a) \) and \( S(t_a) \) are the Fresnel integrals.\(^{20}\) We wish to point out that, for the case of the circular disk, it is not necessary to make the Fresnel approximation to evaluate the integral analytically.\(^{18,19,21}\) However, we have done so to facilitate comparison with Eq. (13).

The square modulus of the field \( |V_{\text{circ}}(z)|^2 \) vs \( \log(z) \) is plotted in Fig. 2 assuming \( 2a = 1 \) mm and \( \lambda = 0.5 \) \( \mu \)m. The axial field strength in the shadow of the circular disk is constant and equal to one. This is the phenomenon of Poisson's spot, namely, the appearance of a tiny bright spot at the center of the shadow. The phenomenon, which can be observed when a circular, opaque obstacle is illuminated by a plane wave, is a tiny, bright spot at the center of the shadow of the obstacle. This is in contrast to the curve for the square obstacle which drops from unity in the far zone to <0.10 at the boundary of the Fresnel region. However, the axial field strength is sufficiently larger than zero to suggest that a dim spot may be observable behind a square disk.

Figures 3(a)–(d) are photographs of the diffraction pattern behind the two previously described obstacles. In each case an expanded and collimated He–Ne laser beam illuminated a glass slide on which a thin chrome obstacle was deposited. The film plane was located \( z = 100 \) mm from the obstacle. The shiny side of the obstacle was oriented toward the film plane. Figures 3(a) and (b) were recorded at the same exposure for direct comparison of the patterns. Figures 3(c) and (d) are the same as Figs. 3(a) and (b) except for an increase in exposure by a factor of 16.

In Fig. 3(a), the circular disk pattern, the dominant features are a tiny bright spot, Poisson's spot, in the center of the shadow and a concentric ring structure. The central dot appears to be as bright as the incident field, in agreement with the calculation. In Fig. 3(b), the square obstacle pattern, one can just begin to discern a dim central spot, as the calculation suggested. The existence of this spot is more firmly established in Fig. 3(d).
The square obstacle diffraction pattern also displays some other curious features. As far as we know these features have not been reported or described in the open literature. The central region of the shadow is a checkerboard pattern of bright and dark areas. Observation of familiar square aperture Fresnel patterns or intuition might lead one to expect this sort of pattern. However, the appearance of radial bands toward the outer part of the geometrical shadow is perhaps surprising.

In a crude way one is tempted to expect that the observed obstacle pattern is the difference between the incident field (uniform plane wave) and the observed aperture pattern. However, a careful application of Babinet's principle requires that the complex fields be subtracted (magnitude and phase), not the intensity recorded on film (magnitude squared). That the obstacle pattern displays features not observed in the aperture pattern indicates that the phase of the diffracted field relative to the incident field is important in the obstacle problem.

We add a final observation regarding the radial bands. We have observed that the number of these bands increases with decreasing \( z \), and they seem to grow from the center of the edges. The surprising details of this diffraction pattern seem to warrant further study.

### IV. Circular Disk vs Metal Sphere

We turn now to a more careful computation of the fields behind the circular disk using the precise expressions from Sec. II. These calculations are useful in analyzing the diffraction pattern and serve as a means for comparison with the rigorous electromagnetic solution for the fields behind a metal sphere. In both cases we assume that the objects are perfectly conducting. Although it is not uncommon for a metal sphere to be observed obstacle pattern. However, a careful application of Babinet's principle requires that the complex fields be subtracted (magnitude and phase), not the intensity recorded on film (magnitude squared). That the obstacle pattern displays features not observed in the aperture pattern indicates that the phase of the diffracted field relative to the incident field is important in the obstacle problem.

