Ultrasonic Microscope Manual（Ver. 1.0）

2022.12 AO Quest

Introduction

This software simulates the beam from the ultrasonic transducer. Mainly, you can see “How much is the focused beam’s power?” This subject is advanced simulation based on wave optics.
In detail, the software simulates that the ultrasonic outputted from the transducer’s end propagates through medium I (e.g. water), then medium II (e.g. mold resin of semiconductor), at last the ultrasonic beam focuses the face of the observation target (e.g. metal wiring etc.).

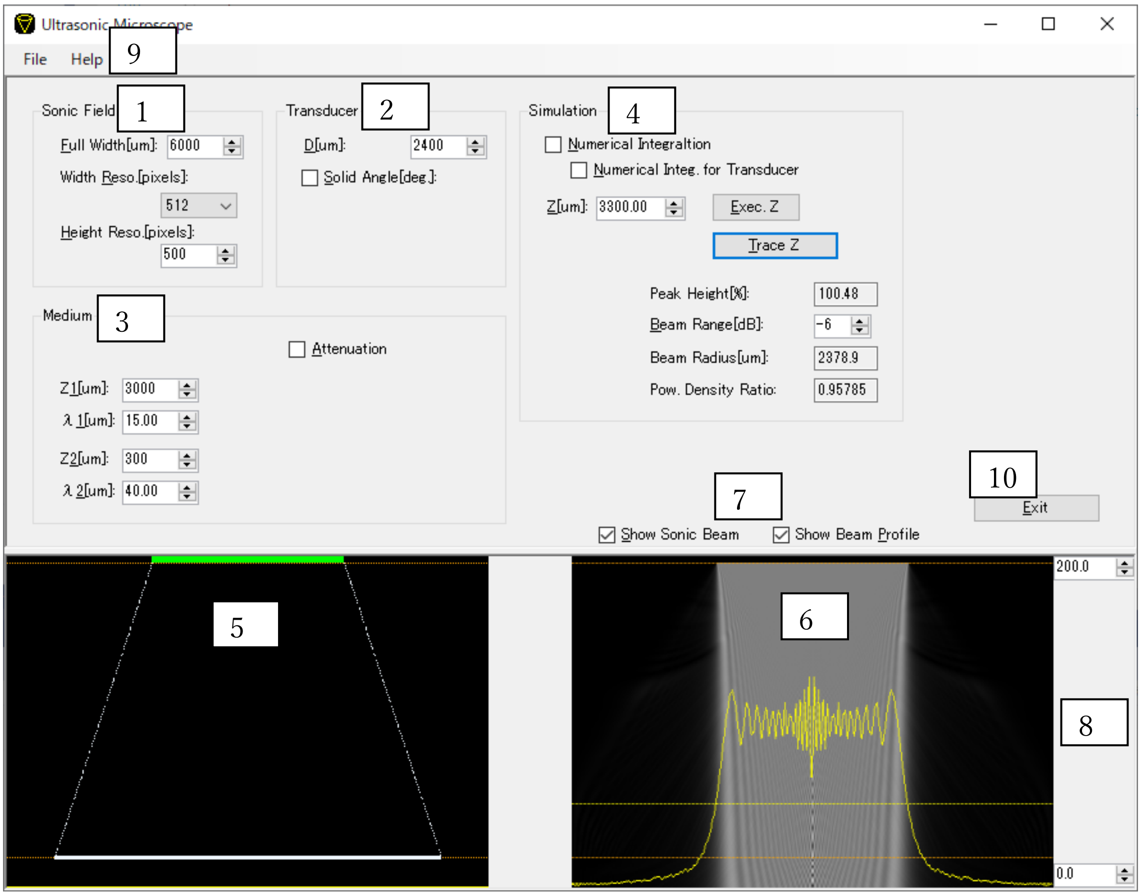
Operation Environment

＊Windows10 64bit, or later
＊. Net Framework4.8

Installation Method

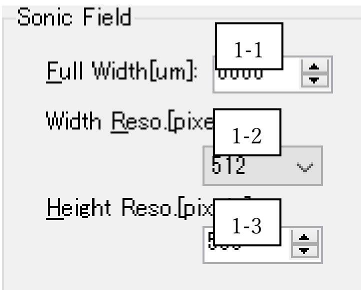
There isn’t installer. Copy the software-folder to any local directory, then execute the software(UltrasonicMicroscope.exe).

