CS7GV2: Mathematics of Light and Sound, M.Sc. in Computer Science.

Reflection

Refraction

Lecture #9: Diffraction

$\boxed{\text{Diffraction}}$

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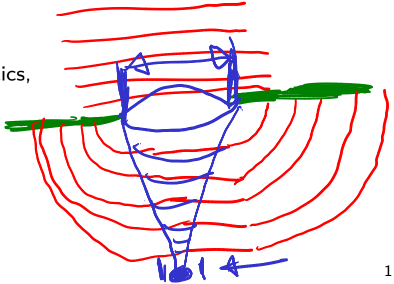


Amplitude away from source

Point source
area source

Speed of light* in m s^{-1} is c

Wavelength in m is λ

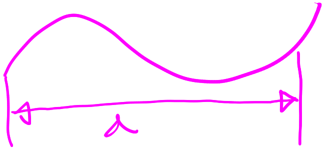
Wave period in s is $T = \lambda / c$

Wave frequency in Hz is $\nu = 1/T$

Angular freq. in rad s^{-1} is $\omega = 2\pi / T$

Wave number in rad m^{-1} is $k = 2\pi / \lambda$

m/s



2π

Amplitude away from source

A phasor encodes max. amplitude $A(\boldsymbol{p})$ and phase $\phi(\boldsymbol{p})$ at position $\boldsymbol{p}$,

$$U(\boldsymbol{p}) = A(\boldsymbol{p}) \exp\{\mathrm{j}\ \phi(\boldsymbol{p})\}.$$

The scalar value of an EM wave vector component at time t can be found as,

$$\begin{aligned} u(\boldsymbol{p}, t) &= \mathrm{Re}\{U(\boldsymbol{p})\ \exp\{-\mathrm{j}\,\omega t\}\} \\ &= A(\boldsymbol{p}) \cos(\omega\ t - \phi(\boldsymbol{p})). \end{aligned}$$

Amplitude away from source

Let $\boldsymbol{p}_1$ be the point source of a wave and let $\boldsymbol{p}_0$ be somewhere else. Let t_{01} be the time it takes for the wave to travel.

$$u(\boldsymbol{p}_0, t_{01}) = \mathrm{Re}\left\{ U(\boldsymbol{p}_1)\, \frac{\exp\{-\mathrm{j}\,\omega\, t_{01}\}}{r_{01}} \right\}$$

where $r_{01} = \|\boldsymbol{p}_0 - \boldsymbol{p}_1\| = c\, t_{01}$ is the Euclidean distance between the points.

Amplitude away from source

$$\omega\ t_{01} = \frac{2\pi}{T}\ t_{01} = \frac{2\pi}{\lambda/c}\ t_{01}$$
$$= \frac{2\pi\ c}{\lambda}\ t_{01} = k\ r_{01}$$

Since there is no explicit time term, this can be used to express the phasor at $\boldsymbol{p}_0$,

$$U(\boldsymbol{p}_0) = U(\boldsymbol{p}_1)\ \frac{\exp\{-\mathrm{j}\ k\ r_{01}\}}{r_{01}}$$

Amplitude away from source

Speed of light* in $\mathrm{m\,s^{-1}}$ is c

Wavelength in m is λ

Wave period in s is $T = \lambda / c$

Wave frequency in Hz is $\nu = 1/T$

Angular freq. in $\mathrm{rad\,s^{-1}}$ is $\omega = 2\pi/T$

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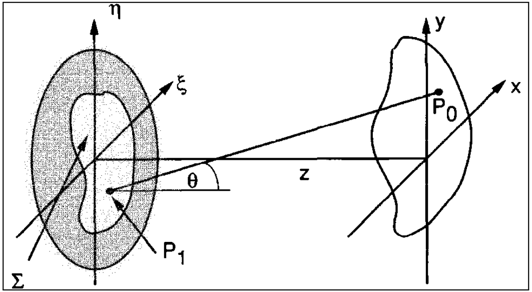
Amplitude after an aperture



