Appendices

A The Fourier Transform

A1 Definitions

The one-dimensional *Fourier transform* of the function $f(x)$ is defined as

$$\Im\{f(x)\} = F(u) = \int_{-\infty}^{\infty} f(x)\exp[-i2\pi ux]dx \tag{A1}$$

The inverse one-dimensional *Fourier transformation* is defined as

$$\Im^{-1}\{F(u)\} = f(x) = \int_{-\infty}^{\infty} F(u)\exp[i2\pi ux]du \tag{A2}$$

The functions $f(x)$ and $F(u)$ are called *Fourier transform pair*.

The two-dimensional *Fourier transform* of the function $f(x,y)$ is defined as

$$\Im\{f(x,y)\} = F(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\exp[-i2\pi(ux+vy)]dxdy \tag{A3}$$

The corresponding inverse two-dimensional *Fourier transformation* is defined as

$$\Im^{-1}\{F(u,v)\} = f(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F(u,v)\exp[i2\pi(ux+vy)]dudv \tag{A4}$$

The Fourier transformation is a powerful mathematical tool to describe and analyse periodic structures. If x is the time coordinate of a signal (unit: *s*), then u is the corresponding frequency (unit: $1/s \equiv Hz$). In the two-dimensional case *(x,y)* are often spatial coordinates (units: *meter*), while *(u,v)* are the corresponding spatial frequencies (units: $1/meter$).

A2 Properties

In the following some useful theorems about Fourier transforms are summarized. These formulas are written for the two-dimensional case.

1. Linearity theorem

$$\Im\{af(x,y)+bg(x,y)\}=aF(u,v)+bG(u,v) \tag{A5}$$

where a and b are constants, $F(u,v)=\Im(f(x,y))$ and $G(u,v)=\Im(g(x,y))$.

2. Similarity theorem

$$\Im\{f(ax,by)\}=\frac{1}{|ab|}F\left(\frac{u}{a},\frac{v}{b}\right) \tag{A6}$$

3. Shift theorem

$$\Im\{f(x-a,y-b)\}=F(u,v)\exp[-i2\pi(ua+vb)] \tag{A7}$$

4. Rayleigh's (Parseval's) theorem

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|f(x,y)|^2\,dxdy=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|F(u,v)|^2\,dudv \tag{A8}$$

5. Convolution theorem

The two-dimensional convolution of two functions $f(x,y)$ and $g(x,y)$ is defined as

$$(f\otimes g)(x,y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}f(x',y')g(x-x',y-y')dx'dy' \tag{A9}$$

where the $\otimes$ denotes the convolution operation. The convolution theorem states that the Fourier transform of the convolution of two functions is equal to the product of the Fourier transforms of the individual functions:

$$\Im\{f(x,y)\otimes g(x,y)\}=F(u,v)G(u,v) \tag{A10}$$

6. Autocorrelation theorem

$$\Im\left\{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}f^*(x',y')f(x+x',y+y')dx'dy'\right\}=|F(u,v)|^2 \tag{A11}$$

7. Fourier integral theorem

$$\Im\Im^{-1}\{f(x,y)\} = \Im^{-1}\Im\{f(x,y)\} = f(x,y) \tag{A12}$$

8. Differentiation

Differentiation in the spatial domain corresponds to a multiplication with a linear factor in the spatial frequency domain:

$$\Im\left\{\left(\frac{\partial}{\partial x}\right)^m \left(\frac{\partial}{\partial y}\right)^n f(x,y)\right\} = (i2\pi u)^m (i2\pi v)^n F(u,v) \tag{A13}$$

A3 The Discrete Fourier Transform

For numerical computations the function to be transformed is given in a discrete form, i. e. $f(x)$ in Eq. (A.1) has to be replaced by the finite series f_k, with integer numbers $k = 0,1,...,N-1$. The continuous variable x is now described as integer multiple of a sampling interval Δx:

$$x = k\Delta x \tag{A14}$$

The frequency variable u is converted into a discrete variable, too:

$$u = m\Delta u \tag{A15}$$

The discrete representation of Eq. (A.1) is then given by:

$$F_m = \Delta x \sum_{k=0}^{N-1} f_k \exp[-i2\pi km\Delta x\Delta u] \quad \text{for } m = 0,1,...,N-1 \tag{A16}$$