Software Function Description



1. Sonic Field

   Set sonic field.



1-1. Full Width

Set sonic field's width[um].

1-2. Width Reso.

Set the resolution of sonic field's width by pixels(sampling count).

1-3. Height Reso.

Set the resolution of sonic field's height by pixels(sampling count). As the software uses FFT(Fast Fourier Transform) , this is 2's power value.

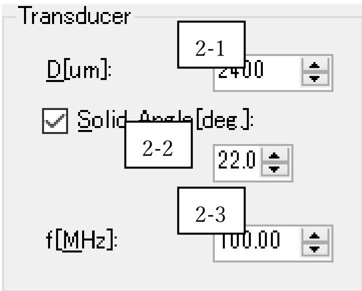
Resulting from (1-2) and this section(1-3),

Width Reso ×Width Reso×Height Reso

the software will simulate in this rectangular.

2. Transducer

Set the transducer. The transducer's aperture is a circle and you can not modify this shape.



2-1. D

Set the transducer's diameter[um].

2-2. Solid Angle

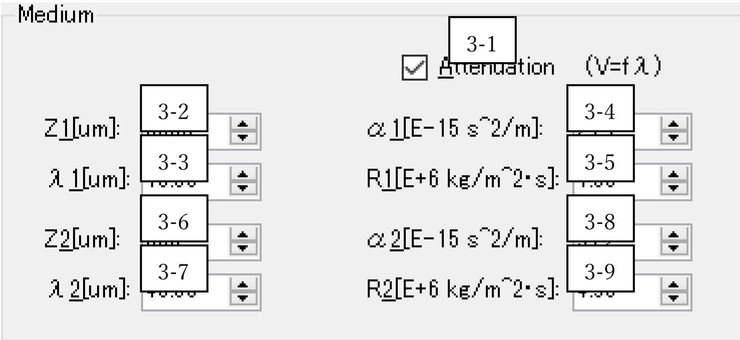
Set the transducer's solid angle[°]. If not checked, the transducer will be a flat plate.

2-3. f

Set the frequency[MHz] to apply to the transducer. This is a parameter for implementing the attenuation model(3-1) through the medium. Basically, the frequency is set by wavelength at medium of next section(3) .

3. Medium

Set medium I and medium II.



3-1. Attenuation

Implement the attenuation through the medium propagation and transmittance between the mediums to simulation model.

3-2. Z1

Set medium Ⅰ's height(thickness)[um].

3-3. λ1

Set the wavelength[um] at medium Ⅰ.

3-4. α1

Set medium Ⅰ's attenuation coefficient[$\times 10^{-15}\ s^2/m$].

3-5. R1

Set medium Ⅰ's acoustic impedance[$\times 10^6\ kg/m^2 \cdot s$]. Transmittance at the medium border will be guided from acoustic impedance's ratio.

3-6. Z2

Set medium Ⅱ's height(thickness)[um].

3-7. λ2

Set the wavelength[um] at medium Ⅱ.

3-8. α2

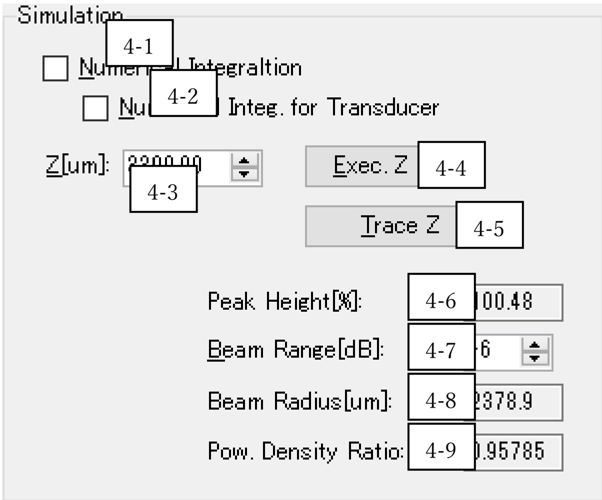
Set medium Ⅱ's attenuation coefficient[$\times 10^{-15}\ s^2/m$.