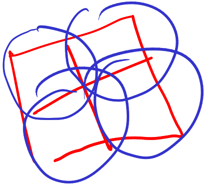
Amplitude after an aperture

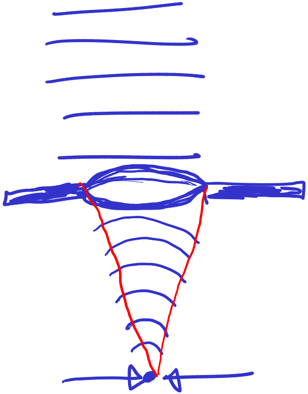
Amplitude at $\boldsymbol{p}_0$ is the integral of the contributions from all possible points $\boldsymbol{p}_1$ in the aperture,

$$U(\boldsymbol{p}_0) = \frac{1}{\mathrm{j}\,\lambda} \iint_{\Sigma} U(\boldsymbol{p}_1)\, \frac{\exp\{\mathrm{j}\, k\, r_{01}\}}{r_{01}} \cos\theta \, \mathrm{d}s.$$

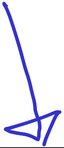
This expresses the Huygens-Fresnel principle of wave summation.

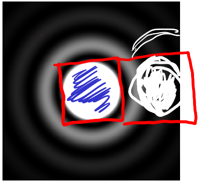
Amplitude after an aperture





Airy disc





BLUR

- An aperture affects wave summation such that unusual constructive and destructive interference arises. Spot dia. $\boxed{2.44\,\lambda\, f/D}$.

$f/D \approx f/\#$

$\lambda = 532\,\text{nm}$

f-number

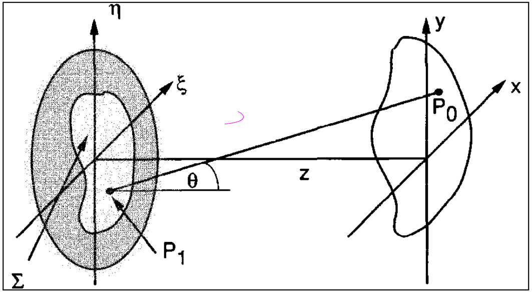
Amplitude after an aperture

This is termed *diffraction* and it happens to all physical waves:

- light
- sound
- vibration (e.g. of water)
- gravitational waves

Diffuse reflection from a rough surface can also be understood as diffraction.

Amplitude after an aperture



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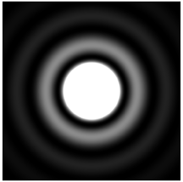
Mathematical expression of HF using phasors.



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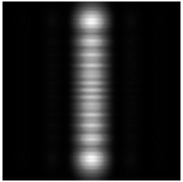
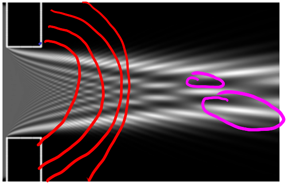


Intensity in $x-y$ plane after a narrow rectangular aperture.



Intensity in $x-z$ plane through and after a narrow rectangular aperture.

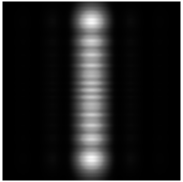
Significant computation is required for *numerical solutions* that simulate diffraction effects through summation of wave amplitudes.

Many different techniques can be used, e.g. *finite element methods*, to find wave amplitudes at discrete volumes in space at successive steps in time.

Note that intensity at distance r_{01} is distributed over a sphere whose surface area is $4\pi r_{01}^2$. So intensity scales $\propto 1/r_{01}^2$.

Since amplitude is the square root of intensity, it scales $\propto \sqrt{1/r_{01}^2} = 1/r_{01}$.

In two dimensional wave propagation (e.g. on water) the amplitude scales $\propto 1/\sqrt{r_{01}}$.