The maximum frequency is determined by the sampling interval in the spatial domain:

$$u_{\max} = N\Delta u = \frac{1}{\Delta x} \tag{A17}$$

The following expression

$$F_m = \frac{1}{N}\sum_{k=0}^{N-1} f_k \exp\left[-i2\pi\frac{km}{N}\right] \tag{A18}$$

is therefore defined as one-dimensional *discrete Fourier transform* (DFT). The inverse transformation is given by

$$f_k = \sum_{m=0}^{N-1} F_m \exp\left[i2\pi \frac{km}{N} \right] \tag{A19}$$

Similar considerations lead to the discrete two-dimensional Fourier transform pair:

$$F_{mn} = \frac{1}{N^2} \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} f_{kl} \exp\left[-i2\pi \left(\frac{km + ln}{N} \right) \right] \tag{A20}$$

$$f_{kl} = \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} F_{mn} \exp\left[i2\pi \left(\frac{km + ln}{N} \right) \right] \tag{A21}$$

for $m = 0,1,...N-1$ and $n = 0,1,...N-1$

Here a quadratic field of sampling points is used, i. e. the number of points in each row is equal to that in each column.

The computation time for a discrete Fourier transform is mainly determined by the number of complex multiplications. A two-dimensional DFT can be factorised into two one-dimensional DFT's:

$$F_{mn} = \frac{1}{N^2} \sum_{k=0}^{N-1} \left[\sum_{l=0}^{N-1} f_{kl} \exp\left(-i2\pi \frac{nl}{N} \right) \right] \exp\left(-i2\pi \frac{km}{N} \right) \tag{A22}$$

The one-dimensional DFT can be programmed most effectively using the so called *fast fourier transform* (FFT) algorithms, invented in the 70th of the last century by Cooley and Tookey. These algorithms make use of redundancies and reduce the number of multiplications for a one-dimensional DFT from N^2 to $2N \log_2 N$. The FFT algorithms are not described here, it is referred to the literature [10].

B Phase Transformation of a Spherical Lens

B1 Lens Transmission Function

The effect of an optical component with refractive index n and thickness d on the complex amplitude of a wave is described by a transmission function τ:

$$\tau = |\tau| \exp\left[-i \frac{2\pi}{\lambda}(n-1)d\right] \tag{B1}$$

This function is calculated in the following for a thin biconvex lens. Such lens consists of two spherical surfaces, see figure B.1. The radius of curvature of the left half lens is R_1, while that of the right half lens is designated R_2. Following sign convention is applied: As rays travel from left to right, each convex surface has a positive radius of curvature, while each concave surface has a negative radius of curvature. Due to this convention R_2 has a negative value. Losses due to reflection at the surfaces and due to absorption inside the lens are neglected; i. e. $|\tau| = 1$. The refractive index is constant for the entire lens.

The lens thickness is a function of the spatial coordinates x and y:

$$\begin{aligned} d(x,y) &= d_1(x,y) + d_2(x,y) \\ &= d_{01} - \zeta_1 + (d_{02} - \zeta_2) \end{aligned} \tag{B2}$$

According to figure B.1 it can be written:

$$\begin{aligned} R_1^{\,2} &= r^2 + (R_1 - \zeta_1)^2 \\ &= x^2 + y^2 + R_1^{\,2} - 2R_1\zeta_1 + \zeta_1^{\,2} \end{aligned} \tag{B3}$$

and

$$\begin{aligned} R_2^{\,2} &= r^2 + (-R_2 - \zeta_2)^2 \\ &= x^2 + y^2 + R_2^{\,2} + 2R_2\zeta_2 + \zeta_2^{\,2} \end{aligned} \tag{B4}$$

Neglecting the quadratic terms of $\zeta_{1/2}$ leads to:

$$\zeta_1 = \frac{x^2 + y^2}{2R_1} \tag{B5}$$

$$\zeta_2 = -\frac{x^2 + y^2}{2R_2} \tag{B6}$$

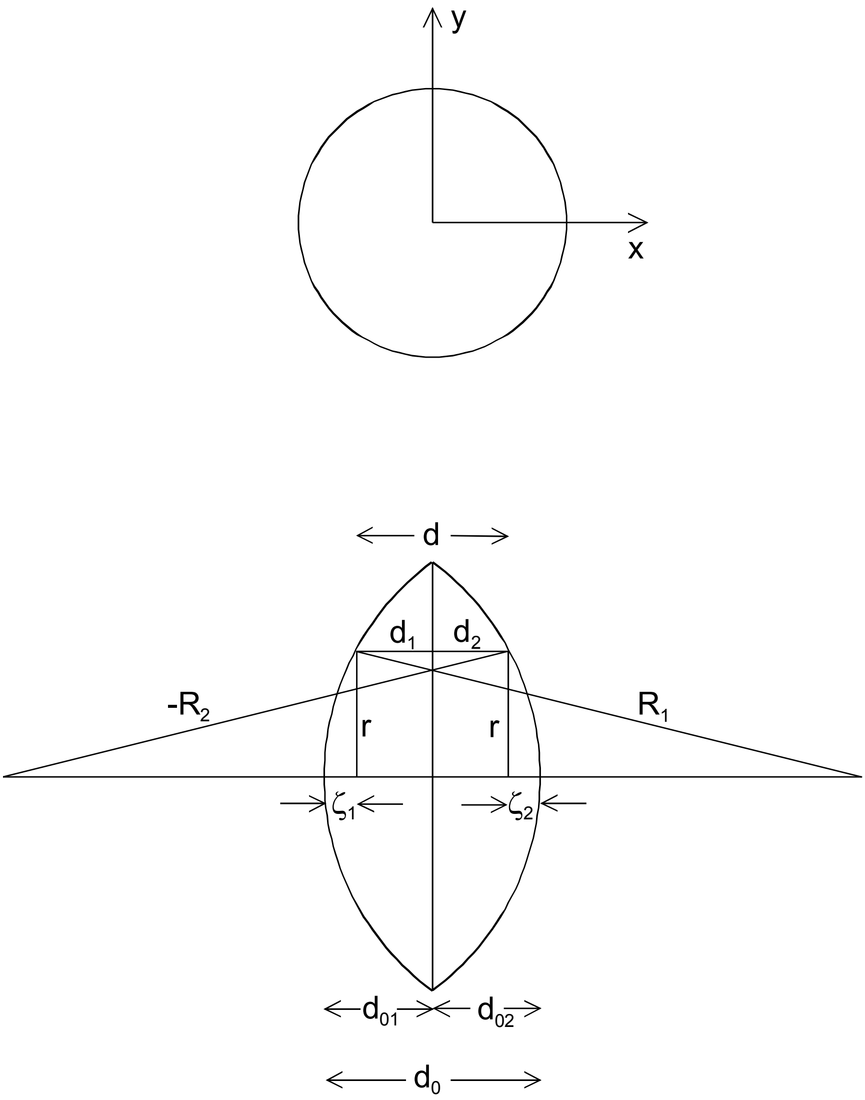

Fig. B.1. Biconvex lens, top view and cross-sectional view

This level of approximation is consistent with the parabolic approximation used in the Fresnel transformation. The thickness is now

$$d(x,y) = d_0 - \frac{x^2 + y^2}{2R_1} + \frac{x^2 + y^2}{2R_2} \tag{B7}$$

With the lens makers equation

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right] \tag{B8}$$

of geometrical optics following lens transmission function is derived:

$$L(x, y) = \exp\left[i\frac{\pi}{\lambda f}\left(x^2 + y^2\right)\right] \tag{B9}$$

The constant factor $\exp(-i\,2\pi/\lambda\,(n-1)d_0)$, which only effects the overall phase, has been neglected.

B2 Correction of Aberrations

In the following the complex amplitude of an object, which is imaged by a lens is calculated. The object is lying in the (ξ, η) coordinate system, the lens is located in the (x,y) system and the image arises in the (ξ', η') system, see figure B.2. The object is described by the complex amplitude $E_O(\xi, \eta)$.