3-9. R2

Set medium Ⅱ's acoustic impedance[$\times 10^6\ kg/m^2 \cdot s$]. Transmittance at the medium border will be guided from acoustic impedance's ratio.

4. Simulation

Execute the simulation.



4-1. Numerical Integration

Set whether to simulate the propagation by spatial domain's numerical integration without using the transfer function for the spectrum.

4-2. Numerical Integ. For Transducer

The transducer which has curvature -in the case that transducer's solid angle was set(2-2), set whether to simulate the propagation to the transducer's end face through medium I .

4-3. Z

Set the distance Z from the transducer's end face as observation face. The observation face will be displayed by yellow line which is Z Position of Observation face(5-5).

4-4. Exec. Z

Simulate the beam profile of the observation face Z described in preceding paragraph(4-3) .

4-5. Trace Z

Trace the sonic propagation from the transducer to the bottom of medium II . The trace's process will be displayed at Beam Display Pane(6).

4-6. Peak Height

Peak intensity[%] of the beam profile will be displayed. This is based on the amplitude of transducer's end face(source vibration) as 100%.

4-7. Beam Range

Set the range of the beam power to calculate at the observation face. In the case that the range of calculating the power is half width at half maximum for the beam profile's peak, set -6dB.

4-8. Beam Radius

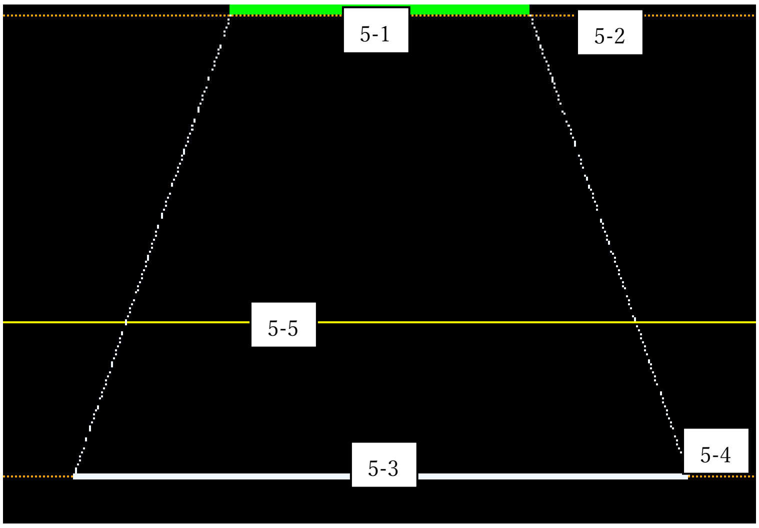
The radius for the range of calculating the power will be displayed. The radius is guided from Beam Range(4-7).

4-9. Pow. Density Ratio

The power density's ratio of the transducer's end face and the observation face will be displayed. The power density is amplitude intensity per pixel unit area(see 1-2). This can check how much the focused power is.

5. Sonic Field Display Pane

The condition of sonic field's settings will be displayed.



5-1. Transducer

The transducer is displayed by green line.

5-2. Border between Transducer and Medium I

The border between the transducer and medium I is displayed by dashed orange line. This line's width will be the simulation space's width.

5-3. Critical Angle Range

The range of critical angle is displayed by white line. Critical angle is guided from medium I 's wavelength(3-3) and medium II 's wavelength(3-7).