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The axial electric and magnetic fields can be computed precisely from Eqs. (6) and (7) for a conducting circular disk, Eq. (9). The results are

\[
E_x(0,0,z) = \frac{z}{d} \exp(i k d),
\]

\[
H_y(0,0,z) = \frac{\sqrt{\mu}}{2} \left[ 1 + \frac{z^2}{d^2} + \frac{a^2}{i k d^2} \right] \exp(i k d),
\]

where \( d = \sqrt{z^2 + a^2} \). The time-averaged Poynting vector, \( \langle \mathbf{S} \rangle = \frac{1}{2} \text{Re}(\mathbf{E} \times \mathbf{H}^*) \), normalized by the magnitude of the incident Poynting vector, \( \langle |\mathbf{S}|^2 \rangle = \frac{1}{2} \langle |\mathbf{E}|^2 \rangle \langle |\mathbf{H}|^2 \rangle \), is

\[
\mathbf{S} = \frac{\langle |\mathbf{S}|^2 \rangle}{\langle |\mathbf{S}|^2 \rangle} = \frac{z^2}{d^2} \left( 2z^2 + \frac{a^2}{2z} \right) \mathbf{z}.
\]

The full electromagnetic solution for scattering from a perfectly conducting metal sphere of radius \( a \) is described elsewhere. Below we write the solution for axial points, i.e., \( r = z, \theta = \phi = 0 \),

\[
E_r = \frac{\exp(ikz) + \frac{1}{kz} \sum_{n=1}^{\infty} \frac{(2n + 1)}{2} \left[ a_n s_n^{(1)}(kz) + ib_n s_n^{(1)}(kz) \right]}{\sqrt{\mu}},
\]

\[
H_r = \frac{\exp(ikz) + \frac{i}{kz} \sum_{n=1}^{\infty} \frac{(2n + 1)}{2} \left[ a_n s_n^{(1)}(kz) - ib_n s_n^{(1)}(kz) \right]}{\sqrt{\mu}},
\]

where \( s_n^{(1)} \) is the \( n \)-th-order Riccati-Hankel function of the first kind and \( s_n^{(1)} \) indicates differentiation with respect to the argument. The coefficients \( a_n \) and \( b_n \) are

\[
a_n = \frac{\psi_n^{(1)}(ka)}{\psi_n^{(1)}(ka)}; \quad b_n = \frac{\psi_n^{(1)}(ka)}{\psi_n^{(1)}(ka)},
\]

where \( \psi_n \) is the Riccati-Bessel function of the first kind.

The normalized Poynting vector is simply

\[
\mathbf{S} = \frac{\text{Re}(\mathbf{E}_r H_r^*)}{\sqrt{\mu}} \mathbf{z}.
\]

Computation of Eqs. (14)–(16) is straightforward, while Eqs. (17)–(19) require some care. However, several studies of these types of calculation have been performed, and requirements for satisfactory convergence and accuracy can be obtained.

We plotted Eqs. (16) and (19) vs \( \log(z) \) for \( 2a = 1 \) mm and \( \lambda = 0.5 \) mm. The results are shown in Fig. 4. In the Fresnel region the two curves differ only slightly. However, in the near field the axial Poynting vector for the sphere goes to zero at the surface of the sphere (\( z = 0.5 \) mm) because of the boundary conditions on \( \mathbf{E} \).
Fig. 5. On-axis field strengths, circular disk vs metal sphere. The square modulus of E and H (normalized by $c/\mu$) for the circular disk (---) and the metal sphere (----) are plotted vs log(z). Again z is in millimeters. The fields for the sphere are oscillating with a period of $\lambda/2$ so only the envelope of modulation is shown; this envelope is the same for both E and H.

Fig. 6. Examination of oscillatory behavior of axial fields behind a metal sphere. The square modulus of the fields, $|E|^2$ (--) and $|H|^2/(c/\mu)$ (----), are shown for (a) $z = 0.5$ mm, (c) $z = 1.0$ mm, and (e) $z = 10.0$ mm. The phase difference between the fields is shown for (b) $z = 0.5$ mm, (d) $z = 1.0$ mm, and (f) $z = 10.0$ mm.
Likewise, the Poynting vector for the disk drops to zero at the surface of the disk \((z = 0 \text{ mm})\). That these two boundaries occur at different physical locations partially explains the difference in behavior of the near-field Poynting vectors. Ultimately, though, this Poynting vector behavior is predicated on the behavior of the electric and magnetic fields.