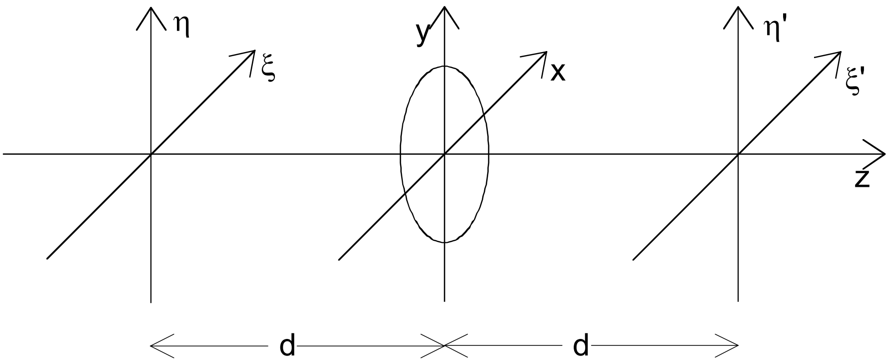

Fig. B.2. Image formation

The complex amplitude in front of the lens is given by

$$E_O'(x, y) = \exp\left[-i\frac{\pi}{\lambda d}\left(x^2 + y^2\right)\right]\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_O(\xi, \eta)\exp\left[-i\frac{\pi}{\lambda d}\left(\xi^2 + \eta^2\right)\right] \times \exp\left[i\frac{2\pi}{\lambda d}\left(x\xi + y\eta\right)\right]d\xi d\eta \tag{B10}$$

where the Fresnel approximation is used. The complex amplitude in the image plane in then given by

$$
\begin{aligned}
&E_O''(\xi',\eta') &\text{(B11)}\\
&= \exp\left[-i\frac{\pi}{\lambda d}\left(\xi'^2+\eta'^2\right)\right]\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_O'(x,y)L(x,y)\exp\left[-i\frac{\pi}{\lambda d}\left(x^2+y^2\right)\right]\\
&\times\exp\left[i\frac{2\pi}{\lambda d}\left(x\xi'+y\eta'\right)\right]dxdy\\
&= \exp\left[-i\frac{\pi}{\lambda d}\left(\xi'^2+\eta'^2\right)\right]\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_O(\xi,\eta)\exp\left[-i\frac{\pi}{\lambda d}\left(x^2+y^2\right)\right]\\
&\times\exp\left[-i\frac{\pi}{\lambda d}\left(\xi^2+\eta^2\right)\right]\exp\left[i\frac{2\pi}{\lambda d}\left(x\xi+y\eta\right)\right]\exp\left[i\frac{2\pi}{\lambda d}\left(x^2+y^2\right)\right]\\
&\times\exp\left[-i\frac{\pi}{\lambda d}\left(x^2+y^2\right)\right]\exp\left[i\frac{2\pi}{\lambda d}\left(x\xi'+y\eta'\right)\right]d\xi d\eta dxdy
\end{aligned}
$$

A magnification of 1 and a focal distance of $f = d/2$ is used for the lens transmission function $L(x,y)$.

The image coordinates can be expressed in terms of the object coordinates:

$$\xi' = -\xi \quad \text{and} \qquad \eta' = -\eta \tag{B12}$$

The minus signs result, because according to the laws of geometrical optics the image is upside down.

The complex amplitude of the image is now

$$
\begin{aligned}
E_O''(\xi',\eta') &= \exp\left[-i\frac{2\pi}{\lambda d}\left(\xi'^2+\eta'^2\right)\right]E_O(-\xi',-\eta')\\
&= \exp\left[-i\frac{\pi}{\lambda f}\left(\xi'^2+\eta'^2\right)\right]E_O(-\xi',-\eta')
\end{aligned}
\tag{B13}
$$

The wavefield in the image plane has to be multiplied therefore by a factor

$$P(\xi',\eta') = \exp\left[i\frac{\pi}{\lambda f}\left(\xi'^2+\eta'^2\right)\right] \tag{B14}$$

in order to generate the correct phase distribution.

This correction factor depends on the wavelength and on the coordinates of the image plane. It can be neglected, if only the intensity of a wavefield has to be calculated after reconstruction ($I \propto P^*P = 1$). This is also valid, if the phase difference of two wavefields, which are recorded with the *same* wavelength, is computed:

$$
\begin{aligned}
\Delta\varphi &= \varphi_1 - \varphi_2 = i\pi/\lambda f\left(\xi'^2+\eta'^2\right)+\varphi_1' - \left[i\pi/\lambda f\left(\xi'^2+\eta'^2\right)+\varphi_2'\right]\\
&= \varphi_1' - \varphi_2'
\end{aligned}
\tag{B15}
$$

This is usually the case in DHI for applications in deformation analysis. However, the correction factor has to be considered, if the phase difference of two wavefields, which are recorded with *different* wavelengths, is computed. This is the case in multi-wavelength DHI for shape measurement.

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