5-4. Border between Medium I and Medium II

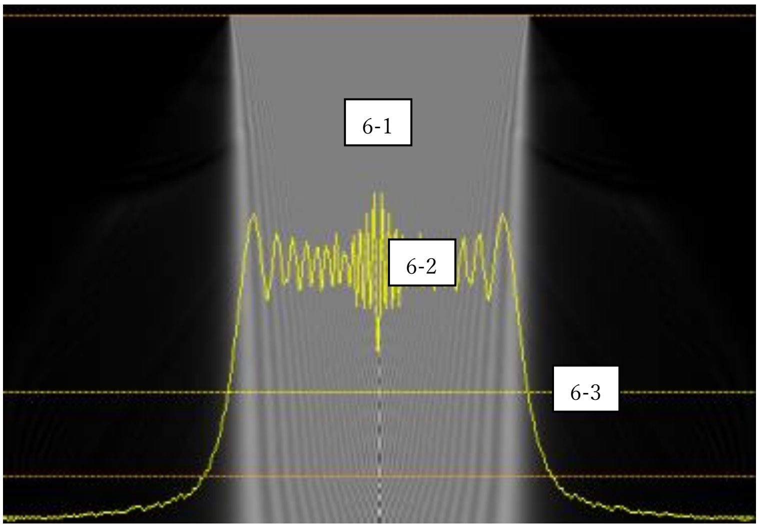
The border between medium I and medium II is displayed by dashed orange line.

5-5. Z Position of Observation Face

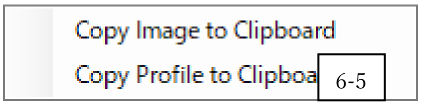
The observation face Z(4-3) is displayed by yellow line.

6. Beam Display Pane

This pane displays the beam image and the beam profile resulting from simulation.



In addition, a context menu can be opened on the pane.



6-1. Beam Image

The beam profile is displayed by monochrome image. The image can be displayed by Trace Z(4-5). The image's display state can be modified or adjusted by Show

Sonic Beam/ Show Beam Profile(7), Beam Image Contrast(8).

6-2. Beam Profile

The beam profile at the observation face Z(4-3) is displayed by yellow line.

6-3. Base Line of Beam Diameter

The level line to calculate the range of the beam power is displayed by dashed yellow line.

6-4. Copy Image to Clipboard

Copy the beam image(6-1) to clipboard.

6-5. Copy Profile to Clipboard

Copy the beam profile(6-2) to clipboard by CSV text format.

7. Show Sonic Beam/ Show Beam Profile

Modify the display state of Beam Display Pane(6).

7-1. Show Sonic Beam

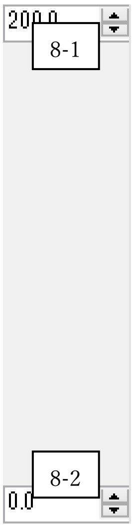
Set whether to display Beam Image(6-1).

7-2. Show Beam Profile

Set whether to display Beam Profile(6-2) and Base Line of Beam Diameter(6-3).

8. Beam Image Contrast

Adjust the contrast of the beam image(6-1). Set thresholds' percentage for adjusting the contrast which is based on source vibration's amplitude as 100%.



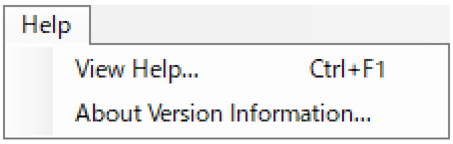
8-1. Upper Limit Threshold

Set the upper limit threshold for contrast. If the beam intensity is equal or greater than this threshold, the beam will be displayed by white(255).

8-2. Lower Limit Threshold

Set the lower limit threshold for contrast. If the beam intensity is equal or less than this threshold, the beam will be displayed by black(0).

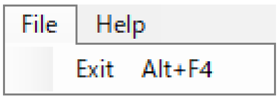
9. Help



View Help	Display Help (this document).
About Version Information	Display Version information.

10. Exit

Exit the software. This can be available from File Menu.



Appendix

Light and Sonic Wave Function

Generally, sonic wave is based on Helmholtz equation(1).

$$(\nabla^2 + k^2)U = \nabla^2 U + k^2 U = 0 \quad (1)$$

$$k = \frac{2\pi}{\lambda} \quad (2)$$

First, this paper mentions (1)'s derivation. Here, k is wave number of pieces per unit length ($\times 2\pi$), it is described as wave number(to be exact, angular wave number)(2). As wave function is the function of position and time, if this is assumed as scalar function, it is considered as scalar theory.