Particularly in the near field, at least for direct detection, it is more appropriate to discuss the electromagnetic fields themselves, especially the electric field, rather than the Poynting vector. We base this statement on our understanding of the physical processes involved in observing or measuring optical fields. When considering the interaction of light with a silver halide grain embedded in an emulsion, a semiconductor photodiode, or a simple two-level atom, the primary term in the interaction Hamiltonian is the potential energy of an electron in an applied field. As a result, the electron transition rate or probability is proportional to the energy density of the field, i.e., the square of the magnitude of the electric field. This electron transition probability is what is observed as exposed film or photocurrent.

We discuss this behavior of the electric and magnetic fields in the near field now. Figure 5 shows the square modulus of \( \mathbf{E} \) and \( \mathbf{H} \) (normalized by \( e/\mu \)) for the circular disk and for the metal sphere. In the case of the sphere, the field intensities are oscillating with a spatial period of \( \lambda /2 \). We put off the examination of this oscillatory behavior momentarily. In Fig. 5, only the envelope of these oscillations is shown. The upper and lower bounds for \( |\mathbf{E}|^2 \) and \( |\mathbf{H}|^2 / (e/\mu) \) are the same. Contrast this behavior with the disk: there are no oscillations. The electric field intensity goes to zero monotonically as \( z \to 0 \), and the magnetic field intensity goes to one-quarter.

To understand the oscillatory behavior of the fields behind the sphere, examine Fig. 6. We have plotted six cycles in each figure. Note in Fig. 6(a) that, at \( z = 0.5 \text{ mm} \) (the edge of the sphere), the electric field intensity is indeed equal to zero, but that the magnetic field intensity is equal to four. The fields undergo full modulation (0–4), the magnetic field reaching a maximum when the electric field reaches a minimum and vice versa. The energy density is alternately contained in the electric and magnetic fields. However, for the range of \( z \) shown, the electric and magnetic fields are very nearly 90° out of phase with each other [see Fig. 6(b)]. Thus, even though the field strengths are at some positions simultaneously nonzero, the Poynting vector is almost zero because of the phase difference.

Figure 6(c) shows the electric and magnetic fields in the vicinity of \( z = 1.0 \text{ mm} \). The fields still have a rather strong oscillatory behavior, although the amplitude has decreased. Figure 6(d) shows that the fields are starting to be in phase; hence, the Poynting vector is growing in magnitude. Finally, in Fig. 6(e) we show the fields at \( z = 10.0 \text{ mm} \). Now the oscillations have almost completely died out. Also, Fig. 6(f) shows that the fields are almost completely phased. At this point the Poynting vector is approaching unity. Indeed, as \( z \) increases, the electric and magnetic field oscillations die out, and the field strengths approach unity. At the same time the fields are in phase. The resulting Poynting vector is a constant.

V. Summary

As the computational results and photographs in this paper show, diffraction patterns in the shadows of disks and obstacles are rich in detail and unanticipated features. A square obstacle forms a dim spot in the center of its shadow; a circular disk forms a much brighter spot. In addition the square obstacle diffraction pattern has a checkerboard bright and dark region in the center and surprising radial bands near the edge of the geometrical shadow.

A comparison of the axial fields behind a conducting disk and a metal sphere shows that it is not correct to assume that the behavior is similar. Sufficiently far behind the objects the fields are nearly the same, but this is definitely not the case in the near field.

The differing behavior of the electric and magnetic fields vs the Poynting vector in the region close behind the sphere brings into question what might be observed. If direct measurements are made, i.e., a detector or film emulsion is placed in the near field, the oscillatory electric field intensity \(|\mathbf{E}|^2\) will be seen. However, one often images the fields behind an obstacle. In such an arrangement the near field features of the sphere will not be noticed. In effect the near-field electric field structure does not propagate.