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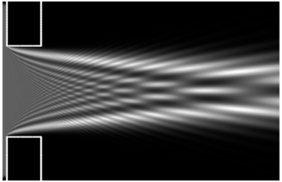

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Fresnel Approximation

Since $\cos\theta = z/r_{01}$, wave summation can be rewritten in more explicit rectangular coordinates as,

$$U(x,y,z) = \frac{z}{\mathrm{j}\,\lambda} \iint_{\Sigma} U(\xi,\eta)\, \frac{\exp\{\mathrm{j}\; k\; r_{01}\}}{r_{01}^2}\, \mathrm{d}\xi\, \mathrm{d}\eta$$

with distance calculated as,

$$r_{01} = \sqrt{z^2 + (x-\xi)^2 + (y-\eta)^2}$$

Fresnel Approximation

To facilitate *analytical solutions*, an approximation for distance r_{01} uses a binomial expansion to replace the square root,

$$\begin{aligned}\sqrt{1+b} &= (1+b)^{\frac{1}{2}} \\ &= 1 + \frac{1}{2}b - \frac{1}{8}b^2 + \ldots\end{aligned}$$

when $|b| < 1$.

Fresnel Approximation

$$r_{01} = \sqrt{z^2}\sqrt{1 + \big(\frac{x-\xi}{z}\big)^2 + \big(\frac{y-\eta}{z}\big)^2}$$
$$\approx z\big[1 + \frac{1}{2}\big(\frac{x-\xi}{z}\big)^2 + \frac{1}{2}\big(\frac{y-\eta}{z}\big)^2\big]$$

using only the first two terms of the expansion with $b = \left(\frac{x-\xi}{z}\right)^2 + \left(\frac{y-\eta}{z}\right)^2$.

(cf. parabolic approx. of spherical wavefront.)

Fresnel Approximation

The same approximation for r_{01} doesn't have to be used for all occurances.

Using the first term only, the denominator $r_{01}^2 \approx z^2$. This can be factored out of the integral into the scaling term,

$$\frac{z}{\mathrm{j}\,\lambda\,z^2} = \frac{1}{\mathrm{j}\,\lambda\,z}.$$

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when $|b| < 1$.

$$\begin{aligned} r_{01} &= \sqrt{z^2} \sqrt{1 + \left(\frac{x - \xi}{z}\right)^2 + \left(\frac{y - \eta}{z}\right)^2} \\ &\approx z\left[1 + \frac{1}{2}\left(\frac{x - \xi}{z}\right)^2 + \frac{1}{2}\left(\frac{y - \eta}{z}\right)^2\right] \end{aligned}$$

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Convolution

Using the first two terms of the approximation,

$$\exp\{\mathrm{j}\ k\ r_{01}\} \approx \exp\Big\{\mathrm{j}\ k\ z\Big[1 + \frac{1}{2}\Big(\frac{x-\xi}{z}\Big)^2 + \frac{1}{2}\Big(\frac{y-\eta}{z}\Big)^2\Big]\Big\}$$

$$= \exp\{\mathrm{j}\ k\ z\}\ \exp\Big\{\mathrm{j}\ k\ z\Big[\frac{1}{2}\Big(\frac{x-\xi}{z}\Big)^2 + \frac{1}{2}\Big(\frac{y-\eta}{z}\Big)^2\Big]\Big\}$$

$$= \exp\{\mathrm{j}\ k\ z\}\ \exp\Big\{\mathrm{j}\ \frac{k}{2z}[(x-\xi)^2 + (y-\eta)^2]\Big\}$$

Convolution

$$U(x, y, z) \approx \frac{\exp\{\mathrm{j}\, k\, z\}}{\mathrm{j}\, \lambda z} \iint_{-\infty}^{+\infty} U(\xi, \eta) \times$$

$$\exp\left\{\mathrm{j}\, \frac{k}{2z}\left[(x-\xi)^2 + (y-\eta)^2\right]\right\}\, \mathrm{d}\xi\, \mathrm{d}\eta.$$

Accurate only for the "near field" close to the aperture because of distance approximation.