By contrast, Maxwell equation which describes light is (3)〜(6). However, it is assumed that there is only electromagnetic field without current and charge(in vacuum etc.) as following.

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \quad (3)$$

$$\nabla \times \vec{H} = \epsilon \frac{\partial \vec{E}}{\partial t} \quad (4)$$

$$\nabla \epsilon \vec{E} = 0 \quad (5)$$

$$\nabla \mu \vec{H} = 0 \quad (6)$$

t: Time

μ: medium's magnetic permeability

ϵ: medium's electric permittivity

$E = E(x, y, z)$: electric field

$H = H(x, y, z)$: magnetic field

x, y, z: space axis

$\nabla \times$=rot: rotation(cross product)

$\nabla = \frac{\partial}{\partial \mathrm{x}}\hat{\imath} + \frac{\partial}{\partial \mathrm{y}}\hat{\jmath} + \frac{\partial}{\partial \mathrm{z}}\hat{k}$: gradient

$\hat{\imath}, \hat{\jmath}, \hat{k}$: x, y, z axis's unit vector

Here, Helmholtz equation can be derived from Maxwell equation. (3) means that if the electric field is given the minute fluctuation(rotation in space), i.e. it expresses to become the minute fluctuation(time variation) for magnetic field.
Now, add rotation to (3)'s left side moreover, then apply (5), it becomes (7).

$$\nabla \times \left(\nabla \times \vec{E}\right) = \nabla\left(\nabla \cdot \vec{E}\right) - \nabla^2 \vec{E} = -\nabla^2 \vec{E} \quad (7)$$

By contrast, add rotation to (3)'s right side too, apply (4), it becomes (8).

$$\nabla \times \left(\nabla \times \vec{E}\right) = \nabla \times \left(-\mu \frac{\partial \vec{H}}{\partial t}\right) = -\mu \nabla \times \frac{\partial \vec{H}}{\partial t} = -\mu \frac{\partial\left(\nabla \times \vec{H}\right)}{\partial t}$$

$$= -\mu \frac{\partial}{\partial t}\left(\epsilon \frac{\partial \vec{E}}{\partial t}\right) = -\mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} \quad (8)$$

Unite, it can be (9).

$$\nabla^2 \vec{E} - \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad (9)$$

It can also be solved for magnetic field (10).

$$\nabla^2 \vec{H} - \mu\epsilon \frac{\partial^2 \vec{H}}{\partial t^2} = 0 \quad (10)$$

Here, light speed and medium refractive index are defined by (11), (12) respectively.

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad (11)$$

$$n = \sqrt{\frac{\epsilon}{\epsilon_0}} \quad (12)$$

μ_0: magnetic permeability in a vacuum

ϵ_0: electric permittivity in a vacuum

Transform (12), then it becomes (13).

$$\epsilon_0 = \epsilon / n^2 \quad (13)$$

Substitute this to (11), it becomes (14).

$$c^2 = \frac{1}{\mu_0 \epsilon_0} = \frac{n^2}{\mu_0 \epsilon}$$

$$\epsilon = \frac{n^2}{\mu_0 c^2} \quad (14)$$

Therefore, assume $\mu = \mu_0$, it becomes (15).

$$\mu\epsilon = \mu\frac{n^2}{\mu_0 c^2} = \mu_0\frac{n^2}{\mu_0 c^2} = \frac{n^2}{c^2} \quad (15)$$

Substitute this to (9), (10), it can be (16), (17).

$$\nabla^2\vec{E} - \frac{n^2}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = 0 \quad (16)$$

$$\nabla^2\vec{H} - \frac{n^2}{c^2}\frac{\partial^2\vec{H}}{\partial t^2} = 0 \quad (17)$$

These are (18)'s format representing wave function u.

$$\nabla^2 u - \frac{n^2}{c^2}\frac{\partial^2 u}{\partial t^2} = 0 \quad (18)$$

In detail, try to consider the wave as polar coordinates function(19).

$$u(r,t) = A(r)\cos\big(2\pi f - \varphi(r)\big) = Re\{U(r)\exp(-i2\pi ft)\} \quad (19)$$

$$U(r) = A(r)\exp\big(-i\varphi(r)\big)$$

$$r = \sqrt{x^2 + y^2 + z^2}$$

A: amplitude function

φ: phase function

f: frequency

Substitute this to (18), it becomes (20).