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Some of these results were presented at the 1987 Annual Meeting of the Optical Society of America in Rochester, NY.

References


estimated $200 million in losses, Kevlar has just reached the break-even point. And with Kevlar patents due to expire in 1990, the company admits that sales will probably level well below original expectations. "Kevlar was supposed to be a home run," said Katrak. But it was not, and the experience has led Du Pont to reconsider the company's basic attitudes.

Company executives now speak of reversing the traditional Du Pont research-and-development approach of finding markets for its discoveries. Now it is taking aim first at markets and seeking products to fill them. The theme of the most recent Du Pont annual report is "Marketing Excellence: A Du Pont Priority." According to Bogner: "They're moving from a product-driven to a market-driven philosophy." For some analysts, the recent changes in Du Pont are a cause for optimism. But others worry that they bespeak a worrisome new impatience at the company, an emphasis on short-term profitability at the expense of the company's traditional commitment to long-term research.

Perhaps a more serious challenge to the Du Pont way comes from the company's recent foray into the high-tech fields of biotechnology and electronics, where the technology cycles are shorter, competition from smaller firms is stiffer, and Du Pont's traditional advantages of patience and size are often more an impediment than a virtue. "It's a marvelous company," said Ralph Hardy, who headed Du Pont's life science program for five years before leaving to join the small Boston-based biotechnology company Biotechnica International, Inc. in 1984. "But there's an intensity in a small company that you don't see at a large corporation like that. In a small company, most employees are participants, and there's nothing like that to bring out the best in an individual. . . In terms of decision-making and getting agreement, you can do more in a day at Biotechnica than I could in a month at Du Pont."

MacLachlan admits that is a concern. "Small companies tend to be a little faster on their feet. They get into the market faster, they have a tendency to be more driven." Du Pont, he said, sometimes is guilty of dragging its feet and sticking with unfruitful research projects too long. But Du Pont officials insist that the company is becoming more flexible, pointing as an example to the Genesis 2000 DNA gene sequencer introduced last fall. The desk-top machine, which cuts the time needed to decipher the biological structure of genes from a matter of months to an afternoon, was created through an unusual collaboration among groups of scientists at the experimental station doing unrelated work.

Working together informally, scientists from the various departments conceived the idea on paper 2½ years ago, and quickly carried the project forward to the point where Du Pont now stands with a very competitive entry in a $100 million-a-year market. "The whole thing was done sub rosa," said MacLachlan. "No one managed it except the people who actually did it." Added Quisenberry: "The success of the development thus far has been the close coupling of science in all the departments and the good sense of management to stay out of the way."

To encourage that kind of spontaneity, Du Pont has since 1979 had a number of special technology committees, drawing together representatives from various departments to promote flexibility and cross-fertilization of ideas. "I can't tell you it worked very well in the beginning," MacLachlan said. "You don't take people who are used to being independent and say 'Now you've got to work together.' But as time goes on you get a culture change. . . Now we have a mechanism in place that forces us to work together."

Will it work? Some analysts still fault the company's efforts in pharmaceuticals and biotechnology for taking too long to come up with marketable products. "At this stage all their efforts in the biomedical area have yet to bear fruit. If they keep doing things as they have so far, they'll have a long way to go," said William R. Young, an analyst with Drexel Burnham Lambert, Inc. in New York. But few doubt that Du Pont will find a way to adapt its corporate culture to the challenges of new technologies. "When people ask me who I worry about at night, I tell them I worry about companies like Du Pont," said Jerry Caulder, president of Myogen, a California company that, like Du Pont, is engaged in developing agricultural chemicals through biotechnology. "Their only real weakness is that they take longer to make decisions. But once they decide to get into an area, they've got the patience, the money, and the direction."