Convolution

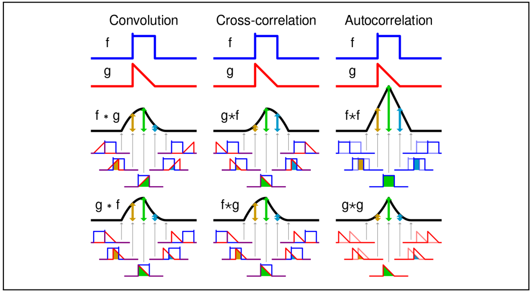
To facilitate analysis, it can be written as a *convolution* of the aperture with a function h.

$$U(x, y, z) \approx \iint_{-\infty}^{+\infty} U(\xi, \eta) \times h(x - \xi, y - \eta) \, \mathrm{d}\xi \, \mathrm{d}\eta.$$

Convolution *kernel* $h(v, w) =$

$$\frac{\exp\{\mathrm{j}\, k\, z\}}{\mathrm{j}\, \lambda z} \exp\left\{\mathrm{j}\, \frac{k}{2z}(v^2 + w^2)\right\}.$$

Convolution



Convolution

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$$= \exp\{\mathrm{j}\,k\,z\}\ \exp\left\{\mathrm{j}\,k\,z\left[\frac{1}{2}\left(\frac{x-\xi}{z}\right)^2 + \frac{1}{2}\left(\frac{y-\eta}{z}\right)^2\right]\right\}$$

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$$U(x,y,z) \approx \frac{\exp\{\mathrm{j}\,k\,z\}}{\mathrm{j}\,\lambda z} \iint_{-\infty}^{+\infty} U(\xi,\eta)\times$$

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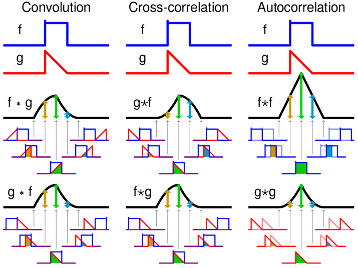

Fourier transform

$$(x-\xi)^2 = x^2 - 2x\xi + \xi^2,$$
$$(y-\eta)^2 = y^2 - 2y\eta + \eta^2.$$

Hence further factorization outside the integral is possible since only those terms in ξ and η need to remain inside.

$$\exp\left\{\mathrm{j}\,\frac{k}{2z}[(x-\xi)^2 + (y-\eta)^2]\right\} =$$

Fourier transform

$$\exp\left\{\mathrm{j}\,\frac{k}{2z}(x^2+y^2)\right\}\times$$
$$\exp\left\{\mathrm{j}\,\frac{k}{2z}(\xi^2+\eta^2)\right\}\times$$
$$\exp\left\{-2\,\mathrm{j}\,\frac{k}{2z}(x\xi+y\eta)\right\}.$$

Note that $k = 2\pi/\lambda$,

$$\frac{k}{2z} = \frac{2\pi}{\lambda}\frac{1}{2z} = \frac{2\pi}{\lambda 2z} = \frac{\pi}{\lambda z}.$$

Fourier transform

$$
\begin{aligned}
&U(x, y, z) \approx \\
&\frac{\exp\{\mathrm{j}\, k\, z\}}{\mathrm{j}\, \lambda z} \exp\left\{\mathrm{j}\, \frac{k}{2z}(x^2 + y^2)\right\} \times \\
&\iint_{-\infty}^{+\infty} U(\xi, \eta) \exp\left\{\mathrm{j}\, \frac{k}{2z}(\xi^2 + \eta^2)\right\} \times \\
&\exp\left\{-\mathrm{j}\, \frac{2\pi}{\lambda z}(x\xi + y\eta)\right\} \, \mathrm{d}\xi \, \mathrm{d}\eta.
\end{aligned}
$$