$$\nabla^2 Re\{U(r)\exp(-i2\pi ft)\} - \frac{n^2}{c^2}\frac{\partial^2}{\partial t^2}Re\{U(r)\exp(-i2\pi ft)\} = 0$$

$$\nabla^2 U(r)\cdot Re\{\exp(-i2\pi ft)\} - \frac{n^2}{c^2}U(r)Re\left\{\frac{\partial^2}{\partial t^2}\exp(-i2\pi ft)\right\} = 0$$

$$\nabla^2 U(r)\cdot Re\{\exp(-i2\pi ft)\} - \frac{n^2}{c^2}U(r)\cdot(-4\pi^2 f^2)\cdot Re\{\exp(-i2\pi ft)\} = 0$$

$$\nabla^2 U(r) + \frac{4\pi^2 f^2 n^2}{c^2}U(r) = 0 \quad (20)$$

Here, wave number's definition (2) can be also written by (21).

$$k = \frac{2\pi}{\lambda} = \frac{2\pi fn}{c} \quad (21)$$

$$\left(\lambda = \frac{c}{fn}\right)$$

Substitute this to (20), it becomes (1), already mentioned.

$$\nabla^2 U(r) + k^2 U(r) = 0 \quad (1)$$

Up to now, put together simply for light and sonic wave.

* Light wave has 2 waves, electric field and magnetic field.
* Sonic wave has only one wave.
* It has a relation between electric field and magnetic field that the minute Fluctuation is rotation (cross product) for each other.

Propagation (Diffraction) Transfer Function

Derive propagation's transfer function from Helmholtz equation(1). First, frequency transform (Fourier transform) is defined as (22), (23) where the diffraction wave is g.

$$G(u,v,z)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}g(x,y,z)\exp\big(-i2\pi(ux+vy)\big)\,dxdy \quad (22)$$

$$g(x,y,z)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G(u,v,z)\exp\big(i2\pi(ux+vy)\big)\,dudv \quad (23)$$

Substitute (23) to (1), it becomes (24).

$$(\nabla^2+k^2)g=0 \quad (24)$$

$$(\nabla^2+k^2)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G(u,v,z)\exp\big(i2\pi(ux+vy)\big)\,dudv=0$$

Integral and differential can be exchanged in the case that the function is continuous and partially differentiable (25).

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(\nabla^2+k^2)\big\{G(u,v,z)\exp\big(i2\pi(ux+vy)\big)\big\}\,dudv=0 \quad (25)$$

Here, assume (26).

$$(\nabla^2+k^2)\big\{G(u,v,z)\exp\big(i2\pi(ux+vy)\big)\big\}=0 \quad (26)$$

If (26), then it results to (25). By contrast, (25) to (26) is NG. However, u,v are variable, then left side of (26) must be an odd function which can make integral value 0 (zero). In the other hand, the object of (26)'s operator (∇^2+k^2) has the transfer function, and this integral is never limited by the odd function. Hereby, it is considered as a differential equation and its solution should be the transfer function. Therefore, (26) is considered as necessary and sufficient conditions. Expand (26), it becomes (27).

$$\begin{aligned}(\nabla^2+k^2)&\big\{G(u,v,z)\exp\big(i2\pi(ux+vy)\big)\big\}\\&=\nabla\left\{\left(\frac{\partial}{\partial x}\hat{\imath}+\frac{\partial}{\partial y}\hat{\jmath}+\frac{\partial}{\partial z}\hat{k}\right)\big\{G(u,v,z)\exp\big(i2\pi(ux+vy)\big)\big\}\right\}\\&+k^2\,G(u,v,z)\exp\big(i2\pi(ux+vy)\big)=0 \quad (27)\end{aligned}$$

Put S for the red letter part, then continue to expand(28).

$$S = \left(\frac{\partial}{\partial x}\hat{\imath} + \frac{\partial}{\partial y}\hat{\jmath} + \frac{\partial}{\partial z}\hat{k}\right)\{G(u,v,z)\exp\big(i2\pi(ux+vy)\big)\}$$

$$= i2\pi u \cdot G(u,v,z)\exp\big(i2\pi(ux+vy)\big) + i2\pi v \cdot G(u,v,z)\exp\big(i2\pi(ux+vy)\big)$$

$$+ \exp\big(i2\pi(ux+vy)\big)\frac{\partial}{\partial z}G(u,v,z) \quad (28)$$

Moreover, apply gradient(29).

$$\nabla S = \left(\frac{\partial}{\partial x}\hat{\imath} + \frac{\partial}{\partial y}\hat{\jmath} + \frac{\partial}{\partial z}\hat{k}\right)S$$

$$= -4\pi^2 u^2 \cdot G(u,v,z)\exp\big(i2\pi(ux+vy)\big) - 4\pi^2 v^2$$

$$\cdot G(u,v,z)\exp\big(i2\pi(ux+vy)\big) + \exp\big(i2\pi(ux+vy)\big)\frac{\partial^2}{\partial z^2}G(u,v,z)$$

$$= -4\pi^2(u^2+v^2)\,G(u,v,z)\exp\big(i2\pi(ux+vy)\big)$$

$$+ \exp\big(i2\pi(ux+vy)\big)\frac{\partial^2}{\partial z^2}G(u,v,z) \quad (29)$$

Substitute this to (27), it becomes (30).

$$-4\pi^2(u^2+v^2)\,G(u,v,z)\exp\big(i2\pi(ux+vy)\big) + \exp\big(i2\pi(ux+vy)\big)\frac{\partial^2}{\partial z^2}G(u,v,z)$$

$$+ k^2\,G(u,v,z)\exp\big(i2\pi(ux+vy)\big) = 0 \quad (30)$$

The exponent can be eliminated because of the common term, it can be (31).

$$-4\pi^2(u^2+v^2)G(u,v,z) + \frac{\partial^2}{\partial z^2}G(u,v,z) + k^2 G(u,v,z) = 0 \quad (31)$$

$$\frac{\partial^2}{\partial z^2}G(u,v,z) = -\{k^2 - 4\pi^2(u^2+v^2)\}G(u,v,z)$$

As second differential leads to same format function, the function which satisfies this must be exponent function(32).

$$G(u,v,z) = \exp\left(i\sqrt{k^2 - 4\pi^2(u^2+v^2)}\cdot z\right)$$

$$= \exp\left(iz\sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - 4\pi^2(u^2+v^2)}\right)$$

$$= \exp\left(i2\pi z\sqrt{\frac{1}{\lambda^2} - u^2 - v^2}\right) \quad (32)$$

As a caution, while deriving from (31), it is necessary to wrap up imaginary number i from the square. This means that the square's inside must be a positive number, then the transfer function must be defined in the scale longer than the wavelength. Up to now, roughly however, it is reached to the transfer function of First Rayleigh Sommerfeld solution(33) [1] described in wave optics.

$$H(u,v;z) = \begin{cases} \exp\left(i2\pi z\sqrt{\frac{1}{\lambda^2} - u^2 - v^2}\right) & u^2 + v^2 \leq \frac{1}{\lambda^2} \\ 0 : & u^2 + v^2 > \frac{1}{\lambda^2} \end{cases} \quad (33)$$

At last, the function which expresses diffraction is called as Green function. And transfer function G would be its spectrum expression.

Numerical Calculation Model

This software calculates sonic wave's propagation by transfer function G(33)(**Fig.1**).