fourier transform

Fourier transform

This integral can be recognised as the (scaled) *Fourier transform* of the (scaled) aperture evaluated at spatial frequencies,

$$f_X = \frac{x}{\lambda z} \qquad f_Y = \frac{y}{\lambda z}.$$

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Fraunhofer Approximation

When z in $\frac{k}{2z}(\xi^2+\eta^2)$ is very big,* this expression is close to 0 so its exponent is close to 1. So it is not essential to use it a scaling factor,

$$U(x,y,z) = \frac{\exp\{\mathrm{j}\,kz\}\exp\left\{\mathrm{j}\,\frac{k}{2z}(x^2+y^2)\right\}}{\mathrm{j}\,\lambda z}$$

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Hence wave summation can be expressed as the (scaled) Fourier transform of the (unscaled) aperture evaluated at frequencies,

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Accurate only for the "far field" distant from the aperture because of distance aassumption.

Fraunhofer Approximation

For intensity $I(x, y, z) = |U(x, y, z)|^2$, the numerator and denominator of the scaling term simplify as follows.

$$\begin{aligned} |\exp\{\mathrm{j}\, kz\}|^2 &= \exp\{+\mathrm{j}\, kz\} \times \\ &\qquad\qquad \exp\{-\mathrm{j}\, kz\} \\ &= \exp\{+\mathrm{j}\, kz - \mathrm{j}\, kz\} \\ &= \exp\{0\} = 1. \end{aligned}$$

Fraunhofer Approximation

$$\begin{aligned} |\mathrm{j}\,\lambda z|^2 &= (+\mathrm{j}\,\lambda z)(-\mathrm{j}\,\lambda z) \\ &= +1\,\lambda^2 z^2 = \lambda^2 z^2. \end{aligned}$$

For a nice alternative derivation of the material in this lecture, see `https://www.youtube.com/watch?v=JKxDa5D3GnQ`.

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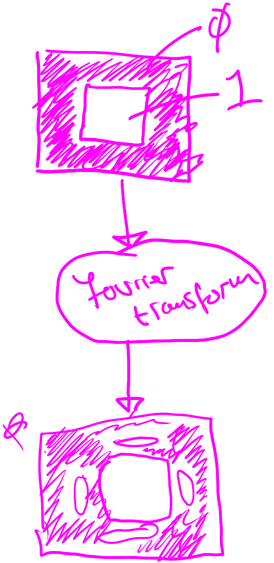
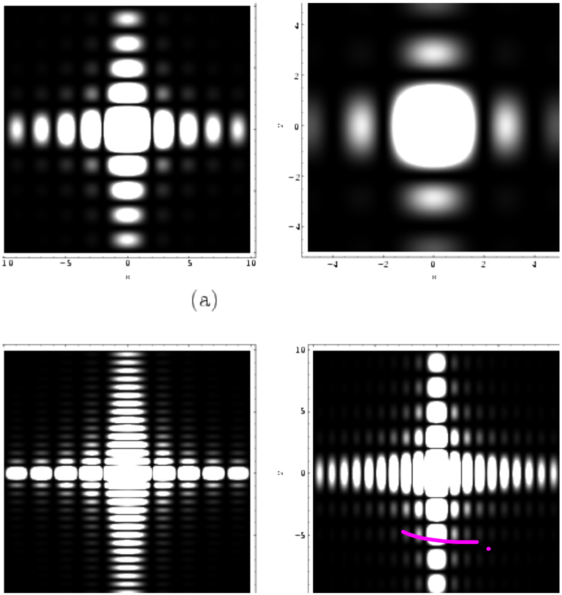
~~More examples~~ ASSIGNMENT

PRACTICE DOING THIS WITH VARIOUS APERTURE SHAPES





(a)