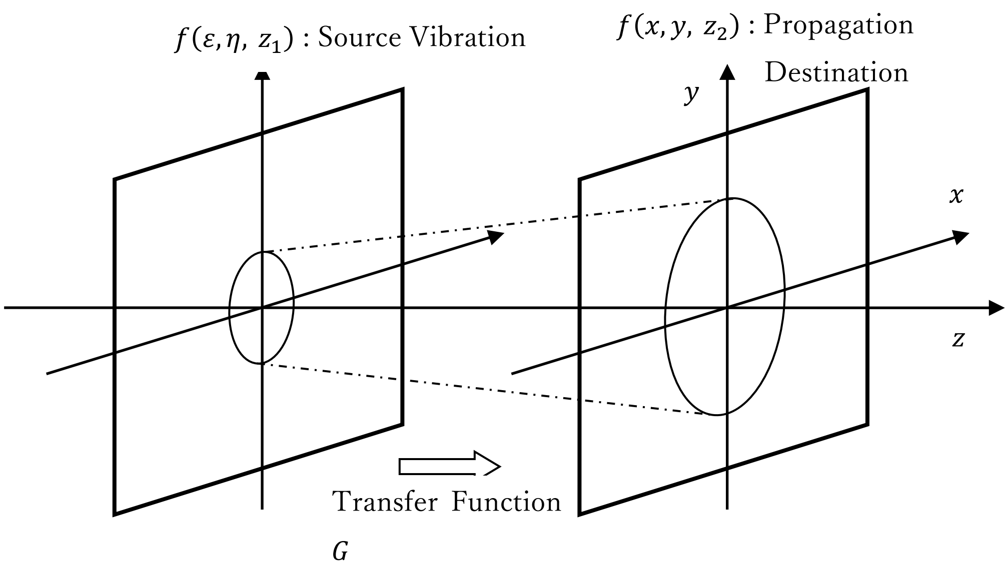


Fig.1 Wave Propagation (Diffraction)

The flow is shown in **Fig.2**.

$f(\varepsilon, \eta, z_1) \to F$: Fourier transform

⇩

$F \times G = F'$: Multiply Transfer function

⇩

$F' \to f(x, y, z_2)$: Inverse Fourier transform

Fig.2 Calculation Flow for Propagation (Diffraction)

In the case using the transfer function, this **Fig.2** flow will be repeated between the transducer, medium's border, and the observation face by sequentially. In addition, for processing the solid angle, the curve's each point(according to z resolution) is applied by this sequence. Here, for the case 0(zero) for (33), there is a concern that the diffraction wave will not be constructed perfectly. However the detail profile just can not be constructed by high frequencies, it is not that the energy will lost. The energy is always kept in 0 order(DC component). As a result, in a tiny distance, it is considered as an approximation. The author thinks that (36) described later represents this, or has of a relation.

It is calculated by Huygens-Fresnel principle in the case of numerical integration(34).

$$f(x, y, z_2) = \iint f(\varepsilon, \eta, z_1)\ g(r) d\varepsilon d\eta \quad (34)$$

$$g(r) = \frac{z_2 - z_1}{i\lambda} \frac{\exp(ikr)}{r^2} \quad (35)$$

$$r = \sqrt{(z_2 - z_1)^2 + (x - \varepsilon)^2 + (y - \eta)^2}$$

necessary $r \gg \lambda$ (36)

In the case of numerical integration compared to the transfer function, following points are poor.

＊precision decrease by repeating four arithmetic operations in addition to decrease,

In addition, about Green function, the author thinks Fourier transform of g is not strictly equals to G. The author's trial could not reach to mathematics proof. If it was possible to prove by mathematics, its correlation might be written on mathematics formula collection. Moreover, (34) is approximation described in wave optics and (36) is an assumption[1]. The former means the assumption in scalar diffraction theory (1). And (36) is same condition for (33). From above, the author considers the correlation of Green function's Fourier transform as the recognition in physics, and also as the approximation. In that case, it may be considered that the transfer function derived from differential equation (1) is a more precise expression. About Numerical integration (35), this is only a physicality that the wave decreases inversely with the square of the distance.

About Attenuation Model

Attenuation coefficient will be multiplied in the space domain for sonic propagation in the medium. As multiplication in the space domain is equivalent to convolution in the spectrum, it is difficult to apply attenuation coefficient to the spectrum directly. This software works by the method that applies Inverse Fourier transform to the transfer function, then applies attenuation coefficient in the space domain, applies Fourier transform, and reconstructs the transfer function. Applying critical angle's limitation and transmittance between mediums will be also done in the space domain.

References

[1] Joseph W. Goodman. Introduction to Fourier Optics 3rd edition.
Morikita shuppan. 2012.

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Inquiry

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